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PROPULSION CHALLENGES AND OPPORTUNITIES FOR HIGH-SPEED TRANSPORT AIRCRAFT

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ABSTRACT

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. This presentation identifies the major challenges confronting the propulsion community for supersonic transport (SST) applications. 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 at least 40-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 liquefied natural gas (LNG) 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.

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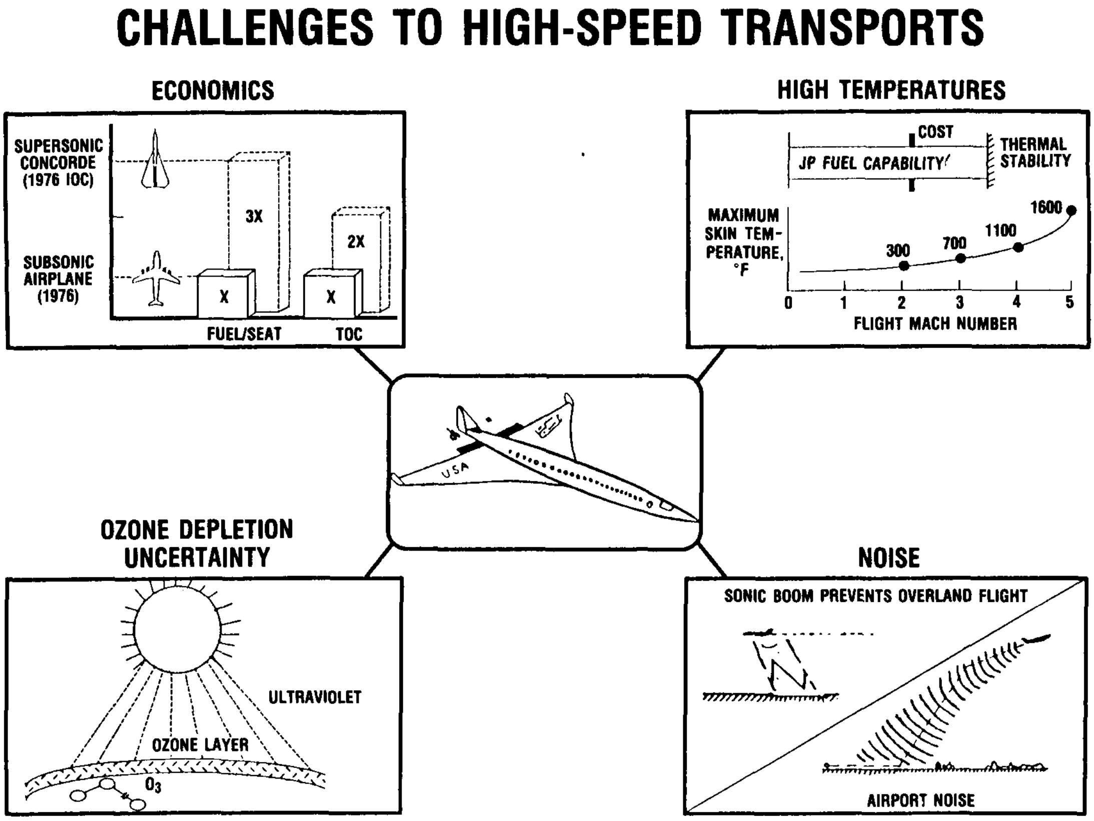
CHALLENGES TO HIGH-SPEED TRANSPORTS

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 (3 times equivalent technology subsonic airplanes) is largely responsible for its uncompetitive economics; the total operating cost (TOC) is twice that of similar technology, long-range subsonic transports. 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 an ever increasing technical challenge arising from high ram temperature levels. In addition to airframe skin temperature problems, 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 3-1/2, but low-cost Jet A is limited to only Mach 2+. While both sonic boom and airport noise levels are currently excessive, only the airport noise problem is of primary concern to the propulsion industry. Another potential environmental issue is the depletion of atmospheric ozone via jet engine exhaust-gas emissions.



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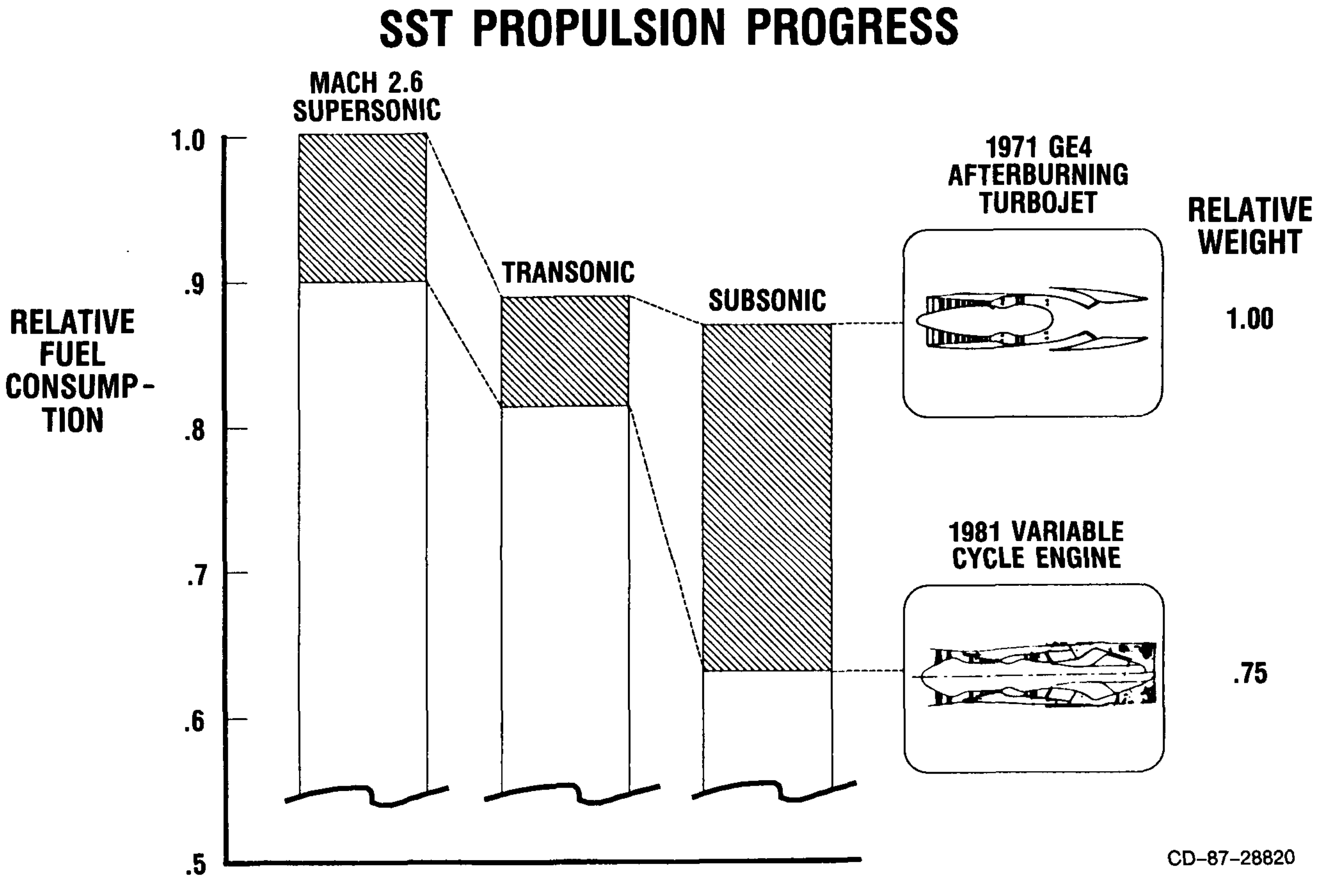
SST PROPULSION PROGRESS

Considerable progress was achieved during the 1970's in the NASA-sponsored variable-cycle engine (VCE) program. Compared to the 1971 GE4 afterburning turbojet (ABTJ), the 1981 VCE's 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. Nevertheless, these gains are insufficient by themselves 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.

