HYPERSONIC DESIGN

ICAS-92-1.8.1

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INTRODUCTION

Hypersonic vehicles are similar to subsonic and supersonic vehicles because each has a propulsion system, an aerodynamic body, devices for stability and control, crewstation, payload, secondary power system , and miscellaneous other systems. The differences between hypersonic vehicles and their slower counterparts include their components, how they are arranged, and their relative importance to the vehicle's design. This paper will give an overview of the major items normally considered in the configuration design process and how those items are related to hypersonic vehicles, such as propulsion system, aerodynamic shape, aerodynamic drag, stability and control, internal arrangements, payload bays, secondary power and thermal protection systems.

MISSION

The first step in any design process is determining what the vehicle's purpose (e.g., transport, military force application, research, or space travel). The mission will help define four important aspects of the vehicle: speed, range, payload, and maneuverability. The hypersonic vehicle's speed and range will define the propulsion, fuel, and thermal protection to be used and strongly affect its length, volume, and shape (Figure 1). The payload will have a variable impact on the volume, and maneuverability is less important than for subsonic and supersonic fighters.

Range and speed are key factors in choosing a hypersonic solution to an aircraft design requirement. As illustrated in Figure 2, the biggest payoff for hypersonic vehicles come with longer ranges. In short–range cases (approximately 500 miles), a subsonic or a supersonic solution would work better. Therefore the range definitions for hypersonics are specified as short range up to 2,000 miles, mid range 3,000 – 8,000 miles, and long range 9,000+ miles.

To aid this discussion, an atmospheric aircraft with a range of 10,000 miles and a cruise speed of Mach 10 (Figure 3) will be used to illustrate the uniqueness of hypersonic vehicles.

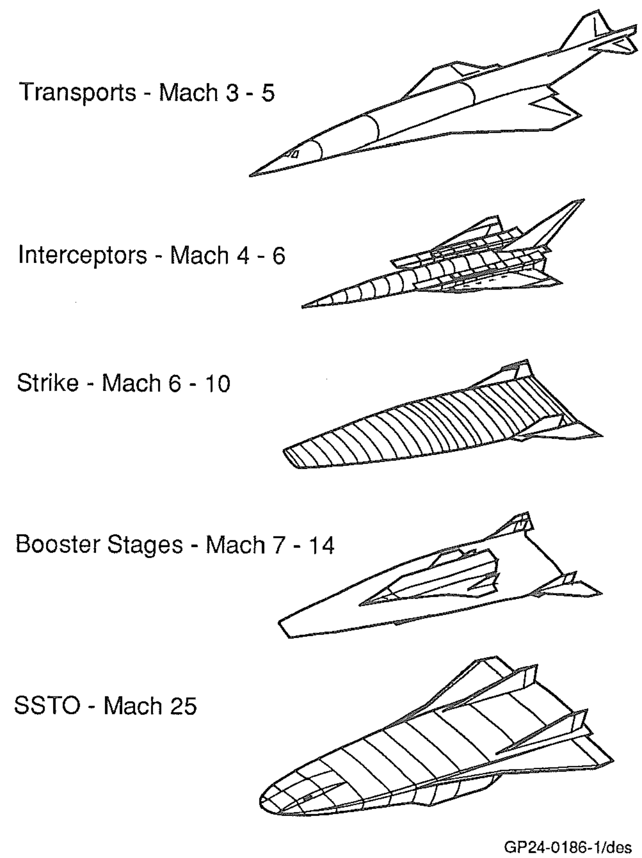

Figure 1. Hypersonic Vehicle Designs

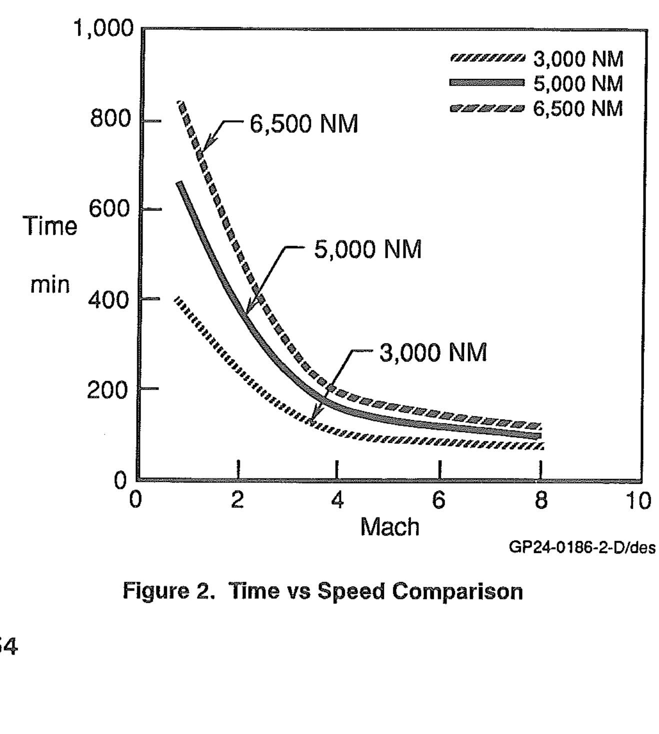

Figure 2. Time vs Speed Comparison

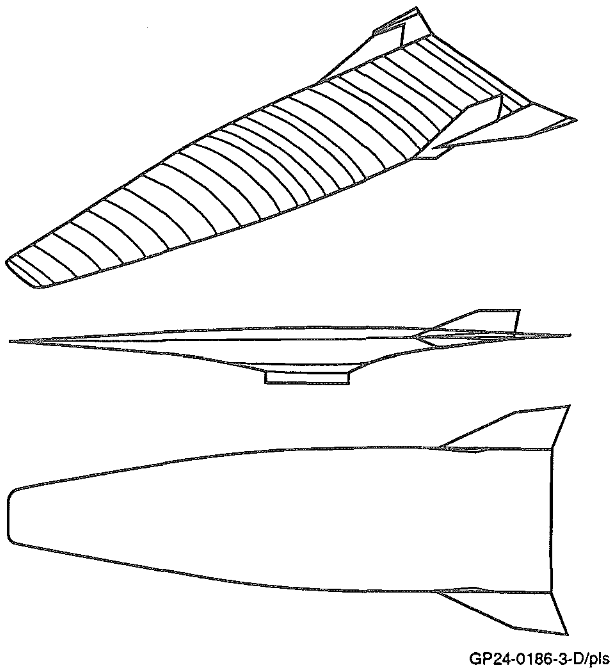

Figure 3. Mach 10 Cruiser

PROPULSION SYSTEM

Once the mission has been identified, the propulsion system is developed. The propulsion system is defined in three segments: power plant, inlet and nozzle.

Power Plant

The power plant, or engine, is based on the most efficient means to reach the maximum Mach number for the configuration.

Figure 4 illustrates the choices available and the capabilities of each. For the example vehicle defined above, the cruise power plant of choice is a scramjet, but the low Mach performance is inadequate to achieve takeoff. The solution in this case is the use of dual power plants: turboramjets from Mach 0–6 and scramjets from Mach 6–10. Dual power plants add complications but that solution is superior to using rockets to accelerate to scramjet operational speeds. Adding rocket engines would mean adding liquid oxygen to the vehicle, which would increase its take off gross weight. In contrast, if the mission required orbital ability, the rocket might be a better alternative.

