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PROPULSION CHALLENGES AND OPPORTUNITIES FOR HIGH-SPEED TRANSPORT AIRCRAFT

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SUMMARY

The major challenges confronting the propulsion community for supersonic transport (SST) applications are identified. Both past progress and future opportunities are discussed in relation to perceived technology shortfalls for an economically successful SST that satisfies environmental constraints.

A very large improvement in propulsion system efficiency is needed both at supersonic cruise and subsonic cruise conditions. Toward that end, several advanced engine concepts are being considered that, together with advanced discipline and component technologies, promise up to 25 percent better efficiency than the Concorde engine.

The quest for higher productivity through higher speed is also thwarted by the lack of a conventional, low-priced fuel that is thermally stable at the higher temperatures associated with faster flight. Extending Jet A-type fuel to higher temperatures and the adoption of liquid natural gas or methane are two possibilities requiring further investigation.

Airport noise remains a tough challenge because previously researched concepts fall short of achieving FAR 36 Stage III noise levels. Innovative solutions may be necessary to reach acceptably low noise.

While the technical challenges are indeed formidable, it is reasonable to assume that the current shortfalls in fuel economy and noise can be overcome through an aggressive propulsion research program.

OVERVIEW OF SST CHALLENGES

For several years there has been a growing interest in the subject of efficient, sustained supersonic cruise technology applied to a high-speed transport aircraft. Although the Concorde ushered in the supersonic transport era, it has not been a commercial success for a variety of reasons. Its poor fuel consumption (three times equivalent technology subsonic airplanes) is largely responsible for its uncompetitive economics - twice the total operation cost (TOC) as similar technology long-range subsonic transports (fig. 1). Very large airframe and propulsive efficiency improvements will be required to alter this situation. In our quest for greater productivity through increased speed, we are confronted with ever-increasing difficulties arising from high ram temperature levels. The challenge is to utilize advanced materials to cope with the high temperatures without incurring excessive weight and cost penalties. In addition, the inability of readily available low-cost fuels to provide adequate thermal stability seriously impedes the pursuit of higher speeds. Expensive JP-type fuels reach thermal stability limits at approximately Mach 4, but low-cost Jet A is limited to slightly above Mach 2.

There are also several challenging environmental issues. While the sonic boom problem is airframe driven, the excessive airport noise levels are due to the very high takeoff exhaust velocities associated with supersonic engines. Engine exhaust gas emissions is another environmental issue requiring attention.

In the remainder of this report, each of these issues will be discussed in more detail, including a summary of previous progress, current status, and future research requirements.

FUEL ECONOMY

Figure 2 summarizes prior progress made in reducing SST engine thrust specific fuel consumption (TSFC). Results are normalized by the cruise TSFC of the 1971 U.S. engine that was first proposed for a U.S. SST. This afterburning turbojet (GE4) performed relatively well at supersonic cruise conditions. But its subsonic efficiency was very inferior to comparable high-bypass-ratio subsonic engines. To mitigate this mismatch between a fixed-cycle engine and varying mission requirements, the nation embarked on a 10-year NASA-sponsored variable-cycle engine (VCE) research program that achieved considerable progress during the 1970's. Compared to the 1971 GE4 afterburning turbojet, the hypothetical VCE engines defined in 1981 (which assumed technology levels beyond 1981) consumed 10 percent less fuel at supersonic and transonic conditions, and 25 percent less at subsonic speeds - reflecting the cycle changing feature of VCE's. A simultaneous 25 percent reduction in engine weight occurred as a result of improved materials. Nevertheless, these gains are insufficient by themselves to obtain good enough fuel economy to enable competition with subsonic aircraft. The subsonic efficiency of the 1981 VCE engines, for example, is still only one-half that of today's high-bypass-ratio turbofans.

The primary cause of the Concorde's high fuel consumption is the dramatic fall in airplane lift-to-drag ratio (L/D) at supersonic speeds - on the order of one-half that of subsonic transports. This is only partially offset by the trend towards increasing overall engine efficiency with flight speed, as shown in figure 3. Installed cruise efficiency shown here includes inlet and nozzle losses, but not nacelle drag, and represents design point values. The lowest curve represents currently operational powerplants. The middle curve indicates that significant improvement is possible with today's available technology for both subsonic and supersonic regimes. The top band projects future opportunities based principally on NASA cycle analyses. Several alternative cycle concepts are represented, including very advanced VCE and turbine bypass engines (lower boundary), and radically different concepts such as supersonic through-flow turbofans (upper boundary). These advanced technology concepts extend the peak propulsion efficiency levels from Mach 2+ to at least Mach 4. Gains of as much as 25 percent over Concorde's Olympus are possible.

Using a simple criterion such as design point efficiency is insufficient to properly convey the overall impact of advanced technology. For example, this plot shows a relatively modest 8 percent gain between 1987-technology VCE's and advanced VCE's (lower line of top band). Not shown, but vitally important, are even larger gains in climb efficiency and engine weight for advanced VCE's. For example, figure 4 displays an example of a "goal" VCE, representing what payoffs would accrue if revolutionary advances in materials and structures technology are achieved. This particular design was generated by General Electric in their recent NASA-sponsored Revolutionary Opportunities for Materials and Structures (ROMS) study (ref. 1). It assumes essentially uncooled stoichiometric engine materials coupled to advanced aerodynamics and structural design technologies. This implies extensive use of nonmetallics and intermetallic materials.

Two levels of technology are quoted here: (1) the uncooled stoichiometric goal level is denoted by the right-hand values (GE ROMS), and (2) a 600 °F cooler level is denoted by the left-hand values (NASA estimate). One-third of the 32-percent ultimate fuel reduction potential is due to a 45-percent engine weight reduction relative to a hypothetical 1984 technology-readiness baseline engine. While achieving uncooled stoichiometric technology is certainly a very long term goal, the magnitude of the payoff is so large that pursuit of high-temperature, minimally cooled cores and advanced VCE components is key to substantial improvement in supersonic flight efficiency.

To obtain even better powerplant performance than afforded by applying advanced technology to the traditional VCE, novel high risk concepts will be required. One potential SST breakthrough is the supersonic fan concept (fig. 5). Instead of using a long and heavy inlet system to efficiently decelerate the intake airflow to the subsonic speeds required by conventional turbomachinery, the supersonic fan efficiently processes air at supersonic throughflow velocities. The advantages include much lower inlet system weight, lighter fan (less stages required for a given pressure ratio), less boundary-layer bleed drag, better inlet pressure recovery, and better matching of bypass ratio variations to flight speed. Of course, there are many unknowns and challenges. What are such a fan's low-speed operating characteristics? How can the core inlet losses associated with unsteady, swirling, supersonic inflow be controlled - or is an aft fan configuration a better solution? Little effort has been expended on this concept to date, although NASA has initiated a concept feasibility research effort.

The potential payoff of supersonic throughflow fan (SSTF) technology for a typical SST application has been analyzed by NASA (ref. 2). One of the major contributors is the inlet size and weight reduction to about one-half that of a conventional supersonic inlet. This also reduces the inlet bleed drag penalty about 70 percent. The installed efficiency is improved nearly 10 percent relative to a comparable-technology conventional engine, the propulsion system weight is reduced about 25 percent, and together these improvements would yield approximately a 22-percent reduction in mission fuel (fig. 6).

