II. EMISSIONS REDUCTION TECHNOLOGY PROGRAM

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The Clean Air Act of 1970 empowered the Environmental Protection Agency (EPA) to set standards for the allowable emissions levels of aircraft gas turbine engines. The standards were issued in July 1973 and become effective in 1979. As early as mid-1971, NASA decided to begin a major program in emissions reduction technology. Work in this area would consist of continuing in-house research on low-emission concepts as well as contracted research with the major aircraft engine manufacturers. This paper is an overview of the contracted Emissions Reduction Technology Program. Subsequent papers present the results of the contract efforts.

The Emissions Reduction Technology Program was begun with two firm objectives in mind. First, it was essential to investigate new combustor concepts that had the potential for significantly lower emissions levels. Considerable research with existing combustors had shown that present concepts would not meet all the 1979 EPA standards and that new approaches were needed. Such new concepts would have to be developed to their full potential, not only from an emissions standpoint but also from the standpoint of conventional performance goals. Second, having once achieved this potential, it would be necessary to measure the combustor emissions reduction in an engine test. A successful engine test would show whether the combustor concept could be installed in an engine and meet the required engine operating constraints while producing fewer emissions. Engine testing was required to achieve the needed pressure levels and to avoid extrapolation of emissions levels from lower pressures. And finally, an engine test would highlight those areas of the combustor that needed further development.

The approach taken was to award multiphase contracts to the engine manufacturers. These phases of combustor emissions research consisted of screening, refining, and engine testing. The first phase would consist of screening many combustor concepts to determine those having the most potential for lower emissions. The best concepts would be further developed during the refinement phase, where combustor performance as well as emissions 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 Emissions Reduction Technology Program would develop technology for representative engines in each of the EPA engine classes shown in table II-1. With the exception of the T4 class, which consists solely of the JT8D family of engines, competitive contracts were awarded in each class. Table II-1 gives the EPA classes, the engines, and the manufacturers that participated in this program. The program conducted on the T2 class engines was called the Experimental Clean Combustor Program and began in January 1973. The engines in the other EPA classes were studied as parts of the Pollution Reduction Technology Program, which began in mid-1974. The other EPA engine classes - P1, T3, and T5 - were not studied as a part of this program. The emissions technology for the P1 class, aircraft piston engines, is discussed in another paper. The T3 class consists solely of the JT3D family of engines, and the T5 class refers to engines for supersonic aircraft and presently covers only the Olympus engine in the Concorde SST.

The emissions goals of these programs were to meet the 1979 EPA Aircraft Engine Emissions Standards. Shown in table II-2 are the 1979 EPA standards for the three gaseous pollutants and smoke for each of the engines in the program. The engines are arranged in order of increasing compressor pressure ratio. The EPA standards are expressed in EPA parameter values for the specified landing/takeoff (LTO) cycle. The production engine values are given as a percentage of the EPA standard values. In general, production engine values exceed the standards by several hundred percent. Therefore, to meet the EPA standards, the combustor technology must have the potential for significantly lower emissions levels than those of existing engines. There are a few instances where emissions standards were already achieved - the nitrogen oxides (NO_x) level for the P2 engine class and smoke for the T2 engine class.

The other program goals are the usual combustor performance goals and are shown in table II-3. A high combustion efficiency is required and must be maintained; pressure losses must be reasonable and within present practice; exit temperature pattern factors must be low; and the combustor must be as capable of altitude relight as the production engine combustor. Finally, the combustor should have adequate durability. Durability testing was not part of this program, but the combustor design must incorporate those durability features and approaches that have been employed in the past. One additional constraint was applied - that all combustor concepts fit within the present engine combustor casing envelope. This constraint was to ensure that the final combustors could be tested in present engines with a minimum of change and that therefore any future use of these combustors would be expedited.

ENGINE EMISSION CHARACTERISTICS

Emission characteristics common to all engine classes are shown in figure II-1. This figure is a plot of production engine emissions as a function of takeoff thrust level. The LTO 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 LTO cycle and are shown as the percentage contribution of each cycle point. Emissions from all engine classes conform very well to this trend. Virtually all the hydrocarbon (THC) and carbon monoxide (CO) emissions are generated at low power, primarily at engine idle. The levels of these pollutants are much reduced at approach power setting and virtually disappear at higher power levels. Typical production aircraft engines have combustion inefficiencies at idle of 4 to 12 percent. This accounts for the high level of hydrocarbon and CO emissions at the idle condition. To reduce these emissions, combustor technology efforts must emphasize increased combustion efficiency at idle. In practice, large reductions in hydrocarbon and CO emissions have been achieved with relatively minor combustor changes.

On the other hand, NO_x emissions are lowest at engine idle and increase as engine power increases. To minimize NO_x emissions, combustor research efforts have emphasized the higher power operating conditions. The combustor modifications that reduce NO_x cannot be easily implemented as significant changes are needed. To reduce NO_x emissions, the flame temperatures must be lowered and the residence time of gases at high temperatures shortened.

Emissions of NO_x are a strong function of engine compressor pressure ratio and its associated discharge air temperature. Figure II-2 shows emissions of NO_x for conventional engine combustors compared with two advanced combustors that were developed here at Lewis. These data were obtained in 1972, and the strong effect of inlet-air temperature on NO_x is evident. Results like these, obtained with advanced technology combustors, showed that substantial NO_x emission reductions are possible.

