The Supersonic Transport

by: JOHN STACK
THE SUPersonic TRANSPORT
by John Stack

Somewhere in the eerie silence beyond the speed of sound there lurks a practical high speed airliner. Whether or not engineers can find it depends on how well they solve an imposing array of technological problems

IN BRIEF: Aeronautical science has reached the point where a small increase in aircraft speed is no longer possible. This is the problem we face in designing an improved intercontinental transport. We must jump from Mach 0.8 to Mach 2, or preferably to Mach 3 or Mach 4, to avoid the uneconomical range in the vicinity of Mach 1. It is a difficult jump to make because it requires many changes in our methods of designing and manufacturing airplanes. For one thing, it is likely that such a transport would be built of steel or titanium; aluminum is not to be trusted at speeds beyond Mach 2.2 and is questionable even there. It is also likely that the transport will have wings with sweep angles that can be changed in flight so that the geometry of the plane can be adjusted for efficient operation at both subsonic and supersonic speeds. There are other problems too. The plane must be cooled (at Mach 3, skin temperatures approach 600° F) to protect passengers, fuel, hydraulic systems and accessories. The pressurization system must be failproof; at 70,000 ft, death from oxygen starvation is nearly instantaneous. Most of all, the plane must be stable and controllable at all speeds if it is to be safe. The problems are difficult, but not beyond the range of present technology. — C.J.L.

Sometime within the next ten years an American-built airliner will lift off the runway and head for Europe at something more than twice the speed of sound. Presumably, it will do so from presently existing runways and within the present limits of air traffic control. Presumably, its 160 passengers will be safe and comfortable at Mach 2 or Mach 3 despite searing external temperatures and ambient pressures low enough to boil blood. Presumably—and this is the severest test—the airline operator will collect the usual tourist fare from the passengers and still have a few coins to jingle together after he's paid the fuel and maintenance bills at the other end.

A supersonic transport is unique to commercial aviation in at least one respect: for the first time, a passenger-carrying aircraft will be unable to ride on the coattails of a military predecessor. Our present jet transports were developed with a confidence that grew from a backlog of many thousands of flying hours with B-47's, B-52's, and KC-135's. There is no such precedent for a supersonic transport. The largest supersonic military airplane, the B-58, is only about a third the size of a practical transport. The B-70 (or RS-70, if you like) is not yet flying and, in any event, is not likely to provide many hours of supersonic flight experience for the transport to lean on.

Before we barge off to Mach 2 or Mach 3, we need to understand our objectives and define our problems carefully. We should be precautionary rather than precocious. Most of all, we should be clear on one point: in engineering terms, the Mach-2 or Mach-3 transport is not attractive simply because we have developed the technology to build one, but because it offers a more efficient way of moving people from here to there than can be accomplished by the present subsonic transports.

Big jump, or none at all

It turns out that the best way to improve the performance of a transport is to increase its speed. Look at the curves at top of the next page. There we have the product of lift over drag, times Mach number, divided by specific fuel consumption (lbs of fuel/HP-hr). The product is a measure of the efficiency of a machine in terms of the amount of fuel it burns per mile, per lb of aircraft weight. We have plotted this product against Mach number. The graph shows curves for a typical subsonic jet and three proposed supersonic configurations. The important thing to notice is that the envelope of the four curves drops sharply at Mach 1, and then climbs slowly with increasing Mach number. This envelope curve reflects typical lift-drag ratios of all aircraft, regardless of configuration. Plotted alone, the lift-drag ratio of a good supersonic aircraft would rise to a peak at about Mach 0.8 and then drop sharply to a near constant for speeds above Mach 1. When the ratio is multiplied by Mach number, the curve beyond Mach 1 climbs nearly linearly. All our data show that the envelope curve continues to climb, even beyond Mach 3.

