VIII. SUMMARY OF EMISSIONS REDUCTION TECHNOLOGY PROGRAMS

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The NASA emissions reduction contract programs for EPA aircraft engine classes P2 (turboshaft engines), T1 (jet engines with thrust under 8000 lb), T4 (JT8D engines), and T2 (jet engines with thrust over 8000 lb) are discussed. Summarized are the most important aspects of these programs, the commonality of approaches used, the test results, and assessments regarding applications of the derived technology.

EMISSIONS REDUCTION APPROACHES

In pursuing the programs' main objective, which is reducing emissions without adversely affecting performance, design approaches involving varying degrees of combustor complexity are being investigated. The intent is to determine what degree of combustor complexity is required to achieve large emissions reductions. The approaches investigated were (1) to retain production combustor essentials (a minor modification), (2) to significantly alter the production combustor (a major modification), and (3) to assess the potential of future technology (a very major modification).

Minor modifications consist of relatively small changes that could be incorporated into the production combustor. Auxiliary hardware, such as fuel manifolding and the engine fuel control, would be retained. Examples of minor modifications include advanced fuel injection systems, such as air-assist and air-blast nozzles; fuel staging; more optimum burning stoichiometry; and variations in airflow distribution. The potential of minor modifications in reducing carbon monoxide (CO), unburned total hydrocarbons (THC), and smoke is good. However, the potential for oxides of nitrogen (NO_x) reduction is only moderate.

Major combustor modifications would significantly alter the production combustor design. Their implementation requires replacing the production combustor with a new design and replacing some of the auxiliary hardware. Examples of this type are multiple-burning-zone combustors and combustors with added fuel injectors. Their potential for reducing all pollutants is good since they incorporate features for scheduling combustion and optimizing performance at all operating conditions.

Very major modifications cannot presently be implemented to realize their full potential in existing practical combustors. This awaits development of new technologies. An example of a very major modification is a prevaporizing-premixing combustor, which would require variable combustor geometry and more consistent airflow control than is presently available. Because of their very good emissions reduction potential, modifications of this type were also evaluated in the contract programs. Effects were simulated. However, optimized implementation of these concepts was not possible.

The degree of combustor modification required to reduce emissions for each engine class is discussed in succeeding sections.

EMISSIONS REDUCTION PROGRAM TEST RESULTS

P2 Program

The Detroit Diesel Allison 501-D22A engine-combustor was studied in the P2 program. This engine, shown in cross section in figure VIII-1, is a turboprop with a maximum shaft horsepower of 4680 and a pressure ratio of 9.7. The production combustor is a can-annular type. Also shown in the figure are production engine emission values as percentages of the 1979 EPA standards. One-hundred percent means that the engine value equals the standard value. Only the unburned hydrocarbons and smoke require substantial reductions for this engine. Carbon monoxide emissions are slightly above the standard. Oxides of nitrogen emissions are substantially below the standard.

The minor combustor modification of the 501-D22A engine, shown in figure VIII-2, incorporated two changes. Air-atomizing fuel nozzles were installed to improve fuel spray quality, and the combustor headplate was restructured to produce reverse flow in the primary zone in order to increase residence time. Results were very good. All standard values were achieved. Carbon monoxide and unburned hydrocarbon emissions were reduced to 17 and 6 percent of standard levels, respectively. Oxides of nitrogen emissions increased slightly to 57 percent but were still substantially below the standard. The smoke level was reduced to 59 percent of the standard.

The major combustor modification of the 501-D22A engine, shown in figure VIII-3, consisted of adding a prechamber to the upstream end of the combustor in order to mix fuel and air before combustion. This design produced results similar to the minor modification for the gaseous emissions. Smoke values were, however, reduced to 4.5 percent of the standard value, a substantial improvement.

The very major combustor modification of the 501-D22A engine, shown in figure VIII-4, was a two-stage burner in which main-stage fuel was preheated and premixed with air. This design produced gaseous emission levels comparable to the major modification. It also produced low smoke levels, 28 percent of the standard.

All combustor modifications evaluated in the 501-D22A combustor envelope achieved the 1979 EPA standards. In fact, all standards were overachieved, even with the minor combustor modification. It thus appears that minor combustor modifications are adequate for standards' achievement for this engine and that the technology derived in this program is capable of early implementation. The NASA program for this engine is now complete. Testing was done in component test facilities at actual engine conditions. Engine tests are not planned.

T1 Program

The AiResearch TFE731-2 engine-combustor is currently being studied in the T1 program. This engine, shown in figure VII-5, has a maximum thrust of 3500 pounds, a pressure ratio of 13.6, and a combustor of the annular reverse-flow type. Production engine emissions levels, also contained in the figure, indicate that substantial reductions of all gaseous emissions are required to achieve standard values. The smoke level shown in the figure is slightly above the standard. Other modifications of this engine model produced smoke levels below the standard.

The minor combustor modification of the TFE731-2 engine, shown in figure VIII-6, consisted of providing air assist through the fuel nozzle at engine idle in order to improve fuel atomization and bleeding air at idle to increase the fuel-air ratio. Results demonstrated substantial reductions of CO and THC but essentially no reductions of NO_x or smoke. The CO standard was nearly attained. The THC level was 25 percent of the standard.

The major combustor modification of the TFE731-2 engine, shown in figure VIII-7, consisted of installing an air-assisted air-blast fuel nozzle. Implementation would require a variable-area swirler. With this modification, the CO standard was nearly achieved, the NO_x standard was barely achieved, and the THC standard was easily achieved. Since testing was conducted at reduced pressures, no smoke data at takeoff pressures were obtained. However, it is anticipated that this modification would easily achieve the smoke standard.

The very major combustor modification for the TFE731-2 engine, shown in figure VIII-8, was a multiple-burning-zone combustor in which main-stage fuel was prevaporized and premixed with air. With this modification, CO levels barely achieved the standard. But THC and NO_x standards were easily achieved. Of particular note, the NO_x level was reduced to 68 percent of the standard.

In summarizing results for this T1 class engine, the data indicate that a major combustor modification is required for EPA standards' achievement and that implementation of this technology requires further development of a variable-area swirler. To date, all combustor tests have been performed in component test rigs. These tests will be concluded shortly, and experimental engine testing of the major modification will begin.

The major modification, the air-assisted air-blast design, has been incorporated into the AiResearch QCGAT program. QCGAT is the acronym for a NASA-sponsored program entitled the "Quiet, Clean, General Aviation Turbofan Program."

T4 Program

The Pratt & Whitney Aircraft JT8D-17 engine-combustor was studied in the T4 program. This engine, shown in cross section in figure VIII-9, has a maximum thrust of 16 000 pounds, a pressure ratio of 16.9, and a combustor of the can-annular type. As shown in the accompanying table, production-engine gaseous emission levels are all considerably higher than the 1979 EPA standards.