EARLY EMISSIONS RESEARCH

Advanced combustor research to obtain low emissions included a variety of approaches. Multiple-burning-zone combustors, specifically the double-annular and swirl-can modular combustors, were investigated. Both air-assist and air-blast fuel injection techniques were studied to evaluate their potential for emissions control. Controlled combustion was studied by varying the fuel and air schedules to advanced combustors.

The double-annular combustor shown in figure II-3 has two concentric burning zones. This short-combustor concept was originally developed by Pratt & Whitney. Air is ducted into the burning zones through ram scoops. This results in very rapid mixing of cold air with hot combustion gases. The result is lower levels of NO_x emissions, as shown in figure II-2.

Another advanced combustor is the swirl-can combustor shown in figure II-4. The swirl-can modular combustor consists of 120 individual modules. Each module has three main parts - a carburetor where fuel and air are mixed, a swirler located at the end of the carburetor tube, and a bluff-body flame stabilizer plate. The many small recirculation zones quickly mix air and combustion products, which produces low NO_x emissions. Figure II-5 shows a swirl-can combustor.

One example of advanced fuel injection techniques is the air-assist nozzle. During idle operation, fuel is sprayed from a duplex fuel nozzle through the small-flow primary nozzle. The spray from the primary nozzle is often coarse, consisting of large-diameter drops, sometimes poorly distributed. The air injected around the primary nozzle through swirlers mixes poorly with the fuel spray. This combination of effects - large drops and poor mixing - results in high levels of hydrocarbon and CO emissions. A very small amount of air bled from the engine compressor and injected through the unused secondary fuel nozzle reduces droplet size, improves uniformity of the spray, and reduces engine idle emissions. Figure II-6 shows how this is done. At idle, air is bled from the compressor and passed through a small supercharger. This high-pressure air flows through the unused secondary fuel manifold and out through the secondary passages in the fuel nozzle. Tests were conducted on a JT8D combustor and bill-of-material fuel nozzle. Figure II-7 shows the air-assist reduction of idle emissions. Emissions of hydrocarbons and CO are given on the ordinate and the injected air differential pressure on the abscissa. Air-assist fuel injection dramatically lowers these emissions - hydrocarbons were decreased by a factor of 8 and CO by nearly a factor of 4. The amount of air injected is quite small, being less than 0.5 percent of the combustor airflow rate at the maximum differential pressure.

Other attempts to improve idle emissions used the double-annular combustor shown in figure II-3. Fuel scheduling involved using only one annulus for combustion during idle operation. Finer and more uniform fuel sprays were obtained by injecting all the fuel through one-half the number of nozzles. As described previously, this improves combustion and reduces emissions of hydrocarbons and CO by decreasing drop size and improving uniformity of the spray. Figure II-8 compares emissions of the double-annular combustor employing fuel scheduling and combined fuel plus airflow scheduling. Emissions reductions are shown as percentages of the unaltered-combustor values. Though it was not as successful as air assist, the emissions with fuel scheduling only were reduced considerably. Air scheduling varied the airflow passing through the combustion zone. In the double-annular combustor, some air was allowed to bypass the burning zones, simulating a variable combustor geometry effect. Bypassing air increases the local fuel-air ratio in the burning zones, and the greater heat release reduces idle emissions. As shown in figure II-8, this technique combined with fuel scheduling reduced idle emissions to well below the baseline values.

Figure II-9 shows the status of engine NO_x emissions at the start of this program. The takeoff-power NO_x emission index for the engines in this program is shown as a function of the combustor inlet-air temperature. The associated engine pressure ratio is also shown on the abscissa. The combined effect of increasing pressure and combustor inlet-air temperature is to increase the NO_x emissions. For comparison, the NO_x emission levels obtained with the NASA swirl-can combustor are also shown. These data, taken prior to the start of this program, showed that significant NO_x reductions are possible, although at the cost of considerable combustor modification.

PROGRAM STATUS

The program schedule (fig. II-10) shows that the T2 engine class program is now nearly completed. This program, conducted on combustors for the JT9D and CF6-50 engines, consisted of the three phases described previously: screening, refining, and engine testing. The program conducted on the JT8D engine combustor is also completed and was taken only through the screening phase. The T1 engine program at Garrett AiResearch is still underway and is nearing the end of the refining phase. Engine tests are planned for mid-1978. The combustor for the TFE-731 engine is a reverse-flow combustor. The program conducted with the Detroit Diesel Allison Division of General Motors used the 501-D22A engine. The combustor for this turboprop engine is a can. As shown in the schedule, the first phase of a planned three-phase program has been completed. The combustor refining and engine testing phases were not considered necessary because tests with the can combustor were conducted at actual engine conditions and achieved all the desired program goals with some margin.

The overall Emissions Reduction Technology Program encompassed a wide variety of combustor types: two large annular combustors for the JT9D and CF6 engines; can combustors of varying sizes for the JT8D and 501-D22A engines; and the small reverse-flow combustor for the TFE-731 engine.

To achieve significant emissions reductions in these combustors, a variety of approaches were employed. Multiple burning zones, improved fuel injection, and air staging were used together or individually in the combustors investigated. Multiple-burning-zone concepts consisted mostly of dividing the combustor into a pilot zone and a main combustion zone. The pilot zone was used for low-power engine idle, was designed for an equivalence ratio near 1, and incorporated delayed mixing to ensure complete combustion and low hydrocarbon and CO emissions. This pilot zone also served to stabilize combustion from the main zone, which was used for high-power operation. This main zone was designed to operate fuel lean and to employ quick mixing to minimize emissions of NO_x. Both series- and parallel-burning-zone combustors were studied and are described in detail in subsequent papers.

