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Technical Report

Aircraft Technology Assessment: Progress in Low Emissions Engine

by

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NOTICE

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Summary

This report is the third in a series whose purpose is to evaluate the potential of various control techniques to reduce emissions, to assess the practicality of such techniques on commercially acceptable engines, and to estimate the time frame in which such techniques can be made available. As this document is the latest and, as such, reviews the situation after the greatest development effort has been made, it reflects more nearly the eventual outcome of the many industry and government programs now in progress.

This report concludes:

1) NOx control for high pressure ratio engines remains in an early stage of development with insufficient control of all four (HC, CO, NOx and smoke) pollutants available and airworthy hardware uncertain.

2) Although substantial reductions in CO can be attained (∿70%), compliance with the proposed standard would require greater reductions (∿80%).

3) Smoke control is well understood, but its control is compromised somewhat by the control for HC and, especially, CO.

4) HC control to the level required is readily achievable only if sector burning is permitted for some engines.

5) The control of HC and CO by sector burning at idle is very effective, but possesses unresolved problems of reliability which, in turn, impact the economics and potentially the safety of the engines.

Section I

FOREWORD

On July 17, 1973, regulations controlling the gaseous and smoke emissions form aircraft engines were promulgated.(3) The fuel venting requirement and certain specific smoke standards are already in force; the principal gaseous pollutant standards originally scheduled for 1979 have now been delayed. The interval between the promulgation date and the compliance date is intended to permit the development of the requisite technology, and in the case of retrofit, for the orderly installation of the new hardware onto the in-use engines.

Two previous reports have been issued (4 and 5) which review the status of the development of the control technology and this report, the third in the series, constitutes an update to the second. This update is required to provide technical support data for the comprehensive review and revision of the standards that is now underway.(6)

Because this report is only an updating of the previous one (5), it is abbreviated. It attempts only to correct obsolete data and analyze particular points relevant to the unanswered issues confronting the revision of the standards.

Section II

INTRODUCTION

Section 231 of the Clean Air Act, as amended by Public Law 91-604, directs the Administrator of the Environmental Protection Agency to:

(1) investigate emissions of air pollutants from aircraft to determine the extent to which such emissions affect air quality and to determine the technological feasibility of control, and

(2) establish regulations for the control of emissions from aircraft or aircraft engines if such control appears warranted in the light of the investigation referred to above.

Furthermore, the Clean Air Act states that any such regulations can take effect only after sufficient time has been allowed to permit the development and application of the requisite technology.

The EPA has complied with both mandates of the Clean Air Act, first, by publishing a report, "Aircraft Emissions: Impact on Air Quality and Feasibility of Control" (1), which concluded that the impact on air quality by aircraft was sufficient to justify control and that such control was technologically feasible, second, by publishing a report, "Assessment of Aircraft Emission Control Technology" (2), which offered the best projection at that time of the feasibility of control with the knowledge then available, and third, by promulgating standards limiting the emissions from aircraft engines (3).

In keeping with the spirit of the instructions to determine the technological feasibility of control and to the time required to permit the development and application of the technology, the EPA established an Aircraft Technology Assessment Program for the purpose of monitoring the many programs for the development of the low emissions technology for aircraft gas turbine engines. This program for gas turbines was begun in July 1974 and has produced two previous reports, "Aircraft Technology Assessment - Interim Report on the Status of the Gas Turbine Program, December, 1975" (4), and "Aircraft Technology Assessment - Status of the Gas Turbine Program, December, 1976" (5).

In March, 1978, the EPA published a Notice of Proposed Rulemaking (6) offering considerable revisions to the existing regulations (3). These revisions were based upon reviews of aircraft air quality impact, economic impact, and technology limitations, the latter being based upon reference 5 and additional material supplied by the industry, NASA, and the U.S. Air Force in the intervening period between the publication of reference 5 and the NPRM (6). The NPRM proposes, among other things, to restrict compliance with the gaseous emissions standards to commercial jet engines of sufficient size and frequency of operation as to warrant their control. This report limits itself to the assessment of the technology involved in those commercial engines which are likely to be affected by the proposed regulations. Emissions control technology for engines not affected by the proposed standards for gaseous emissions as and II-2 present the existing and proposed standards in both the old, english unit format and the new, metric unit format.

The classes of engines referred to in the standards were established by the EPA to categorize the engines according to technical, economic, and safety constraints. In the proposed standards, the subsonic jet classifications become less meaningful in that the gaseous pollutant standards, like the smoke standards, are monotonic and analytic functions of size (thrust) and are not discontinuous at the class demarcations. For reference, the classes are listed in Table II-3.

The emissions levels permitted by the standards are described by an EPA parameter (EPAP) which is defined in the aircraft regulations. Briefly, it is a measure of the total emission of a particular pollutant produced by an engine over a typical landing-takeoff (LTO) cycle normalized with respect to the useful output of the engine over that cycle. As such, larger engines performing greater useful work are permitted proportionally larger amounts of total emissions over smaller engines. The proposed standards changed the definition of EPAP by considering the useful output of the engine to be its rated power rather than, as originally, the total work (integrated thrust times time over the cycle) or total engergy (integrated power times time over the cycle) as appropriate to each class. As a result, the standards no longer give implicit credit to a high idle point (given because a high idle point increases the useful output term in the demonimator in the calcultation of the total work based EPAP, thereby lowering the emissions rating relative to the standards).

TABLE II-1

Comparison Between Original and Proposed Standards
(English Units)

Newly Manufactured Engine Standards

	Original Standard (All Engines) 1979					Proposed Standard (Commercial Only) 1981			1984	1981 (4)
Class	Size	HC	CO	NOx	Smoke	Size	HC	CO	NOx	Smoke
T1	0-8,000 lbs.	1.6*	9.4	3.7	(1)	<6,000 lbs.	No standard			Same
T2,3,4	>8,000 lbs	0.8*	4.3	3.0	(1)	6-20,000 lbs	2.1-0.8	12.9-4.3	4.0(2)	Same
						>20,000 lbs	0.8	4.3	4.0(2)	Same
T5	All (1980)	3.9*	30.1	9.0	(1)	All (1980)		Same		
P2	All	4.9**	26.8	12.9	(3)	All		Deleted		Same
APU	All	0.4***	5.0	3.0	-	All		Deleted		-

Newly Certified Engines Standards

	Original Standard (All engines) 1981				Proposed Standard (Commercial Only) 1984			
Class	Size	HC	CO	NOx	Size	HC	CO	NOx
T1	0-8,000 lbs		No standard		<6,000 lbs	0.4	3.0	4.0
T2,3,4	>8,000 lbs	0.4*	3.0	3.0	>6,000 lbs	0.4	3.0	4.0
T5	All(1984)	1.0*	7.8	5.0	All		Same	
P2	All		No standard		>2,700 HP	0.8**	6.4	8.4

(1) $SN = 331.8 \text{ (lbs. thrust)}^{-0.265}$ (Presented graphically in original standards).

(2) With additional allowance for PR > 25.

(3) $SN = 300.7 \text{ (HP)}^{-0.280}$

(4) All engines, not just commercial.

* Pounds of pollutant per 1000 pounds thrust-hour per cycle.

** Pounds of pollutant per 1000 HP-hour per cycle.

***Pounds of pollutant per 1000 HP-hour.

Table II-2

Comparison Between Original and Proposed Standards
(Metric Units)

Newly Manufactured Engine Standards

	Original Standard (All Engines) 1979					Proposed Standard (Commercial Only) 1981			1984	1981 (4)
Class	Size	HC	CO	NOx	Smoke	Size	HC	CO	NOx	Smoke
T1	0-36 KN	13.4*	78.9	31.1	(1)	<27 KN	No Standard			Same
T2,3,4	>36 KN	6.7*	36.1	25.2	(1)	27-90 KN	17.6-6.7	106.6-36.1	33.0(2)	Same
						>90 KN	6.7	36.1	33.0(2)	Same
T5	All (1980)	30.7*	237.0	70.8	(1)	All (1980)	Same			
P2	All	0.26**	1.43	0.69	(3)	All	Deleted			Same
APU	All	0.24***	3.0	1.8	-	All	Deleted			-

Newly Certified Engine Standards

	Old Standard (All Engines) 1981				Proposed Standard (Commercial Only) 1984			
Class	Size	HC	CO	NOx	Size	HC	CO	NOx
T1	0-36 KN	No Standard			<27 KN	No Standard		
T2,3,4	>36 KN	3.3*	25.0	25.0	>27 KN	3.3	25.0	33.0
T5	All (1984)	7.8*	61.0	39.0	All	Same		
P2		No Standard			>2000 KW	0.045**	0.34	0.45

(1) $SN = 79 \text{ (Rated Kilonewtons)}^{-0.265}$ (Presented graphically in original standards).

(2) With additional allowance for PR > 25.

(3) $SN = 277 \text{ (Rated Kilowatts)}^{-0.280}$ (Presented graphically in original standards).

(4) All engines, not just commercial.

Table II-3

Summary of Aircraft Classes

Class	Type	Aircraft Application
P1	Piston engines (exluding radials)	Light general aviation.
P2	Turboprop engines	Medium to heavy general aviation; some commercial air transport
T1	Small turbojet/fan engines (0-36 KN thrust)	General aviation jet aircraft
T2	Large turbojet/fan engines intended for subsonic flight (greater than 36 KN thrust)	Commercial subsonic transports
T3, T4	Special classes applying to specific engines for the purpose of instituting early smoke standards	Commercial subsonic transports
T5	Turbojet/fan engines intended for supersonic flight	SST
APU	Gas turbine auxiliary power units	Many turbojet/turboprop transports and business jets

It is worthwhile to review the present aircraft emissions situation in order to give the reader some perspective of the demand that the regulations impose on the industry. The emissions performance of current production engines is presented first. Table II-4 presents a list of all production and development engines and for each engine, the standards to which it must now comply, the proposed levels, the emissions performance in the present production (or baseline) configuration, the manufacturer, and an estimate of the engine's production potential, as defined below, which crudely measures the likelihood that the manufacturer will attempt to comply. In addition, Figures 1-4 present in graphical form the same emissions information. The relevant standards for these engines are, of course, the standards for newly manufactured engines, not those for newly certified engines as these engines are either already certified or are expected to be certified prior to the compliance date for such engines.

Production potential is not usually available in hard figures. Generally, though, the production of all engines can be grouped into four categories for EPA purposes:

Table II-4
Summary of Engines and Their Emissions

Class	Engine	Size	Mfr****	HC	CO	NOx	Sk	Production (1981)
T1	1979 Std.	0-35.6 KN		Var.	Var.	Var.	Var.	
Production Engines:								
	TFE 731-2	15.5 KN	AR	46.6/* **	159/*	43.0/*	47/38.2	III
	TFE 731-3	16.5 KN	AR	21.6/*	129/*	52.6/*	51/37.6	III
	JT15D-4	11.1 KN	PWAC	123/*	330/*	35.8/*	14/41.7	III
	JT12A-8	14.7 KN	P&WA	47.1/*	770/*	29.0/*	/38.8	I
	CF700-2D	19.2 KN	GE	97.1/*	861/*	20.2/*	24/36.1	II
	CJ610-2C	13.1 KN	GE	159/*	1450/*	25.2/*	33/40	I
	ALF502D	28.9 KN	LY	14.8/17.0	112/103	28.8/33.0	25/32.4	IV
	M45H	32.4 KN	RR/SN	162/16.2	526/97.1	31.7/33.0	46/31.4	III-IV
	Viper 600	16.7 KN	RR	156/*	924/*	16.3/*	/37.5	I
New Engines:								
	RB401-07	24.6 KN	RR	1.9/*	96.9/*	34.2/*	/33.8	IV
	ATF3	22.2 KN	AR	52.5/*	153/*	37.1/*	/34.7	IV
	ALF502L	33.4 KN	LY	28.6/15.9	136.0/95.5	32.3/33.0	25/32.2	IV
T2, T3, T4	1979 Std	>35.6 KN		6.7	36.1	33.0 + Pressure Corr.	Var.	
Production Engines:								
	JT9D-7	205 KN	P&WA	61.0/6.7	98.5/36.1	61.8/33.0	4/19.3	III
	JT9D-70	228 KN	P&WA	26.0/6.7	87.5/36.1	54.3/33.0	8/18.8	III
	CF6-6D	178 KN	GE	43.3/6.7	96.5/36.1	65.7/33.0	16/20	III
	CF6-50C	222 KN	GE	63.0/6.7	119.5/36.1	60.8/38.1	13/18.9	III
	RB211-22B	187 KN	RR	134.6/6.7	172.3/36.1	51.9/33.4	10/19.8	III
	RB211-524	218 KN	RR	110.4/6.7	145.1/36.1	61.4/34.6	12/19	III
	Spey511	50.7 KN	RR	278.4/12.2	435.8/70.9	68.1/33.0	66/27.9	I-II
	Spey555	43.8 KN	RR	441/13.6	420/79.8	49.5/33.0	/29.0	I-II
(T3)	JT3D-7	84.5 KN	P&WA	356/7.3	294/39.7	31.0/33.0	/24.4	I
(T4)	JT8D-9	64.5 KN	P&WA	35.1/9.9	124.5/55.9	52.2/33.0	23/26.2	II
	JT8D-17	71.2 KN	P&WA	37.3/8.9	112.7/49.9	60.1/33.0	24/25.5	II

Table 11-4 continued

Class	Engine	Size	Mfr****	HC	CO	NOx	Sk	Production (1981)
New Engines:								
	RB410	68.5 KN	RR	/19.3	/52.2	/33.0	/25.8	IV
	RB432	71.2 KN	RR	/8.9	/49.9	/33.0	/25.5	IV
	RB211-535	163 KN	RR	32.4/6.7	96.6/36.1	49.0/33.0	/20.5	IV
	CF34	40.0 KN	GE	53.1/15.4	205/85.2	24.9/33.0	20/30.7	IV
	CFM56	107 KN	GE/SN	12.0/6.7	79.5/36.1	42.8/33.0	/22.9	IV
	CF6-32	157 KN	GE	48.1/6.7	102.1/36.1	69.1/33.0	/21.1	IV
	CF6-80	213 KN	GE	55.0/6.7	/36.1	/45.2	/19.1	IV
	JT10D-4	129 KN	P&WA	/6.7	/36.1	/***	/21.8	IV
(T4)	JT8D-209	82.3 KN	P&WA	/7.5	/41.2	/33.0	/24.5	IV
(T4)	JT8D-217	92.0 KN	P&WA	/6.7	/36.1	/33.0	/23.8	IV
T5	1980 Std	All		30.7	237.0	70.8	Var.	
Production Engines:								
	OLY593-610	171 KN	RR/SN	129/30.7	530/237	70.1/70.8	32/25	II

* No Standard to be met

** xx/xx - (Actual performance)/(Proposed NME Standard)

*** Insufficient data to compute standard, probably 33.0.

**** AR = AiResearch
PWAC = Pratt & Whitney Aircraft of Canada
P&WA = Pratt & Whitney Aircraft
GE = General Electric
LY = Lycoming
RR = Rolls Royce
SN = SNECMA

Production Category	Situation
I	Engines already out of production; engines certain to be out of production by the compliance date for newly manufactured engines.
II	Engines at or near the end of their production, run by the compliance date. The few, if any, units produced after that would not be sufficient to amortize the development and certification cost of a low emissions combustor.
III	Engines in the broad middle of their production run. It is possible to amortize the necessary development and certification costs for emissions control over the remaining production. It is equally possible to consider a cost-effective retrofit of the units produced prior to the compliance date; there are sufficient units to amortize that development and certification costs and to realize air quality gains.
IV	Engines beginning their production run shortly before or after the compliance date for newly manufactured engines. There would likely be insufficient engines built prior to the deadlines to warrant a retrofit program.

HYDROCARBON EMISSIONS VS. RATED THRUST-PRODUCTION ENGINES

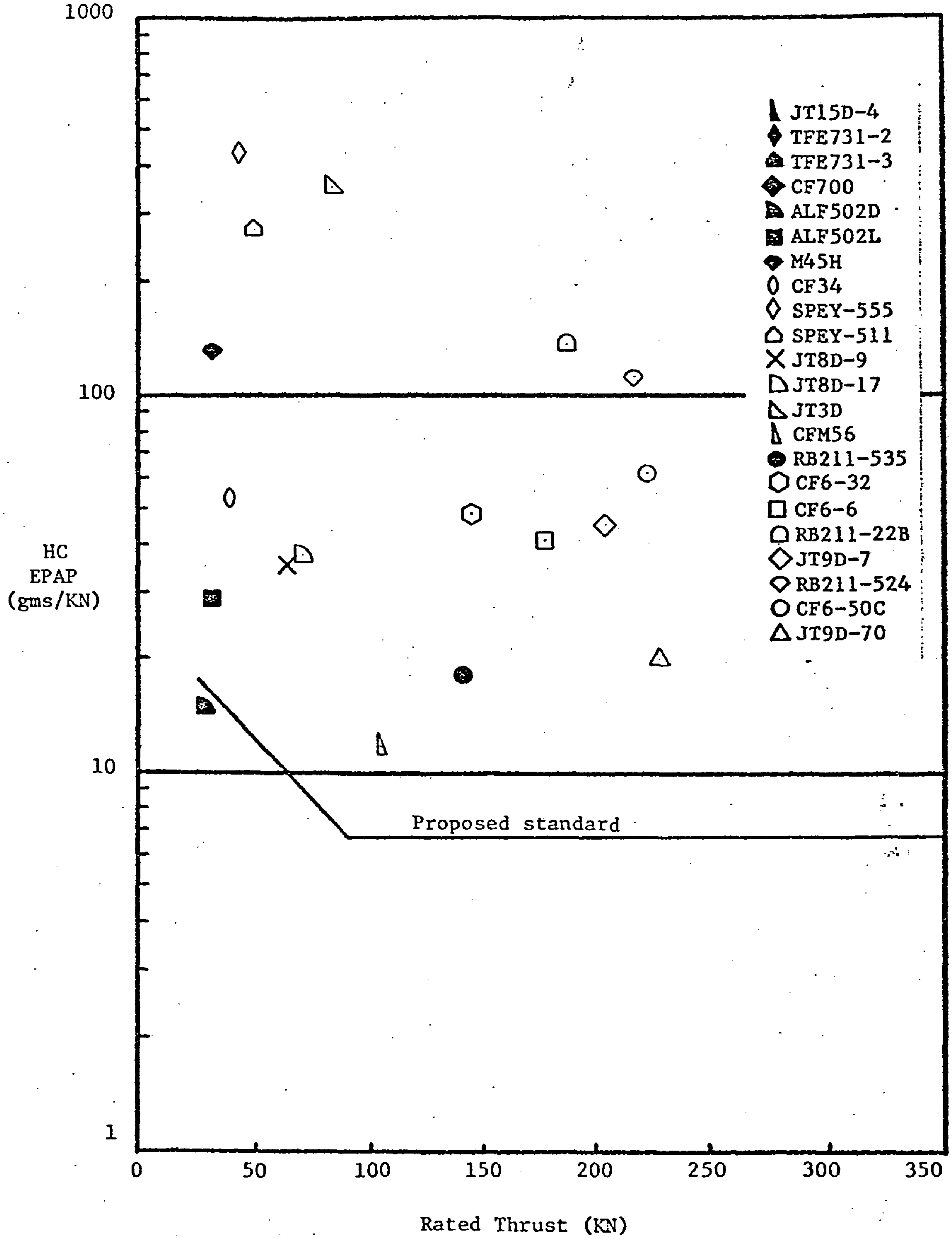


Figure 1

CARBON MONOXIDE EMISSIONS VS. RATED THRUST - PRODUCTION ENGINES

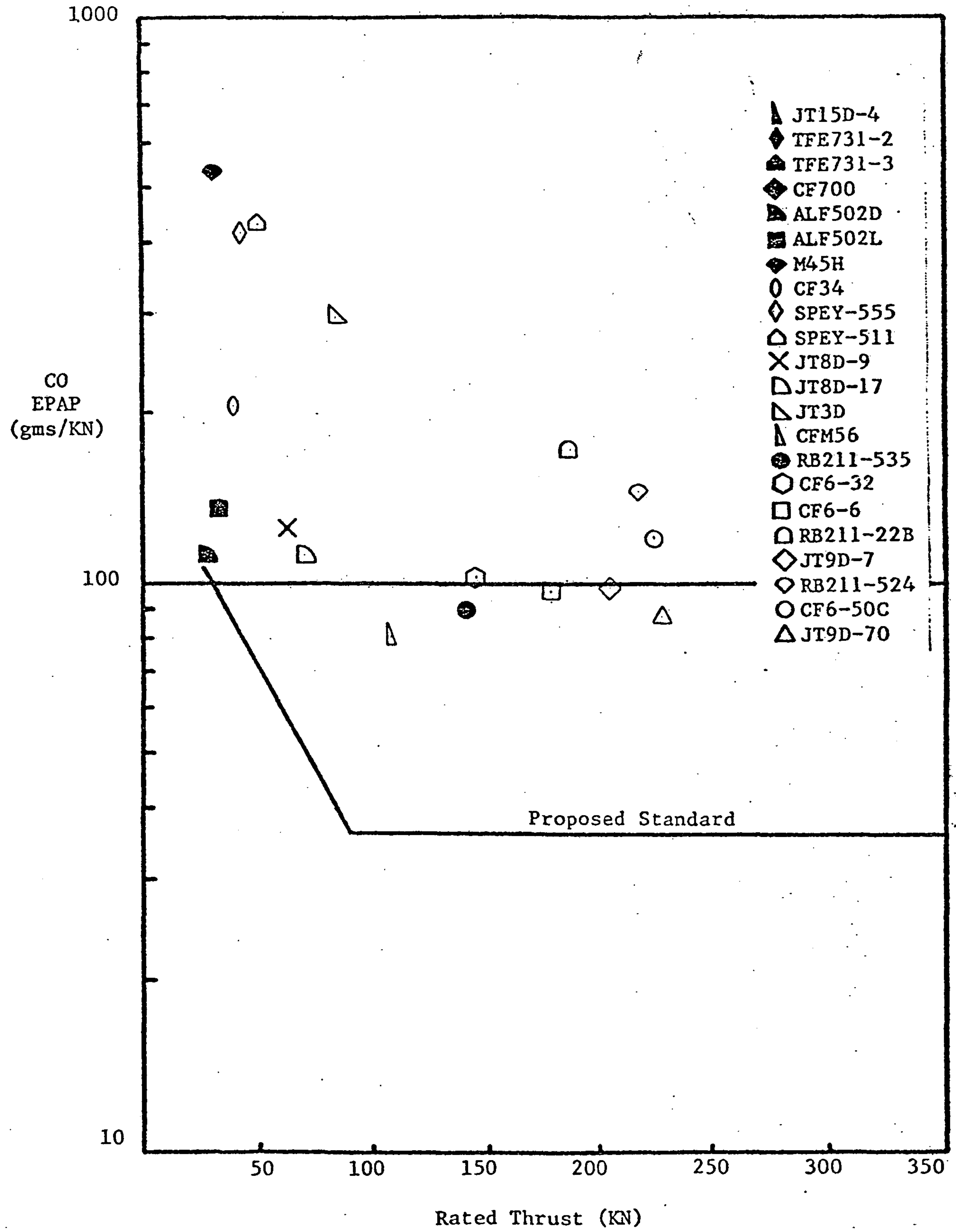


Figure 2

SMOKE EMISSIONS VS. RATED THRUST -
PRODUCTION ENGINES

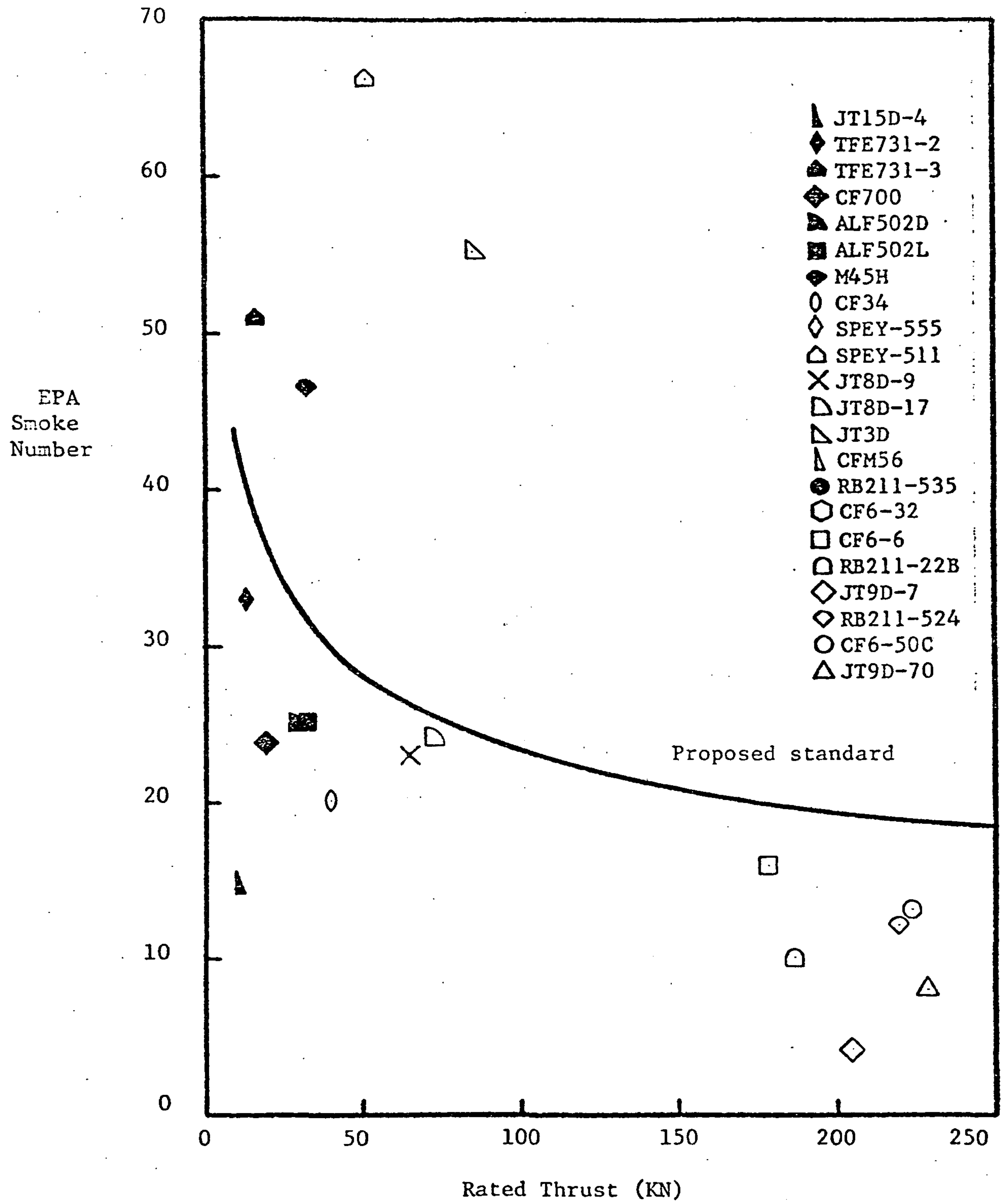


Figure 4

OXIDES OF NITROGEN EMISSIONS VS.
RATED THRUST -PRODUCTION ENGINES

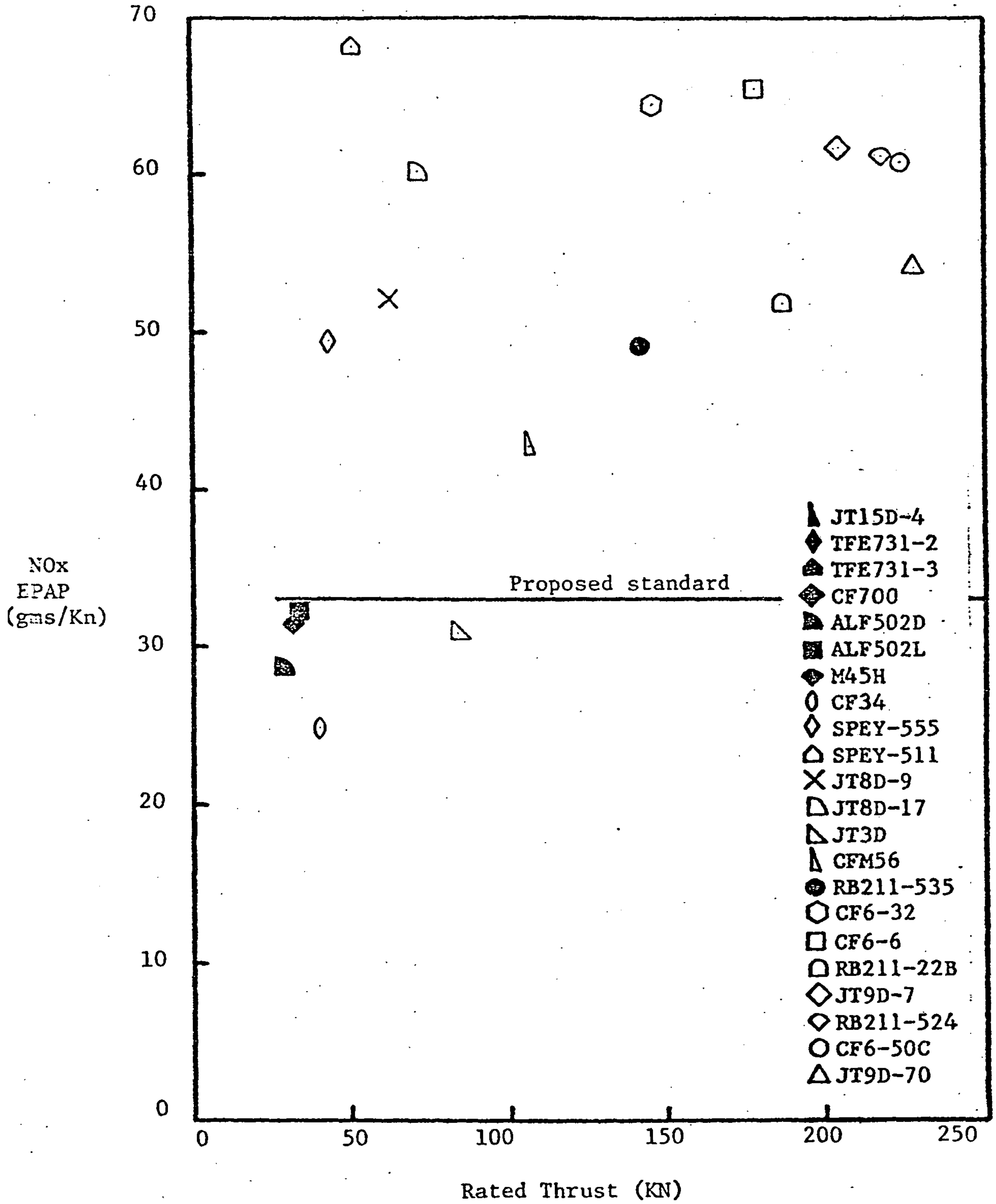


Figure 3

Section III

EMISSIONS CONTROL TECHNOLOGY

There are four pollutants of interest here: the chemical species, CO; the combination of the species NO + NO_2, collectively called NOx (the latter species is the actual pollutant insofar as the formation of smog and toxicity are concerned, but the former will eventually combine with atomospheric O_2 to form the latter at atmospheric temperature due to equilibrium chemistry considerations); the collective group of species of various non-oxygenated hydrocarbons, either raw fuel compounds or compounds created by the cracking, decomposition, pyrolyzing, or polymerization of the fuel, all of which are simply called hydrocarbons or HC.

HC and CO are both products of and occur principally under low power operating conditions conducive to incomplete combustion. Low power operation results in low temperatures and pressures which lead to the chemical reaction rates requiring more time for completion than is available before the fuel-air mixture exists the combustor; thus, the fuel is exhausted from the engine combustor and cooled before it has had a chance to burn completely. In addition, the low temperatures coupled with the lean mixture conditions at idle (very low fuel flow) may lead to regions near the edge wherein the reactions are quenched completely.

Beyond that, the low gas pressure and the low fuel flow requirement lead to poor atomization of the fuel and poor mixing with the air which in turn cause pockets of excessively ruch (no oxygen for burning) or excessively lean (too weak to burn) mixture of fuel and air, both of which will lead to incomplete combustion and hence the emission of unburned or partially burned fuel (HC and CO).

Smoke also is a product of incomplete combustion, but its formation is likely to occur at high temperature and pressure (i.e., high power) if pockets of excessively rich (insufficient O_2) mixture occur. Under this circumstance, the fuel in the pocket cannot burn (because of lack of O_2), but instead pyrolyzes in the hot, high pressure environment laving basically microscopic carbonaceous matter, possibly also coated with a heavy hydrocarbon residue.

NOx, on the other hand, is a product of an unintentional reaction which occurs only at high temperatures (i.e., high power) and with ample O_2, namely the oxidation of nitrogen either from the air itself (the usual case) or from nitrogen bound in the fuel. Unlike the others, once formed it cannot be consumed as it is a final reaction. Fortunately, at the temperatures experienced in gas turbines, the reaction proceeds relatively slowly so as the gas is exhausted, the NOx levels are usually well below equilibrium.

The control of these pollutants is achieved through various mechanisms depending upon the nature of their formation. HC and CO, both being products of incomplete combustion are often treated together. However, HC consumption is fast (producing CO and H_2O, plus intermediate radicals) and occurs in the primary zone of the combustor, whereas CO oxidation is a relatively slow reaction and occurs in the intermediate zone downstream where additional air has been added. Thus, it becomes possible and indeed necessary occasionally to consider the two separately. In any case, control is achieved by enhancing the combustion rates, increasing the residence time in the environment most favorable to combustion, or by improving the mixing of the fuel-air mixture to better utilize the existing potential for reaction. Proper fuel preparation, including thorough atomization and correct spray distribution is particularly useful in controlling HC, but it may also influence the CO levels to a lesser degree.

On the other hand, NOx control is achieved by mechanisms which discourage the oxidation reactions of the fuel bound or atmospheric nitrogen. This is achieved by avoidance of high temperatures (>1800°K) with an ample supply of oxygen. While theoretically simple, such an approach is difficult to implement practically for such will generally lead to operational problems (e.g., flame stability) or excessive low-power emissions or possibly both.

Smoke, while also a pollutant of incomplete combustion like HC and CO, arises from the presence of a different set of conditions and requires a different means of control. Control is achieved either by avoidance of the condition which forms smoke (hot and rich) or by careful tailoring of the airflow distribution in the aft portion of the combustor so that the particulate matter is consumed after it has formed.

Table III-1 lists all the relevant control techniques for aircraft gas turbine engines. The techniques are grouped into HC and CO control on one hand and NOx control on the other. Control techniques can be classified into four broad categories: (1) operational control, (2) fuel preparation, (3) airflow distribution, and (4) staging. Water injection and catalysis are specialized categories which are not of practical significance at this point. A detailed description of each control method is also presented in Appendix A.

Each technique differs in its capacity (or effectiveness) to control each of the pollutants. Similarly each technique has its own level of sophistication (complexity). Beyond these factors, it is also imperative to consider the breadth of utility of each control method (i.e., the extent of application in the inventory of engines) and its impact on both the engine and the airframe. For this purpose, a rating system is established. The system evaluates each of the criteria mentioned above on a scale of one to four. The implications of each number for each of the criteria are summarized in Table III-2. Finally, in Table III-3 are the actual ratings for the various control methods as assessed by EPA. In addition, the expected effect of each technique on smoke production is noted.

Control Technique	Basis	Comment
Operational		
(1) Idle speed	Higher pressure ratio and hotter flame.	Fuel penalty, noise, exessive braking.
(2) Air bleed	Hotter flame and longer residence time.	Fuel penalty, noise, extra valving and ducting for excess air.
Fuel Preparation		
(3) Spray Improvement	Atomization and distribution of fuel to eliminate excessively rich or lean spots flame.	Very simple if effective. Formation of carbon and smoke must be watched. May aid in NOx control (See (15)).
(4) Air blast	Atomization and distribution of fuel to eliminate excessively rich or lean spots in flame through use of air jets driven by liner pressure difference.	Usually must be applied in conjunction with air flow redistribution in liner to maintain stoichiometry.
(5) Air assist	Atomization and distribution of fuel to eliminate excessively rich or lean spots in flame through use of externally supplied air jets.	Complex external plumbing and air pump.
(6) Premix	Distribution and vaporization of fuel to eliminate excessively rich or lean spots in flame.	Flashback, flame stabilization problems. Possibly major revision of engine required to accommodate the necessary geometry.
Air Flow Distribution		
(7) Advanced cooling	Prevents quenching the $CO \rightarrow CO_2$ reaction at the liner wall by cooling air.	Has advantages beyond that of lower emissions.
(8) Rich primary*-1	Hotter flame for consuming CO.	Causes smoke formation, but has good flame stability and relight.
(9) Lean primary*-1	Avoids overly rich pockets which create smoke and HC.	Relight and stability problems.
(10) Delayed dilution	Longer residency at high temperature.	Pattern factor and temperature profile adjustment difficult.
Staging		
(11) Sector burning	This approach provides, in actuality, spray improvement (3) and a richer primary (8) at idle without affecting the combustor design at higher powers.	Fuel penalty at idle due to lower turbine efficiency. Additional fuel control complexity.

* Stoichiometry refers to high power condition. Rich at high power means near perfect (f/a ~ .067) at idle. Lean at high power means very lean at idle.

While all of these methods have potential application in at least a few engines, only a few seem to be prominent at this point in meeting the proposed newly manufactured engine (NME) standards for 1981 and 1984. The first is sector burning (method 11) for HC, CO control which was investigated by General Electric and Rolls Royce for use on the GE, CF6, and CFM56 (joint manufacture with SNECMA) engines and the Rolls Royce RB211 engines. In some cases, it alone is inadequate or faulty and requires additional, minor modifications to the spray or to the airflow distribution in order to achieve the full emissions control and proper operational and mechanical performance. In the case of the CFM56, an increase in the idle speed (method 1), an operational technique, is used. The major performance concerns are fuel control maintenance and turbine distress due to the sector burning at idle. New injectors, if needed, may introduce carbon deposition problems. The principal advantage of sectoring is the lack of influence of the control upon the engine and combustor performance in flight. The difficulty with this technique lies in its mechanical complexity which could adversely affect reliability and lead to in-flight malfunction (sectoring in flight is considered dangerous because of possible engine damage or inability to accelerate, depending on the power level).