Figure 7 displays the impact of potential future technology advances on airplane fuel consumption - recognizing that the key to viable SST economics is fuel cost levels approaching those for future subsonic airplanes. Achieving 100-percent fuel usage parity with the subsonic competition is not necessary because of the increased productivity associated with SST's. However, it is important to at least be in the same neighborhood, which the Concorde and previous SST study airplanes cannot achieve despite their relatively short range capabilities. The impact of advanced propulsion technology is impressive, enabling fuel consumption rates not much different than current long-range subsonic airplanes. Coupling the most optimistic propulsion technology with potential airframe advances (18-percent better L/D and 15-percent lighter structure than SPF/DB titanium at Mach 3) produces encouraging results in the Mach 2 to 4 speed range. Of course these are preliminary first order results subject to refinement as the ongoing studies evolve. Another uncertainty is the possible introduction of a very advanced all-new subsonic airplane with an estimated 11-percent L/D improvement, a 15-percent structural weight (W_{str}) improvement, and a 33-percent propulsion efficiency improvement. The conclusion to be drawn from this analysis is that the SST fuel consumption impediment can be overcome, but it will require very large technology gains in all disciplines: propulsion, airplane aerodynamics, and airframe structures.

MIXED COMPRESSION SUPERSONIC INLETS

Commercial supersonic flight at moderate Mach 2 Concorde speeds can be viewed as relatively straightforward and within industry's technological grasp. Pushing the cruise speed substantially higher is certainly desirable, but introduces a series of ever-increasing technological challenges beyond the fuel economy of just the engine by itself. One of these new challenges is illustrated in figure 8. Conventional external compression inlets accomplish all of their diffusion outside of the intake duct through several oblique shocks and a terminal normal shock located at the cowl lip. This type of inlet delivers adequate performance and is well behaved (stable) under all transport flight conditions up to Mach 2. Beyond Mach 2, though, the performance of external compression inlets rapidly deteriorates because of the excessive cowl drag associated with the increasing cowl lip angle and the inability to increase the number of oblique shocks due to excessive inlet length and weight penalties. Flight beyond Mach 2, therefore, requires a mixed compression type inlet that performs some of the diffusion inside the intake duct through more oblique shocks and a normal shock near the throat. This introduces other problems, notably more boundary-layer bleed to avoid adverse shock - boundary-layer interactions (separation) and inlet shock system instability. The result is a much more complex inlet and control system. Neither transports nor fighters have been flown with such inlets, yet the need for utmost propulsion efficiency will require it for high-speed transports.

Mixed-compression inlets are quite susceptible to a phenomenon known as inlet instability, or "unstart," as illustrated in figure 9. Whenever a flow-retarding disturbance occurs, the internal shock system moves abruptly upstream and repositions itself completely outside the intake duct. This causes an abrupt and severe drop in thrust due to lower recovery and mass flow, and an increase in drag. The precipitating disturbance could be relatively small, such as encountering a strong gust or rapidly changing the angle-of-attack. If the initial disturbance is large (e.g., compressor stall), the transient response can be very severe - possibly unstarting neighboring inlet-engine systems, which would likely throw the airplane into a violent yaw and roll maneuver. To prevent such unacceptable behavior, some form of stability control system is needed.

One inlet stability improvement concept consists of a set of self-actuating bleed valves located in the inlet nacelle (fig. 10). These rapid-response-rate pneumatic valves will open in response to the increase in duct pressure produced by a transient excursion of the inlet terminal shock forward from its steady-state position. As the shock moves forward it exposes the stability bypass plenum to increased pressure and automatically activates the bleed valves which spill inlet bleed air overboard. This increases the inlet mass flow and forces the shock rearward, and thereby reestablishes stability. The valves close when the transient disturbance subsides and the shock has retreated to its steady-state position (refs. 3 and 4).

An experimental wind tunnel test program at NASA Lewis verified the feasibility of this concept during the mid-1970's. A five-fold increase in stability margin was demonstrated by using a YF-12 system simulation. While encouraging, these initial tests represent just a beginning, not an established data base. Considerable research lies ahead to adequately address this important issue.

EXHAUST NOZZLE PERFORMANCE

The exhaust nozzle for an SST must perform well at three critical flight conditions: takeoff, subsonic cruise, and supersonic cruise. The experimental model test results shown in figure 11 (Lewis 8- by 6-ft wind tunnel) of an ejector nozzle show that, while good takeoff and cruise performance was achieved, the subsonic cruise performance was disappointingly low because of flow separation over the inlet doors of the ejector. This shortfall is important because it significantly increases the reserve fuel allowance required to reach an alternate airport. For long-range SST's, the amount of reserve fuel is quite large, equal in magnitude to the payload weight. In addition, it is critical to obtain high nozzle performance at the transonic thrust minus drag "pinch point" to minimize inlet-engine flow matching penalties.

TRANSONIC PROPULSION SYSTEM DRAG

Just as exhaust nozzle performance is critical during subsonic flight, so is the minimization of transonic installation losses associated with inlets and nozzles. The transonic inlet spillage drag, for example, can exceed the entire airframe drag for high design Mach numbers. This problem arises from a major mismatch in inlet flow swallowing capacity (too much) compared to the engine demand (fig. 12). Likewise, the nozzle boattail drag penalty rises rapidly with design cruise speed. Finding solutions to these installation problems is absolutely essential to achieve an acceptable airplane design.

THE HIGH-SPEED TRANSPORT FUEL ISSUE

Conventional jet fuels cannot withstand the high temperatures associated with flight speeds in excess of about Mach 2. If subjected to temperatures above approximately 250 °C (time dependent also), they thermally decompose and form coke deposits that clog fuel supply components and fuel injectors. Consequently, a challenge exists to extend the thermal stability of conventional jet fuel (Jet A) to higher temperatures without incurring a significant fuel price increase, associated with either the manufacture of fuel or special fuel transportation and handling requirements, such as with JP-7 and cryogenics (fig. 13). While the practical use of hydrogen lies far into the future, liquid methane or liquid natural gas remains an intriguing possibility due to its current low price and high thermal stability. Endothermic fuels offer more heat sink capacity, but are fraught with offsetting practical and economic penalties. Uncertain future fuel prices and infrastructure costs cloud the issue of fuel selection and, consequently, airplane design speed as well.

SST TAKEOFF NOISE REDUCTION

The first generation of hypothetical SST's of the early 1970's used afterburning turbojets and would have provoked the irritation of many people living around major airports. Reducing their high jet exhaust velocities (over 4000 ft/s) by oversizing the engines and throttling back during takeoff reduces noise somewhat, but it also increases airplane size too rapidly to be an effective method for more than a few decibels. Each curve in figure 14 represents a series of various amounts of engine oversizing for a fixed mission. Considerable noise reduction progress evolved during the 1970's through a combination of variable cycle features and many noise suppression concepts experimentally tested. However, even this progress is insufficient to meet current FAR 36 stage III requirements. The noise shortfall increases considerably if we select cruise speeds and airplane ranges in excess of those assumed in figure 14. Much research lies ahead if we are to achieve a quiet SST without excessive noise reduction penalties.

Some of the noise reduction concepts illustrated in figure 15 have been explored in axisymmetric configurations suitable for flight speeds up to Mach 2.5. These concepts need data base extensions to higher speeds in both axisymmetric and two-dimensional nozzle configurations. Other concepts have practically no data base at all and are quite speculative. For example, the concept of enhancing exhaust jet mixing with pneumatic oscillators represents a very speculative and technically challenging strategy. The remote augmented thrust system concept guarantees low noise with its high-mass-flow, low-pressure-ratio fan. But it introduces different problems - notably, how to integrate the deployable remote takeoff fans into the airframe.

