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Propulsion Technology Challenges for Turn-of-the-Century Commercial Aircraft

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Abstract

This paper highlights the efforts being performed or sponsored by NASA, working with the U.S. civil aeronautics industry, to address the propulsion system technological challenges that must be met in order to ensure a viable future for the industry. Both the subsonic and supersonic aeropropulsion programs are considered. Subsonic transport propulsion program elements, including ultra-high-bypass-ratio turbofans with attendant noise reduction efforts, high-efficiency cores, and combustor emissions reductions are discussed in terms of goals, technical issues, and problem solutions. Similarly, the high-speed research propulsion efforts addressing a high-speed commercial transport are reviewed in terms of environmental barrier issues, such as oxides of nitrogen and noise reduction, and the related economic issues.

Introduction

The technology investment decisions that are made today will determine whether the technology needed for turn-of-the-century commercial aircraft will be available. The process used in identifying the critical technologies is vital in ensuring that the right technologies are pursued. This process becomes even more important when resources, including personnel and funds, are constrained. Such is the case now with the present worldwide economic situation and, more specifically, with the general decline and accompanying downsizing of the aeronautics industry as a whole. Many of the airlines, the ultimate customer of the civil aviation industry, are struggling for survival. Consolidations and buyouts are occurring as part of the survival process. At best, the outlook is one of only modest growth in the foreseeable future.

To help ensure that NASA pursues the right technologies, NASA has involved the U.S. propulsion system and airplane manufacturers in identifying critical technology needs. The manufacturers, in turn, are involving the commercial airline industry. Through meetings and extensive interactions we are working together so that, to our best ability, the investments being made in technology today will truly provide the technology readiness for turn-of-the-century commercial subsonic and supersonic aircraft.

Outlook

Demands for new aircraft are expected to increase by an average of 5 percent per year (maximum) through the turn of the century.[1,2] However, in light of the present recession in the aeronautics industry, the 5-percent growth projection may be too high.

Currently, Boeing is developing the 777 aircraft and McDonnell Douglas is pursuing partners for a proposed MD12 aircraft. Engines being developed for these aircraft are the General Electric GE90, Pratt & Whitney PW4000 derivatives, and the Rolls-Royce Trent 700 series. These engines feature significant noise reductions below U.S. Federal Aviation Regulations (FAR 36, Stage III), 30- to 40-percent reductions in cruise oxides of nitrogen (NO_x), and approximately 10-percent better specific fuel consumption (SFC). The thrust for these engines ranges from 50 000 to 90 000 pounds.

Looking into the future, a new large, high-capacity subsonic aircraft, a high-speed (supersonic) civil transport (HSCT), or both may emerge as contenders beyond the year 2000, primarily driven by the Far East market.[2-4] For either of these advanced transports to be pursued it must be environmentally acceptable and economically viable with tolerable financial risk.

The large, high-capacity subsonic aircraft will be in the 500- to 800-passenger class and will have a range of 7000 nautical miles.[2,5] The engines will produce up to 100 000 pounds of thrust and have a bypass ratio of 10 to 20. In all likelihood a consortium of international partners will be formed to produce such an aircraft. The consortium will provide the required financial backing for taking on such a venture and will reduce the financial risk to an acceptable level for each of the individual partners. And in fact, as widely publicized in the media, such a consortium is now being pursued.[2,6] This trend is likely to continue as a viable means for meeting the financial needs of developing all new advanced aircraft and for reducing or spreading the financial risk. Thus, the financial benefit realized from such ventures will also be shared worldwide.

For the high-speed civil transport the studies and technology have focused on a Mach 2.4 aircraft having a capacity of 250 to 300 passengers and a range of 5300 to 6500 nautical miles.[7] The engines will be in the 50 000-pound-thrust class. The ultimate engine cycle will likely be a balance between a high-specific-thrust cycle typical of the turbojet and a high-specific-flow cycle characteristic of the turbofan engine. This balance will be decided by how well it meets the takeoff noise and emissions index goals and achieves acceptable cruise performance. In all likelihood a second-generation supersonic transport will also be built by a worldwide consortium to reduce the financial risk of such a venture.

The Concorde and an envisioned second-generation supersonic transport are compared in Fig. 1. Note the increase in range and payload and the more demanding community noise standard and emissions index. Meeting these more stringent goals is considered essential for an environmentally acceptable aircraft.

Civil Aeronautics Environment

Even though the U.S. aerospace industry's favorable trade balance is not growing as fast as in the past (Fig. 2), it remains a significant contributor to our economy, with 1991 sales exceeding $140 billion, of which $36 billion came from the civil transport market. This resulted in a $30 billion positive balance of trade, with the large civil transport market accounting for $19 billion. In the U.S. aerospace industry as a whole over one million people were gainfully employed. However, the U.S. share of the global market has declined in the face of foreign competition. U.S. technological leadership is eroding, and the competition is offering expanded product lines of high-technology aircraft.

A number of factors are having an increasing influence on the civil aviation environment. For example, the International Civil Aviation Organization and the Committee on Aviation Environment Protection are actively considering more stringent noise and emissions standards. Also, the U.S. aviation system is approaching saturation, where further growth will create increasing strain on the system. The U.S. Federal Aviation Administration is requesting increased capacity- and safety-related research and technology.