Two minor combustor modifications were tested for this engine. Both replaced the pressure-atomizing fuel nozzles with an air-blast design. The first modification, shown in figure VIII-10, had a lean-burning primary zone. This design did not achieve any of the gaseous emission standards. However, it did reduce CO and THC levels by more than a factor of 2 below production-engine levels. Smoke levels were reduced to 50 percent of the standard. Oxides of nitrogen levels were not significantly reduced. The second minor combustor modification for the JT8D-17 engine, shown in figure VIII-11, contained a rich-burning primary zone. This design produced lower CO and THC levels than the lean-burning design. These were 117 and 6.5 percent of standard values, respectively. Oxides of nitrogen levels remained high. The rich-burning design did, however, have several disadvantages. Smoke levels were higher than the standard level, and the burner had poor relight characteristics.

After completion of the NASA contract effort, Pratt & Whitney continued development of the lean-burning design. This development resulted in a combustor that retained the gaseous emissions levels displayed in this program, reduced the smoke level to approximately 60 percent of the standard, and had adequate altitude relight performance.

The major combustor modification for the JT8D-17 engine, shown in figure VIII-12, was a multiple-burning-zone, Vorbix combustor design. This design produced the greatest simultaneous reduction of all emissions that was attained in the JT8D program. It significantly reduced all gaseous emissions but achieved the standard only for THC. Smoke levels approaching the standard level were achieved.

The very major modification for the JT8D-17 engine, shown in figure VIII-13, also consisted of a multiple-burning-zone combustor. In this design, both burning stages were supplied with a premixed fuel-air mixture.

The design demonstrated a CO-NO_x trade-off, with reductions in one emission producing corresponding increases in the other emission. This modification produced low levels of THC and smoke, 50 and 8 percent of standard values, respectively. Carbon monoxide levels, however, remained high.

Although production-engine emissions levels were substantially reduced, EPA standard levels for CO and NO_x were not attained with any of the modifications. Vorbix combustor emissions reductions achieved in this program were comparable to those achieved in the T2 program. However, due to the higher specific fuel consumption (sfc) of the JT8D, EPA parameter (EPAP) values were higher than those for the T2 class.

The EPA parameter is a summation of products, at each LTO-cycle point, of the emission index times a time in mode - fuel/thrust parameter. As sfc increases, the multiplying value increases, thereby increasing the EPA parameter number. For example, for assumed 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 order to achieve the same EPA parameter value as the JT9D engine. Similar considerations apply to both unburned hydrocarbons and oxides of nitrogen. Conversely, at least a partial solution to reducing aircraft emissions is significantly improving engine sfc. Significant improvements in higher-power-engine sfc are currently being pursued in another NASA-sponsored program entitled the "Energy Efficient Engine Program."

The NASA program for the JT8D-17 engine is now complete. Testing was performed in component test facilities at actual engine conditions. Experimental engine tests are not planned. Implementation of the Vorbix combustor in a production JT8D engine would require considerable effort, since it would entail replacing the combustor and developing a new engine fuel control.

T2 Programs

The T2 engine class included two contract programs. Program results are discussed individually and summarized together.

Pratt & Whitney program. - The JT9D-7 engine-combustor was studied in the Pratt & Whitney T2 program. This engine, shown in cross section in figure VIII-14, has a maximum thrust of 43 500 pounds, a pressure ratio of 21.2, and an annular combustor. Production engine emissions values, also shown in the figure, indicate that all emissions, with the exception of smoke, require large reductions.

Minor combustor modifications were not investigated for this engine. The major combustor modification, a Vorbix design, is shown in figure VIII-15. The data discussed here are from a full-size JT9D-7 engine equipped with the Vorbix combustor. All EPA gaseous emissions standards were achieved. Values for CO, THC, and NO_x were 74, 25, and 90 percent of standard values, respectively. Smoke levels exceeded the standard level, especially in later engine tests. It appears that the high smoke level resulted primarily from fuel-rich zones at the main combustor inlet. These worsened during engine testing when main combustor airflow was reduced and redistributed to the combustor exit in order to achieve proper combustor exit temperature distributions. It is anticipated that smoke levels would be reduced to acceptable levels with further development.

Several other combustor concepts were also investigated in this program. The most promising of these was the hybrid combustor, a very major modification, which is shown in figure VIII-16. This combustor is a multiple-burning-zone design that combines a premixing pilot combustor with a swirl-can main combustor. It achieved the CO and THC standards but produced NO_x levels 10 percent higher than the standard. Since the hybrid design was evaluated only at test rig pressures, no smoke data at takeoff pressures are available.

General Electric program. - The CF6-50 engine-combustor was studied in the General Electric T2 program. This engine, shown in cross section in figure VIII-17, has a maximum thrust of 50 000 pounds, a pressure ratio of 30, and an annular combustor. Production engine emissions values, also shown in the figure, indicate that large reductions of all gaseous emissions are required for standards' achievement.

Specialized tests were performed with the production combustor to assess its potential for standards' achievement with minor combustor modifications. Sector burning fuel in alternate 90° sectors at idle reduced CO and THC levels to nearly standard values. Redirecting most of the combustor airflow through the combustor headplate to produce lean burning and reduce NO_x was unsuccessful. Oxides of nitrogen levels remained high, and other gaseous emissions were adversely affected.

The major combustor modification to the CF6-50 engine, shown in figure VIII-18, was a double-annular design and produced the best G.E. program results. This design was evolved in the first two program phases. Phase II test rig results are also given in the figure. EPA standard values for CO and THC were achieved, but the NO_x standard was exceeded by 47 percent. Smoke assessments await the engine tests. It is anticipated that this combustor will produce low smoke concentrations.

The engine-combustor hardware when evaluated in phase III produced somewhat higher CO and THC levels than in the rig tests. These increased levels appear to be due to small differences in airflow distributions. It is the belief of G. E. and NASA program personnel that these increased levels can be reduced to the phase II values with additional development.

Several other combustor concepts were also investigated in this program. The most promising of these was the radial/axial design, a very major modification which is shown in figure VIII-19. This combustor combined a conventional pilot burner with a premixing main burner. It achieved the THC standard and reduced NO_x levels to within 10 percent of the standard but did not produce CO levels close to standard values.

T2 program summary. - Major combustor modifications requiring multiple-burning-zone combustors were required for reduction of all emission species for the T2 class. With these major modifications, the Pratt & Whitney Vorbix design and the General Electric double-annular design, CO and THC standard levels were achieved. The smoke standard also appears achievable with both engines. The NO_x standard was achieved with the 21.2-pressure-ratio JT9D-7 but was not achievable with the 30-pressure-ratio CF6-50 engine. Implementation of the major combustor modifications developed in these programs will probably require a large effort since new combustors, auxiliary hardware, and a new engine fuel control will be needed.

The Pratt & Whitney program has been completed. General Electric engine tests have begun and will be completed shortly. Applications of the technology developed in these programs have already been started in other NASA programs. These include the Energy Efficient Engine Program, where both combustor concepts are being applied, and the QCSEE program where the G.E. double-annular combustor is being tested in an F101 combustor housing. QCSEE is the acronym of a NASA-sponsored program entitled the "Quiet, Clean, Short-Haul, Experimental Engine Program." Other potential applications for this technology are in utility gas turbines.