SST EMISSIONS REDUCTION

Previous airport pollution concerns precipitated a NASA emissions reduction research program that led to several emission control mechanisms, including the development of two-zone combustors. The conventional single-zone combustors have their high power efficiency compromised to obtain good low-power ignition and stability. The improved two-zone combustors utilized a pilot stage optimized for idle conditions and a main stage optimized for cruise power. This resulted in leaner, well mixed high-power combustion with approximately one-half as much NO_X emissions assuming the engine cycle remains unchanged (fig. 16). However, our continued quest for higher overall engine efficiency produces even higher cycle temperatures, which increases NO_X production. Hence, the final engine designs of the supersonic cruise research (SCR)/VCE program, if built, would have produced about as much NO_X as the actual engines introduced a decade earlier. Today, we face the same dilemma -

performance-driven designs will increase NO_X, while emissions-driven designs will reduce performance.

One approach to reduce NO_X emissions is to reduce the flame temperature. Another approach is to reduce the residence time of the combustion gas at high temperatures (fig. 17). In the latter approach, two concepts worth pursuing are (1) increasing the velocity through the combustor, and (2) avoiding large recirculation regions within the primary combustion zone. Increasing the combustion velocity involves finding means to avoid excessive pressure losses, as well as maintaining good combustion stability and ignition characteristics. Avoiding large pockets of recirculating hot gases in the primary zone also reduces stability characteristics, thereby requiring the implementation of other stability enhancing features.

CONCLUDING REMARKS

As the 21st century approaches, it is becoming increasingly clear that efficient supersonic cruise flight is within our technological reach. Many challenging propulsion problems need to be addressed, however, before a state of technology readiness is achieved. One possible program plan entails a two-pronged approach: a near-term effort aimed at variable-cycle engine concepts incorporating very aggressive discipline and component technologies, and a far-term effort focused on validating supersonic throughflow technology which offers even higher potential benefits (fig. 18). Continued propulsion system studies as well as a high-speed fuel and fuel systems effort are also needed. Achievement of the propulsion goals outlined herein would indeed revolutionize aircraft capability for the future.

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3. Sanders, B.W.; and Mitchell, G.A.: Increasing the Stable Operating Range of a Mach 2.5 Inlet. AIAA Paper 70-686, June 1970 (NASA TM X-52799).

4. Sanders, B.W.; and Mitchell, G.A.: Throat Bypass Bleed Systems for Increasing the Stable Air Flow Range of a Mach 2.50 Axisymmetric Inlet with 40-Percent Internal Contraction. NASA TM X-2779, 1973.

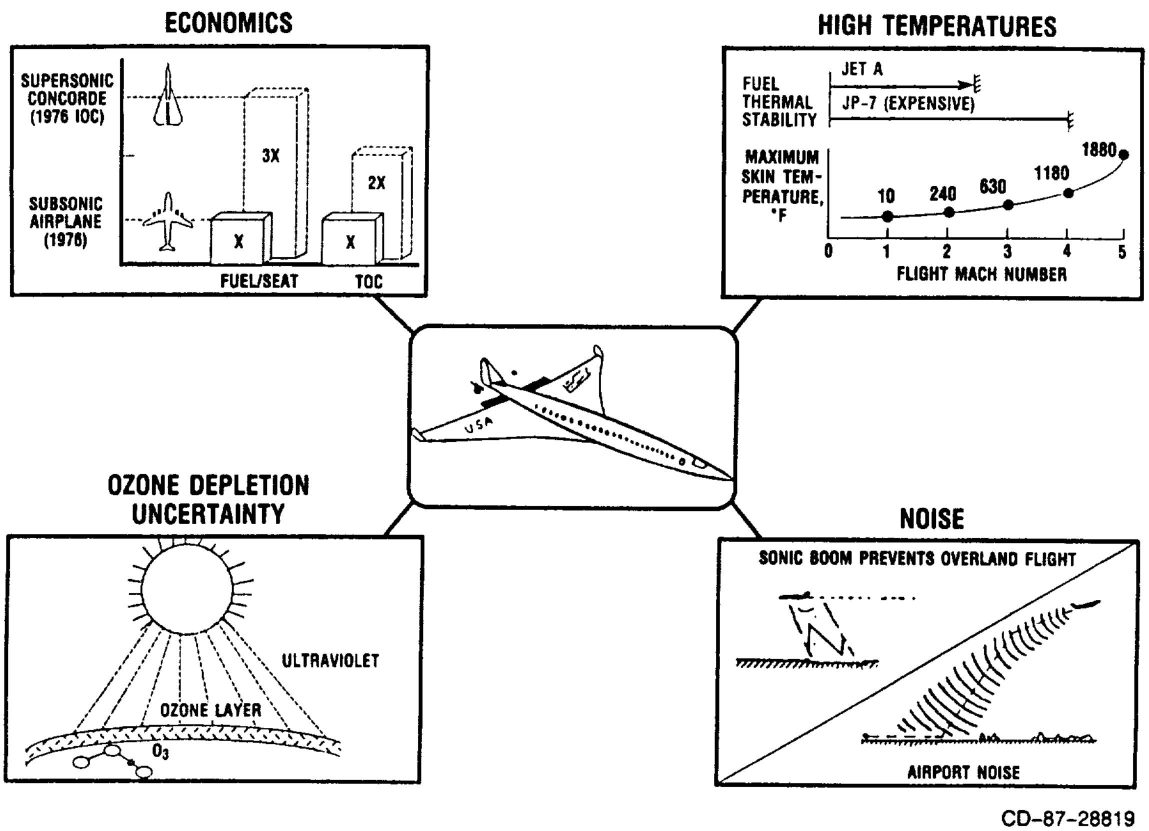


Figure 1. - Challenges to high-speed transports.

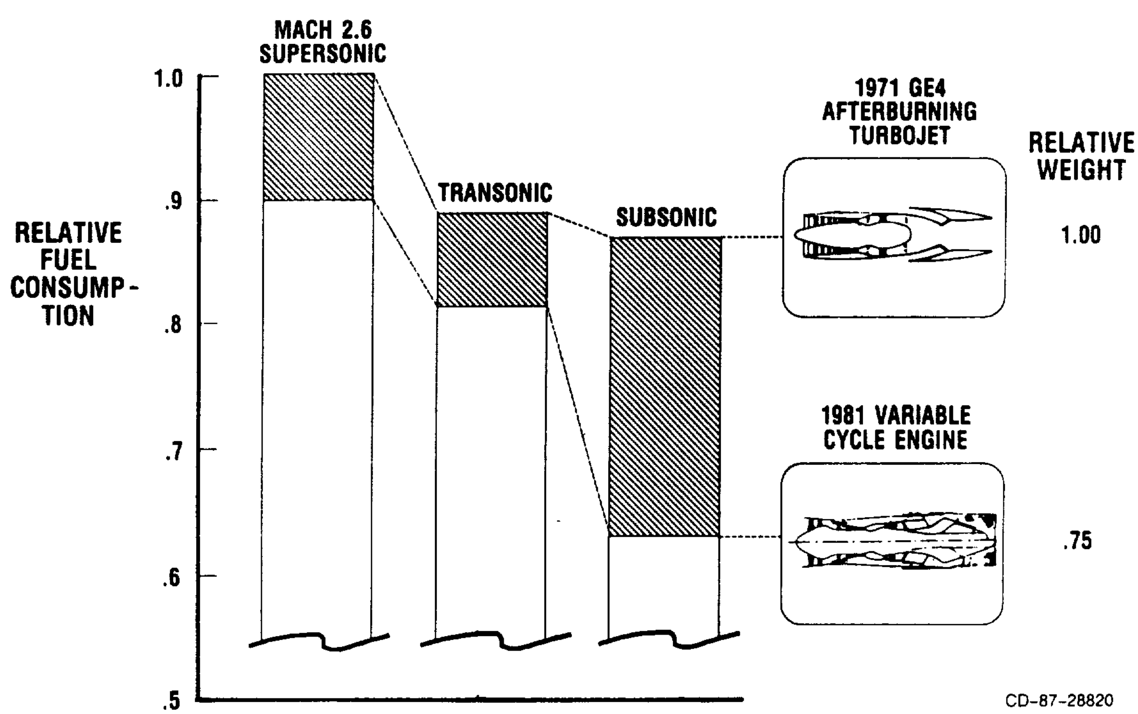


Figure 2. - SST propulsion progress.