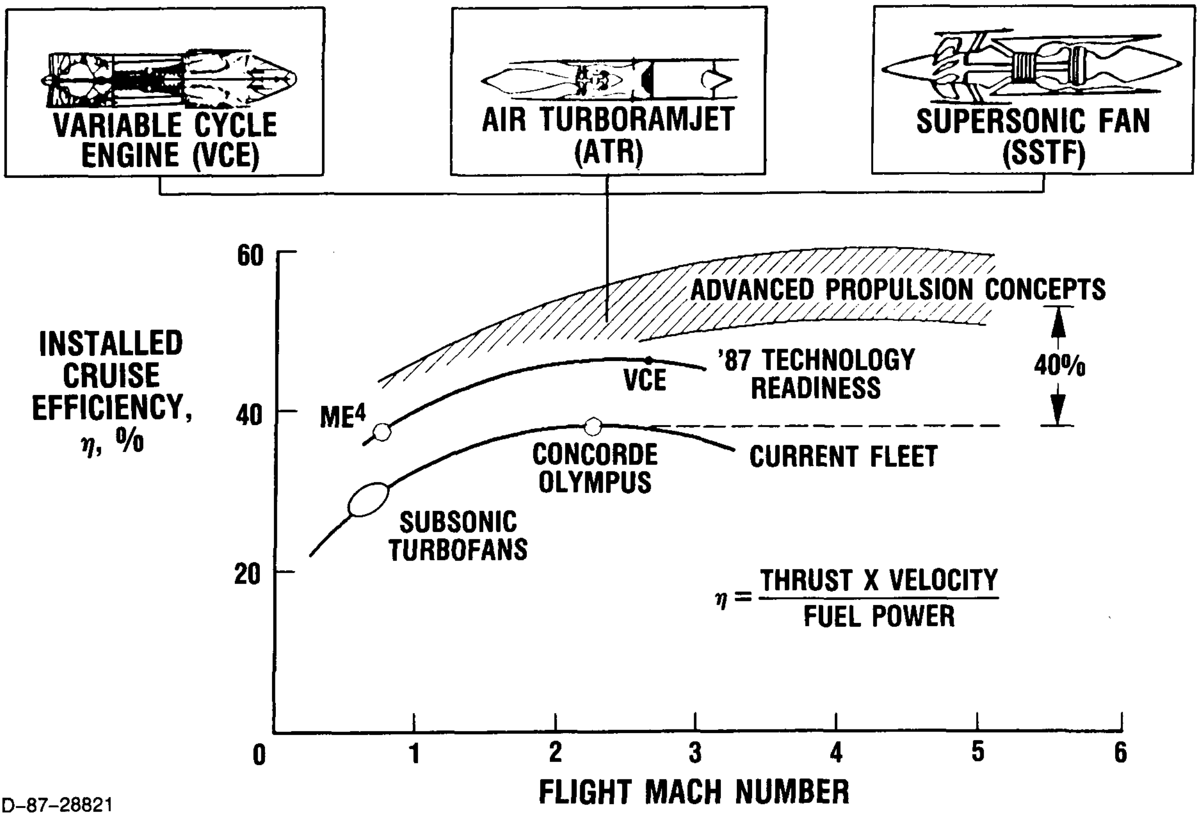


FUTURE HIGH-SPEED PROPULSION PERFORMANCE POTENTIAL

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 which is on the order of 1/2 that of subsonic transports. This is only partially offset by the trend toward increasing overall engine efficiency with flight speed. "Installed cruise efficiency" shown here includes inlet and nozzle losses, but not nacelle drag, and represents design point values. The middle curve indicates that significant improvement is possible with today's available technology for both subsonic (maximum efficiency - E^3 technology) 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 regenerative air turboramjets (ATR's) and supersonic throughflow (SSTF) turbofans (upper boundary). These advanced technology concepts extend the peak propulsion-efficiency levels from Mach 2+ to at least Mach 4. Gains of 40 percent or more over Concorde's Olympus are possible. Using a simple criterion such as design point efficiency is insufficient to properly convey overall impact. 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 also important are even larger gains in climb efficiency and weight for advanced VCE's.

FUTURE HIGH-SPEED PROPULSION PERFORMANCE POTENTIAL



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VARIABLE-CYCLE ENGINE GOAL

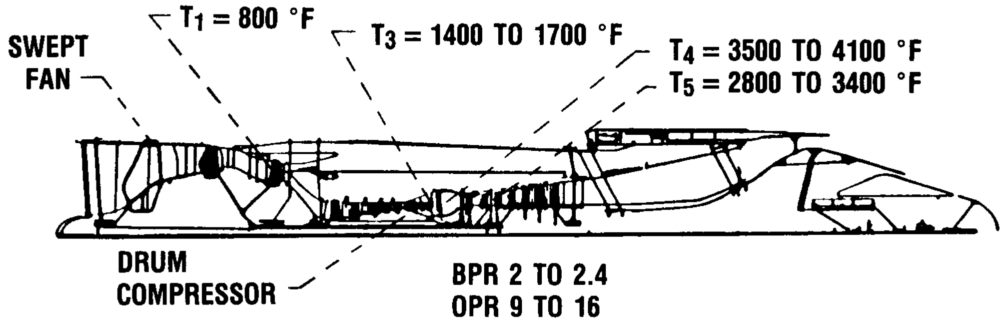
The most obvious contender for a future SST is an advanced variable-cycle engine. This approach builds on the previous VCE philosophy of mitigating the off-design compromises inherent in a fixed-geometry engine. This is accomplished by incorporating enough variable geometry features to yield respectable performance over a wide range of flight speeds and power settings.

Displayed here is 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. 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 full 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 28-percent fuel reduction is due to a 45-percent engine weight reduction relative to a hypothetical 1984 technology-readiness baseline engine.

VARIABLE-CYCLE ENGINE GOAL

POTENTIAL MACH 3 CRUISE CONDITIONS



BPR 2 TO 2.4
OPR 9 TO 16
UNCOOLED BLADES

BENEFITS (MATERIALS AND AERO): 290 PAX 5000 nmi TRANSPORT RELATIVE TO CURRENT TECHNOLOGY AT $1.00/gal.

FUEL	24 TO 28%
DOC	17 TO 20%

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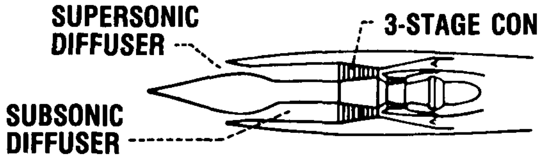
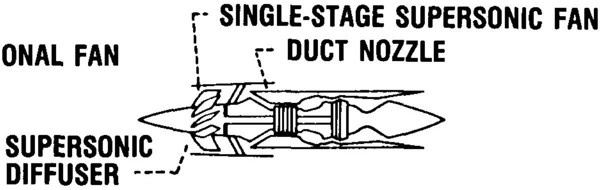
SUPERSONIC THROUGHFLOW FAN ENGINE

One potential SST breakthrough is the supersonic fan concept. 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 (M_0). 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.

