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At hypersonic speeds, aerodynamics and airbreathing propulsion become entwined in one of the toughest knots designers have ever tried to untie

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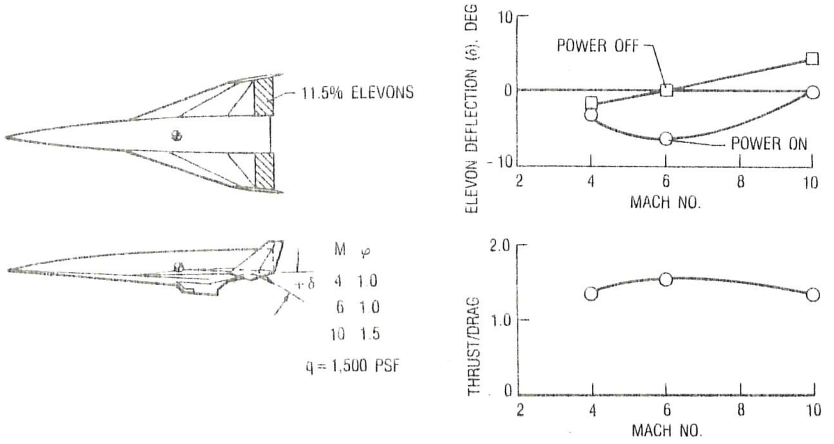
Fitting aerodynamics and propulsion into the puzzle

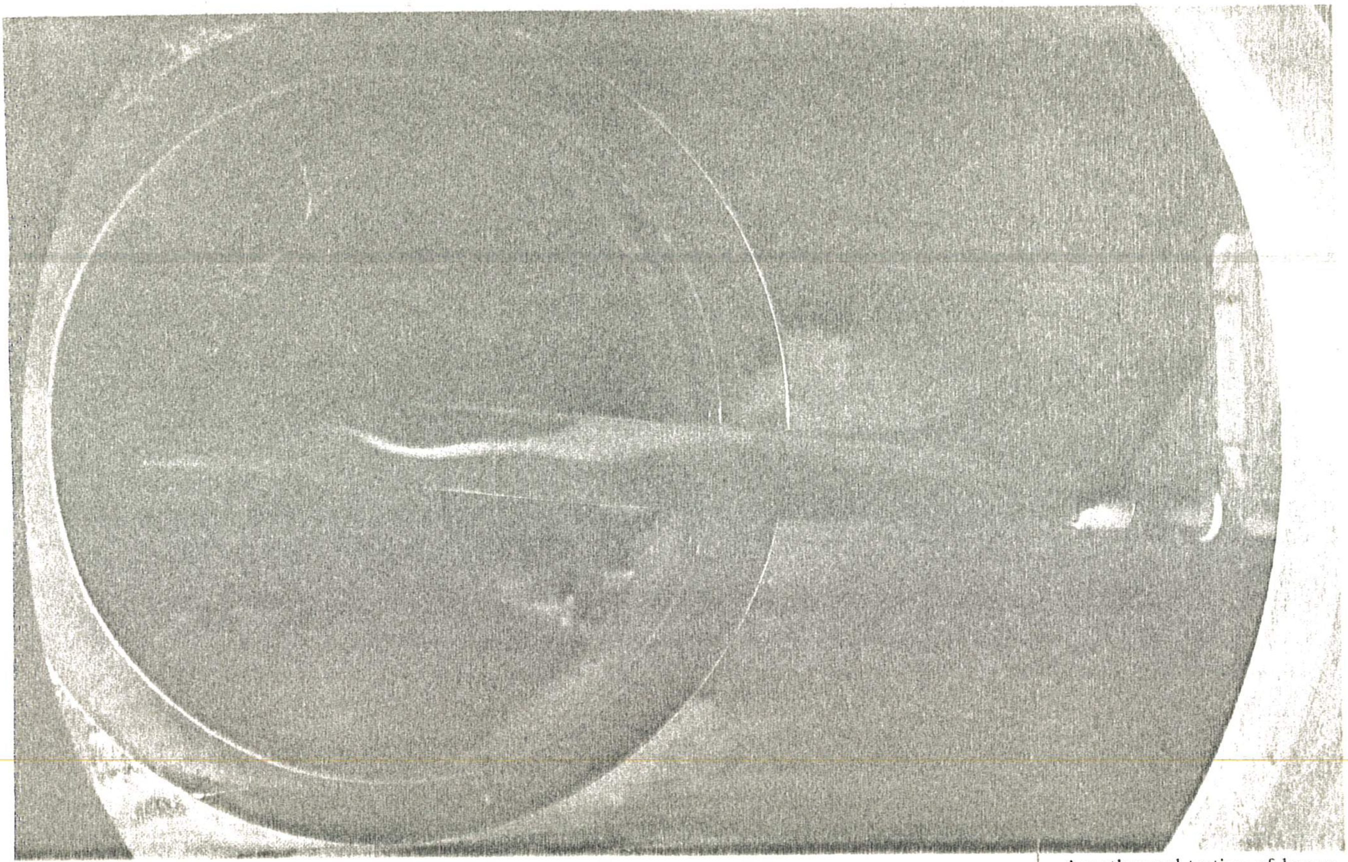
A vehicle that could take off from a standard runway and fly into orbit with airbreathing propulsion would have to be far more sophisticated aerodynamically than the Shuttle. And its design will take into account enormous aerodynamic consequences of massive airflows into and out of the airbreathing engines. In fact, engine influences are so great they will determine the flight profile of the vehicle.

