Wright Brothers Lecture

On the Threshold—The Outlook for Supersonic and Hypersonic Aircraft

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Introduction

I AM deeply honored to have been selected to present the 52nd in this series of lectures commemorating the first powered flights made by Orville and Wilbur Wright at Kill Devil Hill, North Carolina, in 1903. To stand in the shadow of past Wright Brothers lecturers such as Hugh Dryden, John Stack, and Theodore von Kármán (to name only a few) is a humbling experience indeed.

This year we celebrate the 86th anniversary of that December morning when the Wright *Flyer* first successfully flew under its own power. This year also marks (Fig. 1) 42 years since the first supersonic flight of the Bell X-1, 28 years since the North American X-15 first extended the realm of flight into the hypersonic regime, 25 years of Mach 3 military service by the Lockheed SR-71, and 13 years of supersonic airline service by the free world's first supersonic airliner, the British/French Concorde.[1] So perhaps it is fitting that the Wright Brothers Lecture this year is devoted to future prospects for supersonic and hypersonic aircraft.

The thesis of my lecture is that we are on the threshold of a new era of supersonic and hypersonic aviation. The new generation of aircraft that I envision will not replace the need for large numbers of subsonic aircraft for shorter-range flights, but will be needed for new very long-range commercial markets and military missions. I also believe we have a large storehouse of technical knowledge and an ample supply of practical experience to prepare us for this venture. However, some very significant technical challenges remain. I intend to briefly review our past experiences with supersonic and hypersonic aircraft, make some projections about what kind of flight vehicles might be next on the horizon, and describe the technical challenges that must be met in order to bring in the new era of supersonic and hypersonic flight.

U.S. Flight Experience and Past Research and Development Efforts

The exploration of supersonic flight by the X-airplanes in the late 1940s and early 1950s was followed (Fig. 2) by the development of the Century Series of military fighters in the mid 1950s.[2] These aircraft were the first to routinely operate at speeds up to Mach 2 and some, such as the Lockheed F-104, have remained operational into the 1980s. In addition, two supersonic bombers were developed in the 1955–1965 time frame. The Convair B-58 had a Mach 2 maximum speed, and the North American XB-70 prototypes had a Mach 3 cruise capability. The Mach 3+ Lockheed SR-71 was also developed in this time period. After the launch of Sputnik in 1958, the military services shifted their emphasis from ever-faster airplanes to the development of rocket-launched orbital vehicles. Emphasis on military aircraft design shifted to more accurate weapons delivery and more maneuverable fighters. The Century Series fighters were superseded by more advanced supersonic fighters such as the McDonnell F-4, Northrop F-5, and General Dynamics F-111 in the 1960s, and the

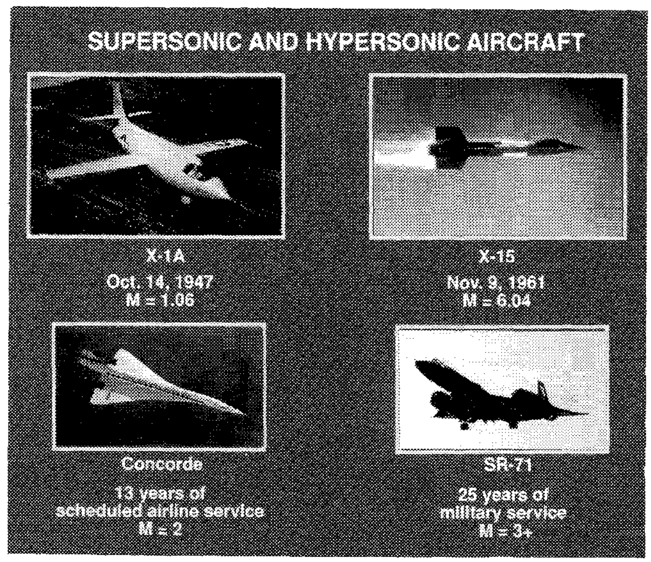
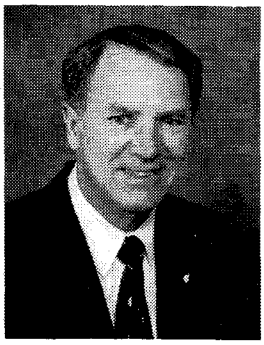


Fig. 1 Supersonic and hypersonic aircraft.



Mr. Harris received his BSAE from the Georgia Institute of Technology in 1958. His aviation experience began as a flight-line attendant and includes that of commercial cropduster pilot, flight instructor, Air Force officer, and NASA research engineer. For 27 years, he was involved in high-speed aerodynamics research and is the author of over 30 NASA reports. As Director for Aeronautics at NASA's Langley Research Center, he has management responsibility for the Center's research in aerodynamics, airframe/propulsion integration, flight dynamics, fluid mechanics, hypersonic propulsion, and vehicle systems integration. Mr. Harris served as the American Institute of Aeronautics and Astronautics (AIAA) Vice-President for Technical Activities from 1985–1987.

Mr. Harris has received the AIAA Lawrence Sperry Award, the NASA Special Achievement Award for Exceptional Service, and the NASA Medal for Outstanding Leadership. He received the Virginia Peninsula "Engineer of the Year" Award in February 1983 and the Presidential Rank Awards of Meritorius Executive in 1984 and Distinguished Executive in 1990.

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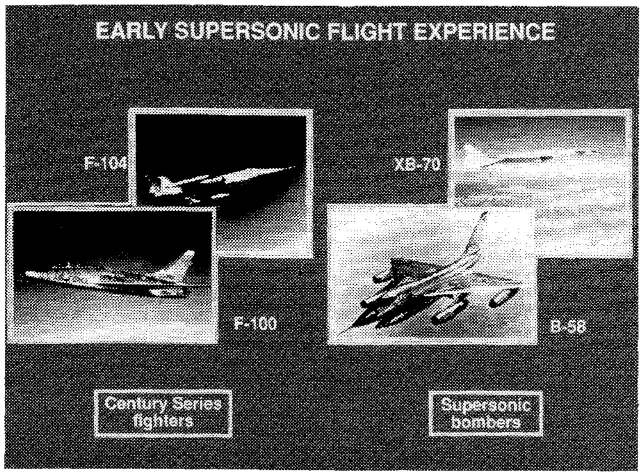

Fig. 2 Early supersonic flight experience.