EMISSIONS SUMMARY - ALL ENGINE CLASSES

Table VIII-1 is a summary of emissions results for all engine classes. Shown is the EPA class, the engine investigated, the combustor modification required, and the emissions results achieved. The THC and CO results were quite similar for all engine classes. Unburned hydrocarbon standards were achieved for all classes. Carbon monoxide standards were either achieved or nearly achieved for all classes, with the exception of T4. The T1 CO results indicate levels slightly over the standard, but these data are conservative since CO levels were not corrected to engine pressures as were NO_x rig data.

However, the difficulty of achieving the NO_x standard increased with increasing engine pressure ratio. For the 9.7-pressure-ratio P2 engine, the NO_x standard was easily achieved with a minor combustor modification. For the 13.6-pressure-ratio T1 engine, the NO_x standard was barely achieved with a major combustor modification. For the 17-pressure-ratio T4 engine, the NO_x standard was not achieved, but the failure was due, in large part, to the high sfc of this engine. For the T2 class, major combustor modifications produced achievement of the NO_x standard with the 21.2-pressure-ratio engine but not with the 30-pressure-ratio engine.

The commonality of the NO_x results can be seen in figure VIII-20, which contains plots of emission index against combustor inlet temperature at takeoff. Recall that NO_x levels are highest at takeoff and increase exponentially with combustor inlet temperature, which increases with engine pressure ratio. The top curve, generated in 1972, contains NO_x data for various production aircraft engines. Open points on this curve are NO_x levels for the production engines investigated in the contract emissions reduction programs. Some data scatter is evident, especially for the P2 turboprop engine. The bottom curve, also generated in 1972, was obtained with an experimental swirl-can combustor here at Lewis. This curve indicates that substantially lower NO_x levels are achievable and was the primary initial impetus for the contract programs. Plotted as solid points on this curve are results of the P2, T1, T4, and both T2 class programs. In spite of the wide variances in engines, combustor types, and sizes investigated, the data line up quite well on the curve. Thus, it appears that roughly the same technology-level reductions of NO_x were achieved in all of the programs. These seem to be the practical limits to which NO_x can be reduced with present engine-combustor hardware.

These data were obtained at fuel flow and airflow splits that produced combustion efficiencies well over 99 percent at takeoff. In addition, satisfactory performance was obtained at the other landing/takeoff cycle points. Still lower NO_x levels are achievable with these combustors but at the expense of unacceptably high CO and THC emissions.

These emissions data represent our most recent efforts in NASA programs geared primarily to near-term applications. Other programs at Lewis and elsewhere are investigating more-advanced emissions reduction concepts. It appears that further NO_x reductions await either advances in these programs or significant improvements in sfc such as those being pursued in the energy efficient engine program.

PERFORMANCE SUMMARY - ALL ENGINE CLASSES

The performance development status of the low-pollution combustors is diagramed in figure VIII-21. The purpose of these contract programs was to evolve new emissions reduction combustor technology. Advanced-technology concepts were applied to existing engine combustors. These concepts were, and currently are, being tested in test facilities and engines. In pursuing emissions reductions, care was taken to ensure that the reductions did not occur at the expense of combustor performance. It does not appear that performance was sacrificed in any of these programs.

However, further development of all combustor concepts would be required by engine manufacturers before engine implementation. More work is needed on durability assessments; combustor exit temperature tailoring; altitude relight optimization, which was performed only for the General Electric double-annular combustor; and development of fuel control systems capable of scheduling fuel to multiple-burning-zone combustors.

POLLUTION SUMMARY

ALL ENGINE CLASSES

EPA CLASS	ENGINE	MODIFICATION REQ'D	% OF 1979 EPA STD			
			THC	CO	NO_X	SMOKE
P2	501-D22A	MINOR	6	17	57	59
T1	TFE731-2	MAJOR	25	107	100	---
T4	JT8D-17	MAJOR	25	207	146	108
T2	JT9D-7	MAJOR	25	74	90	150
T2	CF6-50	MAJOR	38	77	147	---

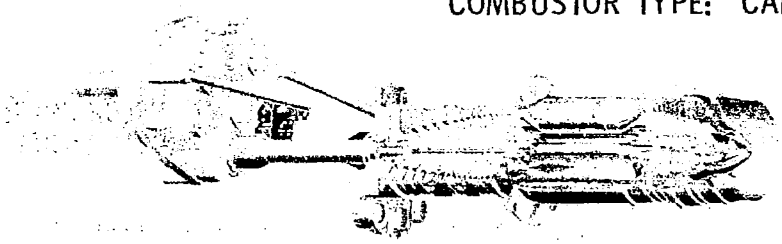
Table VIII-1.

EPA CLASS P-2 TURBOPROP AIRCRAFT ENGINES

SHAFT HORSEPOWER, MAX - 4680

P. R.: 9.7:1

COMBUSTOR TYPE: CAN-ANNULAR



DETROIT DIESEL ALLISON 501-D22A TURBOPROP ENGINE

PRODUCTION ENGINE EMISSIONS

	CO	THC	NO_X	SMOKE
% OF 1979 EPA STD	118	306	48	189

CS-77-498

Figure VIII-1.

MINOR COMBUSTOR MODIFICATION FOR 501-D22A ENGINE

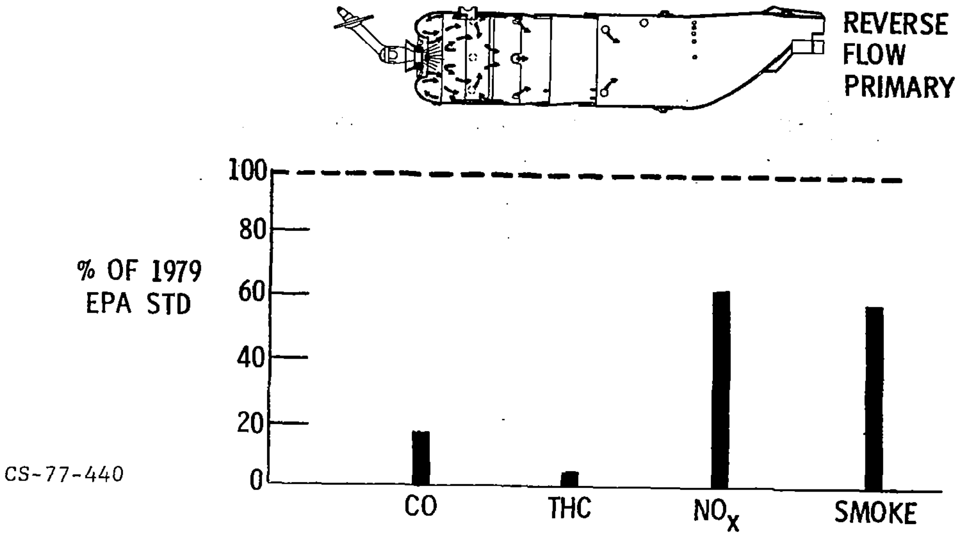


Figure VIII-2.