Subsonic Program Goals and Challenges

The overall goals of the U.S. subsonic initiative are to validate critical airframe, propulsion, and flight system technologies for turn-of-the-century U.S. subsonic transport aircraft and to make these technologies available in time to meet industry development windows for new large, high-capacity subsonic transports (500 to 800 passengers) and a generation of advanced small and medium-size transports. To an ever-increasing extent the technologies are driven by the environmental and economic issues. These advanced subsonic aircraft will have to meet the more stringent noise and emissions standards that are likely to exist for turn-of-the-century aircraft as well as be economically viable in terms of direct operating costs (DOC), efficiency, reliability, and life.

The specific goals for the subsonic propulsion ultra-high-bypass-ratio engine systems are to reduce engine and fan noise to achieve a 7- to 10-dB reduction below FAR 36, Stage III; to improve the compression system efficiency by two points; to reduce NO_x emissions by 90 percent over current technology and to reduce other emission constituents to appropriate levels; to improve turbine efficiencies by two or more points; and to identify and develop advanced materials and structures.

For engines entering service in the year 2000 the overall cycle goals have been set at pressure ratios of 55:1 to 60:1, a 100 deg F increase in peak temperature, a 10-percent improvement in SFC, and a 3-percent reduction in DOC. The overall cycle goals for engines entering service in 2015 are pressure ratios of 75:1, a 300 deg F increase in peak cycle temperature, a 25-percent reduction in SFC, and a 10-percent reduction in DOC.

The goals for the subsonic program are aggressive; however, if they are achieved, significant advances in core thermal efficiency and propulsive efficiency will be made as shown in Fig. 3. In terms of overall efficiency and fuel efficiency the ultra-high-bypass-ratio, high-efficiency core will be nearly competitive with the advanced turboprop. The challenges are in meeting the noise reduction goal of FAR 36, Stage III, minus 7 to 10 dB and in meeting the NO_x emissions goals at the higher cycle pressure ratios and temperatures.

Subsonic Program Elements

The elements of the subsonic program are depicted in Fig. 4. These elements include increasing the overall cycle pressure and temperature ratios, improving the efficiency of the components, and addressing the environmental issues of noise and emissions. The subelements within the noise reduction program are noted in Fig. 5. Included are engine source noise reduction, high-lift systems that will enhance the rate of climb, and engine/airframe integration. As stated earlier, the goal is to reduce noise 7 to 10 dB below Far 36, Stage III. If this goal can be achieved, the capacity of our present air transportation system can be increased significantly under the current curfew constraints imposed at many airports.

A simulator to be used in the experimental program addressing source noise reduction concepts and techniques is shown in Fig. 6. Several advanced concepts will be tested in NASA wind tunnels with this simulator.

A unique concept that has the potential for achieving the higher overall cycle pressure ratios without requiring advanced materials is the wave rotor. This concept was conceived by Brown-Boveri a number of years ago and is currently being used in several automotive applications. The potential DOC reduction from achieving the higher overall cycle pressure ratios and a schematic of the wave rotor used as a topping device for the gas turbine cycle are shown in Fig. 7. The wave rotor achieves the boost in cycle pressure through gas dynamics and its operation is intermittent. As a result, the material temperature within the wave rotor is an average of the compressor discharge temperature and the combustor outlet temperature.

Therefore, the turbine experiences a lower temperature flow relative to the turbine in a conventional engine. Wave-rotor operation is illustrated in Fig. 8. The wave rotor's rotational speed controls the valving, or the porting, of the flow in and out of it. Because only a modest rotational speed is required relative to the gas turbine, material stresses are minimized at the already low mean temperature. Keep in mind that this is an aggressive technology—one example where NASA is reaching far out in its basic research activities. We hope that computational fluid dynamics will allow the full potential of this device to be realized in the future.

High-Speed Research Program Goals and Challenges

The overall goal of the high-speed research (HSR) program is to resolve the environmental challenges facing the introduction of an acceptable high-speed commercial transport (HSCT). These include resolving the atmospheric emissions, airport noise, and sonic boom challenges as well as providing the critical technologies for economical operation. To achieve these goals, NASA is working in partnership with the U.S. civil aviation industry, positioning it to be a leader in the development of a new advanced supersonic transport.

The HSR program is divided into two phases. The objective of phase I is to resolve the environmental issues of atmospheric emissions, airport noise, and sonic boom by 1995. This objective includes the development of low-emission combustor technology and atmospheric models leading to acceptable fleet impact assessments. Also included is the development of source noise reduction concepts, high-lift technologies, and operational procedures leading to aircraft noise impact that is consistent with noise regulations.

The objectives of phase II are to develop and verify, in cooperation with U.S. industry, the high-leverage technologies essential for economic viability. Included are the development of enabling propulsion materials and critical advanced propulsion components and a demonstration of their integration in technology testbeds.

The HSCT source noise challenge is shown in Fig. 9. The figure is based on the worst-case scenario from a noise point of view, which is the turbojet engine cycle. The turbojet cycle requires a mixer/ejector nozzle system to achieve the reduced jet velocity needed to realize the noise reduction goal. Noise suppression in terms of the change in effective perceived noise pressure level (ΔEPNdB) is plotted versus percent of gross thrust loss. The latest technology is shown by the shaded area on the lower right-hand side of the figure; the goal is shown by the oval region in the upper left-hand corner. The plot reflects the challenge in achieving the HSCT noise goal with an acceptable thrust loss on the order of 1 to 3 percent. Noise suppression of as much as 20 EPNdb must be achieved with the turbojet cycle to meet the Stage III requirements. One of the difficulties contributing to the failure to achieve the noise reduction goal to date is that the mixing of the ejector flow with the core flow occurs, to a large extent, outside the nozzle in current nozzle/ejector/mixer configurations. Thus, the acoustic liner tends to be less effective than expected. Efforts to improve the mixing process are being pursued.

