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REDUCTION OF AIRCRAFT GAS TURBINE ENGINE POLLUTANT EMISSIONS - A STATUS REPORT

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E-9601

ABSTRACT

For the past five years, NASA has been sponsoring programs whose objectives were to develop and demonstrate new gas turbine engine combustor technology for the reduction of pollutant emissions. To accomplish simultaneous reduction of unburned hydrocarbons, carbon monoxide, and oxides of nitrogen required major modifications to the combustor. The modification most commonly used was a staged combustion technique. While these designs are more complicated than production combustors, no insurmountable operational difficulties were encountered in either high pressure rig or engine tests which could not be resolved with additional normal development. The emission reduction results indicate that reductions in unburned hydrocarbons are sufficient to satisfy both near and far-term EPA requirements. Although substantial reductions were observed, the success in achieving the CO and NO_x standards was mixed and depended heavily on the engine/engine cycle on which it was employed. Technology for near term CO reduction is satisfactory or marginally satisfactory. Considerable doubt exists if this technology will satisfy all far-term requirements. Control of NO_x emissions was at least marginally successful in a variety of applications but is probably not sufficient to satisfy the requirements of the high pressure ratio engines. Additional technology development in the area of further CO and NO_x reductions therefore appears warranted.

STAR Category 07

The Clean Air Act of 1970 empowered the Environmental Protection Agency to establish standards for the allowable emission levels of aircraft gas turbine engines. The standards were first issued in July 1973[1]. Earlier, in mid-1971, NASA began a major program in emission reduction technology, which would consist of a continuing in-house effort on low emission combustor concepts and of contracted research programs with the major aircraft engine manufacturers. This paper describes the design approaches taken by the manufacturers involved in the contracted programs, gives a comparison of the current results with the EPA standards, and briefly discusses some of the engine related factors that must be considered. In addition, some results from fundamental technology programs which indicate the emission levels that may be approached by advanced low emission combustors of the future are also discussed.

The contracted programs were begun with two firm objectives in mind. First, it was essential to investigate new combustor concepts that had the potential to significantly lower the emission levels. Considerable research with existing combustors had already shown that present concepts would not meet all of the EPA standards. The new concepts would have to be developed not only from an emissions standpoint, but also from a conventional performance goals standpoint. Second, it was necessary to measure the combustor emissions in an engine test. The engine test would show whether the combustor concept could be installed in an engine and meet the engine operating requirements while producing the desired low emissions. Engine testing was also required to achieve the needed pressure levels and to avoid extrapolation of emission levels from lower pressure tests. And finally, engine testing would reveal those areas of the combustor that needed further development.

Multiphase contracts were awarded to the engine manufacturers. These phases consisted of screening, refining, and engine testing. In the first phase, many combustor concepts would be screened to determine those having the most potential for low emissions. The best concepts would be further developed during the refinement phase, where combustor performance and emission reduction would be emphasized. Finally, the best, or most engine ready, combustor would be installed and tested in an engine.

This paper concentrates on NASA programs only. It is recognized, however, that considerable information on low emission advanced technology combustors is being generated in work sponsored by other government agencies (DOD, FAA and EPA) and the aircraft engine industry.

Program Plan

As conceived, the emission reduction technology program would develop technology for representative engines in each of the EPA engine classes. With the exception of the T4 class, which consists solely of the JT8D family of engines, competitive contracts were awarded in each class. Table I shows the EPA classes, the engines, and the manufacturers that participated in the program. The T1 class consists of engines with thrusts less than 36 kN (8000 lb). The T2 class consists of engines with thrusts greater than 36 kN (8000 lb), and the P2 class consists of turboprop engines. Engines in the remaining two EPA gas turbine engine classes, T3 and T5, were not studied as a part of this program. The T3 class consists solely of the JT3D family of engines, and the T5 class consists of engines for supersonic aircraft, at present only the Olympus engine in the Concorde SST.