Improved fuel injection techniques were designed to reduce emissions by improving the uniformity of the fuel-air mixture in order to eliminate fuel-rich regions and the resulting high flame temperatures. In addition, better local control of the fuel-air ratio was possible by staging the combustion process. In each zone the required fuel-air ratio could be optimized, and thus pollutant levels would be minimized.

Combustion air staging primarily investigated the benefits of variable combustor geometry. The concepts studied were variations in swirler blade angle and dilution hole area. By varying the combustor geometry, it was possible to control local fuel-air ratios to those values needed to minimize pollutants for each engine operating condition. In addition, the effect of increased engine bleed was studied as a way to increase local fuel-air ratios during engine idle.

This brief overview explains the approach taken in the Emissions Reduction Technology Program and some of the emissions reduction concepts that were used.

EXPERIMENTAL CLEAN COMBUSTOR PROGRAM

The remainder of this paper summarizes the completed phases of the Experimental Clean Combustor Program - combustor screening and refining. The next two papers describe the subsequent engine testing and results in detail.

A wide variety of combustor concepts were screened. The swirl-can modules mentioned previously, along with premixing concepts, were investigated. Both axially and radially staged combustors were studied, as was simulated variable combustor geometry. Several concepts attempted to utilize the benefits of premixing and prevaporizing the fuel.

Figure II-11 shows the various combustor tested at Pratt & Whitney and figure II-12 the combustors tested at General Electric during combustor screening (phase I). The Vorbix combustor of figure II-11 employs axially staged combustion zones; a swirl-can combustor similar to an NASA design and a radially staged premixing combustor were tested at Pratt & Whitney. General Electric test combustors (fig. II-12) included lean-dome versions of the standard CF6 combustor, a swirl-can combustor consisting of two rows of modules, a radially and axially staged combustor employing premixing in the outer or main zone passage, and a double-annular combustor. A total of 32 combustor configurations were tested during phase I at Pratt & Whitney and 34 configurations at G. E. The concepts carried into combustor refinement (phase II) at Pratt & Whitney were the Vorbix combustor and a hybrid combustor. The hybrid had the good low-power zone of the staged premixing combustor mated to the good high-power capability of the swirl cans. At G. E. the radially and axially staged and double-annular combustors were studied during phase II.

Figures II-13 and II-14 show the combustors developed in phase II and selected for the engine tests (phase III). The production engine combustor is shown at the top in each figure for comparison. The combustor pollution reduction concepts that were employed in these advanced combustors included the use of multiple burning zones, air-blast atomizers, enhanced mixing, and fuel staging. For both combustors the pilot zones were optimized to reduce idle emissions and the main zones were optimized to reduce high-power NO_x emissions.

The results of the phase II refinement for these combustors are shown in table II-4. The emissions for the baseline combustor and the advanced technology combustor are expressed as percentages of the EPA standard. The EPA parameter (EPAP) values for the advanced combustors were obtained by extrapolation to actual engine operating conditions from test rig conditions. At that time this extrapolation represented the best estimate of each combustor's emissions reduction capability. The Vorbix combustor was estimated to meet EPA standards for unburned hydrocarbons and NO_x and as failing to meet the CO standard. A change in the pilot-zone volume was needed and was used in the phase III engine tests. Such an increase should reduce CO levels to a point below the EPA standard. The double-annular combustor met the CO and hydrocarbon emissions, failing only to meet the NO_x emission. The projected level of NO_x was some 43 percent below that of the baseline combustor. This failure to meet the standard highlights a specific problem area of NO_x emissions, that of engine pressure ratio. As illustrated previously, higher engine pressure ratio increases NO_x emissions due to the combined effects of pressure and inlet-air temperature on flame temperature. Advanced technology can reduce the NO_x emissions, but eventually pressure ratio effects may dominate. Comparing NO_x emissions from the JT9D engine and the CF6 engine reflects the pressure ratio trend. The Vorbix combustor in the JT9D-7 at a pressure ratio of 22 meets the EPA standard; the double-annular combustor in the CF6-50 at a pressure ratio of 30 fails to meet the standard.

The Emissions Reduction Technology Program was begun to determine whether low-emissions combustor concepts could be adapted to existing gas turbine engines. The program is nearly complete; and subsequent papers review the progress and status of those efforts.

EMISSIONS REDUCTION TECHNOLOGY PROGRAM
SCOPE

EPA ENGINE CLASS	ENGINE	MANUFACTURER
T1 - TURBOFAN < 8000 lb TH	TFE-731-2	GARRETT AIRESEARCH
T2 - TURBOFAN > 8000 lb TH	CF6-50 JT9D-7	GENERAL ELECTRIC PRATT & WHITNEY
T4 - JT8D ENGINES	JT8D-17	PRATT & WHITNEY
P2 - TURBOPROP	501-D22A	DETROIT DIESEL ALLISON

CS-77-394

Table II-1.

EMISSION GOALS
1979 EPA STANDARDS

ENGINE CLASS	ENGINE	THC		CO		NO_X		SMOKE	
		STD	PROD[a]	STD	PROD[a]	STD	PROD[a]	STD	PROD[a]
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

[a]PRODUCTION VALUES, % OF EPA STANDARD.

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Table II-2.

PERFORMANCE GOALS

PARAMETER	ENGINE MODE	PROGRAM GOAL
COMBUSTION EFF	ALL	99%+
PRESSURE LOSS	CRUISE	6%
PATTERN FACTOR	TAKEOFF/CRUISE	0.25
ALTITUDE RELIGHT	WINDMILLING	ENGINE RELIGHT ENVELOPE
DURABILITY	ADEQUATE AT ALL ENGINE CONDITIONS	

CS-69628

Table II-3.

