GAS TURBINE ENGINE EMISSION REDUCTION TECHNOLOGY PROGRAM

Donald A. Petrash and Larry A. Diehl

Lewis Research Center

SUMMARY

The Clean Air Act of 1970 empowered the Environmental Protection Agency to establish standards for the allowable pollutant emission levels of aircraft gas turbine engines. The standards, first issued in July 1973, established allowable levels for three gaseous pollutants and smoke. The gaseous pollutants were hydrocarbons, carbon monoxide, and the oxides of nitrogen. These emission standards were sufficiently stringent that combustor technology existing at the time was not sufficient to permit the design of the advanced combustors that would be needed to meet the standards. NASA therefore began a major program in emission reduction technology. The program consisted of in-house experimental research on low-emission advanced combustor concepts and a contracted research program with the major aircraft engine manufacturers. The purpose of this presentation is to review the results of the contracted research program with emphasis on the high-bypass-ratio turbofan engines which power the large commercial aircraft.

INTRODUCTION

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. 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 gives an overview of the contracted emission reduction technology programs, which were begun with two firm objectives.

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.

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 parameter 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 (NO_x) level for the P2 class and the smoke for the T2 class.

CHARACTERISTICS OF ENGINE EMISSIONS

Emission characteristics common to all engine classes are shown in figure 1. This figure is a plot of typical production engine emissions as a function of takeoff thrust level. The landing-takeoff cycle points are identified on the abscissa with their associated thrust levels. The ordinate values were obtained by summing the species emission index values over the landing-takeoff cycle and are shown as the percentage contribution at each cycle point. Emissions from all engine classes conform very well to this trend.

Virtually all hydrocarbon and carbon monoxide (CO) emissions are generated at low power, primarily at engine idle. These emissions are significantly reduced at approach power levels and virtually disappear at high power levels. Typical production aircraft engines have combustion inefficiencies at idle of 4 to 12 percent. This accounts for the high hydrocarbon and CO emissions at idle. To reduce these emissions, combustor research must be directed toward increasing combustion efficient at idle. In practice, relatively large reductions in hydrocarbon and CO emissions have been achieved with relatively minor combustor modifications.

Oxides of nitrogen emissions, on the other hand, are at a minimum at engine idle and increase as engine power increases. To reduce NO_x emissions, combustor research must be directed toward the high power operating conditions. In general, NO_x reduction requires the lowering of the flame temperature and reduction of the residence time of gases at high temperatures. In practice, significant reduction in NO_x emissions require relatively major combustor modifications which are difficult to implement.

EARLY EMISSIONS REDUCTION RESEARCH

Before the contracted emission reduction technology program had even been planned, advanced combustor research at Lewis had identified several approaches to obtain low emissions. The research had indicated two promosing multiple-burning-zone combustors - specifically, the double-annular and swirl-can modular combustors. Both air-assist and air-blast fuel-injection techniques were studied to evaluate their potential for reducing emissions. Controlled combustion was also studied by varying the fuel and air schedules to the advanced combustors.

Some of the results obtained in 1972 tests are shown in figure 2, which shows the NO_x emissions for conventional combustors and the two advanced combustor concepts tested at Lewis. Note that the NO_x emissions are a strong function of combustor inlet-air temperature. This is because the inlet-air temperature is directly related to the combustion flame temperature and NO_x formation. This figure also indicates that NO_x control will be more difficult with high-pressure-ratio engines since an increase in engine compressor pressure ratio results in an associated increase in combustor inlet-air temperature. The advanced combustors did demonstrate significant reductions, and these results showed that substantial NO_x emission reductions were possible.

Improvements in fuel atomization may have a dramatic effect on pollutant emission levels. During engine idle, the fuel is sprayed from the duplex nozzle through the small-flow primary nozzle. This results in a spray that is generally coarse, consisting of large, sometimes poorly distributed drops. This combination of large drops and poor distribution results in high levels of hydrocarbon and CO emissions. An air-assist nozzle uses a small amount of air bled from the engine compressor and injects it through the unused secondary fuel nozzle. This air-assist reduces droplet size, improves the uniformity of the spray, and thereby reduces engine idle emissions. Typical results obtained from the application of this technique are shown in figure 3. The tests were conducted on a JT8D combustor and a production fuel nozzle. Emissions of hydrocarbons and CO are given on the ordinate and the injected air differential pressure on the abscissa. The use of air-assist considerably lowers the emissions: hydrocarbons were decreased by a factor of 8 and CO by nearly a factor of 4. The amount of air injected was quite small, being less than 0.5 percent of the combustor airflow at the maximum differential pressure.