There are two conclusions to be drawn from
Fig. 1. Speed of a supersonic transport must be high to avoid the low-efficiency range above Mach 1. Efficiency is measured here in terms of lift, drag, specific fuel consumption, and speed. Tests show that curves for faster aircraft continue to rise beyond Mach 3.

Fig. 2. An aluminum aircraft cannot be pushed much beyond Mach 2. Aluminum loses strength at Mach-2 temperatures and drops even further as exposure time is increased. The 100-, 500-, and 5000-hour curves are for samples heated without load, then tested. Notice that titanium is somewhat better than steel in the Mach 2.5 to Mach 3.5 range.
The problems considered titanium airplanes, helped us to sort out... °F—because aluminum is easier to do than a steel one. It would... be made. The real question is not whether we should build a Mach-2 transport or a Mach-3 transport. The real question is: What material should we use? We can make the supersonic airplane out of aluminum or we can make it of steel or titanium. There are serious problems no matter which we choose.

Superficially, aluminum appears to be a more conservative choice. The technology of aluminum fabrication for aircraft is highly advanced. We know how to weld it, how to bend it, how to extrude it, how to join it, and most of all, how to manufacture it inexpensively. But aluminum suffers from loss of strength at high temperatures. At Mach 2, skin temperatures exceed 200°F because of heating caused by skin friction. Skin friction slows the air, converting its kinetic energy to heat. We have very little data for aluminum at 200°F and above. We know almost nothing about fatigue at these temperatures and very little about loss of strength when the material is exposed to high temperatures for long periods of time. We do know that the aluminum will lose about 10 to 15% of its room-temperature strength at Mach-2 temperatures and this means we'll have to add more structure to make up for that. For transport aircraft use, aluminum is out of the question for speeds much above Mach 2.

Airline operators have pushed their slide-rules back and forth and concluded that a Mach-2/Mach-3 transport must be in the air about 10-12 hrs/day, make an average of four flights a day, and have a 30,000- to 50,000-hr flying life (12-17 years of normal use) to make the thing a paying proposition. When I look at these figures, I'm afraid of aluminum. It's not just the temperature, but the fact that the airplane will be heated and cooled about four times a day. More than this, on landing, the plane may be coming down through rain clouds with skin temperatures high enough to boil any water that strikes it—and that certainly isn't going to do the material any good. When I add all this together I feel we have a slight chance to build a 50,000-hr Mach-2 aircraft in aluminum.

The steel-titanium choice

The problems are no less severe with steel or titanium. At this stage we tend to consider steel and titanium under the same headings. One is more expensive and less well explored than the other, but the fundamental problems are about the same. With steel or titanium, the temperature problems in the basic structure pretty much disappear but in their place are a bundle of fabrication problems. The B-70 and the X-15, both steel and titanium airplanes, helped us to sort out some of these fabrication problems, but many still remain. If we choose steel or titanium, a large portion of the development money will have to be invested in a new generation of tools and jigs; and we will have to develop better ways to weld, bend, and form steel, and find better ways to make steel or titanium honeycomb.

With steel, maximum Mach numbers can go considerably above 3 and that creates some new problems. At Mach 3, skin temperatures are in the 500°F to 600°F range. Radomes, seals, windows, hydraulic systems—all these have to withstand the searing temperatures without failure. In addition, there are 160 or more passengers inside this oven along with several hundred thousand pounds of jet fuel. These problems are largely unsolved.

In sum, an aluminum airplane would probably be easier to do than a steel one. It would most certainly be cheaper (present Federal

![Diagram](image_url)

Fig 4. An airplane passing through Mach 1 below 45,000 ft generates a sonic boom with an overpressure (pressures in excess of normal atmospheric pressure) too great to be tolerated on the ground. Pressures greater than 1.5 psf could damage ground structures, would most certainly cause adverse public reaction.
THE SHAPE OF SPEED...

...in subsonic range...

...starts with a sphere. It has minimum surface to volume ratio, hence, low skin-friction drag. But turbulence is high, leading to...