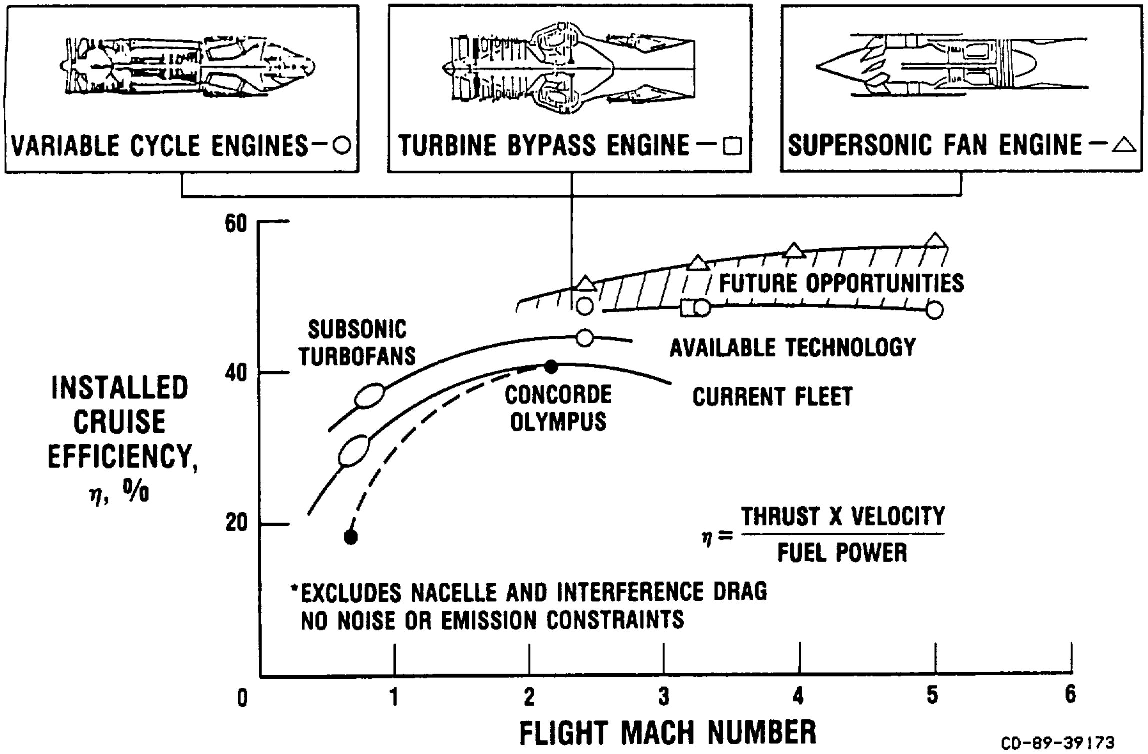


Figure 3. - Future high-speed propulsion performance potential.

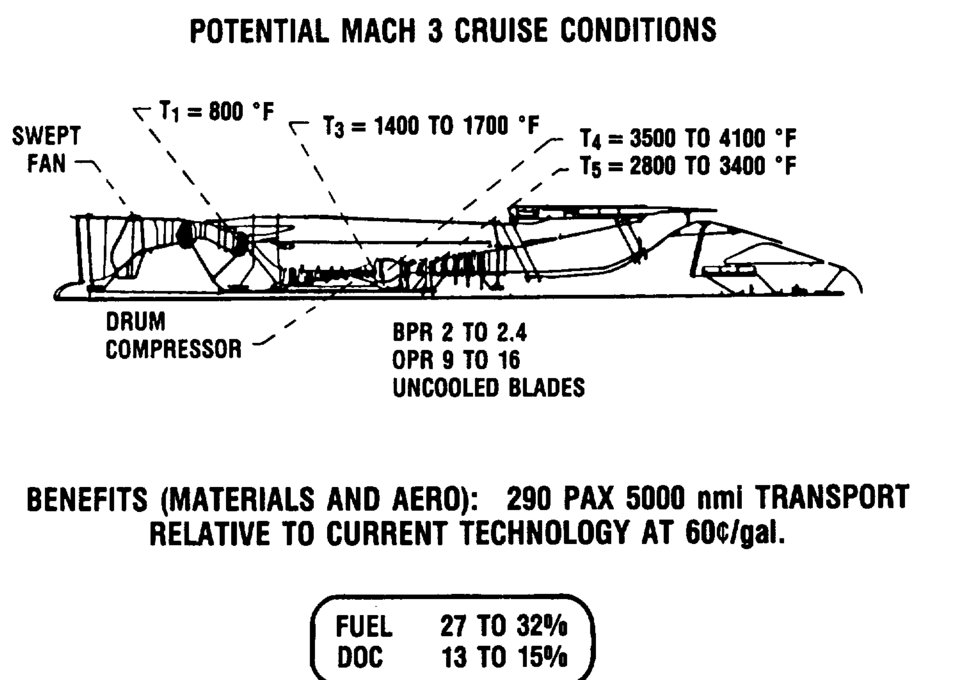
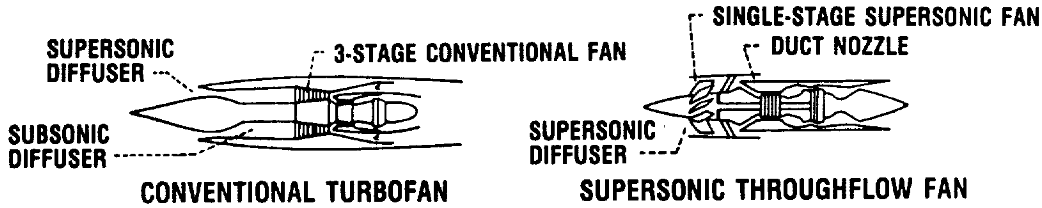


Figure 4. - Variable-cycle engine goal.



SUPERSONIC THROUGHFLOW FAN ENGINE FEATURES
- SHORT, ALL SUPERSONIC INLET
- SINGLE-STAGE SUPERSONIC FAN
- BPR DECREASES WITH M_0

IMPLICATIONS
- LOWER WEIGHT, LOWER INLET DRAG
- LOWER WEIGHT AND COST, RUGGED BLADING
- HIGHER CRUISE THRUST

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Figure 5. - Supersonic throughflow fan engine.