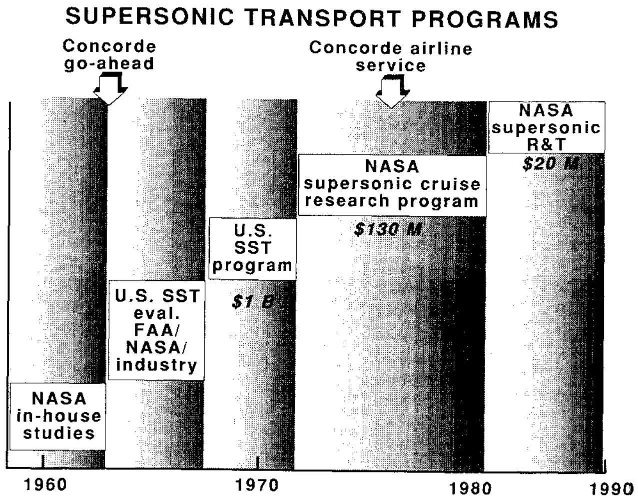

Fig. 3 Supersonic transport programs.

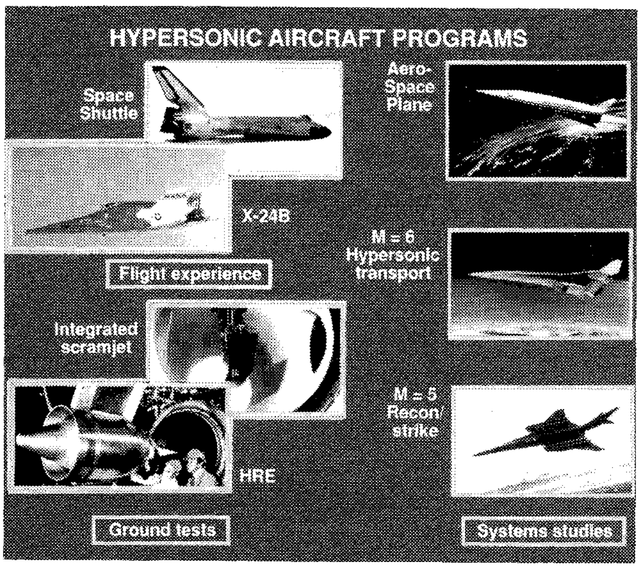

Fig. 4 Hypersonic aircraft programs.

Grumman F-14, McDonnell-Douglas F-15, General Dynamics F-16, and McDonnell-Douglas/Northrop F-18 in the 1970s. All of these aircraft have maximum speeds in the range from Mach 2–2.5 Fighters with similar high-speed capabilities were also developed in Europe and the Soviet Union.

On the civil front in the early 1960s, interest was rapidly developing in the United States and Europe in the development of a supersonic airliner (Fig. 3). In the United States, NASA began in-house studies in the late 1950s.[3] The British and French governments announced the go-ahead for the Concorde in 1962[4] and the U.S. government began feasibility studies that culminated in an evaluation of industry design proposals in 1966. Boeing and General Electric were selected as airframe and engine contractors to develop a U.S. supersonic transport (SST). Approximately $1 billion was invested by the U.S. government in the program by 1971 when the program was cancelled. The NASA Supersonic Cruise Research Program was then started to provide a focused effort on the problems that had been identified in the U.S. program. This NASA effort lasted about 10 years and another $130 million was invested.[5] Since then, NASA has continued to invest about $3 million per year on supersonic cruise basic research.

Since cancellation of the X-15 program in 1968, Air Force and NASA programs have continued to develop the key technologies necessary for hypersonic aircraft (Fig. 4). In the 1960s, the Air Force sponsored extensive studies of aerospace plane concepts that included airbreathing as well as airbreathing-plus-rocket vehicles with horizontal takeoff and landing capability. At the same time, the Air Force and NASA flew a series of lifting-body research vehicles to explore the landing characteristics of boost-glide vehicles with low lift-drag ratios. This activity culminated in the Martin-Marietta X-24A and X-24B flight tests in the early 1970s. This early research has paid off in the development of the NASA/Rockwell Space Shuttle, which is currently providing hypersonic flight experience as it performs its operational missions.

Late in the X-15 program, NASA initiated the Hypersonic Research Engine (HRE) Program which was to have flown a supersonic combustion ramjet (scramjet) engine on the X-15.[6] Termination of the X-15 flight program in 1968 eliminated the possibility of operational scramjet engine flight tests. Nevertheless, NASA continued with extensive ground testing of two Garrett/AiResearch HRE engines at the NASA Lewis and Langley Research Centers. At this same time, the Navy sponsored extensive scramjet propulsion research at the Johns Hopkins University Applied Physics Laboratory.[7] Although this work was specifically directed toward missile applications, the resulting technology has applications to both aircraft and missiles. Following the HRE Program, NASA focused its efforts on a new modular airframe-integrated scramjet concept that seemed to offer the greatest potential for aircraft applications. Extensive ground tests that began at Langley in the late 1970s resulted in the first convincing demonstration of net thrust performance in the early 1980s.

Throughout the 1960s and 1970s, NASA and the Air Force sponsored industry design studies of hypersonic aircraft systems for both civil and military missions. The results of these studies, along with the advances in high-speed propulsion and high-temperature materials technology, led to the President's decision in 1986 to initiate the National Aero-Space Plane (NASP) Program. The goal of the NASP Program is to develop the technologies required for airbreathing flight to near-orbital speeds and to demonstrate them through flight tests of a new experimental airplane, the X-30. Performance goals for the X-30 are single stage, horizontal takeoff and landing, airbreathing propulsion to about Mach 15, and rocket-powered transition to low-Earth orbit.

Despite all of these research efforts and the impressive gains that have been made in the technologies for supersonic and hypersonic flight, the maximum speed of operational aircraft has remained, for the last two and a half decades, in the Mach 2–3 range.

What's Next—Potential Future Flight Vehicles

Current subsonic transport aircraft are capable of flying very long distances at cruise Mach numbers up to about 0.85. The Boeing 747-400, for example, has a maximum range of over 7000 n. mi., which is about one-third of the Earth's circumference. Flights of this distance currently require about

15 h in the air. Longer distances, such as from New York to Sydney, Australia, for example, would take over 18 h.

The big advantage of future supersonic and hypersonic aircraft is their potential for reducing long-range flight times and, in turn, increasing civil aircraft productivity, passenger comfort and convenience, and enhancing military aircraft operational capability. To bound the Mach numbers and flight distances that might be of interest in future long-range supersonic and hypersonic aircraft, first consider the land masses of planet Earth.