SUPERSONIC THROUGHFLOW FAN ENGINE



CONVENTIONAL TURBOFAN



SUPERSONIC THROUGHFLOW FAN

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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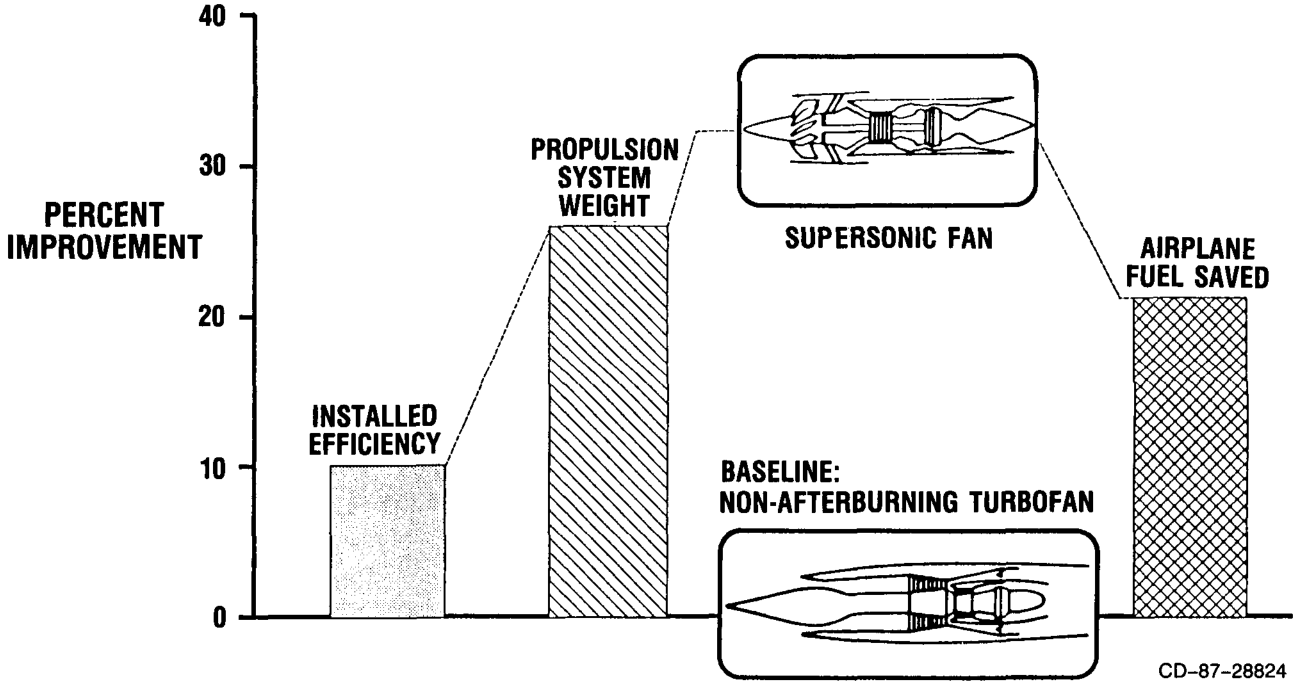
BENEFIT OF SUPERSONIC THROUGHFLOW FAN

The potential payoff of supersonic throughflow fan (SSTF) technology for a typical SST application has been analyzed by NASA in-house (NASA TM-100114). One of the major contributors is the inlet size and weight reduction to about 1/2 that of a conventional supersonic inlet. This also reduces the inlet bleed-drag penalty. Furthermore, the higher SSTF inlet recovery leads to more thrust/airflow at cruise, and less transonic-spillage drag when external compression inlets are used. The 35-percent larger cruise thrust/airflow could mean a smaller engine is required dependent on the engine-sizing criteria. In the payoffs quoted here, takeoff thrust/weight was held fixed to maintain good takeoff performance.

BENEFIT OF SUPERSONIC THROUGHFLOW FAN

MACH 3 COMMERCIAL TRANSPORT
300 PASSENGERS, 5500 nmi RANGE



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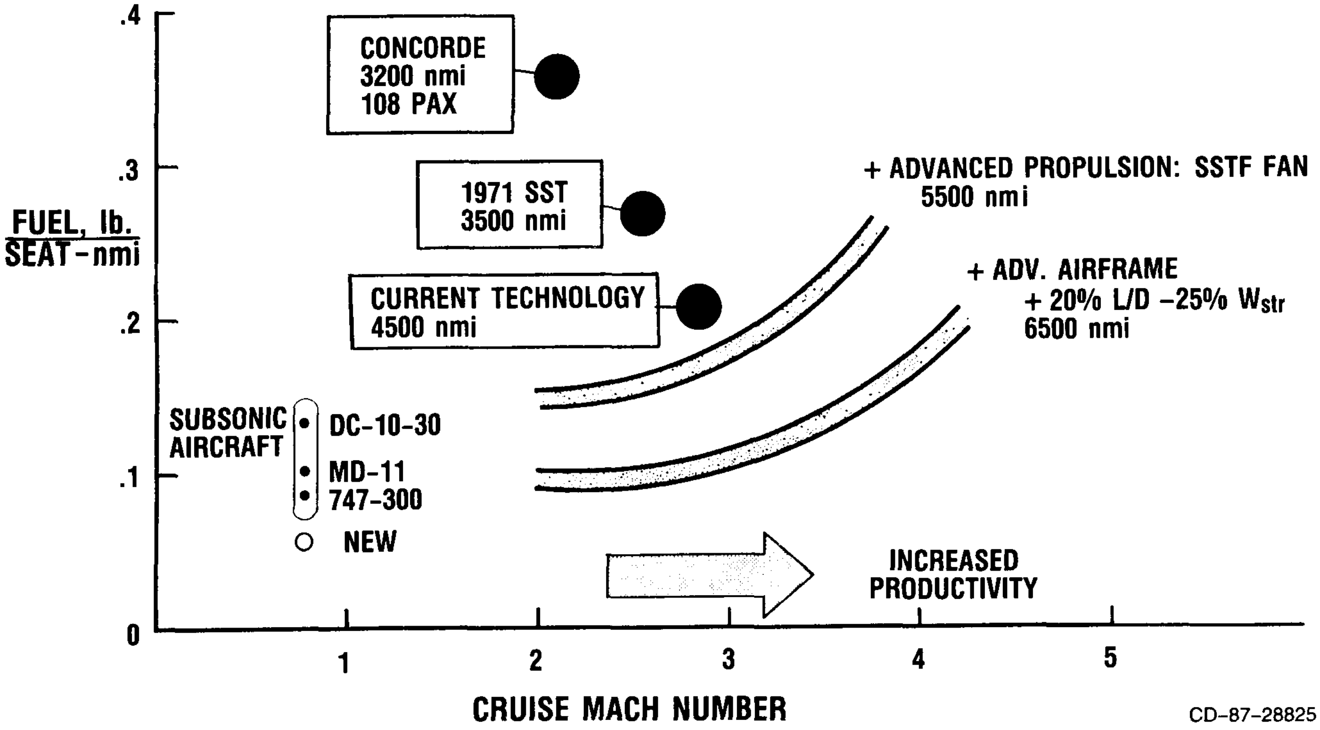
ADVANCED SUPERSONIC TRANSPORTS COULD ACHIEVE COMPETITIVE FUEL ECONOMY

This chart displays the impact of potential future technology advances on airplane fuel consumption while 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 shorter ranges. 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 in L/D and structural weight (W_{str}) produces encouraging results in the Mach 2 to 4 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. An estimate of that possibility is included here that has an 11-percent L/D improvement, a 15-percent structural weight 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, aerodynamics, and structures.