RESULTS AND DISCUSSION

Because of the time required for a detailed discussion of all the programs and because of the thrust of the present conference, the T2 class engine will be emphasized in this discussion of the emission reduction technology program. The two engines studied in this part of the program were the Pratt & Whitney JT9D-7 and the General Electric CF6-50, both high-bypass-ratio turbofan engines which power current large aircraft.

The Pratt & Whitney JT9D-7 (fig. 4) engine has a maximum thrust of 205 kN (46 150 lb), a pressure ratio of 22:1, and an annular combustor. The production engine emission values (also shown in the figure) indicate that all emissions with the exception of smoke require large reductions. Figure 5 shows the production JT9D-7 combustor and the advanced low-emissions combustor that was used in the engine tests. The advanced-technology, Vorbix combustor is an axially staged design. The pilot zone has been optimized to reduce hydrocarbon and CO emissions at engine idle. And the main zone was optimized to reduce high-power NO_x emissions. In all, the pollution reduction concepts used to design the Vorbix combustor included multiple burning zones, air-blast fuel injectors, enhanced mixing, and fuel staging. Clearly, this combustor modification is more than minor and will require further development before it can be put into service.

The data obtained from the full-scale engine test of the Vorbix combustor are shown in figure 6. The CO, hydrocarbons, and NO_x emissions were 74, 25, and 90 percent of the EPA standard values, respectively; smoke levels exceeded the EPA standard value. The high smoke level appears to be result of fuel-rich zones at the main combustor inlet. It is felt that smoke levels can be reduced to acceptable levels.

The General Electric CF6-50 (fig. 7) engine has a maximum thrust of 224 kN (50 000 lb), a pressure ratio of 30:1, and an annular combustor. The production-engine emission levels shown in the figure also indicate that large reductions in all gaseous emissions are required to meet the emission standards. Figure 8 shows the production CF6-50 combustor and the advanced low-pollutant combustor used in the engine tests. This advanced-technology, double-annular combustor is a radially staged design. Again, the pilot stage was optimized to reduce hydrocarbon and CO emissions at engine idle, and the main zone was optimized to reduce the high-power NO_x emissions. As with the Vorbix, the double-annular combustor used the low-pollutant concepts of multizone burning, air-blast fuel injectors, enhanced mixing, and fuel staging.

The data that were obtained from the full-scale engine test of the double-annular combustor are shown in figure 9. Also shown are the best values obtained during the combustor refinement phase of the program conducted in the combustion test facility. Preliminary analysis of the engine-test data yields values for CO, hydrocarbons, and NO_x of 147, 38, and 187 percent of the standard value. The smoke level is also considerably above the EPA standard value. These disappointing results had not been anticipated. As can be seen, rig test values 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 acceptable levels.

Table III is a summary of all the emission results obtained in the program, with the engines ordered by increasing engine pressure-ratio. The unburned hydrocarbon standards were achieved for all engines. Carbon monoxide standards were essentially achieved for all but the JT8D and the CF6-50. The difficulty of achieving the NO_x standard increased directly with increasing engine pressure-ratio. The 501-D22A engine, with a 9.7:1 pressure ratio, easily met the NO_x standard with only a minor combustor modification. The TFE-731 engine, with a 13:1 pressure-ratio, barely met the NO_x standard and required a relatively major combustor modification. The JT8D, which has a 17:1 engine pressure-ratio, did not achieve the standard, in large part because of the high specific fuel consumption of the engine. For the T2 class engines, major modifications to the combustor of the JT9D, with an engine pressure-ratio of 22:1, did result in achievement of the NO_x standard, but the CF6-50 with an engine pressure ratio of 30:1 did not meet the standards.