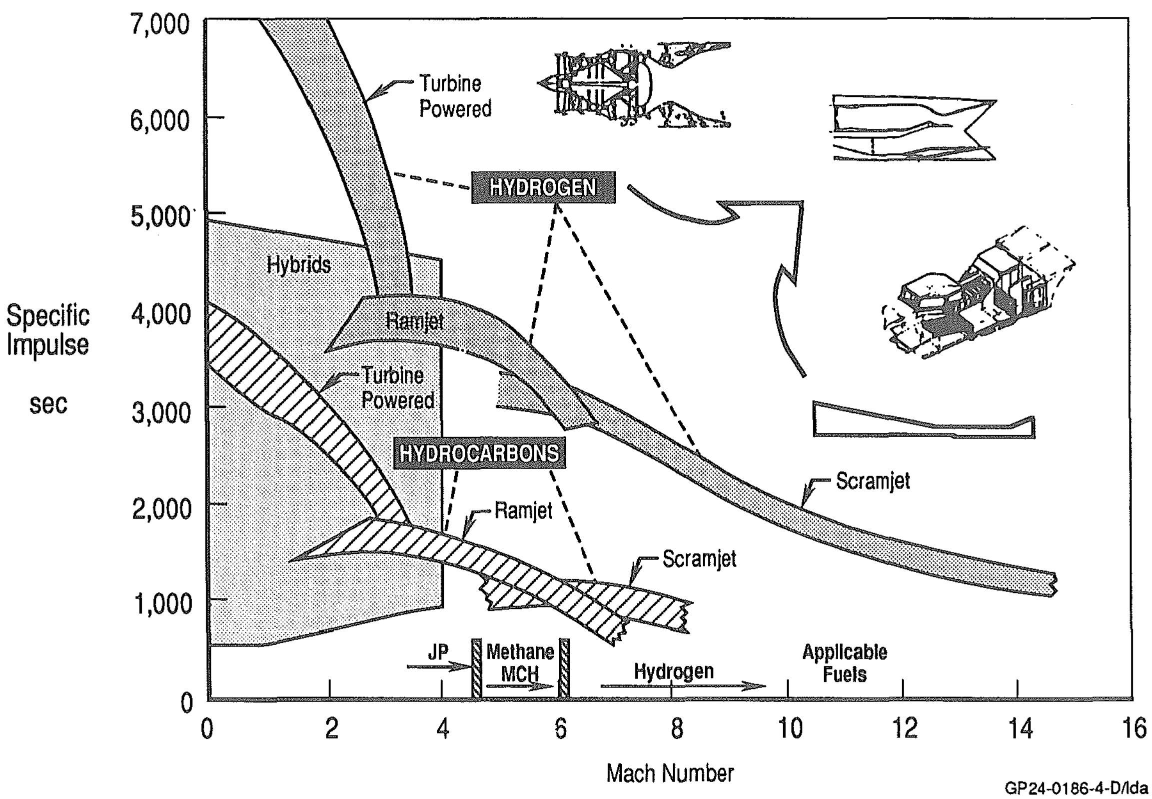

Figure 4. Air Breathing Engine Cycle and Fuel Trends

Inlet

As with power plants, inlet types have a range at which they are best suited, Figure 5. Inlets are designed to provide the best performance at a specified Mach number while minimizing drag. This is done by making the shocks that are formed from the external ramps, to touch on the lower lip of the inlet (called shock on lip), the same process used for supersonic design. Unfortunately, as speed increased the length of the inlet required to get shock on lip gets longer. Around Mach 6, the length required to get shock on lip and keep the all shock out of the internal inlet become impractical. Above Mach 6, highly integrated mixed compression inlets are used. The highly integrated mixed compression inlets are of sufficient length that they define the lower forward portion of the airframe. The example vehicle needs this type of inlet to operate at its cruise speed. To accommodate the turboramjets, a moving ramp (Figure 6) is added, allowing it to act like an upside down mixed compression inlet. The ramp is closed after the scramjet has sufficient thrust to power the vehicle on its own.