High-specific-thrust and high-specific-flow engines are compared in terms of the noise reduction required to meet FAR 36, Stage III, in Fig. 10. The high-specific-thrust engines (i.e., turbojets or very low-bypass-ratio turbofans) require about a 20-dB noise reduction as noted earlier. The high-specific-flow engines (i.e., moderate- to high-bypass-ratio engines) require from 12 to 15 dB of suppression—significantly less than the high-specific-thrust engines.

The basic parameter controlling noise is jet velocity. The effect of jet velocity on sideline noise is shown in Fig. 11 along with examples of high-specific-flow and high-specific-thrust engines. Note that the high-specific-thrust engines have a higher jet velocity and require a larger reduction in noise, whereas the high-specific-flow engines operate with a lower jet velocity and require less noise suppression to meet FAR 36, Stage III. The variable-cycle engine/inverter flow valve (VCE/IFV) can meet the noise goal without the aid of suppression devices. However, as is often the case in balancing an engine cycle to meet a given goal, nothing comes free. Such is the case for the VCE/IFV, where mechanical complexity and weight must be balanced against meeting the noise reduction goal. A mixed-flow turbofan with a modest bypass ratio may very well provide a suitable overall balance.

The HSCT NO_x emissions challenge is shown in Fig. 12, where the NO_x emissions index in grams of NO_x per kilogram of fuel is plotted versus an NO_x severity parameter. Present-technology combustors fall within the shaded area bounded by "current combustors" and the "best achievable" combustors. The stringent goal for the HSR program is shown in the lower right-hand corner and reflects the need for significant improvements in combustor design. Advanced concepts involving rich burn/quick quench/lean burn combustors and premixed/prevaporized combustors are being studied in basic flame tube experiments.

High-Speed Research Program Elements

The elements of the HSR program for achieving the noise reduction goals are shown in Fig. 13. The major thrusts include the development and application of analysis and prediction codes with a focus on the jet noise aspect. Concepts being studied include, but are not limited to, inverted velocity profiles and ejectors for reducing the average jet velocity. The mixing process is a key issue with the mixer/ejector concepts and is being addressed both analytically and experimentally.

A new facility at the NASA Lewis Research Center for pursuing nozzle acoustic research is illustrated in Fig. 14. The nozzle acoustic test rig is located within a 130-foot-diameter, acoustically treated dome.

The elements of the HSR emissions reduction program are shown in Fig. 15. Two basic concepts are being studied—the lean premixed/prevaporized and the rich burn/quick quench/lean burn. Codes are being developed and applied to analyze and predict the performance. Also, basic experiments are being conducted to validate the analytical codes.

A major activity in setting goals for NO_x emissions is the modeling of the upper atmosphere to assess how an HSCT fleet would deplete the ozone layer. The partial results of these studies are shown in Fig. 16. The study assumed that 70 billion kilograms of fuel would be burned per year by a fleet of 600 HSCT's. The calculations were made for three combinations of cruise Mach number and altitude and for emissions indices of 5, 15, and 45. The shaded area represents what is considered an acceptable impact on the ozone layer. Thus, a cruise Mach number/altitude range of 1.6/18 or 2.4/18 and indices of 15 will cause less than 1-percent reduction in ozone.

Summary

NASA's aeronautical propulsion program covers a broad spectrum of flight regimes and includes new initiatives for both advanced subsonic transports and supersonic transports. Both basic research and focused research-and-technology activities are being pursued. Solving the environmental challenges of noise and emissions facing the air transportation system is at the forefront of all programs. However, economic issues are also being addressed and solving them is vital to any success story in the aviation market. The U.S. Government is increasing its support for civil aeronautics programs. This trend is expected to continue into the next century.

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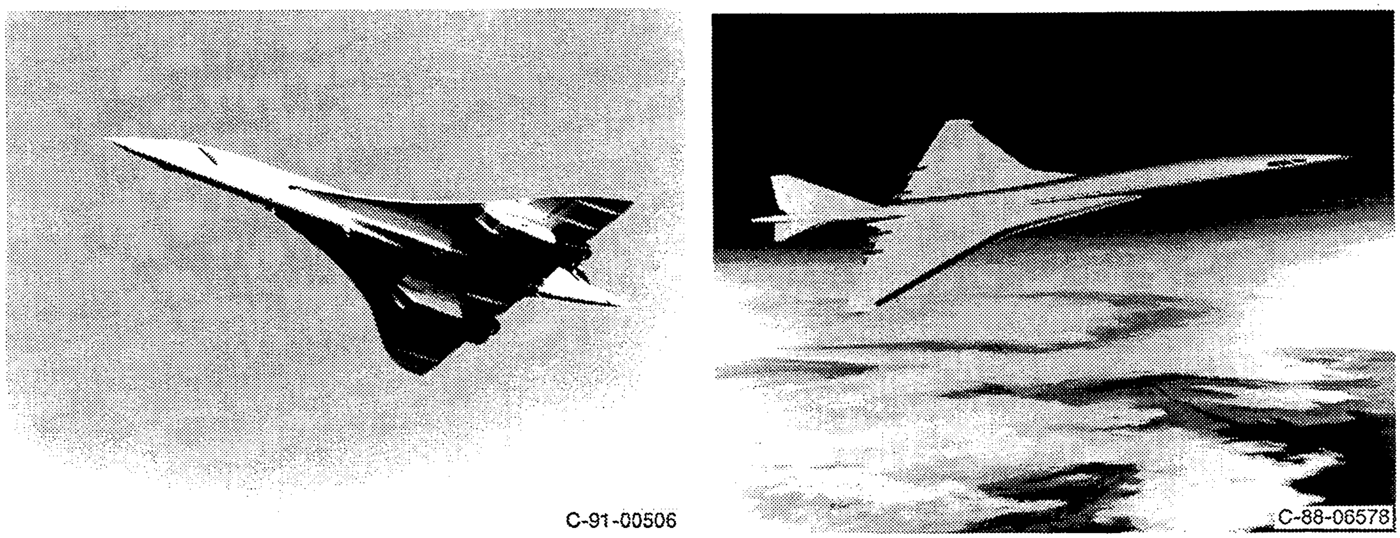