IMPACT OF TECHNOLOGY ON FUEL ECONOMY

300 PASSENGERS



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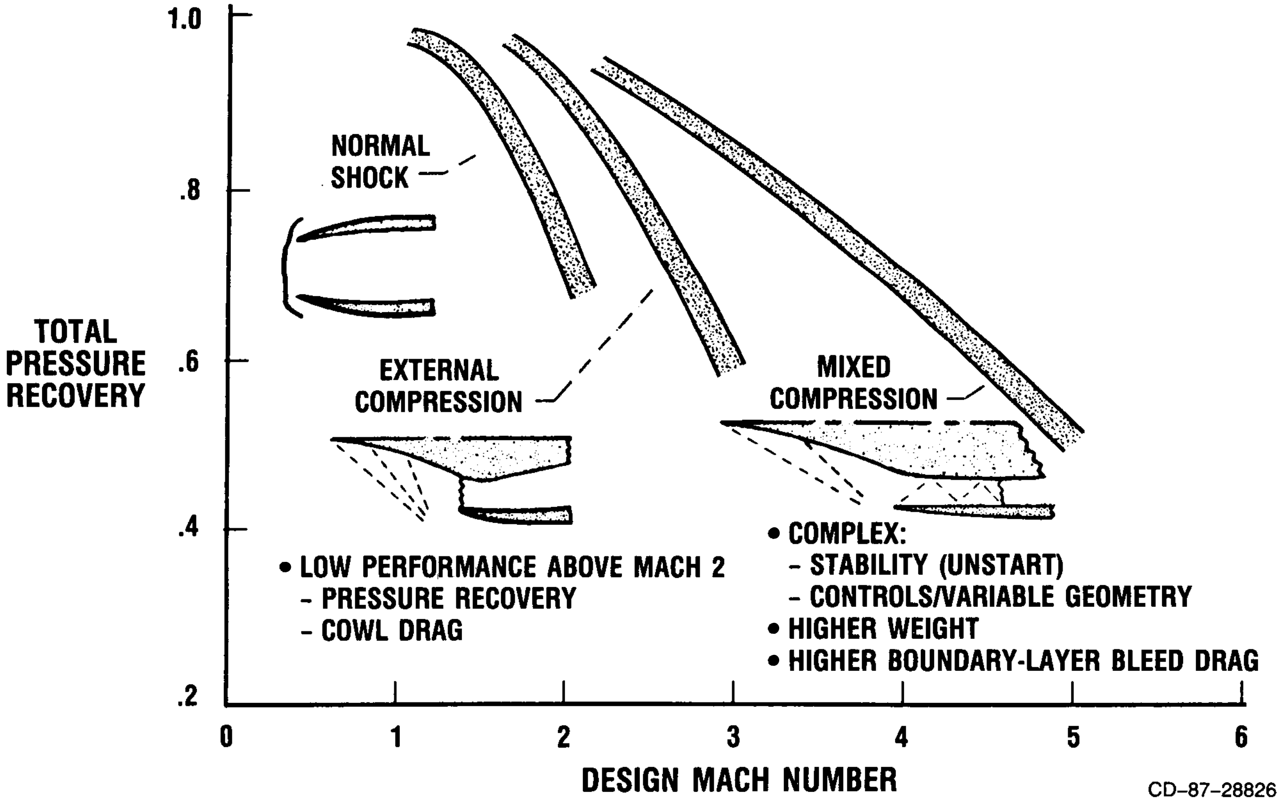
SUPERSONIC INLET PERFORMANCE

Commercial supersonic flight at Concorde speeds (Mach 2) 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. One of these new challenges is illustrated here. 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 because of 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 operationally with such inlets, yet the need for utmost propulsion efficiency will require it for high-speed transports.



SUPERSONIC INLET PERFORMANCE

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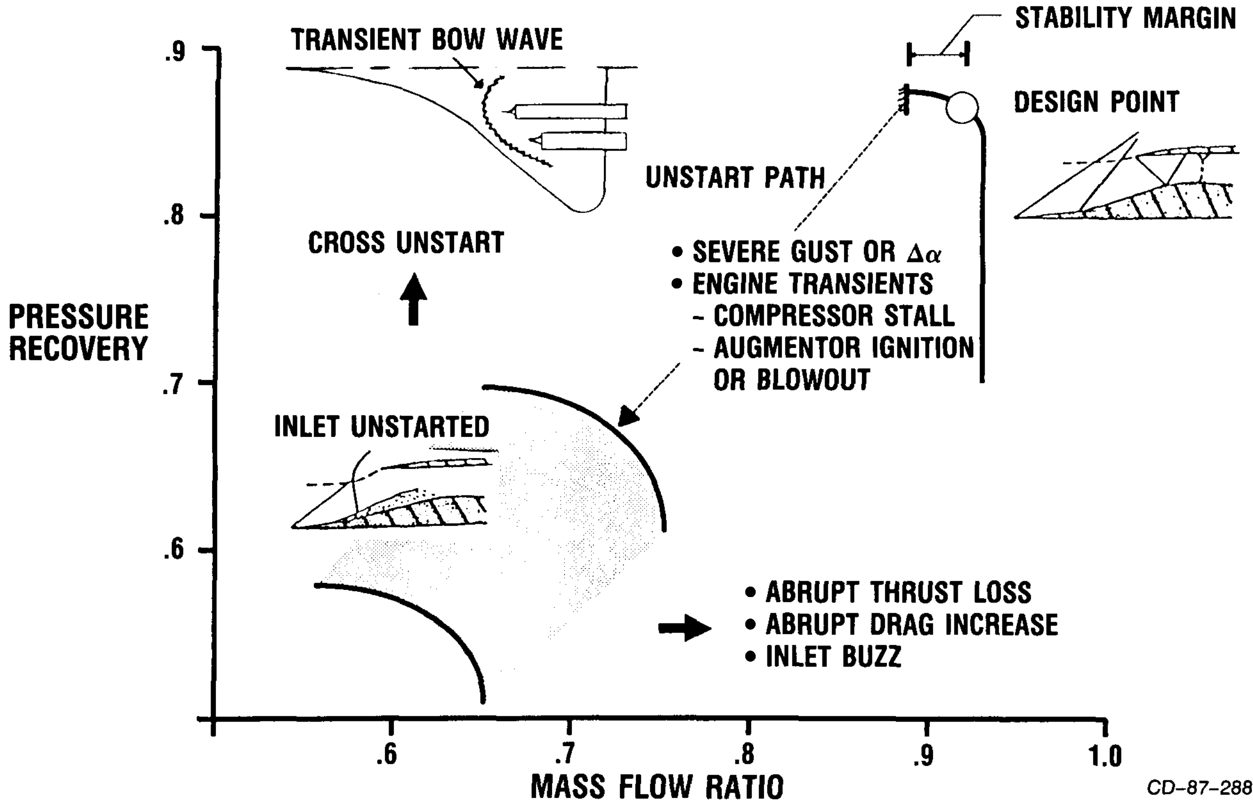
MIXED-COMPRESSION SUPERSONIC INLET INSTABILITY

Mixed compression inlets are quite susceptible to a phenomenon known as inlet instability or "unstart." 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 undesirable behavior, some form of stability control system is needed.