MAJOR COMBUSTOR MODIFICATION FOR 501-D22A ENGINE

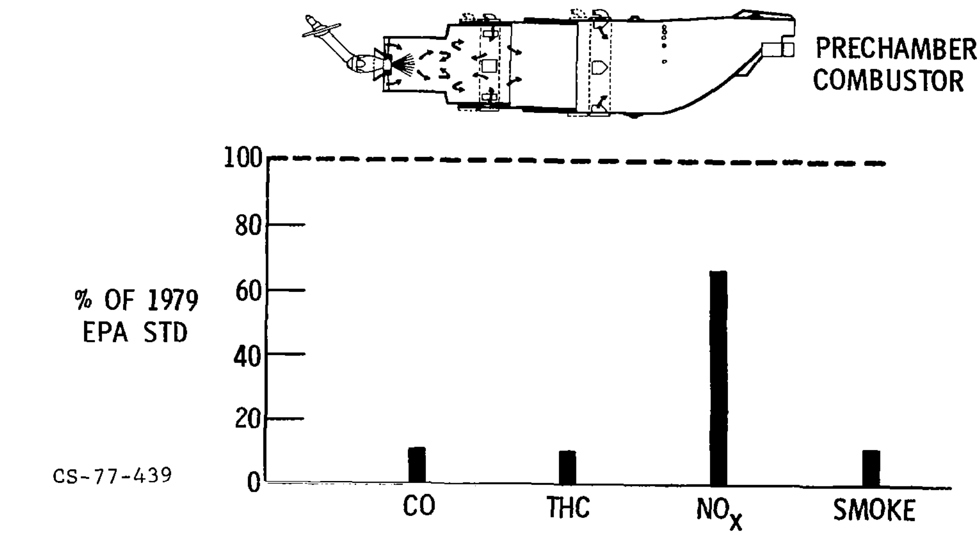


Figure VIII-3.

VERY MAJOR COMBUSTOR MODIFICATION FOR 501-D22A ENGINE

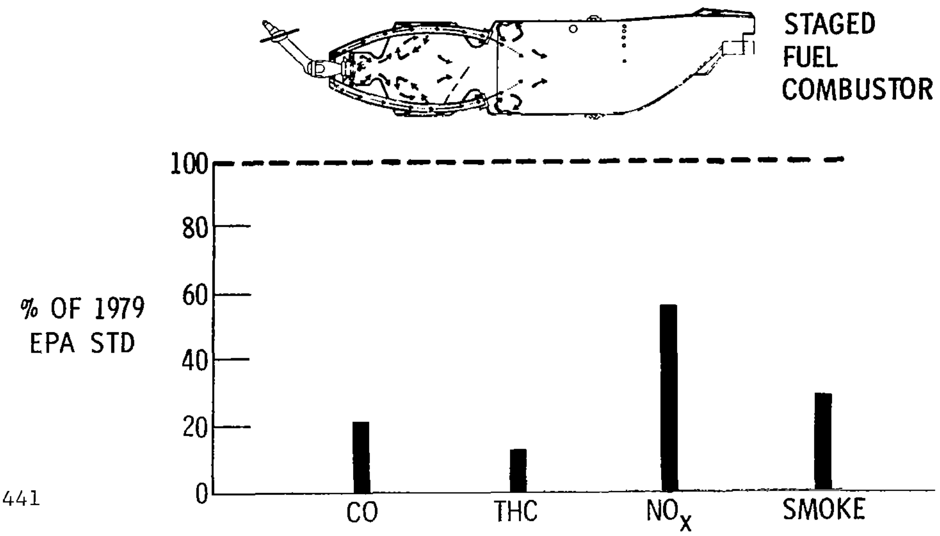


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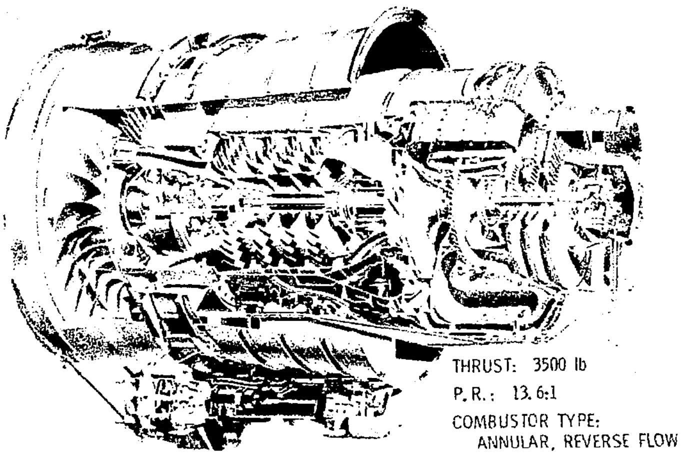
Figure VIII-4.

EPA CLASS T-1 JET AIRCRAFT ENGINES UNDER 8,000 POUNDS THRUST



AIRESEARCH TFE731-2 ENGINE

PRODUCTION ENGINE EMISSIONS

	CO	THC	NO_x	SMOKE
% OF 1979 EPA STD	180	331	162	118

CS-77-499

Figure VIII-5.

MINOR COMBUSTOR MODIFICATION FOR TFE731-2 ENGINE

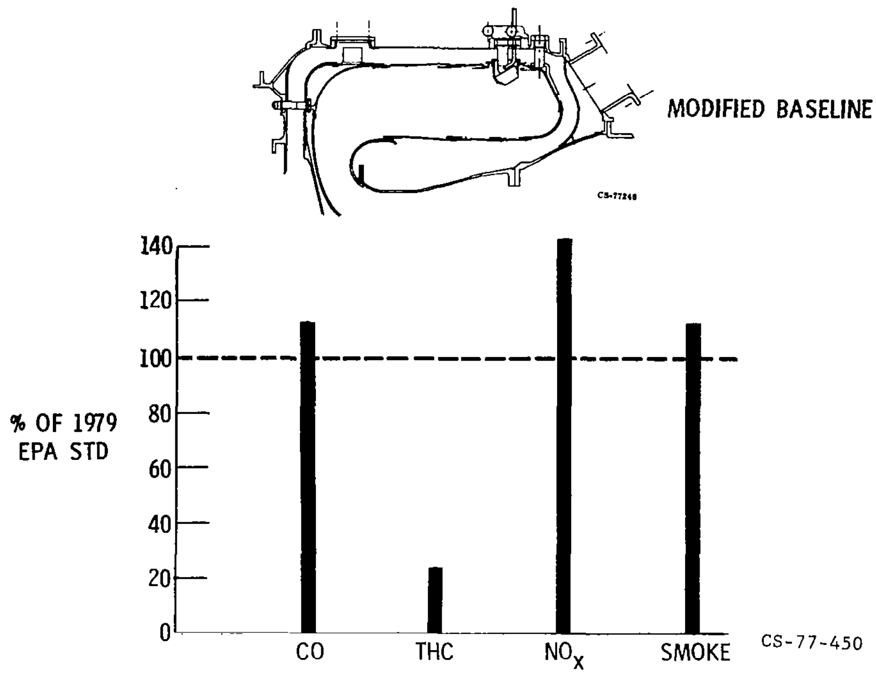


Figure VIII-6.

