ADVANCED TECHNOLOGY FOR CONTROLLING POLLUTANT

EMISSIONS FROM SUPERSONIC CRUISE AIRCRAFT

Robert A. Duerr and Larry A. Diehl
Lewis Research Center

SUMMARY

This paper presents and discusses some of the results obtained from research and development programs being sponsored or conducted by NASA. The objectives of these programs were to evolve and evaluate new gas-turbine-engine combustor technology for the reduction of pollutant emissions. Activities ranging from investigating variations of conventional combustion systems to evaluating advanced combustor concepts have been and continue to be pursued. Projected results from far-term technology efforts aimed at applying the premixed-prevaporized and catalytic combustion techniques to aircraft combustion systems indicate a potential for significant reductions in pollutant emission levels.

INTRODUCTION

This paper describes NASA-sponsored programs whose objectives were to evolve and evaluate new gas-turbine-engine combustor technology for the reduction of aircraft engine pollutant emissions.

Concern over the possibly adverse environmental effects of the first-generation supersonic transports drew attention to the exhaust pollutant emissions produced by the gas-turbine engines used to power these aircraft. Two general areas of concern were expressed: urban pollution in the vicinity of airports and pollution of the stratosphere. The principal urban pollutants were carbon monoxide and unburned hydrocarbons during idle and taxi and oxides of nitrogen and smoke during takeoff and climb. Oxides of nitrogen were also considered to be of concern during high-altitude cruise flight.

In response to growing concern over the possible undesirable effects of gaseous pollutant emissions from aircraft engines, NASA initiated in 1971 an Emissions Reduction Research and Technology program. This program and the results obtained to date are the basis for this paper. In 1973 the Environmental Protection Agency issued gaseous pollutant emission standards for aircraft engines, to be implemented by 1979. Since that time the EPA has continuously examined and studied the impact of aircraft engine emissions on air quality and has closely followed the advancing technology for control of these pollutant emissions. In March 1978, the EPA issued a Notice of Proposed Rule Making that would amend the standards. The EPA has not yet taken final action on the proposed amended standards. For the purposes of this paper we have chosen the proposed EPA standards as the basis for comparing and evaluating advanced combustor concepts.

The three gaseous emissions of primary interest are carbon monoxide, unburned hydrocarbons, and oxides of nitrogen. Figure 1 illustrates schematically an aircraft engine combustor of the type used in various proposed engines for the first-generation supersonic transport (SST) aircraft. Below the sketch are bar graphs illustrating the levels of pollutants typical of these engines during landing-takeoff operation. These pollutant levels are based on an average of engine test data from the Rolls-Royce Olympus 593 and limited information obtained during prototype evaluation of the General Electric GE4 and the Pratt & Whitney JTF-17 engines. The characteristic features of the main combustor are noted in the sketch. It has a single burning zone, the primary portion of which tends to operate fuel rich. Large amounts of air bypass the combustor primary zone and are admitted further downstream to cool and dilute the combustion products. These combustors all have a step-louver-constructed, film-cooled liner; and a large portion of the total combustor airflow is used to cool the liner. The EPA has established six engine classes for gas-turbine-powered aircraft; class T5 has been designated for engines used to power supersonic commercial aircraft. The emission levels shown below the sketch are expressed as values of the proposed EPA parameter, or EPAP, and are obtained by integrating the engine emissions over a specified landing-takeoff cycle. The method of calculating the EPAP is described in the appendix. The proposed EPA standards for class T5, newly certified engines are shown as a dashed line for each of the pollutants. Levels of emissions produced by the first-generation SST significantly exceed the proposed EPA standards and thus indicate a need for reducing the pollutant emissions from this class of engines.

This paper presents and discusses some of the results obtained from research and development programs being sponsored, directed, or conducted by NASA. Although we recognize that much important work is being done at universities and in private industry, or sponsored or conducted by other government agencies (DOD, FAA, EPA, etc.), this paper concentrates on NASA programs only. Activities ranging from investigating variations of conventional combustion systems to evaluating advanced catalytic techniques are being pursued. Applications of these techniques to future aircraft engines are being considered. The results pertinent to pollutant emission reduction efforts are presented and discussed, along with an assessment of the projected development difficulties and a forecast of potential emission level reductions.

DEVELOPMENT OF CURRENT-TECHNOLOGY COMBUSTORS

The NASA Emissions Reduction Research and Technology program, as conceived in 1971, had both near-term and far-term goals. The near-term program concentrated on achieving a large and immediate reduction in pollutant emissions. It mainly addressed the then current-technology engines used to power subsonic commercial aircraft. The near-term program, conducted largely under contract, is essentially complete.

The far-term program had the overall goal of developing the technology necessary to define the minimum pollutant emission levels that aircraft gas-turbine engines could achieve. This far-term program was and continues to be conducted both in-house at the Lewis Research Center and through research grants to universities and contracts with industry.

The specific objectives of the near-term emission reduction program were to investigate new combustor concepts with the potential for significantly lower emission levels and to measure the emission reduction obtainable with these new combustors in actual engine tests. The approach taken to achieve these objectives was to let multiphase contracts with the major aircraft engine manufacturers to devise and investigate new combustor concepts. In the first phase, a variety of new combustor concepts were screened to determine those with the greatest emission reduction potential. In the second phase, those concepts were further refined, and finally the best or most "engine ready" combustor concept was tested in an engine to measure the emission reduction obtainable.

Two of the near-term programs were conducted by Pratt & Whitney and General Electric using the JT9D and CF6 engines, respectively. The results of these programs are applicable to supersonic cruise aircraft engine technology, and some elements of the resulting concepts have been incorporated into the currently proposed designs for the Pratt & Whitney Variable Stream Control Engine (VSCE) and the General Electric Double Bypass Engine (DBE).