MIXED COMPRESSION SUPERSONIC INLET INSTABILITY



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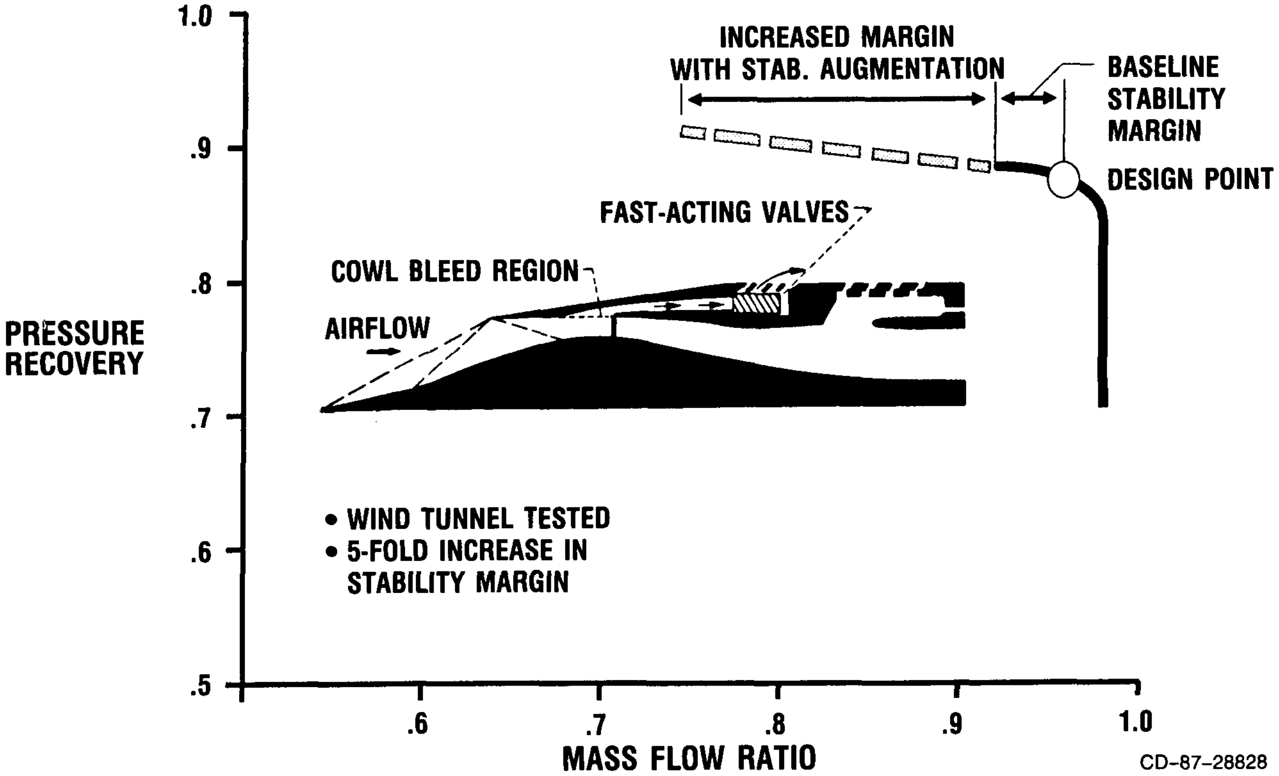
MIXED-COMPRESSION INLET STABILITY IMPROVEMENTS

This inlet stability improvement concept consists of a set of self-actuating bleed valves located in the inlet nacelle. 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.

An experimental wind tunnel test program at NASA Lewis Research Center verified the feasibility of this concept during the mid 1970's. A five-fold increase in stability margin was demonstrated using a YF-12 system simulation. Considerable research lies ahead, however, to adequately address this important issue.

MIXED COMPRESSION INLET INSTABILITY IMPROVEMENT



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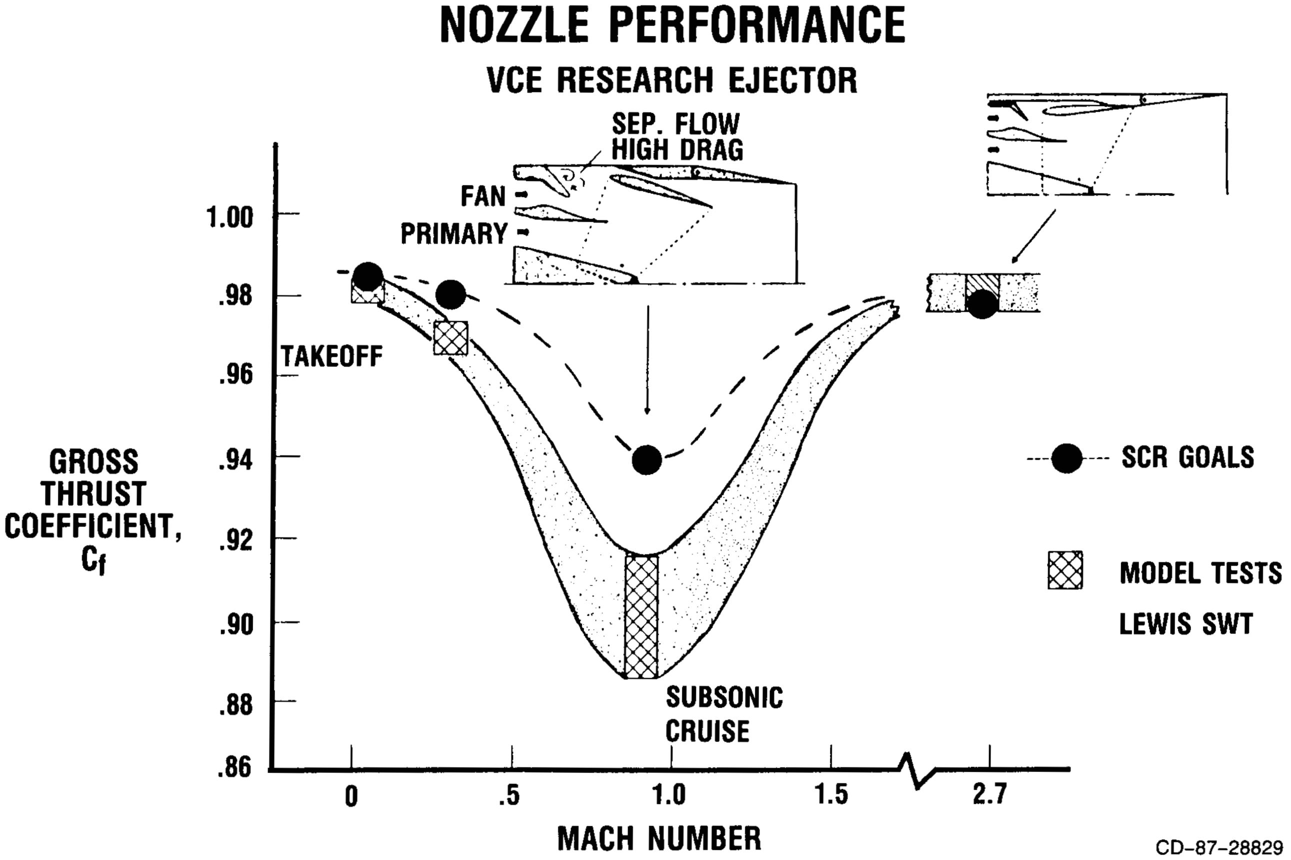
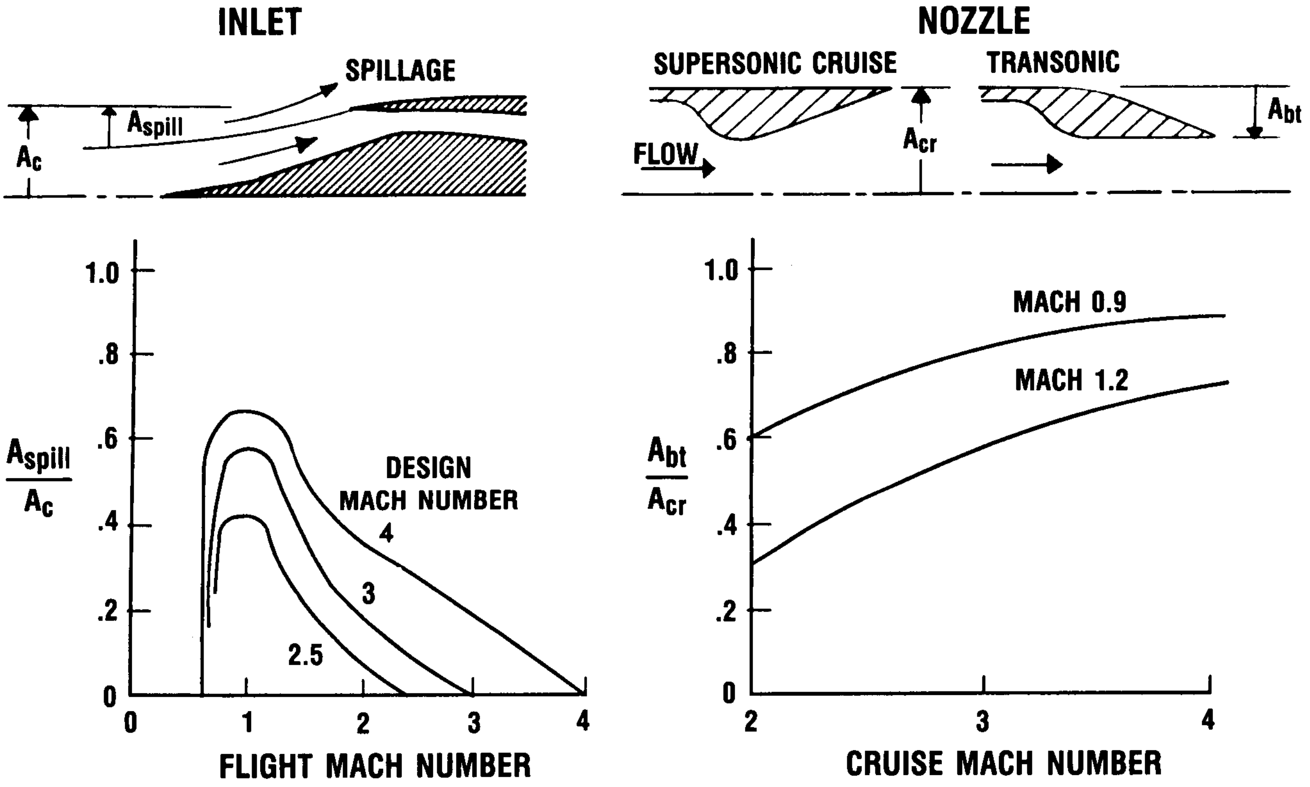
NOZZLE PERFORMANCE