The second major approach for HC, CO control is selective azimuthal burning (method 22). This is closely related to sector burning, but by dividing the annular into a sufficient number of sectors, the in-flight hazards of sector burning disappear because there are enough burning zones to preserve symmetry: in flight operation is then acceptable. Also, the complexity of the fuel control system and the need for a failsafe mechanism is removed. It offers less emissions control than

Rating of Control Techniques

Factor	1	2	3	4
Control Capacity: (How much control is possible in terms of reduction or absolute level in specific applications for which the system can be effective; how many applications there are for which the control is effective is not considered.)	Very strong control of the pollutants for which intended. Generally capable of bringing these pollutants to below the statutory emission values regardless of the engine in question.	Strong control of the intended pollutants. Generally capable of very effective control, although not necessarily to the levels required by the regulations except in the most favorable situation.	Modest improvement possible.	Minor changes; little effective control.
Complexity: (Exclusive of installation problems or inherent limitations due to peculiar application; reflects only the technical difficulties encountered in getting the system to perform as planned.)	State of the art; little or no difficulties encountered in the development of the concept on most engines for which it would be intended.	Only some moderate difficulty anticipated in the development of the concept, usually associated with combustor durability or performance; development straightforward.	A number of difficulties must be overcome in developing flightworthy hardware; preservation of other design criteria requires a compromise of goals, emissions and performance.	A number of basic problems are unresolved and are expected to yield to solution only with difficulty; in fact, perhaps not all of the development problems have been considered.
Application: (Considers how many engines potentially might benefit from the control concept.)	Potential exists for use in virtually all engines.	Many engines could achieve emissions benefit from the control concept.	Several engines are appropriate candidates.	Control concept is useful in only isolated situations.
Impact on the Engine:	No change at all.	Minor changes such as fuel manifold number or location, alterations to the fuel control, additions to the accessory space that do not radically influence the packaging within the nacelle, small durability sacrifice.	Significant changes such as additional or larger fuel nozzle ports, large additional space for pumps, etc., that result in major packaging revisions within the nacelle, considerable durability sacrifice, weight increase, etc.	Change in the overall dimensions of the basic engine or major components (e.g., pressure caseing, shaft lengths).
Impact on the Airframe:	No change at all.	Minor changes in weight, noise, or fuel consumption.	Modification of plumbing around the engine such as air-bleed ducts, or minor changes to the nacelle to accomodate hardware; moderate increase in fuel consumption, etc.	Significant changes in weight and balance, redesign of wing or nacelle to accomodate additional hardware.

Table III-3

Control Technique	Ref. No.	Control Capacity	Effect on Smoke	Complexity	Application	Impact Engine	Impact Airframe	Comment
Idle Speed	(1)	2(HC,CO)	None	1	1	1	2	
Air Bleed	(2)	2(HC,CO)	None	1	1	1	3	
Spray Improvement	(3) (15)	1(HC), 2(CO) 4(NOx)	None Increase	1-2	4	1	1	
Air Blast	(4)	2(HC,CO)	None	2	3	1-2	1	Limited to higher pressure rates at idle. May need to change the stoichiometry.
Air Assist	(5)	1(HC) 2(CO)	None	1	3	3	2	The external compression is a difficult mechanical problem.
Premix-1	(7)	2(HC) 3(CO)	Decrease	3	2	3	1	
Advanced Cooling	(3)	3(HC) 2(CO)	None	3-4	2	1-2	1	May receive non-emissions benefit.
Rich Primary-1*	(8)	2(HC,CO)	Increase	3	2	2	1	
Lean Primary-1*	(9)	3(HC,CO)	Decrease	3	4	2	1	
Delayed Dilution	(10)	3(CO)		3	4	4	1	
Sector Burning	(11)	1(HC) 2(CO)	None	2	2	2	1	In-flight malfunction is a concern.
Selective Azimnthal Burning	(22)	2(HC) 3(CO)	None	1	2	1	1	Safe in-flight; less effective than sector burning (11).
Quick Quench	(12)	2(NOx)		3	2	1	1	Low power emissions may be high.
Rich Primary-2*	(13)	3(NOx)	Increase	3	2	2	1	Low power emissions may be high.
Lean Primary-2*	(14)	2(NOx)	Decrease	3	1	2	1	Flame stability questionable,
Premix/Prevap	(16)	2(HC,CO,NOx)	Decrease	4	2	3	1	low power emissions may be high. Flashback is a concern.
Fuel Staging	(17, 18)	2(HC,CO,NOx)	Increase	3-4	2	3-4	2	May not scale down to small engine size.
Variable Geometry	(19)	2(HC,CO,NOx)	Decrease	4	2	4	1-3	Mechanical reliability in question.
Catalysis	(20)	1(HC,CO,NOx)	?	4	2	4	4	Not readily available to small engines.
Water Injection	(21)	1(NOx)	None?	2	2	2	3	Not practical.

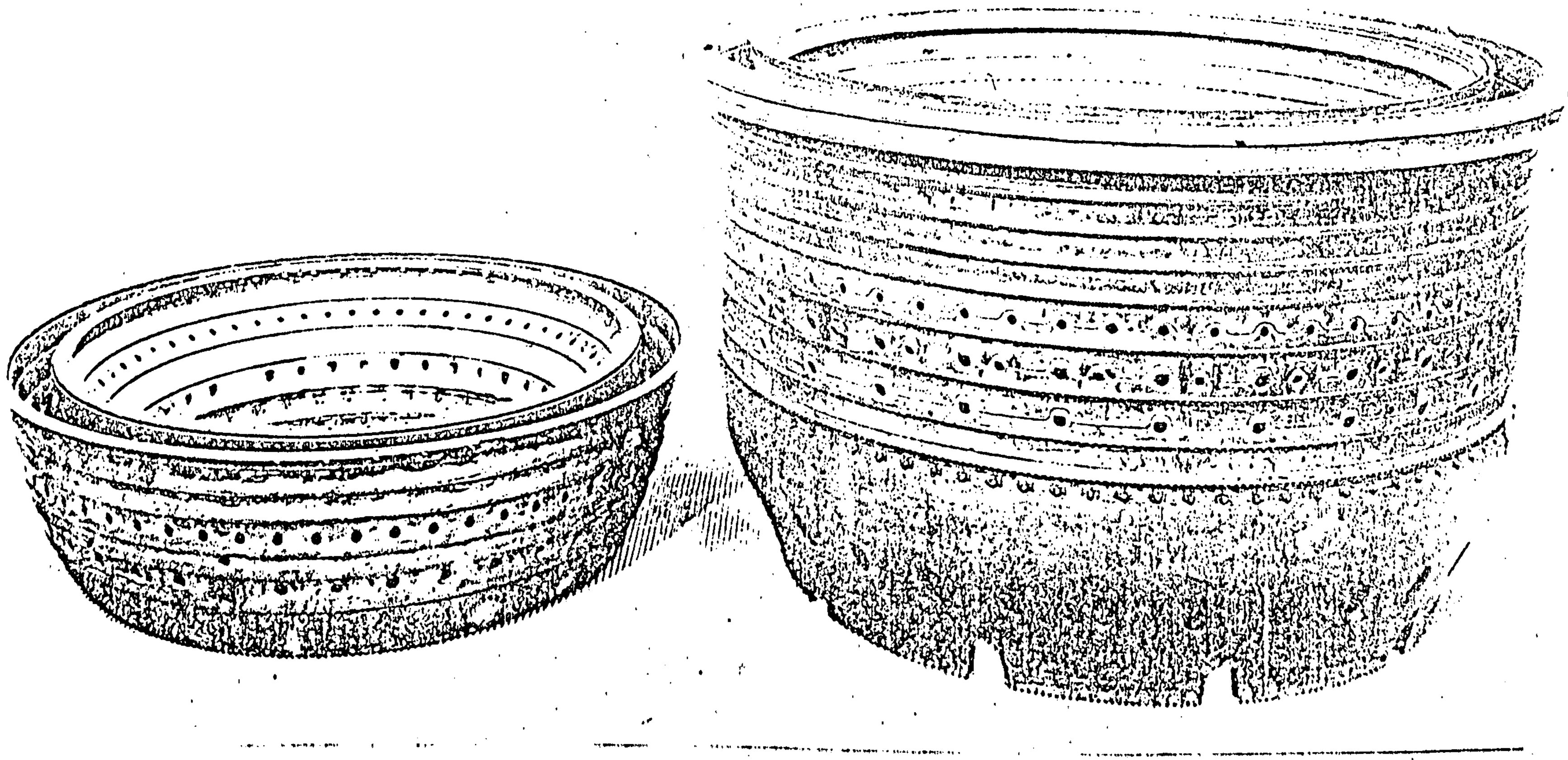
does sector burning because it is less able to optimize the stoichiometry and because of the numerous quenching zones between several burning zones.

The third major control technique for HC, CO control is the use of airblast nozzles, (method 4) combined with airflow redistribution (methods 7-10) to achieve the necessary stoichiometry. This approach is expected on the Pratt and Whitney JT8D, JT9D, and, if built, JT10D engines. The use of airblast nozzles alone on production type combustors gave inadequate performance because of the alteration of the stoichiometry and forced the use of additional techniques to tune the combustor to acceptable emissions and performance (e.g., altitude relight, durability, temperature profile, etc.). In total, this approach leads to changes of the stoichiometry and cooling air patterns in flight which lead usually to increased smoke and degraded combustor performance.

One of the major features of the NPRM is the required retrofit of in-service T2 and T4 class engines to achieve compliance with the 1981 newly manufactured engine levels. Unfortunately, installation into in-service equipment may not be quite as simple to achieve as installation into newly manufactured equipment because of the need to replace or modify parts that would be properly installed new on a new engine or aircraft. Examples would be nozzles, fuel controls, igniters (causing perhaps a rework of the outer casing), combustor liners, and for sector burning, squat switches sensing the aircraft on the ground so the fuel control can distinguish between flight and ground modes because (sector burning is in general prohibited in flight.

For NOx control (NME 1984), the leading technology is fuel staging, (methods 17 and 18) due largely to the joint NASA-industry Experimental Clean Combustor Program (1973-1977) wherein, first, single stage techniques such as lean burning (method 14) were found inadequate if employed alone, and second, fuel staging was investigated to resolve the deficiencies of the single stage controls. The latter investigation was carried through to a technology demonstration in two test engines (not flightworthy). Two different approaches to fuel staging were investigated, axial staging (method 17, used on the JT9D-7) and radial staging (method 18, used on the CF6-50). Application or transfer of this technology to other engines, even related ones, is not always easy, however, and has not been pushed by the manufacturers thus far. For instance, the radially staged combustor developed in the CF6-50, called the "Double Annular" can be installed on a CF6-6 only with considerable modification to the basic engine, including the casing, although it can be employed directly into the CF6-50 with only direct changes in the fuel plumbing and fuel control. This is because the double annular airflow requirement into the double dome calls for a dump type diffuser from the compressor as is found on the CF6-50. The smooth diffuser found on the CF6-6 would have to be replaced by a dump type in order to utilize the double annular idea (Figure 5). Similarly, use of the double annular concept in the CFM56 is questionable because its much smaller size (Figure 6) does not lend itself readily to staging involving physical separation of the zones. This separation increases considerably the S/V ratio and reduces simultaneously the residence time. When combined with the overall smaller geometry of a smaller engine, both factors adversely impact the HC and CO emissions.

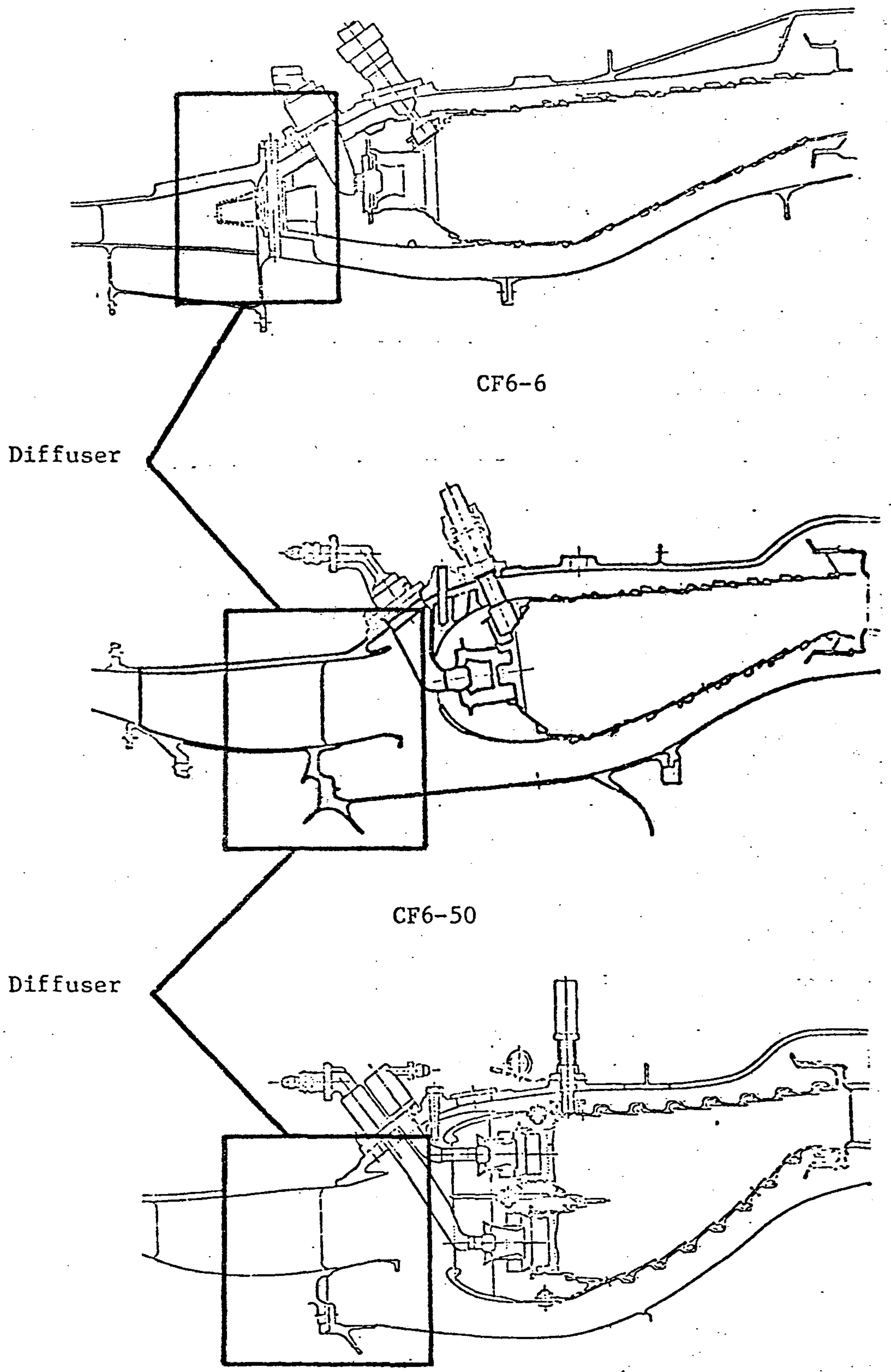
SIZE COMPARISON BETWEEN THE CFM56 AND CF6-6 COMBUSTORS



CFM56 CF6-6

Figure 6

COMPARISON OF DIFFUSERS BETWEEN THE CF6-6 AND CF6-50 ENGINES



Double Annular Combustor in CF6-50

Figure 5

Rolls Royce did not benefit in this technology development by direct association with the program and consequently has not yet engine tested a fuel staged combustor in an RB211. Its recent investigations have, however, explored the benefits of both radial and axial staging and it has leaned in favor of the former because of the packaging constraints imposed by the relatively short combustors of the RB211 family (a similar situation to the CF6).

NOx control by fuel staging is in the exploratory development stage and is not yet ready for final development into specific engines for certification of airworthiness. Developmental problems for which solutions have not yet been identified are (1) the achieving of all four emissions goals simultaneously, (2) insufficient cooling air for acceptable durability performance, and (3) engine performance degradation, notably transient response. Other shortcomings in the concepts at present are considered normal for this stage of development and would be expected to be resolved in due course.

As indicated in the preceding paragraphs, manufacturers have often found it necessary to combine more than one emission control concept. This is, in fact, the rule rather than the exception. Such compounding may be necessary because of the inadequacy of a single control concept to sufficiently reduce the emissions, or it may be necessary because of combustor performance deficiencies brought about by the use of a single control scheme. In the former category would be the combining of airblast nozzles with liner airflow redistribution. In the latter would be the utilization of fuel staging with separate lean and rich primary zones. Often the rationale is a combination of the two.

The adding on of one control scheme upon another is not guaranteed to produce a geometric compounding of results; there may be, in fact, no improvement at all despite the fact that each separately may be quite effective. For example, while redesigned nozzles and sector burning may individually produce emissions reductions, the first because of improved atomization, the second because of atomization and stoichiometry, their joint use is likely to be no better than the sector burning alone because that in itself already accomplishes that which the redesigned nozzles purports to do (i.e., improve atomization).

On the other hand, complementary forms of control may achieve synergetic results: redesigned nozzles combined with advanced cooling techniques may together serve to reduce emissions that result from different mechanisms of formation (i.e., poor atomization and mixing in the primary vs. wall quenching on the liner). It is also possible that the use of only one control will aggravate a condition which will lead to the formation of more pollutants and hence will require two or more control schemes to balance each other. A significant example of this situation is the use of airblast nozzles which while providing better fuel atomization and mixing, also leans the primary zone stoichiometry by its own airflow. This may result in an excessively lean mixture so that an airflow redistribution to richen the primary is also required. Together, the two approaches provide improved atomization, better mixing, and optimal stoichiometry. Similarly, the conflicting requirements of NOx control and HC, CO control require a combination of control techniques, most notably through fuel staging in which the two separate portions utilize control techniques applicable to the particular pollutants which are expected from them.

The above discussion makes repeated reference to the conflict between emissions and combustor performance and this reference is continued in Section IV. Therefore, a brief explanation of combustor performance is appropriate. The criteria by which combustor performance is judged are related to both economic and safety considerations. The economic criteria are created by the users while the safety criteria are dictated by the users, the FAA, and common sense. Combustor performance itself is two-fold: operational and mechanical.

Operational performance is measured primarily by ground ignition and engine acceleration, altitude relight, and flame stability (combustor response to engine transients, either intentional or accidental). Mechanical performance standards are largely determined by economic considerations and the principal criteria are durability, coking, and carbon deposition. The first two are obviously considerations for the cost of maintaining the system, but the third may not be so apparent. Carbon deposition impacts the engine durability and hence maintenance cost first through the turbine erosion which occurs when particles are broken off the combustor or nozzle surface and sent downstream, and, second, by its adverse effect on the combustor cooling (due to a change in the radiative emissivity).

Table III-4 lists the best emissions performance that has been achieved in each engine. These data are also presented graphically in Figures 7-9. However, in a few cases the data may represent combustor rig data rather than engine data (e.g., CJ610) or possibly educated extrapolation from data of a related engine (e.g., RB211-535 figures originated from RB211-22B data). Most importantly, though, the data may be from a configuration which has been found unflightworthy (e.g. Spey 511) or otherwise projected as unsafe. The purpose of this table is merely to present in concise form the kind of control that is achievable by the control methods listed. The standards proposed for each engine are presented also as a point of comparison. A more accurate interpretation of the situation of emissions reduction is to be found in Section IV, Industry Status.

Table III-4
Summary of Best Emissions Performance

Class	Engine	Size	HC	CO	NOx	Sk	Date of Availability	Comment
T1	Production Engines							
	TFE731-2	15.5 KN	4.5/*	59.8/*	50.5/*	/38		External air assist.
	TFE731-3	16.5 KN	----------No Data----------			/38		
	JT15D-4	11.1 KN	1.4/*	108/*	47.7/*	/42		Primary/injector modification.
	JT12A-8	14.7 KN	-------No Technology-------					
	CF700-2D	19.2 KN	14.7/*	861/*	20.2/*	/36		Nozzle modification.
	CJ610-2C	13.1 KN	23.4/*	1440/*	25.2/*	/40		Nozzle modification.
	ALF502D	28.9 KN	14.8/17.0	112.4/103	28.8/33.0	/32.4	Certified	Airblast nozzle/leaner primary.
	M45H	32.4 KN	30.1/16.2	170/97.1	37.0/33.0	12/31	Jan. 1979	Advanced cooling (dbl. blown ring).
	Viper600	16.7 KN	-------No Technology-------					
	New Engines							
	RB401-07	24.6 KN	----------No Data----------				Jan. 1979	Advanced cooling (dbl. blown ring)
	ATF3	22.2 KN	----------No Data----------					
	ALF502L	33.4 KN	9.1/15.9	92.2/95.5	35.4/33.0	/31.2	1979	Combustor same as 502D. Idle at 10.7%. NOx high.
T2, T3, T4	Production Engines							
	JT9D-7	205.3 KN	4.5/6.7	24.6/36.1	47.4/--	<20/19.3.		Aerating nozzle/rich primary.
			2.1/6.7	30.2/36.1	26.2/33.0	30/19.3		Low NOx combustor (Vorbix staging).
	JT9D-70	228 KN	4.0/6.7	20.0/36.1	48.5/--	<10/18.8		Aerating nozzle/rich primary
	CF6-6D	178 KN	1.8/6.7	28.3/36.1	65.7/--	16/20.0		Sector burning.
	CF6-50C	224 KN	1.0/6.7	37.1/36.1	60.8/--	/18.9		Sector burning/dome and nozzle modification.
			2.4/6.7	49.8/36.1	44.7/38.7	/18.9	1986-87	Low NOx combustor (DbJ. Annular)
	RB211-22B	187 KN	4.2/6.7	28.8/36.1	64.0/--	/19.8		Sector burning and rich primary (Phase II).
	RB211-524	218 KN	3.1/6.7	22.4/36.1	70.2/--	/18.7		Sector burning and rich primary (Phase II).
	Spey 511	50.7 KN	23.0/	162/	68.2/	/	Approach abandoned, performance not acceptable	Reflex airspray.
	Spey 555	43.8 KN	36.1/12.2	186/79.8	55.2/--	/29.0	Approach abandoned, performance not acceptable	Piloted airblast.
	JT3D-7	84.5 KN	158/--	232/--	53.0/--	13.3/25.0	Jan. 1981	Leaner primary & airblast; intended for T3 smoke retrofit only.
	JT8D-9	64.5 KN	----------No Data----------					
	JT8D-17	71.2 KN	7.6/8.9	49.4/49.9	68.4/--	/25.5		Aerating nozzle/rich primary.
			1.6/8.9	83.1/49.9	41.0/33.0	27/25.5		Lox NOx combustor (Vorbix).
	New Engines							
	RB410	68.5 KN	----------No Data----------					
	RB432	71.2 KN	----------No Data----------					
	RB211-535	163 KN	8.9/6.7	54.7/36.1	51.3/--	/21.2		Sector burning and rich primary (Phase II).
			2.5/6.7	67.5/36.1	30.3/33.0	/21.2		Rich primary and quick quench.
	CF34	40 KN	12.7/14.4	80.0/85.2	27.0/33.0	20/29.7		Sector burning.
	CFM56	107 KN	0.9/6.7	42.0/36.1	43.5/--	/22.9	Date of Cert.	Sector burning at 6% idle.
	CF6-32	157 KN	2.0/6.7	29.8/36.1	64.1/--	/21	Date of Cert.	Sector burning.
	CF6-80	213 KN	2.0/6.7	/36.1	/	/19.1	Date of Cert.	Sector burning.
	JT10D-4	129 KN	----------No Data----------					
	JT8D-209	82 KN	2.2/7.5	33.6/41.2	54.9/--	15/24.5	Date of Cert.	Aerating nozzle/rich primary.
	JT8D-217	92 KN	----------No Data----------					
T5	Production Engines							
	OLY593-610	171 KN	<30.7/30.7	<237/237	<70.8/70.8	/25	Jan. 1980	Blown ring.

* No standard.

HYDROCARBON EMISSIONS VS. RATED THRUST -
LOW EMISSIONS ENGINES

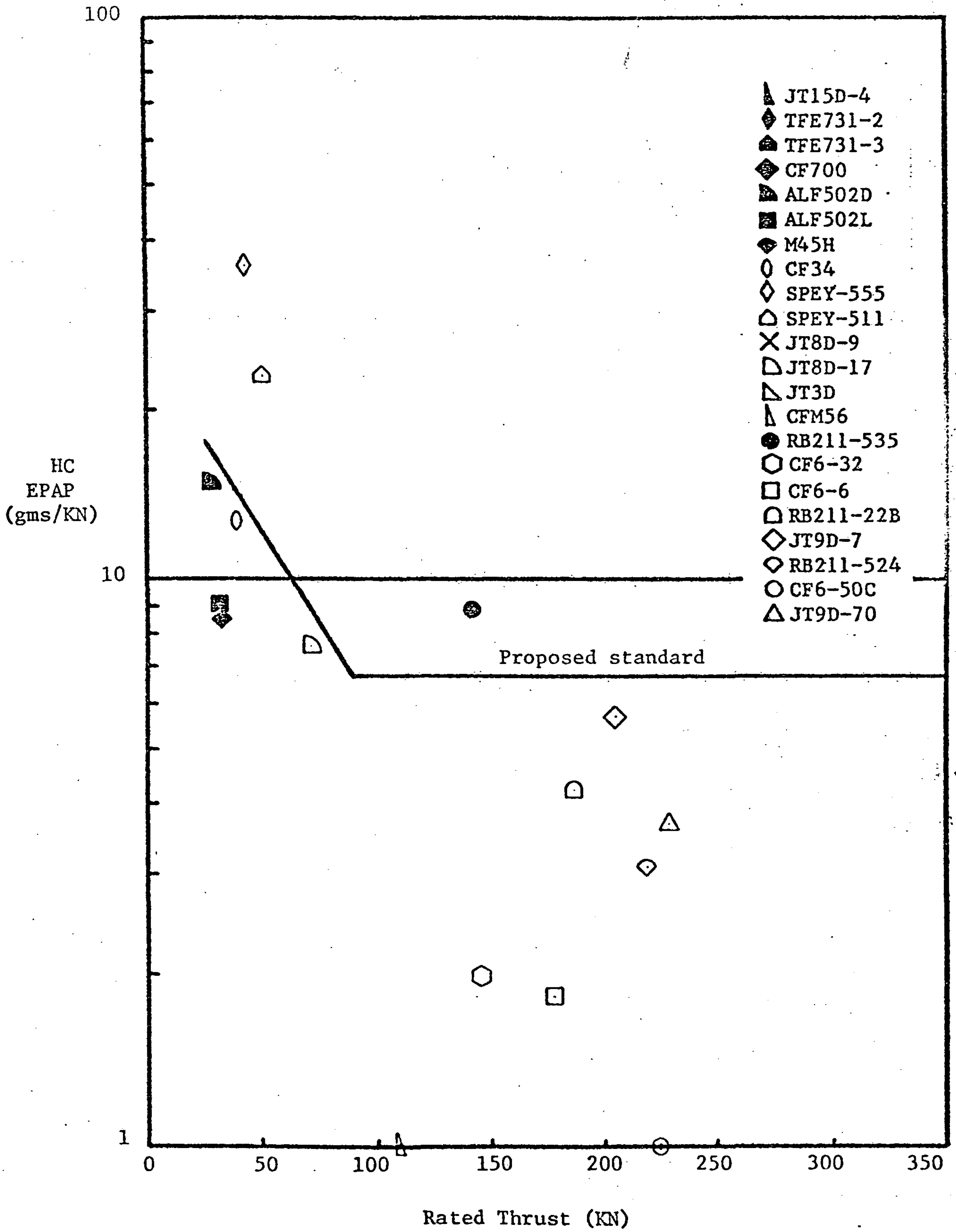


Figure 7

CARBON MONOXIDE EMISSIONS VS. RATED THRUST –
LOW EMISSIONS ENGINES

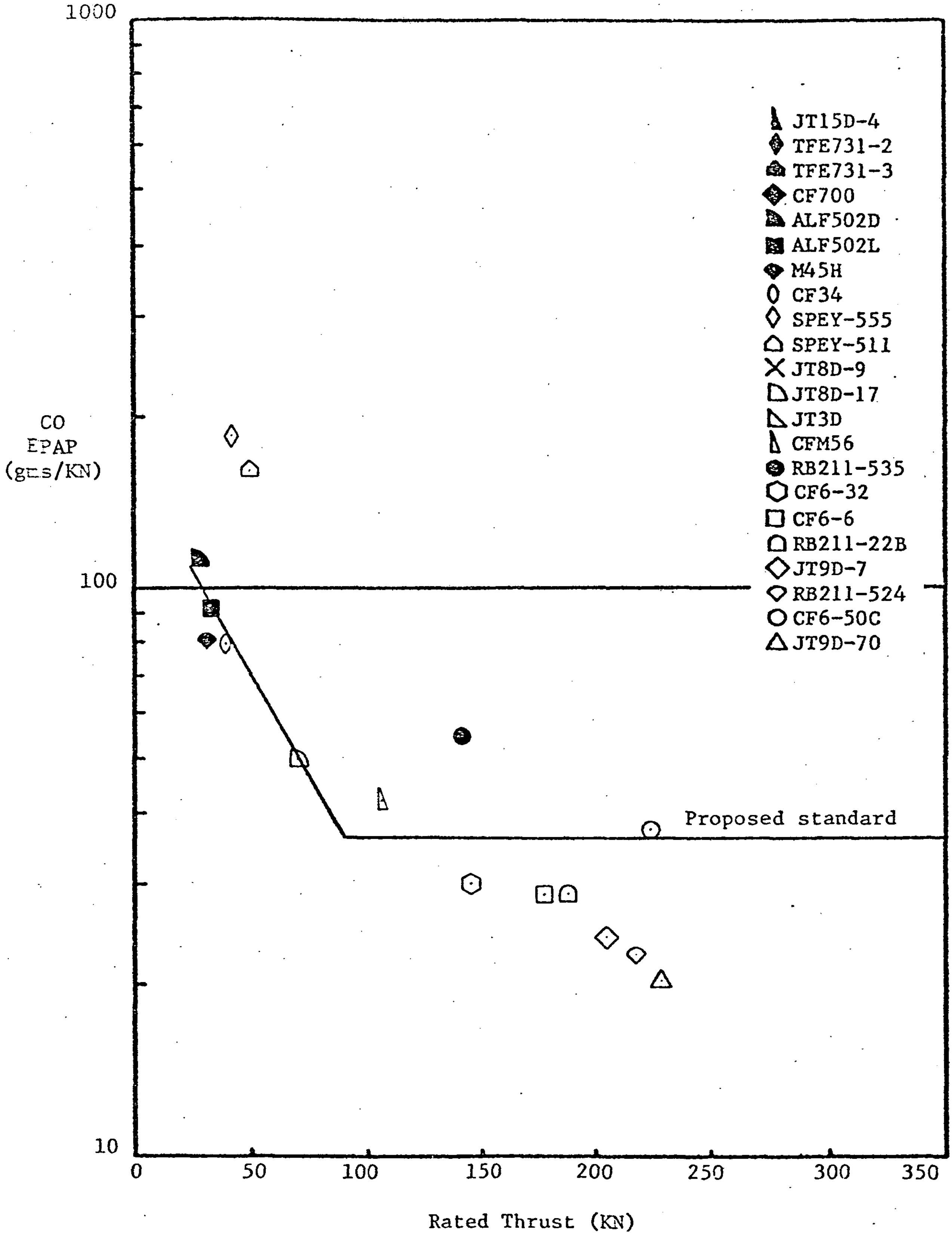


Figure 8

OXIDES OF NITROGEN EMISSIONS VS.
RATED THRUST-LOW EMISSIONS ENGINES

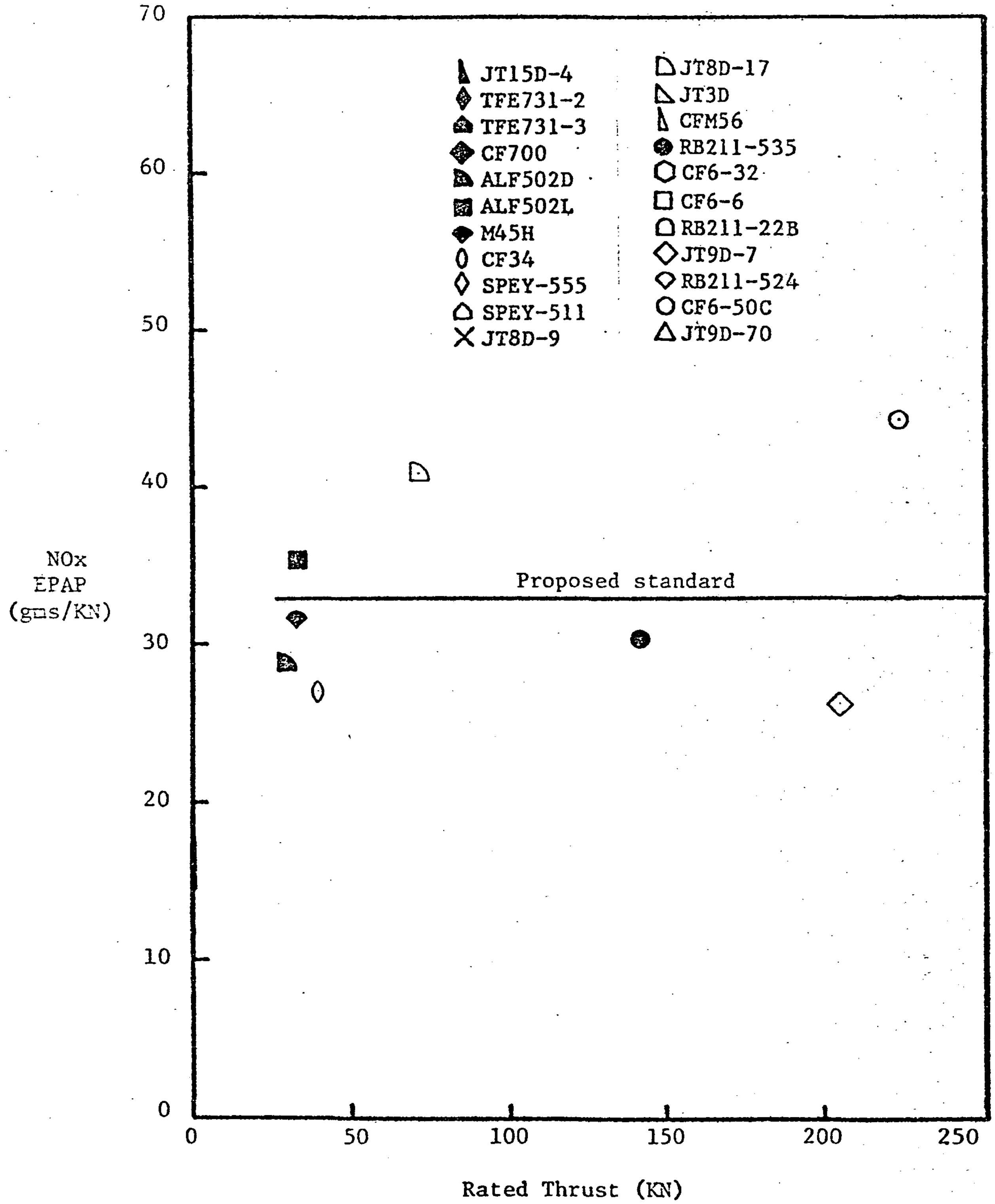


Figure 9

Section IV

INDUSTRY STATUS

The discussion in this section is limited to those engines which will be affected by the standards, namely those in commercial service with a rated thrust of 27KN or greater. Engines in this category are limited to those made by only four manufacturers, General Electric, Pratt and Whitney Aircraft, and Rolls Royce (certain engines involve joint ventures with other manufacturers) and possibly Avco Lycoming. Each manufacturer and its products will be treated separately.

1. General Electric

General Electric is a large diverse manufacturing company in the United States. Its commercial aircraft engine operations are located in Cincinnati, Ohio (CF6, CFM56) and in Lynn, Mass. (CF34, CF700, CJ610). The CFM56 is a joint venture with SNECMA of France, the core of which is based upon the military F101 engine designed for the B-1 bomber. In addition to these civil engines, GE makes a number of military varieties, some of which are essentially the same as the civil engines. A summary of the company's civil engines is presented in Table IV-1.

Summary of Research and Development Effort CF6, CFM56

CF6

General Electric's NOx control effort has centered largely around

Table IV-1

General Electric Engines

Engine	Class	Thrust	BPR	PR	Combustor	Application	Cert. Date	Number Delivered	Production Category
CF6-50	T2	224 KN	4.4	29.8	A	DC-10,B747,A300			III
CF6-6	T2	175 KN	5.9	24.5	A	DC-10			III
CF6-32	T2	145 KN	4.8	24.4	A	Potentially B757		0	IV
CF6-80	T2	213 KN	---	32.0	A	B767, A310	1981	0	IV
CFM56	T2	107 KN	5.9	25.6	A	Possibly B707,A300B11		0	IV
CF34	T2	40 KN	6.0	19.5	A	None		0	IV
CF700	T1	20 KN	1.9	6.6	A	Falcon 20,Sableliner75A			II
CJ610	T1	13 KN	0	6.8	A	Learjet 24/25			I

PROSPECTUS

			Prospects of Meeting:						
			Emissions Performance				Operational	Mechanical	
Engine	1981	1984	HC	CO	NOx	Sk	Performance	Performance	Time
CF6-50	poor*		X	X					X
		poor		X	X		X	X	X
CF6-6	poor*		X	X					X
		marginal		X	X		X	X	X
CF6-32	poor*		X	X					X
		marginal		X	X		X	X	X
CF6-80	marginal			X					
		marginal		X	X		X	X	X
CFM56	marginal			X					
		fair		X					X
CF34	good								
		good							

* Assuming sector burning is not used.

the NASA Experimental Clean Combustor Program (ECCP). This portion of the jointly funded program with NASA utilized the CF6-50 engine as a testbed, but it should be considered as a technology demonstration program having application to annular combustors in general, within geometric limitations. The ECCP was divided into three phases, the first being a screening of several concepts involving premixing, air-blast, lean primary burning, and fuel staging incorporating some or all of the previous concepts. The second phase involved refinement of selected concepts and the third phase was an engine test of the best. The program is now completed (except for documentation of the final engine testing). The final concept developed by GE is termed the double annular combustor and is shown in Figure 10. It is a radial fuel staging concept and is particularly well suited to GE engines which have short annular combustors and are, therefore, less amenable to the physically longer axial staging concept (e.g., the Pratt and Whitney JT9D Vorbix). A detailed description of how such staging reduces emissions given in Section III and Appendix A.