...a stretched-out sphere. Minimum turbulence occurs when length-to-thickness ratio of a fuselage is somewhere between 3 and 6. But besides skin-friction drag, there is also...

...drag due to lift, the drag created when the wing "leans" on the air. It is smallest when wing is long and narrow. Wing must also be made thick because of large bending loads at root.

...in supersonic range...

Third source of drag, shock-wave drag, occurs at supersonic speeds. Subsonic fuselage must be stretched further, wings must be shortened and made thinner.

Wing is also swept back to reduce component of air velocity normal to leading edge. This further decreases the effective length-to-thickness ratio of the wing.

Compromise shape has variable sweep wings to give long, narrow wings for subsonic flight, short, swept wings for supersonic flight. This is the SCAT-15, one of a series of NASA proposals for a supersonic transport.

Aviation Agency estimates: $13-$15 million apiece for aluminum; $22.6 million for steel. England and France have already selected the lighter metal (reinforced with steel and titanium at critical places) for their jointly developed Mach-2.2 Concorde. However, there are other factors to consider. An airplane that's easy to build and cheap to produce could easily be too expensive to fly.

Room enough to move around in

No matter what the material, we should strive to build an airplane that offers the most technologically conservative improvement over the present subsonic jets. What this really means is that flexibility must be built in throughout the design, so that we have enough room to move around in if, at first flight, some points of the design specifications are not met. With aluminum, there is very little room to move. If everything is optimized for Mach 2.2, say, everything has to work as designed. If something fails to perform as expected, the plane will have to be flown at reduced speeds until the difficulty is worked out. As speed is reduced, we begin to slide down the efficiency
Fig. 6. Supersonic airplanes with short wings may have to operate on the "back side of the power curve" at speeds below 200 knots. This is an unstable (and somewhat dangerous) situation in which the pilot must add power to slow down.

curve into the worst range above Mach 1. We're losing on economics fast. I view such an airplane as a go/no-go proposition; either everything works as expected or the plane is too expensive to operate. It seems entirely unwise to proceed with such expensive go/no-go vehicles, particularly when research is already in hand for a more reasonable enterprise.

There is an even more serious objection to aluminum. Even if the airplane should meet its design specifications, there is no further room for improvement. The basic aluminum structure cannot be pushed beyond Mach 2.2 or so because of the temperature problem. As new refinements in aerodynamics and powerplants come along, the aluminum airplane cannot take advantage of them; it is flying against its growth limit the first day it flies. For a machine that has to be in service more than ten years to pay its way, that doesn't make very sound commercial sense.

All this, and subsonic—too

Regardless of how fast and how efficiently the supersonic transport flies when it is above the speed of sound, it will have to slow down to subsonic speeds for some part of each flight. Not only must the plane fly in this range, it must fly well. Every detail of the performance I have examined points in one direction: The supersonic transport must be a better subsonic aircraft than our present subsonic jets; on top of this, it has to fly supersonically. Let's look at some of the reasons.

Present take-off and landing speeds are as high as they dare go. Yet it is the most critical phase of flight in the present subsonic jets. Operators would like to have lower speeds on the runway, and they should be lower. The only way they can be reduced is to improve the airplane's handling performance at low speeds.

Noise in the vicinity of the airport remains a problem and will be an even bigger headache with the much larger engines of a supersonic jet. No matter what you do to reduce the noise at the source (sound suppressors, lower jet velocities) there is nothing quite so effective as getting the noise further away from the people who complain. Present jets enter and leave the runways on a path having about a $2\frac{1}{2}^\circ$ slope. If this could be increased to $10^\circ$, the plane would be four times as far from the ground and the noise would be reduced. To increase glide angle without increasing landing speed calls for an airplane with better low-speed handling characteristics than our present jets.