Figure 5 shows contour lines of constant great circle range from New York and Frankfurt expressed as a fraction of the Earth's circumference. From New York, transatlantic flights require global range fractions of about 15% and transpacific flights require about 30%. Range fractions of 40% would essentially cover all of the Earth's land mass from the continental United States if flights for western Australia could depart from the west coast. Similarly, taking Frankfurt as a central location in western Europe, essentially all of the Earth's land mass can be reached with range fractions of about 40%.[8] Thus, it appears that the global range fractions for long-range high-speed civil aircraft fall in the neighborhood of 15–40%. Since Concorde currently operates at Mach 2 for a maximum global range fraction of about 15%,[9] perhaps a goal for future civil aircraft should be in the 25–40% range. For military missions, it might be necessary to travel similar distances and return either to the United States or to friendly territory. A similar analysis indicates that the desired global range fractions for long-range military missions might be in the neighborhood of 50–70 percent.

Shown in Fig. 6 is the flight block time as a function of global range fraction for several cruise Mach numbers. Also indicated by the shaded regions are the global range fractions and Mach numbers that I believe to be of primary interest for future high-speed civil transport aircraft and military reconnaissance/strike aircraft. Cruise Mach numbers of 2–3 for civil aircraft, which are consistent with Concorde and currently operational military aircraft, would reduce the block time for transpacific flights from about 14 h to about 4–6 h. Mach 5–6 military aircraft could provide worldwide coverage in about 4 h. Mach numbers greater than about 10–15 provide an insignificant improvement in block time for both civil and military aircraft. Much greater distances would be required for these higher speeds to pay off in block time. Thus, it appears that the Earth is not big enough to warrant aircraft that cruise faster than about Mach 10–15.

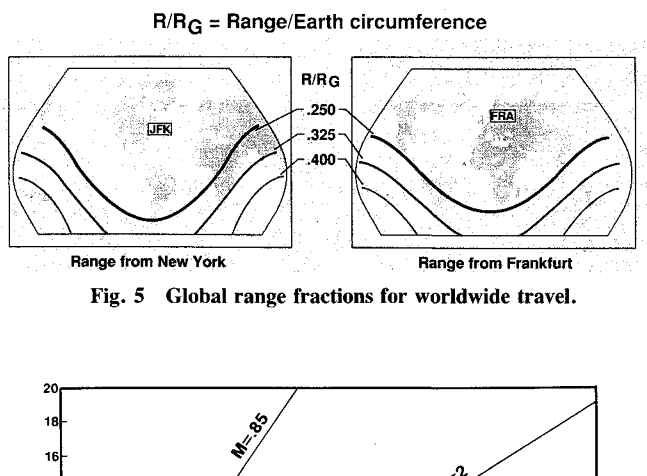

Fig. 5 Global range fractions for worldwide travel.

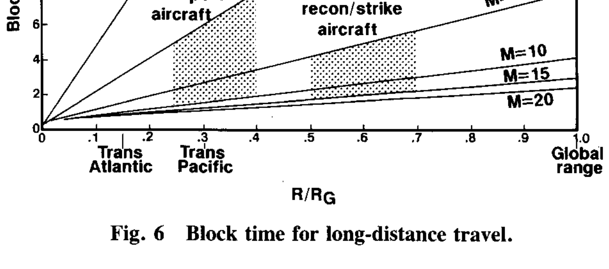

Fig. 6 Block time for long-distance travel.

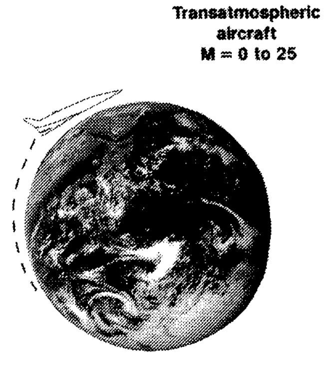

Fig. 7 Airbreathing flight to orbit.

Figure 7 suggests an additional potential future high-speed flight vehicle that could effectively utilize the higher speeds. Aircraft that could climb and accelerate through the atmosphere to Mach numbers and altitudes near that for orbital insertion might provide the capability for more flexible basing and significantly cheaper orbital access. Horizontal takeoff and landing capability would allow launch and recovery operations from numerous airports worldwide. Airbreathing propulsion and aerodynamic lift would provide more efficient use of the atmosphere and enable single-stage-to-orbit capability. As mentioned earlier, the NASP Program is a current national effort aimed at providing this kind of capability.

Thus, at least three types of future flight vehicles in the supersonic and hypersonic flight regimes might be next on the horizon. The first is a new high-speed civil transport that has global range fractions in the neighborhood of 25–40% and cruise speeds of at least Mach 2–3, but certainly not greater than about Mach 8–10. Recent studies by Boeing[10] and McDonnell-Douglas[11] indicate that a viable commercial market will exist for Pacific-range, Mach 2–3 aircraft in the first decade of the 21st century—less than 20 years from now. Such an aircraft could provide transpacific service with block times approaching 4 h. The second future vehicle type is a hypersonic military reconnaissance/strike aircraft with global range fractions of the order of 50–70% and cruise speeds above Mach 5, but less than about Mach 10–15. Such an aircraft could perform worldwide military operations in less than 4 h. For reconnaissance missions, this capability would allow the assessment of rapidly developing tactical situations where real-time data are essential. Detailed studies, however, are required to determine the operational feasibility of this class of aircraft. The third type of future vehicle is a transatmospheric aircraft that can climb and accelerate to orbit.

Design Concepts and Technology Status

It is important to remember that supersonic and hypersonic aircraft operate in a unique flow regime that is quite different from that of subsonic aircraft (Fig. 8). The shock-wave patterns at high Mach numbers present an extremely complex flowfield that requires that each component of the aircraft, such as the wing, fuselage, and engine nacelles, be carefully integrated into the whole configuration for efficient flight. As indicated in Fig. 9, the energy loss associated with shock waves produces drag that is avoided altogether by most subsonic aircraft. The shock waves also propagate away from the aircraft and eventually intersect with the ground, resulting in a

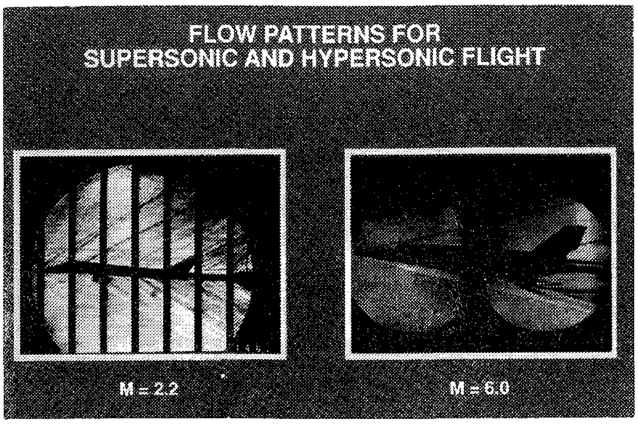

Fig. 8 Flow patterns for supersonic and hypersonic flight.