The engine test in phase III of the ECCP served as both a proof of concept demonstration (with partial success) and, in fact, went one step further by attempting to provide flightworthy quality hardware in the demonstration. Unfortunately, but perhaps predictably, this was at least partially responsible for the failure of the system to live up to the expectations of phase II. The specific revisions to the engine hardware for phase III included a modified inner liner, revised liner cooling, additional allowance for thermal expansion, and changes in the

DOUBLE ANNULAR COMBUSTOR CONFIGURED FOR THE CF6-50

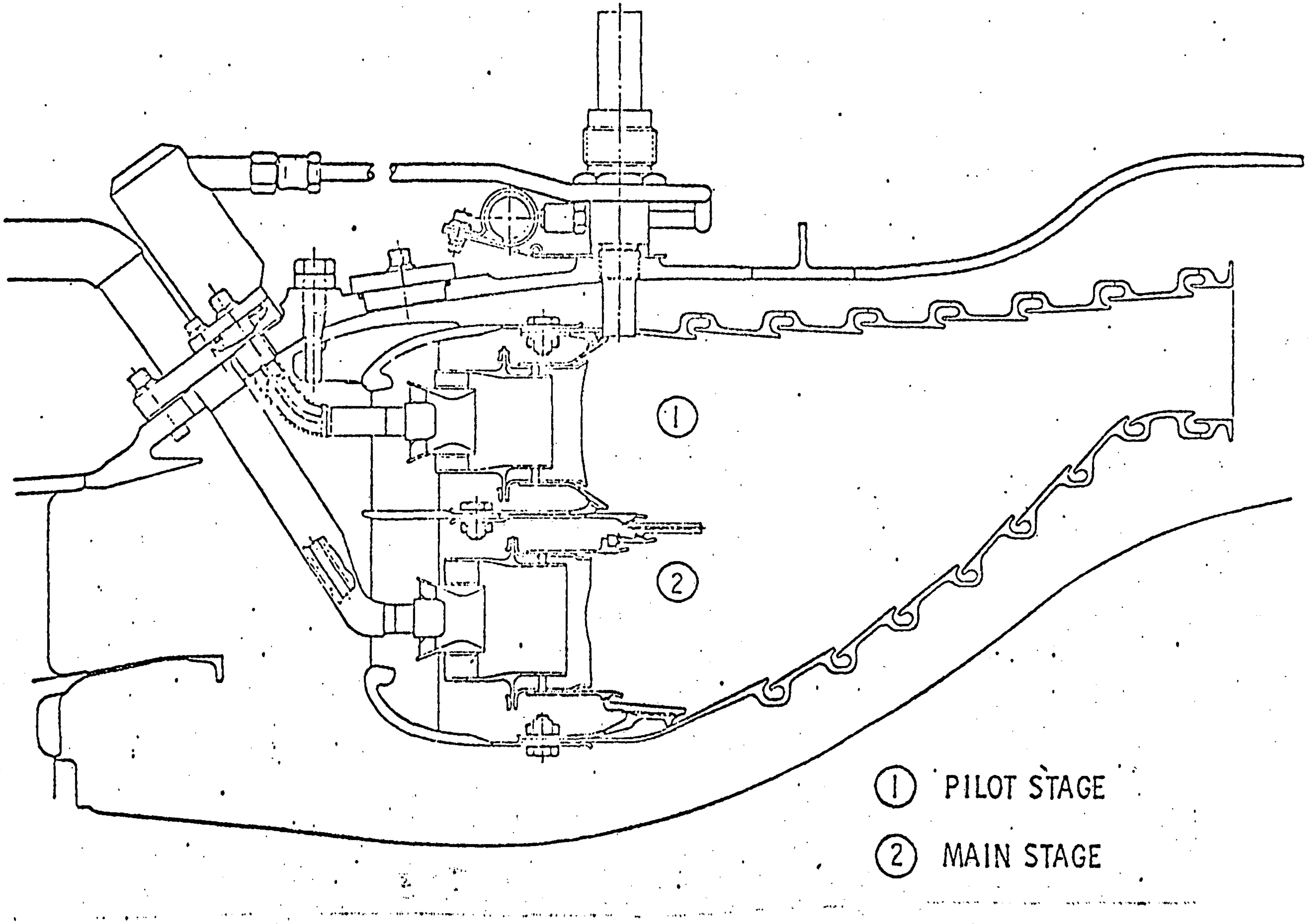


Figure 10

connections between liner parts. Together these changes led to a more durable combustor, but one which also suffered from an inferior fuel injection pattern and degraded mixing which manifested itself through a deteriorated emissions performance. However, a realistic development program must eventually address the durability problem and as the phase II results suggested that the emissions were successfully under control, turning attention to durability was a reasonable next step.

Current problems with the double annular combustor as presently configured in the -50 are: (1) high CO - due largely to the hardware changes incorporated in the engine test to aid durability (the Phase II rig version had acceptable CO); (2) high NOx - a definite problem although GE sees some room for improvement; (3) high smoke - due to inadequate mixing in the robust version which if eliminated would bring the NOx down, too (the Phase II rig version had acceptable smoke); (4) durability - mostly an unknown but the uncooled centerbody is definitely subjected to a severe environment and the lean front end (primary) leaves less cooling air for the liner (see Table IV-2); (5) temperature profile - the high air demand of the double burner dome (as seen in Table IV-2) to run lean in the main burner plus have a separate pilot burner plus the cooling air requirement for the liner leaves only 2% of the air left to trim T_4 instead of the usual 20%-30%, and impacts the turbine durability); (6) flow control - an altitude compensating control is necessary to distinquish at equal flow rates between high altitude cruise (both annuli burning) and approach (pilot only). Any change in the configuration to improve upon these problems must retain the other expected operational performance levels such as acceleration, relight at altitude and so forth.

On the positive side of the ledger, however, ground start, altitude relight, lean blowout, pressure loss, carbon deposition, cruise combustion efficiency, liner wall temperature, and engine acceleration all meet or appear to meet engine requirements. The exit temperature pattern, although out of specification, could be at least partially due to the high fuel-air ratio required by the "worn" test engine. This is presumed because temperature pattern exhibited a hot hub consistent with an over fueling (by 17%) of the main stage inner annulus. Sufficient refinement of the pattern may then be possible despite the shortage of dilution air (Table IV-2) with which to work (the temperature profile can also be affected by manipulation of the airflow pattern within the primary zone although this may be anticipated to be deleterious to emissions). Finally, it should be observed that despite the excess fuel no liner hot spots or carbon deposition was observed.

Table IV-2

CF6 Airflow Distribution

	CF6-50 Standard	CF6-50 Double Annular	
Dome:	35%	Primary 25% Main 51%	76%
Cooling:	32%	22%	
Dilution:	33%*	2%	

*Not all of this is required for temperature trimming. The CFM56, for instance, uses about 20%.

Double annular staging apparently requires single stage operation at approach as well as at ground idle (both stages at high power) in order to lower the CO (the use of only one stage creates better atomization and more concentrated burning). This creates the additional need to ascertain in detail the staging behavior in flight, both in normal operation and with malfunctioning in the fuel control logic or in the valving. The single stage operation at approach does contribute to the high NOx level which is of concern (about 18% of the cycle NOx arises in the approach mode).

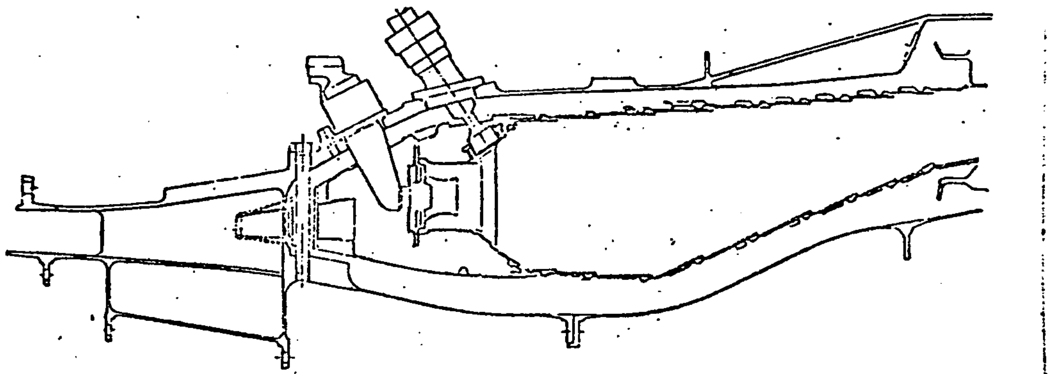
The present design allows no room for significant simplification in terms of liner configuration, number of fuel nozzles, and manifolding. Hence, it may be expected that cost estimates based upon the present configuration are realistic.

A double annular configuration has been designed for the CF6-6 engine (Figure 11) and although differing in detail from the CF6-50 configuration, it is in essence the same, working on the same principle and with similar design parameters. Certain problems have been identified with the use of the double annular concept in the CF6-6, however. Presently, the -6 has a smooth diffuser which is incompatible with the flow pattern needs of the wide dome of the double annular combustor; hence, a step or dump diffuser, similar to that employed in the -50 is needed (scaled to size, of course). Because the diffuser and casing are integral (compressor rear frame), this change would necessitate a major redesign of that high pressure shell at a cost estimated by GE in the neighborhood of 40 million dollars, if pursued. The ensuing changes in the external dimensions, although not large, would impact the nacelle packaging of the components external to the engine casing, such as the fuel manifold, compressor bleed, etc. Another problem is that the large fuel nozzles required by the double annular concept do not fit readily in the -6 which now uses smaller nozzles. Beyond requiring larger holes in the casing, the larger nozzles have a significant effect on the flow pattern and pressure drop across the combustor. For these reasons, direct scaling of the -50 design is not considered feasible, and additional development work specific to the -6 would therefore be necessary, even if all the deficiencies identified in the -50 program were remedied.

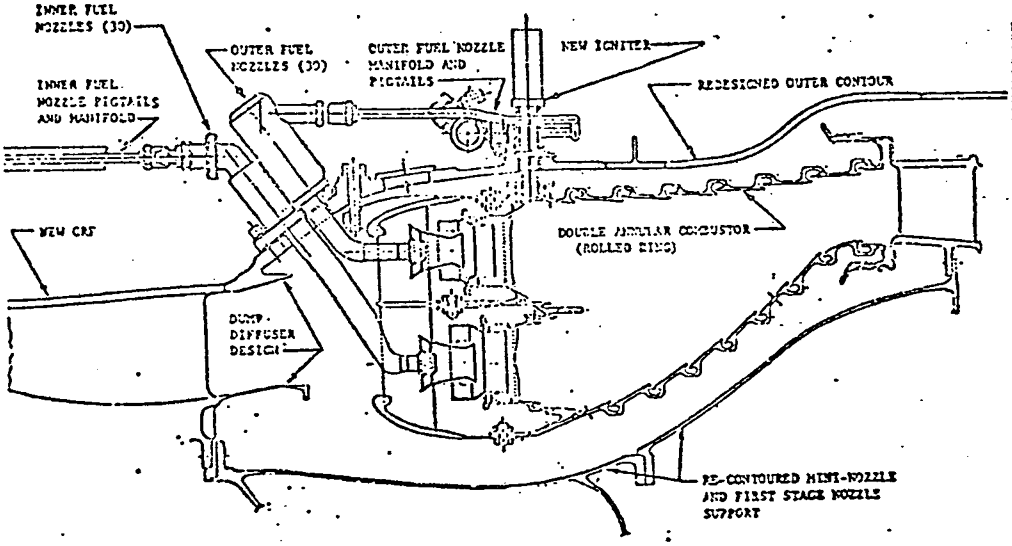
The CF6-32 is a clipped fan CF6-6 having the same core and hence the same combustor, and although operating at different conditions, it is expected that the -6 design will be adequate in the -32. GE has not yet committed to testing the -6/32 configuration even in combustor rigs.

GE is actively continuing its double annular technology development, though, in the NASA Energy Efficient Engine (E^3) Program. This is also a technology demonstration program (not a prototype development effort) in which it is hoped to demonstrate more efficient components and engine cycles on an engine assembled from these new components and sized to the 110-130KN range. Thus, this development does not directly relate to the CF6 development and, in fact, the GE combustor configuration and size are more related to the CFM56. Nonetheless, the technology improvements should be relevant. Principal advances to be explored are (1) single fuel injector stem per nozzle pair, (2) cooled

COMPARISON BETWEEN PRODUCTION AND LOW NOx COMBUSTORS IN THE CF6-6



Production



Double Annular

Figure 11

centerbody (separating the stages), (3) advanced cooling, and (4) better NOx and smoke control. The best airflow pattern refinements for emissions and operational performance will be sought.

GE has also pursued independent investigation of simpler concepts through their IR&D funding. These concepts include compressor bleed, advanced idle, sector burning, nozzle modification, and liner redesign (airflow redistribution). These approaches are directed at HC and CO control only and despite their relative simplicity, they can be quite effective. Much of the preliminary investigation was done on the developmental CFM56 (F101) as the early CF6 effort was devoted principally to the NASA ECCP.

GE elected to continue development of the sector burning concept in the CF6 for the proposed 1981 requirement. The governing principles behind the sector burning concept are described in Section III and Appendix A. Although sector burning creates a fuel control problem with its staging at idle, a very desirable feature is that during proper operation, there is no effect of the emissions control on the combustor in flight so concerns about operational and mechanical performance are considerably reduced. Used alone, this method is sufficient only in the CF6-6 and probably CF6-32 engines. The CF6-50 and -80 would still suffer from high CO because of their very short combustors. CO, in fact, tends to be a problem in all of the GE engines due to their short combustor designs which allow inadequate time for its oxidation to CO_2. A short combustor is pursued because it requires less liner cooling air (hence more is available for radial temperature distribution trimming and for turbine cooling) and it creates a shorter and hence lighter engine.

The CF6-50, in addition to the sector burning, requires new fuel nozzles to improve the mixing and local stoichiometry in the primary. The new nozzles insure that at idle all the fuel is being injected through only the primary orifice in each of the pressure-atomizing duplex nozzles, thus providing greater atomization. From existing data this solution gives the CF6-50 a 15% margin in CO emissions, but because of the anticipated engine-to-engine variability, there may still be compliance problems. Further reductions could be achieved by increasing the idle power, but as this is an engine already in use, such a procedure would run afoul commitments to the airframe manufacturers and would particularly be difficult to implement in a retrofit program (proposed in-use compliance requirement by 1985).

A major concern with sector burning is the effect of the asymmetric thermal loading at idle when the fuel is sectored in the annulus. The most favorable fuel distribution with regard to emissions is to have a single large sector off and the remaining sector on (here 180° on and 180° off). This, however, is the most adverse for the turbine stator and guide vanes. Furthermore, the frame distortion may cause increased wear on the rotor blades with subsequent efficiency losses at all power modes. In addition, the asymmetric heat imput reduces the mechanical efficiency of the turbine which leads to a fuel economy penalty during the sectoring mode.

The fuel control and delivery system also has additional complexity (see Figure 12), but this is outside the hot section and is thus easier

FUEL CONTROL FOR SECTOR BURNING

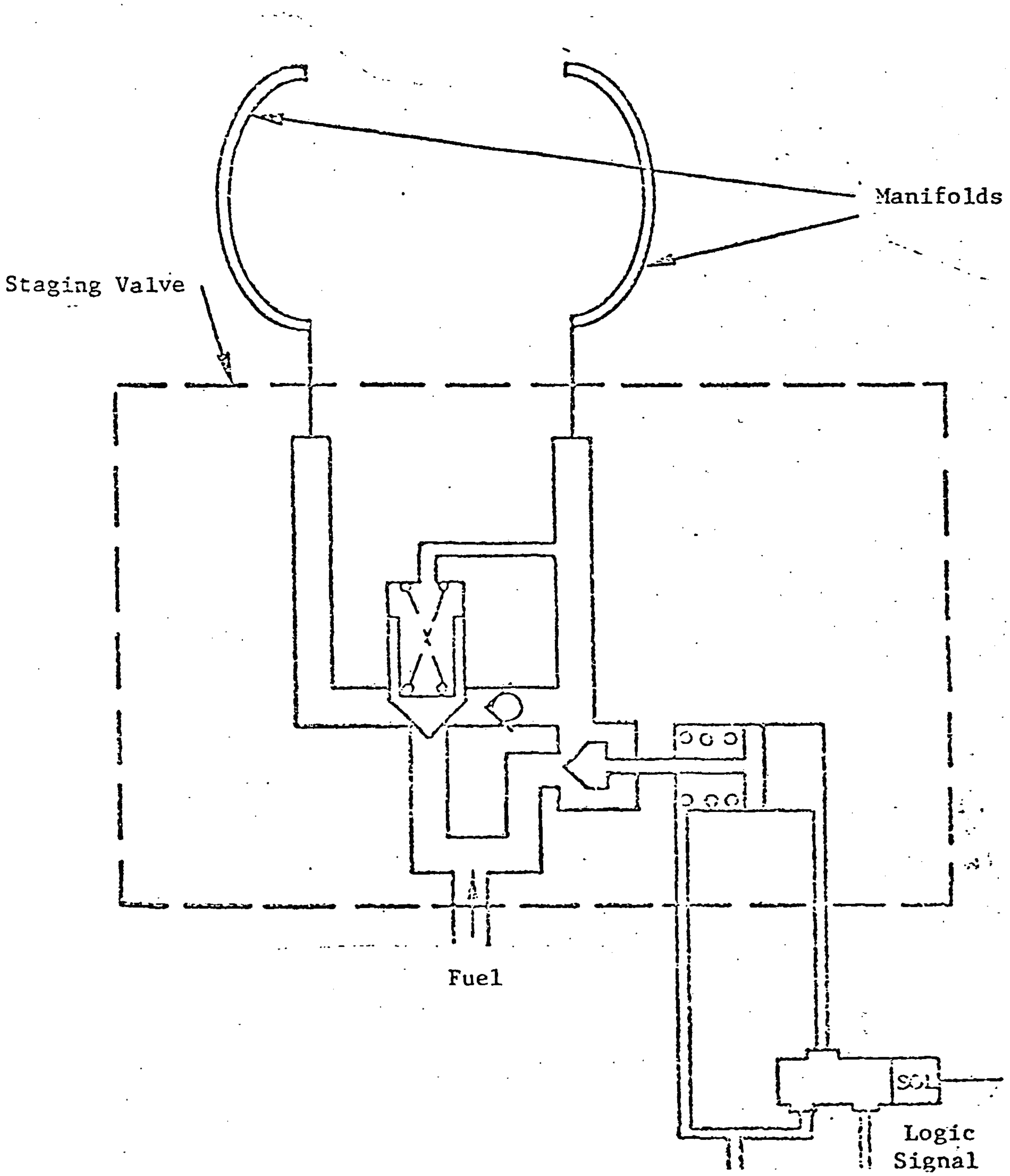


Figure 12

to handle. The fuel control must be able to sector when required, must distinguish between in-flight idle and ground idle, and must be fail-safe (any failure will cause the system to revert to full annular operation at the proper flow rate). The failsafe mechanism is crucial to the safety of the system as inadvertent sectoring in flight might lead to engine damage or inability to accelerate, depending on the power level at the time.

Sector burning development ceased in 1979, however, when GE was informed by its customers that, in their opinion, sector burning's potential hazards and idle fuel penalty rendered it unacceptable. GE has since reverted to a selective azimuthal burning arrangement. This involves selective nozzle firing at idle, but instead of a single, large sector being turned off (eg, 180 sequential degrees), this concept might turn off, say, 120 degrees distributed over five individual sectors [for instance, if there are 30 fuel nozzles, at idle, a pattern of 4 on and 2 off would be repeated 5 times]. This arrangement permits acceleration in flight and avoids the hazards of asymmetrical thermal loading on the guide vanes and stators which could damage the engine. Thus, there is no potential in-flight safety problem and the system is used for both flight and ground idle. However, the emissions performance is degraded somewhat.

A new dome is to be incorporated, partly to help emissions, but largely to improve pre-existing deficiencies in the mechanical performance of the original combustor. This dome is a version of the new design that was developed for the new CF6-80 engine and hence represents little additional development effort or expense.

CF6-80

The CF6-80 is a new engine family based upon the best technology of the CF6-50, but incorporating many new features. It constitutes a new family because in its conception total design flexibility was permitted. As a consequence, major changes in the hardware are:

(1) Aerodynamically superior fan blades (same diameter),

(2) 15 cm reduction in length of diffuser,

(3) 8 cm reduction in combustor length and replacement of the conventional brazed ring type with a new machined rolled-ring type,

(4) Elimination of the turbine midframe (18 cm),

(5) New low pressure turbine.

The overall length is shortened by 4 cm, the engine lightened by 130-230 kg, and cruise specific fuel consumption is improved by 6% over the CF6-50.

The new combustor incorporates a revised airflow pattern to improve burner life and performance. Less cooling air is admitted at the dome which permits (1) a richer front end (and hence better relight) and (2) more cooling air for the aft liner (and hence a cooler line). A longer version of this improved combustor will be used in new CF6-50s and may be also available as a retrofit option. In response to airline desires, GE will make every effort to avoid the use of sector burning as a control technique, but the shorter length will work to the disadvantage of CO control; on the other hand, it will work to the advantage of NOx control and may help to mitigate the adverse effect of the very high pressure ratio.

The anticipated control scheme is selective azimuthal burning which was discussed in the CF6-50 section. The necessity for in-flight operation requires a minimum of 5 sectors in order to preserve sufficient symmetry. With 30 fuel nozzles, this means 4 on - 2 off, 5 times around. With this operation, altitude relight is marginal; however, a 2 on - 1 off arrangement, 10 times around (ie, 10 sectors), resolves this difficulty, but at a cost of further reduced emissions effectiveness. Table IV-3 summarizes the known abilities of the different concepts as applied to the CF6-80.

Table IV-3

performance of Control Techniques

Control	HC EPAP
Sector Burning	
15 on - 15 off, once around	1
Sective azimuthal burning	
4 on - 2 off, 5 times around*	6
2 on - 1 off, 10 times around*	12

* possible for in-flight use

Little information about NOx control is known at this time. However, it is apparent that the small available volume will make the incorporation of staged systems quite difficult. Yet, because of the small size, cooling air requirements are reduced and more air is therefore available to the two stages of a double annular combustor with, perhaps, sufficient air left for temperature profile tailoring: this may make the staged combustor more viable in this application, if it can be fitted in.

CFM56

This engine, designed jointly with SNECMA of France, has a core which is derived from the military F101 engine. The cycle of the hot core is roughly that of the military engine, but the initial combustor intended for the military was not suitable for commercial use and consequently a program for the development of a proper combustor was established. Much of the emissions development was done on this later model combustor (the PV combustor) which is shown in Figure 13.

In addition to a design effort to configure the double annular concept to this engine (Figure 14), GE has pursued other avenues of NOx control during the development of this engine through IR&D funding. This approach attempted to make use of the short configuration of the combustor which tended to lower NOx levels anyway (short residence time). Because of the short design, special effort had been made to achieve proper combustion in a very short distance by excellent fuel preparation (atomization and evaporation) and mixing with the air. This feature, aided if necessary by sector burning at idle, could be sufficient to permit the application of a quick quench approach to NOx

PV COMBUSTOR (CFM56)

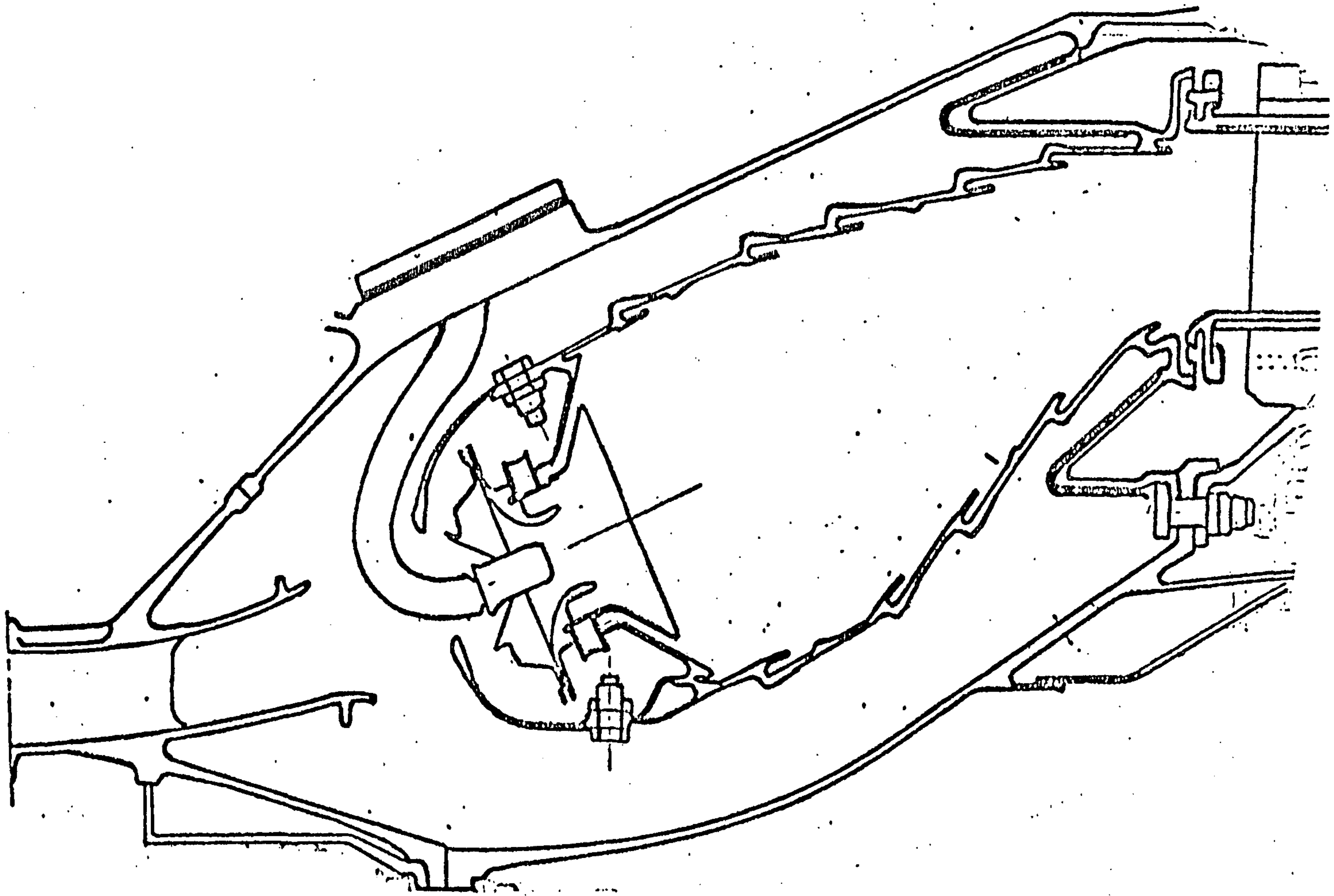


Figure I3

DOUBLE ANNULAR CONFIGURATION FOR CFM56
(SHOWN HERE, ENERGY EFFICIENT ENGINE PROPOSAL)

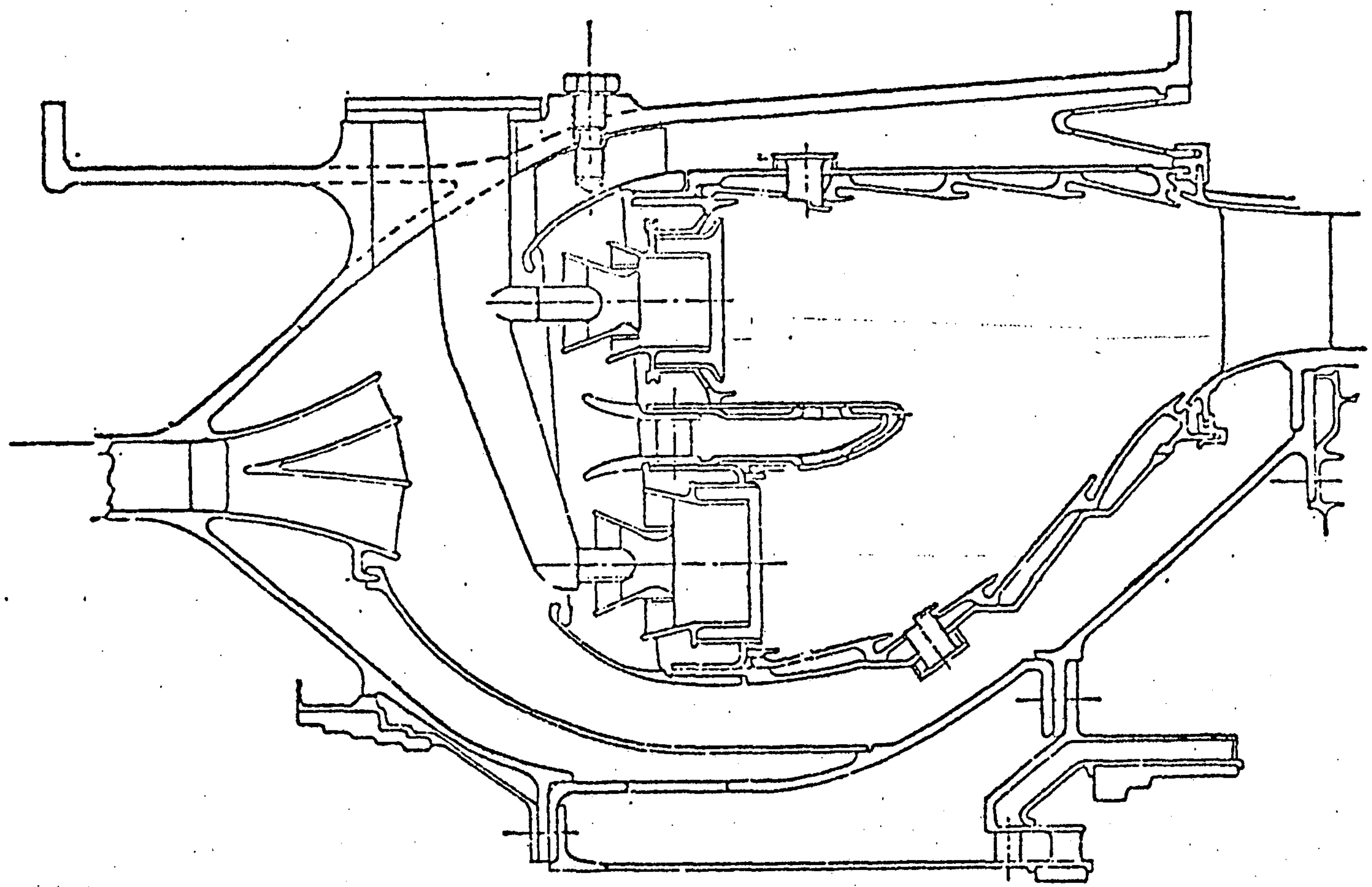


Figure 14

control (see Section III and Appendix A) and yet have acceptable low power emissions. The advantage of such an approach is first mechanical simplicity versus, e.g., staging, and second, inherent flame stability compared with lean flame NOx control. As explained in Appendix A, however, the drawback to quick quenching is that while it quenches the $N_2 \rightarrow NO$ reaction (a benefit), it also at idle quenches the $CO \rightarrow CO_2$ reaction and possibly also the oxidation of HC (a detriment). Very quick combustion as occurs in an advanced combustor may bypass that difficulty. Rig testing in an F101 testbed with the original combustor demonstrated a 30% reduction in the NOx EI. Later testing in the new combustor, however, was not as successful, and further exploration was shelved. Development of a double annular combustor for this engine has not proceeded beyond the design study because of the need to resolve the developmental problems of the concept on the parent engine (CF6-50) first.

HC, CO control by sector burning and selective azimuthal burning (SAB) was investigated early in the F101 combustor rig. The new PV combustor with SAB had better emissions than the original combustor with SAB; however, its operational performance was degraded considerably and the CO was still too high. Specifically, the pattern factor and altitude relight were deficient and the CO was twice the standard. In addition, the liner cooling requirement was not met. A subsequent program to remedy these deficiencies through variations in the venturi configuration of the airblast nozzles, the fuel spray angle, the primary stoichiometry, and the manner of dilution air entry (the degree of penetration) was undertaken. There developed a tradeoff situation between relight capability on one hand and CO and smoke on the other. CO and relight remain as problems and exploration to resolve the relight deficiency is continuing, but presently any improvement in relight is made at the expense of CO which is not too sensitive to the burning arrangement in this case because the origin of the CO problem is not in the primary zone (where selective burning helps), but rather in the secondary which is too short to permit oxidation of the CO. CO remains an unresolved problem if the final standard is equal to the proposed value.

CF34

The CF34, a civil version of the military TF34 may be regulated if used on an airframe finding commercial application. This engine has received the least work especially now in light of its likely exclusion through the general aviation exclusion. In anticipation of commercial use, selective azimuthal burning has been investigated on a prototype engine and a modified combustor simulating sector burning has been rig tested (sector burning alone left the CO too high). Because of its high bypass (6) leading to a low takeoff SFC, its moderate pressure ratio (20), and its short combustor leading to short residence times, the baseline engine already meets the proposed 1984 NOx requirement.

CF700, CJ610

As the CF700 and CJ610 would not be controlled under the proposed requirement and as the information in the December, 1976 report is still essentially correct and current, these engines will not be considered here.

Table IV-4 presents a summary of emissions performance of the GE engines. Rig data are identified. A projection of the performance of the double annular combustor in the CF6-6 and CF6-32 is made, but none is made for the CFM56 because of the scaling uncertainties. Expected availability of the technology is also given based upon the manufacturer's current position and existing or anticipated problems.

Table VI-4

General Electric Performance

Engine	Concept	Technology Category	EPAP HC	EPAP CO	EPAP NOx	Sk	Development Status*	Projected Implemen-tation Date	Origin of Data*
CF6-50	Proposed Std.		6.7	36.1	38.1	19			
	Production		63.0	119.5	60.8	13	IS		
	Sector Burn w/ Nozzle Mod.	2	1.0	37.1	60.8		SE		ET ET
	Dbl. Annular	3	2.4	49.8	44.7		R	1986-7	Rig
	Selective burning (SAB)	1	12.0				ID	1983	ET
CF6-6	Proposed Std.		6.7	36.1	33.0	20			
	Production		43.3	96.5	65.7	16	IS		ET
	Sector Burn	2	1.8	28.3	65.7	16	SE		ET
	Dbl. Annular	3	2.8	61.5	35.2			1986-7	Proj.
	SAB	1	11.0				ID	1983	ET
CF6-32	Proposed Std.		6.7	36.1	33.0	21			
	Production		48.1	102.1	64.1		IS		Proj.
	Sector Burn	2	2.0	29.8	64.1		SE		Proj.
	Dbl. Annular	3	3.2	72.6	35.6			1986-7	Proj.
	SAB	1	12.0				ID		
CF34	Proposed Std.		14.4	85.2	33.0	30			
	Development	2	53.1	205.0	24.9	20	ID		ET
	SAB	1	12.7	80.0	27.0	20	ID	Cert. Date	
CFM56	Proposed Std.		6.7	36.1	33.0	22.9			
	Mod. PFRT	2	12.0	79.5	42.8				ET
	Sector Burn.	2	1.5	51.7	42.8				ET
	SB + adv. idle	2	0.9	42.0	43.5				ET
	SAB	1	4.0				IS		ET
CF6-80	Proposed Std.		6.7	36.1	45.2				
	Sector Burn	2	2.0						Rig
	SAB	1	6.0				ID	Cert. Date	Rig

* IS = In Service SE = Service Evaluation ID = In Development

2. Pratt and Whitney Aircraft

Pratt and Whitney Aircraft (P&WA) is a division of the United Technologies Corporation (UTC). P&WA is the major producer of jet engines for commercial aviation, its most popular being the ubiquitous JT8D (B727, B737, DC-9). It also manufactures the JT3D and the JT9D as well as several models of military engines. Another division of UTC is Pratt and Whitney Aircraft of Canada, a manufacturer of small jets and turboprops for business aircraft. A summary of the company's engines is presented in Table IV-5.

Summary of Research and Development Effort

JT9D

NOx control for annular combustor engines originated around the NASA Experimental Clean Combustor Program (ECCP). This portion of the jointly funded program with NASA utilized the JT9D-7 engine as the testbed, but, as in the GE case, this effort should be considered a technology demonstration program, applicable generally to annular combustors such as are also found in the JT9D-70, JT10D, and other engines of similar geometry, specifically those capable of housing the relatively long vorbix configuration when it is properly sized for its operational performance requirements.