In the figures that follow, the emission levels of advanced combustors incorporated in the P&W VSCE and the GE DBE are projected. These projections are based on standard correlating expressions developed during the JT9D and CF6 engine tests. Assuming that technology similar to that achieved in the JT9D and CF6 engine tests could be achieved in the advanced supersonic engine cycle, the JT9D and CF6 engine data have been extrapolated to the combustor conditions that would exist in the VSCE and DBE.

The Vorbix combustor concept used in the JT9D engine is illustrated in figure 2, and the combustor is shown in figure 3. (Vorbix is an acronym meaning vortex burning and mixing.) The cross-sectional sketch of this combustor (fig. 2) shows that there has been a departure from the types of combustor used in the past. This combustor has two burning stages arranged in series: The pilot stage is optimized for control of carbon monoxide (CO) and total hydrocarbons (THC) at low power, and the main stage is optimized for control of oxides of nitrogen (NO_x). The main stage becomes operational at all engine conditions beyond idle. It is separately fueled and is ignited by the pilot stage. The bar graphs shown below the sketch in figure 2 compare the emissions of the first-generaton SST engine with estimated emissions for the Vorbix combustor as contained in the VSCE. The estimates are based on projections of emission data obtained in JT9D engine tests. The advanced engine cycle used for the present versions of variable-cycle engines differs significantly from that of the first-generation SST engine. The combustor inlet pressure and temperature and combustor exit temperature are all significantly higher than in the first-generation SST engine and thus impose a much greater NO_x emissions control problem. In this case, considerable technological effort is required just to maintain the NO_x emission levels of the first-generation SST. The projected CO emissions were reduced by over a factor of 5, THC emissions by over a factor of 40, and NO_x emissions by 10 percent.

The double-annular combustor, which was tested in an experimental CF6 engine, is illustrated schematically in figure 4 and shown in figure 5. This combustor concept is also a two-stage combustor, but here the pilot and main stages are arranged in parallel and result in a combustor with two annular burning zones. The outer or pilot zone is used at all operating conditions and is designed to minimize idle pollutants. The inner or main zone is functional at all engine conditions above idle and is designed to reduce high-power pollutants. As was done for the Vorbix combustor in figure 2, the bar graphs in figure 4 compare the first-generation SST emissions with the estimated emission levels for the double-annular combustor as contained in the DBE. The estimates are based on projections of emission data obtained in the CF6 engine tests. Projected CO emissions were reduced by 75 percent and THC emissions by a factor of 25; but estimated NO_x emissions increased by about 40 percent, a reflection of the more stringent cycle constraints mentioned earlier.

The projected engine emissions from application of these two emission-controlled combustors are summarized in figure 6. The combustor sketch shows the significant features of the typical emission-controlled combustor. Multiple burning zones are used: a pilot for engine-idle emission control, and a main zone for all higher power operating conditions. Air-blast fuel injectors are often used in the main stage to achieve fine fuel drops intimately mixed with combustion air. Since most of the air is now used in controlling the combustion process, very little air is available for dilution and temperature profile tailoring. Similarly the amount of air available for liner film-cooling is reduced, and advanced cooling schemes must be employed. The bar graphs summarize the average, estimated emission levels for the emission-controlled combustors and show significant reductions in CO and THC, but a slight increase in NO_x. The estimated THC emissions virtually disappeared, and this suggests that no further development is required to reduce levels of this pollutant. These projections prompted further work in reducing the CO and NO_x emission levels.

ADVANCED IDLE EMISSIONS CONTROL TECHNOLOGY

The results of the two programs discussed in the previous section indicated a need for reducing CO emissions over the landing-takeoff cycle by at least a factor of 2 in order to achieve the proposed EPA standards. Since CO emissions are usually most predominant at the idle power setting, an idle emissions reduction program was conducted with the objective of investigating new combustor concepts with the potential for significantly lower engine idle emissions levels.

To achieve this objective, a contract was let with industry for the investigation of three unique combustor concepts with nonconventional design features. The testing and evaluation of the concepts were confined to typical idle conditions. Application of this technology to a practical combustor system could be realized through variable-geometry schemes or by using one of these designs as the pilot stage of a multistage combustor.

All three concepts tested showed dramatic reductions in CO and THC emissions. The simplest design of the three, the hot-wall combustor, is shown in figure 7. The main feature of the hot-wall combustor is a thermal-barrier coating applied to the inside surface of the combustor liner to reduce wall quenching of the combustion gas reactions. These refractory-coated surfaces along with an impingement-cooled liner - with no film cooling whatsoever - resulted in greatly reduced quenching losses at the walls. Also, the secondary dilution air jets are placed far downstream in order to further reduce quenching for maximum reaction of the fuel and air.

The design features of the hot-wall combustor are shown in figure 8 as incorporated into the pilot stage of a hypothetical multistage combustor. The refractory surfaces of the inner liner walls and the use of impingement cooling result in minimized wall-quenching effects. The pilot combustor is designed for optimum burning rates at idle.

The projected emissions for such a combustor operating in an engine over the EPA standard landing-takeoff cycle are also shown in figure 8. Carbon monoxide emissions are significantly lower than those from the emission-controlled combustor. The NO_x emission level is essentially unchanged from that of the emission-controlled combustor since most NO_x is generated in these combustors during high-power operation.

This low-power emissions reduction program, in conjunction with the emissions-controlled combustor program, demonstrated dramatic reductions in CO and THC emissions at idle. The far-term emissions reduction program was directed toward achieving significant reductions in NO_x emissions and additionally reducing the low levels of idle pollutant emissions achieved earlier.

FAR-TERM EMISSIONS CONTROL TECHNOLOGY

At high-power operation, high flame temperature is the most important factor in the formation of oxides of nitrogen. Experimental data as well as analytical predictions indicate that NO_x emissions vary exponentially with flame temperature. Therefore, the far-term efforts have been concentrating on the technique of lean burning, in which decreasing the combustion-zone equivalence ratio lowers the flame temperature with a resultant reduction in NO_x formation.