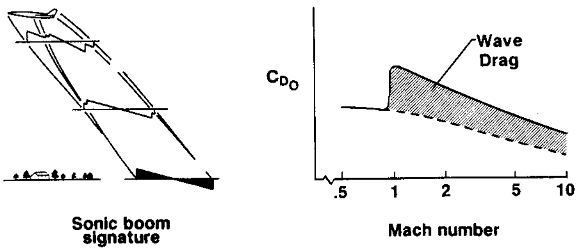

Fig. 9 Wave drag and sonic boom.

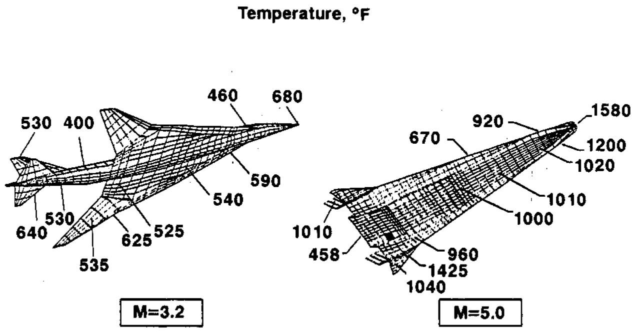

Fig. 10 Aerodynamic heating.

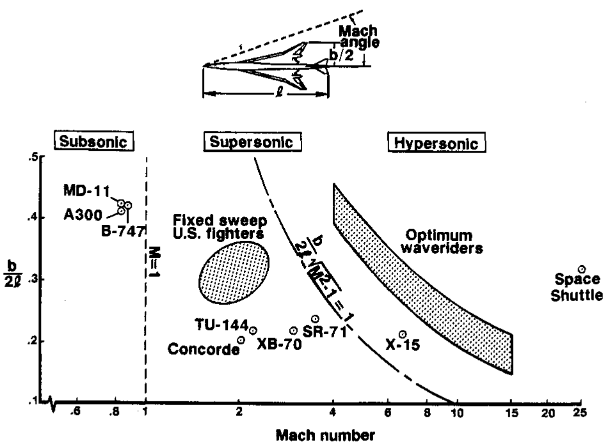

Fig. 11 Aircraft classification by speed regime.

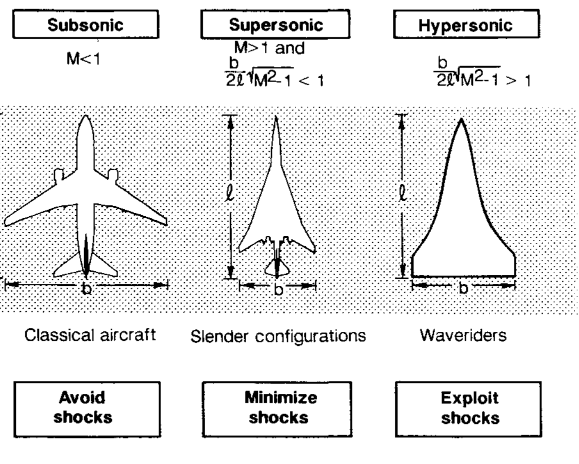

Fig. 12 Design approaches for aircraft classes.

sonic boom. Dealing with the effects of shock waves becomes a major part of the design challenge.

Another fundamental design problem for supersonic and hypersonic aircraft is aerodynamic heating (Fig. 10). At a Mach number of 3.2, much of the aircraft surface is exposed to temperatures in the 500°F range with stagnation temperatures approaching 700°F. At Mach 5, temperatures of about 1000°F exist over much of the surface and stagnation temperatures approach 1600°F.[11] Special high-temperature materials and structures are required at these temperatures, and at higher Mach numbers active cooling is required for some parts of the structure.

Design Approaches for High-Speed Aircraft

One approach to classifying aircraft designs in relation to speed regime, suggested by Küchemann,[12] is illustrated in Fig. 11. The ratio of semispan to length is taken as a measure of configuration slenderness and is shown as a function of maximum cruise Mach number. Subsonic aircraft, exemplified by the Boeing 747, McDonnell-Douglas MD-11, and Airbus A300, tend to optimize at high values of semispan-to-length ratio because of their high-aspect-ratio wings. The distinction between supersonic and hypersonic designs is taken as the dividing line where the semispan-to-length ratio is equal to the tangent of the Mach angle. Therefore, for the supersonic designs that may have subsonic leading edges, we can maintain relatively weak shock waves, and for the hypersonic designs we must accept strong shock waves.[13] This leads to the three design approaches (also suggested by Küchemann) illustrated in Fig. 12. Long-range subsonic aircraft are essentially designed to achieve the highest cruise Mach number that can be attained and still avoid the adverse effects of shock waves.

Supersonic aircraft, in order to achieve long-range capability, can be designed to minimize shock losses by keeping the configuration slender, that is, a low value of semispan-to-length ratio. As shown in Fig. 11, the short-range supersonic U.S. fighters, which are not designed for efficient cruise performance, fall in the semispan-to-length ratio range of about 0.25–0.35 in contrast to the lower values approaching 0.2 for the Concorde, TU-144, XB-70, and SR-71 long-range supersonic cruise designs. As a result of the more than 30 years of supersonic operational experience and 25 years of SST research and design studies, very sophisticated design approaches have been developed for slender supersonic configurations.[14,15]

Much less is known about how to optimize long-range hypersonic airplanes. Since this class of aircraft must accommodate strong shock waves, it has been suggested that a class of configurations, called waveriders, could be developed to exploit the flow characteristics of the strong shocks.[12] The range of semispan-to-length ratios for a series of viscous optimum waverider concepts, developed by K. G. Bowcutt,[16,17] is also shown on Fig. 11. Also shown for reference are the X-15 and the Space Shuttle. Much more research is needed to explore the potential of waveriders and to assess their practicality for aircraft design.

Aerodynamics

The aerodynamic potential for slender supersonic configurations is indicated in Fig. 13. The Concorde, which represents early 1960s technology, has a maximum cruise lift-drag ratio of about 7 at Mach 2. By the end of the NASA Supersonic Cruise Research Program in 1982, designs had been developed with cruise lift-drag ratios of about 9 at Mach 2.7. Current NASA studies indicate that further improvement in supersonic lift-drag ratio of about 30% is possible by the year 2000 through the application of arrow-wing technology, advanced wing/body/nacelle integration, and supersonic hybrid laminar flow control. For the longer term, W. Pfenninger[18] and R. T. Jones[19] have indicated that even greater improvements can be attained through more radical design approaches. The Pfenninger concept utilizes externally braced high-aspect-ratio swept wings, a three-body fuselage, and extensive use of laminar flow. If this concept can be practically designed, it would improve lift-drag ratio by about 80% over the 1982 technology. The Jones concept is an oblique flying wing that could adjust its sweep angle to provide high-aspect ratio for takeoff and landing and high sweep for supersonic cruise. Although not proposed by Jones, this concept could also employ laminar flow control and potentially improve lift-drag ratio by about 70–100% at slightly lower Mach numbers. Both of these latter concepts would have to rely heavily on advanced control systems technology.