MAJOR COMBUSTOR MODIFICATION FOR TFE731-2 ENGINE

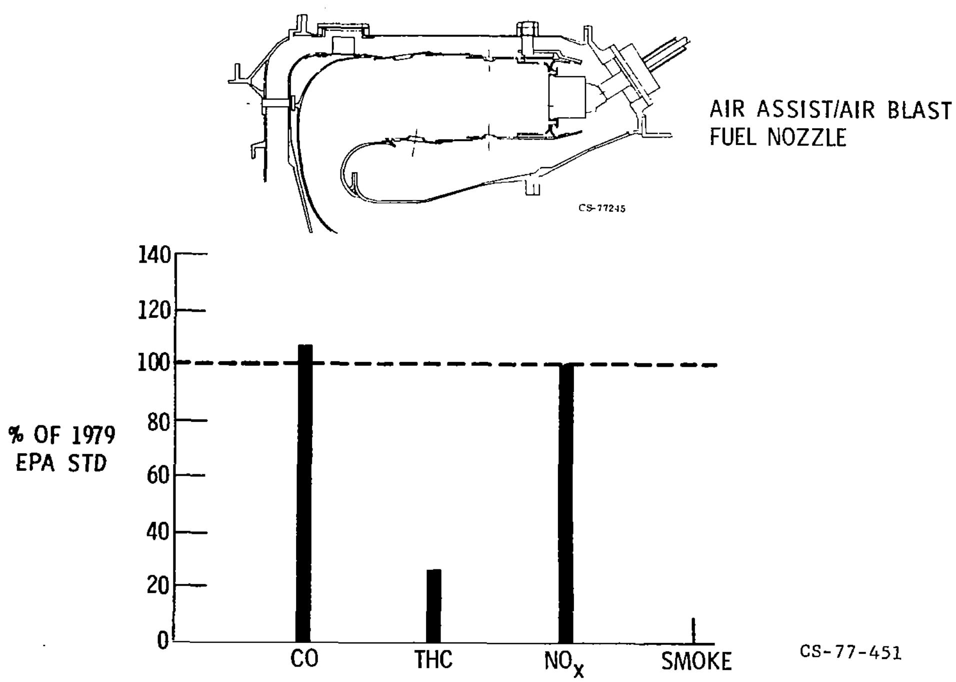


Figure VIII-7.

VERY MAJOR COMBUSTOR MODIFICATION FOR TFE731-2 ENGINE

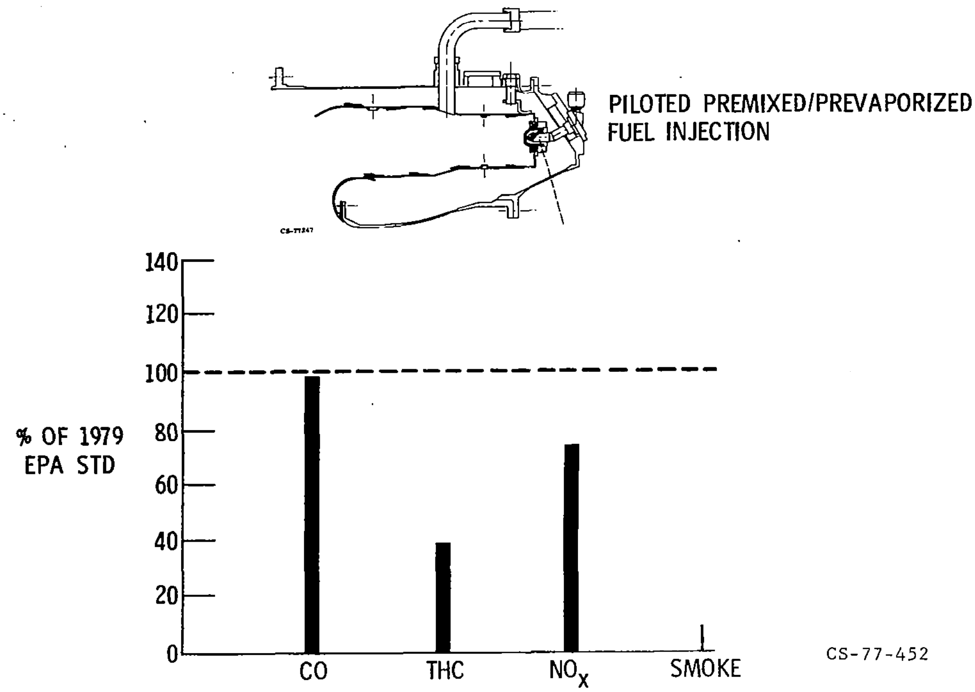
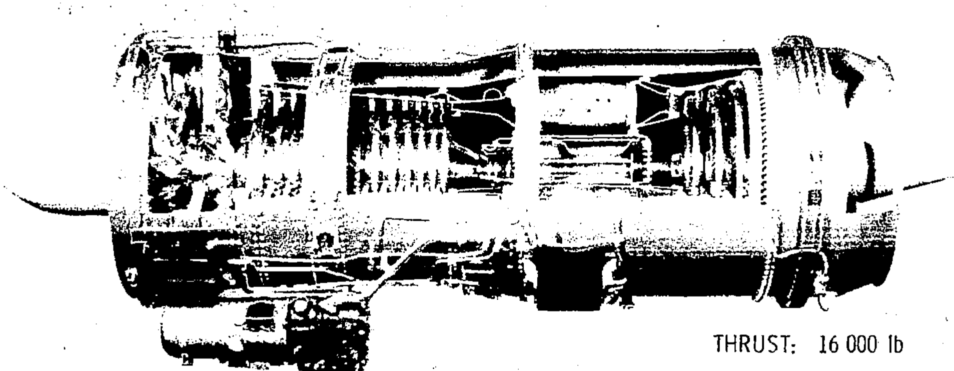


Figure VIII-8.

EPA CLASS T-4 -- JT8D ENGINES



P & W JT8D-17

THRUST: 16 000 lb
P.R.: 16.9:1
COMBUSTOR TYPE:
CAN-ANNULAR

PRODUCTION ENGINE EMISSIONS

	CO	THC	NO_X	SMOKE
% OF 1979 EPA STD	360	500	260	120

CS-77-496

Figure VIII-9.