Concorde		HSCT
3000	Range, n mi	5000-6500
128	Payload, number of passengers	250-300
400 000	Weight, lb	750 000
Exempt	Community noise standard	FAR 36, Stage III, 3 dB
Premium	Fare levels	Standard + 10 to 15%
20	Emissions index	5

Figure 1.—Current outlook for high-speed research program.

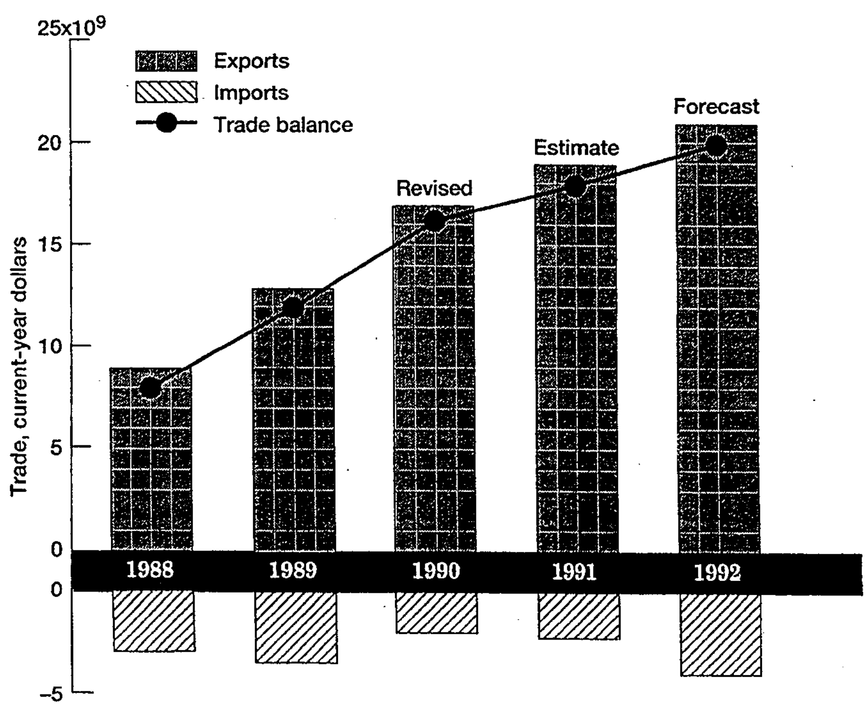


Figure 2.—U. S. trade in large civil transports. (From ref. 8.)

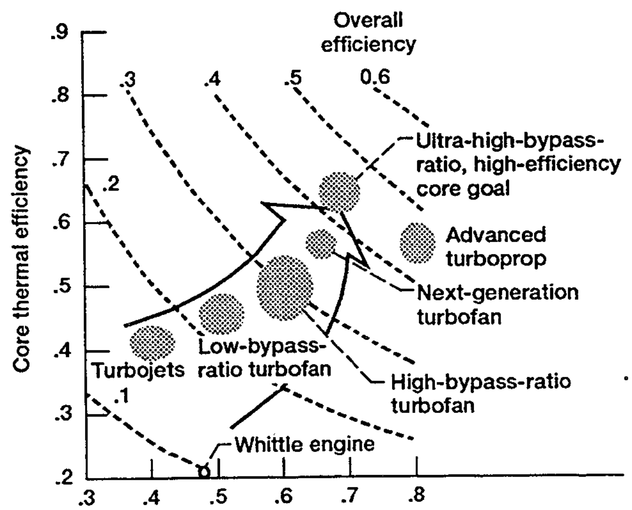


Figure 3.—Subsonic efficiency challenge.