The results presented have been compared with the 1970 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 JY9D-7 and CF6-50 engines. Although such a comparison is not completely valid, it is the EPA's intent that a newly certified engine be designed from the beginning with emissions control in mind and that design aspects such as pressure ratio, bypass ratio, allowable combustor volumes, and pressure drop and their influence on engine emission levels be considered. Such was not the case with the engines cited. The comparison does indicate where 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 technology may be necessary if high-pressure-ratio engines are to achieve the required NO_x levels.

CONCLUDING REMARKS

The emission reduction technology program discussed in this report represents 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 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.

TABLE I. - SCOPE OF EMISSIONS REDUCTION TECHNOLOGY PROGRAM

EPA engine class	Engine	Manufacturer
T1 - turbofans	TFE-731-2	Garrett AiResearch
T2 - turbofans	CF6-50 JT9D-7	General Electric Pratt & Whitney
T4 - JT8D engines	JT8D-17	Pratt & Whitney
P2 - turboprops	501-D22A	Detroit Diesel Allison

TABLE II. - EMISSION GOALS FOR 1979 EPA STANDARDS

Engine class	Engine	THC		CO		NO_x		Smoke	
		Standard	Production value, % of standard	Standard	Production value, % of standard	Standard	Production value, % of standard	Standard	Production value, % of standard
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

TABLE III. - POLLUTION SUMMARY FOR ALL ENGINE CLASSES

EPA class	Engine	Engine pressure ratio	Modification required	THC	CO	NO_x	Smoke
				Percent of 1979 EPA standard			
P2	501-D22A	9.7	Minor	6	17	57	59
T1	TFE-731-2	13	Major	25	107	100	---
T4	JT8D-17	17	↓	25	207	146	108
T2	JT9D-7	22	↓	25	74	90	150
T2	CF6-50	30	↓	38	77-147	147-187	132

TABLE IV. - POLLUTION SUMMARY FOR

T2 CLASS ENGINES

Engine	THC	CO	NO_x
	Percent of 1981 EPA standard		
JT9D-7	50	106	90
CF6-50	76	110-211	147-187

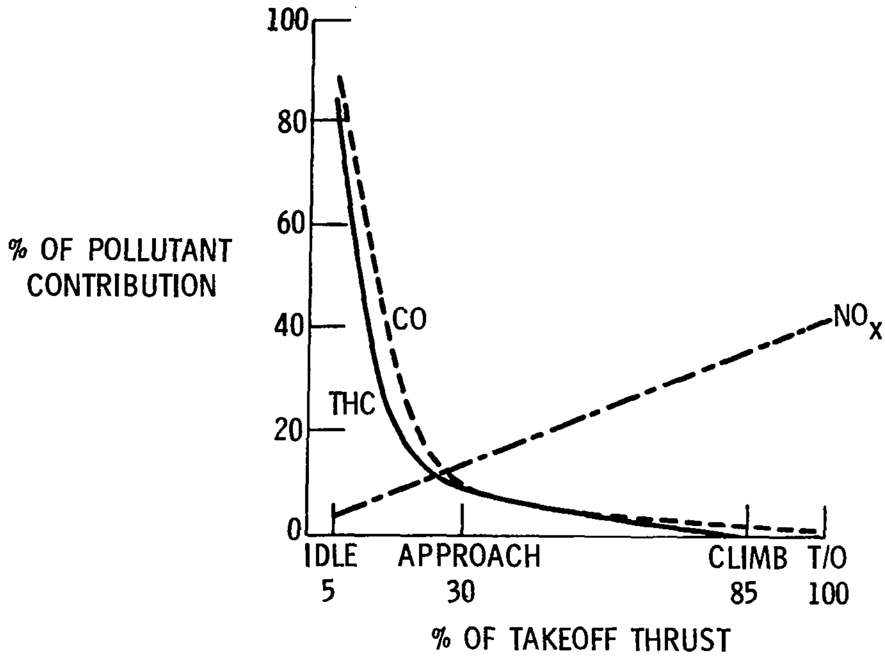


Figure 1.- Typical engine emission characteristics.