MINOR COMBUSTOR MODIFICATION FOR JT8D-17 ENGINE

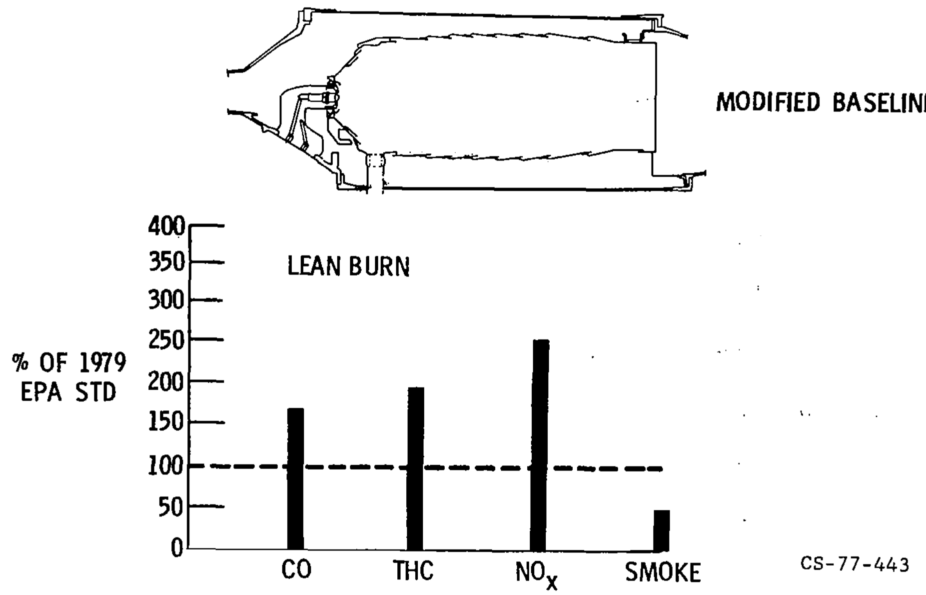


Figure VIII-10.

MINOR COMBUSTOR MODIFICATION FOR JT8D-17 ENGINE

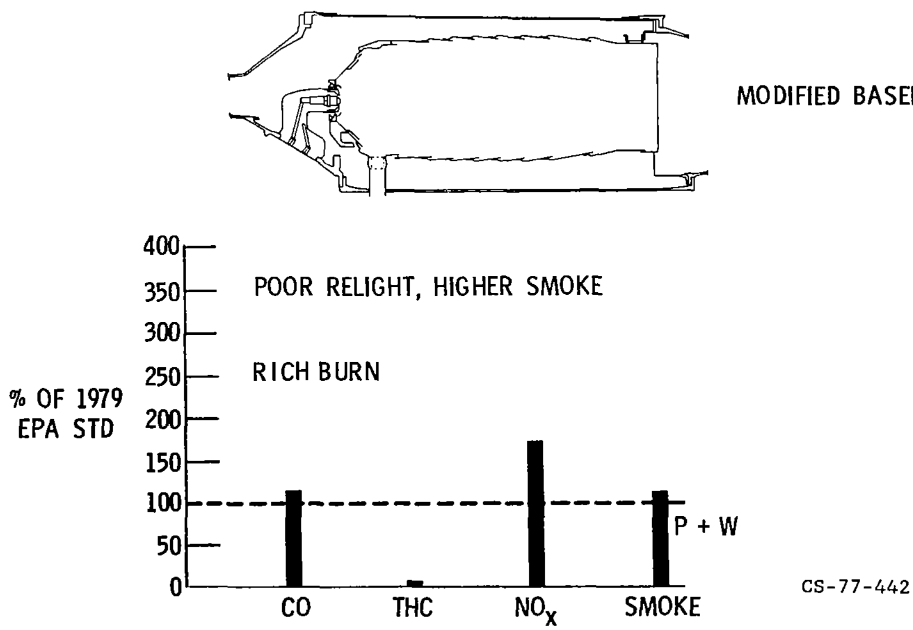


Figure VIII-11.

MAJOR COMBUSTOR MODIFICATION FOR JT8D-17 ENGINE

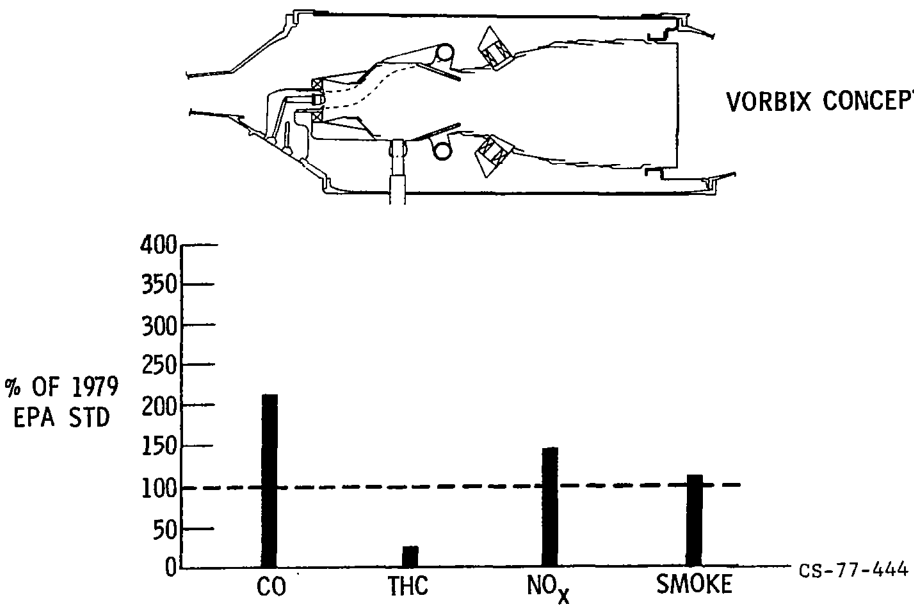


Figure VIII-12.

VERY MAJOR COMBUSTOR MODIFICATION FOR JT8D-17 ENGINE

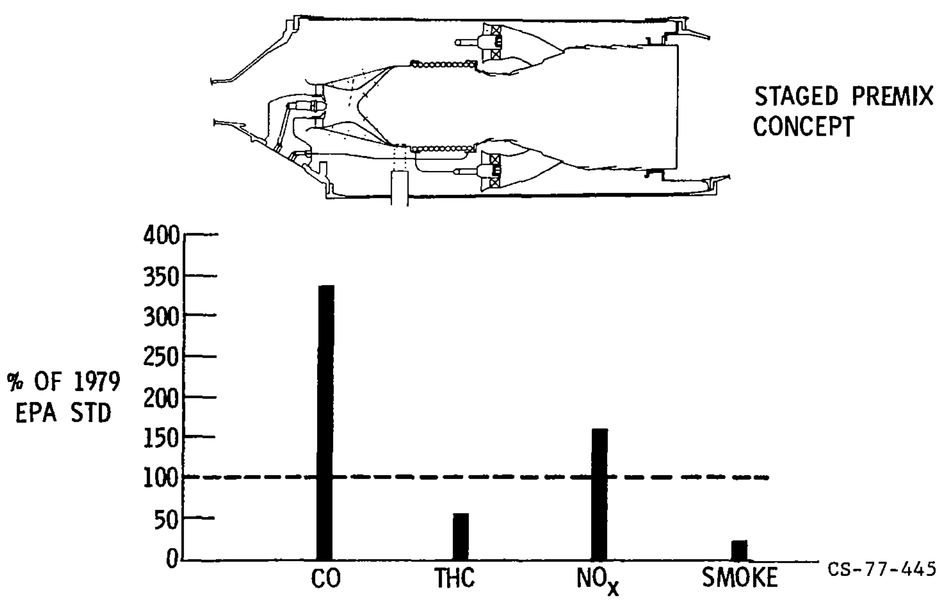
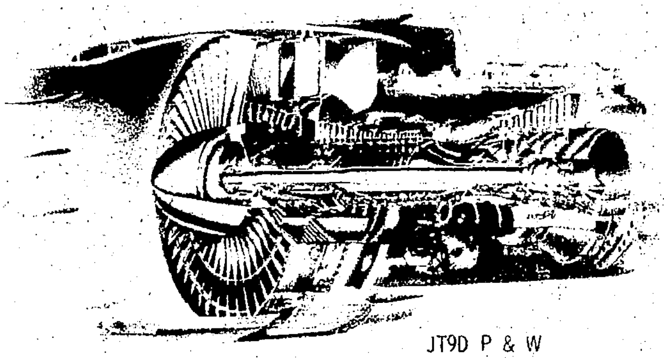