The most compelling argument for having a good subsonic airplane follows from the restrictions imposed by the sonic boom. Theory and experiments with B-58's both confirm the fact that a supersonic transport aircraft must pass through Mach 1 at altitudes above 45,000 ft to keep the overpressures caused by the boom to low values on the ground. Overpressures have been experienced that have broken windows. Certainly these overpressures must be kept below any annoyance level. So the airplane has to climb to 45,000 ft subsonically. That's about the service ceiling of the present jets at take-off gross weights and is another reason why the supersonic aircraft has to be a better subsonic airplane than the ones we're flying now.

Added to these factors is the time the airplane must spend flying at speeds below the speeds it's designed for. It is estimated that about 85% of the fuel will be burned during these "off-design" phases of the flight—taxi, runup, takeoff, climb, acceleration to cruise and possibly stuck on holding patterns at the other end of the flight. To keep this fuel expenditure to the minimum, the airplane must fly at subsonic speeds with an efficiency at least equal to that of present jets.

Look again at the efficiency curves on p. 51. The ideal supersonic airplane would have an efficiency curve that was as high as (or higher than) present subsonic jets in the region
Below Mach 1, and as high as possible at the design cruise speed; the curve should follow the envelope of the four curves shown. Unfortunately, there is no single configuration that will satisfy all these conditions. You can't draw a practical compromise between a subsonic configuration and a supersonic configuration any more than you can find compromises between apples and bananas; the flow laws at the two speeds are not the same.

**Design for minimum drag**

The difference in flow laws that interests the aircraft designer is the way in which they relate to the airplane's drag. At subsonic speeds, drag comes principally from two sources. The first of these, drag due to skin friction, is minimized by reducing the surface area of the aircraft. Ideally, the designer would like to use a sphere, if this has the minimum surface area for a given enclosed volume. But despite its low surface area, it creates a turbulent wake as it moves through the air and is therefore a poor shape for an airplane. So, to make a low-drag fuselage, he stretches the sphere out to minimize the turbulent wake. This puts the length-to-thickness ratio somewhere between 3 and 6.

The other source of drag at subsonic speeds is drag due to lift. This is simply the drag caused by the wing as it "leans" on the air creating a downward velocity component (downwash) in the air (see marginal sketch). It is smallest when the aspect ratio (the length of the wing divided by its width) is large. High-aspect-ratio wings have their centers of pressure (the points where the lift can be considered to act) far out on the wing, forcing the designer to make the wing thick enough to handle the beam loading. Hence, a typical subsonic wing is long, narrow and thick.

At supersonic speeds, there is a third source of drag. This third source of drag—wave drag—comes from the shock wave generated at supersonic speeds. Unfortunately, wave drag is a function of the thickness ratio squared, thus making the ideal subsonic shape too thick. Wave drag is reduced by decreasing the thickness of the fuselage and wings. It approaches a minimum for the fuselage at length-to-thickness ratios in the range of 11 to 14 (wings are made even thinner than this). So, starting with the ideal subsonic shape, the designer stretches the fuselage out into a long, slim cylinder. He also chops off a large portion of the wingspan to bring the centers of pressure closer to the fuselage, which permits him to make the wing thinner at its root. He adds the chopped-off area to the chord of the wing to decrease thickness-to-length ratio and retain needed lifting area. Finally, he sweeps back the leading edge as much as possible. The effect of wing sweep is to decrease the velocity component normal to the leading edge, thus decreasing the thickness-to-length ratio in a streamwise direction.