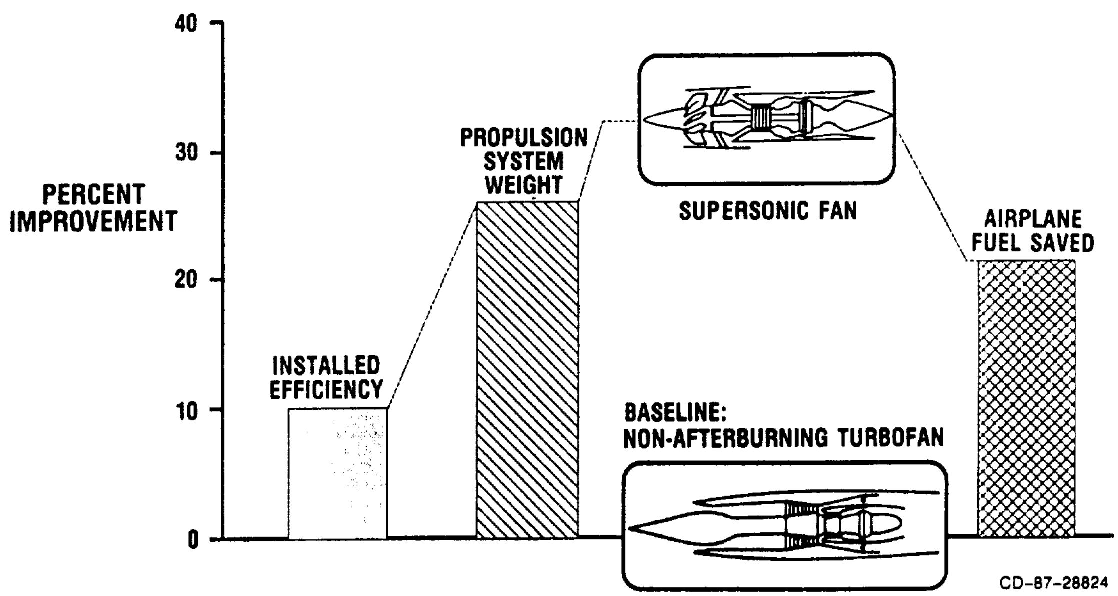

Figure 6. - Benefit of supersonic throughflow fan (Mach 3 commercial transport, 300 passengers, 5500 nmi range).

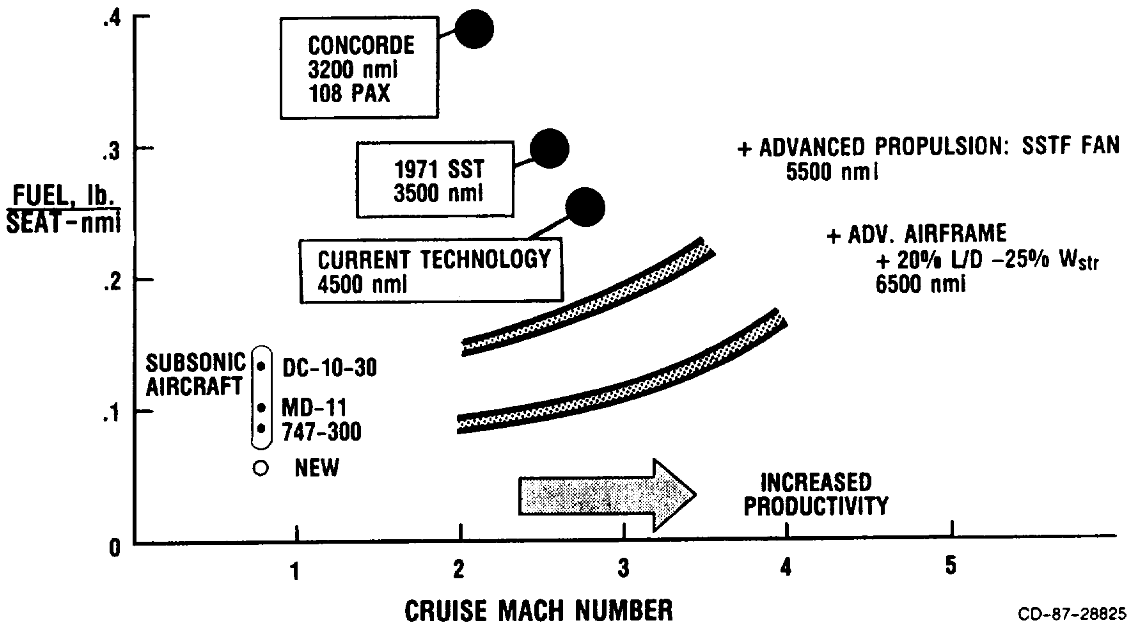

Figure 7. - Impact of technology on fuel economy (300 passengers).

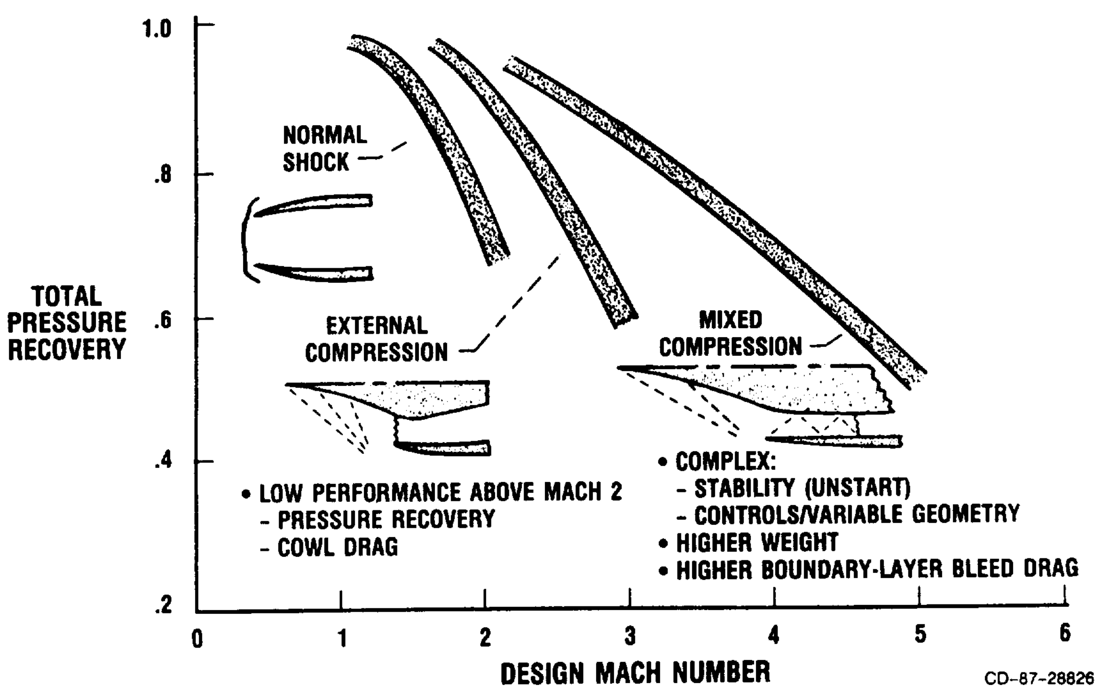

Figure 8. - Supersonic inlet performance.

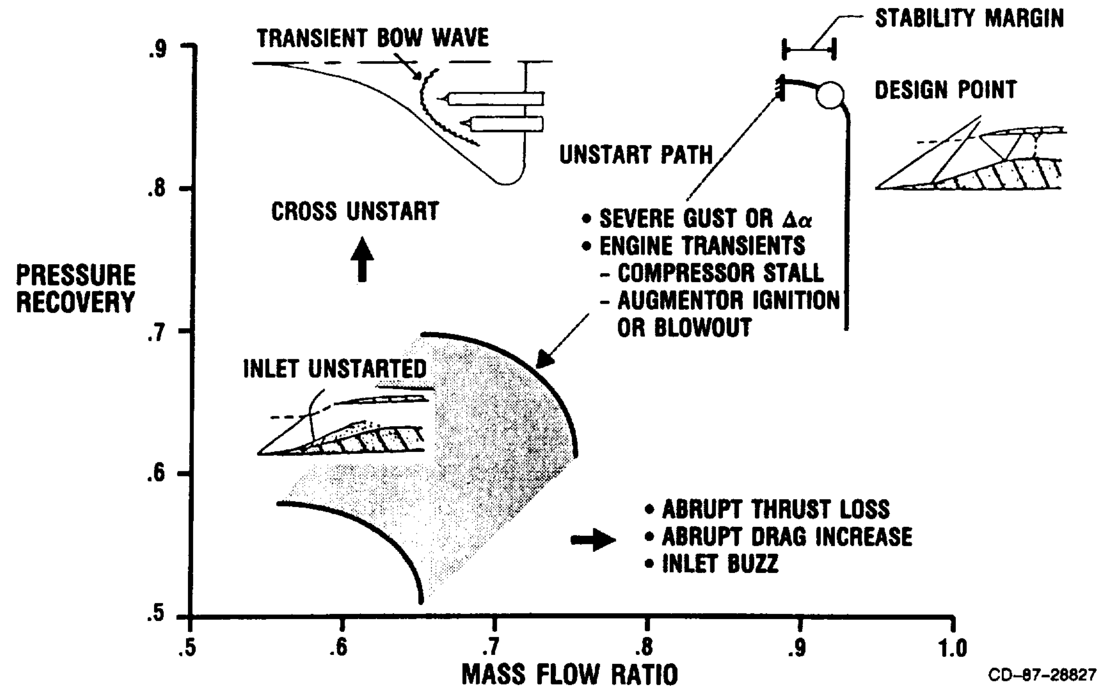

Figure 9. - Mixed-compression supersonic inlet instability.