High lift-drag ratios are much more difficult to achieve at hypersonic speeds because of strong shock waves and strong viscous effects (Fig. 14). Practical aircraft designs in the Mach 5–6 speed range tend to have cruise lift-drag ratios in the 5.5–6.0 range based on wind-tunnel tests extrapolated to full scale.[20,21] The calculated potential for further improvement in maximum lift-drag ratio from the use of viscous optimum waverider configurations is shown in this figure. Also shown is an example Mach 6 optimum waverider design.[17] More research is needed to determine whether these significant improvements can be verified by experiments and whether propulsion and control systems can be integrated into the configuration without losing the aerodynamic benefits.

Propulsion

Propulsion potential in terms of specific impulse is shown in Fig. 15 as a function of Mach number for various propulsion

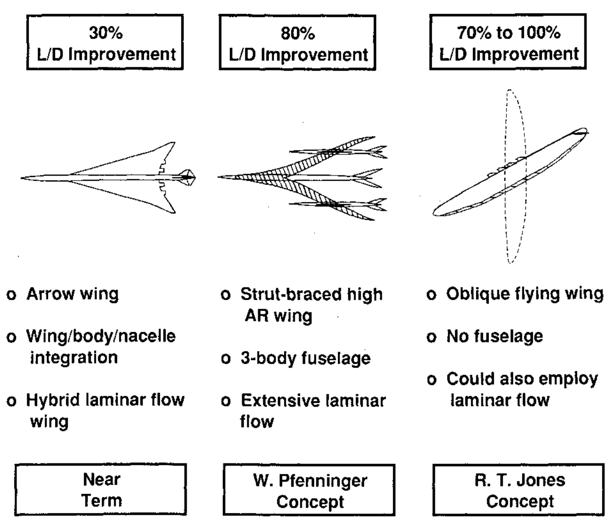

Fig. 13 Aerodynamic potential for slender configurations.

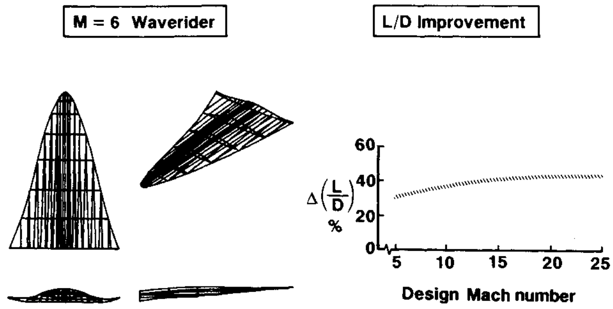

Fig. 14 Aerodynamic potential for waveriders.

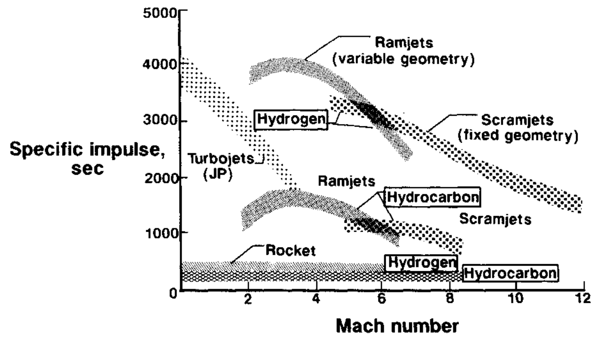

Fig. 15 Propulsion potential.

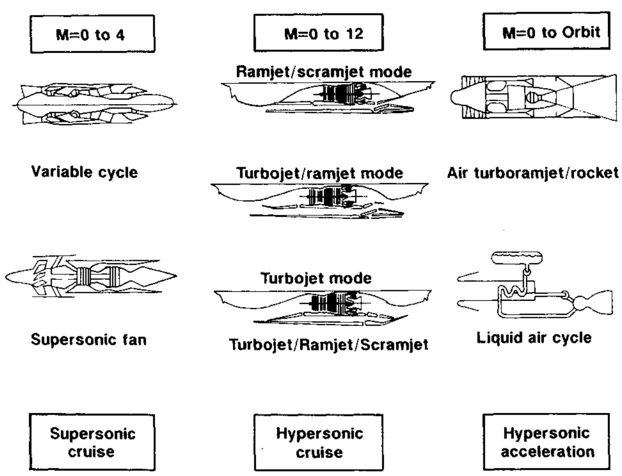

Fig. 16 Example propulsion options.

system options. Both hydrocarbon and liquid hydrogen fuel potentials are illustrated. Turbojets provide good performance up to Mach numbers of about 3.5. Above that, ramjet performance is good up to about Mach 6, where pressure and temperature losses become excessive. Above about Mach 6, the supersonic combustion ramjet, or scramjet, provides the best performance.[6,22] By maintaining supersonic flow through the combustor of the scramjet, less compression is required by the inlet, combustion temperatures are reduced, and feasible engine materials and structures are possible to much higher Mach numbers. Because of the large high-speed performance advantages and the tremendous heat-sink capacity of liquid hydrogen, the hydrogen-fueled scramjet offers an attractive propulsion option for Mach numbers greater than about 6. Up to Mach numbers of about 8, ground-based engine tests have confirmed that the scramjet performance levels shown in the figure can be achieved. Above about Mach 8, adequate ground capability for propulsion testing does not exist in the United States.

Detailed engine design studies for supersonic and hypersonic aircraft applications have been conducted by the Air Force, Navy, and NASA since the 1960s.[13,14,20,22] Some example designs are illustrated in Fig. 16. Two engine concepts currently under study for supersonic cruise aircraft are the variable-cycle engine and the supersonic flow-through-fan engine. The variable-cycle engine operates as a conventional turbofan at subsonic speeds and as a high-pressure-ratio turbojet at supersonic speeds. The supersonic fan has the potential for lower weight and higher efficiency than a conventional turbofan by avoiding the complexity of slowing the external flow to subsonic speeds before entering the fan. The feasibility of this new concept is currently being studied by the NASA Lewis Research Center.

For cruise aircraft that fly in the speed range above about Mach 4, a combination turbojet/ramjet/scramjet engine is an attractive option. At subsonic speeds the ramjet inlet is closed off and all of the inlet air flows through the turbojet. At speeds greater than about Mach 3, airflow to the turbojet is closed off and all of the air flows through the ramjet/scramjet.