The goal of these programs was to meet the 1979 EPA Aircraft Engine Emission Standards. Table II shows the 1979 standards for the three gaseous pollutants and smoke for each of the engines in the program. The EPA standards are expressed in EPA parameters values for the specified landing-takeoff cycle. The production engine values are given as a percentage of the EPA standard values. In general, the production values exceed the standards by several hundred percent. Therefore, to meet the EPA standards, combustor technology had to be developed with the potential for significantly lower emission levels. Noteworthy are a few instances where the standards were already achieved - the oxides of nitrogen (NOx) level for the P2 class and the smoke for the T2 class.

Low Emission Combustor Design Approaches

The relationship between engine operating conditions and the combustion process is illustrated in figure 1. This figure describes the causes, effects, results, and corrective actions required to control the pollutant emissions at the two extreme operating conditions, i.e., low power idle and high power takeoff. During low power idle operation, combustor inlet temperature, T_{in}, and pressure, P_{in}, and fuel-air ratio, F/A, are low causing the effects which contribute to combustion inefficiency and thus the production of CO and THC. At high power takeoff, combustor inlet temperature and pressure, and fuel-air ratio are all high which results in high combustion flame temperature, plus the other effects shown, all of which contribute to the production of NO_x. Since aircraft gas turbine engines must operate effectively at both extremes (idle and takeoff) and many conditions between them, low emission combustors that are compatible to all operating conditions must be developed. If we observe the list of corrective approaches shown in figure 1, we can recognize that a delimma exists at the two operating extremes. Those corrective approaches which can reduce CO and THC are directly the opposite of those required to reduce NOx with one exception; improved fuel distribution. The challenge then is to develop advanced combustor technology that can take advantage of a needed correction at a particular engine operating condition without adversely effecting the pollutant production at the other operating conditions.

The need to effectively control all the emissions over the entire engine operating range leads the combustor designer to the staged combustor design. One stage (pilot) is designed to control THC and CO emissions at idle and the other stage (main) is designed to control NOx emissions at high power. Versions of this approach were studied by all of the contractors.

Some of the programs (T1, T4, P_2) were structured to investigate varying degrees of combustor design complexity on emission reduction potential. For those efforts, design modifications consisting of minor modifications such as improving fuel atomization and changing fuel-air distribution to improve idle emissions performance were evaluated. These designs, of course, lacked the capability for control of all of the undesirable to emissions. The design approaches taken in each of the programs will now be reviewed.

Figure 2 illustrates two modifications to a can-annular type combustor used in the Detroit Diesel Allison 501-D22A engine. The reverse flow combustor concept represents a rather minor modification in that only the flow distribution along the liner wall was changed and a more efficient(better atomization) fuel nozzle was installed. The pre-chamber combustor represents somewhat of an increase in complexity but still has only one fuel injection zone. Both of these combustors have been evaluated in rig tests and the results from the reverse flow design will be discussed later. A modification such as the reverse flow combustor probably represents the minimum type of modification that could be employed to reduce emissions.

As noted earlier, the baseline NOx emissions of the 501-D22A were substantially below the EPA required value. This allowed the combustor designer the rare opportunity to "trade" NOx emissions for improved CO and THC performance without exceeding the EPA standards for any pollutant. Thus, for this engine minor combustor design changes proved highly successful. A more detailed discussion of the designs evaluated, in this program can be found in the contractor final report[2].

Two levels of design complexity related to modifying the combustor used in the Garrett-AiResearch TFE 731-2 engine are shown in figure 3. The modified conventional configuration, figure 3(a), utilized air-assist fuel injection and increased combustor bleed to improve fuel atomization and fuel-air distribution. As with the 501-D22A reverse flow combustor, this modification is considered minor and the emission control potential is limited. The piloted airblast injection concept, figure 3(b), was designed to have variable geometry features in the fuel injector and was more complicated than the modified conventional combustor.

A very major combustor modification consisting of a staged combustor with a lean burning premixed/prevaporized main stage was also studied[3]. Results to date have been generated in combustor rig tests. The piloted airblast design will be tested in the TFE 731 engine later this year.