Following takeoff, the vehicle must climb and accelerate rapidly to a speed where the principal propulsion system, a supersonic-burning ramjet, or scramjet, takes over. Once velocity exceeds this changeover Mach number, the vehicle must accelerate and climb through a corridor with the highest mass flow of air past the aircraft that the airframe will allow despite such concerns as flutter and structural and aerothermodynamic loads. This flight profile is necessary because the scramjet engine has no compressor and depends entirely on the forward motion of the aircraft to push air through it. Since mass flow per square foot is proportional to dynamic pressure, the trajectory must follow the line of highest practical dynamic pressure, about 1,500 psf. This is about six times the dynamic pressure encountered by airliners, about twice that proposed for a supersonic transport capable of flight at Mach 3, and the pressure that would be experienced by an aircraft flying 660 knots at sea level.

At a Mach number near 12, limits on the temperature of the heat shield will force the pilot to lower the dynamic pressure, and thrust, by pulling back on the stick and climbing faster into thinner air. Unfortunately, this excursion occurs over that portion of the trajectory where the highest thrust minus drag is desirable. Materials that could stand higher temperatures or better cooling of the heat shield would delay this power loss.



Airframe-engine integration calculations yield elevon deflection angles required to trim a typical vehicle at various Mach numbers. Assumptions include elevon area at 11.5% of wing planform area and free stream dynamic pressure at 1,500 psf. Results both with and without fuel flow are shown. A stoichiometric equivalence ratio φ of 1.5 at Mach 10 means that to meet structural cooling and mass flow requirements 50% more fuel must be added to the flow than can be burned.



Aerothermal testing of hypersonic configurations in the Langley 20-in. Mach 6 tunnel uses a phase-change paint technique.

Reynolds numbers above 100×10^6 will exist on the vehicle well into the hypersonic Mach number range, assuming a length of about 150 ft. At these high Reynolds numbers, a turbulent boundary layer will cover major segments of the airframe and raise skin friction and aerodynamic heating far above that produced by laminar flow. On the other hand, turbulent boundary layers may make inlet unstarts—a reversal of the airflow—less likely and better maintain high pressure recovery and mass capture.

After decades of experimental and theoretical research, much is known about the physics of boundary layer transition on constant pressure surfaces at subsonic and supersonic speeds. Less is known about transition at hypersonic speeds; not because of lack of effort, but quently, there is a good possibility that boundary layer transition will move well aft. Active structural cooling may significantly hasten this process. However, if the inlets must ingest thick laminar boundary layers of slow air, engine performance may be reduced. In addition, susceptibility will rise to shock-induced separation, displacement of the inlet shock structure, and reduced inlet performance.

On the other hand, maintaining laminar flow will allow the vehicle to stay because factors that were insignificant at lower speeds assume major roles at hypersonic speeds. For example, the thicker boundary layer at hypersonic speeds has the effect of adding to the effective thickness of the wing, which causes the leading edge to create a stronger shock. Shock wave interactions and entropy swallowing, which come into play at hypersonic speeds, exert a strong influence on transition. Entropy swallowing means air that passes through the bow shock at greater angles farther from the centerline loses more available energy to entropy and thus has less to add to the boundary layer when it merges with it downstream. In addition, data on hypersonic boundary layer transition are difficult to gather because of noise radiating from the boundary layers of nearby tunnel walls in the small test sections found in high-speed tunnels. To overcome this, researchers are looking at the effects of noise on boundary layer transition. At NASA-Langley, experimentalists have gathered flight-quality transition data in a supersonic "quiet" tunnel specially designed to minimize acoustic influences from the facility. A Mach 6 nozzle for this facility is currently in design.