Since the local flame temperature is a significant factor in controlling NO_x production, local fuel distributions with locally rich pockets of fuel and air must be avoided. This requires that the fuel and air be uniformly mixed throughout the combustion zone. In addition, it may be necessary to prevaporize the fuel. Large fuel droplets in the combustion zone are consumed by a diffusion flame that surrounds the evaporating droplets. This process takes place at near-stoichiometric conditions, and the high temperatures produce excessive NO_x emissions. Thus, combustors with provisions to prevaporize the fuel and to premix the fuel and air may be necessary to realize the full NO_x reduction potential of lean-burning techniques.

The concept of catalytic combustion offers the potential of even further reductions in pollutant emissions. By using a catalyst bed consisting of a ceramic honeycomb substrate impregnated with catalytic material, stable efficient combustion occurs at even leaner overall equivalence ratios.

Even though lean, premixed-prevaporized combustors and catalytic combustion appear to have the potential for achieving very low levels of pollutant emissions, considerably more effort is required before either of these technologies could be applied to aircraft engine combustion systems. These concepts then formed the basis for the far-term emission reduction program.

The objective of the far-term program is to evolve the technology needed for developing combustors with minimum pollutant levels. The approach taken to achieve this objective relies heavily on a continuing effort in basic and aplied research. The degree of risk and overall level of complexity associated with the adaptation of advanced techniques are more severe than in the near-term programs. Fundamental studies are viewed as a requirement to close gaps in our understanding of key problem areas and to provide a basis for establishing technology to a point where adaptation of a new approach to combustor hardware is practical. As mentioned earlier, two techniques appear particularly attractive in terms of their potential for reducing NO_x: the lean, premixed-prevaporized and catalytic combustion techniques. NASA has begun efforts to evolve and evaluate lean, premixed-prevaporized and catalytic combustors. It is anticipated that as these types of combustors continue to evolve, additional problem areas requiring more fundamental study and improved approaches to the adaptation of the fundamentals may be identified.

Before lean, premixed-prevaporized combustors can be applied to aircraft engines, additional research is required in several areas. Figure 9 shows a conceptual drawing of a lean, premixed-prevaporized combustor. It is a staged design, as are the previously discussed advanced combustors. The pilot stage has been configured to include features, such as a hot-wall liner, that minimize idle pollutants. The main stage contains a fuel injector, a premixing-prevaporizing section, and a flameholder. Maintaining a wide operating range while burning as lean as possible may require control of the airflow as well as the fuel-flow splits between the two stages. To achieve this required airflow control, a variable-geometry device has been included in the diffuser section.

The key areas of required research are also indicated in figure 9. Combustor inlet airflow characteristics must be known to assure uniform fuel-air distributions. Engine transient characteristics must be identified and studied to avoid autoignition and flashback in the fuel-air mixing passage. Practical schemes for varying the combustor geometry and controlling the combustor operation must be identified. For the premixing section of the main stage to operate successfully, information is needed on techniques for predicting and achieving the required fuel distribution and vaporization. Autoignition and flashback may be problems in the premixer. More data on these phenomena are needed over the range of engine operating conditions, including engine transients.

Lean stability and altitude relight capability need special attention with these systems. Because the majority of the combustor airflow must pass through the main stage to satisfy the lean-burning requirement, less air will be available to cool the combustor liner than in current-technology combustors. It, therefore, appears likely that the application of advanced liner-cooling schemes to this type of combustor will be required to avoid liner durability problems.

Digital engine controls will likely be required for the additional complexity of variable geometry. It is anticipated that full-authority digital control technology will be available in the future. However, additional study is needed to examine the control aspects of variable-geometry combustors and to establish transient response requirements.

The required research areas for catalytic combustors are listed in figure 10. In general, all the problem areas associated with premixed combustion apply equally well to the catalytic technique. Unique problems introduced with this technique include the activity of the catalytic materials over wide operating ranges, long-term degradation and poisoning of the catalyst, and thermal durability problems associated with continuous and cyclic operation of the catalyst bed. Although considerable progress has been made in the past few years on research associated with catalyst and substrate materials, considerably more effort in these areas will be required.

NASA has sponsored or conducted research programs investigating these required research areas and their application to lean, premixed-prevaporized and catalytic combustors. During the next several years combustors based on the principles of lean, premixed-prevaporized and catalytic combustion will be designed, built, and evaluated.

Estimated emission levels for lean, premixed-prevaporized and catalytic combustors operating over the EPA standard landing-takeoff cycle are shown in figure 11 and compared with the previous estimates. The cross section of the combustor shows some of the essential features of these designs. The combustor is a staged type, with variable geometry and optimized pilot-stage technology. In the main stage, lean combustion occurs downstream of the flameholder or, in the case of the catalyst shown in the inset, in the catalyst bed.

The estimated achievable CO and THC emission levels, shown in the bar graphs in figure 11, are based on the successful integration of optimized pilot-stage features as discussed previously. The emission control strategies employed here were aimed at further reducing NO_x emissions. The third set of bar graphs shows that, in terms of the integrated EPA parameter, NO_x levels may be further reduced by 55 to 60 percent. It is interesting that the pilot stage, which is necessary for engine startup and wide-range operation, may contribute more NO_x during engine idle than the main stage contributes during high-power operation. Thus the pilot stage is limiting the minimum achievable NO_x emission levels for the specified landing-takeoff cycle used in computing the EPA parameter.

The actual achievable levels may be somewhat different when these emission control techniques are developed into operational engine hardware. However, the further reduction in pollutant emissions offered by the far-term program is considerable and indicates the significant potential for reduced-pollutant-emission combustion systems for future aircraft engines.

CONCLUDING REMARKS

The advanced technology concepts described in the previous sections show potential for similar emission reductions at supersonic cruise conditions. The projected cruise emissions of oxides of nitrogen for the various programs discussed herein are compared in figure 12. The bar graphs show significant reductions in NO_x emissions as more technological advances are incorporated into the combustor design. No EPA standards have been proposed for controlling NO_x emissions at cruise.