For transatmospheric aircraft, very high acceleration capability is needed to achieve the high level of kinetic energy required for orbital insertion. Two airbreathing engine concepts that can provide both high acceleration capability within the atmosphere and rocket thrust for orbital insertion and deorbit are the air turboramjet/rocket and the air liquefaction cycle engine. Both of these concepts were extensively studied in the 1960s.

Propulsion/Airframe Integration

As aircraft flight speed increases, careful integration of the propulsion system into the airframe design becomes increasingly important.[21,23] Three examples are given in Fig. 17. Although the wings of supersonic cruise aircraft provide some inlet precompression, most of the compression is done by ramps or spikes that are an integral part of the engine inlet. The wing then must be designed to accommodate the pressure field from the engine nacelles to provide favorable interference.

For an efficient hypersonic cruise aircraft, the entire underside of the fuselage becomes a part of the propulsion system. The forebody provides a major part of the inlet compression, and the afterbody provides the needed expansion area as part of the nozzle. For transatmospheric aircraft, which must have high acceleration capability, large amounts of air must be captured by the engine inlets to provide the needed excess thrust. An extreme case is illustrated in the figure by the conical configuration, which not only maximizes the amount of air captured but also utilizes the entire forebody surface for precompression and the entire afterbody as a nozzle expansion area.

Because of the extremely complex flow fields involved in propulsion/airframe integration and the difficulty in achieving exact flow simulation in wind tunnels at these speeds, we must rely heavily on advanced computational codes for the design of airbreathing hypersonic aircraft. An example calculation for a generic hypersonic vehicle at Mach 16 flight conditions is shown in Fig. 18. The upper part of the figure shows particle traces of the flow about the configuration, including the flow through and around the scramjet propulsion system with spillage. The lower part of the figure shows pressure contours between a cross section of the forebody and the shock system and indicates the flow entering the inlet. Very complex computations such as this are extremely important in the design of hypersonic aircraft.

Materials and Structures

For supersonic aircraft which operate at Mach numbers less than about 3.5, several material options are available at today's state of the art[5,14] (Fig. 19). The development of new composite materials such as metal matrix and carbon fiber-reinforced resins offer the potential of significant weight savings for this class of high-speed aircraft. Taking a conventional titanium airframe structure as the baseline, it is estimated that by the year 2000 the potential structural weight saving could be of the order of 30 to 40 percent.

At hypersonic speeds, the thermal environment becomes much more hostile. Active cooling of the engine structure is probably required for Mach numbers above about 5, and active cooling of some parts of the airframe structure is necessary at Mach numbers above about 15. Significant progress, however, is currently being made in the development of new

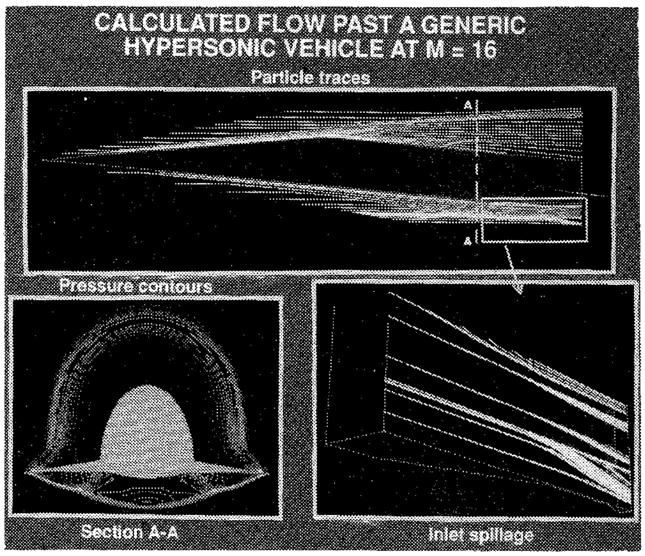

Fig. 18 Calculated flow past a generic hypersonic vehicle at $M = 16$.

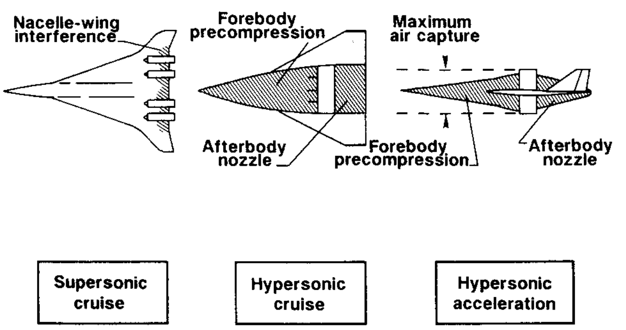

Fig. 17 Propulsion/airframe integration.

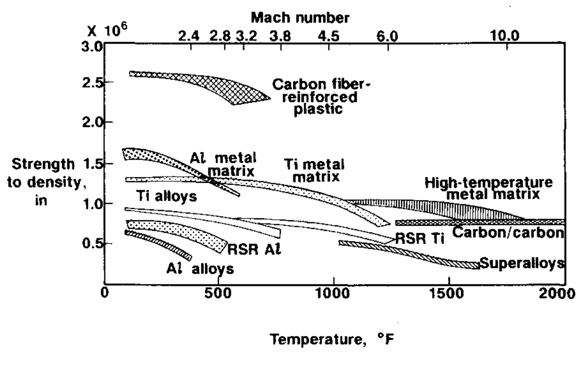

Fig. 19 Structural materials for high-speed aircraft.

high-temperature materials under the sponsorship of the NASP Program.

NASA has extensively studied actively cooled structural concepts for application to hypersonic cruise aircraft[6] (Fig. 20). The engine concept shown in the figure is regeneratively cooled by circulating the cryogenic hydrogen fuel through cooling jackets on the engine walls before injecting the fuel into the combustor. The fabrication and materials technology required to obtain reasonable thermal fatigue life for the cooling jacket has been developed and experimentally validated. For the airframe structure, a series of design and fabrication studies resulted in three actively cooled structural panels for thermal/structural testing. The test panels include one insulated with a René-41 heat shield and two bare panels of different construction. The panels use aluminum as the structural material and a water-glycol mixture as the coolant to transfer heat to the liquid hydrogen fuel. Application of the new high-temperature materials technology to a Mach 6 airplane is estimated to result in potential structural weight savings of about 20% by the year 2000.