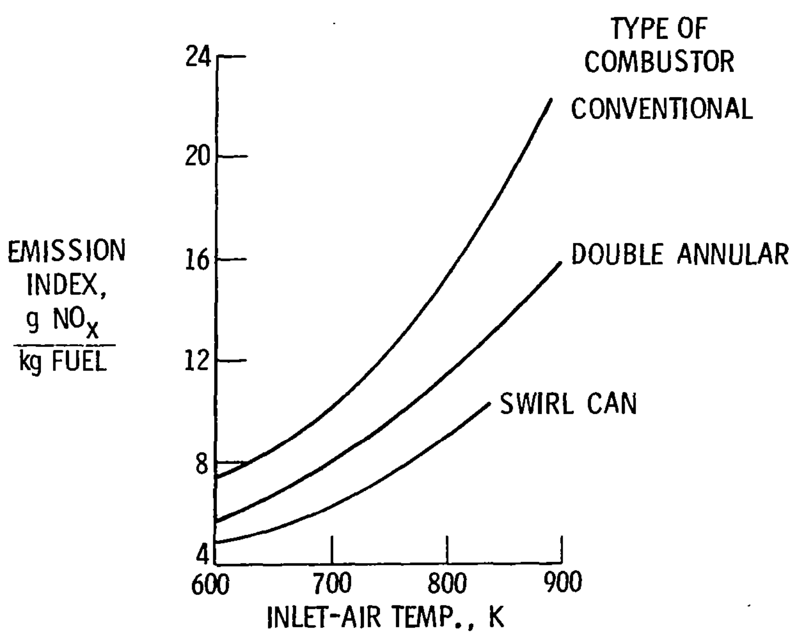


Figure 2.- Oxides of nitrogen emissions as function of combustor-inlet temperature. Combustor pressure, 6 atm.

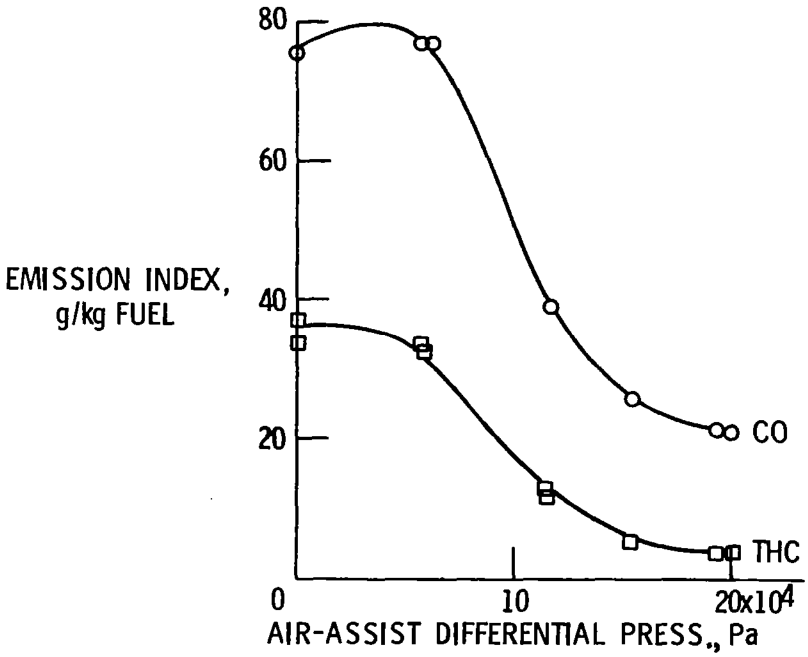
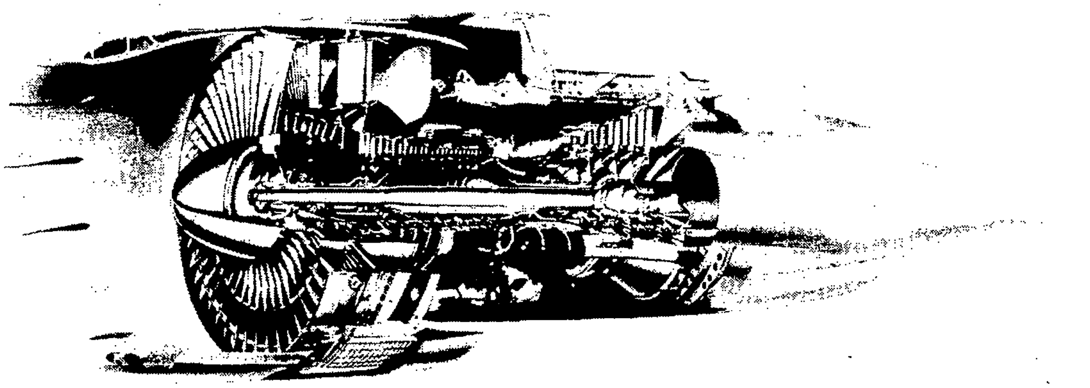