**Wings that rotate**

There are a few fixed configurations that have fair performance in both the subsonic and supersonic ranges. But it is an awkward compromise. Such designs generally improve low-speed performance by degrading high-

![Diagram](fig7.png)

*Fig. 7. The turbofanjet is a more efficient choice for supersonic aircraft because it matches the thrust requirements for acceleration and cruise more closely than the pure turbojet when both engines are sized for the transonic acceleration point. Moreover, the turbojet cannot use all its thrust on takeoff because of noise.*
In light of what we know today, the best answer seems to be a design that allows the sweepback of the wing to be changed in flight. Variable-sweep wings were first tried on the X-5, a small research airplane designed and built in the early 1950's. In the X-5, it was not sufficient to simply rotate the wings; they had to move forward and aft as they rotated to keep their centers of pressure close to the center of gravity of the plane. Because of this, the variable-sweep mechanism was complex, required a comparatively thick wing-root, and added a large factor to the structure weight. Since then, we have discovered how to locate wings and pivot so that the fore-and-aft movement is unnecessary.

The variable-sweep configuration has several advantages. In the first place, it provides a better compromise between the ideal subsonic and the ideal supersonic geometries. With the wings extended, it produces higher lift at low speeds and because of this, the aircraft can be designed for a lower gross weight for a given payload. Moreover, with a high aspect ratio, all of the lift-and-drag producing devices—flaps, slots, ailerons—are much more effective.

The variable-sweep design also overcomes one of the principal disadvantages of fixed, low-aspect-ratio wings. An aircraft with short stubby wings must assume a very high angle of attack to develop the necessary lift at low speeds (see sketch in margin). With some of the supersonic designs now on the drafting board, this high angle of attack creates so much drag below 200 knots that the pilot may have to add power as he brings the nose up for landing. Effectively, the pilot must add power to slow down; the aircraft operates in what is known as the “back side of the power curve”—an undesirable attitude not recommended for commercial machines. I am an old aeronautical engineer and I wouldn’t want to be one of the 160 sitting back there while the fellow up front is sliding down the back side of the power curve to a landing.

As a consequence of its good efficiency at low speeds, the variable-sweep geometry offers the possibility of using the transport as a subsonic carrier for short-haul flights. This is more than a frivolous advantage. Commercial carriers estimate that the supersonic transport will have to be in service 10 to 12 hours a day to ensure a reasonable operating profit. Because of its high speed, service hours will be severely limited; for instance, if one left New York at 5 PM the plane would arrive in Paris at 1 AM on the following day. The airplane could be refueled and ready for the return flight to New York by 2 AM. But who would want to board a flight leaving at that hour to arrive in New York at 10 PM?

One can see that to provide convenient arrival and departure times and yet meet utilization requirements, the airplane must either be scheduled for fill-in routes or possibly circumnavigate to the West. A variable-sweep airplane could fly these fill-in routes at speeds close to Mach 1 and altitudes around 35,000 ft and still operate economically.

A handful for the pilot

Regardless of whether the supersonic transport has variable-sweep wings, it will most certainly have a different shape from that of our present subsonic transports. I foresee that this will cause problems with dynamic stability and control. For one thing, the mass of the machine is highly concentrated along the centerline, compared with anything that has preceded it. We must be careful as we rush off to build a machine operating at very high speeds, high altitudes, high temperatures, and having reduced damping, reduced control effectiveness and not too desirable a mass distribution. We have little flight experience with such aircraft. NASA has tested some configurations on their flight test simulator in the Ames Laboratory at Moffet Field, Calif. The airplanes seem to be flyable. In some cases, however, qualified jet pilots have had the plane yaw as much as 6 deg during a simulated engine failure before they could get hold of it. If that happened in real flight, the inlet flow to the other engines might be so disturbed that it would put them out too.

There are a number of other aerodynamic problems to be sorted out. One is the possible reduction of drag through boundary-layer control. Some simple tests have shown that lift-to-drag ratio can be improved by a factor of about 1.3 (at Mach 3) by bleeding some air into the boundary layer between the wing surface and the surrounding air. This could reduce the gross weight of the aircraft by 50,000 lb (where total weight of the supersonic transport will probably be around 350,000 lb) and is consequently an important matter to study.