Figure VIII-13.

EPA CLASS T-2 JET AIRCRAFT ENGINES OVER 8000 POUNDS THRUST



PRODUCTION ENGINE EMISSIONS

	CO	THC	NO_x	SMOKE
% OF 1979 EPA STD	198	488	197	56

Figure VIII-14.

MAJOR COMBUSTOR MODIFICATION FOR JT9D-7 ENGINE

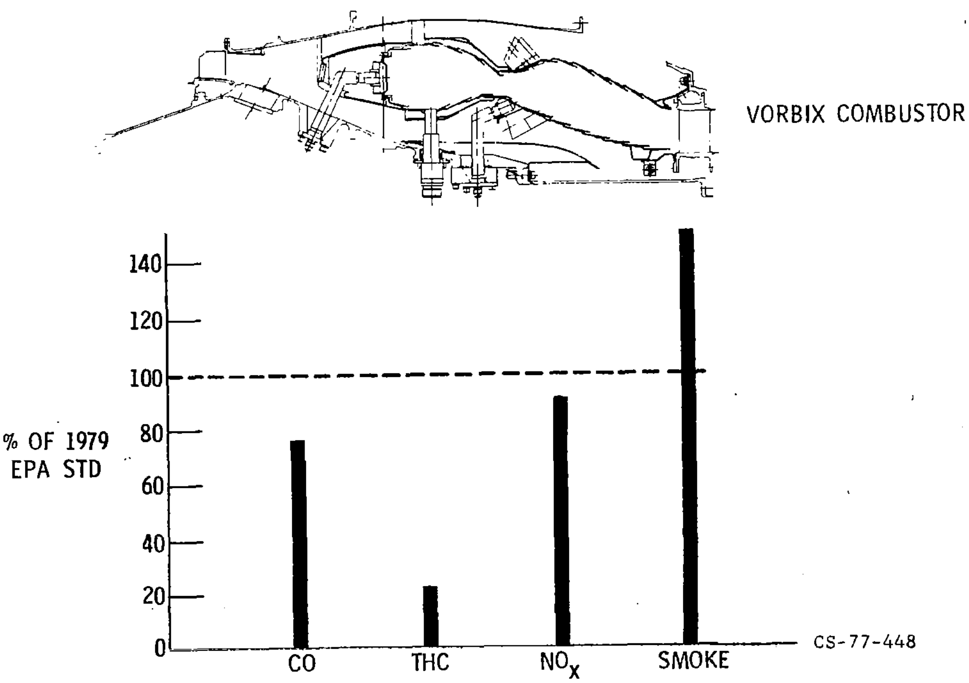


Figure VIII-15.

VERY MAJOR COMBUSTOR MODIFICATION FOR JT9D-7 ENGINE

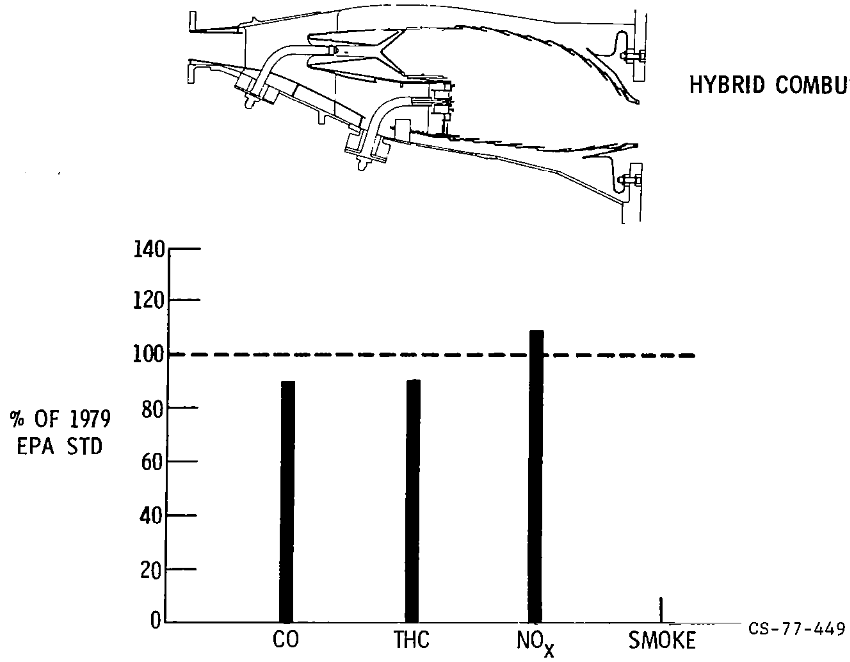
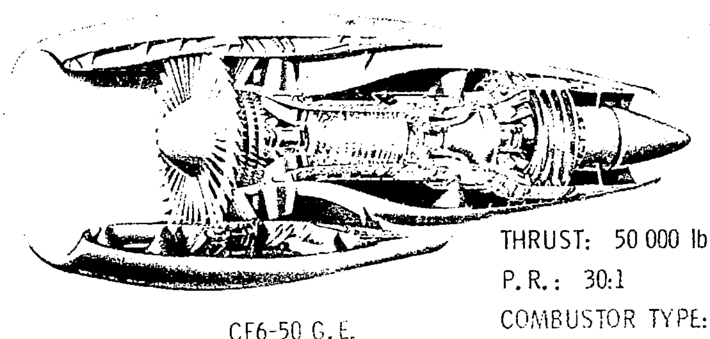


Figure VIII-16.

EPA CLASS T-2 JET AIRCRAFT ENGINES OVER 8,000 POUNDS THRUST



PRODUCTION ENGINE EMISSIONS

	CO	THC	NO_X	SMOKE
% OF 1979 EPA STD	[illegible]	[illegible]	257	68

CS-77-495

Figure VIII-17.