Figure 3.- Effect of improving fuel atomization on gaseous emissions.



PRODUCTION ENGINE EMISSIONS,
% OF 1979 EPA STD.:

CO	THC	NO_X	SMOKE
198	488	197	56

Figure 4.- EPA class T2 jet aircraft engine JT9D-7. Thrust, 205 kN; pressure, 22:1; type of combustor, annular.

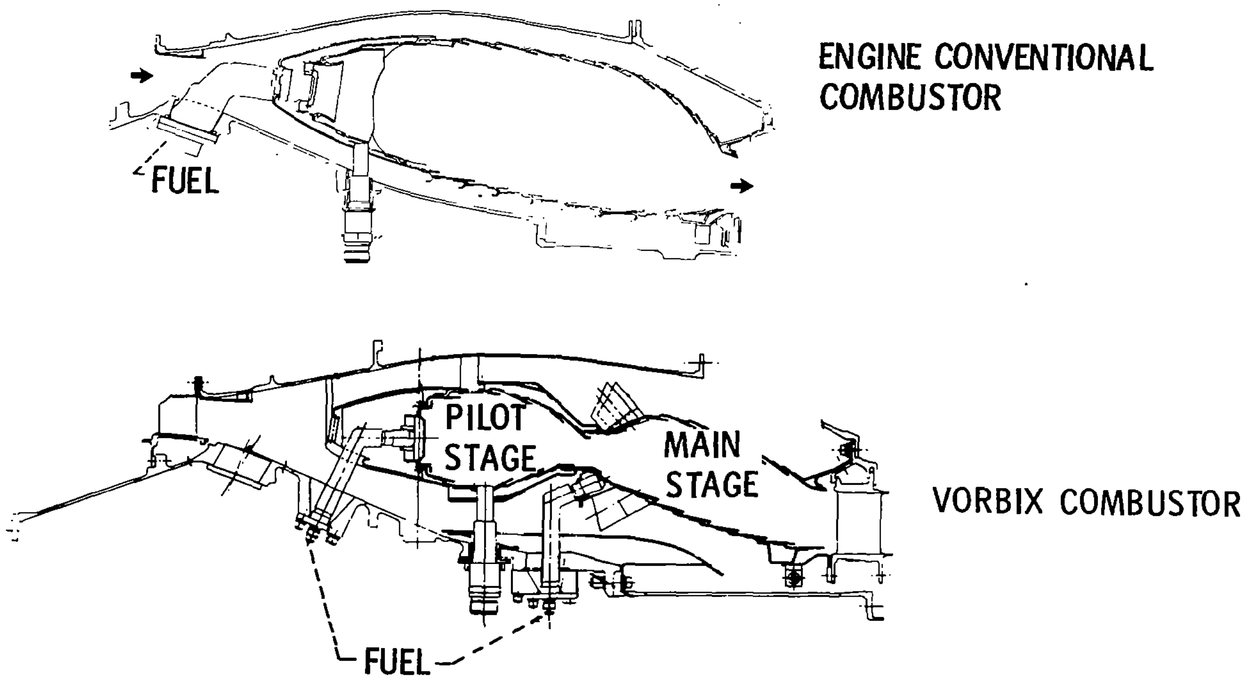


Figure 5.- Low-emission, staged combustor for the JT9D-7 engine.