The combustion systems in future supersonic cruise engines may well be markedly different from those presently in use if low-pollutant-emission combustion systems are found to be required. Much work, however, still remains to be accomplished before these advanced systems can be considered for actual application. Trade-offs between emissions, performance, altitude relight capability, durability, maintainability, and complexity must be evaluated in future experimental programs. In the far term, continuing research and technology programs must be pursued to validate that the minimum pollutant emission levels achieved in rig tests can in fact be realized in gas-turbine-engine combustion systems.

APPENDIX - CALCULATION OF PROPOSED

ENVIRONMENTAL PROTECTION AGENCY PARAMETER (EPAP)

The proposed Environmental Protection Agency parameter is expressed as

$$\mathrm{EPAP} = \frac{1}{F_N} \sum_{i=1}^{M} \left[(\mathrm{EI})_i T_i (\dot{W}_F)_i \right]$$

where

F_N installed net thrust of engine, kN

EI emission index of pollutant, g pollutant/kg fuel

T time in mode, min

W_F fuel flow rate, kg/min

M number of engine conditions (M = 7 for supersonic cruise engines)

The times in mode for the main combustor and the duct burner are given in the following table:

Combustor	Engine condition				
	Idle	Takeoff	Climb	Descent	Approach
	Time in mode, min				
Main	26.0	1.2	2.0	1.2	2.3
Duct burner	----	1.2	2.0	---	---

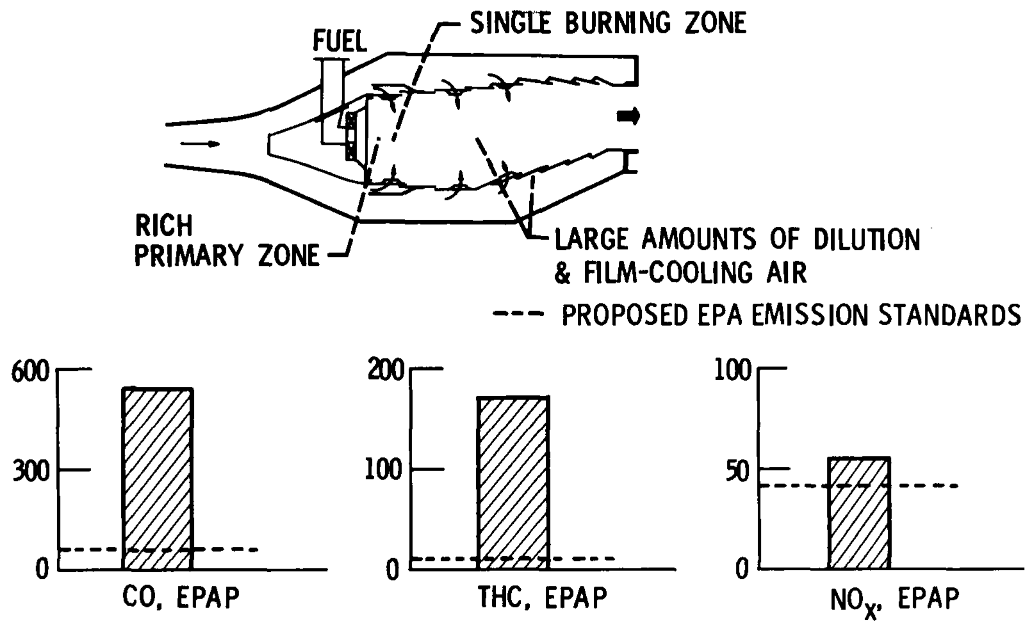

Figure 1.- First-generation SST combustor technology.

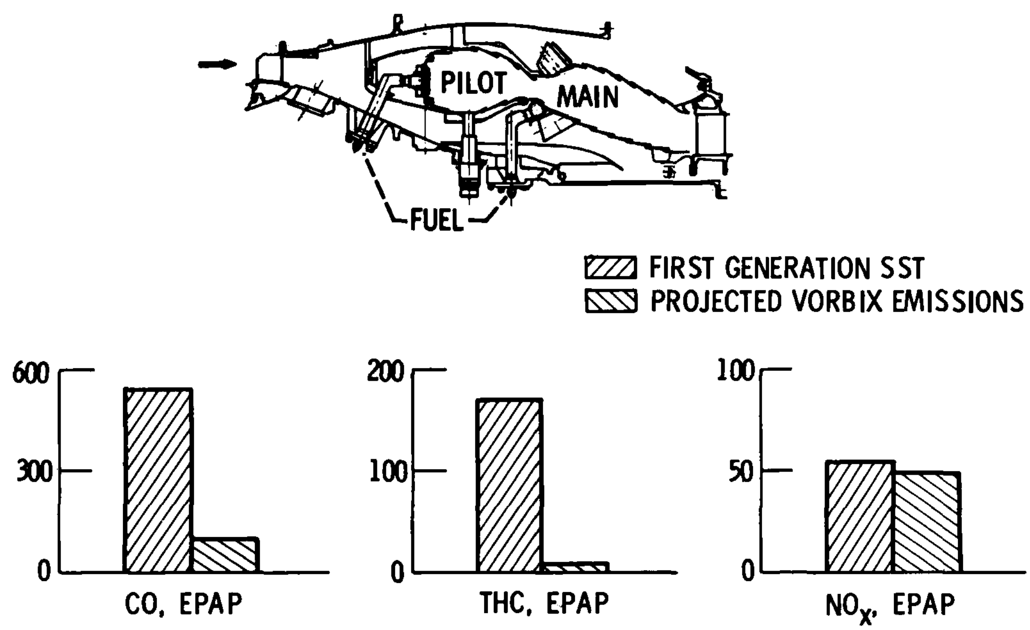

Figure 2.- Projected emission levels for advanced supersonic engine using Vorbix combustor.