Figure 4 depicts two modifications to the can-annular combustor used in the Pratt & Whitney JT8D-17 engine. Minor modifications to this design, figure 4(a), included the use of air-blast nozzles for better fuel atomization and changes to the fuel and air flow schedules to vary the burning zone stoichiometry. The second approach, figure 4)b), is an axial staged design. The pilot and main stage are arranged in series. This type of design is obviously more complicated and entails a greater development risk. This use of the staged type of combustor is necessary however, if all the undesirable engine emissions must be reduced to satisfy environmental requirements. A more complex premixed/prevaporized concept was also studied as part of this effort[4]. All concepts in this program were subjected to combustor rig testing which exactly simulated engine operating conditions.

A variety of staged combustion techniques were studied in the early phases of the T2 class engine programs [5-6]. The concepts which were used in the final program phase, engine verification testing, are shown in figures 5 and 6. Figure 5 compares the axial staged vorbix combustor developed for the Pratt & Whitney JT9D-7 engines with the engine baseline combustor. The staged combustor design developed for the General Electric CF6-50 turbofan engine shown in figure 6 represents a parallel type of staging. The function of the two stages is the same as in the vorbix. Both the double annular and the vorbix designs have undergone testing in their respective engines. The results from these tests will be discussed in the subsequent section.

Results and Discussion

Emission Reduction

The results of the test programs conducted with the 501-DD2A reverse flow concept, the TFE 731-2 piloted airblast, the JT8D-17 vorbix concept, the JT9D-7 vorbix concept, and the CF6-50 double annular concept are summarized in Table III. The 501-D22A reverse flow concept was able to meet all of the EPA emission standards with ample margin. As noted earlier, the ability of this concept to achieve these low levels with only a minor combustor modification being required was due to the low initial level of the baseline combustor NOx emissions relative to the EPA standards. The results shown for the TFE-731-2 piloted airblast concept are based on rig tests extrapolated to the correct engine operating conditions. Unburned hydrocarbons are well below the standard value while CO and NOx are approximately at the limit specified by the standards. Better definition of the CO and NOx values plus a determination of the smoke level awaits the engine test. The JT8D-17 vorbix concept was successful at meeting only the unburned hydrocarbon standard. A major factor in the inability of this concept to meet the standards is due to the high specific fuel consumption (sfc) of the JT8D engine. This influence of sfc will be discussed in more detail later. The vorbix concept tested in the JT9D-7 engine successfully met all of the gaseous emission standards, however, smoke levels exceeded the EPA standard value. The high smoke level appears to be a result of fuel-rich zones at the main combustor stage inlet. It is felt that smoke levels can be reduced to acceptable levels without major compromise in other emissions. Analysis of the data from the double annular combustor tested in the CF6-50 engine is not complete. Therefore, the data in the table shows a range of values from rig test data on the low end to engine data on the high end. Preliminary analysis of the engine-test data yields values for CO, hydrocarbons, and NOx of 147, 38, and 187 percent of the standard value. The smoke level is also considerably above the EPA standard value. These results had not been anticipated. As can be seen, rig test for CO and hydrocarbons were below the EPA standard values. The combustor tested in the engine had been substantially altered from the version tested in the previous phase. Most of the modifications involved "upgrading" the combustor to an "engine ready" status. Additional rig testing, conducted in an attempt to restore the lost emissions performance, was only partially successful. However, the results of the earlier phase of the program encourage our belief that engine emission levels of CO, unburned hydrocarbons, and smoke can be reduced to the EPA standard values.