Overall Performance

Combining all of these potential technology advances in aerodynamics, propulsion, and structures suggests that future supersonic aircraft could have significantly higher levels of performance than current designs and that the potential for practical hypersonic aircraft might be coming within our reach. Figure 21 shows the Breguet range factor, which is a measure of the propulsion system and configuration aerodynamic efficiencies including the chemical efficiency of the fuel, as a function of design Mach number. Shown for comparison are the levels for current long-range cruise airplanes such as the B-747, Concorde, and SR-71. These estimates indicate that future supersonic cruise aircraft in the Mach 2–3 range could have Breguet range factors as good as those for current subsonic aircraft. Considering also the potential for significant improvement in structural weight fractions from new materials technology, the outlook for a new generation of economically viable long-range supersonic cruise aircraft looks quite good. It should be recognized, however, that these technologies are not yet in hand, and a concentrated research effort is required to bring them to a state of maturity for commercial application.

At hypersonic speeds some form of high-energy cryogenic fuel, such as liquid hydrogen or liquid methane, appears to be required for extremely long-range missions and as a heat sink for thermal cooling. The high specific energy of liquid hydrogen results in very attractive Breguet range factors, even when the aerodynamic performance penalty for the low density of hydrogen is taken into account. The required technical advances for hypersonic cruise aircraft are considerably less in hand than those for supersonic cruise. However, the NASP Program, which is focused on developing the technologies for hypersonic acceleration to Mach numbers near 25 for orbital insertion, is rapidly advancing many of the key technologies that are also needed for hypersonic cruise. These technologies should be ready for application to high-priority military missions early in the 21st century.

It should be noted, as indicated on Fig. 21, that new technology advances such as hybrid laminar flow control and more efficient turbofan propulsion systems will result in much more efficient subsonic aircraft in the early 2000s as well. In addition, if liquid hydrogen fuel should become commercially available and economically competitive with hydrocarbon fuel, it would similarly benefit the range performance of subsonic and supersonic aircraft.

Environmental Issues

Environmental issues (Fig. 22) are a major concern for all new commercial aircraft, but particularly so for supersonic and hypersonic aircraft. As an aircraft's cruise speed increases, the altitude at which it flies also increases. At Mach numbers of about 3–4, the best cruise altitude falls in the region of highest ozone concentration at midlatitudes. Therefore, the impact of the engine exhaust on ozone depletion is a major concern.[21] NASA has recently initiated extensive studies to assess the impact of nitrous oxide and other products of combustion on the ozone layer. Ozone studies from the 1970s that were a part of the U.S. SST Program were not conclusive. Some of the results indicated that ozone would be depleted and others showed that it would be increased. The upper atmospheric chemistry models that are available today are much more sophisticated than those of the 1970s and should produce more definitive results. It is clear that significant levels of ozone depletion from high-flying aircraft will not be acceptable. Once the magnitude of the problem

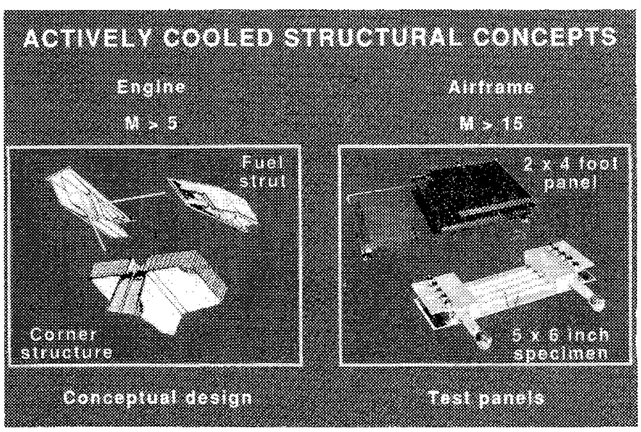

Fig. 20 Actively cooled structural concepts.

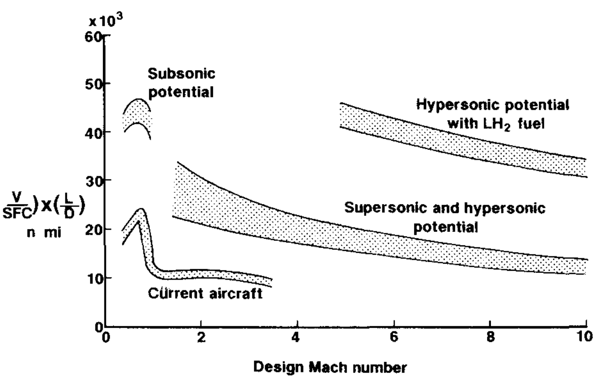

Fig. 21 Breguet range factor.

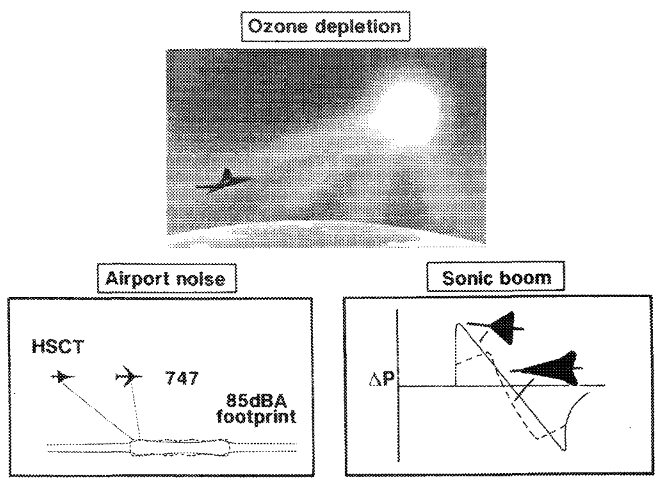

Fig. 22 Environmental issues.

is better understood, it is believed that solutions can be found through advances in combustion technology or fuel additives.[24]

Airport noise is another major concern for high-speed aircraft. Preliminary results from studies by Boeing and McDonnell-Douglas are encouraging for aircraft designed to cruise up to about Mach 3.[10,11] The high-thrust engines allow much steeper climbout for the supersonic aircraft so that the 85-dBA footprint can be potentially smaller than for subsonic aircraft. However, to meet all of the noise regulations applicable to subsonic transports will require an advancement in engine noise-suppression technology.

The sonic boom is an obvious environmental concern for all supersonic and hypersonic aircraft. Design approaches that reduce or alter the pressure rise to minimize the impact of the boom have been developed. However, no one knows how small the sonic boom has to be in order to be acceptable to the public. Fifty-two countries around the world currently prohibit civil aircraft from generating sonic booms that reach the ground.[24] Recent studies by Boeing have indicated that a supersonic commercial aircraft would be economical without overland flight by selecting overwater routes.[10] The suggested design approach would be to shape the aircraft for the lowest sonic boom that is technically feasible and plan to fly the aircraft at subsonic speeds for the overland parts of its flight.

Technical Challenges and Potential

Now let us consider the technical challenges that must be met in order to bring in the new era of supersonic and hypersonic flight.