SUMMARY OF CLASS PROGRAM RESULTS
PHASE II: COMBUSTOR REFINEMENT

	THC	CO	NO_X
	EMISSION LEVEL, % OF 1979 EPA STANDARD		
PRATT & WHITNEY JT9D-7 ENGINE:			
CONVENTIONAL COMBUSTOR	488	198	197
VORBIX COMBUSTOR	38	151	73
GENERAL ELECTRIC CF6-50 ENGINE:			
CONVENTIONAL COMBUSTOR	538	251	257
DOUBLE-ANNULAR COMBUSTOR	38	70	142

Table II-4.

TYPICAL ENGINE EMISSION CHARACTERISTICS

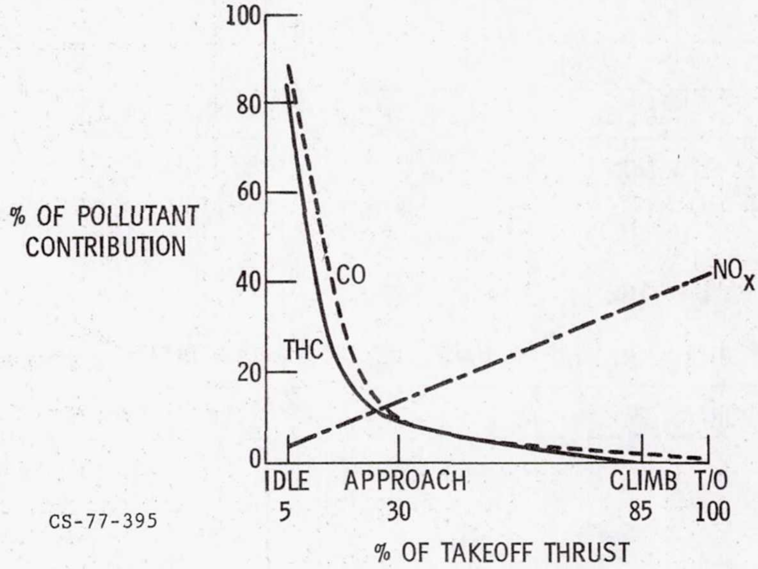

Figure II-1.

NO_x EMISSIONS WITH COMBUSTOR–INLET TEMPERATURE

6 ATM COMBUSTOR PRESSURE

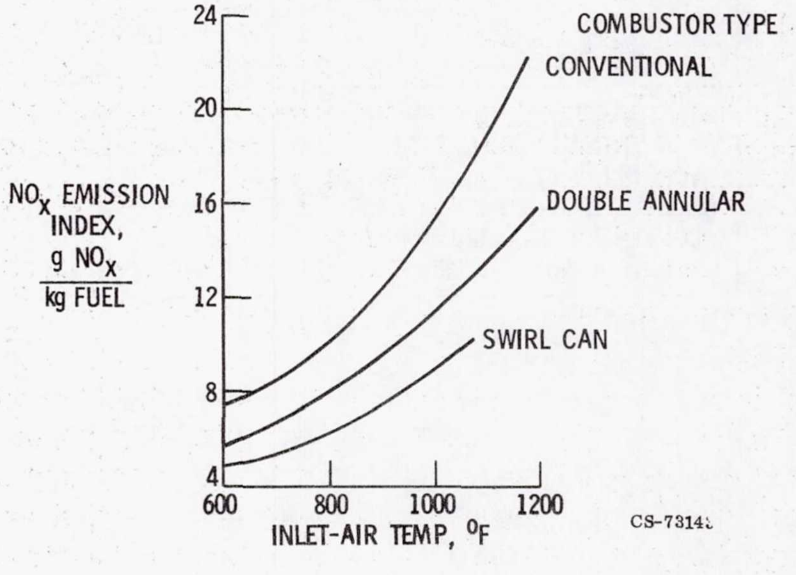

Figure II-2.

DOUBLE-ANNULAR COMBUSTOR

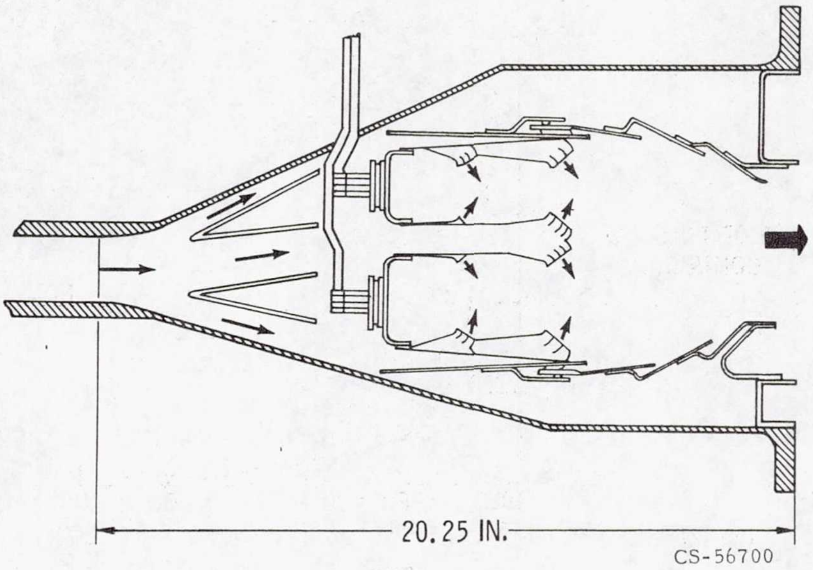

Figure II-3.