The results presented have been compared with the 1979 EPA standards. More stringent gaseous emissions standards will apply to newly certified aircraft gas turbine engines in 1981. Table IV shows the levels achieved in terms of the 1981 standards for the advanced technology combustors tested in the JT9D-7 and CF6-50 engines. Such a comparison does not accurately represent the real needs of engines which will be certified after 1981. It is the EPA intent that a newly certified engine be designed from the beginning with emissions control in mind and that design aspects such as pressure ratio, by-pass ratio, allowable combustor volumes, and pressure drop and their influence on engine emission levels be considered. This was not the case with the engines cited. The comparison does indicate what additional emission reduction technology development is required. Although emission control of unburned hydrocarbons appears well in hand, the same cannot be said of carbon monoxide. While further development of present technology may bring more CO reductions, it is not clear if it will be sufficient to satisfy all requirements. It is clear that new technologies will be necessary if high-pressure-ratio engines are to achieve the required NOx levels.

As mentioned above, at least a partial solution to reducing aircraft emissions for engines of the future is by engine design features, particularly those which tend to improve the engine sfc. Significant improvements in higher power sfc are being pursued in the NASA sponsored Aircraft Efficient Engine Program. This influence of sfc is revealed by an analysis of the EPA parameter which is a summation of the product of sfc and emission index over the specified LTO cycle. An earlier discussion had indicated that sfc played a significant role in the JT8D-17 vorbix concept being unable to meet CO and NOx emission standards while the similar JT9D-7 vorbix did demonstrate compliance. For example, if we assume CO emission index values of 20 at idle, 5 at approach, 0.5 at climbout, and 0.4 at takeoff, which are typical values achieved with Vorbix combustors in both the T4 and T2 programs, the EPAP for the JT9D-7 is 3.9, but that for the JT8D-17 is 7.5. The JT8D-17 level is nearly twice as high as the JT9D-7 level. This means that the JT8D-17, a much older engine, must produce one-half the pollutant level (in terms of the combustor emission index) in order to achieve the same EPA parameter value as the JT9D engine. Similar considerations apply to both unburned hydrocarbons and oxides of nitrogen.

Engine Related Factors

In order to properly assess the applicability of the various low emission combustor concepts to in-service aircraft engines, one must certainly consider the impact on the overall engine operating characteristics. Other factors such as maintainability and safety must also be considered. Evaluation of these factors must be undertaken to properly assess whether or not trade-offs between emissions, performance and operational characteristics are required. Some of the factors of concern, but certainly not all, will be discussed in this section.

One important factor that must be considered in assessing the applicability of converting the low emissions concepts into production type engine combustors is the impact of the increased complexity that some of these concepts have brought forth compared to the baseline combustors currently in use. No significant problems would be expected in applying the reverse flow concept to the 501-D22A engine since minor or no changes in the engine fuel system and fuel control functions should be necessary. Applying the piloted-airblast type concept to the TFE-731-2 engine would require some changes to the engine/combustor structure but would not be expected to significantly effect the engine fuel system or control. The level of emission control produced by these concepts, Table III, should therefore, be possible to achieve with the minimum possible impact on the design of other engine components.

The staged concepts, such as the double annular and vorbix, will certainly increase the complexity of both the engine fuel system and the required control functions. For example, the number of fuel injectors needed to adapt the staged double annular concept to the CF6-50 engine would be twice the number currently used on the baseline combustor. The same order of increase is required to adapt the vorbix concept. In addition, the staged concepts will require an additional fuel manifold and the fuel flow to the two manifolds must be controlled independently and accurately. Studies conducted by both GE and P&WA have shown that this increase in complexity is of concern and will probably require continued development. Although the fuel manifolds and control employed were satisfactory for these tests, they would not be acceptable for a flight engine.

Many operational factors such as meeting engine starting requirements, acceleration and deceleration requirements, and combustor staging were evaluated in the engine tests. Engine starting of the JT9D required higher than recommended fuel flow rates. Engine acceleration times were acceptable, but slower than production JT9D values. Both problems require additional development in the way of improved pilot nozzle spray characteresitics at engine starting fuel flows and improved fuel manifolding techniques. Similar problems were not encountered with the double annular combustor in the CF6-50 engine. Smooth transitions were observed during staging with both designs. The vorbix combustor did exhibit main-zone fuel injector coking. This resulted from overheating of residual fuel following the shutdown of the main stage. Additional development will be required to solve this problem. Other factors such as exit temperature distribution, liner coke deposits and liner overheating were either already satisfactory or comparable to conventional combustors at this stage of their development.