The exhaust nozzle for an SST must perform well at three critical flight conditions -- takeoff, subsonic cruise, and supersonic cruise. These experimental model test results (Lewis Research Center, 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 -- and, for long-range SST's, the amount of reserve fuel is quite large. 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

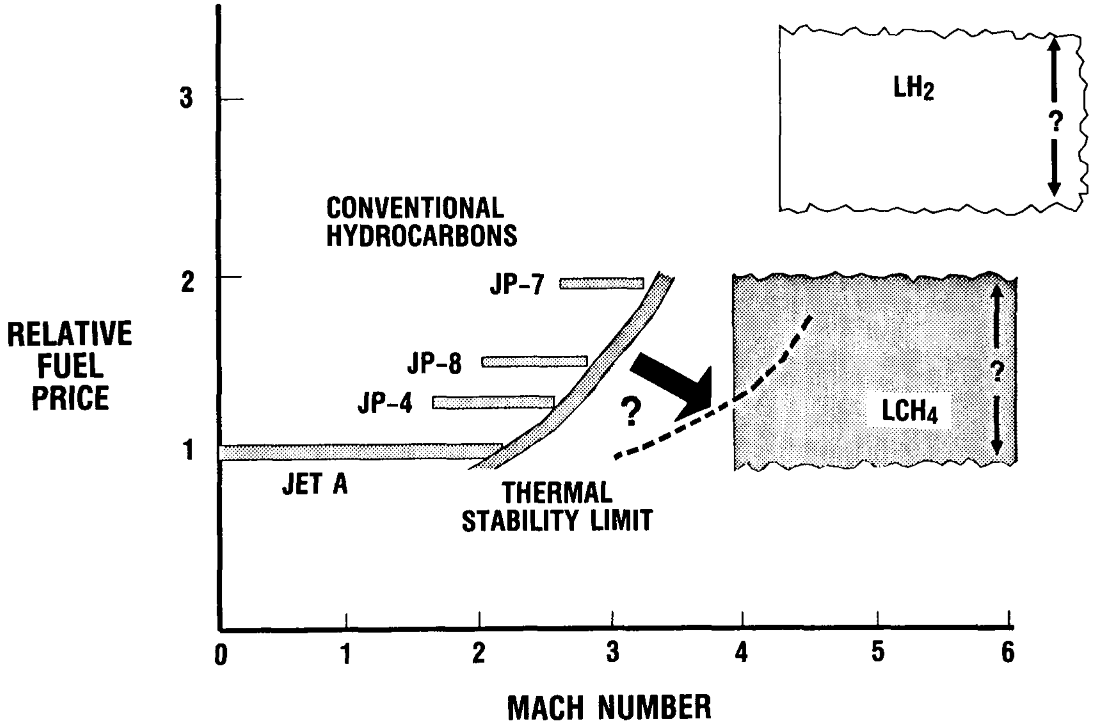
Just as exhaust nozzle performance is critical during transonic flight, so also is the minimization of transonic installation losses associated with inlets and nozzles. The transonic inlet spillage drag, for example, can exceed the entire airframe drag for high design Mach numbers. This problem arises from a major mismatch in inlet flow-swallowing capacity (too much) compared to the engine demand. 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.


TRANSONIC PROPULSION SYSTEM DRAG

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. 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 -- either in the fuel manufacture or associated with special fuel transportation and handling requirements (such as with JP-7 and cryogenics). While the practical use of hydrogen lies far into the future, liquid methane or LNG remains as an intriguing possibility because of 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.

THE HIGH-SPEED TRANSPORT FUELS ISSUE



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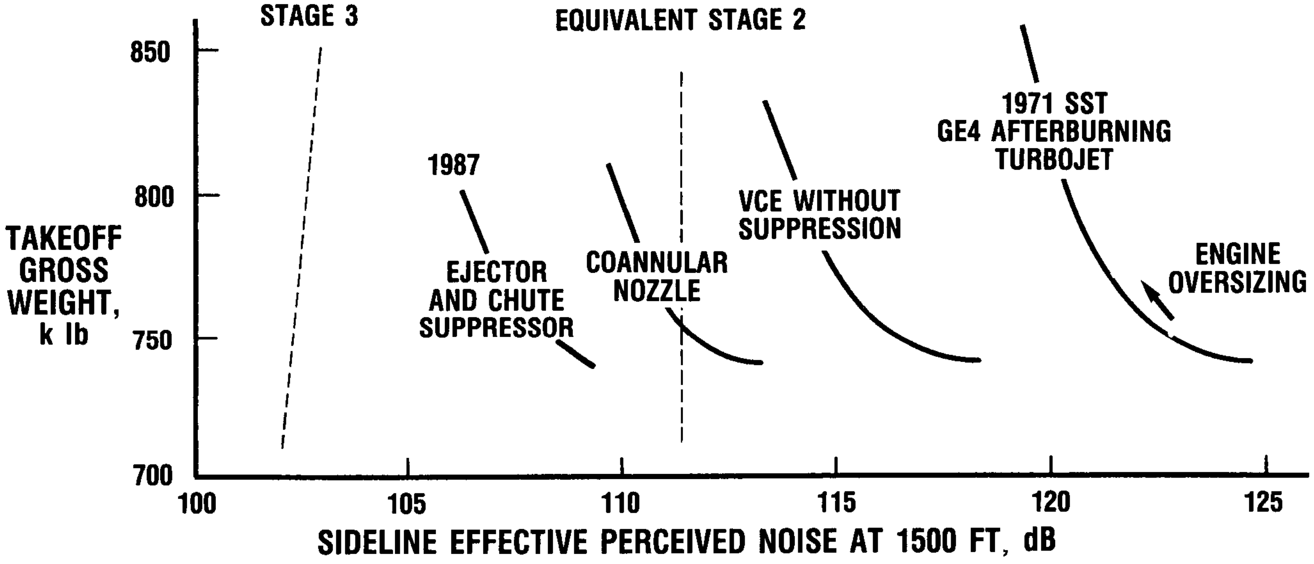
PROGRESS IN SST TAKEOFF-NOISE REDUCTION

The first generation of hypothetical U.S. 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 dB. Each curve 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. Much research lies ahead if we are to achieve a quiet SST without excessive noise reduction penalties.