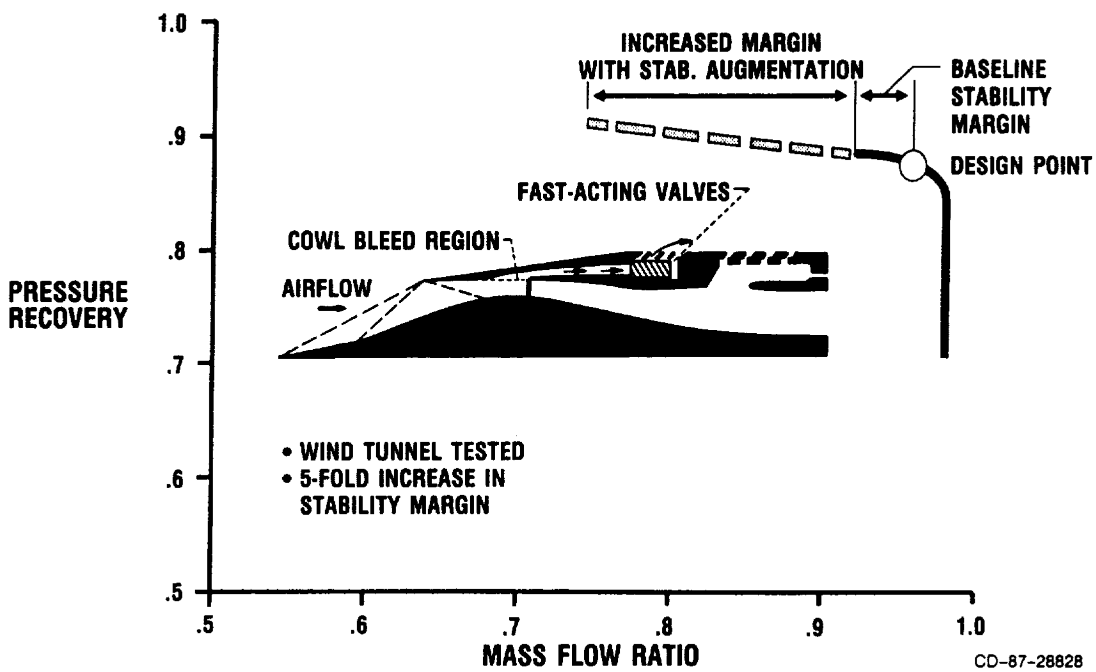

Figure 10. - Mixed-compression inlet stability improvements.

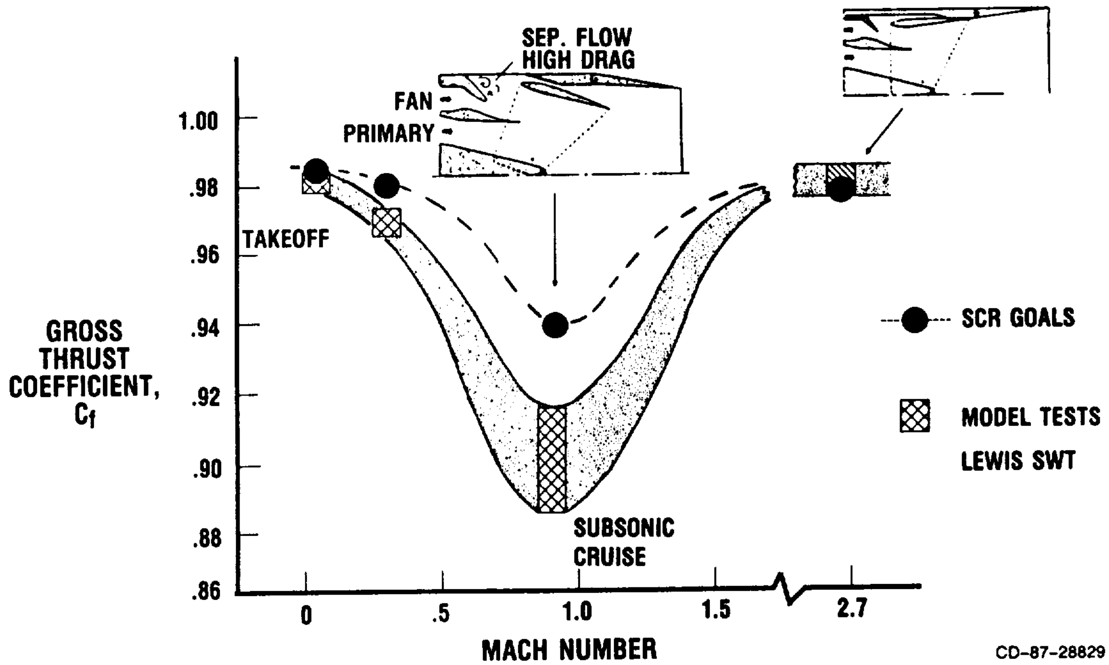

Figure 11. - Nozzle performance (VCE research ejector).

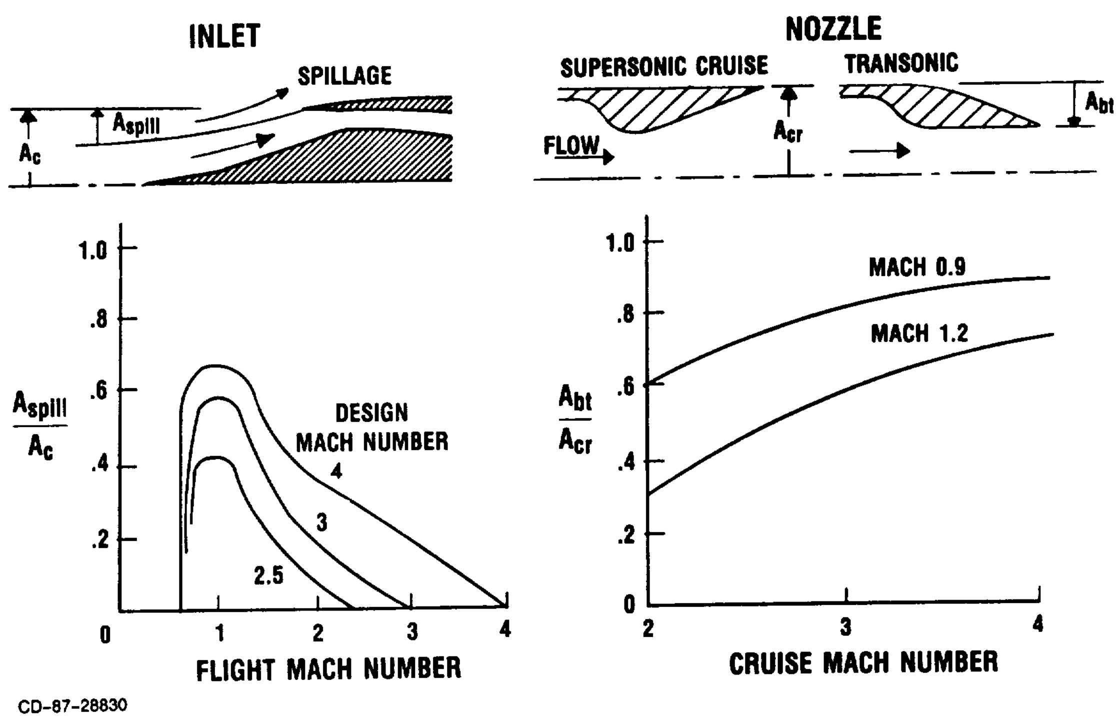

Figure 12. - Transonic propulsion system drag.