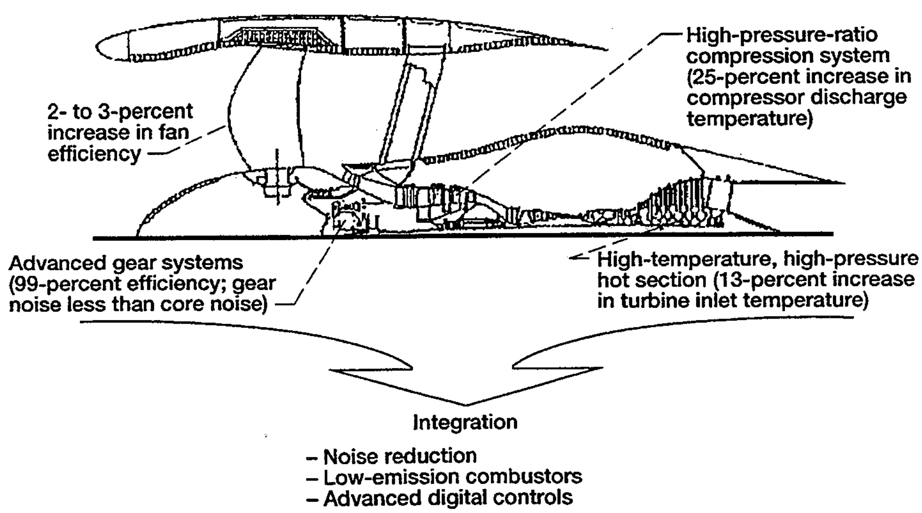
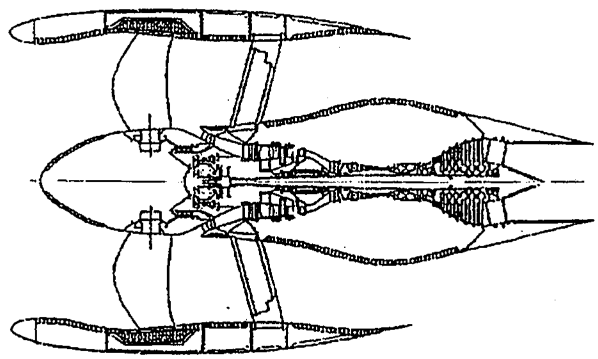
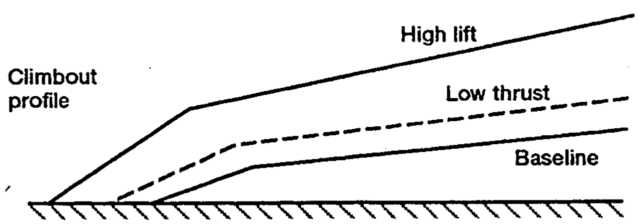


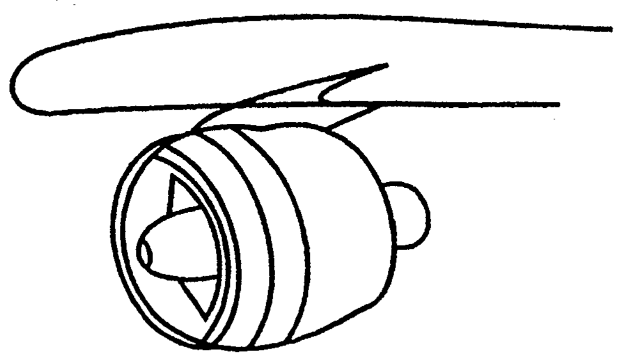
Figure 4.—Subsonic propulsion program elements. Goal, 50-percent increase in overall pressure ratio.



(a) Engine source noise reduction.



(b) High-lift systems.



(c) Engine/airframe integration.

Figure 5.—Subsonic noise reduction program elements.

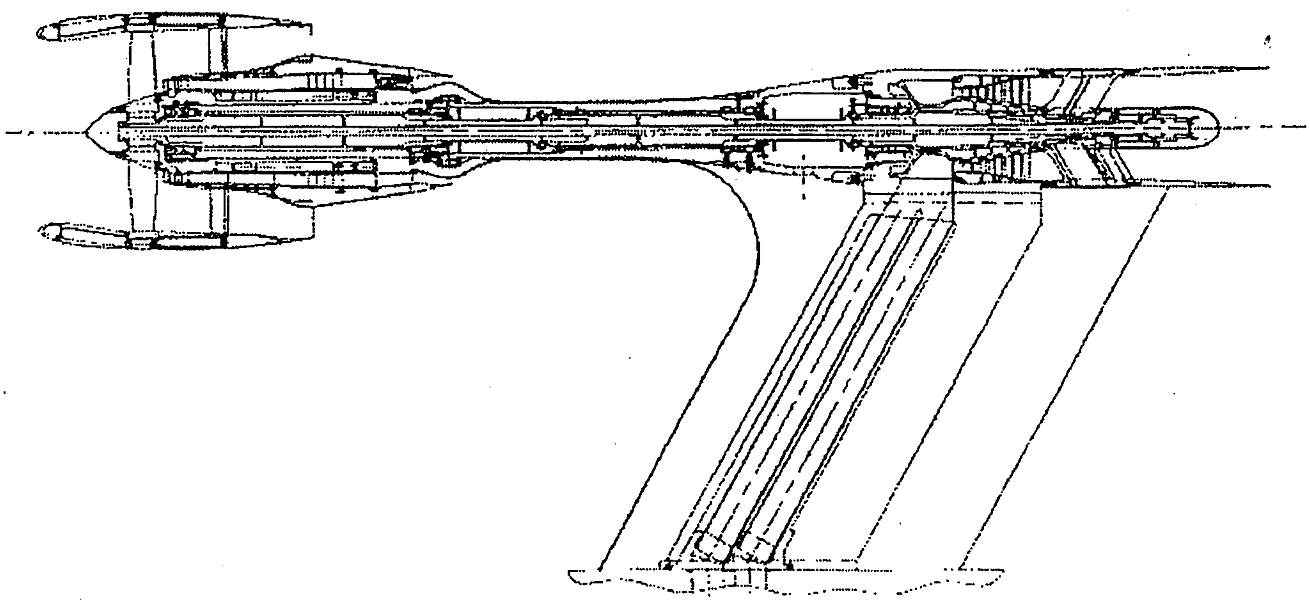


Figure 6.—Ultra-high-bypass-ratio propulsion simulator.