PROGRESS IN SST TAKEOFF NOISE REDUCTION

MACH 2.4 TO 3.2 EXPERIMENTAL DATA BASE



CONCLUSION: CONSIDERABLE RESEARCH EFFORT WARRANTED

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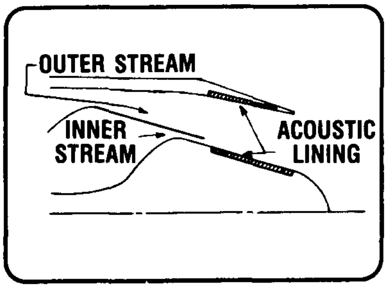
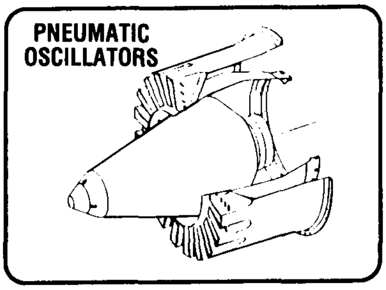
JET NOISE REDUCTION CONCEPTS

Some of the noise reduction concepts illustrated here have been explored in axisymmetric configurations suitable for Mach 2-3 airplanes. These concepts need data base extensions for two-dimensional nozzles suitable for higher flight speeds. Other concepts have practically no data base at all and are quite speculative. For example, the concept of cancelling source noise by superimposing an out of phase second source has made significant strides recently and appears suitable for discreet frequency noises such as produced by a propeller. Extending this idea to cancel broadband jet noise with passive secondary noise sources (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 remote deployable takeoff fans into the airframe.

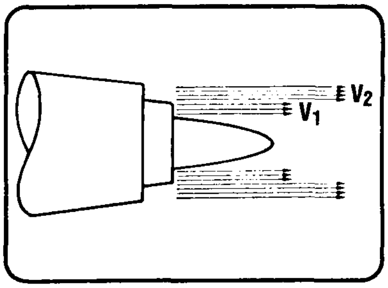
JET NOISE REDUCTION CONCEPTS



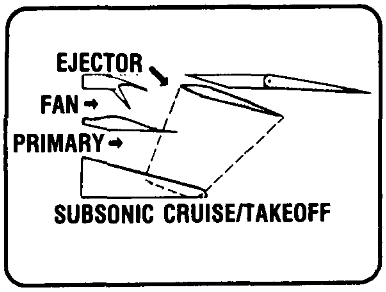
ACOUSTIC LINING



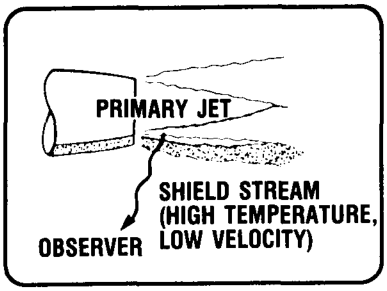
SUPPRESSOR



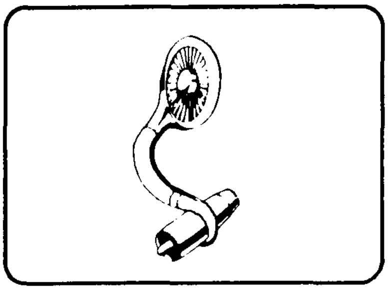
INVERTED VELOCITY PROFILE



EJECTOR



THERMAL ACOUSTIC SHIELD



REMOTE AUGMENTED THRUST SYSTEM

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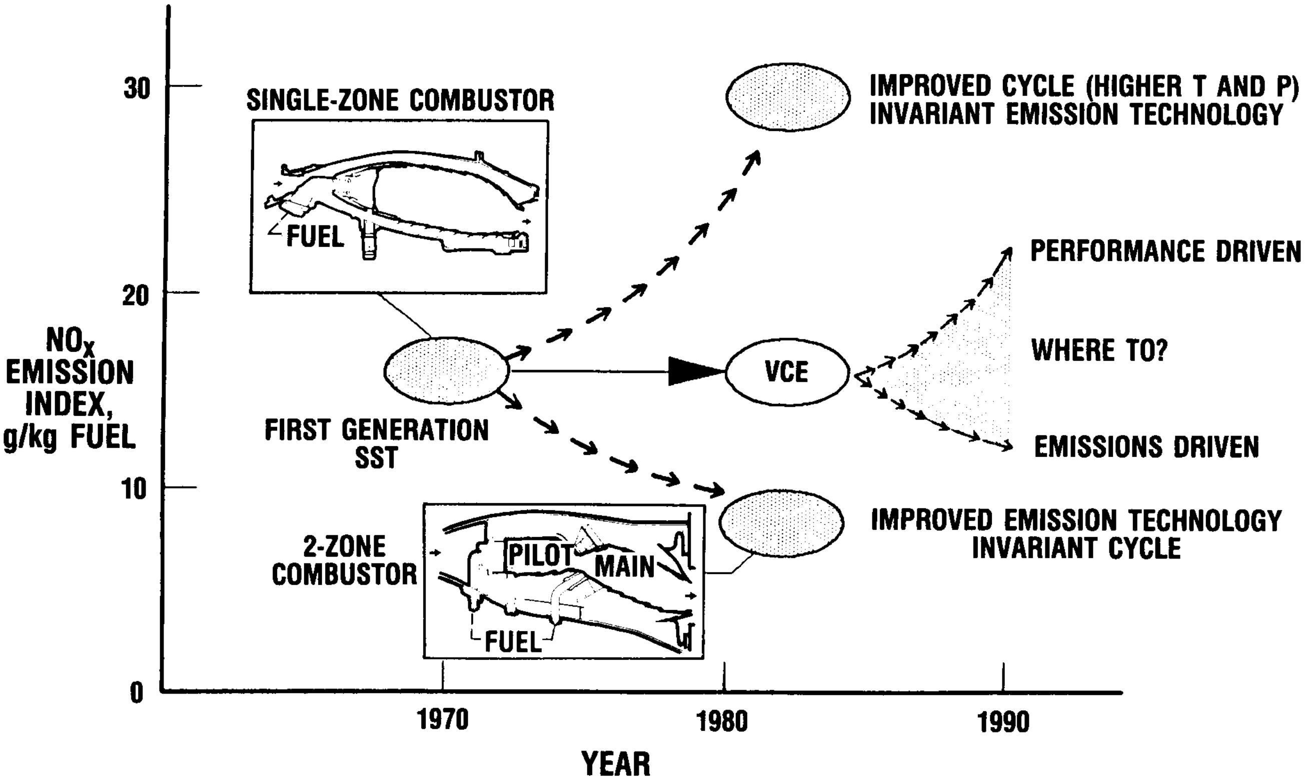
PROGRESS IN SST CRUISE NO_X-EMISSION REDUCTION

Presently, it does not appear that we have a known problem with SST engine emissions. There is some concern, however, that we might have a future problem if ongoing analyses conclude that significant upper atmospheric ozone depletion would be caused by a fleet of NO_X-emitting SST's. Previous airport pollution concerns precipitated a NASA emissions-reduction research program that led to the development of several control mechanisms including two-zone combustors. The 1970's engines had single-zone combustors that had their high-power efficiency compromised to obtain good low-power ignition and stability. The improved two-zone combustors used a pilot stage optimized for idle conditions and a main stage optimized for cruise power. This resulted in leaner, well-mixed cruise combustion with approximately one-half as much cruise NO_X emission assuming the engine cycle remains unchanged. However, our continued quest for higher overall engine efficiency produces ever 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.