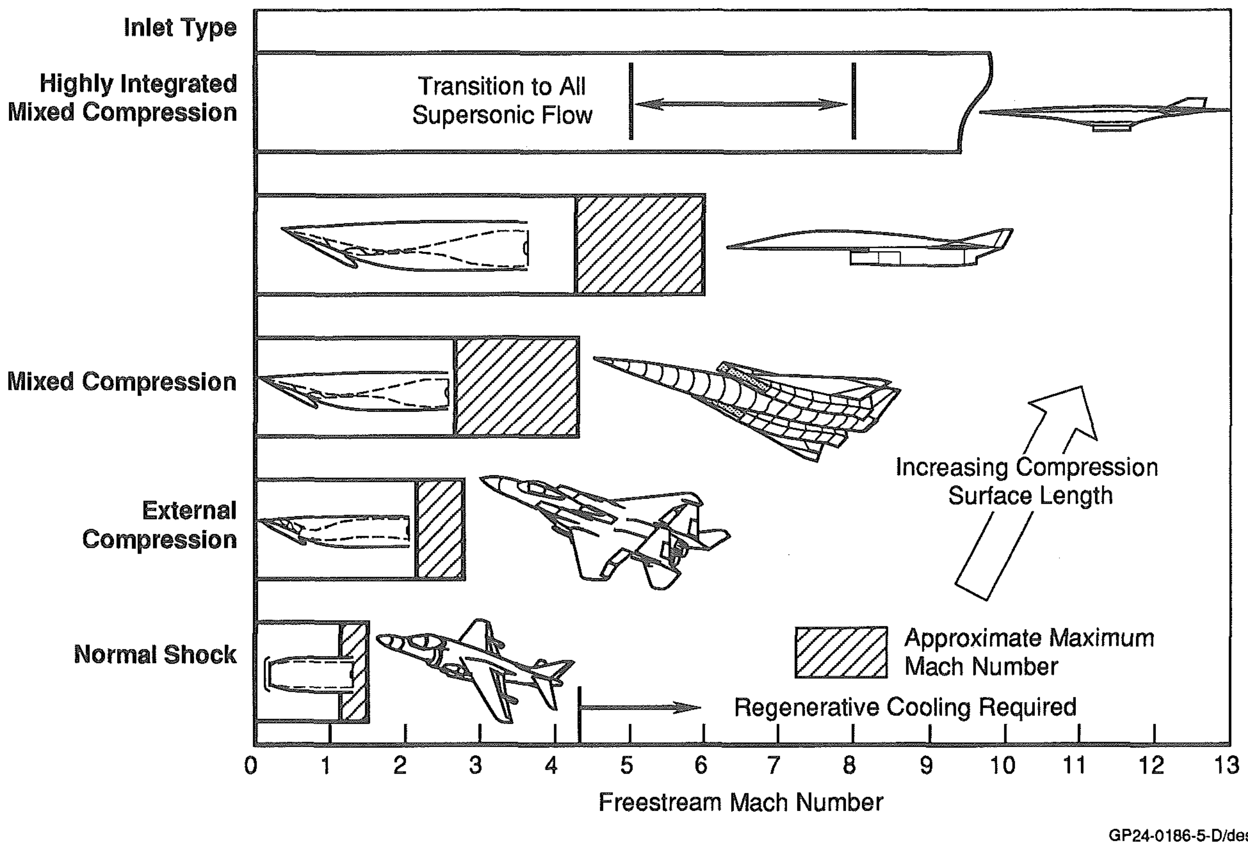

Figure 5. Inlet Trends as a Function of Mach Number

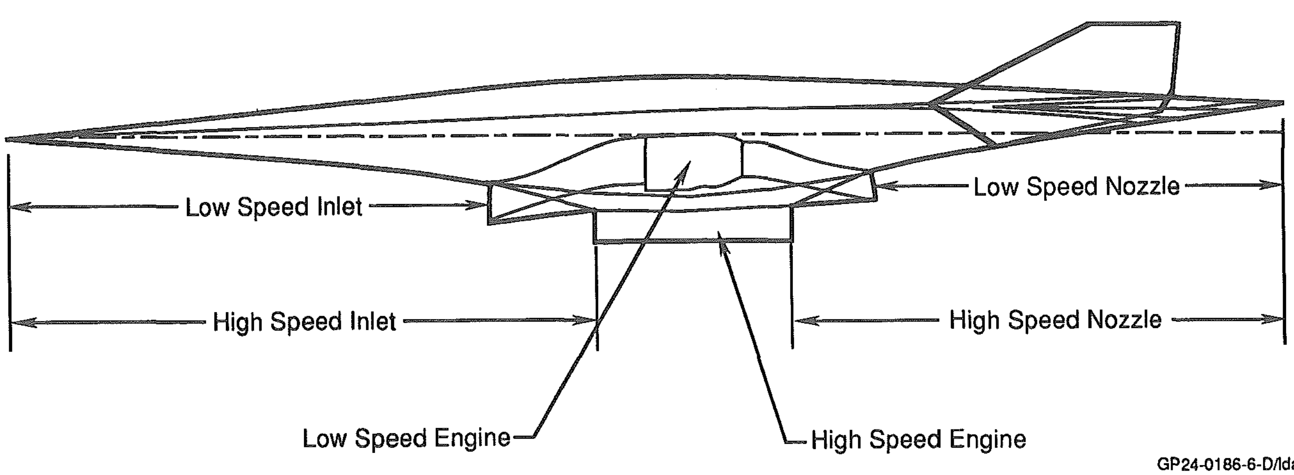

Figure 6. Mach 10 Engine Configuration

Nozzle

Nozzles, like inlets, have a tendency to grow in length as speed increases, Figure 7. The growth in length is to improve nozzle efficiency. Ideal efficiency is achieved by designing the nozzle to have sufficient area ratio (exit to throat) such that the exit pressure is equal to ambient. To achieve this at high Mach numbers requires tremendously high area ratios (or expansion ratios). The combination of large area ratio requirements and limitations in nozzle wall divergence angles can result in heavy nozzle designs. Hence at Mach numbers above 6, the aft surface of the aircraft is generally used for additional exhaust gas expansion. For the Mach 10 aircraft the ideal nozzle is an aft expansion surface. This aft expansion surface defines the bottom aft fuselage.

AERODYNAMIC SHAPE

In general, hypersonic vehicles need high fineness ratios (fuselage length/fuselage diameter, l/d), low wing loadings, and high lift to drag (L/D) ratios (our sample vehicle has an l/d of 8, a wing loading of 50 LBS/SQ FT, and an L/D of 6). These vehicles can be configured as anything from wing–bodies to lifting bodies (see Figure 8). This involves direct tradeoffs between the ability to carry low density, high specific impulse (ISP) fuels such as methane and hydrogen and the lower L/D of the resulting bulkier shape. The choice of fuel is primarily motivated by the fuel characteristics and the Mach regime in which the vehicle will be operated (Figure 4). Vehicle operation at faster speeds requires increasingly more energetic fuels. As the fuel choice progresses from kerosene to hydrogen, the volumetric fuel fraction gets larger, and vehicle integrations tend away from wing–body and towards lifting body designs. As this happens, the maximum L/D ratio decreases, and the volumetric efficiency {[(vol)exp2/3]/Splan} increases.

The external configuration and moldline of a hypersonic vehicle is determined by the desired aero/propulsion integration. This in turn is dictated to a great extent by the baseline mission as discussed earlier. A blended non–circular lifting body is a good fuselage choice to fulfill our example vehicle's mission. This blends a smooth aerodynamic shape around the complex propulsion system and large hydrogen fuel tanks while maintaining excellent volumetric efficiency. The blended non–circular lifting body is essentially a waverider type forebody plus engine package and nozzle system optimized for the design cruise speed. While the integration results in L/Ds much lower than that for ideal waveriders, the vehicle also has the required volume and has good flying characteristics at off–design conditions.