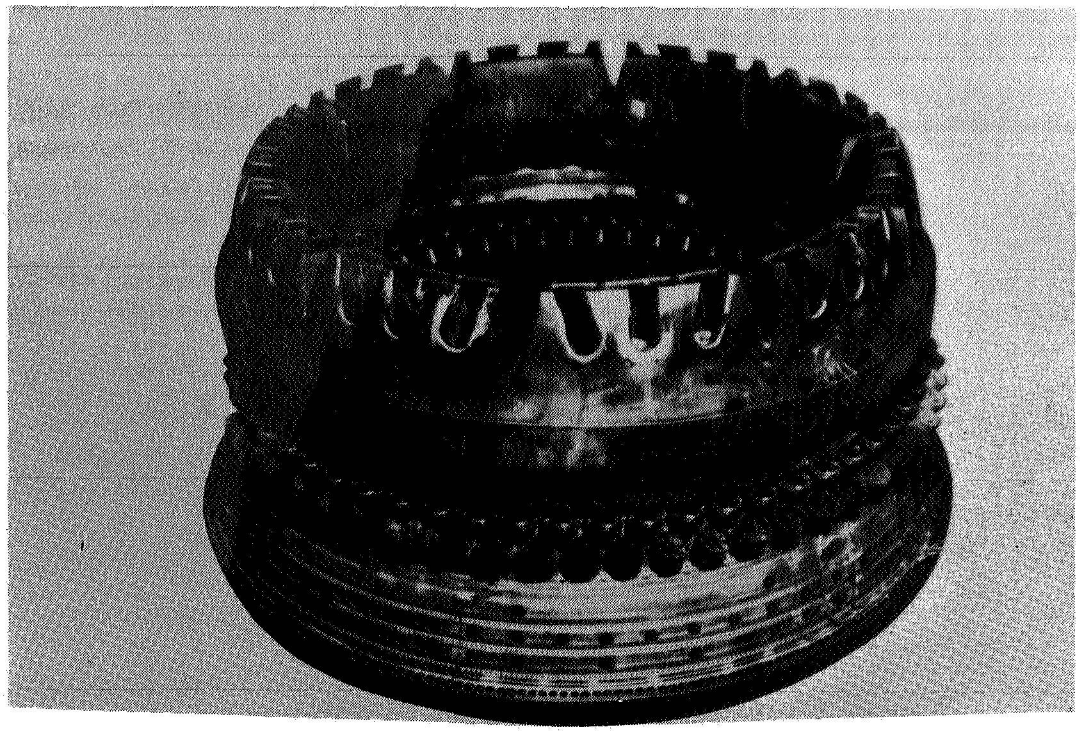

Figure 3.- Prototype Vorbix combustor.

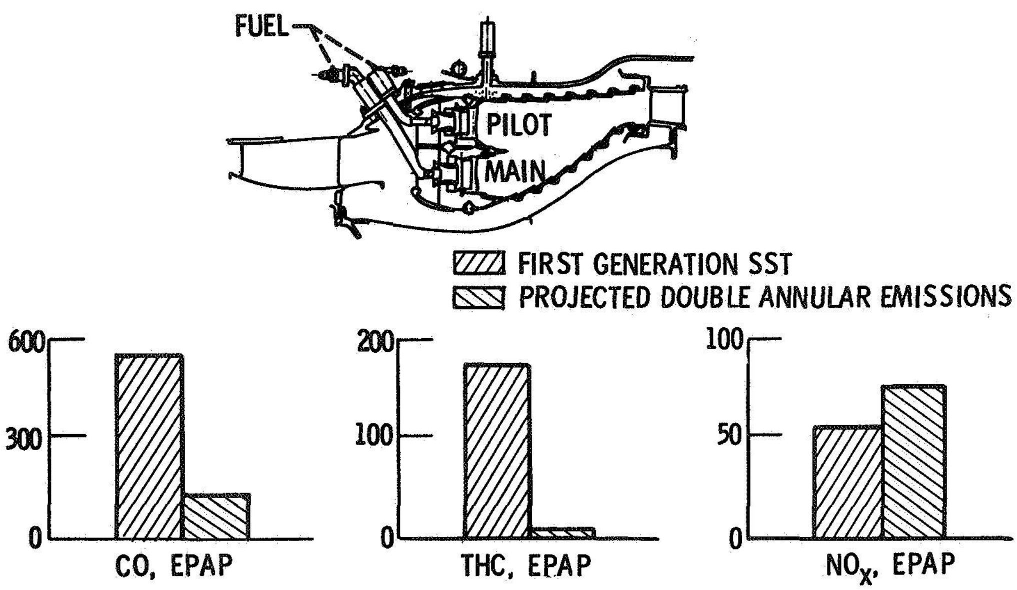

Figure 4.- Projected emission levels for advanced supersonic engine using double-annular combustor.