I believe that the United States can develop, by the year 2000, a Pacific-range supersonic transport (Fig. 23) that is both economically viable and environmentally acceptable. We now have more than 20 years of operational experience with both civil and military supersonic cruise aircraft. The 30 years of focused NASA research and the previous U.S. SST Program have made giant strides in developing the key technologies that are required. The United States is currently investing millions of dollars in the Integrated High-Performance Turbine Engine Technology (IHPTET) and Advanced Technology Fighter Engine (ATFE) programs that could have major spinoffs for a long-range supersonic cruise aircraft. The obvious major concern is the environmental impact, which NASA is already studying. Many experts agree that the needed technology can be developed by the year 2000 if a concentrated research effort is started now. There is no question that such an aircraft will be developed; the only question is who will develop it and when? Research and development programs are already underway in Europe and Japan. The major technical challenges for the supersonic aircraft are the development of 1) an efficient supersonic engine that has both low takeoff noise and emissions and which has no detrimental impact on atmospheric ozone, 2) supersonic laminar flow over about 50% of the wing surface, and 3) lightweight composite materials that can withstand surface temperatures in the 500°F range.

As mentioned earlier, the potential for long-range hypersonic aircraft (Fig. 24) is much less of a certainty than that for the supersonic aircraft. However, the SR-71 is reaching its design life, and it has recently been announced that it will be phased out of service. A Mach 5–6 aircraft that could provide worldwide operational coverage in 4 h would make an attractive replacement. Both the Air Force and NASA studied vehicles such as this in the 1960s and 1970s. Operations analysis by military experts is required to determine the current feasibility and relative priority of such a future system. In the meantime, very high-temperature materials and hypersonic propulsion technologies that are currently under development in the NASP Program will provide enabling spinoffs to the hypersonic cruise aircraft. More research is needed to develop the waverider configuration concepts that offer the potential for more efficient hypersonic cruise flight. The major technical challenges for this class of aircraft are the development of 1) an efficient integrated airframe/propulsion configuration concept, 2) lightweight materials and structures that can withstand surface temperatures in the 1000°F range, 3) an efficient high Mach-number inlet with low bleed and leakage penalties, 4) highly integrated flight path and propulsion controls, and 5) high-temperature seals and lubricants that can function in the hypersonic flight environment.

The technologies for transatmospheric aircraft (Fig. 25) are currently being developed in the $3 billion NASP Program. If successful, it will provide the technologies for a new class of aircraft that might enter service in the early 2000s and have the ability to fly to orbit. However, since existing U.S. ground testing capability is inadequate above about Mach 8 to develop propulsion systems and to validate the airframe/propulsion system integration, the program is relying heavily on advanced computational fluid dynamics (CFD) and computational structural mechanics (CSM) for both design and analysis. Thus, an X-airplane is required for the high Mach-number technology development and validation. The major technical chal-

Fig. 23 Supersonic aircraft potential.

Fig. 24 Hypersonic aircraft potential.

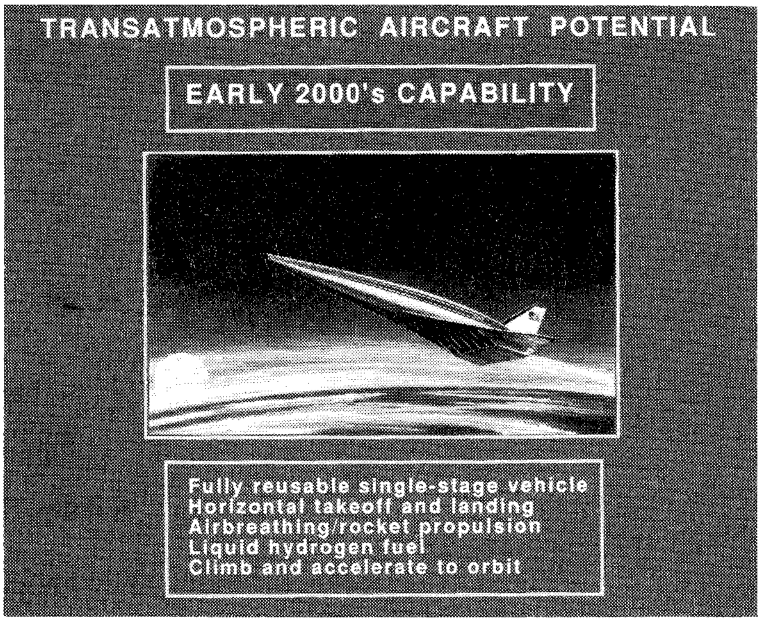

Fig. 25 Transatmospheric aircraft potential.

lenges for transatmospheric aircraft are the development of 1) a new class of lightweight, very high-temperature materials, 2) reliable actively cooled structures, 3) a ramjet/scramjet propulsion system capable of operation up to about Mach 15 in combination with a low-speed propulsion system for subsonic flight, 4) validation of CFD and CSM computer codes that can be used with confidence at high Mach numbers, 5) intelligent flight-path and propulsion controls, and 6) a successful flight test program for the X-30 to validate the integrated vehicle and control performance.

Concluding Remarks

As stated at the outset, I believe that aeronautics is on the threshold of radically new supersonic and hypersonic flight capabilities. The new high-speed aircraft will not replace the need for subsonic aircraft, but will satisfy the growing need for very long-range commercial markets and military missions. Their advantage will be the ability to reduce long-range flight time and, in turn, increase civil aircraft productivity, passenger comfort and convenience, and enhance military aircraft operational capability. The key technologies needed for these new aircraft have advanced significantly over the past 30 years. We now have 25 years of Mach 3 military service by the Lockheed SR-71 and 13 years of Mach 2 scheduled airline service by the British/French Concorde. Yet significant technical challenges still remain before we are ready to move into the new era of supersonic and hypersonic aviation.

I believe that these challenges can be met and that the payoff from doing so will be enormous. A Mach 2–3 civil transport aircraft could provide transpacific flights in about 4 h by the year 2000. Both Boeing and McDonnell-Douglas have indicated that a viable commercial market will exist by that time, and focused R&D programs are already underway in Europe and Japan. Hypersonic military aircraft in the Mach 5–6 range could provide worldwide military missions in about 4 h by the early 2000s. For reconnaissance missions, this capability would allow assessment of rapidly developing tactical situations where real-time data are essential. Transatmospheric aircraft with the capability to climb and accelerate to Mach numbers and altitudes near that for orbital insertion could provide more flexible operational capability and cheaper orbital access in the early 2000s. The results of these developments will strengthen U.S. military capability and assure continued world leadership for U.S. aerospace products well into the 21st century.

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