The additional hardware required to apply staged concepts to engines may impact maintenance requirements. The increased number of fuel injectors and fuel manifolds needed for the staged designs adds to the potential problems and thus may increase required maintenance.

Future Efforts

The discussions given above have indicated areas where additional technology development to reduce CO and NOx emissions to even lower levels may be required. A significant factor in future low emissions combustors also involves aircraft gas turbine fuels. In order to increase availability and decrease cost, fuels of the future may differ significantly in specifications from those currently employed. The general deterioration in quality of presently obtainable crude oils as well as the potential necessity of obtaining fuels from alternate sources such as tar sands, shale oil, and coal may also impact specifications. The full impact of these changes has not yet been evaluated. It is clear however, that the decrease in the hydrogen content of future fuels will tend to offset the gains made in the recent smokeless combustion designs. Change in fuel volatility coupled with the lower hydrogen content will tend to increase idle emissions of CO and THC. Thus emission reduction technology that is now only marginally acceptable may not be acceptable in the future. Several recent fundamental technology programs have indicated approaches that have potential to further reduce emission levels by as much as an order of magnitude. Some of these approaches are briefly described below.

Programs are being conducted to explore further optimization of pilot stages and primary zones that will minimize CO and THC emissions at idle. An example of this work is the Low Power Emission Reduction (LOPER) program being conducted by General Electric under NASA sponsorship. In this effort, several combustor concepts are being screened in a 60° sector rig at idle operating conditions. Figure 7 compares the CO emissions obtained with a "hot-wall" concept to the levels obtained with the vorbix and double annular as well as the conventional JT9D and CF6 combustors. The essential features of the "hot-wall" design include the elimination of liner film cooling air, thermal barrier coating of the combustor liner, and impingement liner cooling which is later injected with the secondary dilution air. Carbon monoxide emission levels below 2 gm/kg fuel have been achieved with this concept. This is approximately an order of magnitude lower than the levels achieved with the low emissions double annular and vorbix combustors. While initial results from this effort are most encouraging, the integration of this concept into a combustor design capable of operation over the entire engine operating regime requires considerable additional effort.

Techniques to further reduce the oxides of nitrogen emissions are by their nature more complicated. One promising technique currently being investigated by NASA is the fully premixed/prevaporized lean burning combustor concept. The potential of this technique has been demonstrated in many flame tube studies. An example of results obtained at NASA and the General Applied Physics Laboratory (GASL) are shown in figure 9. NOx emission indices below 1 g NO_2/kg fuel were achieved in both experiments. The NO_x emission levels were more than an order of magnitude lower than those achieved with conventional combustion approaches and were very close to theoretically achievable values. At combustion efficiencies that would be acceptable (99.5 percent), NOx emission levels as low as 0.5 g NO_2/Kg fuel were achieved. Please note that these levels were achieved under very carefully controlled conditions and should not be considered to be quantitatively representative of what may be achieved in an actual engine environment. NASA is currently conducting a program to evaluate and evolve advanced combustor concepts employing the fully premixed/prevaporized lean burning technique. The objectives, goals, and approach of this program called the Stratospheric Cruise Emission Reduction Program (SCERP) are presented in Table V. The program will be conducted in four phases each successively building upon the knowledge gained in the previous phase. The culmination of the program is expected to be a full-scale engine demonstration of a lean burning (likely a completely prevaporized-premixed combustion technique) variable geometry experimental combustor sometime in the early to mid 1980's.