The ECCP was divided into three phases: (I) preliminary screening of several concepts, (II) refinement of the best, and (III) engine

Table IV-5

Pratt & Whitney Aircraft Engines

Engine	Class	Thrust	BPR	PR	Combustor	Application	Cert. Date	Number Delivered	Production Category
JT9D-70	T2	228 KN	4.9	24	A	B747	1974		III
JT9D-7	T2	205 KN	5.2	21.4	A	B747	1971		III
JT10D	T2				A	None	1979	0	IV
JT8D-209	T2				Cn-A	DC-9-580		0	IV
JT8D-17	T2	71.2KN	1.0	17.0	Cn-A	B727, B737, DC-9			III
JT8D-9	T1	64.5KN	1.0	15.9	Cn-A	B727, B737, DC-9			II
JT3D	T1	84.5KN	1.4	13.5	Cn-A	B707, DC-8			I

PROSPECTUS

			Prospects of Meeting:						
			Emissions Performance				Operational	Mechanical	
Engine	1981	1984	HC	CO	NOx	Sk	Performance	Performance	Time
JT9D-70	good								
		poor			X	X	X	X	X
JT9D-7	good								
		poor			X	X	X	X	X
JT10D	--not known--								
JT8D-209	good								
		poor			X	X	X	X	X
JT8D-17	good								
		poor		X	X	X	X	X	X
JT8D-9	good								
		poor		X	X	X	X	X	X
JT3D	no		X	X	X				
		no	X	X	X				

demonstration. In phase I, three concepts were explored, (1) modification of a conventional combustor (carbureted lean burning combustor), (2) a radial/axial fuel staged combustor with premix/prevap fuel preparation, and (3) an axial staged combustor with conventional injection and mixing (swirl) called the vorbix (VORtex Burning and mIXing), shown in Figure 15. The philosophy behind axial staging is explained in Section III and Appendix A. The vorbix was continued into phase II and extensively optimized so that one version (S27E) was eventually tested in an engine (phase III). The concept performed well in the engine demonstration and showed the viability of the system (see Table IV-6 below).

Additional development work is needed to resolve deficiencies in the concept in order to bring the vorbix to "state-of-the-art" performance, at which time detailed development for specific hardware application could be undertaken. The first deficiency was that while the gaseous emissions were acceptable, the smoke levels were considerably in excess of the standard (30 vs. 19). This was totally unexpected from the results of the rig tests in phase II. Subsequent investigation revealed that the probable cause was the main zone fuel injectors which differed from those used in the rig tests. Presumably, therefore, this problem can be eliminated. The second problem was that several of the operational and mechanical performance criteria were out of specification. In particular, the temperature profile was slightly beyond tolerance and because of the shortage of dilution air (characteristic of lean, staged combustors), control would be more difficult. Also, coking was observed in the main stage fuel lines and carbon was deposited locally within the combustor. Durability was also called into

VORBIX LOW EMISSIONS COMBUSTOR (JT9D-7)

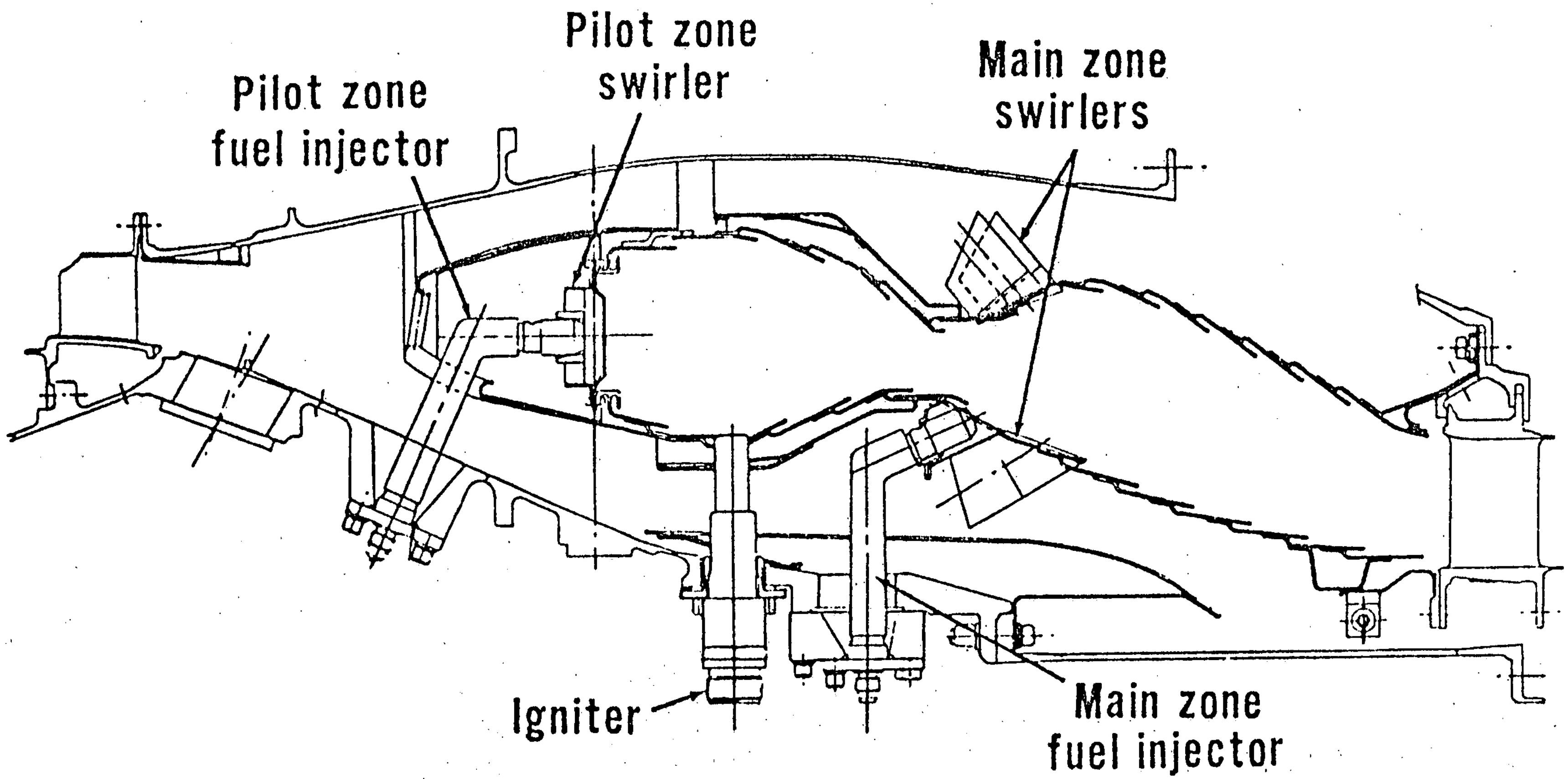


Figure 15

question because of the appearance of localized hot spots on the liner. Finally, the engine performance criteria of ground starting and acceleration were deficient. The latter was marginally acceptable (i.e., met standards) in most cases, but quite inferior to that of the production engine. This was due principally to the time required to fill the main stage fuel manifolds above idle power. Barring a technical solution, it would seem that the definition of a flight idle with both stages fueled would improve the required acceleration sufficiently. This would require a squat switch so that ground idle could be identified and single stage operation used. The ground start problem has been identified as the primary stage fuel injectors. Yet any change to correct this problem would likely influence the altitude relight which at this point has not been well investigated anyway.

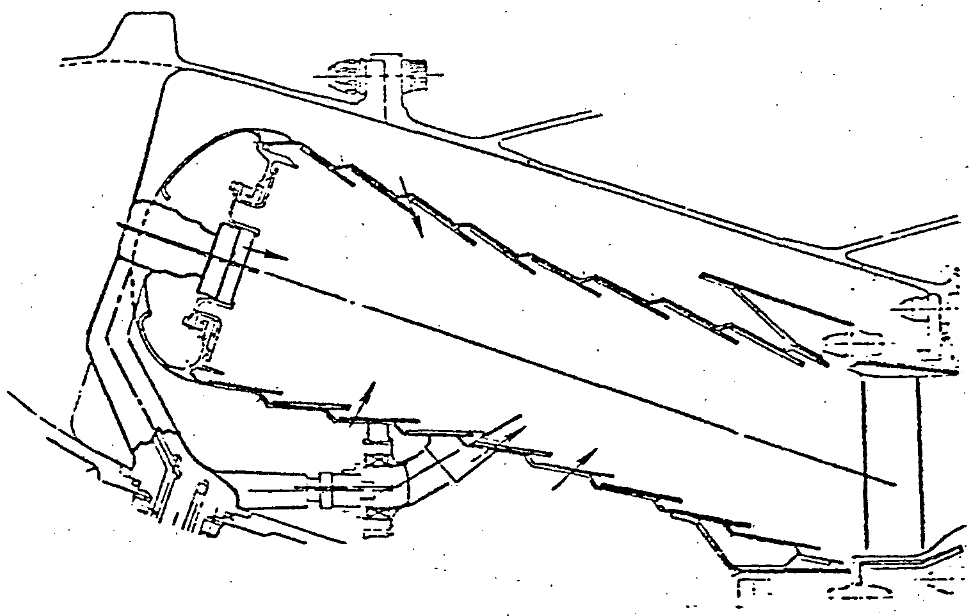
In addition to these emissions and performance problems, the ECCP configured vorbix suffers from certain mechanical complexities, the consequences of which would lead to an expensive and probably difficult-to-maintain piece of hardware. Features like the throat and the 90 nozzles and swirlers in the liner and dome make fabrication difficult and expensive. Also, the axial staging leads to the requirement for either two axially located rings of nozzle holes in the outer pressure casing (costly) or long cantilevered nozzle supports in the interior subjected to the high temperature (coking and structural problems) as shown in Figure 16. The throat section between the two stages is not only difficult to fabricate, but is particularly susceptible to failure because of the high heat transfer and difficulty in cooling the region.

This, of course, would lead to high maintenance expense.

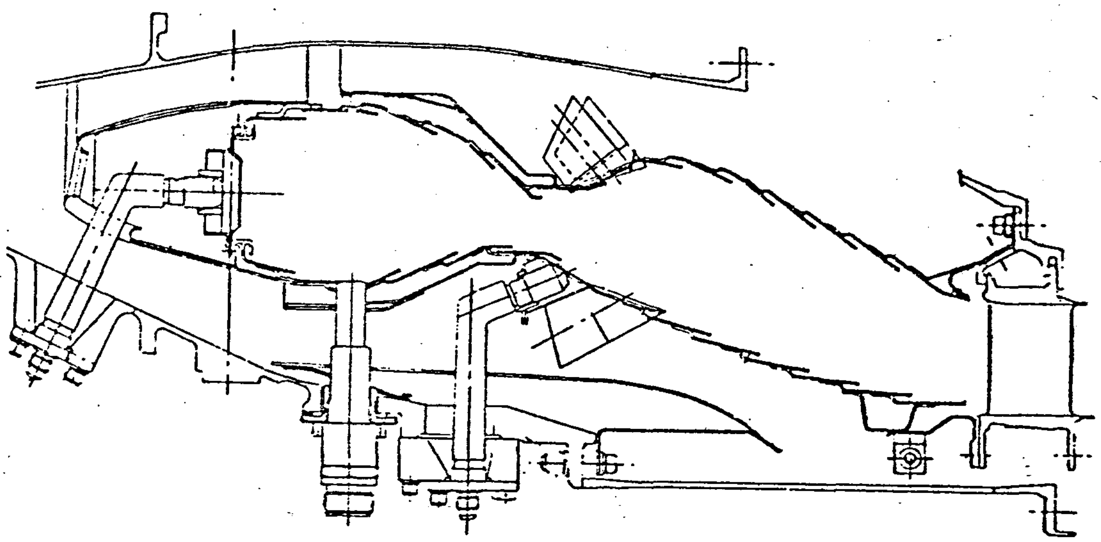
It was found that, at least in the JT9D-7 application, both stages can operate in all flight modes and yet provide acceptable emissions levels. This minimizes the fuel control logic, enhances reliability (by not having the staging cycling on and off repeatedly while on approach), and lessens the coking tendency in the long secondary stage nozzle supports (because fuel is always flowing in flight), or alternatively, improves the engine acceleration (because the secondary fuel manifold, which might otherwise be drained to prevent coking, need not be refilled prior to fuel flowing into the secondary during acceleration). This situation is in contrast to the GE double annular staging system wherein CO control dictated pilot stage operation only up through approach power (30%). Nonetheless, coking in the fuel passage was observed in the main stage (which sees a hotter environment) after the ECCP phase III testing.

Since the conclusion of the NASA ECCP, vorbix work has concentrated on the development of a new simplified and improved vorbix system rather than upon the refinement of the one developed during the NASA work. A simplified system would include, if at all possible, a reduction or elimination of the throat and reduction in the number of fuel nozzles (the latter may badly affect the low power emissions as too few nozzles would lead to very lean zones between the nozzles and subsequent quenching of the reactions). Improvements would include lower smoke levels and improved operational performance obtained through better air distribution and fuel control.

COMPARISON BETWEEN ADVANCED AND ORIGINAL VORBIX CONCEPTS



Advanced E^3 Program Vorbix



Original ECCP Vorbix

Figure 16

The post-ECCP vorbix work has been supported by IR&D funding and the NASA Efficient Energy Engine (E^3) program. The E^3 program is just beginning and is directed towards the demonstration of a lightweight, low specific fuel consumption engine in the 140KN thrust size range. This engine is to be a technology demonstrator only and is not intended by NASA to be a prototype. Hence, the combustor design is not directly usable in the JT9D-7; however, the technology is transferable. The P&WA combustor configuration for the E^3 program will be a throatless vorbix with 24 aerating nozzles in the primary (vs. 30 for the JT9D ECCP) and 48 pressure-atomized carbureted nozzles in the main zone with radial inflow swirlers to provide fuel-air mixing and flame stabilization in the main stage. The fewer nozzles compared with the JT9D-7 should not necessarily be construed as a simplification as it merely reflects the smaller size of the engine (air flow rate: 65 kg/sec vs. 95 kg/sec). The combustor also features a single plane entry of the primary and and main stage fuel nozzle supports which are then cantilevered fore and aft to their respective locations (Figure 16).

The IR&D vorbix study first investigated simplifications of the ECCP configuration which included a reduced number of primary nozzles and variations in the throat size. The rig work was done simulating the JT9D-7 cycle. However, despite variations in the primary stoichiometry, the emissions performance with these simplifications was found to be inadequate. Additional investigations of advanced nozzle concepts including carbureted nozzles and aerating nozzles on reduced length burners (for low NOx) were also carried out. In 1977, the carbureted nozzle work was continued and concepts refined. A new vorbix configuration (Vorbix II) was designed and adapted to a can burner (JT8D). This concept employed the tested high power stage (NOx control) with a new primary stage offering potentially improved low power emissions. This stage utilized the new carbureted nozzles and preheated air for better vaporization and mixing. Testing continues, but no data are available by which to judge the potential of the new configuration.

The status of development work for compliance with the proposed 1981 HC, CO and smoke standards is slightly uncertain at this point because the more explicit idle definition in the March 1978 proposal differs from P&WA's earlier usage on which the bulk of their effort and data are based. This new definition has been found to have an impact on the EPAP values of up to 50% which would vastly reduce or even eliminate their margin for variability in most cases. The information presented here is based on P&WA's interpretation of EPA's original idle definition. The D-7 and D-70 have separate development programs and are discussed separately.

<u>(JT9D-70)</u>

The D-70 has a bulkhead type burner (Figure 17). P&WA began with a rich primary aerating nozzle configuration and met with success after numerous revisions to the liner and nozzle configurations. Pressure atomizing nozzles were also evaluated and found to have inferior emissions performance, however. Development was done with both engine testing for emissions (rig data being considered unreliable) and rig testing for relight, coking, and durability and, in addition, a nozzle support program was also conducted to examine nozzle durability, coking, etc. Despite a persistent tradeoff between smoke and NOx (P&WA was attempting to keep NOx at its January 1976 recommended level), one configuration finally yielded acceptable HC,CO, smoke, and NOx, and acceptably small penalties in pattern factor and combustor pressure drop (Figure 18). Initially altitude relight was deficient, but minor alterations remedied that difficulty, improving relight to beyond that of the production combustor.

Durability remains a concern because the low emissions air distribution is considerably different from that dictated by conventional design. The aerating nozzles, in particular, suffer early distress. Durability assessment of alternate construction techniques, alternate materials, and redesigned nozzles, along with cyclic endurance testing continue. Radial temperature profile tailoring began in late 1977 and should be concluded in time for service evaluation in 1979. Effects on HC, CO emissions are expected to be minor as the dilution air is added too far downstream to impact on the reactions.

<u>(JT9D-7)</u>

P&WA experienced more difficulty with the D-7 combustor which differs from the D-70 (see Figures 17 and 19) by having a short cone (20 of them) burner rather than a bulkhead burner. On the basis of the early (Phase I) ECCP data, P&WA began with a lean primary short cone burner with aerating nozzles, which was compatible with the existing D-7 geometry. After extensive experimentation, it became evident that it

JT9D-70 PRODUCTION COMBUSTOR

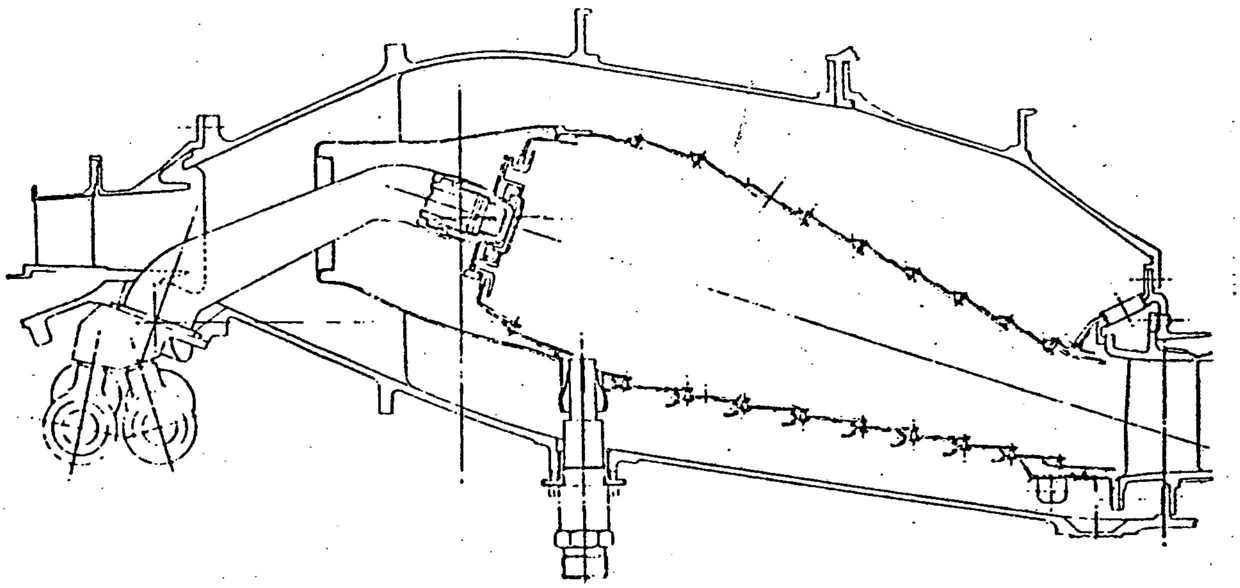


Figure 17

JT9D-70 LOW EMISSIONS COMBUSTOR

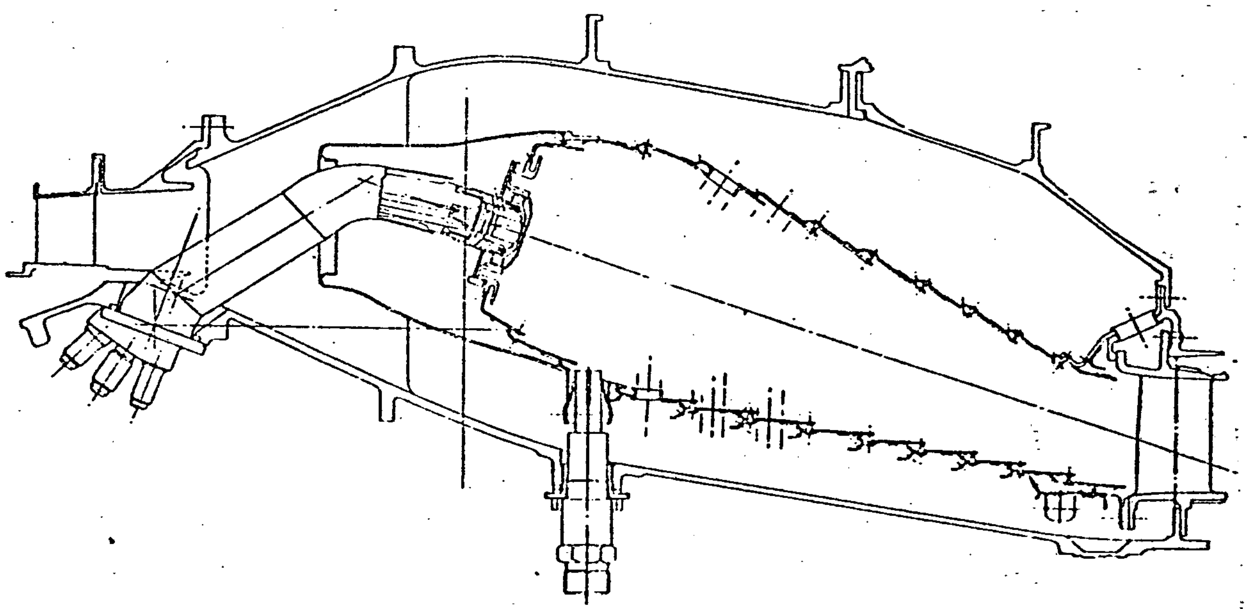


Figure 18

was impossible to satisfy all the emissions requirements (including the P&WA NOx goal of about 60 gms/KN). The short cone burner was deficient because it restricted the fuel distribution in the dome, in fact, washing the walls with fuel and, secondarily, its inherently lower pressure drop limited the turbulent mixing in the primary. Both of these effects promoted the existence of rich pockets, resulting in high smoke. Attempts to reduce the extent of the rich pockets by leaning the overall mixture then resulted in lean pockets elsewhere giving rise to excessive HC, CO; hence a tradeoff existed between HC, CO on one hand and smoke on the other.

P&WA finally abandoned the aerated nozzle short cone burner for an aerated nozzle bulkhead type burner (Figure 20) similar to that used in the D-70. This represented a major change, requiring lengthened nozzle supports, new combustor supports, and a reevaluation of the effectiveness of the diffuser. This change resolved the emissions problem when it was found that smoke could be controlled independently by the amount of air admitted through the swirler surrounding the nozzle. Initial configurations gave unacceptable pattern factor, temperature distribution, relight or pressure drop, but eventually most of these operational parameters have been improved to within acceptable limits. Development is expected to be completed by the end of 1978 and endurance and performance testing will continue through 1979. Service evaluation should begin in 1979.

Table IV-7 summarizes the emissions performance of the important low emissions configurations.

JT9D-7 PRODUCTION COMBUSTOR

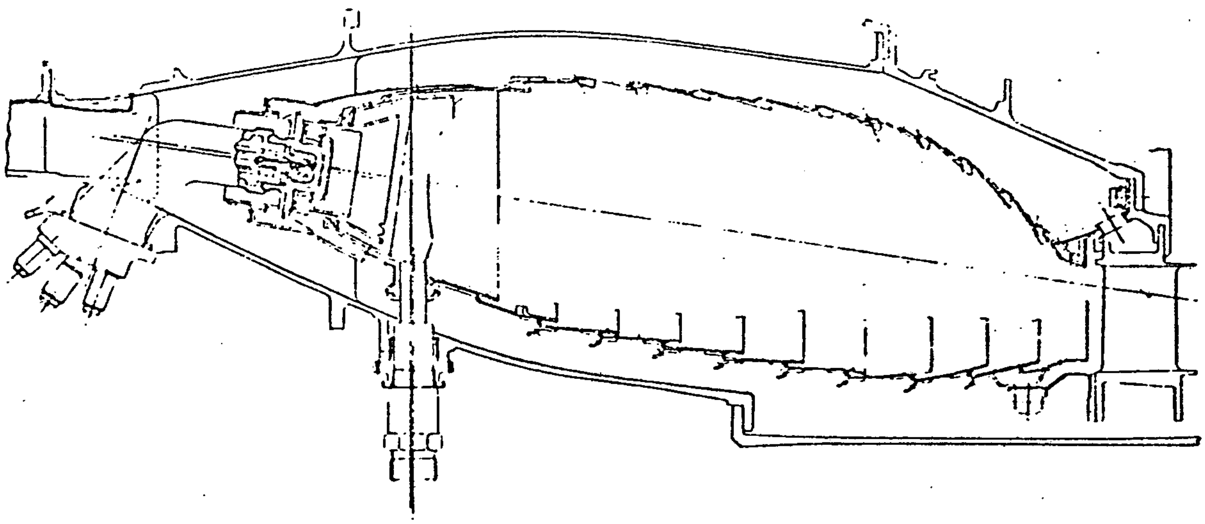


Figure 19

JT9D-7 LOW EMISSIONS COMBUSTOR

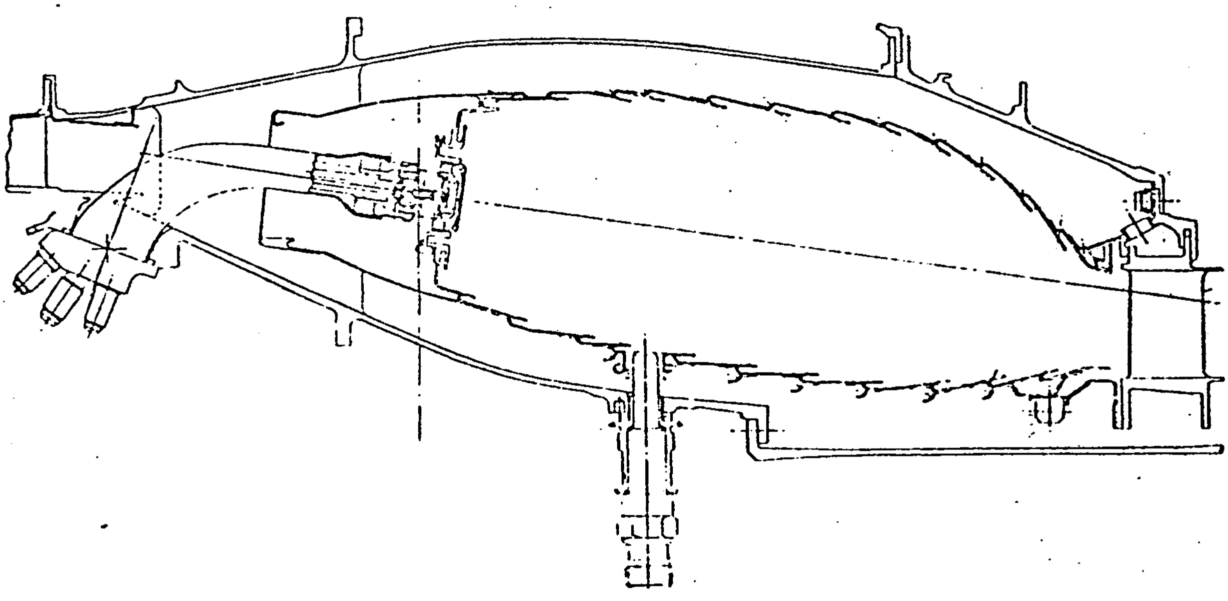


Figure 20

JT8D

The NOx control effort for can-annular engines such as the JT8D has been limited compared with the annular combustor effort. The effort began with the joint P&WA/NASA Pollution Reduction Technology Program, a program which was designed after the ECCP of the JT9D. The program utilized the JT8D-17 and was initially intended to have three consecutive phases, parralleling those of the ECCP. However, the NASA sponsorship was terminated after the first phase, apparently because NASA felt that continued support of low NOx technology for can-annular combustors was a benefit only to P&WA and the JT8D (an older engine to begin with) and hence not of sufficiently general interest to warrant public funding. The program, however, was successful as far as it went. In addition to the NASA work, P&WA has carried on some IR&D supported work.

The NASA work had three elements, each representing a different degree of complexity. The elements are outlined in Table IV-6. The first involved a continuation of some earlier in-house work on airblast and carbureted nozzles with airflow redistribution to affect the primary zone stoichiometry. In general, such an approach is not expected to have much positive influence on NOx. The second element involved the adaptation of the vorbix concept to a can-annular combustor such as in the JT8D. The vorbix in this configuration had an airblast primary in each can and two pressure-atomizing simplex nozzles in the same axial plane injecting into two carburetor tubes which carried the fuel and inducted air downstream until past the throat at which point they entered the can through swirler orifices forming the secondary or main burning zone (Figure 21). The stoichiometry in the carburetor tubes was rich beyond the flammability limit to avoid flashback into the tubes. This configuration minimized the extent to which the internal (to the casing) pressurized fuel manifolds were subjected to high temperature (equal to the compressor discharge temperature 715°K, or higher). The third element relied upon staging again, but with prevaporizing and premixing fuel preparation. For this system to work safely and properly, variable geometry features possibly would be required to control the local stoichiometry at the various power settings; such features were not explored in this program, however. Furthermore, without such features, the total NOx level over the LTO cycle did not improve over that of the vorbix and the CO was worse due to the very lean stoichiometry.

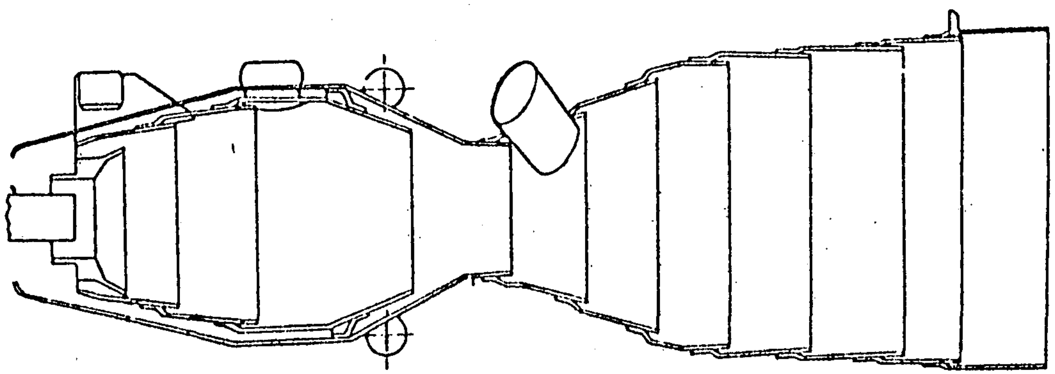
Table IV-6

NASA/Pratt and Whitney JT8D Program Elements

Element I	Minor modifications to the existing JT8D combustor and fuel system; including fuel nozzle modifications and replacement and airflow redistribution.
Element II	Advanced versions of the Vorbix, including carbureted fuel induction into the main stage.
Element III	Premix/prevaporization combustor schemes which employ the vaporized state of the fuel to control flame stoichiometry for emissions control. Variable geometry may be a necessity to achieve acceptable emissions and stable burning, but this was not explored in the study.

The control concepts were tested in a single can (40° sector) rig

JT8D VORBIX (NASA - P&WA PRT PROGRAM)



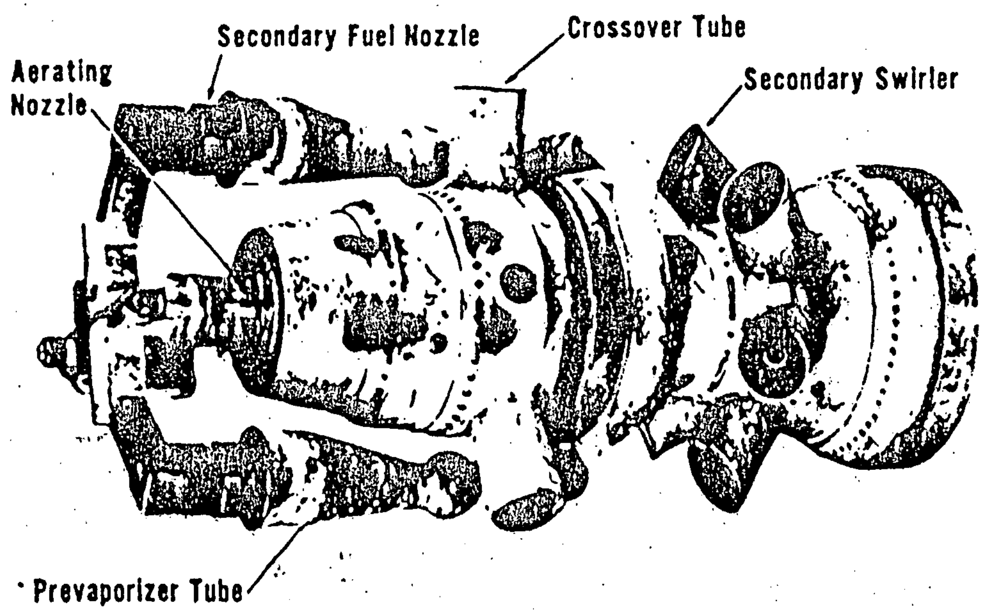


Figure 21

at actual engine conditions which tended to give higher absolute emissions levels than an engine test (based on production combustor data). While a number of deficiencies in operational and mechanical performance could be and were identified in the program, transient phenomena were not even investigated as this requires engine testing for evaluation. Hence, a major portion of the required performance characteristics is not yet known, making evaluation of the vorbix's potential still more speculative.

The emissions performance of the vorbix was good considering the preliminary nature of the experiments. The best configuration, however, met only the HC standard while NOx and smoke were 10% higher than the proposed 1984 standards (higher if a margin for variability were considered) and CO, although improved considerably, was 25% higher. While smoke may be improved by continued development, it is a fact that the combustor performance in terms of the combustor inefficiency and the NOx emissions index (EI) matched that of the JT9D vorbix which has undergone much more refinement (Figures 22-23). It is, therefore, difficult to anticipate significant CO and NOx improvements with this scheme. In fact, the CO level achieved was accomplished by operation at pilot only during approach (as opposed to the JT9D scheme which operated both stages in the air). As this may be considered a detriment (due to the need to cycle staging while in flight), the CO level may instead increase rather than decrease with any further development that would operate only with both stages above ground idle. Performance problems that have been identified already are carbon deposition in the main stage carburetor tubes (due to pyrolysis in the ultra-rich mixtures),

NOx EMISSIONS PERFORMANCE COMPARISON
BETWEEN JT8D AND JT9D VORBIX
COMBUSTORS

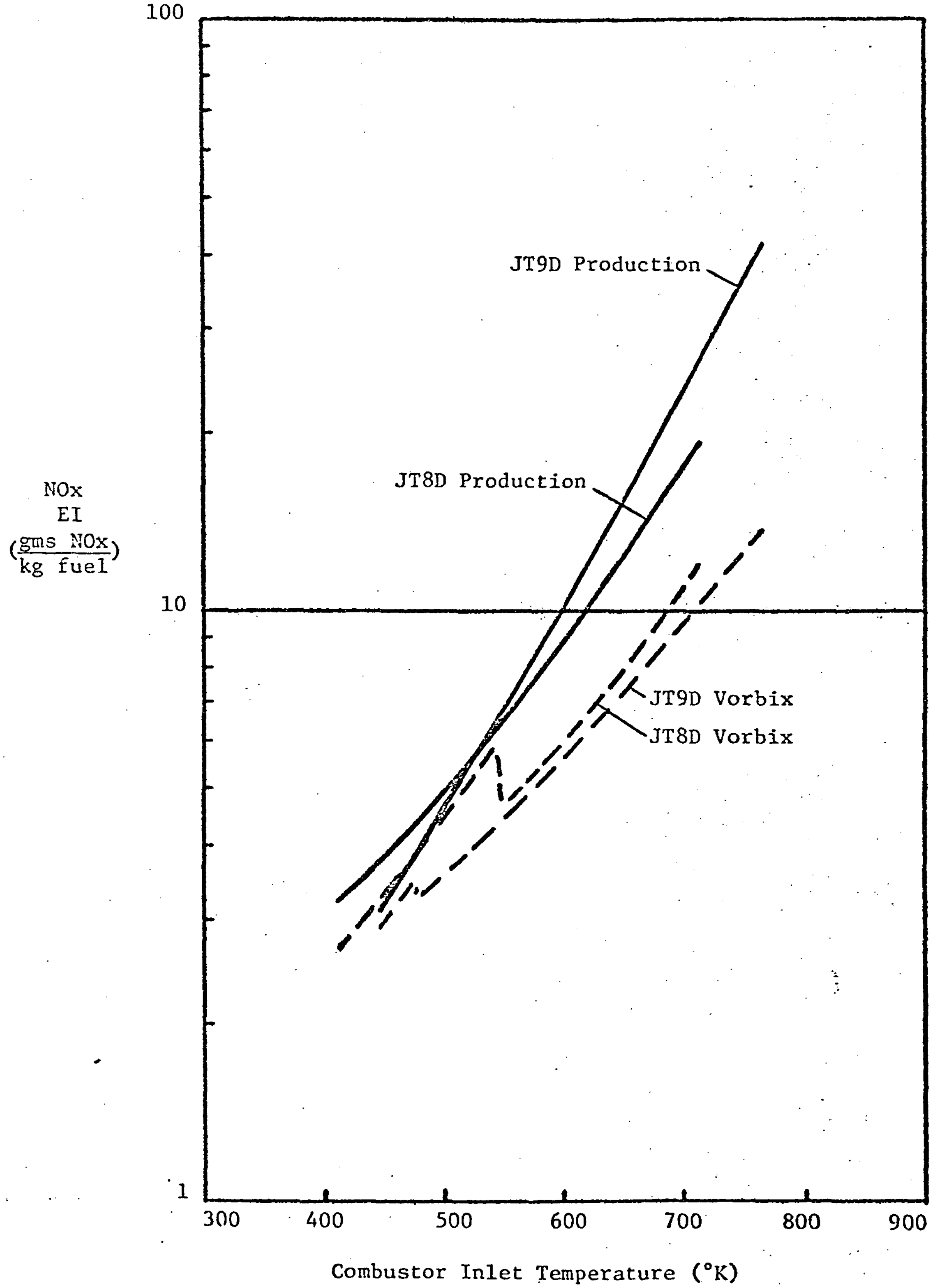


Figure 22

COMBUSTION EFFICIENCY COMPARISON BETWEEN
JT8D AND JT9D VORBIX COMBUSTORS

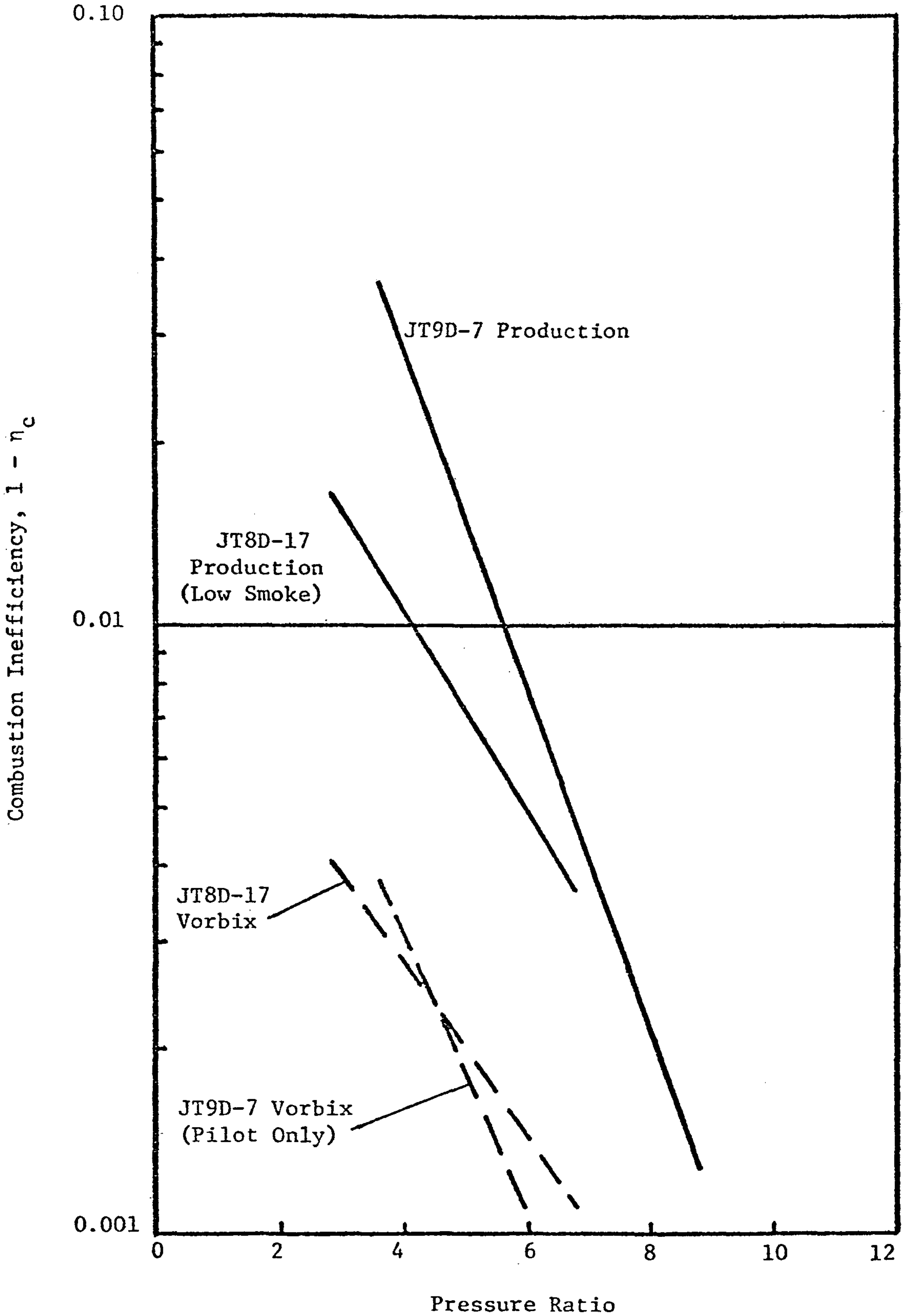


Figure 23

overheating of the liner wall, especially in the throat, pattern factor deficiency and altitude relight (minimally examined). The radial exit temperature profile (important for turbine durability) was not investigated. Temperature profile adjustment with any vorbix can be difficult because the high air demands of the two stages and the cooling requirement leave little left for dilution near the exit. The other operational and mechanical performance deficiencies appear to have no special problems that could not be resolved with normal development.