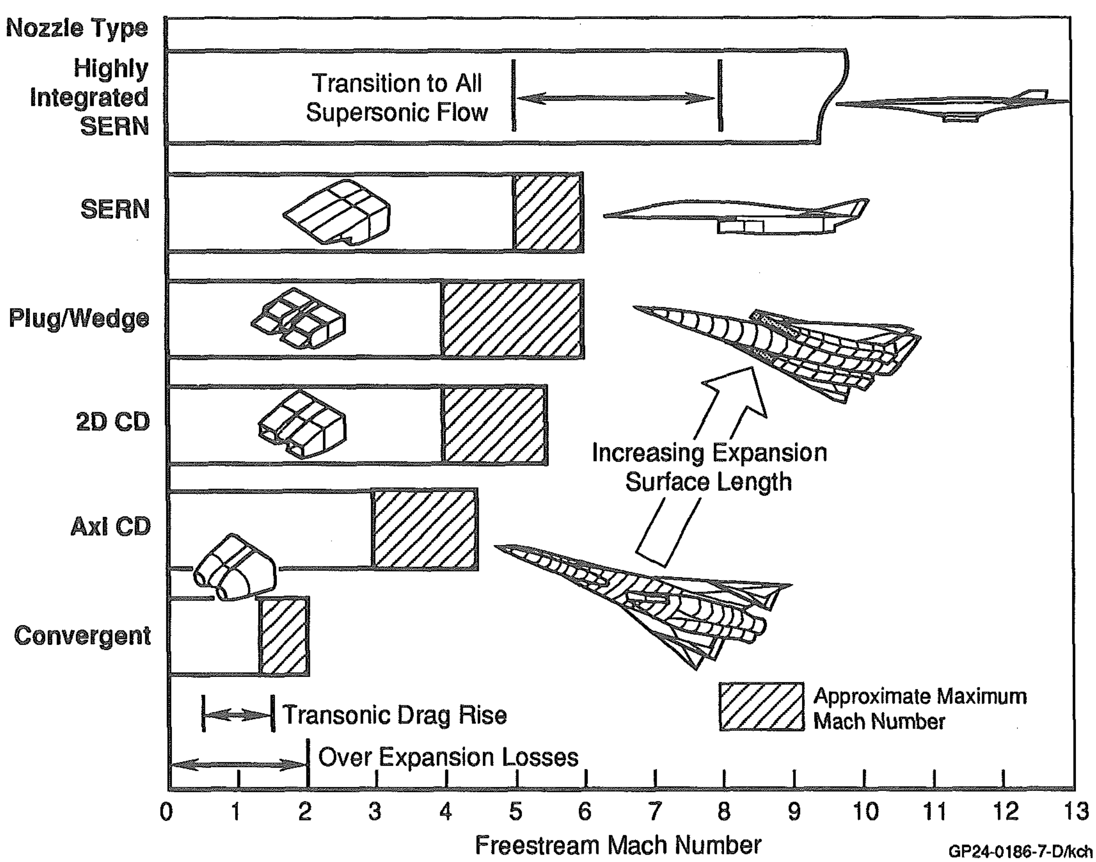

Figure 7. Nozzle Trends as a Function of Mach Number

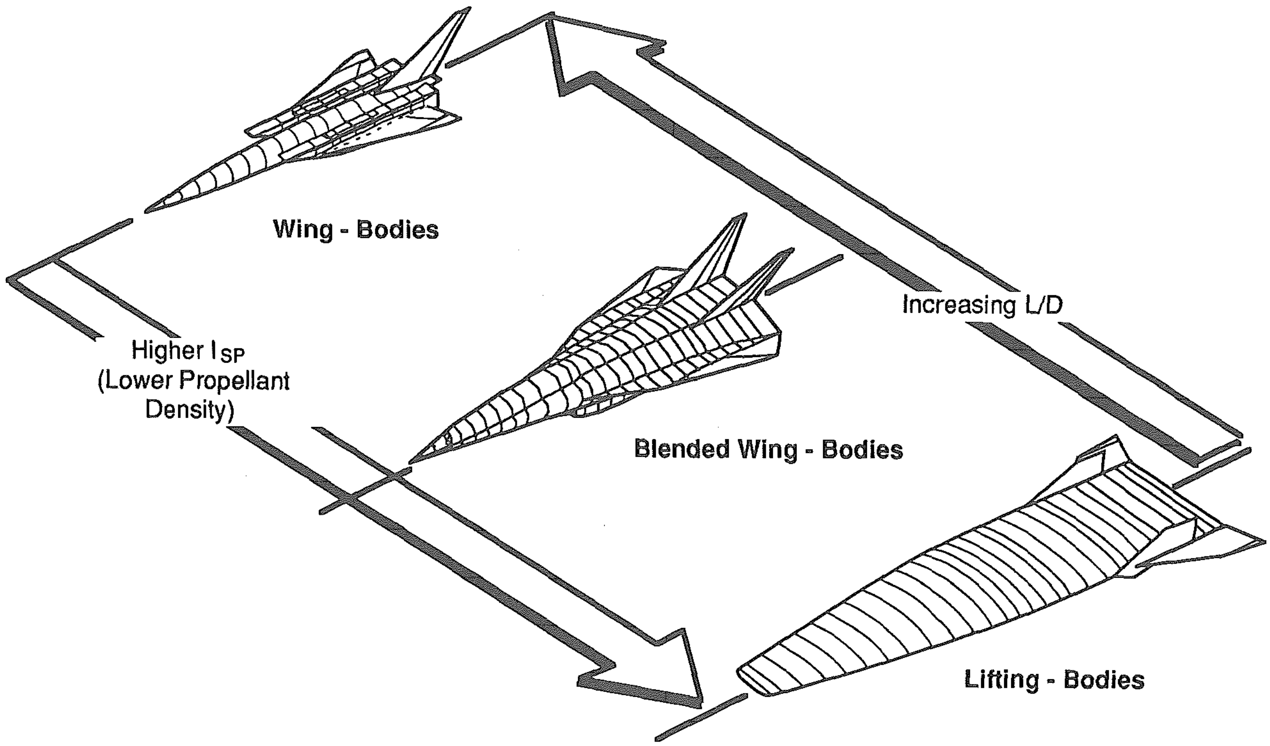

Figure 8. Aerodynamic Shape Represents a Tradeoff Between Thrust and Drag

AERODYNAMIC DRAG

In hypersonic flight, aerodynamic drag has several major components. The largest is wave drag. For example, take a straight wing which has a critical Mach (Mcr) number of 0.7. There is a large increase in drag (called wave drag) at speeds greater than critical Mach. If the wing is swept backward 30 degrees, it "sees" only the component of the flow normal to the leading edge – the actual freestream Mach number can be increased to as high as 0.7/COS 30 DEG = 0.808 before encountering critical Mach number flow on the swept airfoil. Wing sweep is also advantageous in supersonic flow. For a given flight Mach number, there is a Mach cone with a vertex angle mu equal to the Mach angle [arcsin(1/Mach No.)]. If the leading edge of a swept wing is outside the Mach cone, the component of the Mach number normal to the leading edge is supersonic, and a strong oblique shock wave will be created by the wing causing a large wave drag increase as well as thermal and structural concerns. If the leading edge of the wing is inside the Mach cone, the component of the Mach number normal to the leading edge is subsonic, and the wave drag is less. Therefore, a considerable decrease in wave drag can be obtained if the wing is kept inside the Mach cone.

For bodies with blunt noses, the shock angle is going to exceed the Mach angle because of the presence of non–zero thickness (and therefore a vertex angle) at the front of the body. It might seem logical then to use this shock angle as the angle within which the swept wing must keep. Unfortunately, this simple rule does not take into account the fact that, as the shock passes over the body, it bends backward until it approaches the characteristic Mach angle (Figure 9). Although the shock and Mach angles at this point on the body are now the same, the body thickness has had the effect of pushing the shock away from the body (i.e., the shock is now offset from the location it would have had if caused by a flat plate of zero thickness). The amount of this offset is not easily estimated, but a fairly straightforward method can be used to make certain that the vehicle's wings remain within this "bent" shock cone. First, the fuselage, or blended body (minus wings), is designed by itself. Then, a CFD code capable of calculating first–order shock effects should be run to see where the nose shock will fall. Finally, the wings and/or tails should be designed and positioned within this cone.

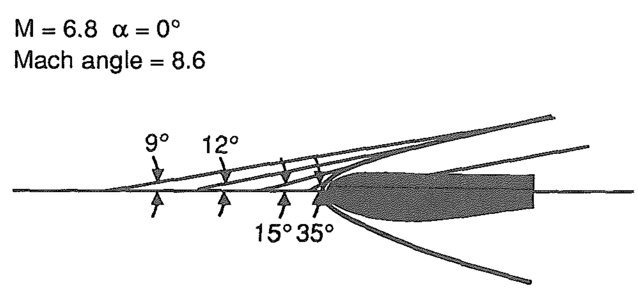

Figure 9. Shock Cone "Bending"

Thrust and drag are interwoven in hypersonic vehicles. As shown in Figure 10, the fatter lifting body has higher transonic wave drag than does the blended wing–body. In both cases, the wave drag coefficient reaches its highest value in the transonic speed range. To make matters worse, airbreathers typically experience a thrust loss transonically due to inlet efficiency losses, flow distortions, etc. In any case, the effect is a transonic "pinch point" where the excess thrust (thrust minus drag) available is at its lowest point. This pinch point then determines what the engine size needs to be to ensure adequate thrust throughout the flight envelope.

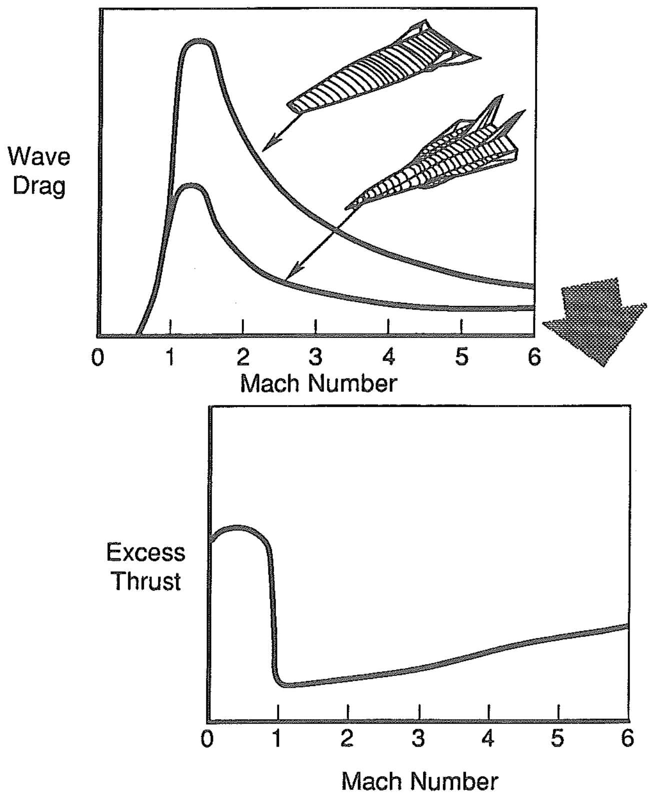

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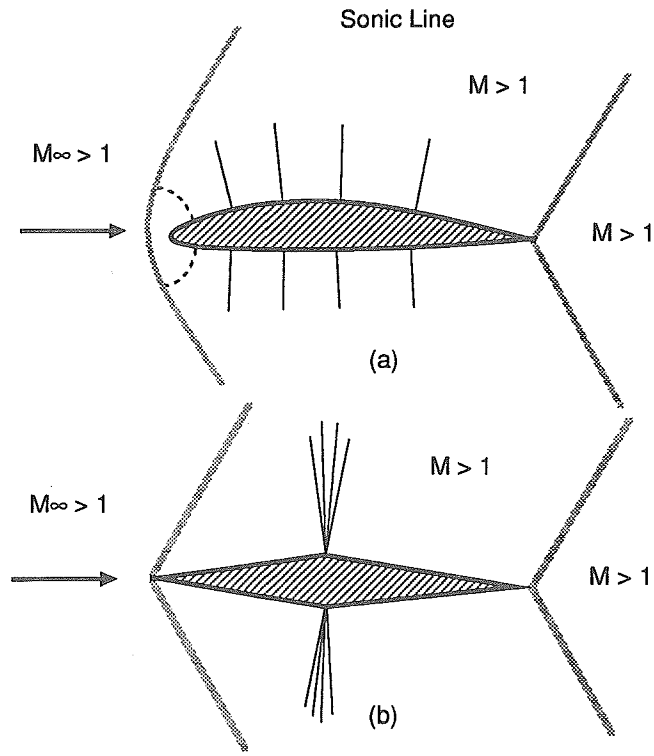
Figure 10. Transonic Operation Is a Critical Design Point