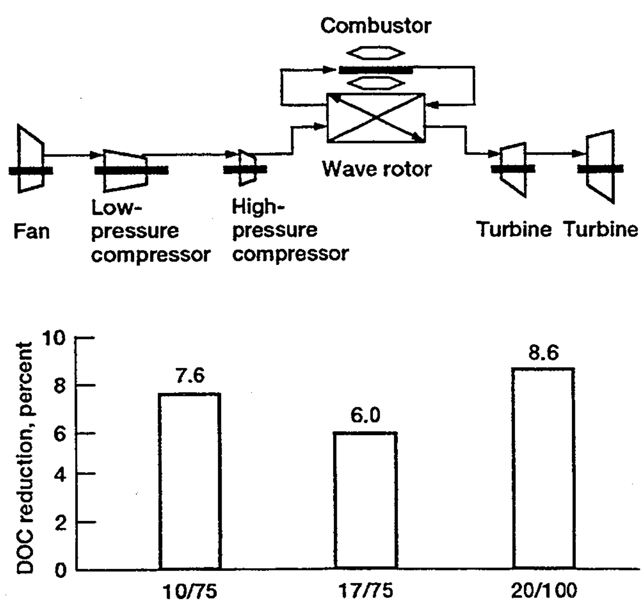


Figure 7.—Wave rotor applied to ultra-high-bypass-ratio engines. Baseline, energy-efficient engine.

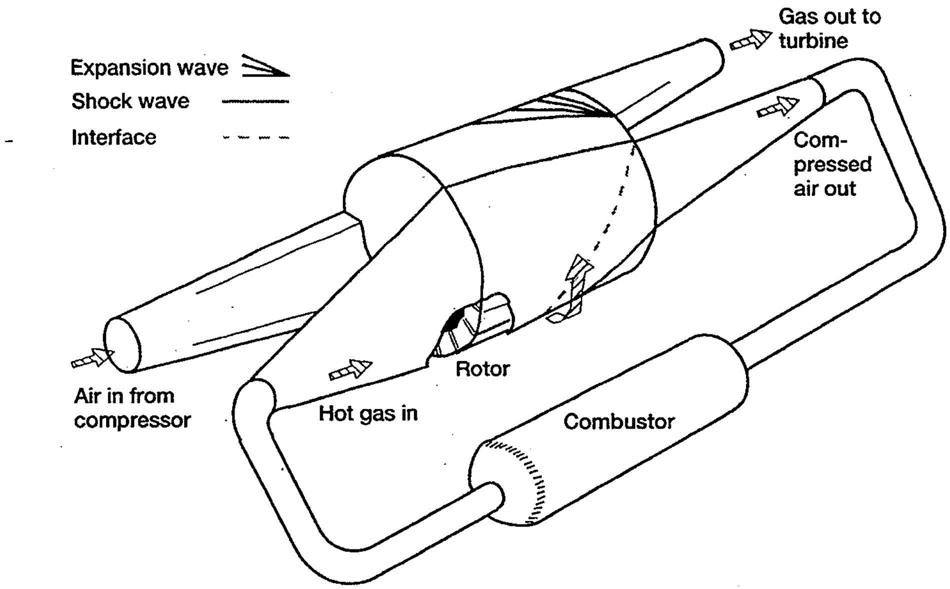


Figure 8.—Wave rotor.

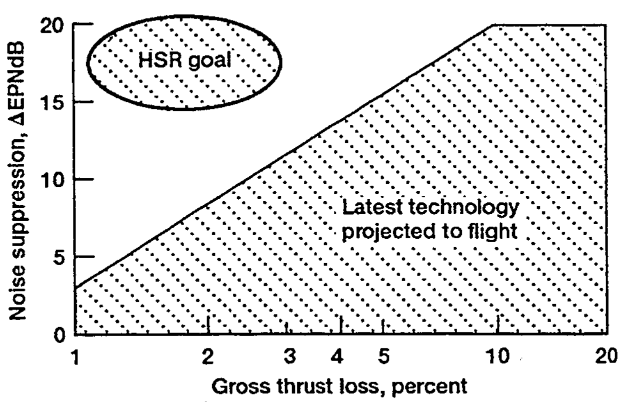


Figure 9.—HSCT source noise challenge.

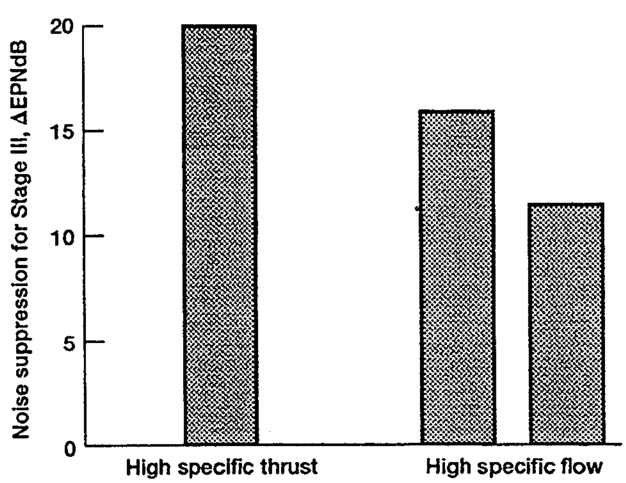


Figure 10.—HSCT exhaust nozzle acoustic challenge.