Perhaps the ultimate in low emissions combustion technology will be obtained by the use of catalytic combustion. When operating properly, this technique has the potential to consume all of the fuel (no CO or THC emissions) while operating at a combustion temperature around 1400 K (negligible NOx emissions). This type of performance has been verified in flame tube type facilities [7-8]. NASA is also conducting Program efforts to evolve and evaluate advanced combustor concepts which utilize catalytic combustion. Problems associated with this technique are formidable. In general, all of the problems associated with lean premixed/prevaporized combustion also apply to this technique as well as several additional constraints/development problems associated with catalyst material. The fuel preparation and distribution is critical; cold starts and catalyst preheat must be solved; narrow limits of operation due to critical catalyst temperature requirements mean that variable inlet and outlet flow geometry is needed; poisoning and catalyst life problems must be solved and problems of substrate durability limit the maximum level of exit temperature. In spite of the many problems associated with the catalytic combustor, it is the concept with the greatest potential for emissions reduction.

Concluding Remarks

The emission reduction programs discussed in this report represent NASA's most recent efforts to reduce emissions for near term applications. Continuing work is addressed to the development of emission reduction concepts that will be required to meet far-term needs. In particular, additional research is needed to further reduce emissions of carbon monoxide and oxides of nitrogen. Fundamental technology programs now underway have indicated that further reductions in CO and NOx by as much as an order of magnitude may be possible. The extent to which this fundamental technology can be converted to practical engine hardware is yet unknown and will require several more years of research by NASA and the engine manufacturers.

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TABLE I. - EMISSIONS REDUCTION TECHNOLOGY PROGRAMS

EPA ENGINE CLASS	ENGINE	MANUFACTURER
T1 - TURBOFAN	TFE-731-2	GARRETT AIRESEARCH
T2 - TURBOFAN	CF6-50 JT9D-7	GENERAL ELECTRIC PRATT & WHITNEY
T4 - JT8D ENGINES	JT8D-17	PRATT & WHITNEY
P2 - TURBOPROP	501-D22A	DETROIT DIESEL ALLISON

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TABLE II. - EMISSIONS GOALS 1979 EPA STANDARDS

ENGINE CLASS	ENGINE	THC		CO		NO_x		SMOKE	
		STD	PROD	STD	PROD	STD	PROD	STD	PROD
P2	501-D22A	4.9	306	26.8	118	12.9	48	29	189
T1	TFE-731	1.6	331	9.4	180	3.7	162	40	118
T4	JT8D-17	.8	500	4.3	356	3.0	260	25	120
T2	JT9D-7	.8	488	4.3	198	3.0	197	20	50
T2	CF6-50	.8	538	4.3	251	3.0	257	19	68

PRODUCTION VALUES AS % OF EPA STANDARD.

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TABLE III. - POLLUTION SUMMARY ALL ENGINE CLASSES

EPA CLASS	ENGINE	ENGINE PR	MODIFICATION REQ'D	% OF 1979 EPA STD			
				THC	CO	NO_x	SMOKE
P-2	501-D22A	9.7	MINOR	6	17	57	59
T-1	TFE731-2	13	MAJOR	25	107	100	---
T-4	JT8D-17	17	MAJOR	25	207	146	108
T-2	JT9D-7	22	MAJOR	25	74	90	150
T-2	CF6-50	30	MAJOR	38	77-147	147-187	132

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TABLE IV. - POLLUTION SUMMARY T2 ENGINE CLASS

ENGINE	% OF 1981 EPA STD		
	THC	CO	NO_x
JT9D-7	50	106	90
CF6-50	76	110-211	147-187

CS-78-271

TABLE V. - STRATOSPHERIC CRUISE EMISSION REDUCTION PROGRAM

OBJECTIVE ESTABLISH AND DEMONSTRATE THE TECHNOLOGY TO REDUCE ENGINE EMISSIONS TO ENVIRONMENTALLY ACCEPTABLE LEVELS OVER THE ENTIRE AIRCRAFT OPERATING RANGE WITH MINIMUM ADVERSE EFFECTS ON PERFORMANCE, WEIGHT, AND COMPLEXITY	
GOALS	• ACHIEVE MINIMUM OF 6- TO 10- FOLD REDUCTION IN SUBSONIC CRUISE NO_x EMISSIONS FROM CURRENT LEVELS • MEET OR EXCEED ESTABLISHED EPA STANDARDS FOR THE LTO CYCLE
APPROACH	• UTILIZE I-H, CONTRACT AND UNIV. GRANT CAPABILITIES • MULTI-PHASE ACTIVITY PHASE I - FUNDAMENTAL STUDIES PHASE II - CONCEPT SCREENING PHASE III - EXPERIMENTAL COMBUSTOR DEVELOPMENT PHASE IV - ENGINE DEMONSTRATION