Another aerodynamic problem that needs to be solved is the matter of twist and camber in the wing. Theory indicates that wings with sweep angles greater than 60 deg should have more camber (roughly speaking, the curvature of the wing's cross section) at the tips than at the roots and should be twisted so that the tip assumes a lower angle of attack. Experiments have shown some improvement in lift-to-drag ratio with this technique, but have not shown the improvement predicted by the the-
ory. This is an area where we need to do some further research to ensure, in the design, the best over-all lift-drag ratio.

**More thrust, more noise**

To push a 350,000-lb airplane through the sonic barrier requires powerful engines; much more powerful than those on present jets. Thrust-to-weight ratios for the transport will have to be on the order of 0.35. Present subsonic jets have thrust-to-weight ratios in the 0.2 range. Presently, General Electric's J-93 developed for the B-70 is one of the few available power plants suitable for operation at Mach 3. But it is a pure turbojet and therefore thought to be unsatisfactory for a supersonic transport. It seems likely that the best choice for a transport will be some form of turbofanjet—a turbojet engine that compresses large quantities of air, bypasses a portion around the combustion chambers, and mixes this cool, dense air with the exhaust. Because the mass of air expelled by the turbofanjet is larger than that for the turbojet, jet velocities can be lower for given thrust.

Yet another advantage of the turbofanjet is that it operates efficiently over a wide range of speeds and power settings (see Fig. 7). This is essential for an aircraft that must operate efficiently at both subsonic and supersonic speeds. The low velocity jet of the turbofanjet also means that it generates less noise, since noise increases exponentially with the jet velocity. This offers the opportunity to increase thrust on takeoff and acceleration by burning fuel in the exhaust system (afterburning).

If speeds of the transport can be pushed up to Mach 3 or beyond, the most efficient form of powerplant might be some kind of augmented turbofanjet combined with a ramjet.

**Where's the heat sink**

Even if we get all the problems of powerplant aerodynamics and structure solved, a number of sticky problems remain. One of the trickiest is cooling. An airplane flying at Mach 3 will have a skin temperature averaging about 500°F. Inside, there are passengers, fuel, hydraulic systems, electronics systems and many other things that cannot be exposed to high temperatures. The passenger cabin must be kept between 68° and 72°F. Ordinary JP-grade fuels (blended kerosenes) cannot be heated much above 225°F before gums begin to form in the fuel lines and on the walls of fuel tanks. We'll need improved fuels or precooled fuels with insulation.

The cooling problem is particularly difficult because there is no place to dump the heat. At Mach 3, the stagnation temperatures are all in the 500°F to 600°F range. (Stagnation temperatures occur at the leading edge of all lifting surfaces where the air is at zero velocity.) Insulation will help to reduce the heat load on the air conditioner, but it adds structure weight to an airplane that already has difficulties meeting a decent payload to gross weight ratio. Whatever the cooling system, like everything else, it's got to be small, light-weight, and consume little power.

Pressurization is another problem on the list. Fail-proof pressurization is essential. The ambient pressure at 70,000 ft is only a little more than 1 in. of mercury. At this pressure, human survival time is measured in seconds. There isn't time to drop oxygen masks to the passengers and we can hardly expect them to wear pressure suits even if it were possible to fit each passenger with a suit tailored to his dimensions. The only answer is to design a fuselage that will not fail under pressure or, at minimum, will develop leaks small enough that the pilot can descend before cabin pressure falls to dangerous levels.

Looking over the list of problems to be solved and reviewing the areas where we know little more than the fact that more research is needed, it is easy to conclude that such a transport can't be built. This conclusion, I believe, is totally incorrect. We can solve the problems if they are defined. The essential technology is largely in hand. Applied wisely and thoughtfully, the technology will lead to a practical, economical replacement for our present intercontinental jets within the next few years. Handled hastily, without sufficient regard for economics or engineering, it could produce a billion-dollar prestige symbol that no one could afford to operate.

*For other arguments in the supersonic-transport debate, see To Dig Deeper, p. 117.*