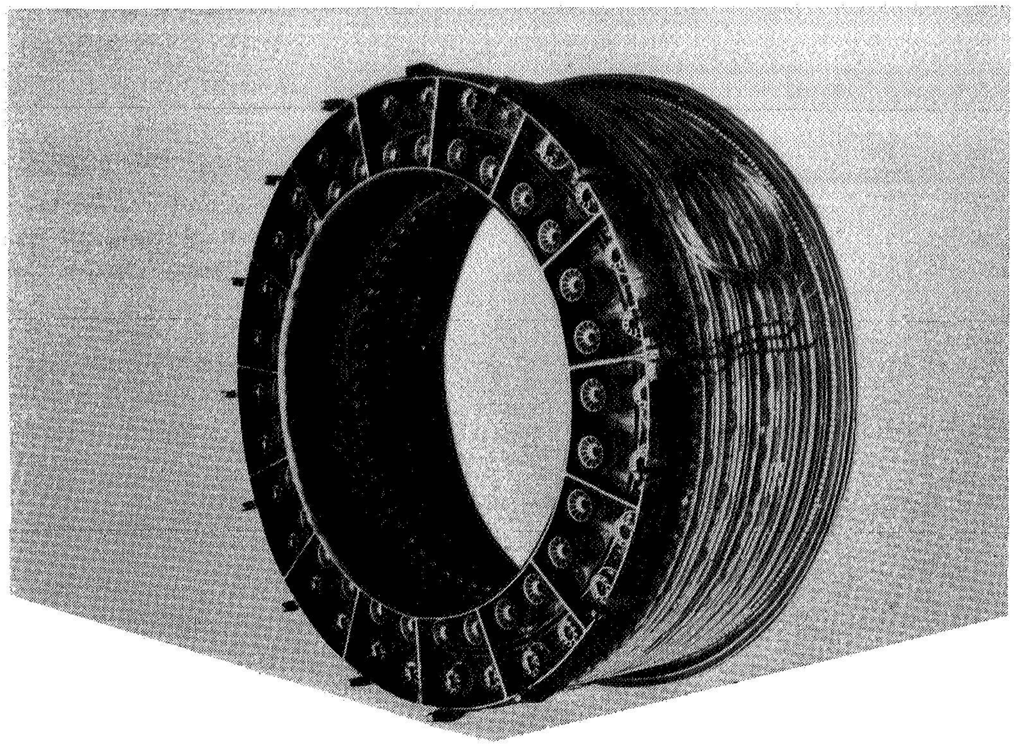

Figure 5.- Prototype double-annular combustor.

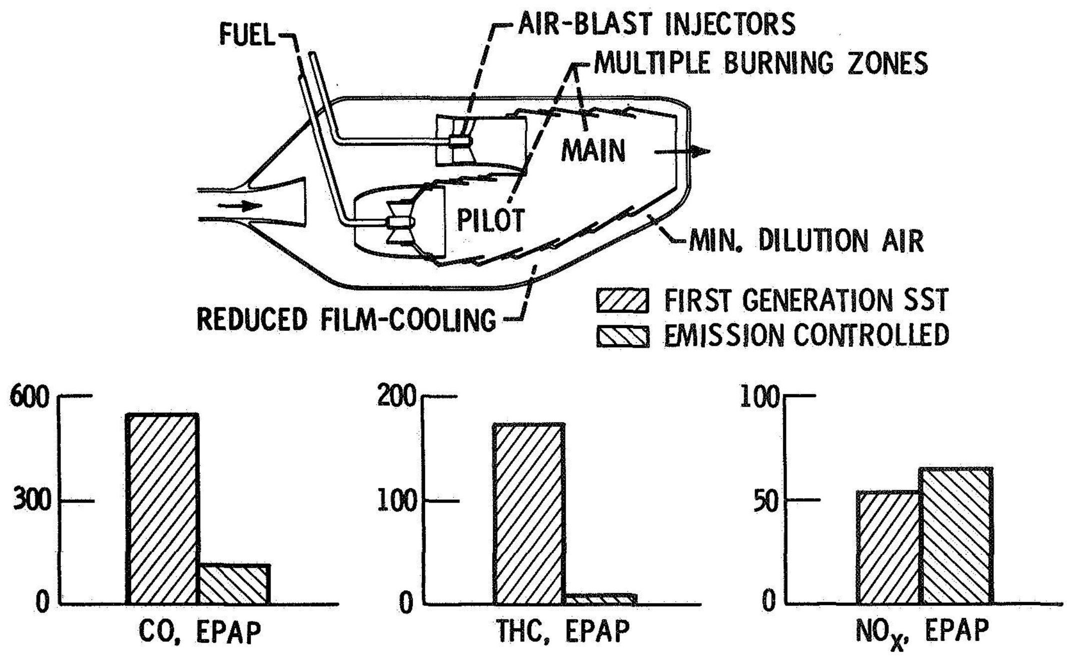

Figure 6.- Projected emission levels for advanced supersonic engine using emission-controlled combustor.

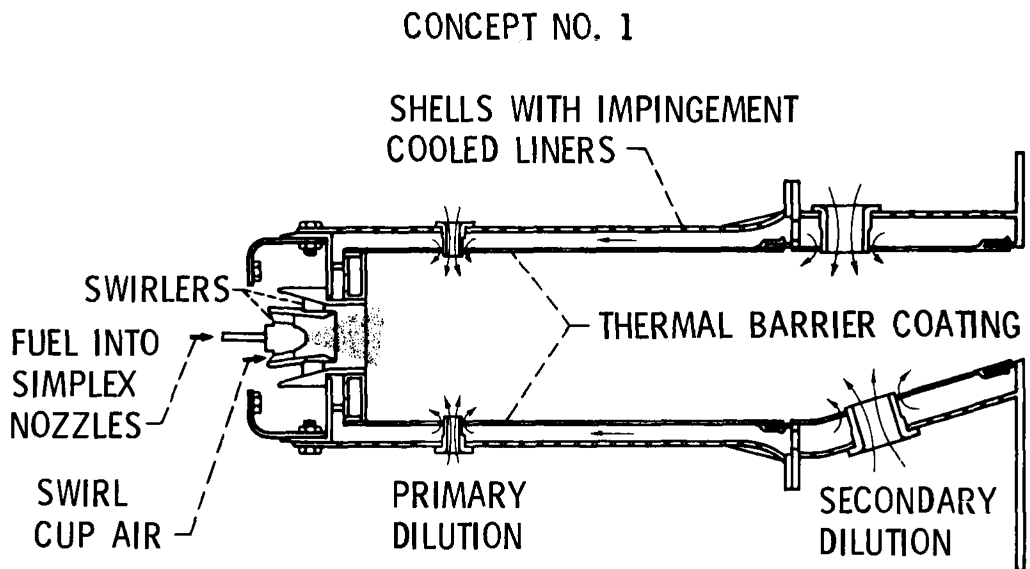

Figure 7.- Hot-wall combustor concept.