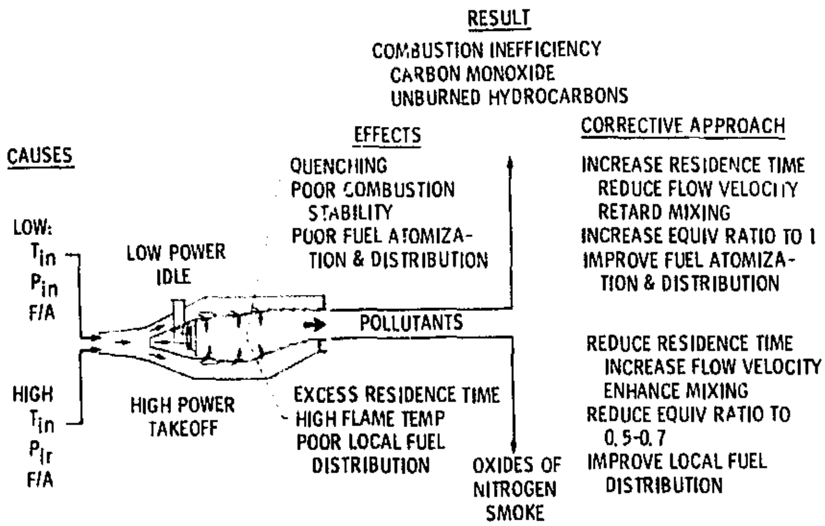

Figure 1. - Aircraft gas turbine combustor pollution considerations.

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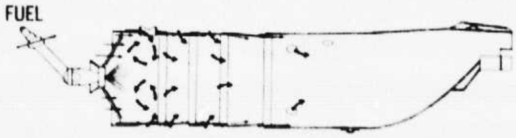
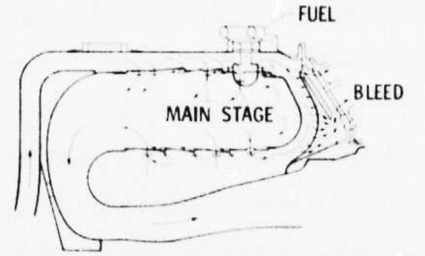


(a) ENGINE CONVENTIONAL (BASELINE) COMBUSTOR.

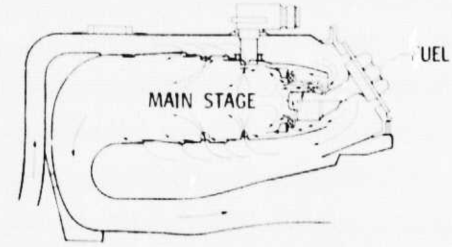
(b) REVERSE FLOW COMBUSTOR CONCEPT.

(c) PRECHAMBER COMBUSTOR CONCEPT.

Figure 2. - Cross-sectional illustration of two low emission combustor concepts for the Detroit Diesel Allison 501-D22 turboprop engine. EPA Class P2.

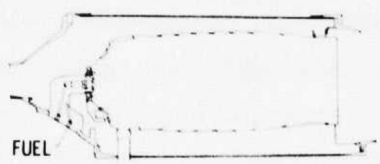


(a) MODIFICATIONS TO BASELINE COMBUSTOR.

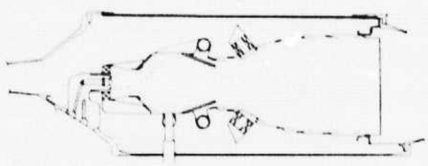


(b) PILOTED AIRBLAST INJECTION COMBUSTOR CONCEPT.