PROGRESS IN SST CRUISE NO_X EMISSION REDUCTION



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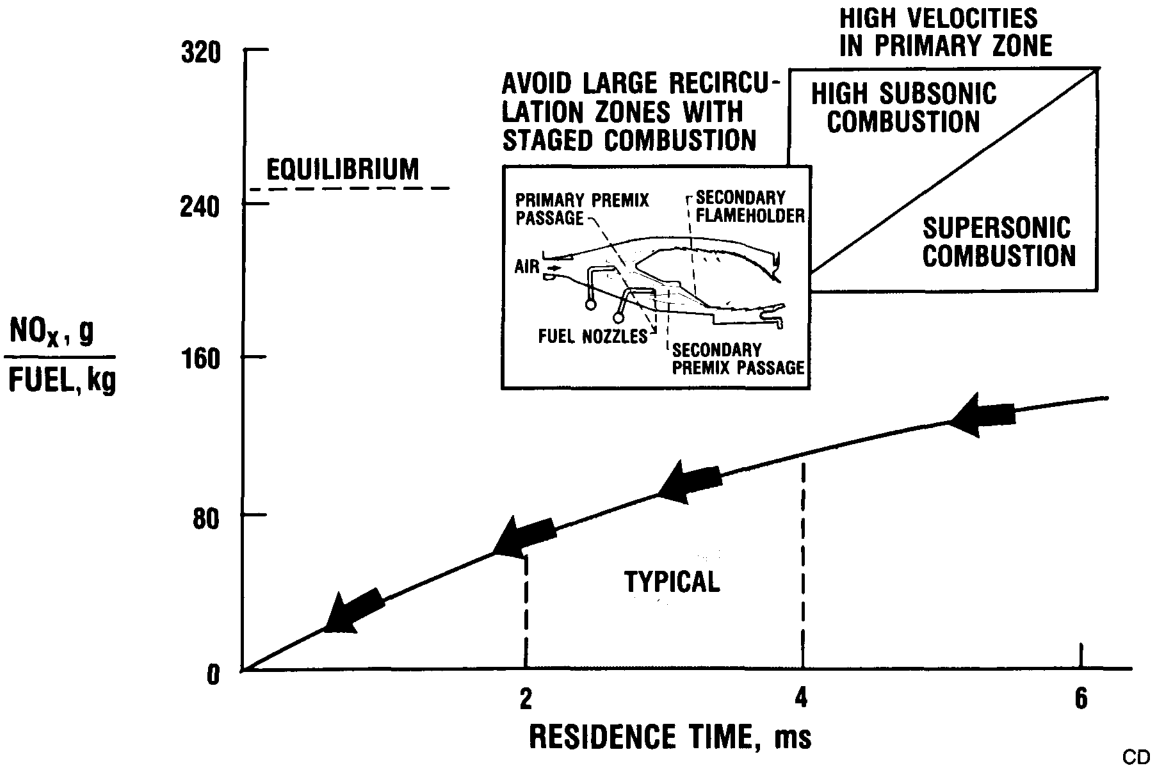
NO_X-EMISSIONS-REDUCTION CONCEPTS

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. 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 to relatively high-subsonic values 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 and, thereby, requires the implementation of other stability-enhancing features.

NO_X-EMISSIONS-REDUCTION CONCEPTS REDUCE RESIDENCE TIME AT HIGH TEMPERATURE



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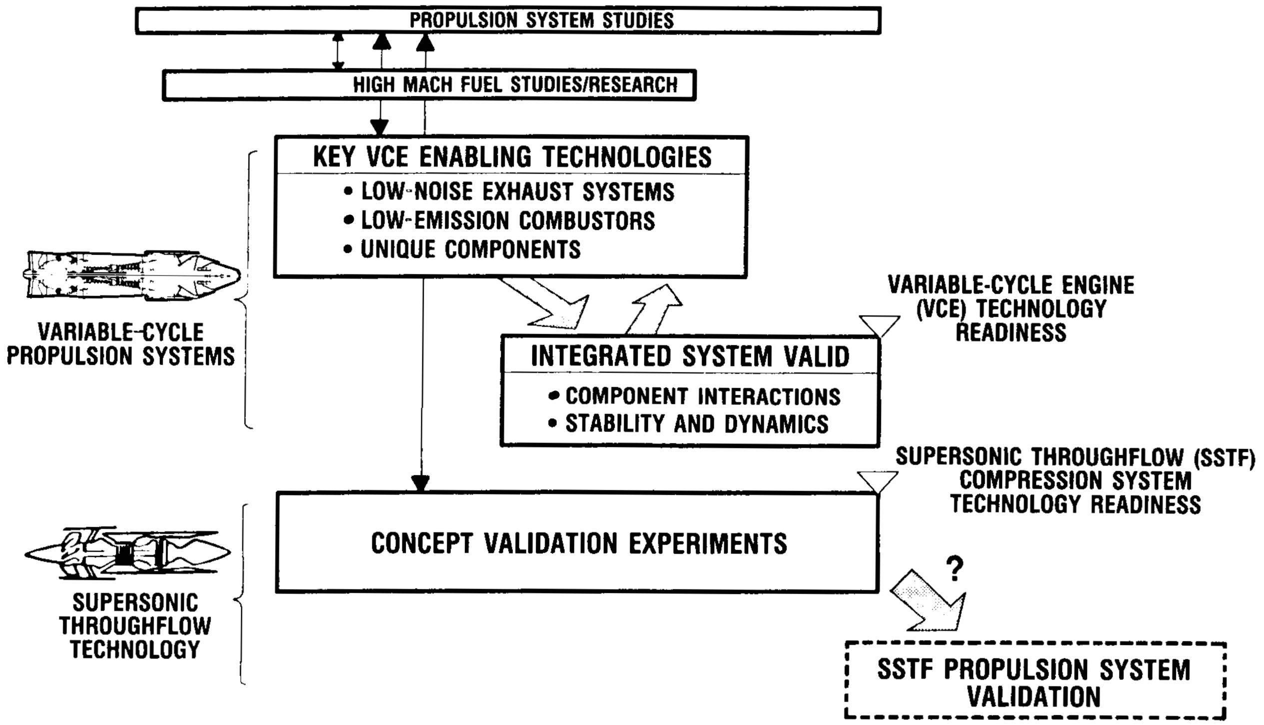
CANDIDATE HIGH-SPEED PROPULSION PROGRAM PLAN

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. Continued propulsion system studies as well as a high-speed fuel and fuel systems effort are also needed. Attainment of the propulsion goals outlined herein would indeed revolutionize aircraft capability for the future.

CANDIDATE HIGH-SPEED PROPULSION PROGRAM PLAN



PROPULSION SYSTEM STUDIES

HIGH MACH FUEL STUDIES/RESEARCH

KEY VCE ENABLING TECHNOLOGIES
- LOW-NOISE EXHAUST SYSTEMS
- LOW-EMISSION COMBUSTORS
- UNIQUE COMPONENTS

VARIABLE-CYCLE PROPULSION SYSTEMS

VARIABLE-CYCLE ENGINE (VCE) TECHNOLOGY READINESS

INTEGRATED SYSTEM VALID
- COMPONENT INTERACTIONS
- STABILITY AND DYNAMICS

SUPERSONIC THROUGHFLOW (SSTF) COMPRESSION SYSTEM TECHNOLOGY READINESS

CONCEPT VALIDATION EXPERIMENTS

SUPERSONIC THROUGHFLOW TECHNOLOGY

?

SSTF PROPULSION SYSTEM VALIDATION

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