On the positive side, though, the combustor possesses a lower than normal pressure drop which can be converted to fuel savings or exchanged for increased mixing and possibly reduced CO. Another favorable feature of this vorbix combustor in the JT8D is that no major changes to the engine are required (diffuser, casing, or transition duct). Only a proper fuel control must be designed.

Further NOx control investigation was conducted by P&WA in 1976 with IR&D funding after the conclusion of the NASA program. The effort centered around achieving a simplification of the vorbix concept by reducing or eliminating the throat and wrap-around carburetor tubes. These proprietary configurations led to compromises in the location of the main stage injection, the degree of swirl (mixing and stabilizing), and the amount of premixing in the main stage (carburetion). The emissions performance of these configurations was degraded, some pollutants substantially (HC, smoke); the operational performance is not known to the EPA. This work is being continued under a general advanced vorbix development program whose emphasis is the improvement in low power emissions, largely through advanced nozzle concepts. Although not considered by P&WA a part of the JT8D low emissions program (possibly because P&WA was convinced EPA would drop the NOx requirement), the experimentation is being performed on a JT8D sized burner can.

The HC and CO control program originated out of the earlier smoke control program and element I of the NASA program, and funding via IR&D has carried the program on. With the control concept selected in 1976 (airblast nozzles with proper airflow redistribution - a richer primary), engine testing began in 1977 for the development of durability and temperature pattern. While the testing has yielded a configuration with less margin than hoped for, a number of operational performance criteria appear to have met or exceeded that of the production version now in use: (1) Better altitude relight, (2) better cold start, and (3) no appearance as yet of durability problems. Two separate, but similar, burners are normally required for the JT8D, one for the D-17 and another for the D-9 model; however, P&WA has concluded that only minor changes will be needed for the D-9 to achieve its proper temperature profile (the D-9 has uncooled first stage turbine valves and hence requires a different temperature profile from the D-17 which has cooled vanes).

Table IV-7 summarizes the emissions performance of several of the important low emissions configurations.

JT10D

This is a totally new engine designed to the anticipated needs of the next generation of commercial aircraft. As it was not selected initially to be used on the new Boeing 757 or 767/777 families, its ultimate utilization is in question. It is intended to be in the 110-160 KN thrust range although its final configuration has not yet been established. If built, it presumably would be certified prior to 1984 and hence its HC, CO emissions levels would be dictated by the proposed 1981 NME standards and not the more severe 1984 newly certified engine (NCE) standards. Like all new larger engines, it employs an annular combustor.

In anticipation of a low NOx requirement, the JT10D casing and combustor housing was designed to accept a vorbix type combustor, patterned after that which would go into the JT9D. However, pending the development of an acceptable vorbix configuration, the 10D would use a conventional, single stage combustor employing only the HC, CO controls used on the JT9D (airblast nozzles and rich primary zone). The success of a vorbix type combustor in this application is, of course, uncertain inasmuch as considerable development work is still required to refine the vorbix into a state-of-the-art concept. Further hardware development would then be required to apply the concept to the JT10D configuration. On the other hand, the P&WA work for the NASA Energy Efficient Engine Program (providing a demonstrator engine in the 100 KN class) should be very helpful as they are continuing development of the vorbix type burner in that program.

Despite P&WA's funding of JT10D emissions since 1973, little about the combustor geometry, performance, or status is known to the EPA at this time.

Table IV-7 presents a summary of the emissions performance of the P&WA engines. Rig data are identified. A projection of the performance of the vorbix combustor, as presently configured, is made for the JT9D-70 for which no testing has been done. Expected availability of the technology is also given based upon the manufacturer's current position and existing or anticipated problems.

Table IV-7
Pratt & Whitney Performance

ine	Concept	Technology Category	EPAP HC	EPAP CO	EPAP NOx	Sk	Development Status*	Projected Implementation Date	Origin of Data*
D-70	Proposed Std.		6.7	36.1	33.0	19			
	Production		31.5	87.5	54.3	8			
	Aerating Nozzle w/ Rich PZ.	2	3.9	24.4	48.5	10	ID, FT	1982	ET
	Vorbix	3	2.0	26.3	35.2		R	1986-8	Proj.
D-7	Proposed Std.		6.7	36.1	33.0	19			
	Production		61.0	150.0	61.8	8	IS		ET
	Aerating Nozzle w/ Rich PZ	2	9.5	28.0	47.4	20	ID, FT	1982	ET
	Vorbix	3	2.1	30.2	26.2	30	R	1986-8	ET
D-209	Proposed Std.		7.5	41.2	33.0	25			
	Baseline								
	Aerating Nozzle w/ Rich PZ	2	2.2	33.6	54.9	15	ID	Cert. Date	Proj.
	Vorbix (NASA)	3	1.4	67.4	40.7		R	?	Proj.
D-17	Proposed Std.		8.9	49.9	33.0	26			
	Production		37.3	112.7	60.1	24	IS		ET
	Aerating Nozzle w/ Rich PZ	2	5.6	46.5	68.4	14	ID, FT	1982	ET
	Vorbix (NASA)	3	1.6	83.1	41.0	27	R	?	Rig
D-9	Proposed Std.		9.9	55.9	33.0	26			
	Production		35.1	124.5	52.2	23			ET
	Aerating Nozzle w/ Rich PZ	2	6.7	48.5	59.1	11	ID	1982	Proj.
	Vorbix (NASA)	3	1.6	88.0	36.0		R	?	Proj.

IS = In Service
R = Research
oj = Projected

SE = Service Evaluation
ET = Engine Test
Rig =

ID = In Development
FT = Flight Test

3. Rolls Royce

Rolls Royce is a large British manufacturing firm, occasionally owned by the British government. Its two major divisions, Bristol and Derby, manufacture a variety of civil and military gas turbine engines of their own design as well as of cooperative design. The civil engines are, in descending order of size, the RB211 family, Olympus 593, RB432 (in development), the Spey family, M45H, RB401 (in development) and Viper for the jets, and the Tyne and Dart for the turboprops. A summary of the company's engines is presented in Table IV-8.

Summary of Research and Development Effort

RB211

The RB211 consists of the original -22 model, the larger -524 model, and the proposed -535 which is smaller than the -22, but has its entire high pressure core intact, including the identical combustor. The -524 was developed with a different combustor designed to alleviate some of the operational problems experienced by the early -22 combustors, such as durability and smoke. That combustor, called the stage I combustor, has since been incorporated virtually unchanged into the -22. Inasmuch as all models of the RB211 presently utilize virtually the same combustor, the discussion will generally consider all models together.

Table IV-8

Rolls Royce Engines

Engine	Class	Thrust	BPR	PR	Combustor	Application	Cert. Date	Number Delivered	Production Category
RB211-524	T2	218 KN	4.5	27.2	A	B747,L-1011	1975		III
RB211-22B	T2	187 KN	5.0	25.0	A	L-1011	1973	540+	III
RB211-535	T2	163 KN		19.3	A	B757			IV
Olympus 593	T5		0		A	Concorde		c.80	I
RB432	T2				A	None		0	IV
Spey 511	T2	50.7KN	0.64		Cn-A	GS-II	1963	1560+	II-III
Spey 555	T2	43.8KN	1.0	16.1	Cn-A	F-28	1963	1560+	II-III
M45H	T1	32.4KN	3.0	16.9	A	VFW-614	1974	38	III-IV
RB401	T1		4.2	16	A	None		0	IV
Viper	T1		0			HS-125			I

PROSPECTUS

			Prospects of Meeting:						
			Emissions Performance						
Engine	1981	1984	HC	CO	NOx	Sk	Operational Performance	Mechanical Performance	Time
RB211-524	poor*		X	X					X
		poor	?	?	X		X	X	X
RB211-22B	poor*		X	X					X
		poor	?	?	X		X	X	X
RB211-535	poor*		X	X					X
		fair	?	?					X
Olympus593	good								
		no std.			X				
RB432	--not known--								
Spey 511	no		X	X		X		X	
		no	X	X	X	X		X	
Spey 555	no					X		X	
		no	X	X	X	X		X	
M45H	marginal		X	X			(Limited Data)		
		poor	X	X	X				

* Assuming sector burning is not used.

Rolls Royce appears to be somewhat behind the U.S. manufacturers in the exploration of fuel staging as a means of NOx control due largely, perhaps, to their lack of participation in the NASA Experimental Clean Combustor Program. However, since then Rolls Royce has begun its own investigation with a goal of a 50% reduction in the NOx EPAP while maintaining acceptable idle emissions; their effort has been financed partly by British government funds. Due to the short combustor design of the RB211, similar to that of the General Electric CF6 family, Rolls has elected to pursue the radial staging approach.

Two alternative designs were chosen for evaluation, with the better of the two slated for a proof of concept demonstration (similar to ECCP phase III) test in March 1979. The selected design (Figure 24) is a double annular combustor with the pilot and main stage nozzles housed within short cones and surrounded by air swirlers to enhance the fuel-air mixing. The approach is similar to GE's inasmuch as both have double annuli of nozzles surrounded by swirlers, forming two stages separated by a centerbody; both require a dump type diffuser to provide airflow acceptable to the dome. However, the differences are also considerable.

The GE combustor has the nozzles piercing the flat dome directly into the burning volume common to all nozzles in the stage (see Figure 10); the Rolls nozzles enter into individual cones wherein mixing, vaporization and some combustion of the fuel occurs prior to passage into the annular burning zone. The Rolls combustor provides for cooling

LOW NOx DOUBLE ANNULAR COMBUSTOR (ROLLS ROYCE)

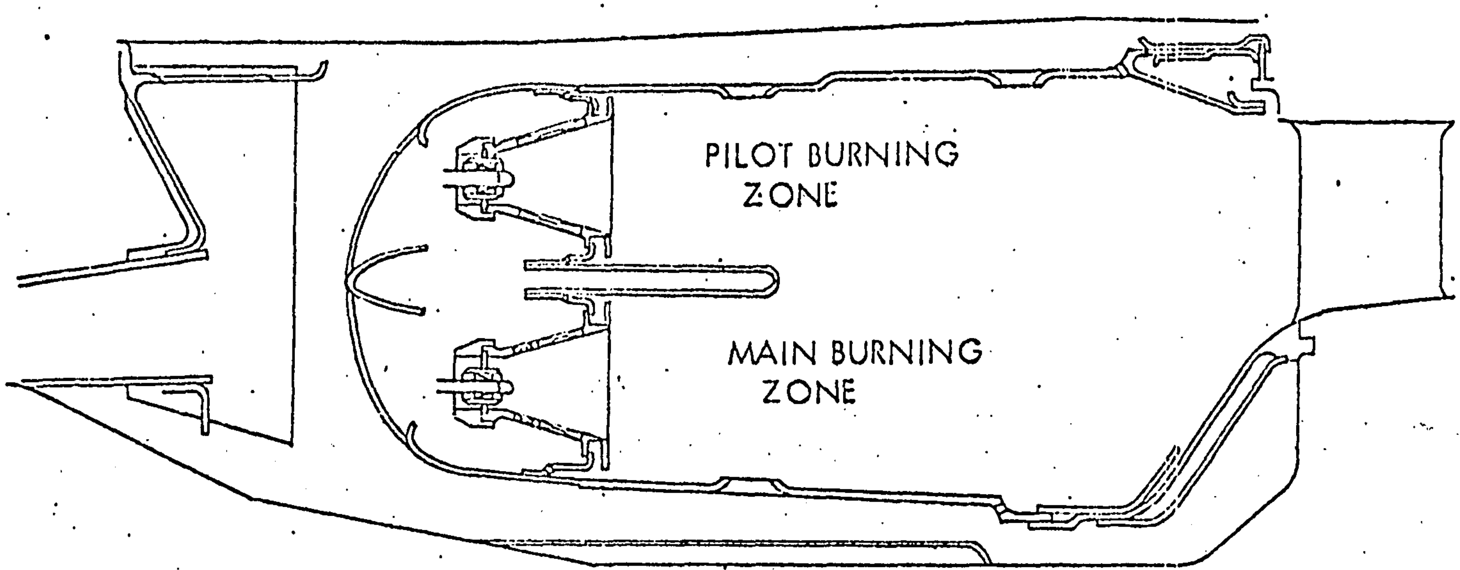


Figure 24

of the centerbody which is not found on the original GE version of the double annular combustor, although a later version as planned for in the E^3 program with NASA has centerbody cooling. The Rolls arrangement requires, unfortunately, a new combustor casing and a new diffuser (the original RB211 diffuser being a smooth type), although not evidently a diffuser casing. The GE combustor was designed to fit into the existing CF6-50 envelope although application in the CF6-6 would require a new diffuser and casing (the -6, like the RB211, has a smooth type diffuser). Also, it is of significance that the Rolls double annular combustor has 72 nozzles fed through 18 bosses. It thus has four times the nozzles of the production engine (18), but manages to minimize the impact on the casing by utilizing the existing boss arrangement. In contrast, the GE double annular combustor only doubles the number of nozzles from 30 to 60, using the same bosses also.

Rig demonstration and development of the concept has been ongoing since mid-1977 and is expected to continue through 1979 in an effort to resolve a number of difficulties which include ignition and temperature profile shortcomings and, especially, inadequate emissions reductions. The actual performance demonstrated to date in the rig is not known to the EPA nor are other important operational points such as the need for in-flight staging (as in the GE combustor). New ideas are still being investigated, but the program is continuing with an engine demonstration (equivalent to the NASA ECCP phase III testing) scheduled early in 1979. Design and development of production quality hardware will begin in 1979 and will involve separate, but similar, combustors for the three variants of the RB211. Full production is possible in 1986, if no major development difficulties arise.

In addition to fuel staging, Rolls Royce has investigated the potential of NOx control via quick quenching used in conjunction with an extended rich primary zone that is swirl driven. This approach was very similar to that explored by GE in the CFM56 engine. Their program goal was a 25% reduction in NOx. This combustor has been tested on a -524 engine and while the excessive CO and smoke demonstrated that this was not a solution in its present developmental state, the potential does exist. The actual EPAP figures for the -524 test are not known, but a Rolls Royce extrapolation of the data to the -535 operating conditions (lower pressure ratio, in particular) predicts that the -535 would meet the 1984 NOx requirement. This is called the stage III combustor and is discussed again in the HC, CO section.

Acceptable HC, CO emissions in the RB211 have followed a long path since the original 1967 design. The original combustor, although possessing a slightly lean primary zone and airblast nozzles (simplex, however) suffered a high degree of non-uniformity (inadequate mixing) which resulted in excessive smoke emanating from rich pockets. Compounding the problem was the fact that the combustor had only 18 nozzles (each 20°) despite the engine being equal in size to the CF6 (30 nozzles) and the JT9D (20). Correction of this problem (smoke being considered a nuisance even before the 1973 regulations) led to a redistribution of, as well as an overall leaner, stoichiometry in the primary, both conditions of which would lead to less smoke production. However, as this led to very lean conditions at idle, the combustion efficiency there suffered, giving the -22 the worst idle emissions among the new high pressure ratio engines. This combustor was referred to as the stage I combustor (Figure 25) and as it entered service in 1975, it permitted the RB211 to comply with the 1976 large engine smoke standard.

A parallel development, the stage II combustor (Figure 26), was initiated at the same time (1973) in an effort to improve the HC, CO emissions and a number of operational and mechanical deficiencies of the stage I burner. This combustor operates with a richer primary (by airflow redistribution and new airblast simplex injectors), and yet provides sufficient uniformity to keep the smoke within limits. The stage II is now entering production in the -22B and -524.

The operational and mechanical performance of the stage II burner is indeed superior to that of the stage I burner; however, it does not provide sufficient emissions control. The control improves in the higher pressure applications. The performance of the -524 (PR = 27), for instance, is roughly equal to that the best non-sector burning CF6-50 technology. On the other end of the spectrum, the smaller -535 (PR = 19) with the stage II burner is little better than the baseline JT9D-7. Hence, Rolls Royce has explored other avenues to supplement or replace the stage II combustor. Operational control by compressor bleed and sector burning, in particular, have been investigated to supplement the stage II combustor. Sector burning by firing 12 of the 18 nozzles (a 240^{o} sector) at idle permits the -524 version to approach HC, CO standards. However, the data available to the EPA show that the -22B, operating at a lower idle

STAGE I COMBUSTOR

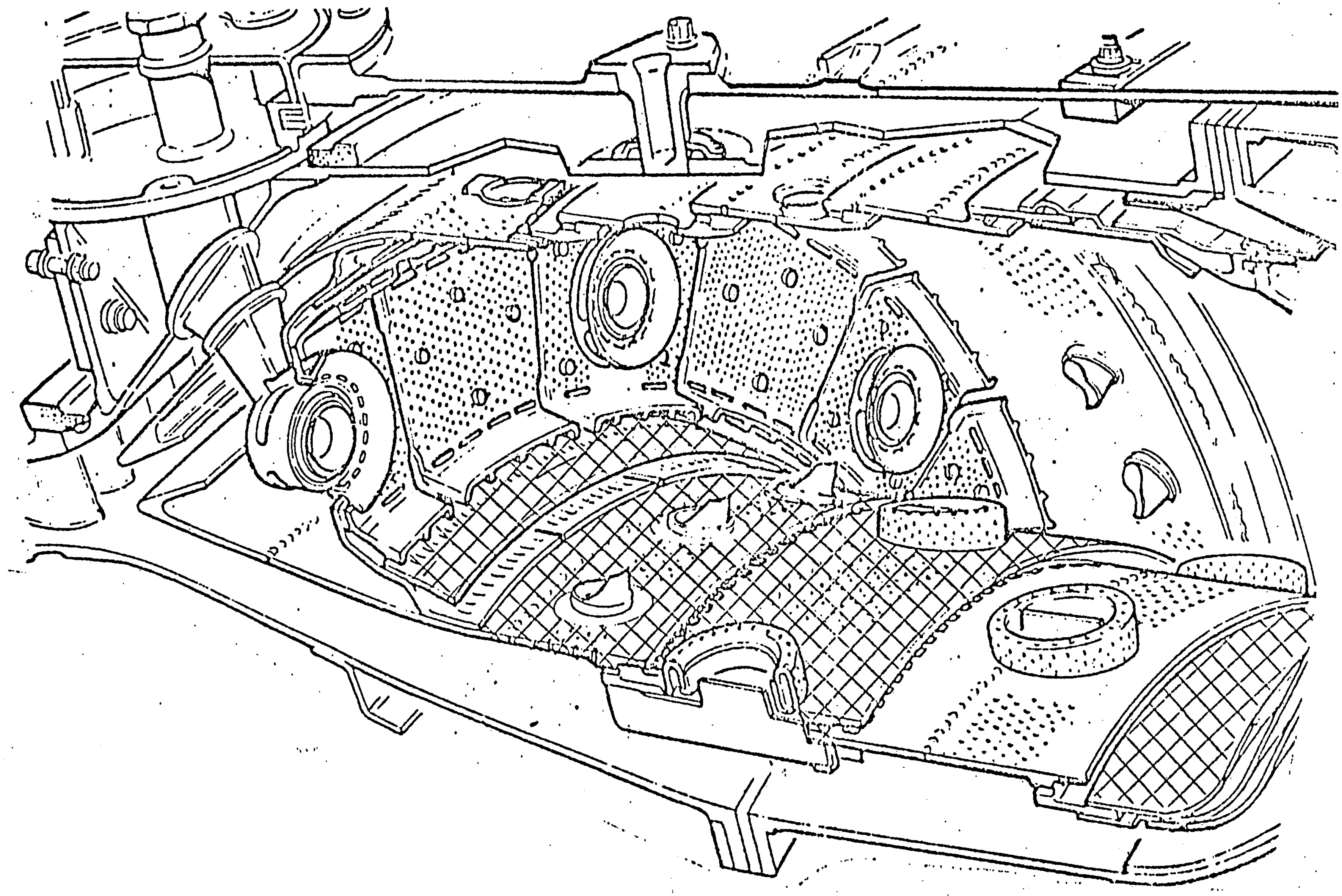


Figure 25

STAGE II COMBUSTOR

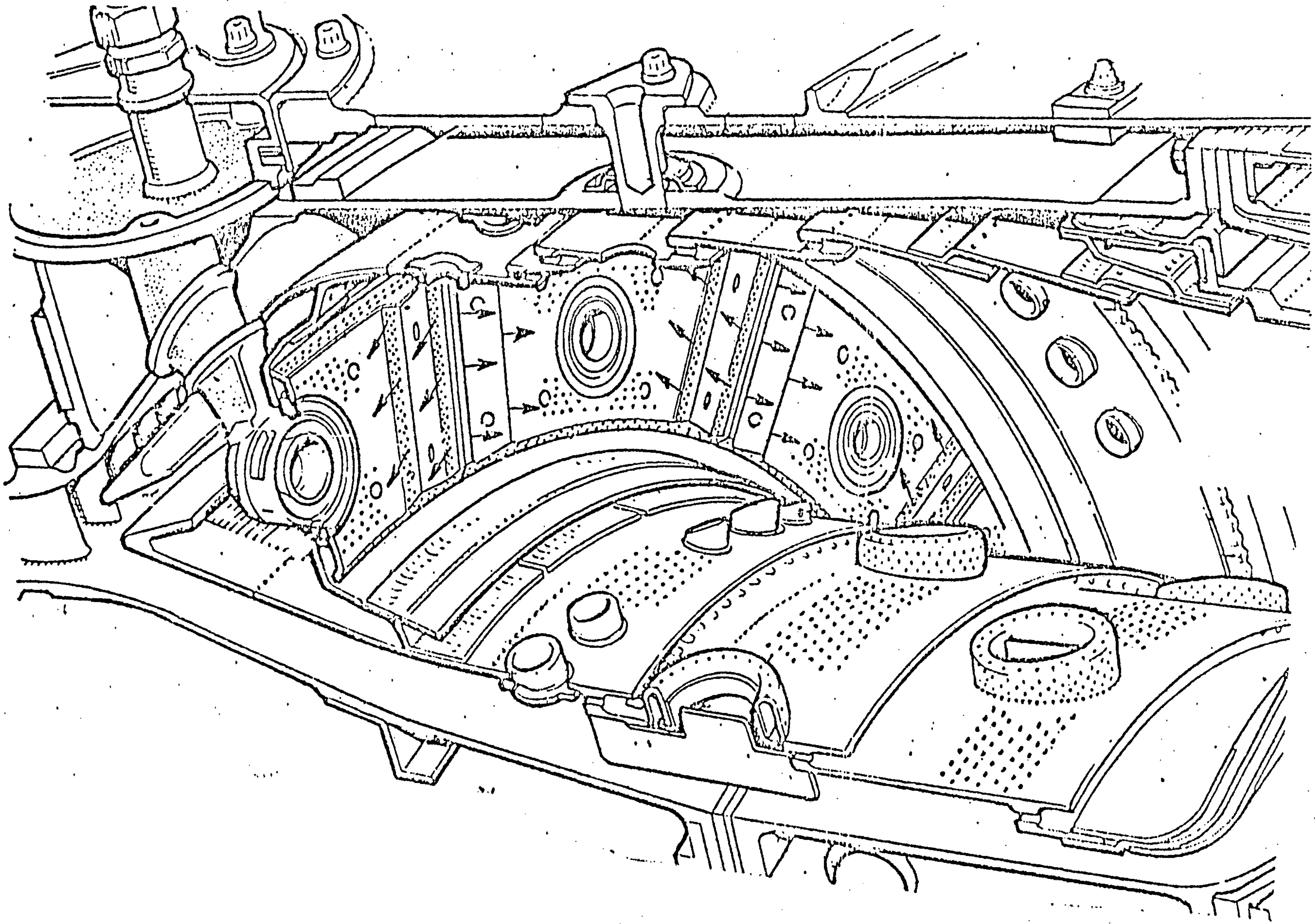


Figure 26

pressure and with a lower rated output, is still well above the standards despite the sector burning. The -535 fares even worse. Additional improvement is not expected by firing fewer than 12 nozzles during dector burning (GE fires only a 180° sector), as the stoichiometry is optimized at 12 firing.

Rolls Royce is committed to the stage II combustor in all applications at the present, largely because of their contractual guarantees for long combustor life, but also because of the economy involved in having a single combustor for all engines. This is true even for the -535 model, which being new, might normally be expected to have a shorter initial combustor life.

As insurance against the failure of the emissions performance of the stage II burner and out of expectation of failure for the -535, which operates at yet a lower idle pressure and with less rated output than the -22B, Rolls began preliminary work in 1977 on the stage III burner, which employs an extended rich primary zone, stabilized by substantial swirl from around the nozzles, and followed by a quench to stop the NOx reactions (Figures 27 and 28). This burner is presently in the research stage and with a commitment to proceed, it would be available in 1985 or 1986 (service evaluation included therein). The only emissions performance data for the stage III combustor which is available to EPA is that from an early version of the combustor which did not have the strong swirl aerodynamics in the primary driven by the swirl cups around the nozzles (see Figure 28). That data shows the emissions performance to be still insufficient.

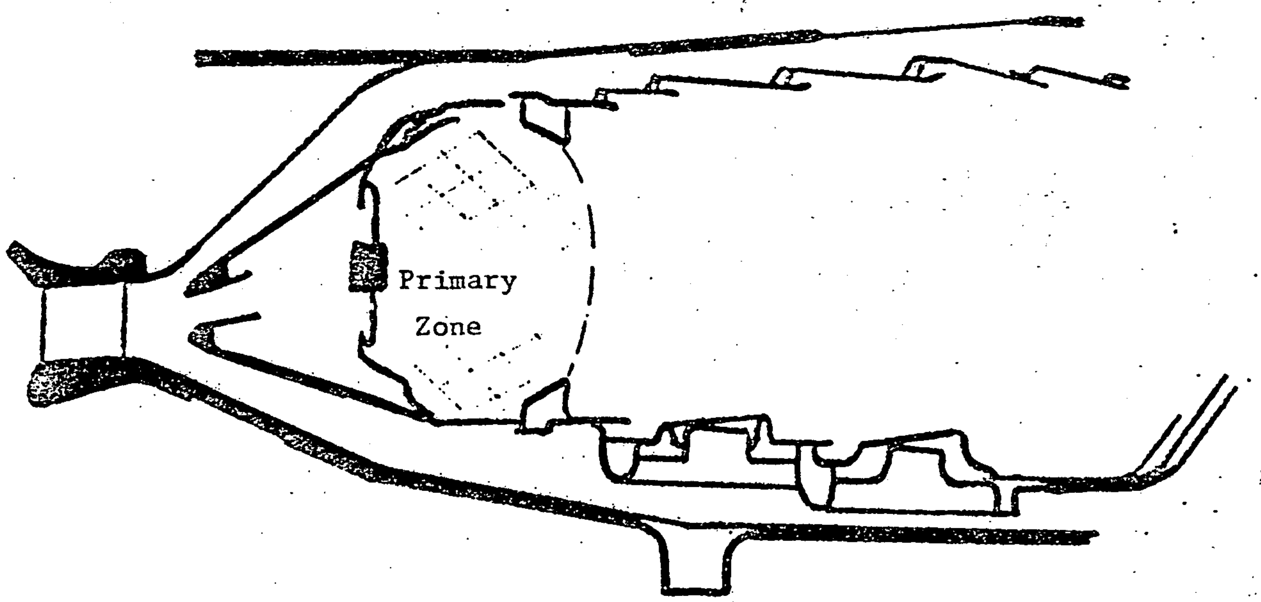
Rolls Royce is predicting that a fully developed combustor with acceptable operational and mechanical performance could have an HC EPAP of less than 20 in an RB211-535 application. This is a considerable improvement beyond the stage II (EPAP = 35), but it is still little better than the baseline JT9D-70 (It must be remembered, however, that the JT9D-70 combustor was designed initially with emissions in mind and is, therefore, much cleaner than other presently produced engines). Significant CO improvements are unlikely because the quick quench design would promote the freezing of the $CO \rightarrow CO_2$ oxidation outside the primary. This represents a prime example of CO-NOx tradeoff inasmuch as this quick quench feature reduces the NOx from an EPAP of 51 for the stage II combustor to possible 30 for the stage III (marginally below the 1984 standard). Nonetheless, the addition of the swirl should have some beneficial effect on the CO level, in particular, although a prediction cannot be made. Again, it is possible that the addition of sector burning to the stage III combustor might provide a sufficiently favorable environment at idle to promote faster CO oxidation and offer additional HC control. However, this cannot be relied upon without demonstration because with the primary already redesigned to provide a hotter, richer flame at idle, further richening may be excessive and in fact increase the CO emissions (see Figure 33).

Table IV-10 presents a summary of the emissions performance of the RB211 family.

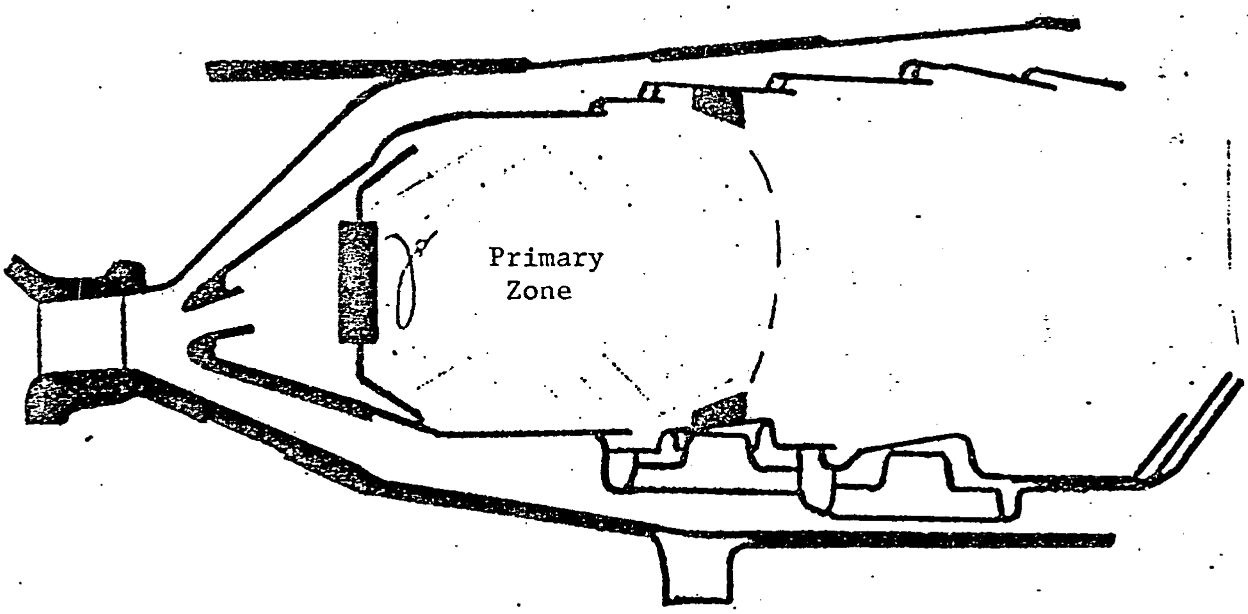
<u>Olympus 593</u>

This is the only T5 class engine in use. It is an outgrowth of an older family of Olympus engines, but was considered best suited to the

COMPARISON BETWEEN LOW EMISSIONS COMBUSTORS



Stage II



Stage III

Figure 27

STAGE III COMBUSTOR

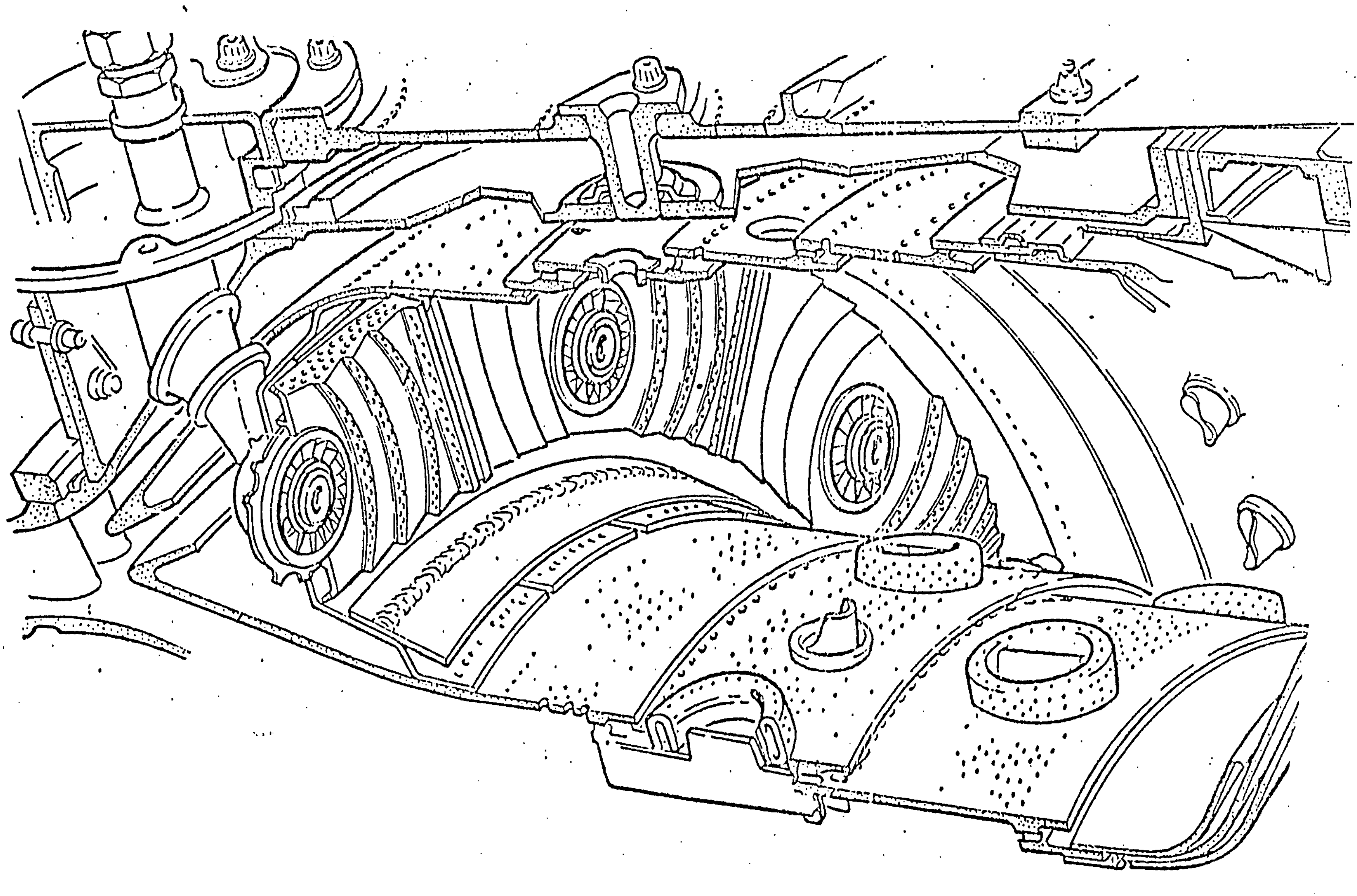


Figure 28

task because it was sized right and possessed the proper thermodynamic cycle for supersonic flight (moderate pressure ratio and no bypass). This engine is a collaborative project, with SNECMA responsible for the development of the afterburner, a feature not found on engines intended for subsonic use. Because of the vintage of parent engine, the 593 began with a can-annular type of combustor (like the P&WA JT8D and RR Spey) with pressure atomizing nozzles. Smoke problems early on precipitated a conversion to an airspray type of nozzle (an airblast nozzle similar to some of GE's with a low pressure orifice surrounded by a swirl ring). This improved mixing and leaned out the primary zone. However, this too proved inadequate, largely because the requirements of coast-down from supersonic flight forced the use of a very rich primary zone. This led to a total redesign of the combustor resulting in the enployment of a modern annular combustor (like, e.g., that in the JT9D or RB211) and vaporizer injectors.