As for the wing (and tail) sections, a sharp leading edge will prevent a large "bubble" of subsonic flow from forming on the leading edge as shown in Figure 11. Also, thin, symmetrical (i.e., uncambered) airfoil sections can be designed such that the air flowing over the top experiences little or no compression. This helps reduce wave drag, but has the drawback of reducing the lift coefficient for critical flight regimes like takeoff and landing. This can be compensated for in part by going to relaxed stability aircraft (so that the tail surface also provides lift) and designing for low



Supersonic Airfoils. (a) Blunt-Nosed Airfoil.
(b) Sharp-Nosed Airfoil

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Figure 11. Supersonic Airfoils

wing loadings. The ideal airfoil for hypersonic flight seems to be either a symmetrical wedge or a biconvex with a thickness/chord ratio of about 4%.

To obtain minimum wave drag for the integrated vehicle, the variation in the total cross–sectional area of the vehicle body, wings, and the tail should be smooth, avoiding significant increases or decreases in area over short distances in the streamwise direction. As seen in Figure 12, the airbreathing hypersonic vehicle (neglecting the two engine packages) has a very smooth profile. The effect of the engine packages is small because most of their cross sectional area is captured for the engine airflow and does not contribute to wave drag. In contrast, the cross sectional characteristics of the Space Shuttle and even the Delta show significant area changes and large base regions. This is not as important for them, however, because they spend little time within the lower atmosphere and are generally going quite slowly when they are at low altitude. For airbreathing vehicles that spend a much longer time in the denser atmosphere, wave drag due to sudden area increases or base areas would have a greater effect on vehicle performance.

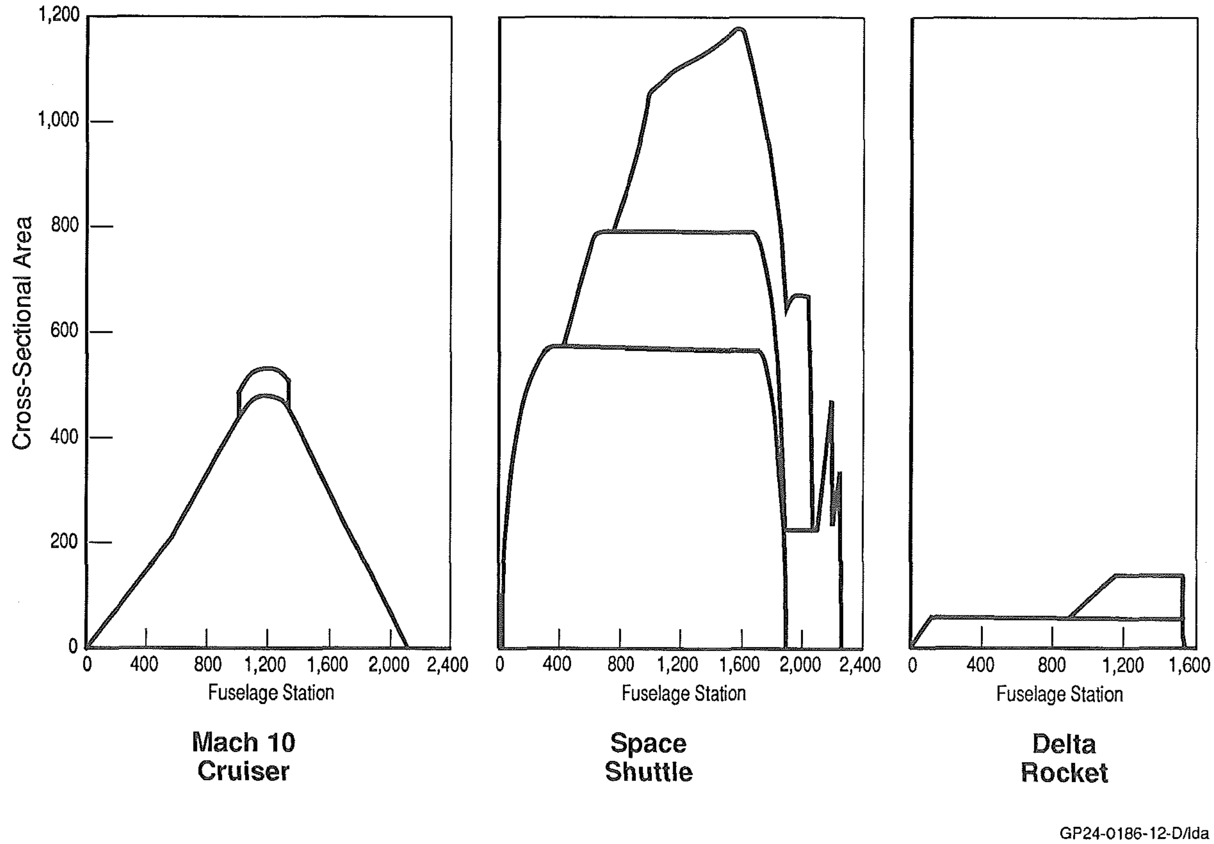

Figure 12. Cross-Sectional Area Plot Comparison

STABILITY AND CONTROL

Hypersonic vehicles have less demanding stability and control requirements than normal high performance aircraft. Studies on our Mach 10 design have shown that the penalties in structural weight, control system sizing, and thermal heating incurred for maneuvering at greater than 3 "g's" do not justify the small increases in turn performance. Turn performance chart (Figure 13) shows that at Mach 10 a 2g turn adds less than three minutes to mission time verses that for a 3g turn. Therefore, it seems best to design this vehicle for 3–3.5g structural limits and use a 2g limit for normal maneuvering. Control of slower (Mach 4–6) wing body designs can be obtained by conventional elevon, rudder, and flap devices. An all–moving wing seems to be the best approach to obtaine pitch and roll control for Mach 10+ vehicles and is integrated in the example vehicle. This method is much smaller than a wing–elevon combination, reducing structural weight and making it easier to keep the wing inside the shock cone. Orbital systems would, of course, also incorporate a reaction control system for transitional vectoring and orbital maneuvering.

CREW STATION

It is critical that a hypersonic vehicle maintain an optimized aerodynamic and thermodynamic shape in order to meet its performance goals. For this reason, the crew station should not influence the fuselage cross–sectional shape of a high Mach cruise vehicle as it has in modern fighters and transports. New methods of visibility must be used to avoid large, "bumpy" canopies and crew stations. To provide forward looking capability, especially for taxi, take–off and landing, several options are available to us other than the conventional "bubble" canopy including helmet–mounted EO/FLIR pictures and flight information displays, a moving map on the main instrument panel, automatic take–off and landing systems, moldline flush side and upward looking windows, "pop–up" cockpits, or a periscope (Figure 14). When all the weight, structural, and technical complexities are evaluated, it seems that the "electronic picture" approach has the highest potential and the least risks. This system has already been proven in flight simulators and in NASA's Fat Albert 737 test aircraft.