Wing temperature and Reynolds number will decrease rapidly with Mach number at the highest speeds. Conse-

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longer on the high dynamic pressure line where the engine performs best. Temperature on the wing 3 ft back from the leading edge will reach 2,000 F at a much higher speed for laminar than for turbulent flow.

Although aerodynamicists can simplify calculations by treating air as inviscid at low speeds, at hypersonic velocities viscosity becomes much too important to ignore. At very high Mach numbers, skin friction drag can account for an unprecedented 50% or more of the total drag.

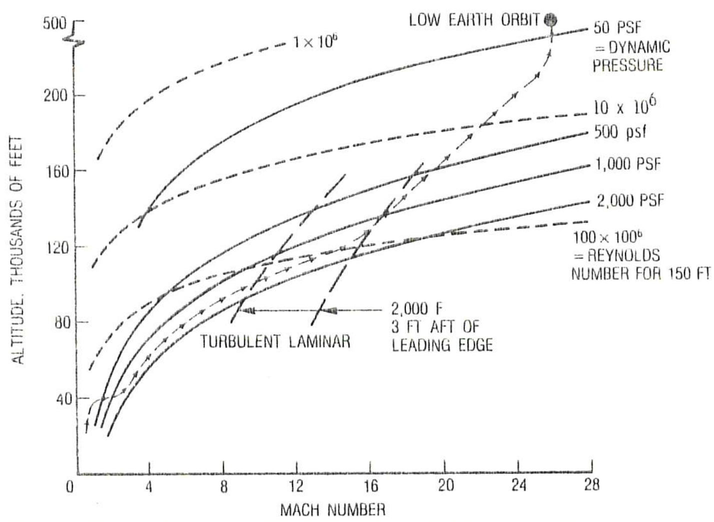
At Mach numbers above 10, real-gas effects become important. Dissociation and recombination of the air cause pressures and shock shapes to deviate from those the designer would expect with an ideal gas. As a result, the boundary layer ingested by the engine may be thickened and stability and control of the vehicle affected. For instance, NASA calculations for a surface having a hinged flap at the trailing edge found that aerodynamic loading on the flap at orbital Mach numbers could be more than 20% higher for a real gas than an ideal gas. If the pilot moved his elevon, he might get a good deal more response than he or his computer bargained for. However, shock-induced boundary layer separation may ameliorate the problem somewhat.

Flying the 1,500-psf ascent has ramifications other than pushing high mass flow through the inlets. It also means that the configuration will be flying near minimum drag with very low lift coefficients so that the component of drag due to lift will be small. Further, as speeds approach orbital, less and less lift will be required to support the aircraft. At times, the configuration may have to fly either at negative aerodynamic lift coefficients or perform roll maneuvers to remain in the desired Mach number-altitude corridor.

When the vehicle crosses the 50-psf dynamic pressure line, it is no longer able to use aerodynamic controls and will have to rely on rockets for attitude control.

Thus far, airbreathing single-stage-to-orbit studies have concentrated on ascent, but descent is of vital importance too. Entry heating can be reduced by increasing vehicle drag by operating at high angles of attack, where the strong shock wave dissipates heat to the air. Immediately the question arises of whether the vehicle can be trimmed at high incidence angles. Here, account must be taken of the highly nonlinear stability characteristics exhibited by many slender configurations at high hypersonic speeds. For such vehicles, pitching moment and lift are not proportional to angle of attack and the center of pressure moves radically aft as the angle increases. In order to keep control forces within bounds, the center of gravity will have to be located between the extreme positions of the center of pressure. At high angles of attack during the descent, the aircraft will have positive stability, but at low angles during ascent it will have negative stability and will have to be under active control by computer.

For any orbital vehicle, cross-range and abort requirements have to be established. The former may require lift-drag ratios near 4 for quick return to the continental U.S. from any orbit inclination. The need of airbreathing propulsion for low drag during ascent then leads to a high entry lift/drag ratio, except for the additional drag of the closed-off inlets, which may be substantial.