EXPERIMENTAL MODULAR COMBUSTOR

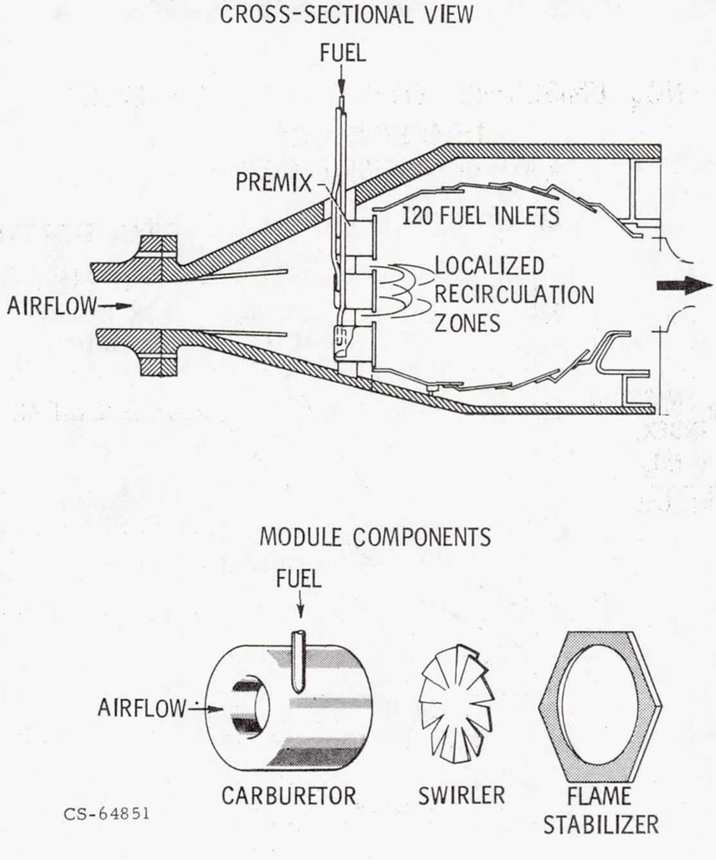

Figure II-4.

HIGH TEMPERATURE SWIRL CAN COMBUSTOR

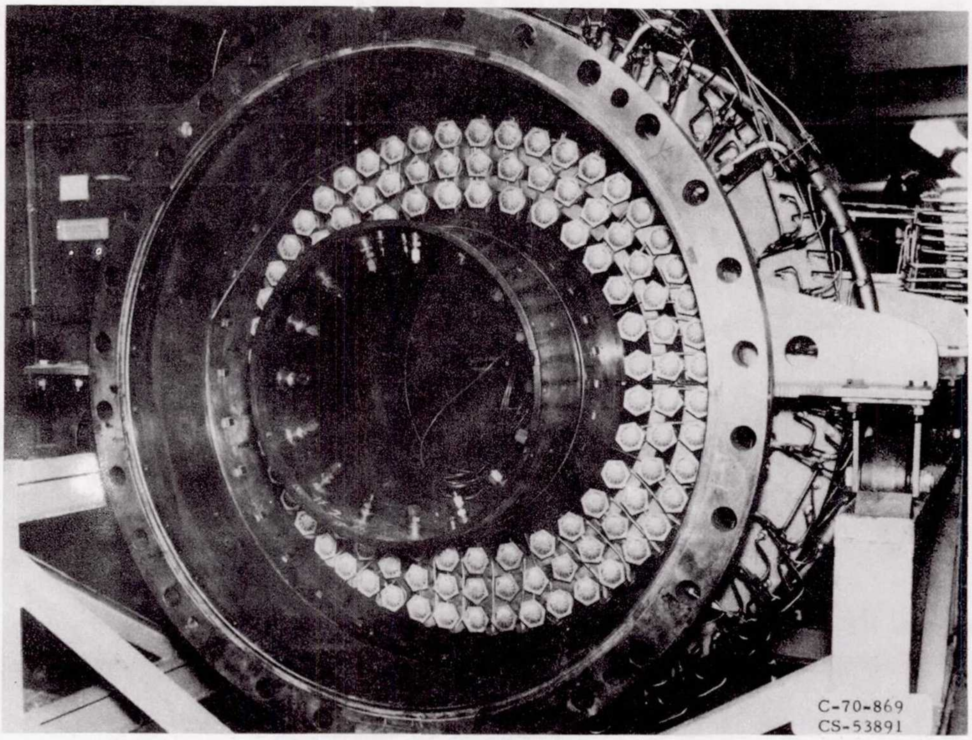

Figure II-5.

AIR–ASSIST FUEL INJECTION

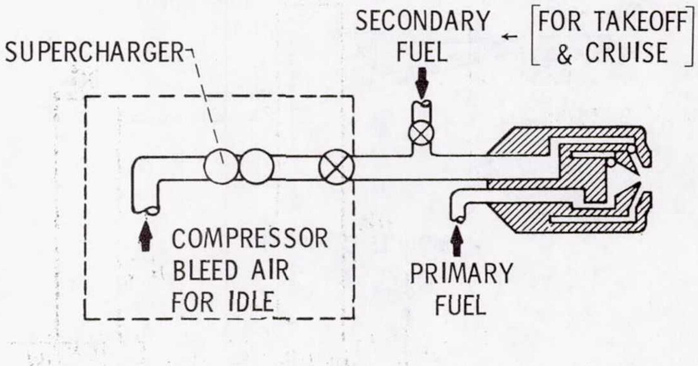

Figure II-6.