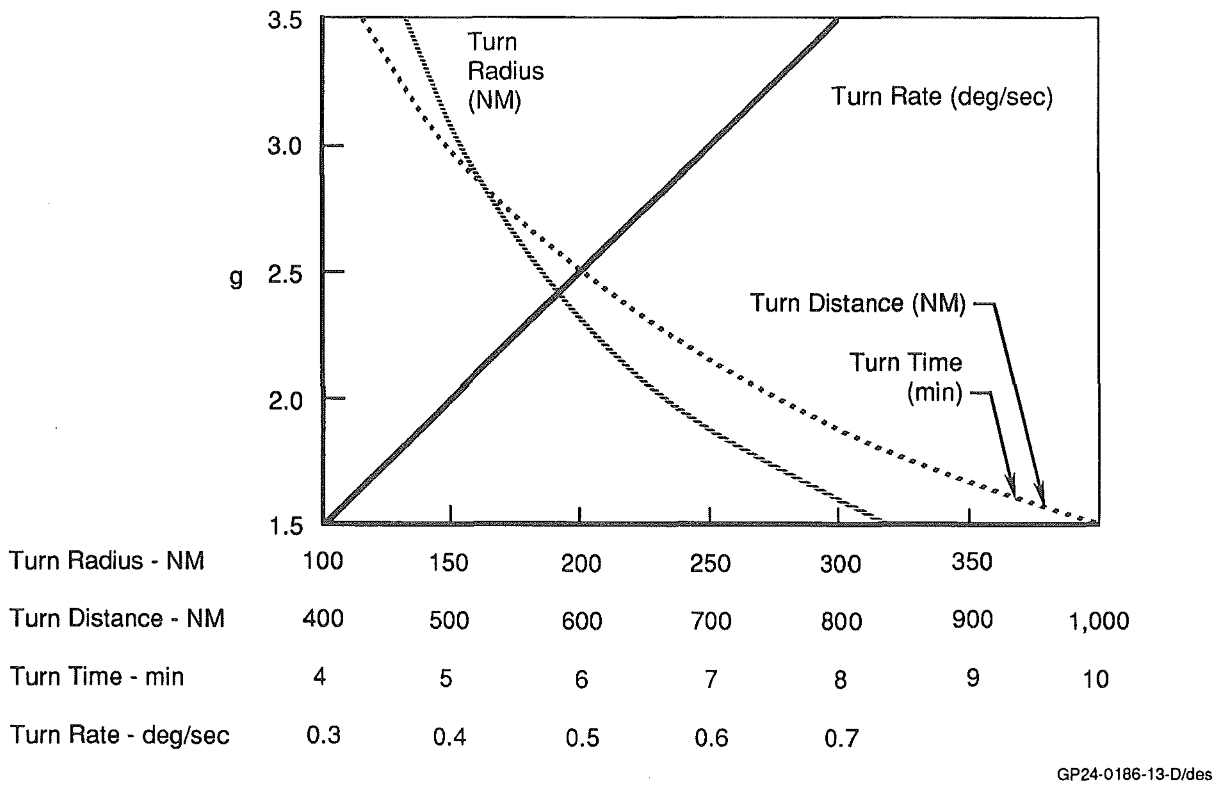

Figure 13. Mach 10 Turn Performance

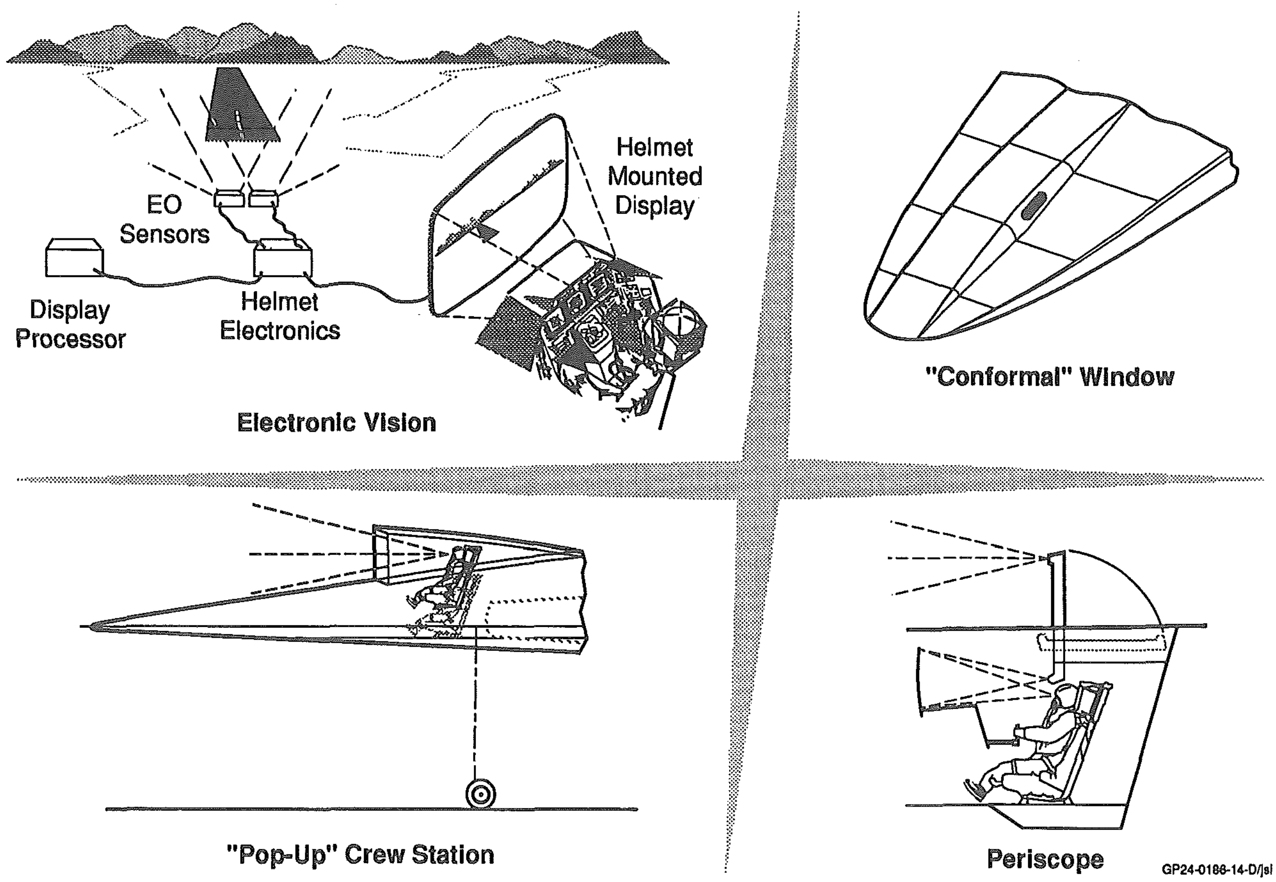

Figure 14. External Vision Options

INTERNAL ARRANGEMENT

A crucial factor for hypersonic aircraft is their volumetric efficiency (i.e., the amount of fuel volume as a percent of total vehicle volume). The higher the volumetric efficiency, the better the overall system will perform. For this reason, it is very important that the crew station and the subsystems be packaged as efficiently as possible. Therefore, it is desirable to collocate the major subsystems and components together with the nose and/or the main landing gear. By doing so, we open up the rest of the vehicle allowing the most efficient integration of the large fuel tanks required. In high Mach systems, enemy fire is not as large a threat as it is with other types of military aircraft, so it is not as important to "hide" routings and subsystems for survivability reasons. In the example vehicle, we have located the crew station and subsystems between the two main landing gear bulkheads. It is an ideal place to tie in lightweight, secondary structure to support the crew station and escape system. It is also a low temperature region of the vehicle and therefore easier to cool. The propulsion systems on these vehicles are generally just aft of the C. G., so it too can be tied into the main landing gear bulkheads. The crew station is also collocated with the avionics bays, equipment bays, and the payload bay. This greatly increases accessibility to subsystems and makes it possible for in–flight avionics and equipment repair and payload management. Collocating the crew station with all the major subsystems, main landing gear, and engine packages, also helps reduce the length and number of lines, cables, and access panels. It also reduces the number of access points (panels,doors) required, enhancing reliability and safety while simplifying the structural design. As we discussed earlier, over–the–nose visibility cannot be obtained anywhere on the aircraft without greatly changing the shape of the upper fuselage. It makes sense, then, to take advantage of the benefits listed above by putting the crew station in the upper–center fuselage, and obtaining visibility by less costly electronic means. Pilots will undoubtedly be uncomfortable with this new approach, but once they realize how safe, reliable, and easy the electronic picture is to use and what huge benefit this has in reduced aircraft size due to this approach, they will accept it as the way of the future.