A trail of arrows traces the flight corridor of an air-breathing single-stage to orbit vehicle. The solid lines are constant dynamic pressure. The short-dash lines are constant Reynolds number, and the long-dash lines are constant temperature with both turbulent and laminar flow.

Many aerodynamic and propulsion uncertainties must be resolved in flight, because existing ground test facilities cannot replicate true temperatures and pressures. Thus, in contrast to the Space Shuttle, the first airbreathing single-stage-to-orbit vehicle will not go for orbit on the first flight, or perhaps even the tenth. Instead, following the precedent of classic NASA research airplane programs like the X-15, it will carefully and gradually expand its flight envelope in both speed and altitude until engineers have enough confidence to send it to low Earth orbit.

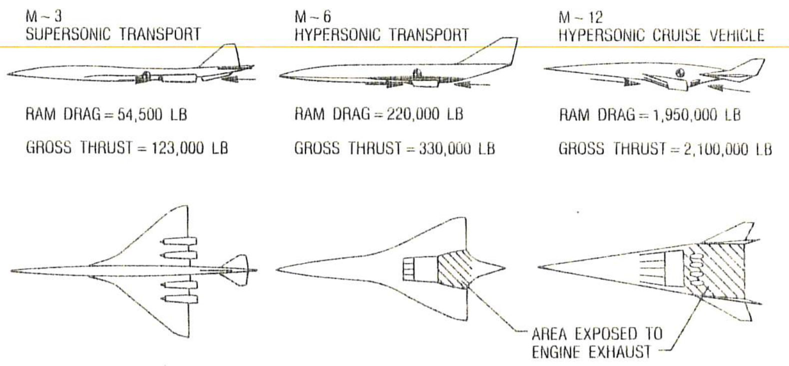
Inlet size required to cruise with a scramjet engine increases dramatically with Mach number until, at high Mach numbers, the configuration is dominated by the propulsion system. Indeed, the entire forebody from the first bow shock wave to the engine cowl is considered part of the inlet system. At very high Mach numbers, the entire afterbody may be used to expand the exhaust flow, reduce pressure drag, and increase the gross thrust. Also, the net propulsive thrust required to cruise or accelerate the aircraft will be the small difference between two extremely large forces, ram drag and gross thrust.

A 500,000-lb supersonic transport capable of Mach 3 would have 54,500 lb of ram drag and 123,000 lb of gross thrust. For a hypersonic transport at Mach 6, these forces would quadruple and triple, respectively. At Mach 12, an orbital vehicle would have a ram drag of 1,950,000 lb and a gross thrust of 2,100,000 lb. One-third to one-half its planform area could be influenced by the exhaust. Since the pressures on these areas are above the freestream pressure, they could add lift and increase the lift-drag ratio and, consequently, cruise performance. For several reasons, not the least of which is the large fuselage volume necessary to contain low-density hydrogen fuel, the lift-drag ratio of hypersonic vehicles is inherently low. Propulsive lift can therefore make a large contribution to vehicle performance.

The propulsive lift may produce a nose-down pitching moment that must be trimmed out along with the basic airframe moments. Previous studies of this problem, dating back to 1970, have shown that the vehicle's aerodynamic control surfaces can handle the job, albeit with an additional aerodynamic penalty due to increased trim drag.

Theoretical engine-airframe integration studies carried out thus far from Mach 4 to 12 have been exploratory and used the best analysis methods available at the time: impact theories on the airframe and two-dimensional assumptions for exhaust flows. No insurmountable obstacles have been encountered. However, much additional research needs to be done, especially over a wide Mach number range with various throttle settings.

One such study, reported in NASA TN-8334, examined a variety of engine installation geometric parameters from Mach 4 to 10 with power on and off. Geometry included longitudinal placement of the scramjet modules and various exhaust-nozzle angles. A stoichiometric, or theoretical chemically ideal, fuel-to-air ratio would accelerate the vehicle from Mach 4 to 6. At Mach 10, fuel flow was increased to give 50% excess fuel, and thrust exceeded drag by about 30%. In any case, such a rich mixture may be needed to cool the engine.



Computational techniques are capable of deriving representative propulsion system forces on three classes of supersonic aircraft.

Elevon control deflections required to trim this vehicle over the Mach number range from 4 to 10 would not be large by any measure. If the propulsion vector contributes to the lift, greater positive deflection would be needed with power on than off. Under both conditions, trends are toward higher positive deflections and greater trim drag penalties at Mach numbers above 10. For a single-stage-to-orbit vehicle, designers must not allow the difference between the power-on and power-off control deflection curves to become excessive, first, because of drag penalties, and second, because pitch or roll maneuvers may require additional deflections.