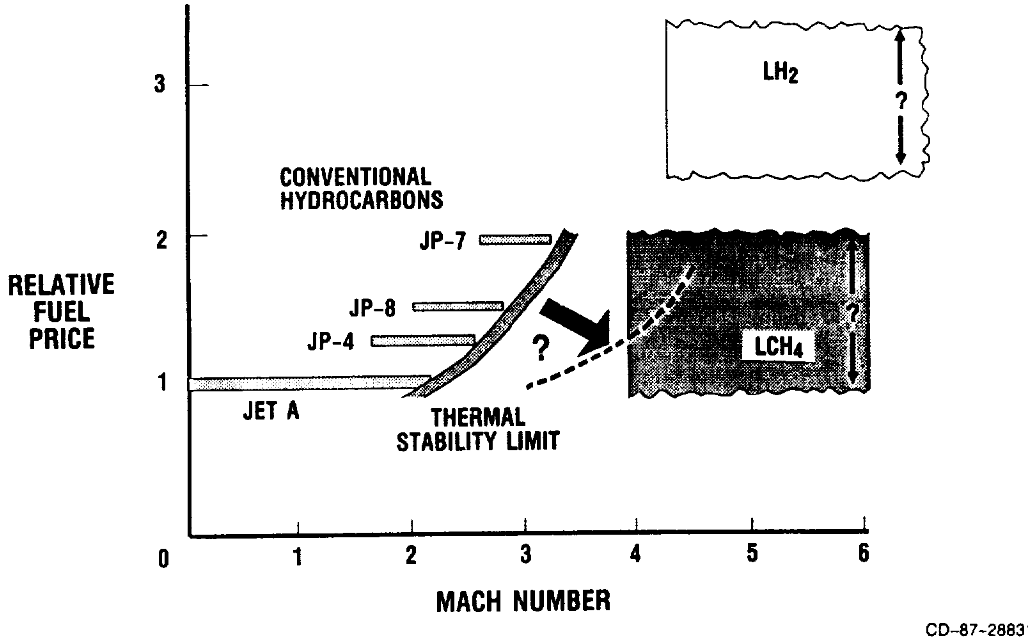

Figure 13. - The high-speed transport fuels issue.

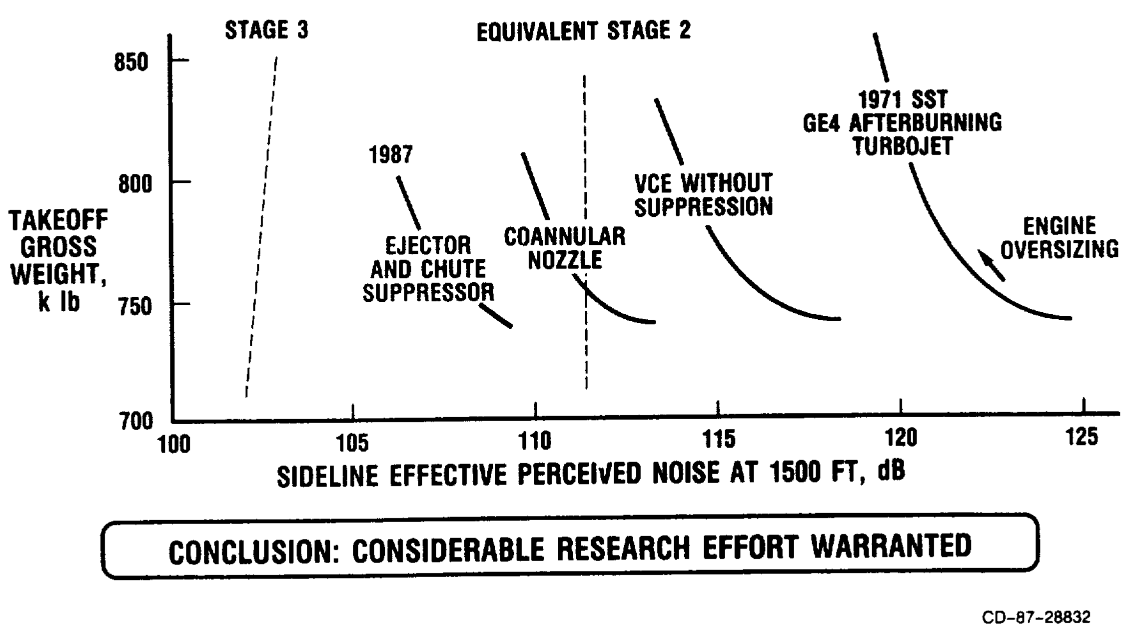

Figure 14. - Progress in SST takeoff noise reduction (Mach 2.4 to 3.2 experimental data base).

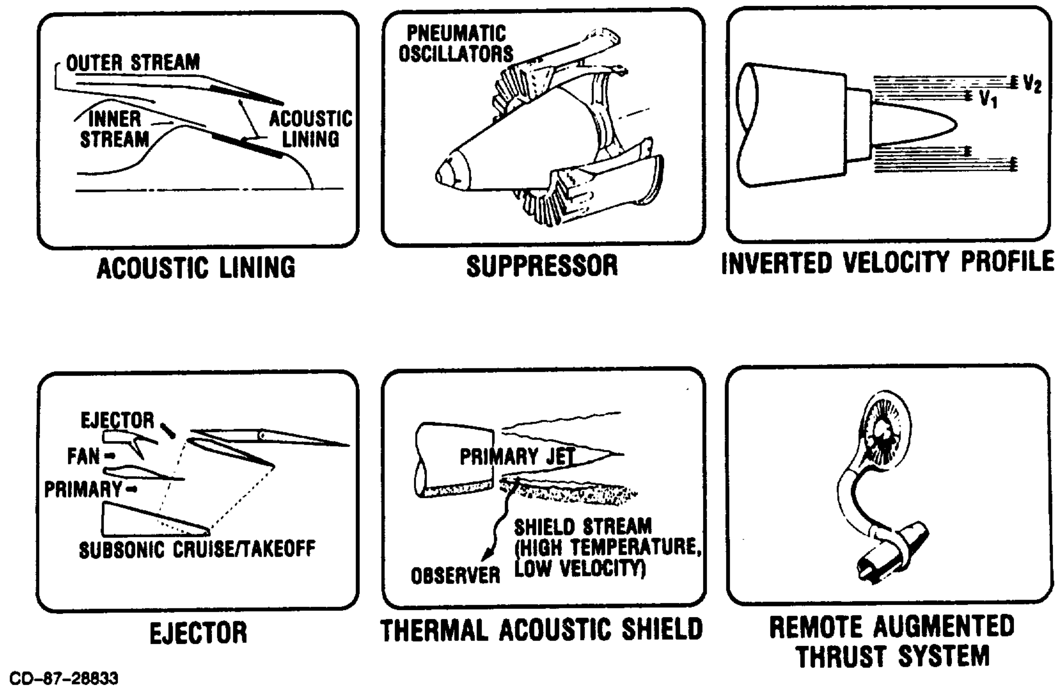

Figure 15. - Jet noise reduction concepts.