Vaporizer injectors are not used by any U.S. manufacturers, but are found in several Rolls Royce combustors of various vintages (see Appendix A, #1). It is basically a premix/prevaporizing concept wherein low pressure fuel is injected into a tube which also contains a portion of the compressor air entering the burner dome. The heat of the combustion within the primary zone into which the vaporizer tube is inserted vaporizes the fuel stream before it flows out of the tube into the primary. The usual configuration has a reverse flow at the exit, making the vaporizer resemble either a "T" or a walking cane ("J") as the case may be. Both the cooling needs of the vaporizer (done by the fuel) and the prevention of flashbacks require very rich stoichiometry in the tube.

Because of the relative leniency of the T5 standards compared with the T2 standards, Rolls Royce is able to comply with the 1980 requirement (HC, CO only) with only the application of their "blown ring" advanced cooling technology. This technology, which is also employed in the M45H (discussed below) controls the amount and direction of cooling air into the dome so that premature quenching of the reactions near the wall is avoided. While this advanced cooling scheme does result in marked HC, CO reductions (to the levels required by the T5 standards), nevertheless, the combustor still has a greater combustion inefficiency at idle than would be expected of a new high pressure fan engine (e.g., the JT9D) run at those operating conditions and using the best HC, CO control (Figure 29), despite the fact that the high pressure engines need and are designed for high liner cooling flows capable of significantly quenching the reaction.

Additional combustion inefficiency (HC, CO) is found in the afterburner employed at takeoff. This is to be expected in light of the low pressure (though high temperature) and short residence time. Methods to improve the combustion efficiency have apparently been identified by SNECMA, the responsible partner, which would raise the efficiency from 95% to 99% (downstream from the exhaust at the completion of reaction).

Such methods would presumably include better and more rapid mixing of the fuel-air mixture, probably at the expense of a slight increase in the pressure drop across the afterburner (and therefore poorer fuel economy).

The standards for T5 newly manufactured engines do not include any significant requirement for NOx control, the standard in fact permitting a minor increase in NOx in exchange for CO control. Consequently, no technology for NOx control has been investigated.

RB432

The RB432 is a new engine now under development which is sized to compete directly with the existing JT8D. The engine was begun as a successor to the Spey although its size has now grown somewhat beyond that. It is essentially a straightforward scale-up of the 25KN RB401 engine which is also under development for the business jet market. Very little is known about the engine at this time in view of its early stage of development. The smaller RB401 has been designed by Rolls to satisfy the presently promulated T1 class emissions standards and consequently, it may be expected that the larger RB432 would perform as well. The combustor is annular with vaporizer nozzles.

Spey

The Spey family consists of a large number of members which originated in 1963 (date of first certification). Being of older vintage,

COMPARISON OF EMISSIONS PERFORMANCE,
JT9D AND OLYMPUS 593

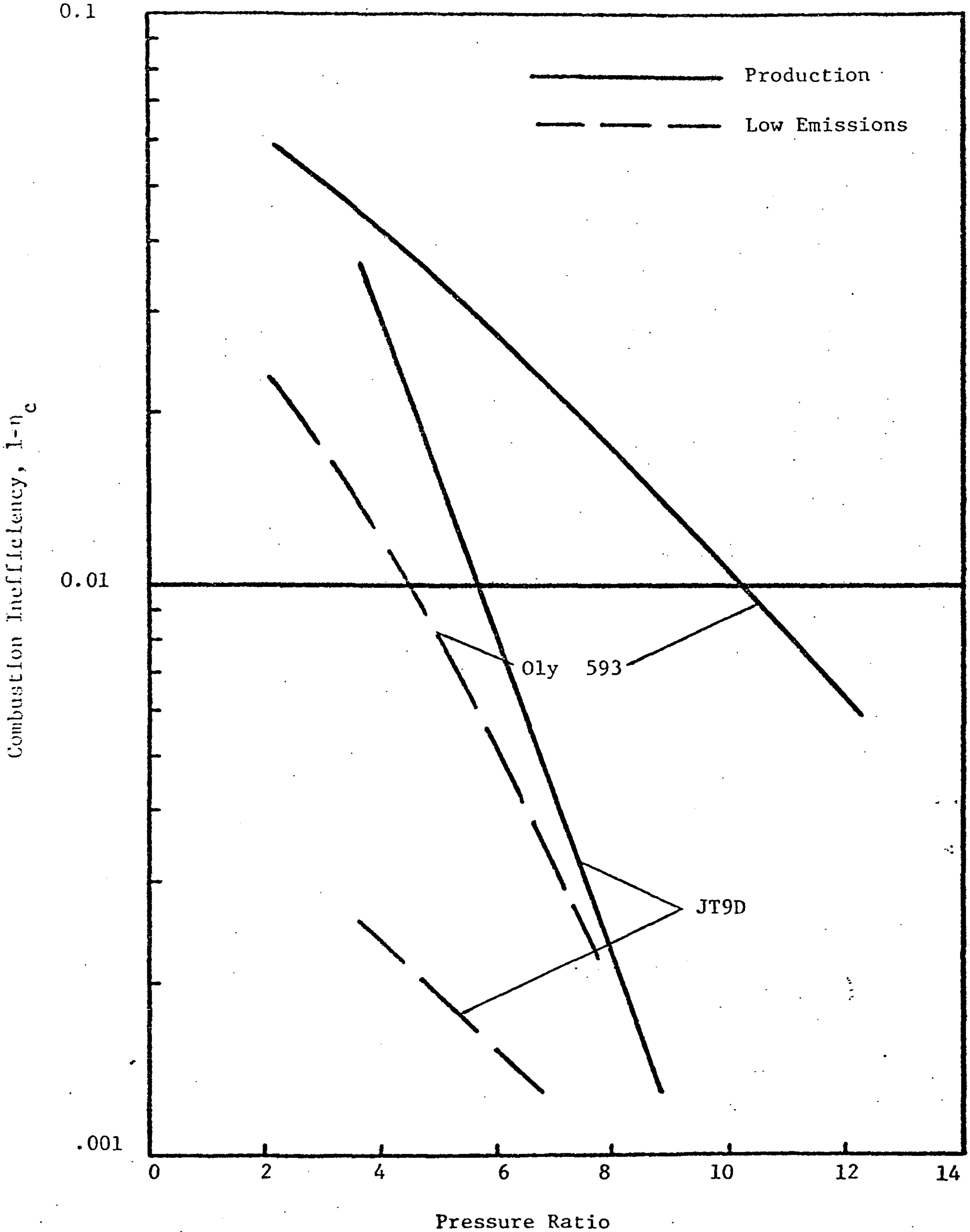


Figure 29

the Spey uses a can-annular burner (Figure 30), with duplex high pressure fuel nozzles. Beyond that, it suffers three additional disadvantages, the first being a low bypass ratio (0.6-1.0) giving it a high sea level SFC compared with modern engines; the second being a larger number (10) of highly loaded short cans, and the third being a burner fabrication technique which uses "wiggle strip" cooling (Figure 31). This approach to supplying cooling air to the burner is simple, but excessive, yielding a can with exceptional durability (16,000 hrs.). The excessive cooling air, coupled with the small size of the cans (implying short residence time and larger surface to volume ratio which enhances the importance of quenching of the reactions by the cooling air) together create an environment conducive to incomplete combustion, especially at idle. Hence, the HC, CO emissions are very high (idle combustion efficiency is only 90%) and extraordinary effort must be made to reduce them. Smoke also is a problem due to poor mixing in the primary zone, a result in part of the small pressure drop across the combustor head which is, in turn, partially a result of the large cooling air flow (low resistance).

Low emissions work first began in 1969 when Rolls was first contracted by the USAF to produce a low smoke combustor for the TF41 (a military Spey). Both a piloted airblast nozzle and a revised combustor head configuration (the conical head) were investigated (Figure 32). These approaches reduced smoke (to SAE No. 14) through improved local stoichiometry, but without any concurrent HC, CO reduction. Additionally, the conical head scheme, which was the better, suffered persistent

Spey Production Burner

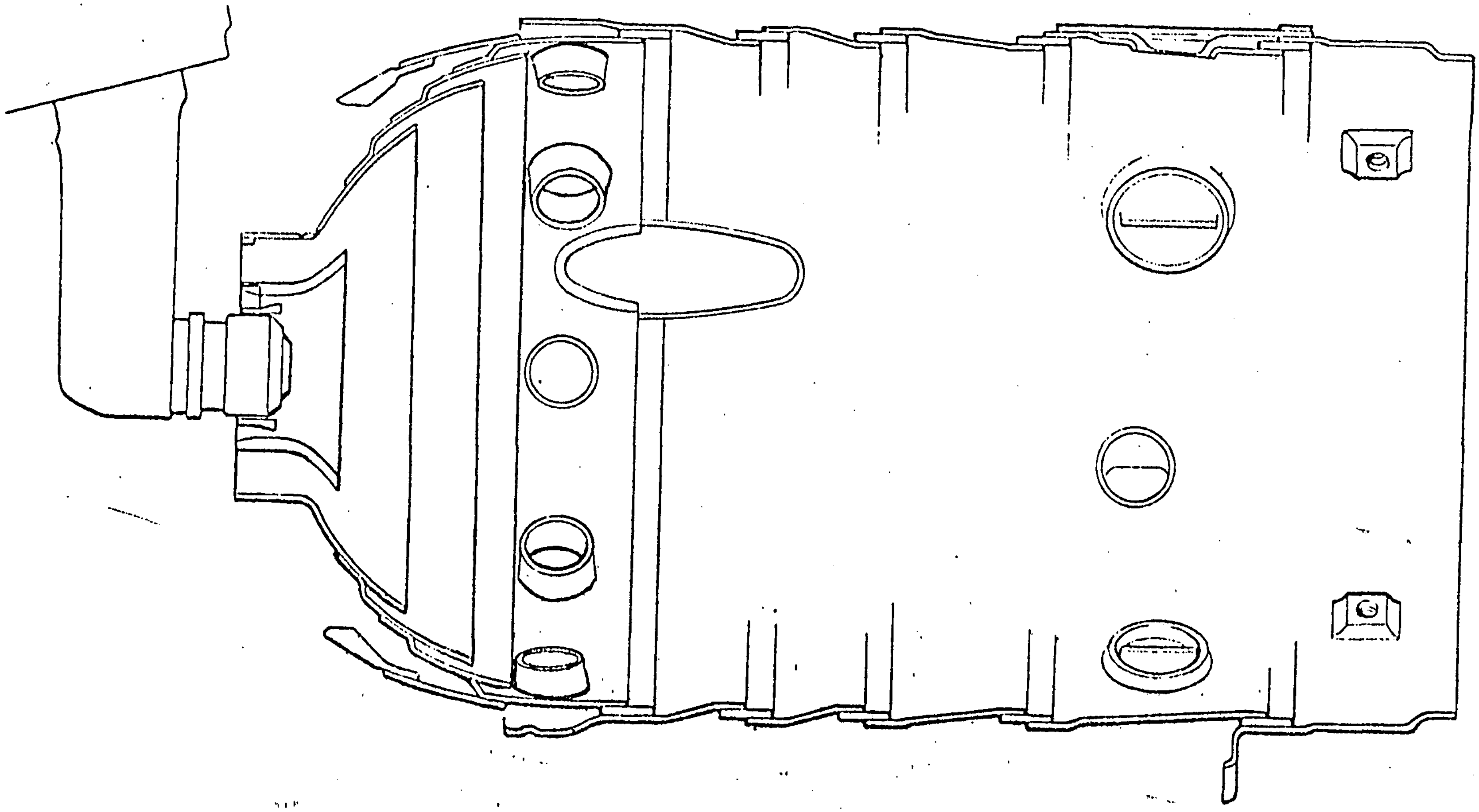
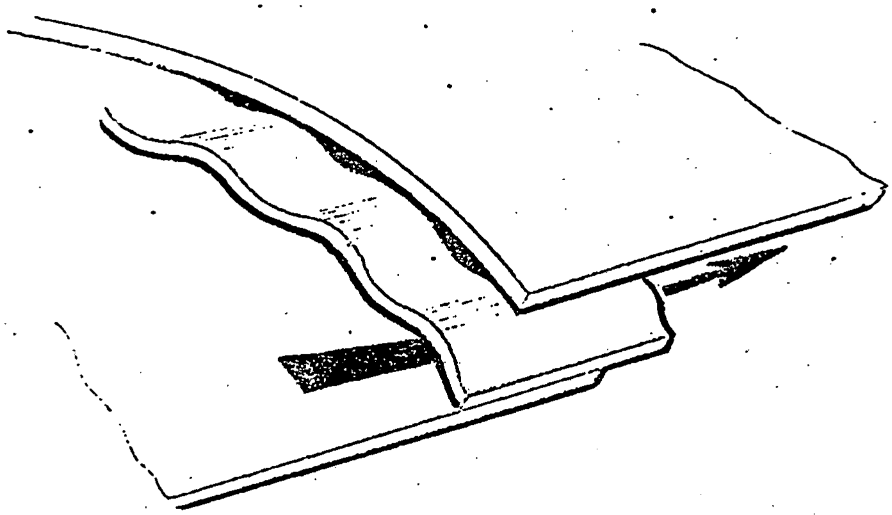
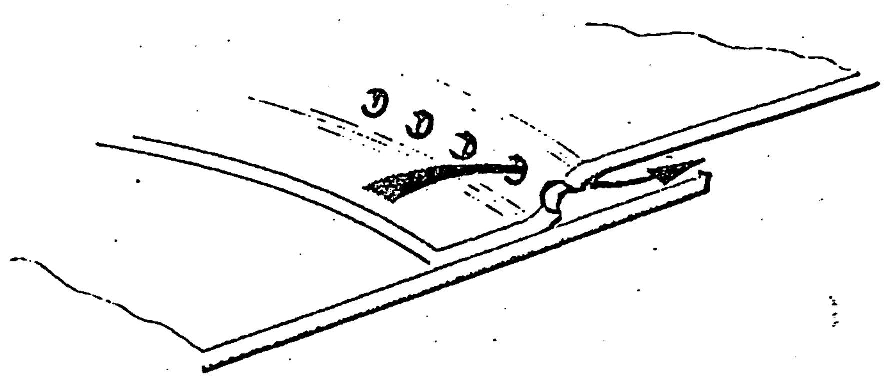


Figure 30

COMBUSTOR LINER COOLING METHODS



Wiggle Strip Cooling



Splash Plate Cooling

Figure 31

and severe carbon deposition and durability problems. A low HC, CO emissions (as well as smoke) investigation was begun in 1972. This program was quite extensive, involving half a dozen different approaches and nearly 400 rig and engine tests through 1976, at which time Rolls concluded that while substantial reductions to the HC and CO could be made, compliance with the existing HC and CO standards (and for that matter, with the proposed regulations) was impossible. The basic concepts that were investigated are listed in Table IV-9.

TABLE IV-9

Low Emissions Investigation - Spey

1. Improved atomization
2. Airblast nozzles
3. Sector burning
4. Advanced cooling
5. Vaporizer nozzles
6. Reflex airspary burner (RAB)

There was a considerable variation in the degree of success and the difficulties encountered among these six concepts. Improved atomization was possible by rescheduling the duplex nozzle fuel flow to run on the primary only at idle. The primary, being sized for ignition, gave good atomization at low power and, if used alone, afforded some reductions. Apparently, though, this was not the principal source of the emissions as the amount of control was quite modest. Piloted airblast nozzles reduced smoke by leaning the primary zone some and improving mixing at

CONICAL HEAD BURNER (LOW SMOKE)

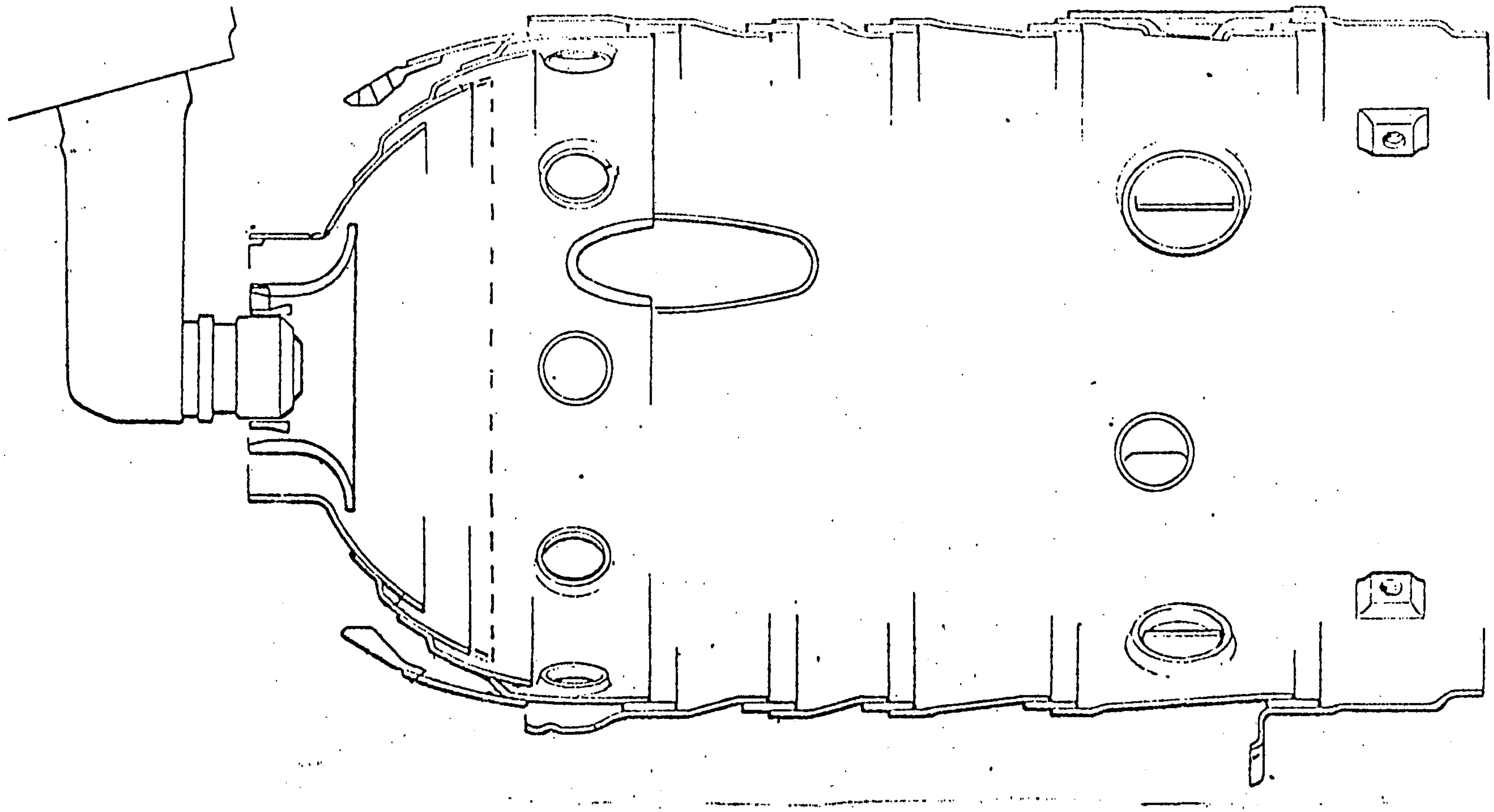


Figure 32

high power, but had even less effect on the emissions at low power, both because poor atomization was not the principal source and because the airblast feature was least effective at the low pressure drops experienced at idle.

Sector burning provided considerable reduction, especially of HC, by richening the primary (the Spey runs slightly lean at full power, and leaner yet at idle in normal operation) and improving atomization. This large improvement would not necessarily be witnessed with combustor configurations other than the production (its success is very dependent upon the sensitivity of the combustion efficiency to the fuel/air ratio in the primary as is seen in Figure 33), but inasmuch as sector burning alone cannot achieve compliance, then compounding of this with other schemes for emissions reduction would be mandatory. However, it is understood that this sector burning was achieved by the elimination of only 3 of the 10 cans (leaving a 252° sector on). GE fires only a 180° sector to achieve its reductions and while this adds to the potential operational and mechanical problems, it is likely to be more effective. An engine test of sector burning with 3 cans out resulted in the burnout of some nozzle guide vanes so the mechanical problems are indeed a reality. Also, sector burning in a can-annular system results in peculiar crossover flow patterns resulting from a difference in pressure drop between the lit and unlit cans. This possibly would affect the liner durability. On the other hand, the primary zone stoichiometry is not the only contribution to the emissions problem as was discovered during the investigation of advanced cooling.

Impact of Combustor Design on
Effectivenss of Sector Burning

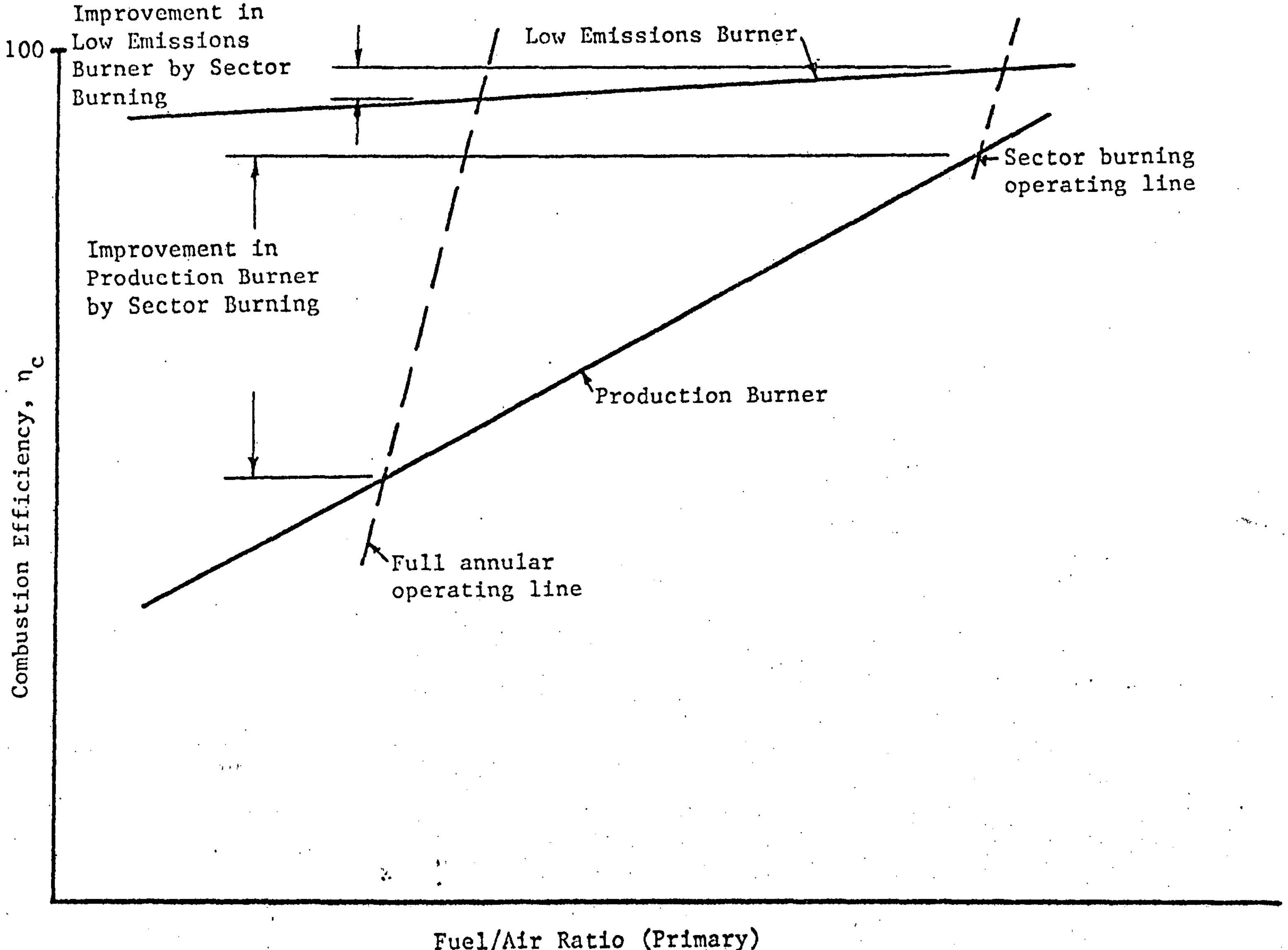


Figure 33

Advanced cooling schemes are based upon recognition that the primary source of HC, CO emissions in the Spey is the reaction quenching that occurs adjacent to the lean primary at idle. Sector burning, in contrast, richens the primary to reduce the quenching effect, but advanced cooling attacks the problem directly by designing the combustor to survive without the excessive film cooling that is provided (without choice) by the "wiggle strip" construction. The basis of the advanced cooling is the use of a new composite sheet material (unknown to EPA) which is more durable in the thermal environment than what is now used in production. This requires less cooling air to provide the same excellent life and, therefore, permits the redesign of the cooling air patterns accordingly. Fabrication problems have been solved and the operational perfofmance has not degraded. The major mechanical problem seems to be the interface between with the composite and the conventional materials in the latter half of the liner. Experiments have shown that about half of the quenching was at the head and the other half in the front portion of the liner, so all of this must be made of the new material. Idle combustion efficiency increased from 90% to 96.9% using production nozzles which is, unfortunately, still insufficient. Continued development would necessarily consider the effect of compounding schemes, in particular, the mating of the advanced cooling burner with such as cross stream aerated injectors, piloted airblast nozzles, sector burning, blown rings (see Olympus or M45H), and enhanced mixing domes ("potted head").

Vaporizer nozzles were investigated early, being a standard feature on other Rolls Royce engines (e.g., M45H). Although emissions were reduced some (smoke especially) and most operational criteria were satisfactory, relight was much degraded, evidently due to the airflow disturbance resulting from the blockage caused by the vaporizers themselves (5 per can). This in turn led to the development of the reflex airspray burner (RAB).

The RAB as developed is not merely a fuel injector concept, although that is an important facet of it. The RAB includes a radical change in the primary zone aerodynamics, specifically a dual reversal flow which acts as an aerodynamic staging system (see Figure 34). The first reversal is sized for idle and the second for takeoff. At takeoff, the first zone burns excessively rich (without fuel staging, it still accepts all the fuel) and acts as pilot zone for the second reversal. A simplex injector is employed and located within a carburetor tube which acts as a vaporizer. Evaluation of numerous variants has led to a best version attaining a 98.4% combustion efficiency at idle with an improved pattern factor. Additional work resolved earlier head cooling problems, but the deteriorated ignition and relight has remained intractable. In theory, the concept also has the potential for NOx reduction by controlling the residence time in the second reversal zone. Although two attempts at control gave 30% and 50% reductions, they could not be achieved without deterioration of the still high idle emissions.

The RAB and the advanced cooling approaches gave the best emissions (Table IV-9), but because of the constraint upon resources, Rolls was

REFLEX AIRSPRAY BURNER

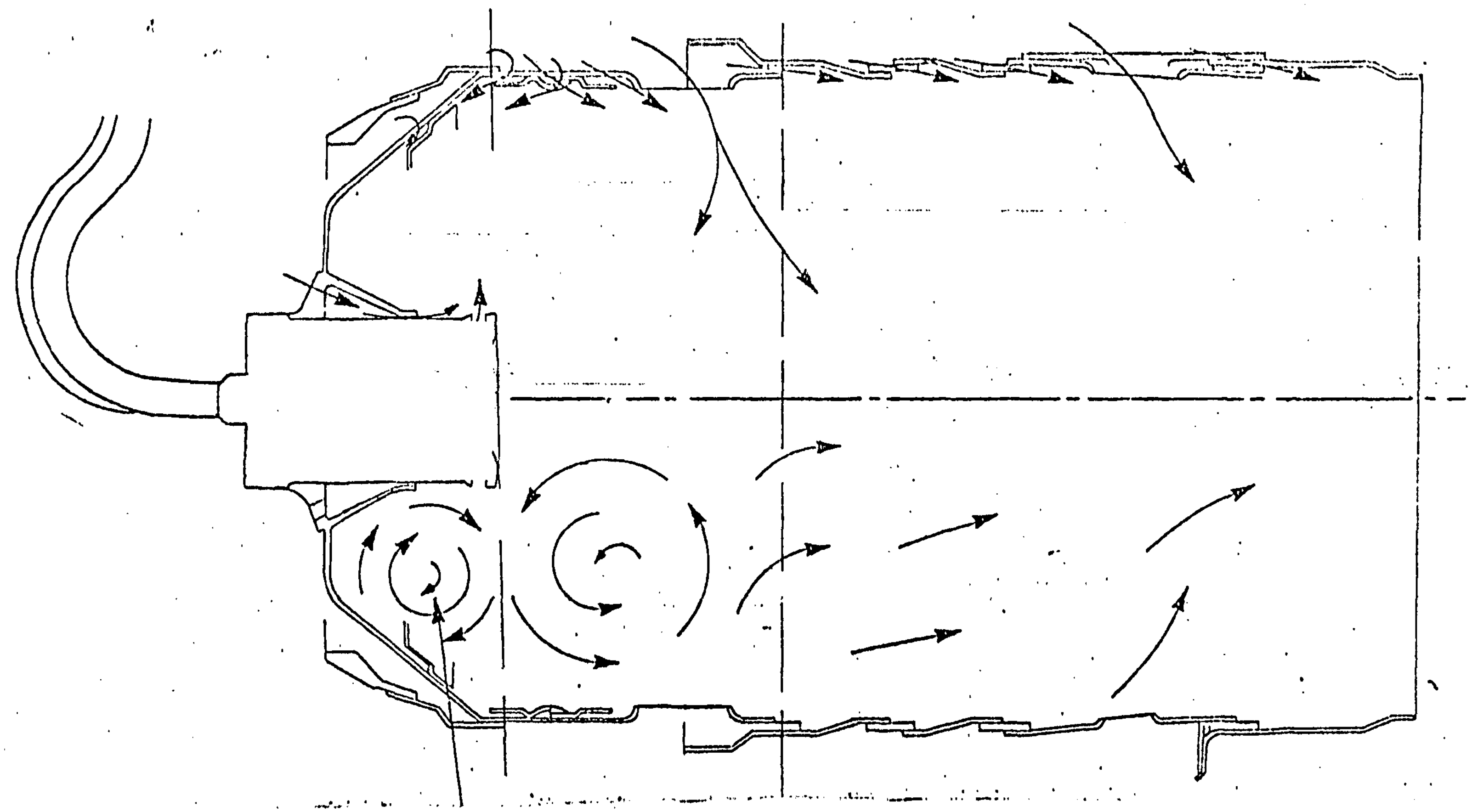


Figure 34

forced to select only one for continued development. In 1977, Rolls chose to abandon the RAB for although it gave the best emissions, the relight and ignition problems appeared insurmountable while, on the other hand, advanced cooling seemed to have the potential to at least match the RAB emissions performance with better operational performance.

Table IV-10 summarizes the Spey performance to date.

M45H

The M45H was originally a collaborative project with SNECMA and was developed for application in the short haul airlines, the VFW-614. The airliner, however, had few buyers and production ceased in 1978 after only 16 were built, thus leaving the M45H without purpose. Since 1976 Rolls Royce has taken over full responsibility for the engine which is now its own. The engine is quiet and fuel efficient which is likely to be favored in future aircraft for which its size is appropriate. A large refanned version using the same core, called the M45SD (RB410) has been demonstrated and should expand its potential for future application. In fact, the -SD at 64KW is sized slightly larger than Spey and so is a potential replacement. The -SD remains a collaborative venture with SNECMA and Dowty Rotol.

The engine utilizes an annular combustor with vaporizer nozzles (walking cane configuration). Its production version is quite high in HC and CO due to reaction quenching at the wall by entrainment of the fuel into the film cooling air. However, employment of the "blown ring" advanced cooling technique, used also in the Olympus 593, brings the HC and CO emissions to within the proposed standards. The NOx emissions are already below the proposed level because of the moderate pressure ratio and low sea level SFC which occurs as a result of the moderately high bypass ratio. It remains to be seen, however, if there is sufficient margin (for CO and NOx especially) for variability, but if not, slight modifications to the liner to provide a better airflow distribution may prove sufficient. Other low emissions concepts which had been investigated earlier on the M45H were redesign of the vaporizers, alternative schemes to fuel the vaporizers (specifics unknown), and leaner primary zone stoichiometry, but none of these were successful in lowering the emissions to the requisite level.

Further low emissions development work has ceased pending the identification of a new application of this engine.

Table IV-10 presents a summary of the emissions performances of the various Rolls Royce engines. While most data was obtained by engine testing, some was from either rig testing or was derived from extrapolation from other conditions (e.g., the RB211-535 data). In certain cases, the data, while showing excellent emissions control, may also reflect unflightworthy hardware or operationally defective systems. Therefore, care should be exercised in the evaluation of the potential success an engine may have in achieving a given emissions level.

Table IV-10
Rolls Royce Performance

gine	Concept	Technology Category	EPAP HC	EPAP CO	EPAP NOx	Sk	Development Status*	Projected Implemen-tation Date	Orgin of Data*
211-22B	Proposed Std.		6.7	36.1	33.0	20			
	Production		135	172	51.9	15	IS		ET
	Phase II	2	8.3	49.6	61.7	18	ID,FT		Rig
	Phase II w/ sector burn	2	4.2	28.8	64.0		ID	1982	Rig
	Double Annular	3					R	1986+	
211-524	Proposed Std.		6.7	36.1	34.6	19			
	Production		110	145	61.4	18	IS		ET
	Phase II	2	6.0	39.0	68.0	18	ID,FT		Rig
	Phase II w/ sector burn	2	3.1	22.4	70.2		ID	1982	Rig
	Double Annular	3					R	1986+	
211-535	Proposed Std.		6.7	36.1	33.0	21			
	Phase II	2	19.1	90.0	49.0		ID	1983	Rig ('78)
	Phase II (7% idle)	2	32.4	96.6			ID	1983	Rig ('79)
	Phase II w/ sector burn	2	8.9	54.7	51.3		R	1986	Proj
	Rich PZ w/ Quick Quench	2	2.5	67.5	30.3		R	1986+	Rig
lympus593	Proposed Std.		30.7	237.0	70.8	25			
	Production		129	530	70.1	26	IS		ET
	Blown ring	2	<30.7	<237	<70.8		ID,FT	1980	Proj
pey MK511	Proposed Std.		12.2	70.9	33.0	28			
	Production		278	436	68.1	66	IS		ET
	RAB	2	23.0	162	68.2		ID	Cancelled	ET
	Advance cooling	2	75.5	229	58.0		ID	1982	Rig
pey MK555	Proposed Std.		13.6	79.8	33.0	29			
	Production		441	420	49.5		IS		ET
	RAB	2	36.1	186	55.2		ID	Cancelled	
	Advance cooling	2	75.6	232	54.2		ID	1982	
45H-01	Proposed Std.		16.2	97.1	33.0	31			
	Production		162	526	31.2	46	IS	In abeyance	ET
	2 Blown rings (7% idle)	2	30.1	169.9	37.0	12	ID	pending new orders	Rig

IS = In Service
R = Research

SE = Service Evaluation
ET = Engine Test

ID = In Development
FT =

4. Avco Lycoming

Avco Lycoming (generally referred to as simply "Lycoming") is a U.S. manufacturer of both piston engines (Williamsport, PA) and gas turbine engines (Stratford, CT) for aircraft. It is a subsidiary of the larger Avco Corporation. The gas turbine division produces principally shaft power turbines for fixed wing aircraft and helicopters, largely for military applications. Of interest here, however, is the new ALF 502 turbofan engine of the T1 class. Because of its size (29-34 KN), it would be subject to the proposed standards if used commercially. A description of the ALF502 is given in Table IV-11.