Previous engine-airframe integration studies did not consider maneuvering flight, yaw, or other realistic situations where, for example, some engine modules

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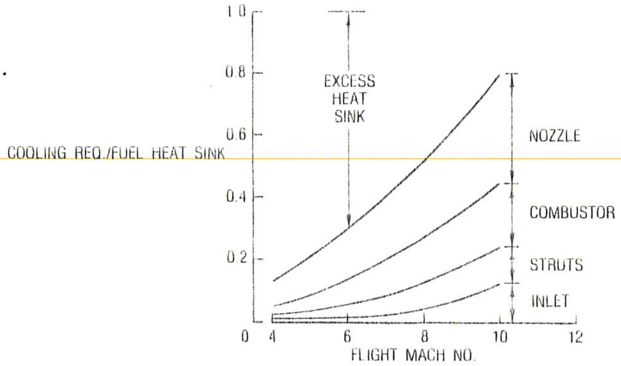
jet and turbojet are operating. The ramjet helps in transonic flight, primarily by reducing drag, even though its efficiency is rather poor at these speeds. As the aircraft accelerates, the ramjet takes on an increasing thrust load. The turbojet begins to spool down at about Mach 2.5 while remaining in full afterburner. It is finally shut down at Mach 3. The ramjet then provides all the thrust for Mach 3 to 5 acceleration and cruise.

The air turboramjet (ATR) requires greater technology advancement, which may extend the use of rotating engine systems to much higher Mach numbers than the conventional turbojet. Both the ATR and a typical jet engine have a compressor and a turbine that drives the compressor. In the jet engine, the incoming air is compressed, heated, and then passed through the turbine. High turbine inlet temperatures limit the use of a typical jet engine to speeds less than about Mach 4. However, the incoming air for the ATR totally bypasses the turbine, going directly to the exhaust nozzle after having been compressed and heated by combustion. The ATR turbine is driven by a high pressure, fuel rich gas. This gas might be the fuel itself, regeneratively heated by a heat exchanger located in the path of the engine exhaust gases upstream of the exhaust nozzle. It might also be driven by a fuel-rich gas obtained by burning the fuel with liquid oxygen in a gas generator. After passing through the turbine, the fuel-rich gas is injected into the main burner where it is mixed with the air and burned at or near stoichiometric conditions upstream of the nozzle.

So far, research has revealed no fundamental problems that would keep a practical hypersonic airbreathing vehicle from approaching orbital velocity.

At Mach 10, cooling the components of a hypersonic propulsion system requires 80% of the heat-sink capacity of the fuel.



Aerodynamics
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might produce less thrust due to flow asymmetry. Advanced, more capable computational fluid dynamics methods are now available to calculate both airframe and exhaust forces and moments.

Considering the 1,950,000-lb ram drag at Mach 12, it does not take much imagination to picture what would happen if the countervailing thrust suddenly vanished. Thus, in engine-airframe integration studies, it is critically important to examine all flight conditions and throttle settings to forestall such a probably fatal occurrence.

At some point in the trajectory, a kick rocket will be fired and the scramjet inlets might have to be closed off to protect the engine interior surfaces from high temperatures. Aerodynamically, this presents a different configuration. Inlet and exhaust forces and moments would be dissimilar from those with the engine running. Again, however, the airframe designer must ensure that the aerodynamic controls have enough authority to trim the vehicle.

When validating theoretical engine-airframe integration calculations in the wind tunnel, substitute gas mixtures must simulate actual exhaust products. No single model can be run in the tunnel and answers read directly off the instruments. Instead, six different partial models, some running with power on and some with power off, must be tested over the desired angle of attack range. At the end, results of all the tests will have to be integrated to give forces and moments on a complete vehicle. Great care must be taken at each step to prevent unavoidable experimental errors from getting out of hand and making the final results meaningless. Suitable facilities to study this problem exist only below Mach 10. At higher flight speeds, the computer must be relied on entirely.

The toughest problems in aerodynamics and propulsion integration are associated with boundary layer flows, inlet aerodynamics, heat transfer, and aerothermostructural loads. These already are the targets of intensive study. Taking off from a runway and flying to orbit on airbreathing engines remains the ultimate challenge in the aeronautical sciences, but in five years, the technology could be ready to pull it off.

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