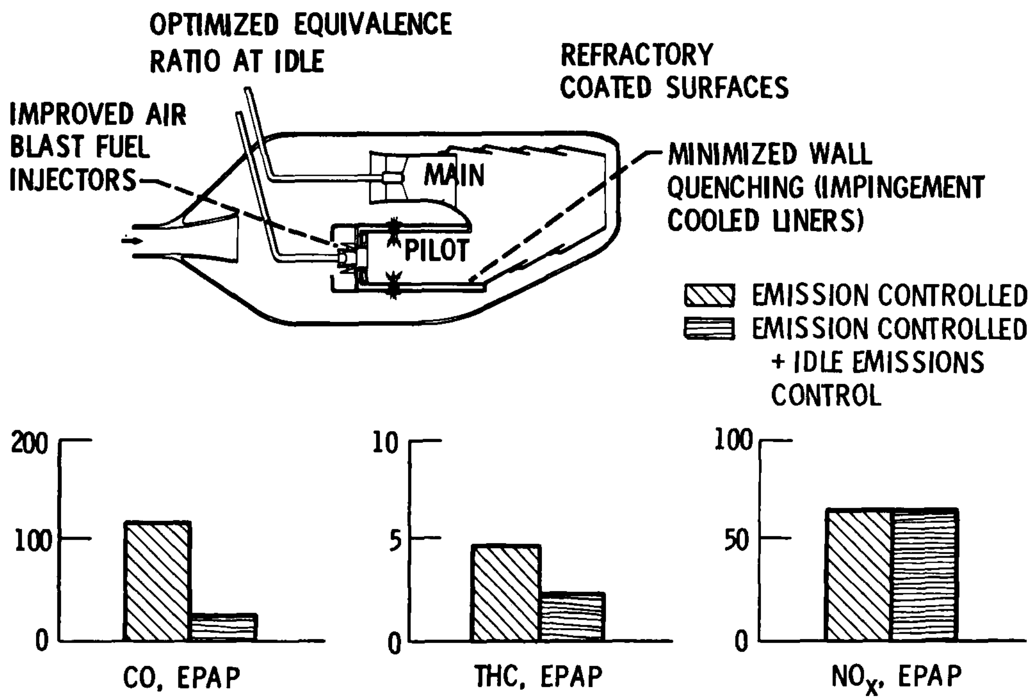

Figure 8.- Projected emission levels for advanced supersonic engine using idle-emission-controlled combustor.

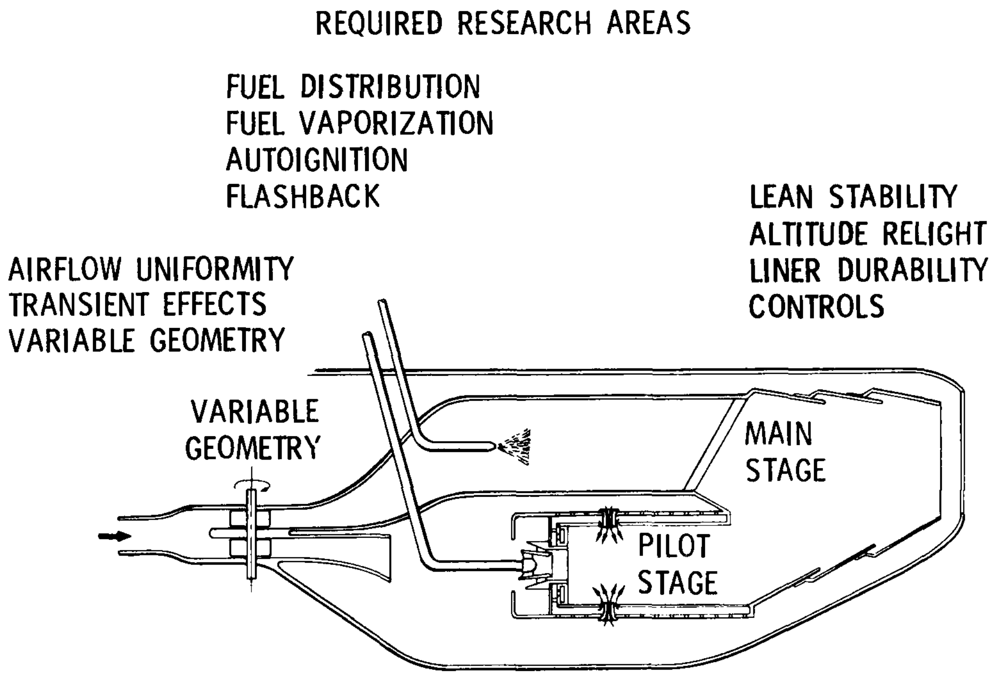

Figure 9.- Required research areas in lean, premixed-prevaporized combustor technology.