Summary of Research and Development Effort

It was recognized early that the prototype 502 would not comply with the standards promulgated in 1973.

The basic engine core is that of the T55 turboshaft engine (2800 KW), a design which dates back to about 1960. That core was first tried in jet applications in the F-102, a military predecessor to the ALF502 series. Although the cores are essentially the same, minor combustor modifications are necessary in the new applications in order to provide acceptable performance in the new environment (e.g., increased cooling in higher pressure applications). The combustor is a reverse flow annular type and is the only such one affected by the proposed standards.

Table IV-11

Lycoming Engines

Engine	Class	Thrust	BPR	PR	Combustor	Application	Cert. Date	Number Delivered	Production Category
ALF502D	T1	28.9KN	5.8	11.1	RFA	None	1976	0	IV
ALF502H	T1	29.8KN		11.4	RFA	HS146	--	0	IV
ALF502L	T1	33.4KN		13.3	RFA	Challenger	1979	0	IV

PROSPECTUS

			Prospects of Meeting:						
			Emissions Performance				Operational	Mechanical	
Engine	1981	1984	HC	CO	NOx	Sk	Performance	Performance	Time
ALF502D	fair			X			X		
		fair		X			X		
ALF502H	?								
		?							
ALF502L	fair			X			X		
		marginal		X	X		X		

The baseline engine, employing the T55 standard dual orifice nozzles, required more than a 50% reduction in HC and CO emissions to meet the 1973 mandated levels. This was due largely to the fairly low combustor inlet temperature experienced at idle which made vaporization difficult and the reaction speed slow. Countering this to some degree was the excellent fuel dispersion which arose from the large number of nozzles (28, each covering only a 13° sector).

Methods to reduce HC, CO emissions logically centered around means to enhance the fuel vaporization. Vaporizing injectors similar to those used by Rolls Royce on some of its engines were investigated; however, because of the low air temperature entering the combustor, the vaporizers could not function adequately. This was unfortunate in that such injectors have the potential to reduce high power NOx production sufficiently (15% or more) on the 502 to achieve compliance with that standard also.

Airblast injectors were also tried with greater success. These injectors, supported by combustor airflow redistribution, provided the best HC, CO control although the best configuration still failed to meet the 1973 HC and CO requirements and, in addition, suffered from degraded operational and mechanical performance. Subsequent development to improve upon these deficiencies increased the HC, CO emissions somewhat (certification configuration). Variations in the primary zone stoichiometry, cooling air flow mixing patterns, and residence times were explored and tradeoffs between reductions in HC and CO on one hand and radial temperature profile, pattern factor, and the lean stability limit on the other were found to exist which could not be eliminated.

Lycoming has never emphasized research on NOx control, preferring instead to rely upon the output of the NASA Pollution Reduction Technology Program for Small Gas Turbines (PRTP-SGT), the contract for which had been awarded to AiResearch rather than Lycoming. This program will be completed in 1979. Nonetheless, Lycoming claims to have examined NOx control techniques such as premixing, fuel staging, and staged air introduction. Nothing is known about the extent of the work and presumably it has not been carried beyond preliminary rig testing. Activity in this area was continuing in 1977, but no further information has been provided.

With the loss in 1976 of the contract for the U.S. Coast Guard medium range surveillance aircraft which would have used the ALF502H model, the first use of the 502 now appears to be the Canadian Challenger (formerly Learstar 600), a new business jet which employs two 502L engines. The L version, using nearly the same combustor as the D, (except for minor durability changes) also fails the 1973 requirements. In fact, at the originally specified idle of 1800 KN, it suffered a greater combustion inefficiency (HC and CO) than the H model, apparently because of its even lower pressure and temperature. To achieve compliance, Lycoming resorted to an advanced idle point which is an operational control technique. Unfortunately, the approach borders on the desperate in this case, for an idle power of 10.7% is required (3580 KN) which has precipitated a need for thrust spoilers at idle, thus adding weight as well as noise. In fact, while the 10.7% is ample for an adequate margin for variability under the 1973 standards, the proposed standards, although relaxed in principle, do not give "credit" for a high idle in the denominator of the control parameter and hence nearly all of the margin is eliminated. How Lycoming plans to deal with this is uncertain at this time.

Certification of the Challenger is planned with the high idle and thrust spoilers and is expected next year. Under 1973 standards, Lycoming was in an excellent position to comply in a timely fashion; however, with the proposed standards and the eroded margin, its status is less certain, although the two year delay should be sufficient for adjustments to be made. The biggest advantage for Lycoming and the Challenger is the general aviation exclusion which eliminates the ALF502 from control unless, perhaps, Federal Express decides upon the Challenger in addition to its freight fleet. The ALF502 is also scheduled for use on the new four engined HS146 short haul airliner by British Aerospace Corporation (formerly Hawker Siddeley). However, this aircraft appears to be aimed principally at the European market and thus would not be under the umbrella of the standards. Should U.S. commuter airlines decide to buy it, however, Lycoming would again be confronted with the issue whether to proceed with advanced idle in this application for emissions control.

Table IV-12 summarizes the emissions performance of the various 502 configurations.

Table IV-12
Lycoming Performance

Engine	Concept	Technology Category	EPAP HC	EPAP CO	EPAP NOx	Sk	Development Status*	Projected Implementation Date	Orgin of Data*
ALF502D	Proposed Std.		17.0	103	33.0	32			
	Prototype		31.0	183	38.3				
	Airflow distribution plus airblast nozzles	2	14.8	112	28.8	25	IS	Cert.	ET
ALF502L	Proposed Std.		15.9	95.5	33.0	31			
	Baseline (same as 502D Cert. configuration)		28.6	136	32.3		FT	1982	ET
	Advanced idle	1	9.1	92.2	35.4		FT	1982	ET

* IS = In Service
R = Research
Proj = Projected
SE = Service Evaluation
ET = Engine Test
Rig =
ID = In Development
FT = Flight Test

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APPENDIX A

EMISSIONS CONTROL TECHNIQUES

HC and CO Techniques

Operational Control Techniques

1. Increase in Idle Speed - As engine power is increased, HC and CO levels generally decrease as a result of higher temperatures and pressures at the combustor inlet. However, the NOx level may increase because of the increased temperature in the combustor. The increased idle speed is limited on turbofan and turbojet engines by the capability of the aircraft brake systems as there is an increase in thrust at idle. This problem does not exist with turboprop (class P2) engines as the thrust can be held nearly constant by properly varying the propeller pitch with engine speed. However, there is an attendant increase in fuel consumption and noise with increased engine speed.

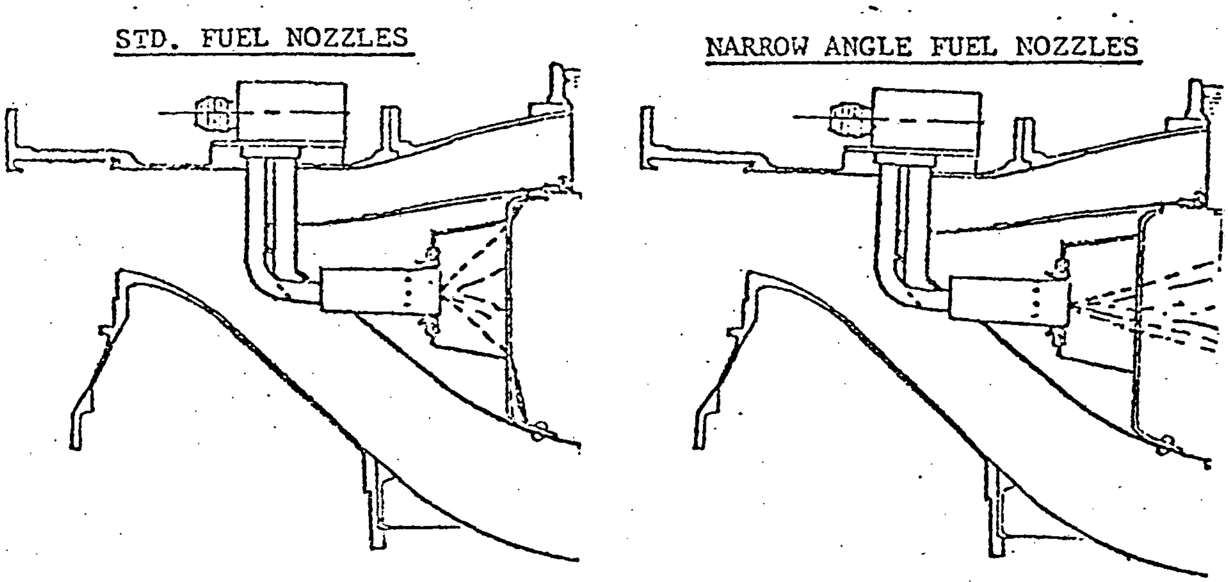
2. Airbleed - Airbleed (of compressor air) is a means of increasing the work load of an engine with, hopefully, the same result as occurs by increasing the idle speed (another form of work load), yet without the concomitant penalty of higher thrust and its ensuing braking requirement. To be effective, the engine must increase its fuel consumption with the bleed to provide the necessary energy for compressing the extra air and to maintain the idle power. Failure to do so will cause the engine to lose power and the emissions to rise.

Fuel Preparation Control Techniques

3. Spray Improvement - Design changes to pressure atomizer nozzles can lead to changes in the character of the fuel droplet size distribution. Decreasing the flow number (equal to the fuel flow rate divided by the square root of the injector pressure differential) reduces the droplet size. This in turn reduces the evaporation time and strongly influences the amount of HC left unburned. To a lesser extent, the change in the evaporation rate affects the local fuel-air mixture ratio and thus the local temperature which would likely affect the CO and NOx levels. This approach is not universally profitable, however, as at very low combustor inlet temperatures, no degree of atomization will improve the droplet evaporation for there is simply insufficient heat available.

Incorporation of this approach into a hardware system involves changing both the pressure differential across the injector and the orifice diameter as otherwise the fuel flow rate would be increased at each power setting because of the change in pressure. Changing the pressure differential requires only a new set of valves and possibly a pressure boost in the fuel pump.

In addition, nozzle design changes intended to optimize the fuel spray cone angle, and thus the distribution of fuel in the primary zone, are relatively easy to incorporate into a combustor. Decreasing the angle of a wide (richening the mixture) angle spray cone reduces wall wetting and increases the local equivalence ratio to produce a hotter flame which in turn helps to reduce HC and CO. Similarly, widening the spray angle reduces the equivalence ratio, providing a leaner mixture which might be necessary in the case of an excessively rich mixture (insufficient oxygen to burn the fuel). There is no impact on the system hardware as only the fuel nozzle is changed and the new one is no more complex than the old. The new heat release distribution, however, may require changes in the liner cooling air.

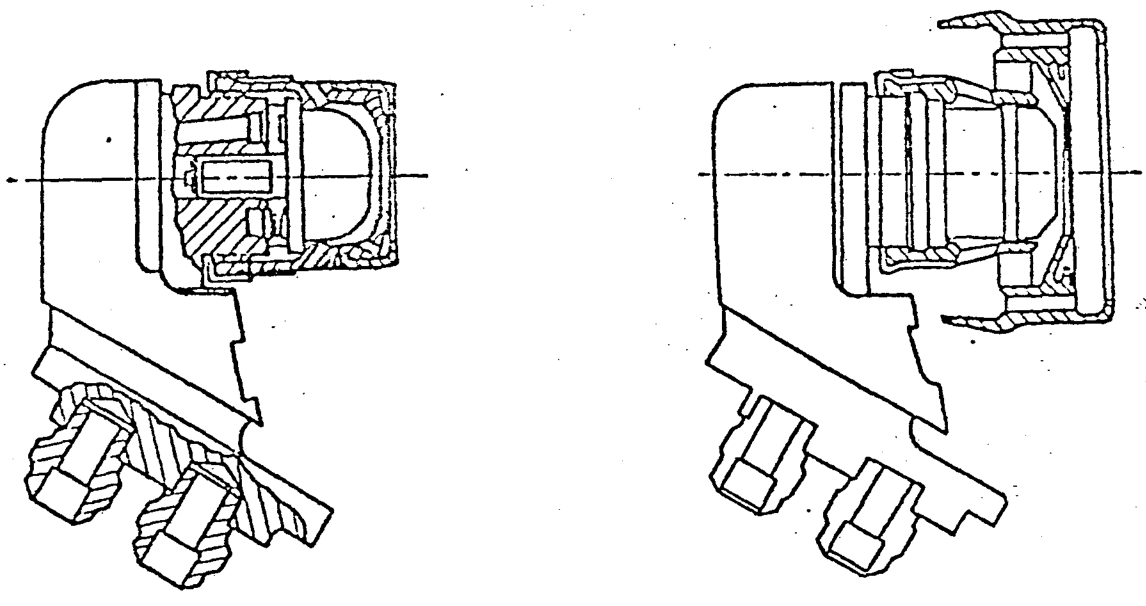


GE CJ610

4. Airblast - The pressure differential that exists between the compressor and the combustor is employed to achieve high velocity air through a venturi system in the fuel nozzle. This high velocity air is directed at the fuel stream as it comes off a lip. The fuel is thus sheared off and shattered into minute droplets, conducive to dispersion and complete evaporation. The addition of the airblast air into the primary affects the stoichiometry and consequently it proves necessary to redistribute the airflow throughout the liner in order to reestablish the

optimal fuel-air ratio pattern.

Success in improving the combustion efficiency by utilizing this technique has varied among the manufacturers depending upon the extent to which the liner flow was optimized. Also, it has been found that NOx increases slightly at idle as a result of the better combustion efficiency. At low power and especially in low pressure ratio engines, the pressure differential across the injectors is reduced causing the air velocity around the fuel injectors to be reduced. Therefore, the airblast effect on fuel atomization tends not to be as effective at low power where the bulk of the HC and CO is formed. The concept also tends to be less effective in reverse flow annular combustors as the nozzle is located so as not to be able to take advantage of the dynamic component of the pressure.



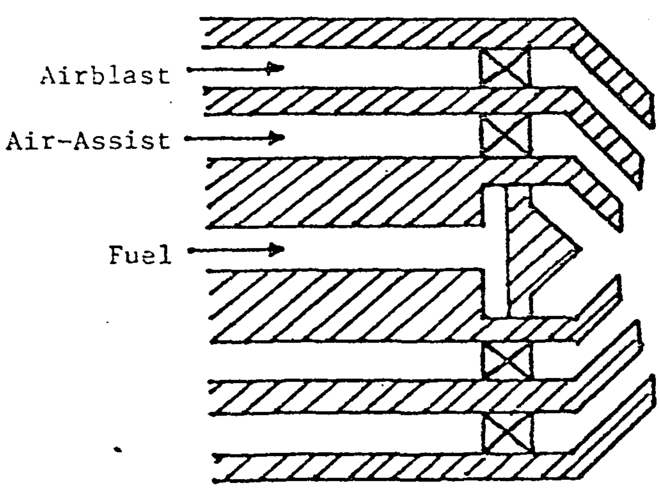
Conventional Pressure Atomizing Nozzle

Airblast Nozzle

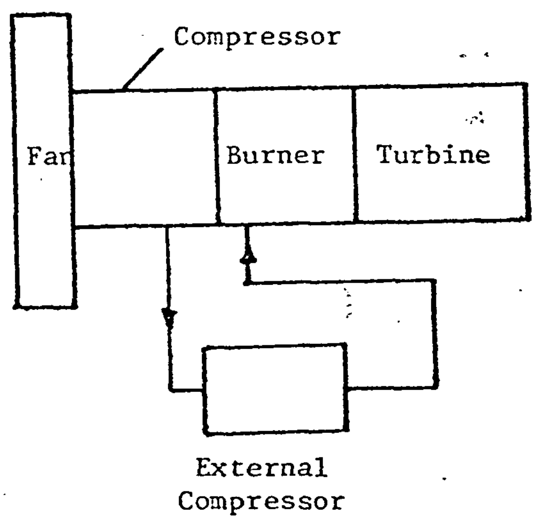
P&WA JT8D

5. <u>Air assist</u> - In the air-assist technique compressor air is diverted and compressed externally, and then discharged around the fuel injectors. This high velocity air is directed through the fuel injectors in a manner similar to the airblast technique and achieves the same goals. However, the external compression provides high velocity air at all powers so this technique may be expected to be more effective than airblast in controlling HC and CO at idle.

The use of air assist would have a large impact on aircraft hardware systems because of the requirement to bleed compressor air and compress it externally with an auxiliary compressor. The externally compressed air is more effective than the air of the airblast concept and so less is needed. This then has a less marked impact on the stoichiometry so that the need to redistribute the liner airflow is considerably lessened.



Air-Assisted, Airblast Fuel Nozzle



AiResearch TFE731 Concept

6. Premix(1)* - The basic idea is that HC and CO emissions often arise because of poor mixing within the primary so that while the average equivalence ratio in the primary may be acceptable (roughly stoichiometric at idle), there are zones of excessively rich or lean mixture, both of which lead to HC and CO production. One way to prevent this is to premix (and prevaporize) the fuel prior to the flame zone so that the additional mixing time will lead to a more homogeneous mixture. In order to prevent flashback of the flame, the premixing can be compromised a bit by keeping the local equivalence ratio above the stable deflagration limit in the premix zone. Upon entering the flame zone, further mixing can occur, permitting combustion. Although this can lead to less than perfect mixing and thus reintroduce to a degree the original problem, the HC and CO emissions are much improved because of the partial mixing and total fuel evaporation in the premix zone. The excessively rich premix zone can lead to carbon deposition, however.

NOx cannot be controlled by this approach unless total and lean premixing occurs which directly leads to the flashback problem, making premix for NOx control considerably more complex (premix(2)).

Implementation of this scheme into an existing design can be difficult in that the rather major combustor modifications must normally

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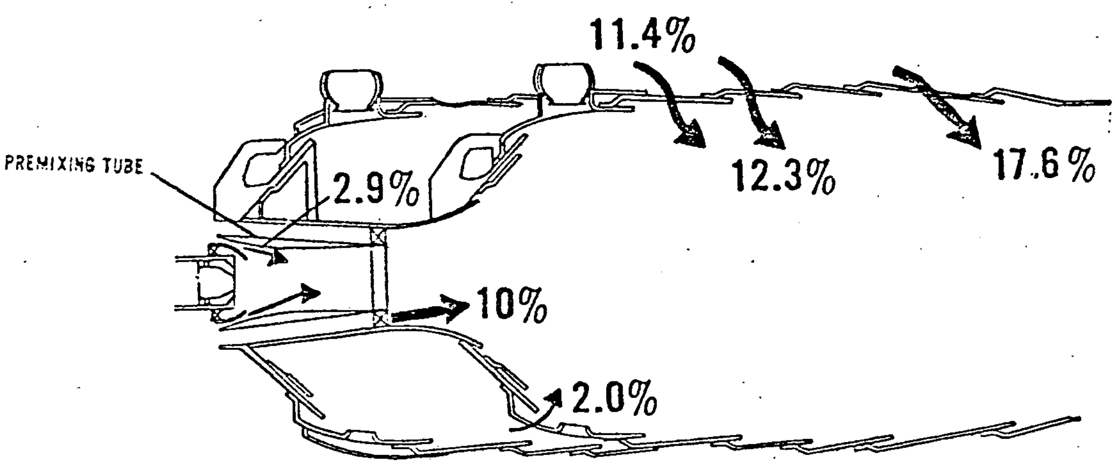
*Number refers to one of two different degrees of control generally recognized possible with this concept.

be kept within the constraints of the existing envelope. The more space that is taken for the premix region, the less that is available for dilution and pattern factor adjustments. Ideally, the combustor would be made longer with the premix zone merely being tacked on to the existing geometry (with some airflow adjustments).



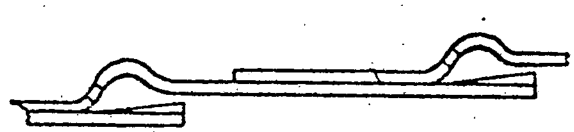
P&WA JT8D

Air Flow Distribution Control Techniques

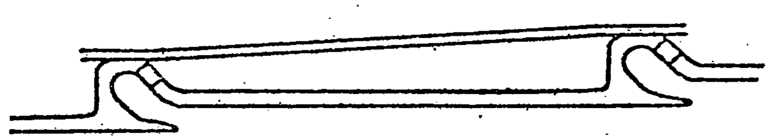
7. Advanced Cooling - High pressure ratio engines which operate at high combustor temperatures require high levels of cooling air to control the temperature of the liner (the amount of cooling air required is even higher because the high pressure ratio causes the cooling air to be proportionally hotter and therefore less effective). This cooling air, upon entering the liner, tends to quench the reactions of the burning fuel near the wall, especially that of $CO \rightarrow CO_2$. Any advanced cooling technique which will provide the requisite cooling

effect while at the same time reducing the air needed may improve CO emissions and possibly also HC emissions. The key to its effectiveness is the degree to which combustion, principally CO oxidation, is occuring near the wall.

The overall impact of such a revision is considerable for it represents essentially a totally new combustor. While benefits beyond simple emissions control may be accrued (combustor of greater longevity), the development cost is likely to be high.



Old



New

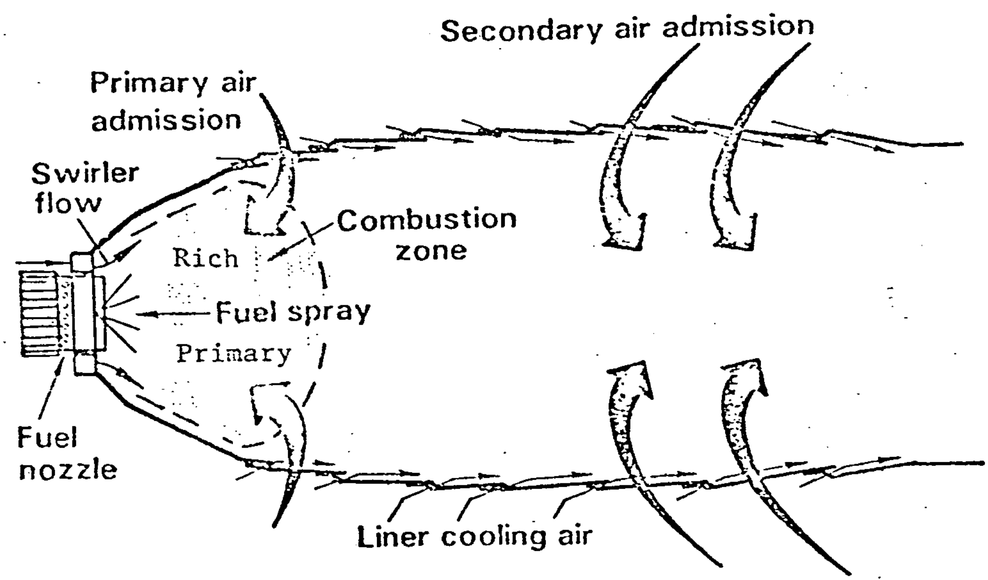
GE CF6 Combustor liner

8. Rich Primary (1) - the term "rich" applies to the stoichiometry at the design point (high power). Such a condition leads naturally to near perfect stoichiometry in the primary at idle. This results

in a very hot flame which is most conducive for evaporating and burning the fuel despite the quite low pressure experienced at idle. The hot flame does leave considerable equilibrium CO which must be consumed by proper temperature control (>1500°K) in the intermediate zone.

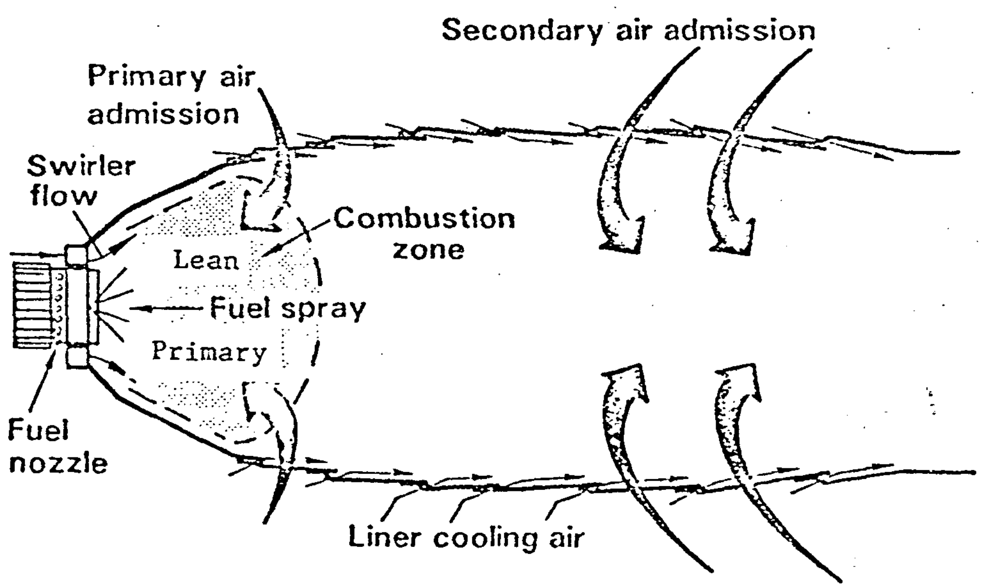
The biggest difficulty with the rich primary concept is that because it is rich (excess fuel) at the high pressure high power condition, there is a strong tendency to produce smoke in the primary which in turn must be consumed in the intermediate and dilution zones. This is not readily done so smoke control is usually done another way, by running the primary with perfect or slightly lean stoichiometry, not rich. Thus, smoke control in this instance opposes HC, CO control.

It is also possible to have excessive HC levels despite the favorable flame temperature if the mixing and fuel distribution is inadequate, thus leaving pockets of excessively rich mixture which cannot burn. Proper spray characteristics and atomization are thus required.

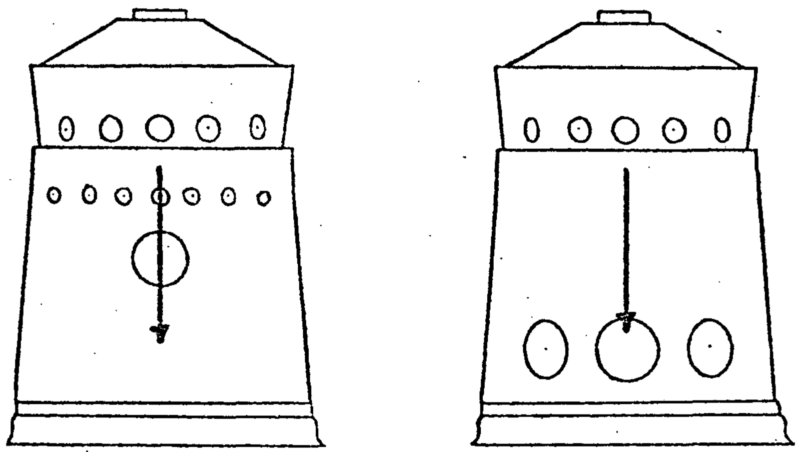


9. Lean Primary (1) - As noted above, this approach intrinsically produces low smoke at high power. However, at idle the mixture is even leaner. If done properly, this is beneficial because excessively rich pockets are avoided, thus controlling HC, and the CO level may be lower than in the rich primary case because the lower flame temperature will result in a lower CO equilibrium level. In any event, the CO will have to be consumed in the intermediate zone.

Difficulties with this approach lay in the possibility of excessively lean pockets wherein the reactions may be quenched (Excessive HC and CO) and in flame stability and relight (especially at altitude). Also, as this approach utilizes more air up front in the primary, there is necessarily less for use in the aft portions for cooling and temperature profile control (dilution). This can have serious ramifications for combustor and turbine durability.



10. Delayed Dilution - By delaying the introduction of dilution air, a longer combustion zone at intermediate temperatures is provided. This increases the residence time of the reactants which allows the CO to CO_2 conversion to approach equilibrium and for unburnt hydrocarbons to be consumed. The temperature in the intermediate zone should be, however, low enough so that NOx formation rates are slow. The difficulty lies in adjusting the air flow into the intermediate zone properly at all power settings so it is hot enough for CO consumption, yet cold enough to prevent NOx, and still achieving flame stability, liner durability, etc.



Conventional Liner   Delayed Dilution Liner

Allison 250

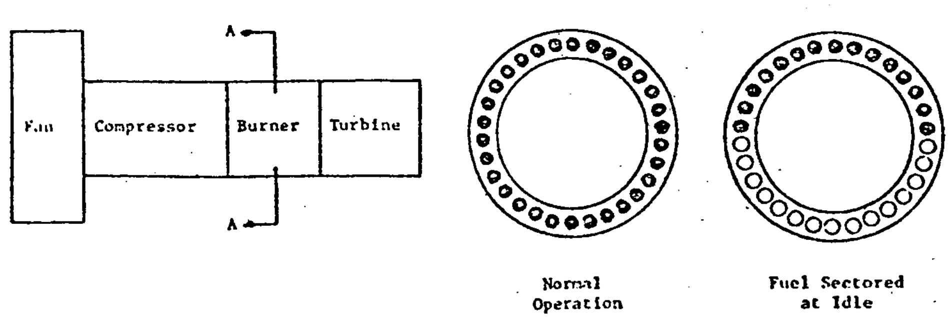
Staging Techniques

11. Sector Burning - Sector burning is a circumferential fuel staging technique designed to combine elements of the spray improvement and rich primary control techniques (3 and 8) and at the same time not affect in any way the combustor at high power (e.g., smoke from a rich primary). If the baseline combustor has a lean primary, then at idle

when the combustor is burning quite lean and at low flame temperature, the combustion efficiency is poor, resulting in much HC and CO, because of inadequate heat to vaporize the fuel and to stimulate the $CO \rightarrow CO_2$ reaction. This problem is resolved by cutting off the fuel entirely to part of the combustor (usually about half) and injecting it with the rest of the fuel into the remaining part of the combustor. This has two beneficial effects: (1) the pressure drop across the nozzle is necessarily increased, improving atomization and (2) the fuel/air ratio is increased (richened) so that a hotter flame exists, improving vaporization of the fuel and enhancing the $CO \rightarrow CO_2$ reaction.

Hardware requirements include a split manifold, proper cracking pressure of the valving in the nozzles, an additional valve in the fuel control system to control the sector burning itself (with an override to avoid it entirely while in flight), and a sensing device to determine flight vs. ground activity. Changes in the nozzle orifices may be necessary to provide proper fuel flow at all power, regardless of the sector (on or off at idle).

The primary concerns with this system are the reliability of the more complex fuel control system and the possible degradation of the turbine efficiency at idle (while sector burning) with an ensuing fuel penalty.

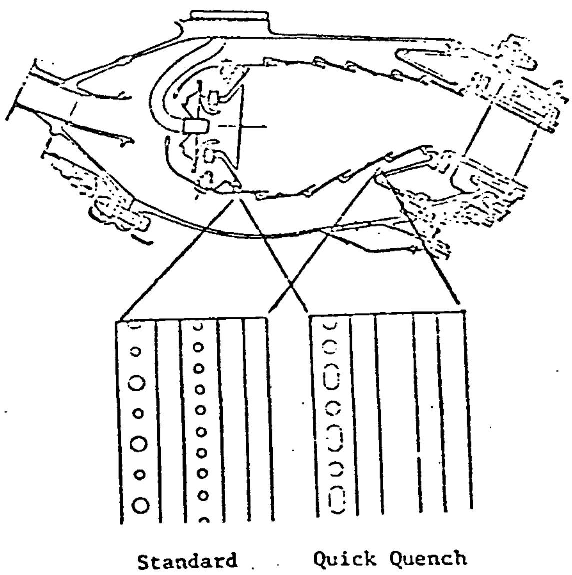


GE CF6-50

NOx Control Technique

Air Flow Distribution Control Techniques

12. Quick Quench Primary - The idea here is to introduce the intermediate air as close as possible to the upstream dome or bulkhead so as to minimize the extent of the primary zone. This zone, operating at high power near to the stoichiometric point, produces a very hot flame (2600°K) well in excess of that needed to activate NO production. The reaction time to equilibrate NO at this temperature is only a few milliseconds so in order to avoid significant NO production, it is necessary to introduce the intermediate air quickly to quench the NOx producing reactions (temperature < 1800°K). However, as the quench temperature should still be in excess of 1500°K in order not to quench the CO oxidation, great care is required to properly tailor the airflow. The problem is that the quick quenching occurs also at idle and if tuned to work correctly for NOx control at high power, it tends to quench the HC and CO consuming reactions at idle producing excessive low power emissions.



GE CFM56

13. Rich Primary (2) - A sufficiently rich primary at high power will provide a cooler flame and a shortage of oxygen, both of which will discourage NO formation. As there will be further reaction in the intermediate zone where more air is available to burn the excess fuel (and create NO), it is necessary to carefully tailor the airflow in order to maintain the cool flame throughout. This approach is not satisfactory, however, because of the high smoke levels and the generally poor low power emissions (HC, CO) which arise from the excessively rich primary which occurs at idle.

14. Lean Primary (2) - The lean primary zone is achieved by introducing a larger percentage of the total combustor airflow into the primary zone. In sufficient amount, this creates a very lean, and therefore, cool flame which prevents the formation of NOx by lowering the $N_2 \rightarrow NO$ reaction rate.

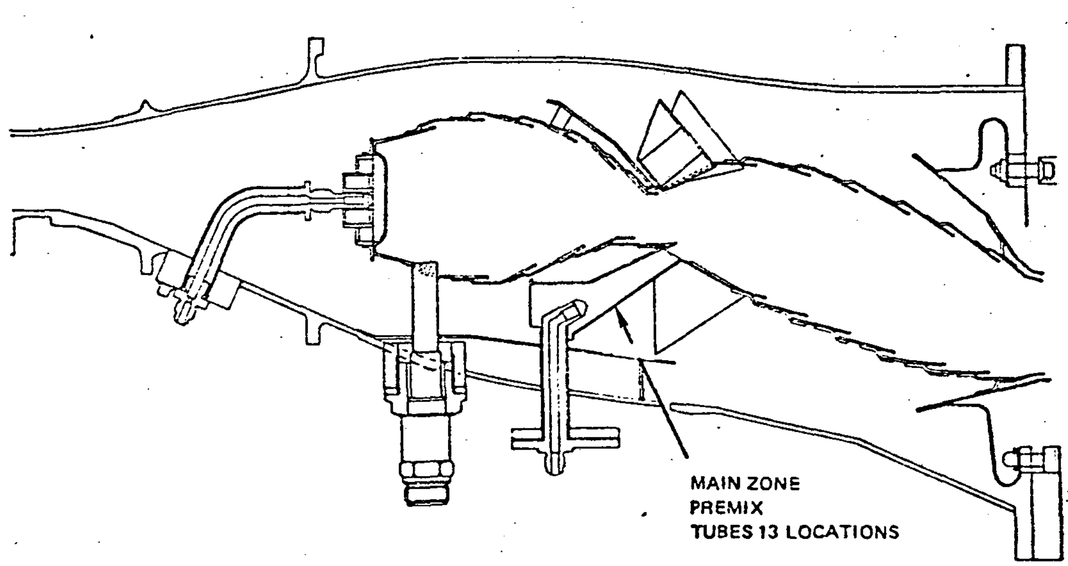
Several problems are created, however, by this procedure. First, the large amount of air into the primary creates a shortage of air downstream for use in cooling and temperature profile control (dilution). This may adversely affect the durability of the liner (cooling) and the turbine downstream (temperature profile). Second, HC and CO emissions are very much affected adversely. Too cool a flame at high power may quench the CO oxidation as well as the NO production. More importantly, however, is the fact that being lean at high power implies a very lean flame at low power (e.g., idle) so that under those adverse conditions of low temperature and pressure, the fuel may not vaporize, the HC and CO oxidation reactions will proceed too slowly, and in the extreme case, will cease (flame instability). This also creates altitude relight problems.

Fuel Preparation

15. Spray Improvement - The spray improvements discussed in (3) also affect NO production. Better atomization eliminates droplet burning (locally stoichiometric and hot) and the spray angle affects the fuel distribution (local hot spots). Better atomization is universally good for all pollutants, whereas a change in the spray angle may adversely affect one or more pollutants while favoring the others, or it may favor all. The outcome depends on other factors in the primary zone, specifically the initial fuel-air distribution, the airflow pattern through the dome and the amount of cooling air.

16. Premix/Prevap - Fuel and air are mixed in a prechamber prior to entering the primary combustion zone. This premixing allows combustion to occur at a much leaner condition where NO formation rates are slower. This technique is most applicable to high pressure ratio engines, which produce the high combustor inlet temperatures required to sufficently vaporize the fuel. With the premix concept careful attention must be given to the prechamber exit conditions. Exit velocities of the fuel-air mixture must be high enough at all power levels to prevent flashback which is very damaging to the liner and the nozzle. Also, in creating a uniform lean primary zone, stability may be a problem leading to altitude flameout and difficulties in relighting. Low power emissions(HC, CO) may be a problem if adequate mixing and vaporization do not occur at idle where the conditions are much less favorable.

The premix concept requires a significant change to the combustor liner geometry since the premix chamber must be included in the combustor. This may lead unavoidably to a longer overall combustor, thus to major changes in the engine configuration. The alternative, to exchange some of the combustor length in the dilution zone for the premix mechanism, also can lead to complications because there is then less space available to tailor the temperature profile at the turbine inlet. This compounds the already difficult tailoring job precipitated by the shortage of dilution air arising from the lean (excess air) primary (see 14).