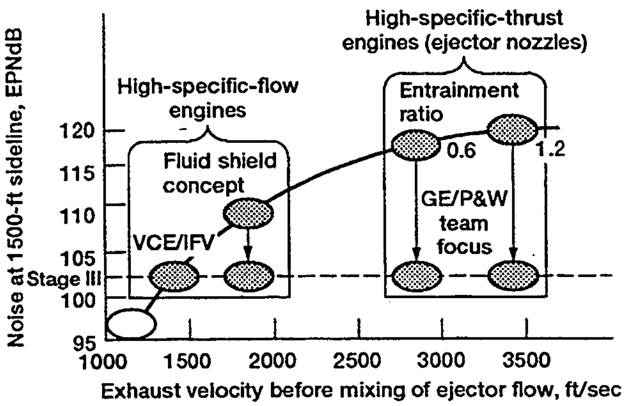


Figure 11.—HSCT noise reduction challenge. Two basic noise reduction approaches: high-specific-flow engine + modest noise reduction; high-specific-thrust engine + aggressive noise reduction.

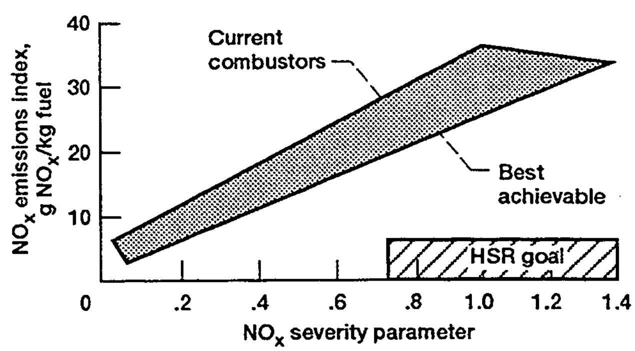


Figure 12.—HSCT NO_x emissions challenge.

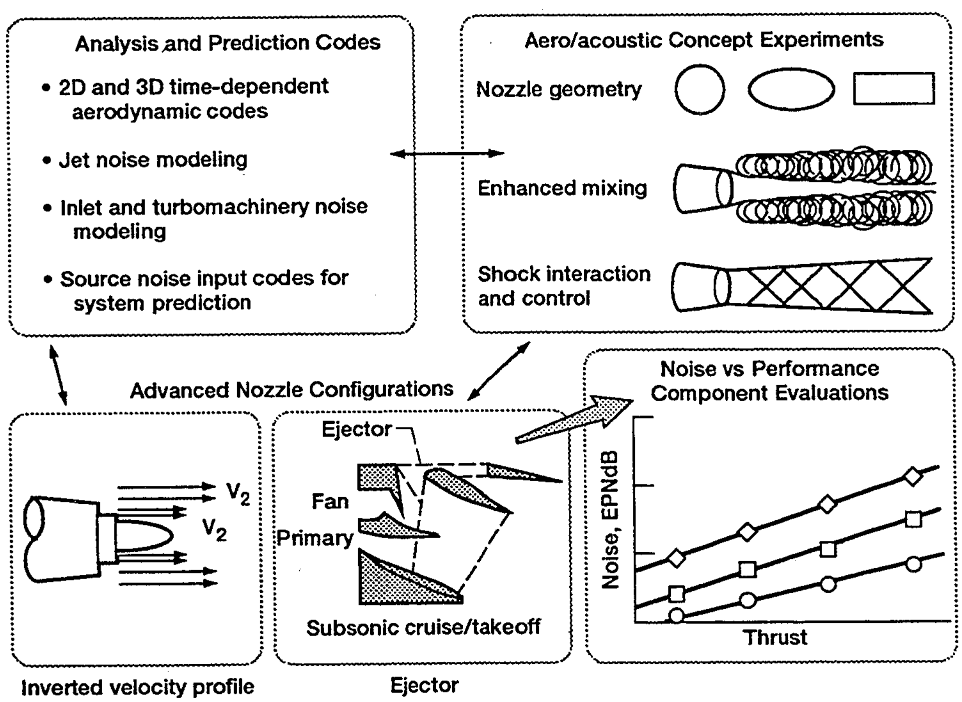


Figure 13.—HSR noise reduction program elements.

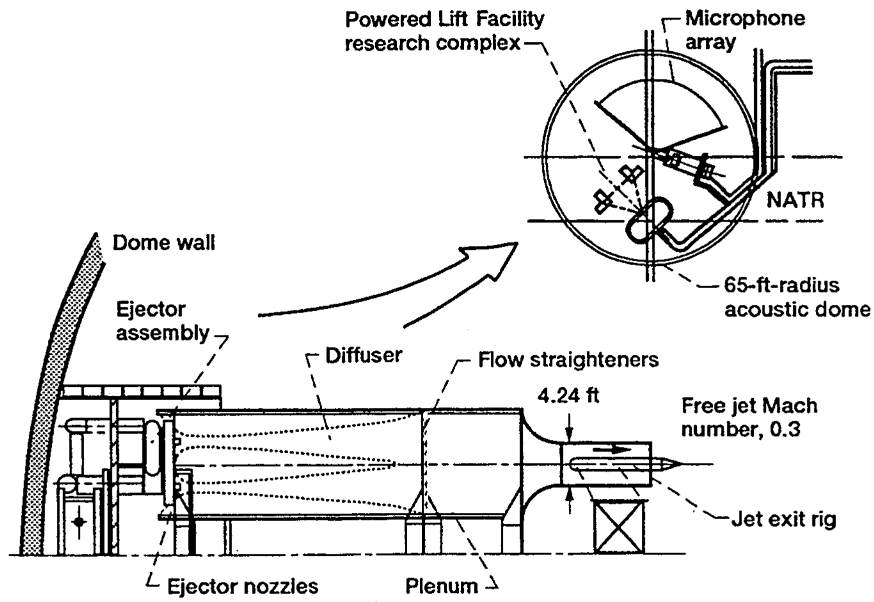


Figure 14.—Nozzle acoustic test rig (NATR).