EFFECT OF IMPROVING FUEL ATOMIZATION

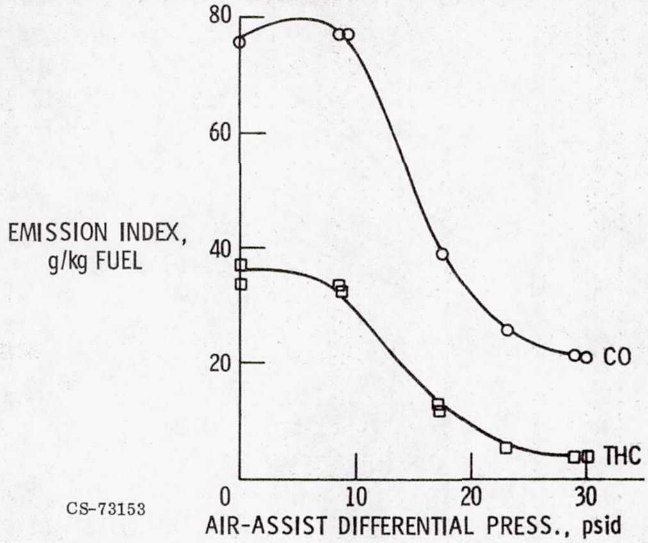

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Figure II-7.

EFFECT OF FUEL AND AIRFLOW SCHEDULING ON IDLE EMISSIONS

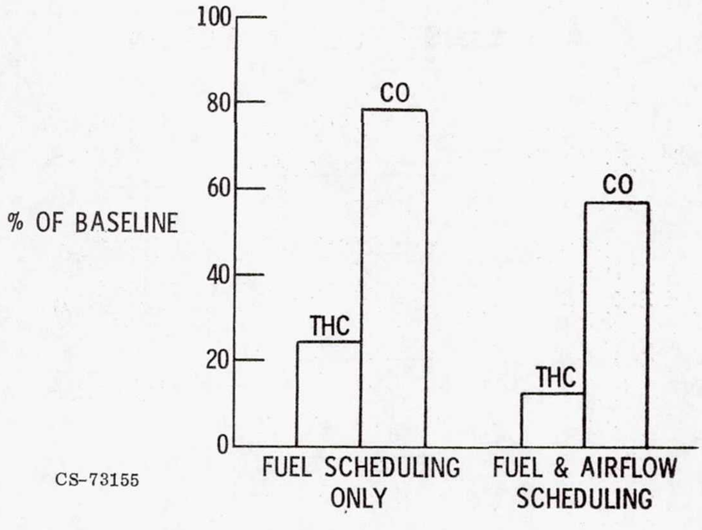

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Figure II-8.

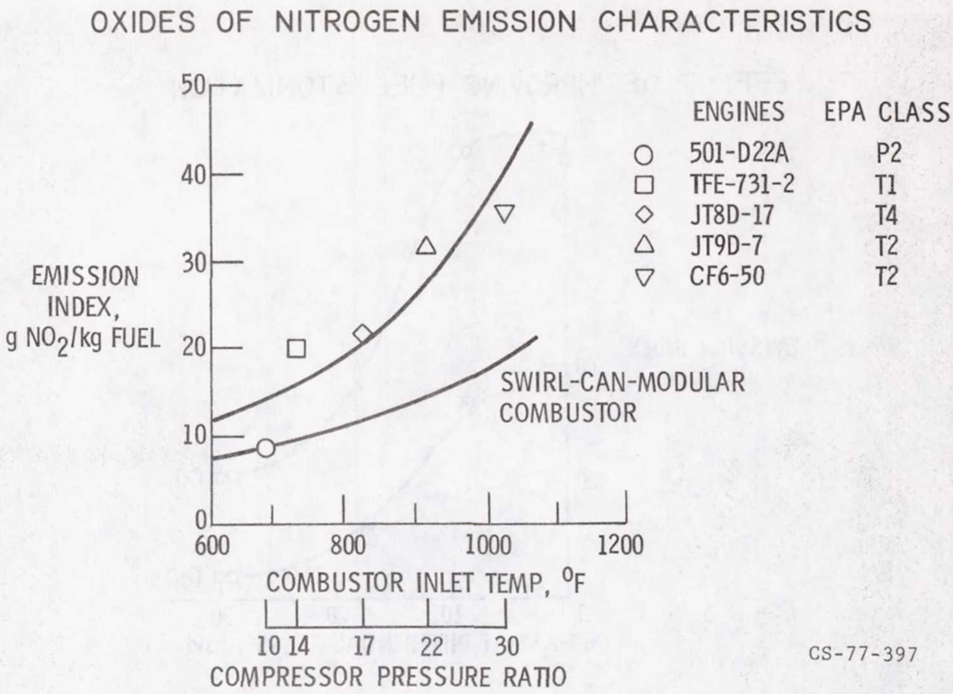

Figure II-9.