Premix combustor as seen on an axially staged(18) combustor

P&WA JT9D-7

Staging Techniques

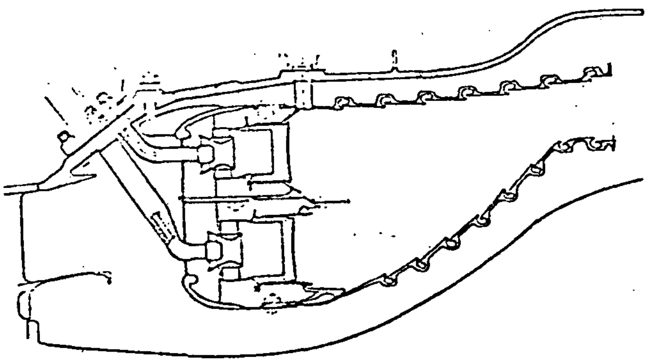
17. and 18. Fuel staging - The combustor is divided into two regions, each having its own fuel injection system. These are termed the pilot stage and the main stage. At low power, fuel is supplied only

to the pilot stage, thereby allowing a much higher local fuel/air ratio than would be possible if the fuel were distributed throughout the combustor. This is basically the rich primary approach (8). This mixture is then able to burn hotter, enhancing droplet evaporation (aiding HC burning) and CO oxidation. Some form of fuel preparation control (3 or 4) would also be incorporated.

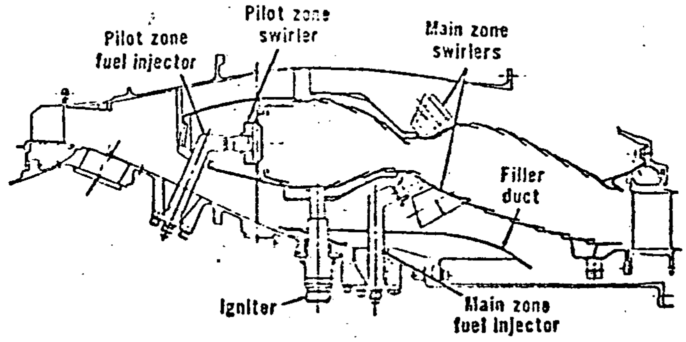
At high power, the bulk of the fuel is injected into the main stage which designed to burn lean for NOx control (concept 14) and low smoke. Flame stability is provided by the primary stage which is still burning rich. The pollutants produced by the primary at high power (CO and smoke) should be consumed when diluted by the much larger main stage flow.

Staging requires two manifolds and two fuel injection locations and adds to the complexity of the fuel supply system and the fuel control. The combustor liner is also more complex with additional cooling and temperature profile problems.

There are two basic types of fuel staging here, radial (17) and axial (18). In the former case, the stages are in parallel and fit more readily within a short combustor volume. In the latter case, the stages are in series. Its primary advantage is that the upstream primary stage is better located to act as a flame stabilizing agent on the main stage which may then be run more lean.



Radial Staging (17)
GE CF6-50

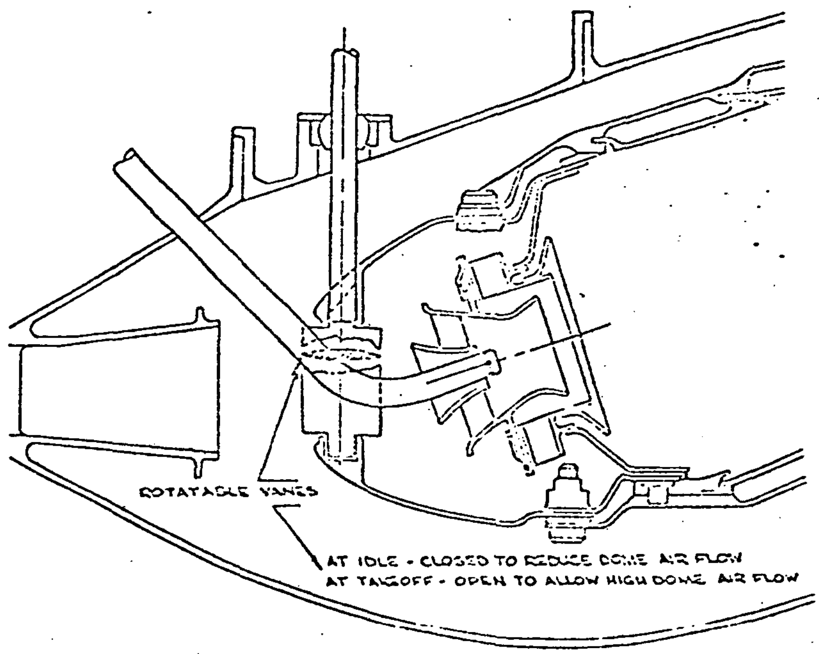


Axial Staging (18)
P&WA JT9D-7

19. Variable Geometry - Variable geometry (or air staging) provides airflow control of the primary and intermediate zones such that the stoichiometry provides stable efficient combustion with a minimum of NOx production over the complete operating range of the engine. Air enters the combustor through holes equipped with a mechanism (usually a sliding ring) that meters the airflow in proportion to the fuel flow. With this system the primary zone fuel air ratio can be controlled to be soichiometric at idle power for HC and CO reductions, and to be lean (but stable) at high power for NOx reductions. However, as there is no flame stabilizing mechanism here, the degree of lean burning, and hence the NOx reduction, is limited.

This system has a number of operational drawbacks, primarily the reliability of the mechanical system in such a severe environment which is a safety issue. However, the notion of moving mechanical systems in severe environments is not new to gas turbines; variable pitch compressor stators and variable turbine nozzle guide vanes do exist. Failure of the mechanism, however, must not prevent the engine from providing adequate operational performance over its flight regime.

VARIABLE GEOMETRY COMBUSTOR

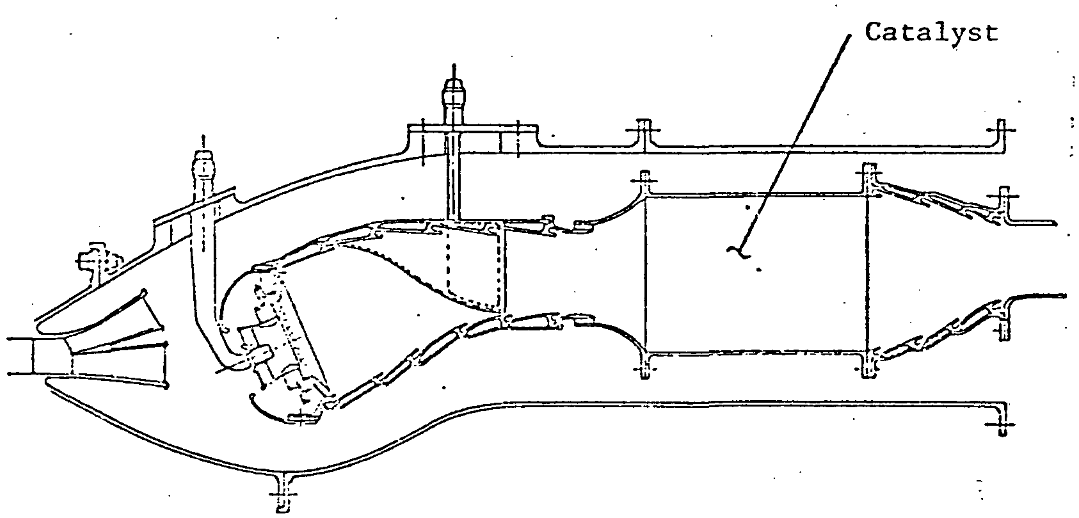


Catalysis

20. Catalysis - Catalysis is a process by which a special substance, usually a solid substrate, causes the acceleration of a chemical reaction while not being permanently affected itself. Catalysis is often used on current automobiles to limit the emissions of HC and CO by the placement of the catalyst in the exhaust gas so that these pollutants, which are products of incomplete reaction in the cylinders, can be consumed.

In an aircraft engine, however, the catalyst would have to be placed in the combustor proper. This then permits the reaction to proceed under uniformly lean conditions, thereby giving a cooler flame and less NOx production while still consuming the HC and CO through the enhancement of the reaction rate.

Primary development problems are getting the catalyst to work quickly during the warm-up period, prevention of poisoning of the catalyst, prevention of mechanical wear on the catalyst material, prevention of excessive pressure loss through the catalyst bed, and prevention of flashbacks into the premixed air-fuel upstream of the catalyst. Recent investigations suggest that, if used for NOx, a catalyst would probably have to be used in conjunction with variable geometry in order to keep the stoichiometry within limits acceptable to the catalyst.



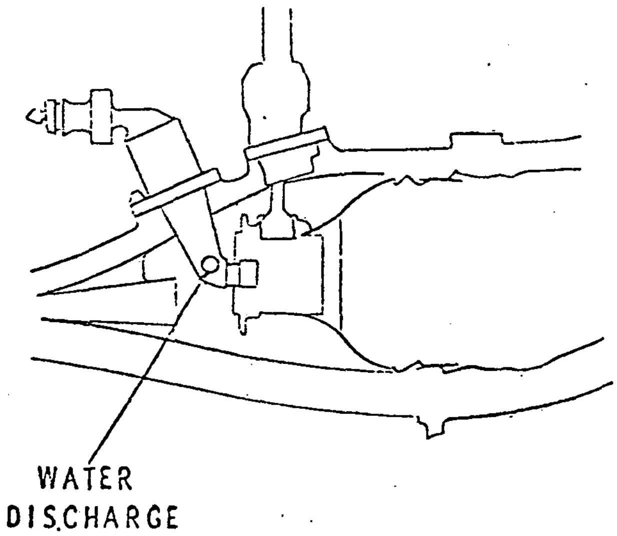
Catalyst Combined with Axial Staging

General Electric

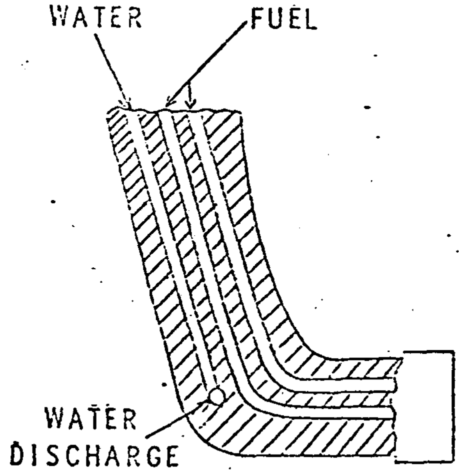
Water Injection

21. Water Injection - Water injected into the primary zone of the combustor results in a lower primary zone temperature. This lower primary zone temperature in turn results in a significant reduction in NOx as a result of the lower $N_2 \rightarrow NO$ reaction rate. However, if the temperature is reduced too much, an increase in CO occurs due to the quenching of the CO oxidation. Water flow rates equal to that of the fuel flow rate are possible giving a 50% reduction in the NOx level.

The use of water injection presents a number of problems: (1) The increased aircraft weight due to the mass of water carried may reduce the useful payload of the aircraft. (Usually, however, water injection results in increased thrust, and hence the payload possibly can be increased if takeoff performance is the critical factor); (2) Higher fuel consumption is required to maintain turbine inlet temperatures; (3) Precautions must be taken to prevent ice formation in the water injection system for operation at ambient temperatures below the freezing point of water; and (4) water must be demineralized in order to prevent turbine blade corrosion and pitting. The use of tap water results in substantial turbine deterioration and thus compromises safety and engine reliability. Also, demineralized water can be very expensive (over $0.30 per gallon) depending upon the location. Logistics for demineralized water may be a problem also, especially for those aircraft using smaller, more remote fields.



CF6 COMBUSTOR



CF6 SPRAY NOZZLE

New Procedures

22. Selective Azimuthal Burning (SAB) - This control technique for HC and CO is an offshoot of the sector burning concept (11). The two drawbacks to sector burning are recognized as (1) fuel penalty while in operation as a consequence of the severely asymmetric loading on the turbine, and (2) the potential hazard arising from a malfunction that might cause sector burning in flight. At higher power, the turbine would be damaged, and at flight idle, the engine might be unable to accelerate. SAB removes both of these difficulties.

The essence of the method is to reduce the number fuel nozzles in operation at idle so as to improve the atomization of those in use and, especially, to improve the local stoichiometry. This is, of course, precisely the procedure and rationale for the sector burning idea. In this case, however, the distribution of those nozzles firing and those off is more or less uniform around the annulus. For instance, in the CF6-50, sector burning would include a solid 180^0 sector (15 nozzles) off and the other 180^0 sector on. For selective azimuthal burning, on the other hand, a typical arrangement might be to distribute 20 firing nozzles into 5 segments of 4 each so that each segment will be separated by 2 off nozzles [ie, 4 on - 2 off, 5 times around]. Many other arrangements are possible and the optimum is chosen by the competing demands of emissions control performance, operational performance (eg, relight), and mechanical performance (eg, pattern factor).

This method eliminates the problems of sector burning because it provides sufficient symmetry around the annulus. Thus, at idle, the turbine efficiency and acceleration are not noticeably degraded, and at low power above idle, the pattern factor is not so poor as to cause significant turbine damage. It follows then that SAB can be used successfully in flight, thus removing the need for much of the complex plumbing and the failsafe mechanism needed to prevent a malfunction from leading to inadvertent sector burning in flight.

There is, of course, a drawback to this procedure: it is not as effective as sector burning in reducing HC and CO. There are two reasons for this. First, in order to provide an acceptable temperature distribution for the turbine, fewer nozzles can be turned off. Hence the stiochiometry and atomization quality are comprimised. Second, quenching of the reactions always occurs at the boundary between a reaction zone and an adjacent, cool airflow. Sector burning has only two such boundarys, whereas SAB has several, the number depending upon the geometry (eg, for the 4-2 case mentioned above, there are 5 such quenching boundarys). There would be, therefore, a motivation towards the minimum number of quenching boundaries and towards fewer nozzles in operation at idle. This would be nothing more than sector burning. The practical limit is the point at which the drawbacks of sector burning come into play, that is, where SAB can no longer be used in flight because of possible turbine damage or failure to accelerate, or where the degradation of the turbine efficiency leads to significant fuel penalty. In fact, if the method were to be used in flight on a normal basis, then there are other performance considerations that weigh on the selectionof the actual geometry. The system must

(1) provide stable combustion over flight envelope, (2) be able to relight over same envelope, and (3) be able to accelerate <u>from starting power</u> (sub-idle), as well as (4), accelerate from flight idle.

APPENDIX B

ENGINE DATA

Engine: CF34

Thrust (KN)	PR	BR	S/V (m^{-1})	Idle
40	19.5			6.4%

Baseline	P_3 (atm)	T_3 (°K)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC*	EI CO*	EI NOx*	Sk
Idle	3.1	447	4.0	173	.0119	.0487	28.2	104.8	2.2	
Approach				430		.0018	0.2	6.9	3.1	
Climbout				1230		.006	0	2.4	11.2	
Takeoff	19.5			1480		.0004	0	1.9	14.2	20
						EPAP	53.1	205.0	24.9	

Sector Burning at Idle

Idle				173**		.0146	6.7	38.1	3.3	
Approach										
Climbout										
Takeoff										20
						EPAP	12.7	80.0	27.0	

Idle		
Approach		
Climbout		
Takeoff		

*EIs estimated from EPAP values.
**Assumed unchanged.

Engine: CFM56

Thrust (KN)	PR	BR	S/V (m^{-1})	Idle
107	25.6		35.0	4% (not [illegible])

Mod. PERT	P_3 (atm)	T_3 (°K)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle	3.6	463		360		.0189	8.0	51.7	3.5	
Approach	10.6	617		1087		.0013	0.4	4.0	9.3	
Climbout	21.9	762		3042		.0003	0.1	1.0	20.6	
Takeoff	25.6	779		3758		.0002	0	1.0	23.9	
						EPAP	12.0	79.5	42.8	

Sector Burning at Idle (15 of 20)

Mod. PERT	P_3 (atm)	T_3 (°K)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle				360*		.0083	0.8	32.6	3.5	
Approach										
Climbout										
Takeoff										
						EPAP	1.5	51.7	42.8	

Sector Burning at 6% Idle (15 of 20)

Mod. PERT	P_3 (atm)	T_3 (°K)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle				400*		.0057	0.3	23.4	4.3	
Approach										
Climbout										
Takeoff										
						EPAP	0.9	42.0	43.5	

*Based on full annular performance. It is understood that with sector burning the turbine efficiency may be degraded at idle to the point that additional fuel would be required to maintain power.

Engine: CF6-32

Thrust (KN)	PR	BR	S/V (m^{-1})	Idle
145			24.8	4%

	P_3 (atm)	T_3 (°K)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle	2.6	427		443		.0482	36.1*	73.3*	4.3	
Approach	9.7	599		1584		.0014	0.2	5.5	11.0	
Climbout	21.5	749		4772		.0002	0.1	0.6	29.0	
Takeoff	23.1	766		5779		.0002	0.1	0.6	33.2	
						EPAP	48.1	102.1	64.1	

Sector Burning Projection

	P_3 (atm)	T_3 (°K)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle				443**		.0055	1.3*	18.7*		
Approach										
Climbout										
Takeoff										
						EPAP	2.0	29.8		

Double Annular Projection

	P_3 (atm)	T_3 (°K)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle						.0117	2.0	42.9	3.7	
Approach						.0046	0.6	17.7	8.6	
Climbout						.0005	0.1	1.8	14.0	
Takeoff						.0004	0	1.6	16.3	
						EPAP	3.2	72.6	35.6	

*Estimated from EPAP values.

**Based on full annular performance. It is understood that with sector burning the turbine efficiency may be degraded at idle to the point that additional fuel would be required to maintain power.

Engine: CF6-6D

Thrust(KN)	PR	BR	$S/V(m^{-1})$	Idle
174.8	24.5	5.9	24.8	3.34%

							EI			
Production	P_3 (atm)	T_3 (°R)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	HC	CO	NOx	Sk
Idle	2.7	435	10.1	483	.0132	.0489	36.0*	76.9*	4.6	
Approach				1728		.0014	0.2	5.5	12.1	
Climbout				5206		.0002	0.1	0.6	32.4	16
Takeoff	24.5	779	71.2	6304	.0244	.0002	0.1	0.6	39.7	
						EPAP	43.3	96.5	65.7	

Sector Burning at Idle

Idle				483**		.0056	1.1*	19.9*	4.6	
Approach										
Climbout										
Takeoff										
						EPAP	1.8	26.1	65.5	

Double Annular Projection

Idle						.0112	1.9	41.0	4.0	
Approach						.0040	0.6	14.8	8.7	
Climbout						.0005	0.1	1.8	15.6	
Takeoff						.0004	0	1.6	18.1	
						EPAP	2.8	61.5	35.2	

*Estimated from EPAP values.

**Based on full annular performance. It is understood that with sector burning the turbine efficiency may be degraded at idle to the point that additional fuel would be required to maintain power.

Engine: CF6-50C

Thrust (KN)	PR	BR	S/V (m^{-1})	Idle
224.2	29.8	4.4	27.2	3.4%

Production	P_3 (atm)	T_3 (°K)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle	2.9	429	13.8	548	.0110	.0765	59.3*	109.4*	3.5*	13
Approach	11.7	630	47.6	2394	.0140	.0010	0.2	3.9	12.0	
Climbout	25.9	786	92.1	7034	.0214	.0001	0.1	0.7	29.1	
Takeoff	29.8	820	103.0	8554	.0231	.0001	0.1	0.7	33.9	
						EPAP	63.0	119.5	60.8	

Sector Burning at Idle with Nozzle Modification

	P_3 (atm)	T_3 (°K)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle				548**		.0079	0.7*	31.4*	3.5*	
Approach										
Climbout										
Takeoff										
						EPAP	1.0	37.1	60.8	

Double Annular

	P_3 (atm)	T_3 (°K)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle						.0103	1.8*	37.7*	4.0*	
Approach						.0028	0.5	10.1	10.0	
Climbout						.0005	0.1	1.8	19.1	
Takeoff						.0004	0	1.6	25.5	
						EPAP	2.4	49.8	44.7	

*Estimated from EPAP values.

**Based on full annular performance. It is understood that with sector burning the turbine efficiency may be degraded at idle to the point that additional fuel would be required to maintain power.

Engine: JT3D-7

Thrust(KN)	PR	BR	S/V(m^{-1})	Idle
84.5	13.5	1.4		[illegible]

Production	P_3 (atm)	T_3 (°K)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI* HC	EI* CO	EI* NOx	EI* Sk
Idle				460		.1561	149	119	1.4	
Approach				1400		.0043	2.6	8.5	4.6	
Climbout				3720		.0011	0.8	1.5	9.4	
Takeoff				4525		.0008	0.6	0.9	12.0	
						EPAP	356	294	31	

Aerating Nozzle/Leaner PZ Combustor

Aerating Nozzle/Leaner PZ Combustor	P_3 (atm)	T_3 (°K)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI* HC	EI* CO	EI* NOx	EI* Sk
Idle						.0788	66.0	94.1	2.3	
Approach						.0026	1.2	6.7	7.8	
Climbout						.0005	0.3	1.2	16.0	
Takeoff						.0004	0.3	0.7	20.3	
						EPAP	158	232	53	

Idle		
Approach		
Climbout		
Takeoff		

*EIs estimated from earlier data.

Engine: JT8D-9

Thrust(KN)	PR	BR	S/V(m^{-1})	Idle
64.5	16.9	1.04	25.2	7.0%*

Production	P_3** (atm)	T_3** (°K)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle	2.7	404		476		.0168	10.0	34.5	2.9	
Approach	6.6	530		1072		.0037	1.7	9.4	5.6	
Climbout	14.7	673		3044		.0008	0.5	1.7	14.2	
Takeoff	16.9	708		3744		.0007	0.5	1.2	17.9	23
						EPAP	35.1	124.5	52.2	

Aerating Nozzle/Rich PZ Combustor Projection

						Comb. Ineff.	HC	CO	NOx	Sk
Idle						.0053	2.2	14.5	3.3	
Approach						.0010	0.3	3.4	6.4	
Climbout						.0003	0.2	0.6	16.0	
Takeoff						.0002	0.2	0.2	20.3	
						EPAP	7.8	51.3	59.1	

Vorbix Projection

						Comb. Ineff.	HC	CO	NOx	Sk
Idle						.0049	0.26	20.0	2.4	
Approach						.0013	0.14	5.2	5.3	
Climbout						.0022	0.32	8.3	8.6	
Takeoff						.0015	0.15	5.8	11.2	
						EPAP	1.6	88.0	36.0	

*Quoted value, unrealistically high.
**Estimates

Engine: JT8D-17

Thrust (KN)	PR	BR	S/V (m^{-1})	Idle
71.2	17.4	0.99	25.2	7.0%*

Production	P_3 (atm)	T_3 (°K)	$\dot{M}_a$ (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle				531		.0160	10.2	31.0	3.3	
Approach				1275		.0037	2.0	8.5	6.1	
Climbout				3588		.0010	0.8	1.0	15.2	
Takeoff				4482		.0008	0.7	0.7	19.2	24
						EPAP	37.3	112.7	60.1	

Aerating Nozzle/Rich PZ Combustor **

Aerating Nozzle/Rich PZ Combustor	P_3 (atm)	T_3 (°K)	$\dot{M}_a$ (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle	Production Values					.0049	2.1	13.7	3.7	
Approach						.0010	0.3	3.2	7.0	
Climbout						.0003	0.2	0.6	17.3	
Takeoff						.0002	0.2	0.2	21.9	
						EPAP	7.6	49.4	68.4	

Advanced Vorbix (II-9) Rig Test

Advanced Vorbix (II-9) Rig Test	P_3 (atm)	T_3 (°K)	$\dot{M}_a$ (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle	2.87	412	14.2	514	.0100	.0046	0.25	18.9	2.7	
Approach	6.83	535	30.9	1247	.0112	.0011	0.14	4.9	5.8	
Climbout	15.08	678	60.0	3553	.0164	.0019	0.32	7.8	9.3	
Takeoff	17.40	714	67.1	4406	.0182	.0013	0.15	5.5	12.1	27
						EPAP	1.6	83.1	41.0	

*Quoted value, unrealistically high.
**EIs estimated from EPAP values.

Engine: JT8D-17
(continued)

Thrust (KN)	PR	BR	S/V (m^{-1})	Idle
71.2	17.4	0.99	25.2	7.0%*

Production	P_3 (atm)	T_3 (°K)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle										
Approach										
Climbout										
Takeoff										

Advanced Vorbix (P&WA proprietary configuration)

Advanced Vorbix	P_3 (atm)	T_3 (°K)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle						.0075	3.0	22.2	3.3	
Approach		Production				.0012	0.3	4.5	8.0	
Climbout		Values				.0008	0	3.8	12.2	
Takeoff						.0005	0	2.4	14.3	
					EPAP		10.0	85.9	53.3	

Idle										
Approach										
Climbout										
Takeoff										

*Quoted value, unrealistically high.

Engine: JT9D-7

Thrust (KN)	PR	BR	S/V (m^{-1})	Idle
205.3	21.4	5.2	19.3	7.0%

Production	P_3 (atm)	T_3 (°K)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle	3.6	447	20.6	780	.0105	.0360	26.4	57.0	3.1	
Approach	8.8	588	43.7	2109	.0134	.0013	0.6	3.3	7.4	
Climbout	19.1	736	81.0	6010	.0206	.0004	0.3	0.4	31.6	4
Takeoff	21.4	764	88.6	7303	.0229	.0004	0.3	0.4	42.4	4
						EPAP	45.4	98.5	61.8	

Aerating Nozzle/Rich PZ Combustor		Comb. Ineff.	HC	CO	NOx	Sk	
Idle		.0056	2.9	13.2	2.9		*
Approach		.0013	0.6	3.3	7.4		
Climbout		.0004	0.3	0.4	23.1		
Takeoff		.0004	0.3	0.4	30.8	<20	
		EPAP	5.7	24.6	47.4		

Vorbix (S27E)		Comb. Ineff.	HC	CO	NOx	Sk
Idle		.0038	1.0	12.8	2.9	
Approach		.0029	0.5	10.8	4.7	
Climbout		.0004	0.1	1.2	11.6	
Takeoff		.0003	0.1	1.0	13.8	30
		EPAP	2.1	30.2	26.2	

*EIs estimated from EPAP value.

Engine: JT9D-70

Thrust(KN)	PR	BR	S/V(m^{-1})	Idle
228	24.2	4.9		7%

Production	P_3* (atm)	T_3* (°K)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle	4.1	465		853		.0228	12.0	53.0	3.0	
Approach	10.0	612		2449		.0007	0.3	1.7	7.8	
Climbout	21.6	764		7199		.0002	0.2	0.2	25.6	
Takeoff	24.2	793		8791		.0002	0.2	0.2	31.6	8
						EPAP	20.0	87.5	54.3	

Aerating Nozzle/Rich PZ Combustor

						Comb. Ineff.	HC	CO	NOx	Sk
Idle						.0044	2.0	11.4	2.9	
Approach						.0007	0.3	1.7	7.8	
Climbout						.0002	0.2	0.2	21.7	
Takeoff						.0002	0.2	0.2	28.9	<10
						EPAP	3.8	20.0	48.5	

Vorbix Projection

						Comb. Ineff.	HC	CO	NOx	Sk
Idle						.0031	0.9	10.1	3.3	
Approach						.0026	0.4	9.5	5.8	
Climbout						.0003	0.1	0.9	14.5	
Takeoff						.0003	0.1	0.8	17.4	
						EPAP	2.0	26.3	35.2	

*Estimated

Engine: JT8D-209

Thrust (KN)	PR	BR	S/V (m^{-1})	Idle
85.6	19.2	1.62	25.2	7%*

	P_3 (atm)	T_3 (°K)	$\dot{M}$ (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle										
Approach										
Climbout										
Takeoff										

Aerating Nozzle/Rich PZ Combustor Projection

	P_3 (atm)	T_3 (°K)	$\dot{M}$ (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle			544				0.74	10.7	3.4	
Approach			1265				0.12	2.3	7.9	
Climbout			3511				0.02	0	16.7	
Takeoff	19.2		4355				0.01	0.9	21.3	
						EPAP	2.2	33.6	54.9	15

	P_3 (atm)	T_3 (°K)	$\dot{M}$ (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle										
Approach										
Climbout										
Takeoff										

*Quoted value, unrealistically high

Engine: M45H-01

Thrust (KN)	PR	BR	S/V(m^{-1})	Idle
32.4	16.9	3.0	23.75	7.0%*

Production	P_3 (atm)	T_3 (°K)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	Sk
Idle	3.0	424	5.24	191	.0101	.0935	59.5	178.4	1.5	
Approach	6.5	541	10.8	526	.0135	.0183	7.4	51.0	3.6	
Climbout	14.6	693	21.2	1498	.0196	.0024	0.7	7.9	9.3	
Takeoff	16.9	723	23.8	1793	.0209	.0021	0.8	6.2	11.5	46.3
						EPAP	162.4	526.0	31.2	
Double Blown Ring										
Idle				200		.0222	10.7	55.5	2.1	
Approach				508		.0043	1.0	14.7	5.1	
Climbout				1444		.0009	0.2	3.0	10.9	
Takeoff				1753		.0006	0.2	2.0	13.1	12
						EPAP	30.1	169.9	37.0	

* Normal minimum idle is 7.6%

Engine: Spey Mk555

Thrust (KN)	PR	BR	S/V (m^{-1})	Idle
43.8	16.1	1.0	38.7	Min.

	P_3 (atm)	T_3 (°K)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Production										
Idle	2.1	388	6.86	341	.0138	.141	130.0	117.7	0.9	
Approach	7.0	546	22.2	793	.0099	.0118	8.3	20.0	5.9	
Climbout	14.2	667	39.5	2126	.0150	.0005	0.5	0	14.7	
Takeoff	16.1	698	43.3	2606	.0167	.0048	5.1	1.1	19.0	
						EPAP	441	420	49.5	
RAB										
Idle				301	.0122	.0235	11.4	57.4	3.4	
Approach				785	.0098	.0029	1.7	4.9	7.9	
Climbout						.0008	0.1	3.9	14.0	
Takeoff						.0008	0	4.3	16.1	
						EPAP	36.1	186.1	55.2	
CVS										
Idle				305	.0124	.0380	24.3	72.0	3.1	
Approach				785	.0098	.0029	2.0	5.1	8.2	
Climbout						.0008	0	3.6	13.7	
Takeoff						.0008	0	3.4	15.4	
						EPAP	75.6	232.0	54.2	

Engine: Spey Mk511

Thrust(KN)	PR	BR	S/V(m^{-1})	Idle
50.7	19.9	0.64	38.7	Min.

Production	P_3 (atm)	T_3 (°K)	M (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle	2.2	407	7.5	401	.0149	.094	76.7	117.4	1.1	
Approach	8.0	575	23.6	998	.0117	.011	7.2	20.3	7.9	
Climbout	17.1	700	47.2	2619	.0154	.0016	1.3	2.1	19.2	
Takeoff	19.9	734	52.4	3202	.0170	.0012	1.0	1.8	23.3	
						EPAP	278.4	435.8	68.1	

RAB	P_3 (atm)	T_3 (°K)	M (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle				370	.0137	.0165	6.7	46.3	3.8	
Approach				990	.0116	.0002	1.4	3.3	9.1	
Climbout						.001	0	4.3	16.2	
Takeoff						.0009	0	4.1	18.8	
						EPAP	23.0	161.6	68.2	

CVS	P_3 (atm)	T_3 (°K)	M (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle				377	.0140	.0355	22.9	67.2	1.1	
Approach				900	.0116	.0022	1.6	3.6	9.4	
Climbout						.0008	0	3.4	15.5	
Takeoff						.0005	0	2.3	17.5	
						EPAP	75.5	229.0	58.0	

Engine: RB211-22B

Thrust(KN)	PR	BR	S/V(m^{-1})	Idle
187	25.0	5.0	20.11	Min.

							EI			
Phase I	P_3 (atm)	T_3 (°K)	M (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	HC	CO	NOx	Sk
Idle	3.6	446	18.1	627	.0096	.100	86.8	104.9	2.3	
Approach	10.6	616	46.1	2007	.0120	.010	5.8	21.1	8.2	
Climbout	22.1	752	83.2	5555	.0185	.001	0.9	1.6	25.4	
Takeoff	25.0	781	91.5	6716	.0204	.001	0.8	1.4	33.2	
						EPAP	134.6	172.3	51.9	

Phase II

Idle				571	.00875	.0131	5.6	35.0	4.3	
Approach				1989	.0120	.0007	0.3	1.9	12.4	
Climbout				5550	.0185	.0005	0.4	0.7	29.0	
Takeoff				6712	.0204	.0004	0.3	0.6	34.3	
						EPAP	8.3	49.6	61.7	

Phase II with Sector Burning

Idle				568	.0087	.007	2.54	19.6	5.5	
Approach										
Climbout										
Takeoff										
						EPAP	4.2	28.8	64.0	

Engine: RB211-535

Thrust (KN)	PR	BR	S/V (m^{-1})	Idle
142	19.3		20.11	Min.

Phase II	P_3 (atm)	T_3 (°K)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle	3.1	424	15.8	544	.00955	.022	11.1	52.2	4.3	
Approach	8.3	574	36.8	1561	.0118	.001	0.28	3.4	9.3	
Climbout	17.0	701	65.0	4340	.0188	.0007	0.46	1.1	21.4	
Takeoff	19.3	727	71.6	5305	.0206	.0006	0.41	1.0	25.0	
						EPAP	19.1	90.0	49.0	

Phase II with Sector Burning

Phase II with Sector Burning	P_3 (atm)	T_3 (°K)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle				540	.00947	.011	4.9	30.8	5.4	
Approach										
Climbout										
Takeoff										
						EPAP	8.9	54.7	51.3	

Phase III with Quick Quench

Phase III with Quick Quench	P_3 (atm)	T_3 (°K)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle				539	.00946	.009	0.84	37.2	3.9	
Approach						.002	0.55	5.3	6.3	
Climbout						.001	0.49	2.0	11.8	
Takeoff						.001	0.50	2.1	13.9	
						EPAP	2.5	67.5	30.3	

Engine: RB211-524

Thrust (KN)	PR	BR	S/V (m^{-1})	Idle
218	27.2	4.5	20.11	Min.

Phase I	P_3 (atm)	T_3 (°K)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle	3.7	453	19.7	661	.0093	.093	79.8	99.8	2.5	
Approach	11.3	629	50.9	2498	.0136	.009	5.8	17.8	9.1	
Climbout	23.9	771	94.4	6684	.0197	.0007	0.7	0.7	30.2	
Takeoff	27.2	801	104.1	8120	.02167	.001	1.0	0.8	40.5	
						EPAP	110.4	145.1	61.4	

Phase II	P_3 (atm)	T_3 (°K)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle				609	.00854	.011	4.5	30.7	4.4	
Approach				2477	.0135	.0007	0.4	1.7	13.6	
Climbout				6677	.01966	.0004	0.3	0.6	32.1	
Takeoff				8144	.02165	.0002	0.1	0.5	38.3	
						EPAP	6.0	39.0	68.0	

Phase II with Sector Burning	P_3 (atm)	T_3 (°K)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle				604	.0085	.0058	2.1	16.9	5.5	
Approach										
Climbout										
Takeoff										
						EPAP	3.1	22.4	70.2	

Thrust (KN)	PR	BR	S/V(m^{-1})	Idle
171	15.5	0		4.7%

Engine: Olympus 593

Production	P_3 (atm)	T_3 (°K)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	Sk
Idle				1140		.0584	36	118	2.5	
Descent				2360		.0380	22	82	4.0	
Approach				4550		.0201	8.5	55	6.5	
Climbout				9100		.0059	1.5	20	12.5	
Takeoff*	15.5			12700		.0003	0	1.1	22.3	
Afterburner**				10000		.0207	6.6	64.5	0	
						EPAP	129	530	70.1	

Blown Ring (Projected Worst Case)

						Comb. Ineff.	EI HC	EI CO	EI NOx	Sk
Idle						.0166	7.2	44.8	2.5	
Descent						.0162	7.7	41.3	4.0	
Approach						.0110	2.9	36.8	6.5	
Climbout						.0039	0.8	13.8	12.5	
Takeoff*						.0002	0	0.7	22.3	
Afterburner**						.0102	3.4	31.4	0	
						EPAP	30.7	237	70.8	

*Data on this row refer to main burner only.
**On during Takeoff only.

Engine: ALF502D

Thrust (KN)	PR	BR	S/V (m^{-1})	Idle
28.9	11.1	5.8	38.6	6.22

Cert. Config.*	P_3 (atm)	T_3 (°K)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI			
							HC	CO	NOx	Sk
Idle	2.3	397	3.6	168	.0130	.0139	5.6	40.7	2.9	3
Approach	5.0	499	8.0	354	.0123	.0028	0.6	11.0	5.9	9
Climbout	9.8	614	13.1	1005	.0213	.0002	0.1	0.5	9.2	25
Takeoff	11.1	639	14.4	1205	.0232	.0002	0.1	0.5	10.1	25
						EPAP	14.8	112.4	28.8	
Dual Orifice Pressure Atomization (Baseline)										
Idle						.0256	11.9	67.6	4.1	
Approach						.0042	1.2	15.0	6.8	
Climbout						.0002	0.1	0.5	12.3	
Takeoff						.0002	0.1	0.5	13.7	23
						EPAP	31.0	183.4	38.3	

Idle		
Approach		
Climbout		
Takeoff		

*Includes airblast nozzle and combustor liner cooling air adjusted for durability.

Engine: ALF502L

Thrust (KN)	PR	BR	S/V (m^{-1})	Idle
33.4	13.3		38.6	5.3%

Baseline	P_3 (atm)	T_3 (°K)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle	2.1	381	3.76	173	.0128	.0240	12.6	56.0	2.6	5
Approach	5.6	511	8.06	478	.0165	.0020	0.3	8.6	4.7	13
Climbout	11.7	636	15.3	1185	.0215	.0001	0	0.7	10.7	25
Takeoff	13.3	662	16.82	1416	.0234	.0001	0	0.7	12.1	25
						EPAP	28.6	136.0	32.3	

Idle at 10.7%	P_3 (atm)	T_3 (°K)	M_a (Kg/S)	M_f (Kg/hr)	f/a	Comb. Ineff.	EI HC	EI CO	EI NOx	EI Sk
Idle	3.18	426	5.29	200	.0105	.0098	3.4	31.8	3.8	
Approach										
Climbout										
Takeoff										
						EPAP	9.1	92.2	35.4	

Idle		
Approach		
Climbout		
Takeoff		