EJECTION SYSTEM

This leads us to one of the more controversial issues of hypersonic vehicles: the need for appropriate escape systems. Four options are available: standard ejection seat, encapsulated seat, separable capsule, or no ejection system (Figure 15). The first two options are limited in speed and altitude: ejection seats are only good up to 50 K FT and

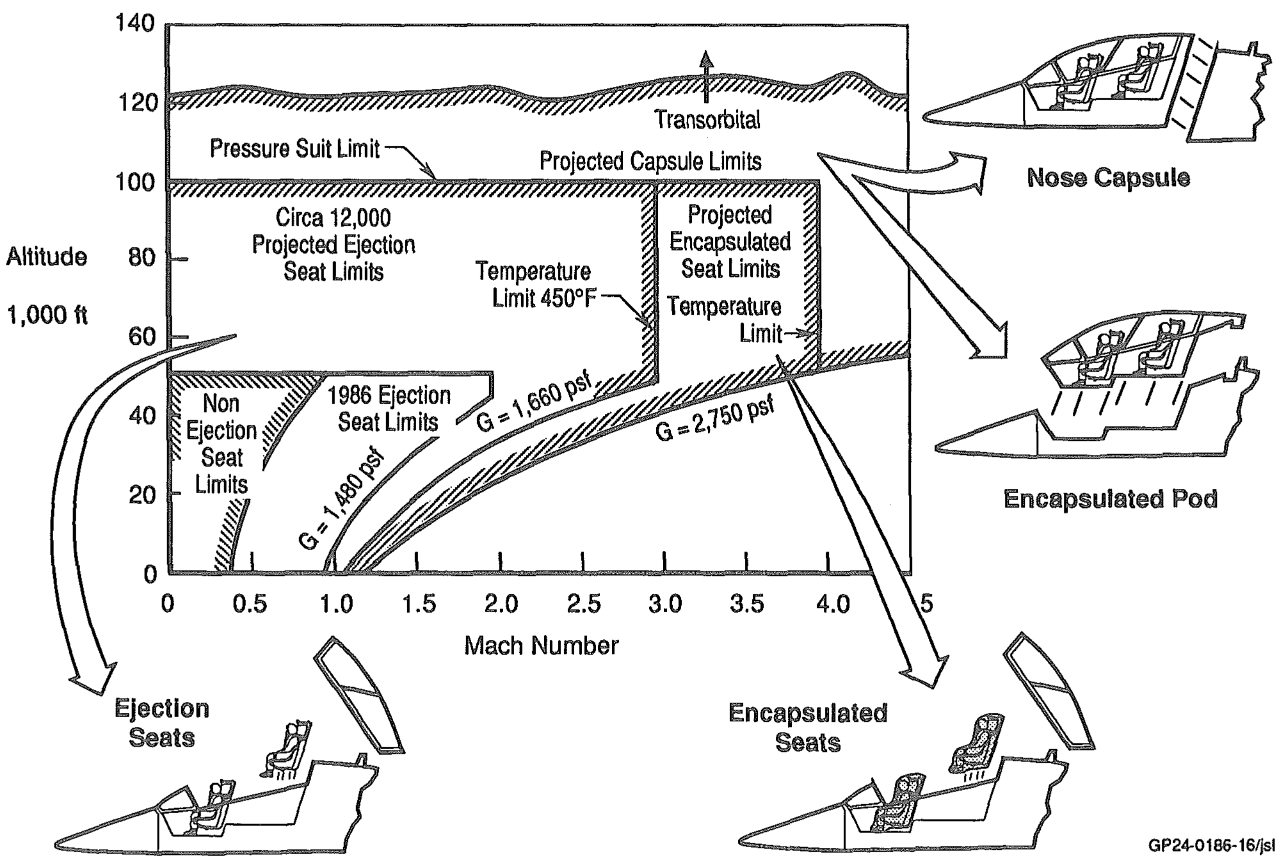

Figure 15. Operating Regions of Escape Systems

Mach 2.0, and encapsulated seats are good up to 100 K FT and Mach 4.0. Both envelopes are inadequate given the cruise envelope for most hypersonic vehicles. If one of these systems were incorporated, the damaged vehicle would have to be maneuvered into the operating range of the ejection system before the crew could bail out. A separable capsule is useable throughout the flight envelope (including orbit). However, this type of system is extremely heavy, very complicated, expensive, and generally requires changes in the "ideal" geometric shape of the vehicle (such as putting crew station in the nose). The weight and aerodynamic impacts cause these vehicles to grow beyond their already large size. The last option, no ejection system, is very controversial for pilot's and should be avoided. Because safety studies show that most non-combat–related ejections occur during take–offs and landings, and considering the great weight impacts of a separable capsule, standard ejection seats or encapsulated seats seem to be the best choice.

PAYLOAD BAY

Bays for dispensable payloads on vehicles operating from MACH 6 to orbit are best located at the center of gravity near the upper surface (such as in the Space Shuttle). This area has the least harsh thermal and dynamic pressure environments for open payload cavities. Payloads could be ejected straight up through the cavity opening or rearward from a pop–up wedge. More conventional lower surface center body bay can be used on systems operating below Mach 6 where the propulsion system does not take up the entire lower fuselage and where the thermal and aerodynamic impacts are not as great.

SECONDARY POWER

Secondary power is normally designed after the initial configuration is completed because the turbomachinery of the engines serves as the power unit. In hypersonic designs that use ramjet or scramjet engines or that operate in space, Auxiliary Power Units (APUs) must be carried. An APU is usually a small turboshaft engine driving an accessory package. In most current aircraft, APUs are only used for emergencies or during ground operations. For hypersonic vehicles like those above, the APUs are running constantly during operations. To supply the all secondary power for the vehicle, the APU will end up being of significant size and requiring a sizeable amount of dedicated fuel. The APU will also require its own inlet (oxidizer source) and exhaust. The inlet for APU will become almost as complicated as the variable geometry inlets of current supersonic aircraft. Space operations will become complex because not only fuel but oxidizer will have to be carried and accounted for either for the APU or its space equivalent; the fuel cell. The secondary power system, including fuel and means of oxidation cannot be "stuffed in later". It must be designed in from the beginning.

THERMAL PROTECTION SYSTEM

Thermal protection is another area that is considered in the latter stages of the design process for current airframes. The process usually consists of material selection and placarding the airframe to limit aeroheating. Figure 16 shows the temperatures that would be found around the example vehicle. Materials alone are insufficient to deal with all of the heat problems and most high temperature materials do not provide high structural strength. Active cooling techniques are effective and structurally stronger, but heavy. The solution is to combine different schemes of protection, using them in the most effective arrangements. Figure 17 provides an example on how the different schemes could work together.