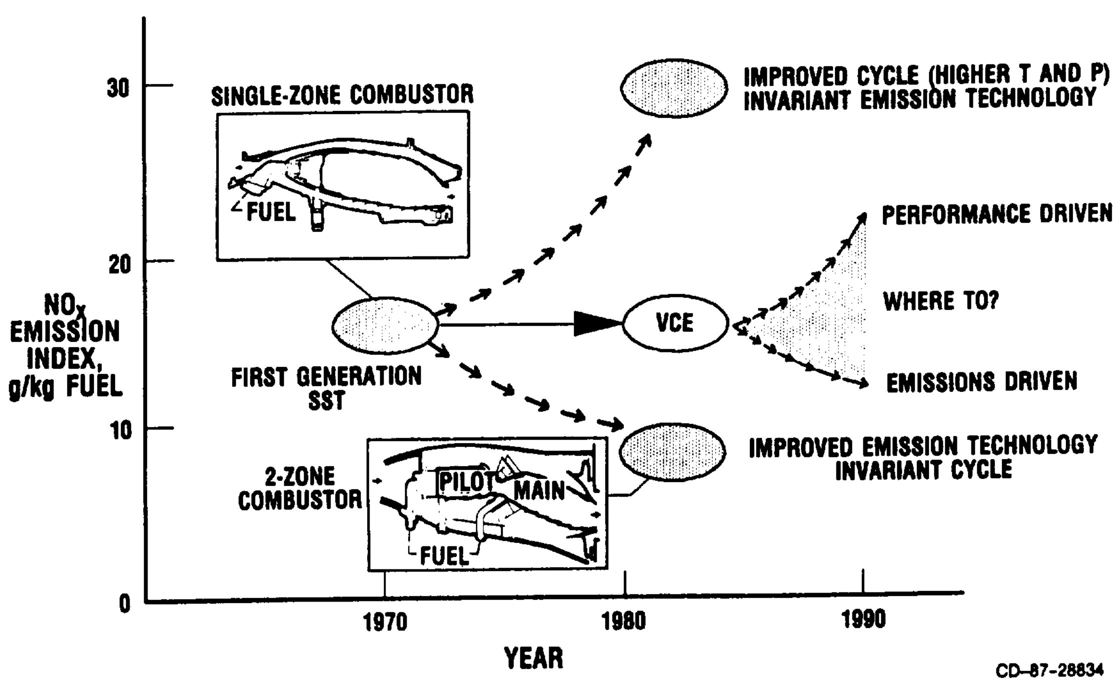

Figure 16. - Progress in SST cruise NO_X emission reduction.

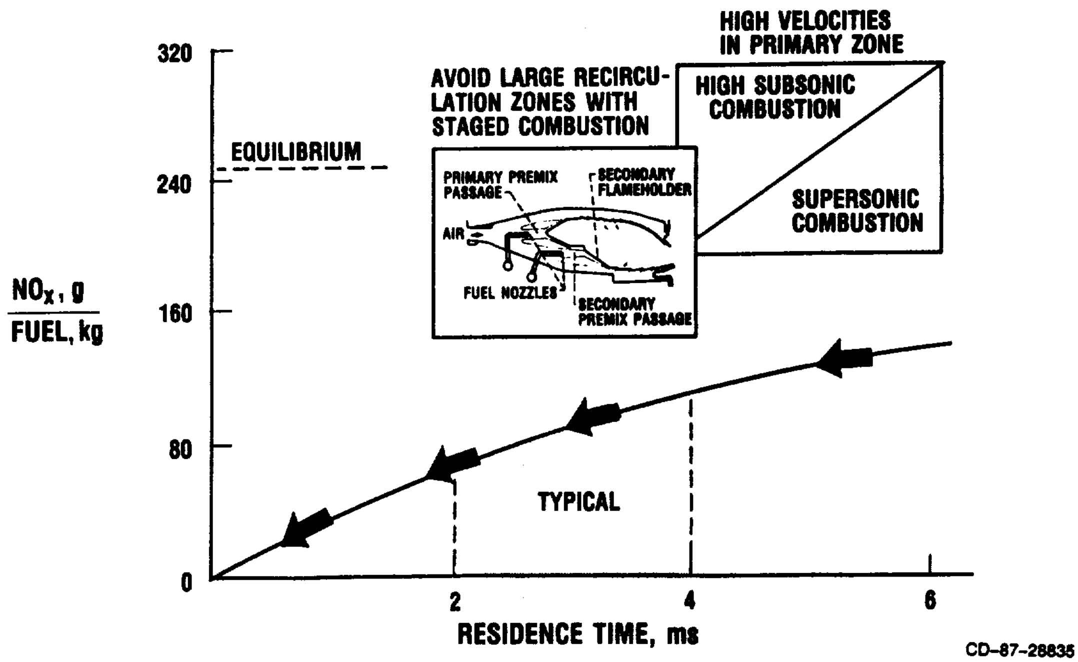

Figure 17. - NO_X emissions reduction concepts.

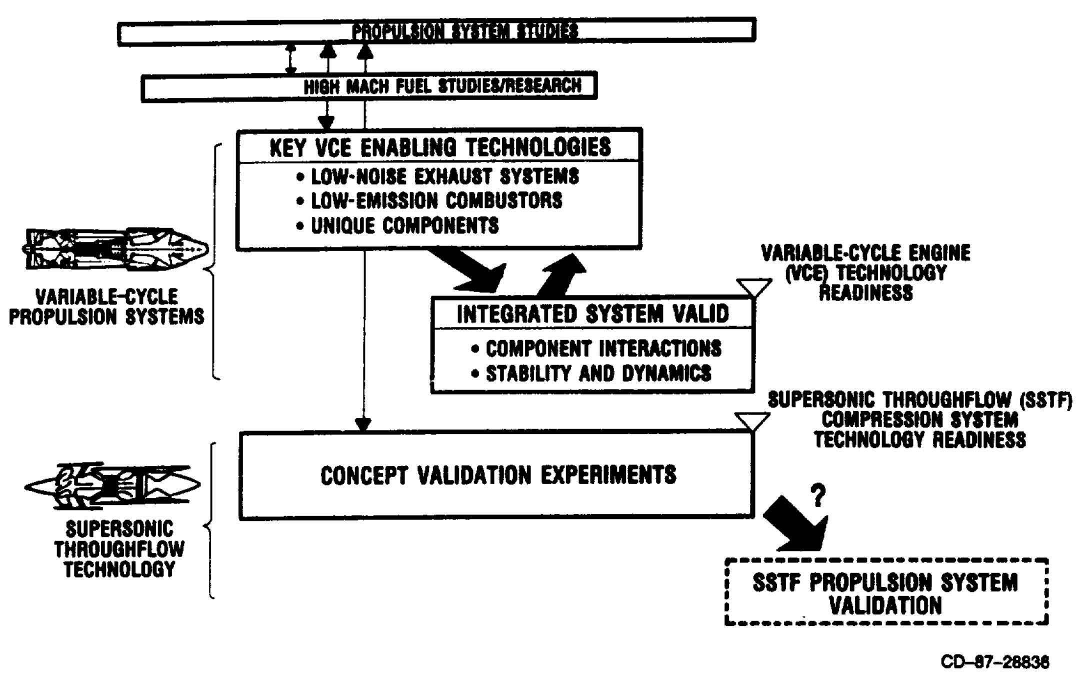

Figure 18. - Candidate high-speed propulsion program plan.