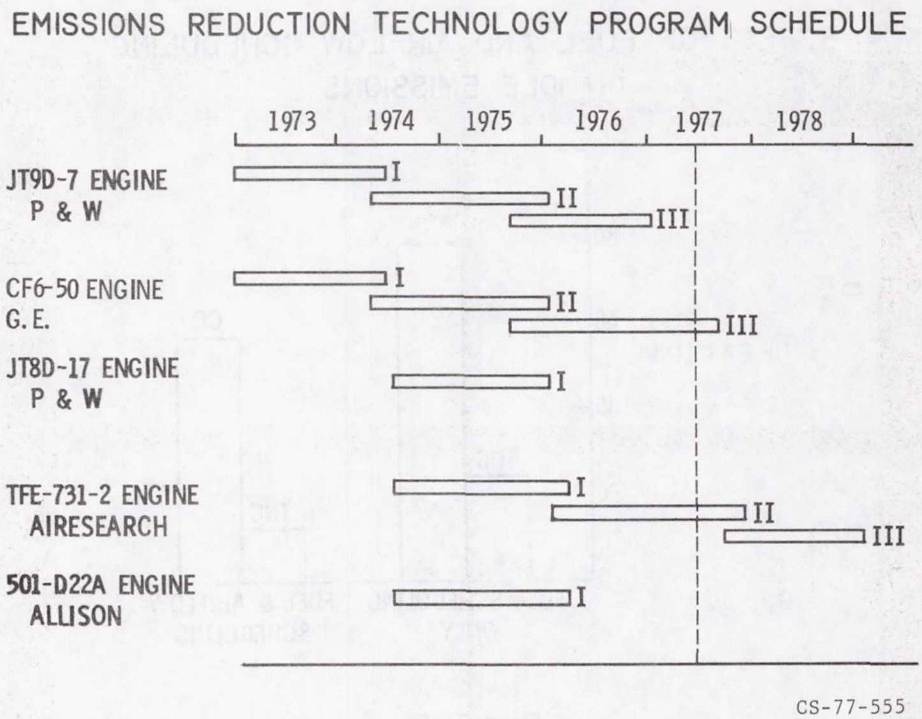

Figure II-10.

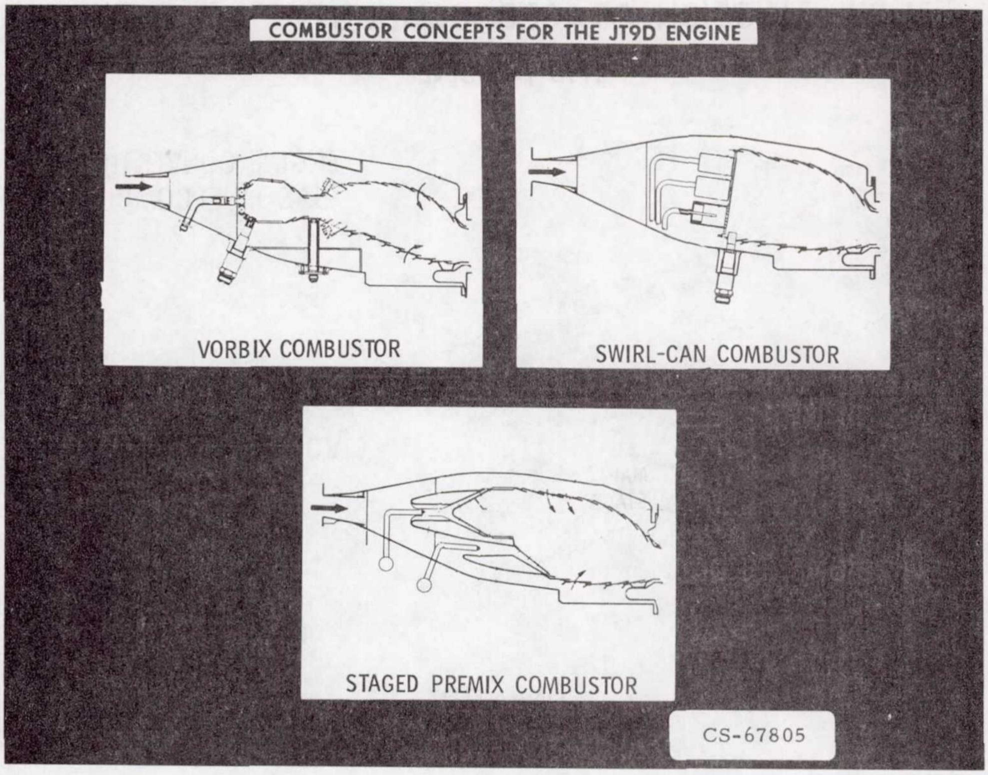

Figure II-11.