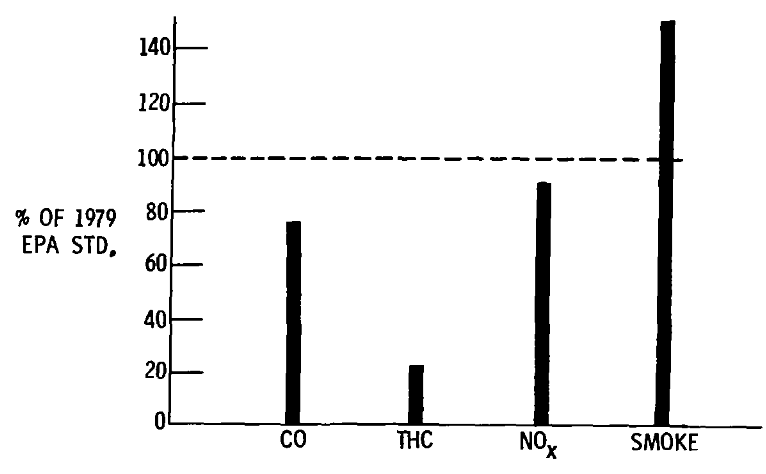


Figure 6.- Emissions results from Vorbix combustor tests in JT9D-7 engine.

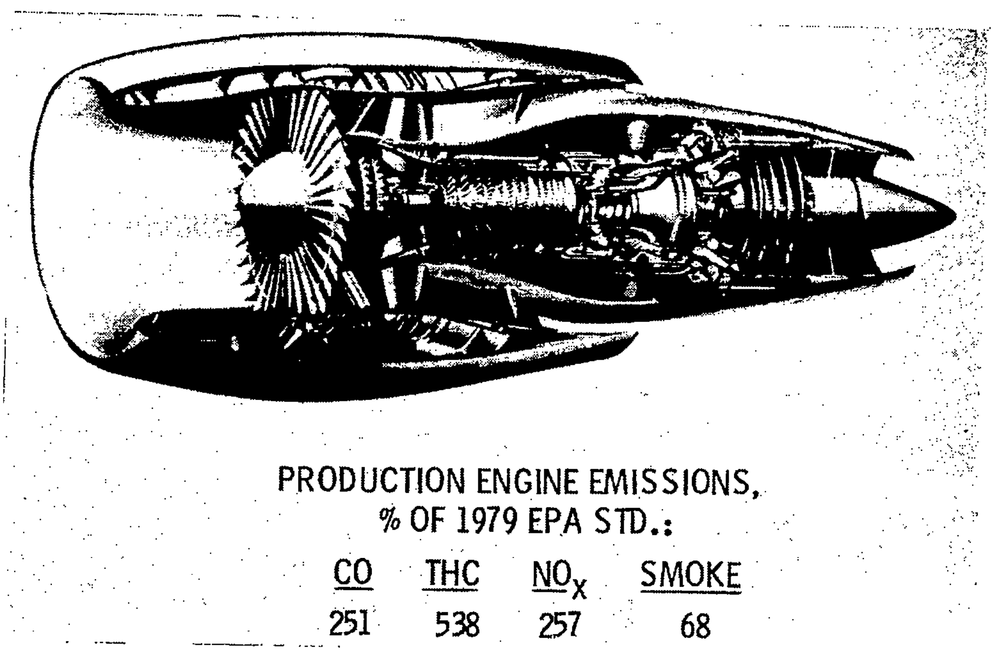


Figure 7.- EPA class T2 jet aircraft engine CF6-50. Thrust, 224 kN; pressure ratio, 30:1; type of combustor, annular.