Thermal protection must be kept in the designer's mind from the outset. In all hypersonic vehicles it will be necessary to limit the number of access panels (potential breaks in the thermal protection system) to the vehicle. This is another reason for consolidating equipment. The wheel wells are required and make good access areas.

SUMMARY

Hypersonic vehicles are a challenge for the designer. The items of importance in current airframe design change greatly as speed increases. Propulsion systems grow in their size and impact on the design. Crew stations and payloads become less dominant at the higher Mach numbers. A good designer will be one who can handle the new order of importance for the old design considerations and the introduction of new considerations (secondary power, thermal protection) that have not been considered heavily in the initial design phases for slower vehicles.

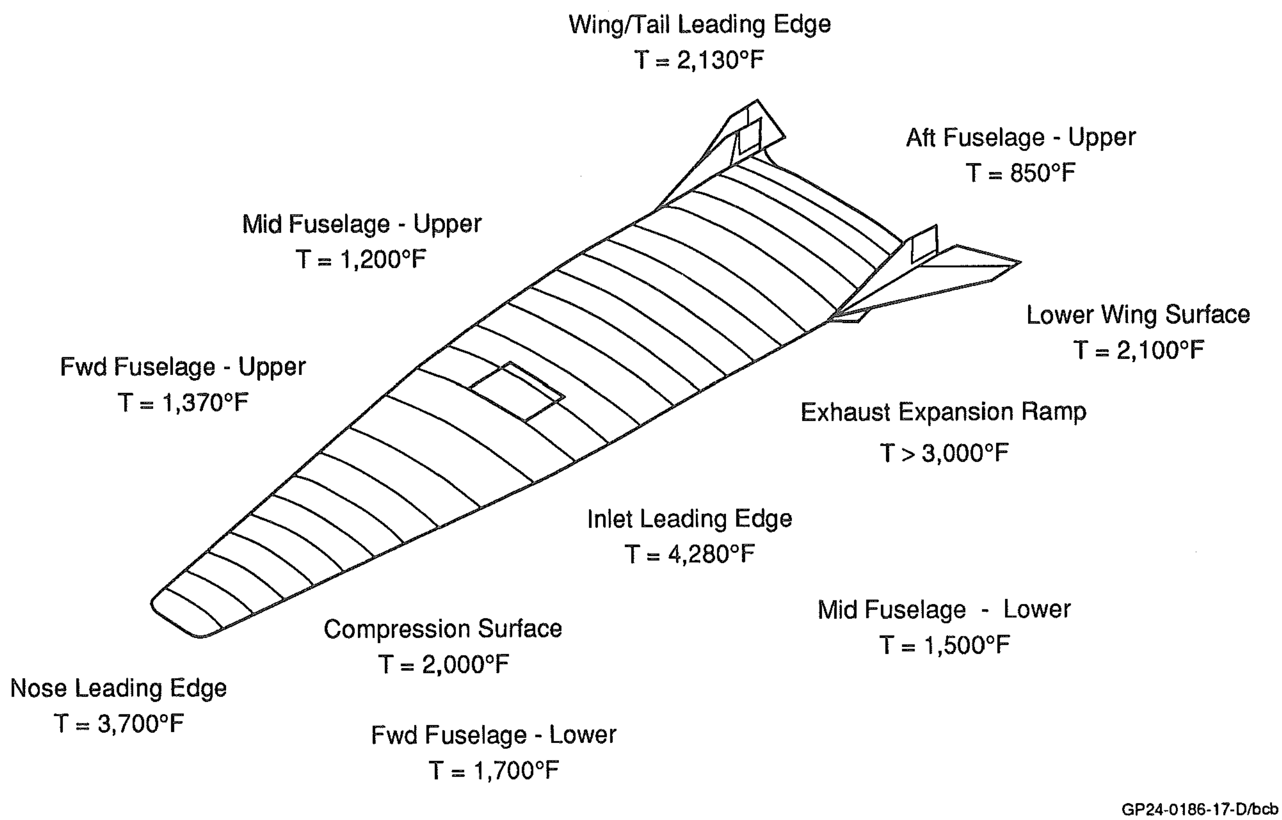

Figure 16. Mach 10 Cruiser Peak Surface Temperatures
Radiation Equilibrium Temperatures

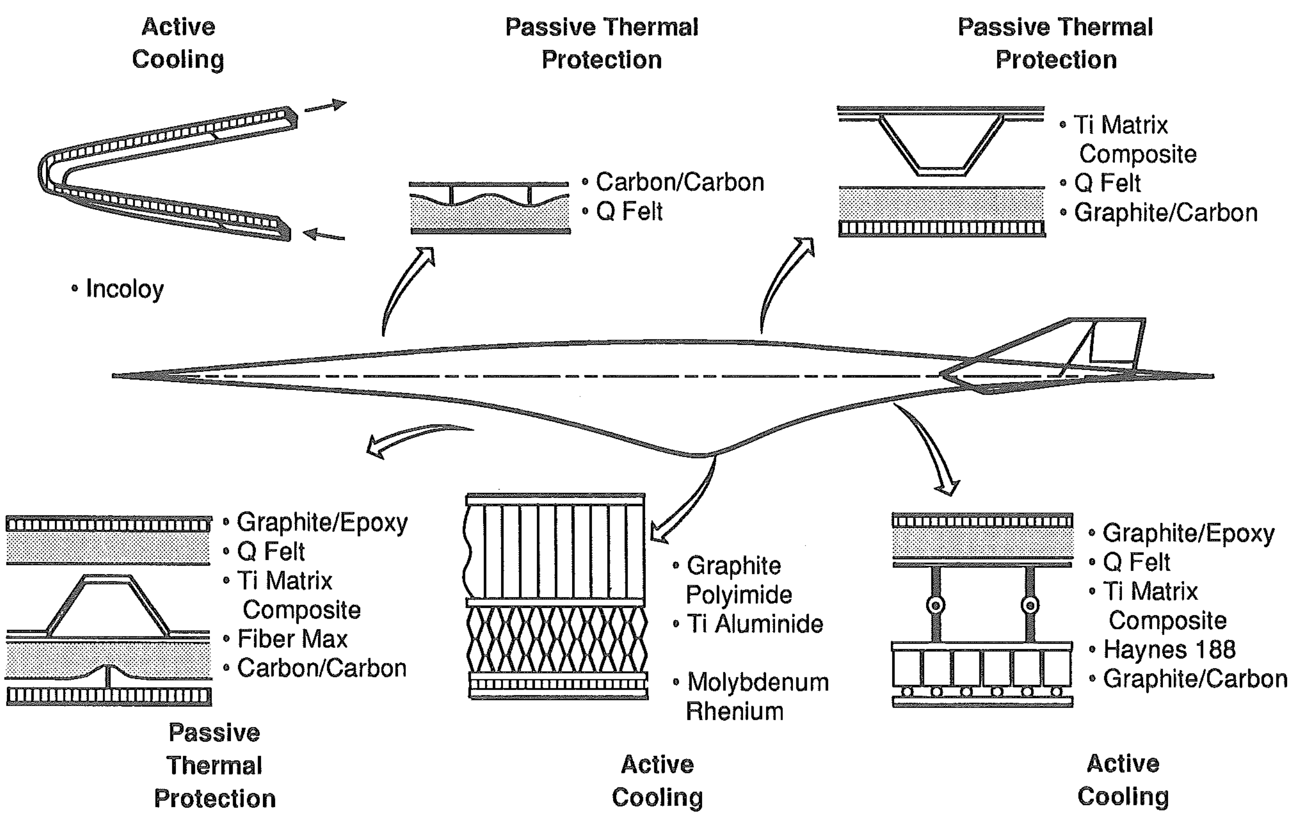

Figure 17. Thermal Protection Systems