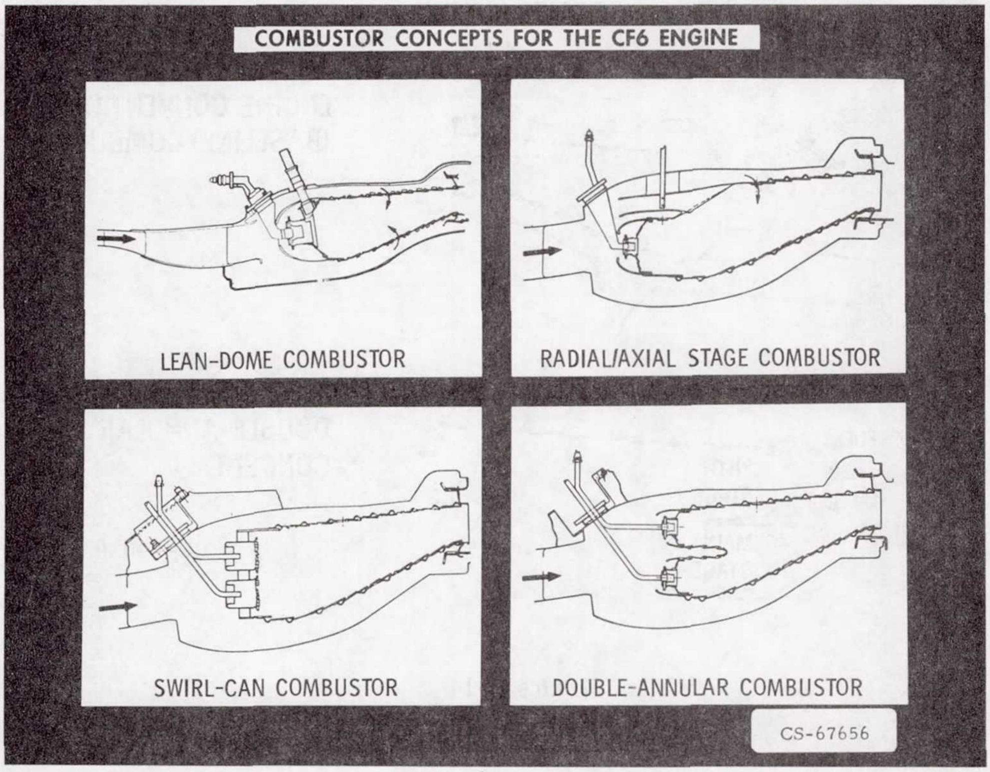

Figure II-12.

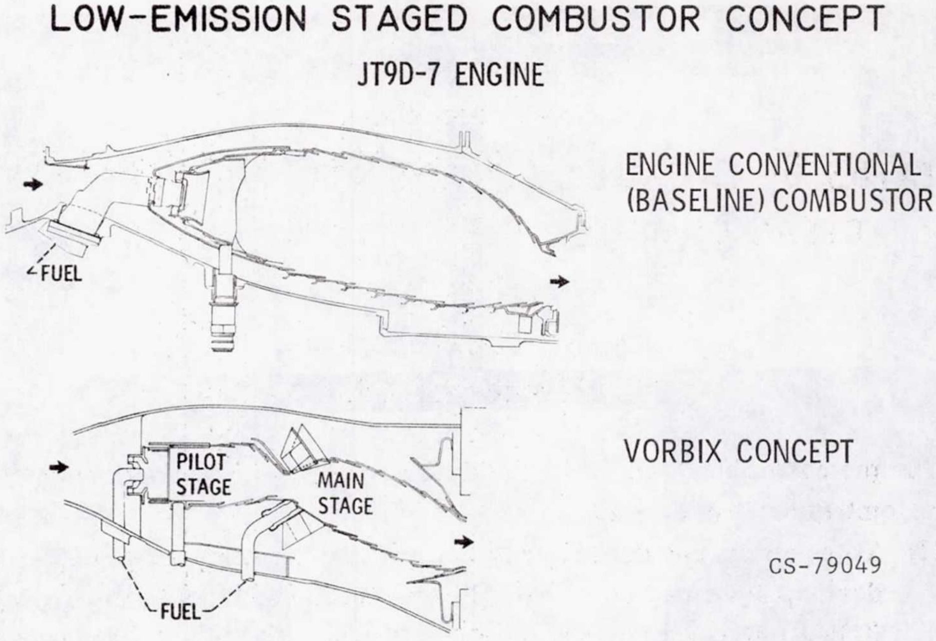

Figure II-13.

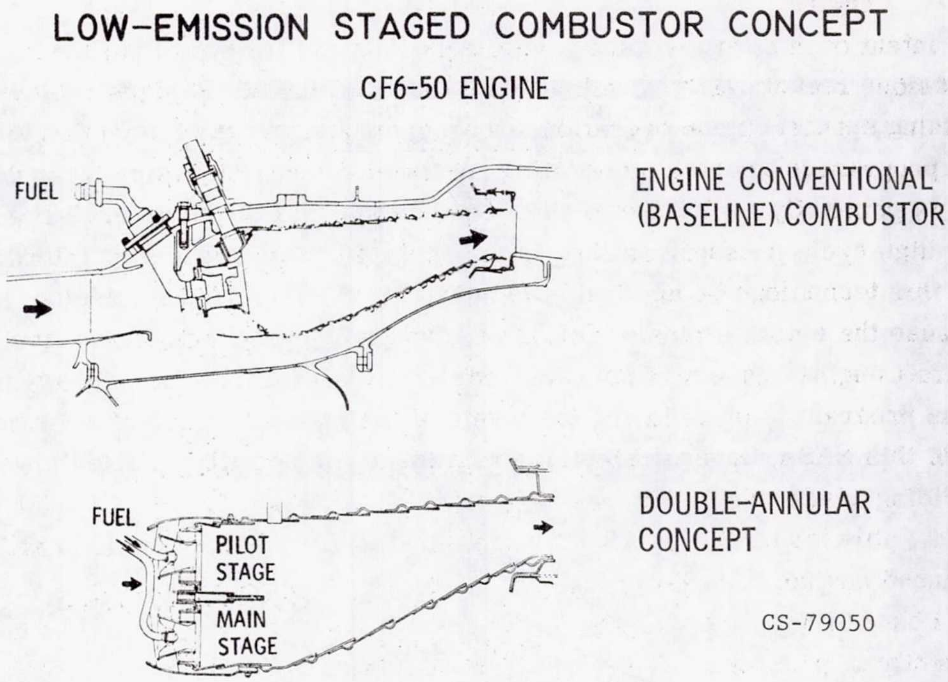

Figure II-14.