MAJOR COMBUSTOR MODIFICATION FOR CF6-50 ENGINE

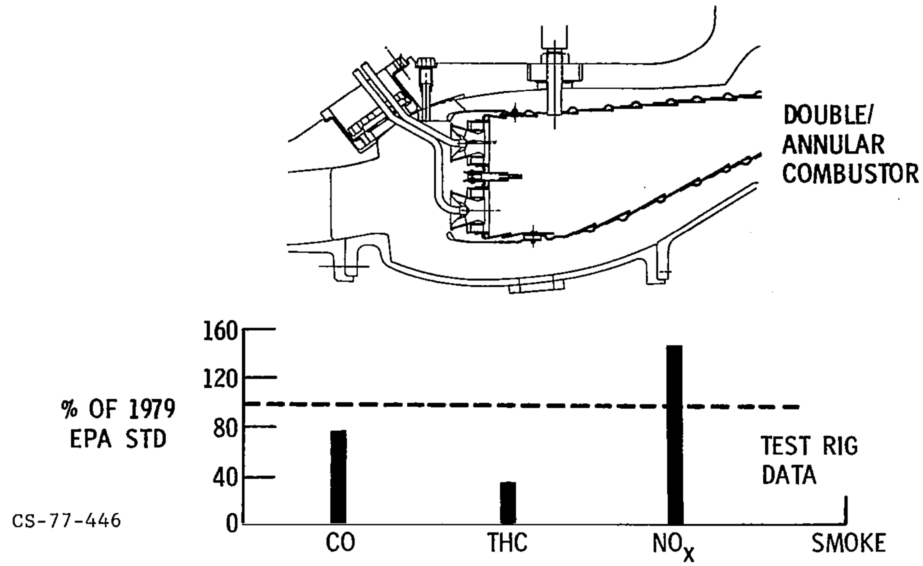


Figure VIII-18.

VERY MAJOR COMBUSTOR MODIFICATION FOR CF6-50 ENGINE

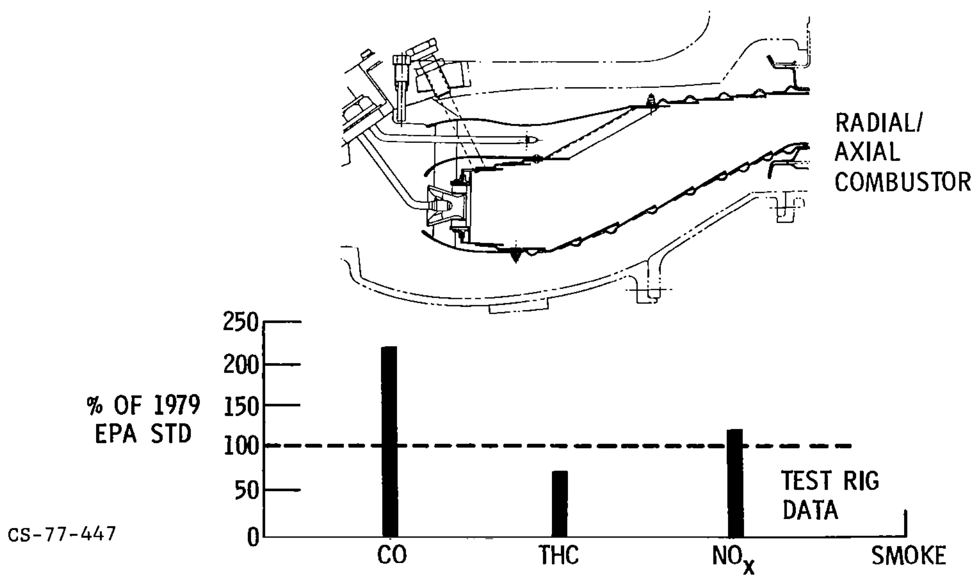


Figure VIII-19.

OXIDES OF NITROGEN EMISSION CHARACTERISTICS

EFFECT OF INLET TEMP & TECHNOLOGY LEVEL

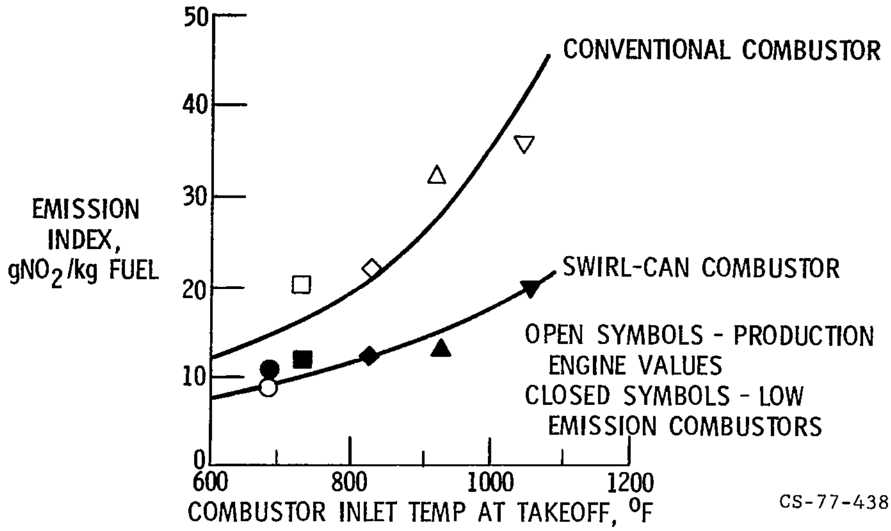
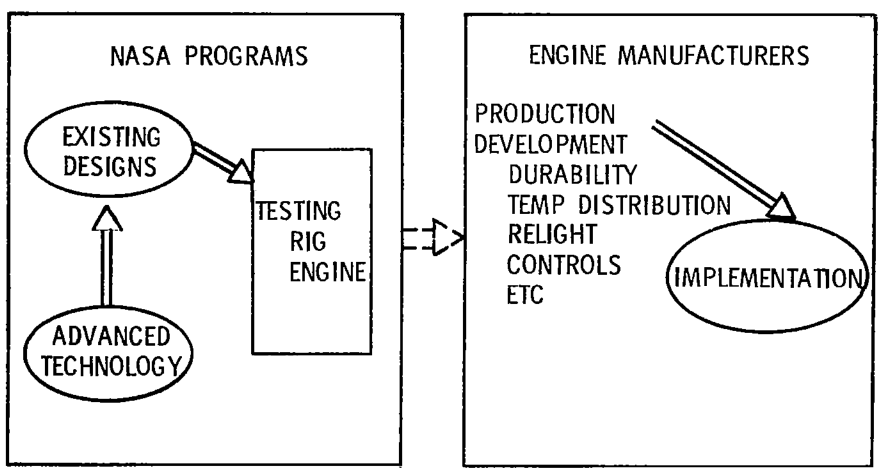


Figure VIII-20.

DEVELOPMENT STATUS

ALL ENGINE CLASSES



CS-77-435

Figure VIII-21.