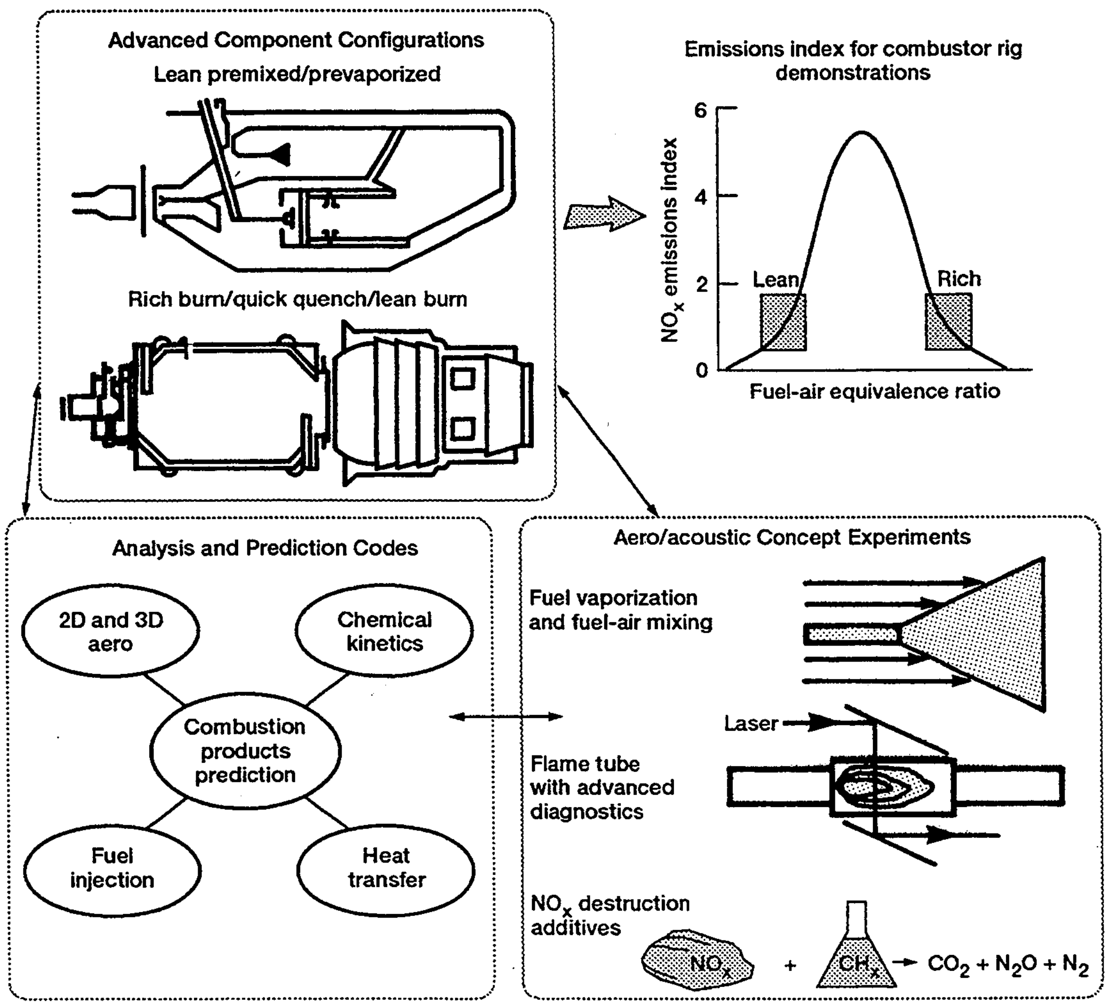


Figure 15.—Elements of HSR emissions reduction program.

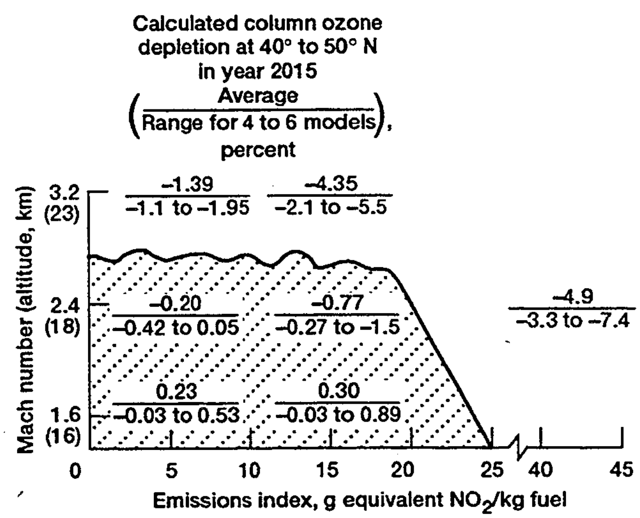


Figure 16.—Current atmospheric assessment. Heterogeneous chemistry assumptions: 70 Billion kg fuel/yr (~ 600-HSCT fleet).

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