Figure 3. - Cross-sectional illustration of emission reduction modifications for the AiResearch TFE731-2 turbofan engine combustor. EPA Class T1.



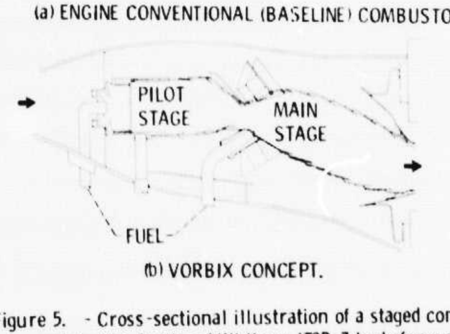
(a) ENGINE CONVENTIONAL (BASELINE) COMBUSTOR.



(b) VORBIX CONCEPT.

Figure 4. - Cross-sectional illustration of a staged combustor concept for the Pratt and Whitney JT8D-17 turbofan engine. EPA class T4.

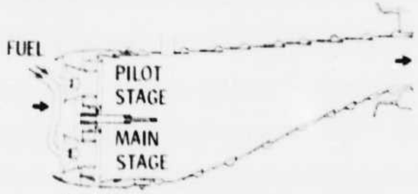
(a) ENGINE CONVENTIONAL (BASELINE) COMBUSTOR.



(b) VORBIX CONCEPT.

Figure 5. - Cross-sectional illustration of a staged combustor concept for the Pratt and Whitney JT9D-7 turbofan engine. EPA Class T2.

(a) ENGINE CONVENTIONAL (BASELINE) COMBUSTOR.



(b) DOUBLE ANNULAR CONCEPT.

Figure 6. - Cross-sectional illustration of a staged combustor concept for the General Electric CF6-50 turbofan engine. EPA Class T2.

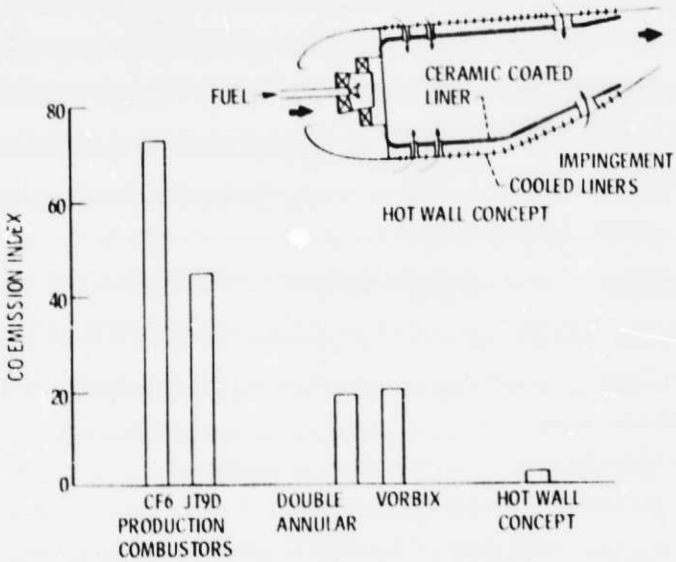


Figure 7. - Comparison of idle CO emissions for several levels of combustor technology.

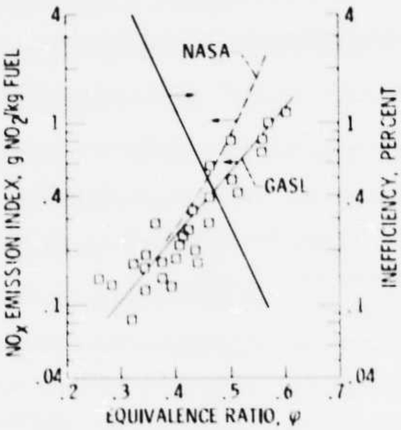


Figure 8. - Effect of equivalence ratio on NO_x in a prevaporized-premixed combustion scheme. Jet A fuel; residence time, 2 milliseconds; inlet temperature, 830 K; inlet pressure, 40 N/cm^2.