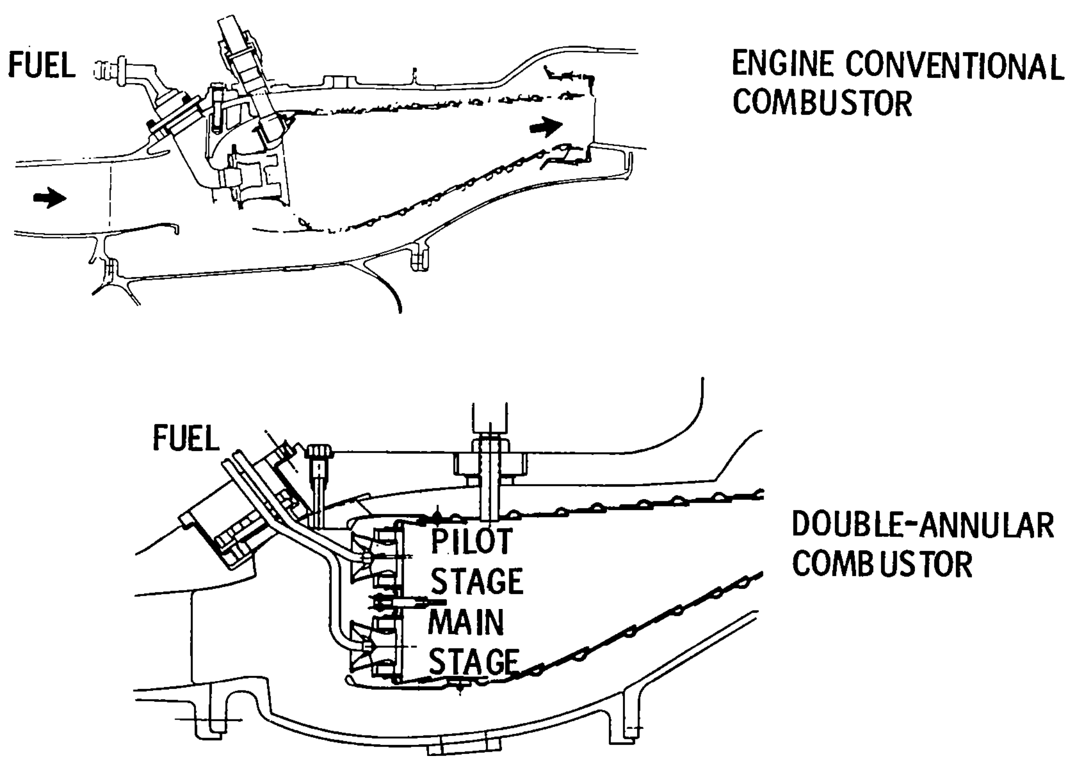


Figure 8.- Low-emission, staged combustor for the CF6-50 engine.

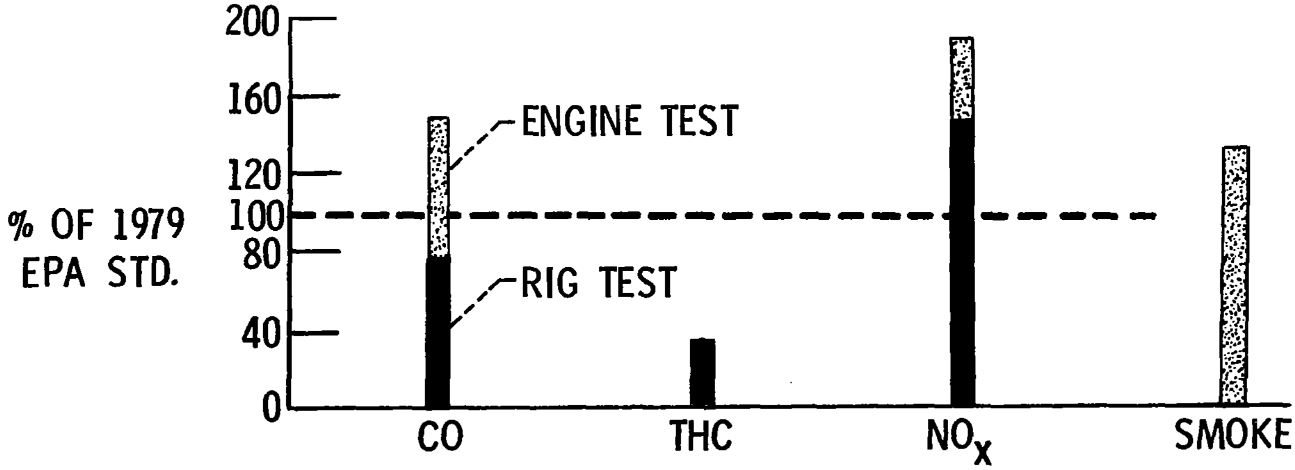


Figure 9.- Emission results from double-annular combustor tests. Full-scale tests conducted in CF6-50 engine.