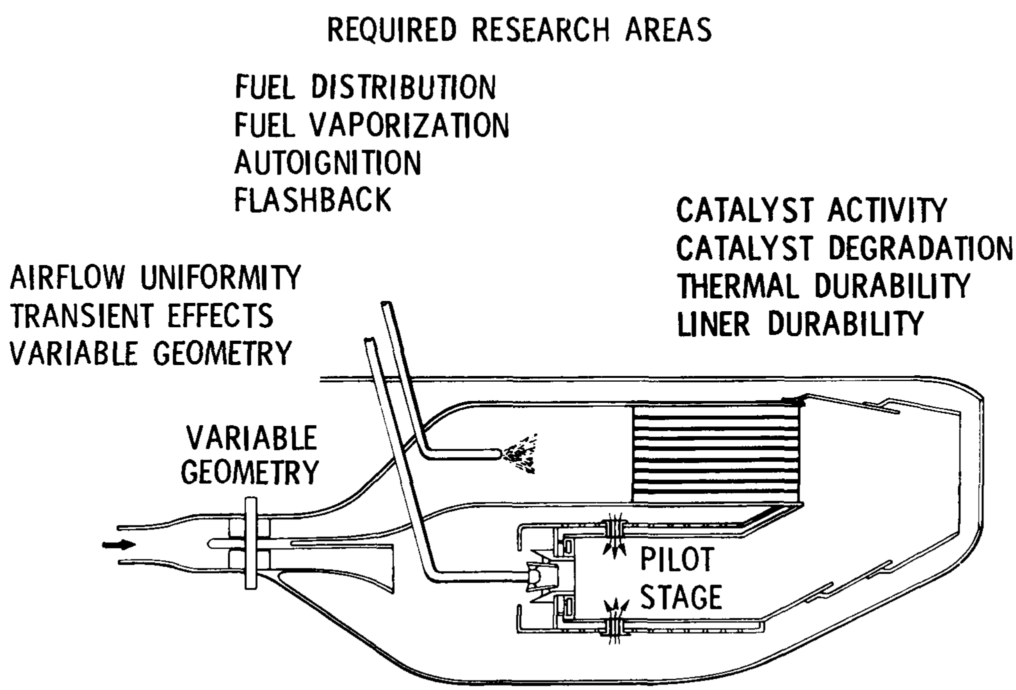

Figure 10.- Required research areas in catalytic combustor technology.

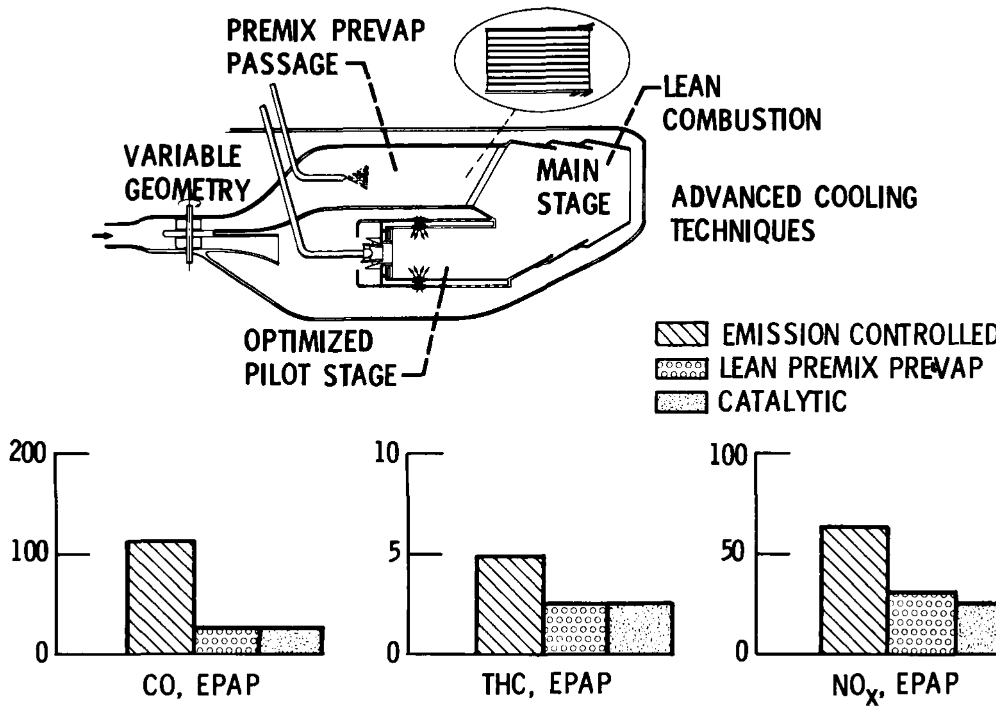

Figure 11.- Projected emission levels for advanced supersonic engine using far-term combustor technology.

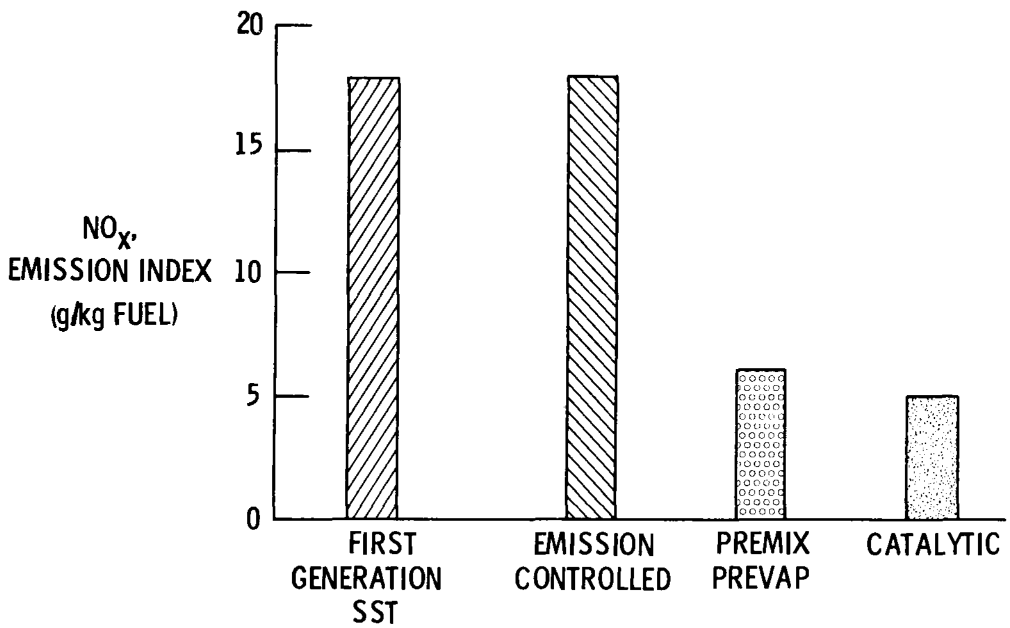

Figure 12.- Comparison of projected cruise NO_x emission levels.

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