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Analytical Evaluation of the Impact of Broad Specification Fuels on High Bypass Turbofan Engine Combustors

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By

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16. Abstract

An in-depth analysis of six conceptual combustor designs for the CF6-50 high bypass turbofan engine and six conceptual combustor designs for the NASA/GE E^3 high bypass turbofan engine was performed to provide an assessment of the major problems anticipated in using broad specification fuels in these aircraft engine combustion systems. The conceptual combustor designs are representative of both state-of-the-art and advanced state-of-the-art combustion systems. Each of the 12 concepts was analyzed to estimate combustor performance, durability, and pollutant emissions when using commercial Jet A aviation fuel and when using Experimental Referee Broad Specification (ERBS) fuel. The results of this study indicate that lean burning, low emissions, double annular combustor concepts can accommodate a wide range of fuel properties without a serious deterioration of performance or durability. However, rich burning, single annular concepts would be less tolerant to a relaxation of fuel properties. Also, as the fuel specifications are relaxed, autoignition delay time becomes much smaller which presents a serious design and development problem for premixing-prevaporizing combustion system concepts.

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1.0 SUMMARY

In this effort, an assessment was made of the major problems anticipated in using aircraft turbine engine fuels with relaxed fuel specifications in both state-of-the-art and advanced state-of-the-art aircraft turbine engine combustion systems. This study was limited to the design of engine combustion systems and did not encompass assessments of any problems related to airframe fuel systems. Two engine designs were selected for this study - a production turbofan engine, the General Electric CF6-50; and an advanced energy efficient turbofan engine, the NASA/GE E^3.

For each of these two turbofan engines, combustion system requirements were determined and six different combustion systems were conceptually designed. These combustors were designed to use Jet A fuel and a broad specification fuel (ERBS). Compared to Jet A fuel, ERBS fuel has a higher aromatic content and a higher final boiling point.

Each of the 12 concepts was analyzed to estimate combustor performance, durability, and emissions with Jet A fuel and with ERBS fuel. A comparative evaluation of the conceptual designs was made in terms of the following criteria:

1. Fuel flexibility (flexibility to handle current and broad specification fuels).
2. Combustion performance.
3. Exhaust pollutant emissions.
4. Design complexity.
5. Reliability.
6. Maintainability.
7. Durability and operating life.
8. Effect on overall engine weight.
9. Effect on overall engine fuel consumption.

Estimates were made as to how far Jet A fuel specifications can be relaxed without degrading CF6-50 or advanced turbofan engine performance or without encountering fuel stability problems. Properties of the ERBS fuel were carefully examined in order to determine the possibility that any of these properties might limit the use of this fuel for turbofan engine applications. Problems associated with integrating each combustor with the two engine designs were evaluated, and each combustor concept was evaluated in terms of the design complexity required to achieve good performance with the two fuels. Finally, the most significant anticipated problem areas were identified and recommendations made for areas of future study.

The results of this study suggest that, in general, turbofan engines with lean burning, low emissions double annular combustion systems can accommodate a rather wide range of fuel properties without a serious deterioration of performance or a serious increase in exhaust emissions. A lean burning double annular combustor, designed for the E^3 cycle condition, is predicted to meet all engine performance and emission requirements with a significant relaxation of fuel specifications.

Rich burning, single annular combustor design concepts would be somewhat less tolerant to a relaxation of fuel specifications. As the hydrogen content of the fuel is decreased, emission levels increase and combustor liner cooling air must be increased to offset the effects of higher flame radiation levels on combustor liner temperatures. This increase in liner cooling air results in higher levels of combustor exit peak temperatures.

All of the concepts considered in this study are expected to have good performance with both Jet A and ERBS fuel. As indicated by recent test results with both fuels, combustion efficiency will be close to 100% at simulated takeoff conditions with no discernible effect of fuel type on combustor pressure loss.

From a performance and emissions standpoint, two lean burning, premixing-prevaporizing combustor design concepts analyzed as a part of this study would be quite tolerant to a relaxation of fuel specifications. However, these concepts would require extensive development effort to meet the reliability and durability objectives of the turbofan engines. Also, as the fuel specifications are relaxed, the autoignition delay times for premixing systems become much smaller which present a serious design and development problem for these concepts. Further studies and experimental efforts are needed for a more thorough exploration of this problem.

2.0 INTRODUCTION

The purpose of this study was to perform an in-depth analysis of the effect of relaxing jet aircraft fuel specifications on the design and estimated performance, emissions, and durability of both current state-of-the-art and advanced state-of-the-art commercial conventional takeoff and landing (CTOL) wide-body jet aircraft engines.

Fuel flexibility may be an important aircraft engine design requirement in the future because of projected changes in the supply and quality of conventional petroleum feed stocks and because of the use of nonpetroleum feed stocks, such as shale oil and coal syncrudes. The broadening of aviation fuel specifications would minimize the amount of energy required to process these lower quality feed-stocks and thus minimize fuel costs. Ultimately, a compromise will have to be reached between the degree of increased cost and complexity of designing aircraft engines for broader specification fuels and the degree of reduction in energy consumption and cost of producing a broader specification fuel.

For many years, the primary fuel for commercial aircraft engines has been Jet A, or fuels with similar specifications, produced from domestic crude oil. However, domestic crude production peaked in 1971 and has been steadily declining since that time while demand has continued to increase. The shortfall has been made up by imports of both crudes and products, and today these supply over 42% of the total demand. Since imported crudes and products are not dependable source of supply, capabilities for using a broader range of petroleum products, including higher-boiling products, in commercial aircraft engines represent an important need.

The most abundant fossil fuel in the United States is coal, and processes are being developed to convert it to liquid fuels. These fuels differ materially from petroleum crudes in that they are largely aromatic. Although theoretically these fuels can be converted into high quality crudes, the cost in the near term would be prohibitive. Also, newly developed petroleum feed stocks generally have higher aromatic content and the aromatic content is expected to steadily increase in the future as lower quality feed stocks and heavier distillate fractions are utilized. Therefore, it is prudent to evaluate the effects of highly aromatic fuels on the operating characteristics of current combustion system designs and also on the operating characteristics of advanced combustion systems designed for low exhaust emissions.

In general, fuels with higher aromatic content burn with more luminous flames. Higher flame luminosity results in higher heat reduction to the combustor liner which requires higher levels of liner cooling flow to hold the liner temperature to the values necessary to meet the combustor life requirements. Higher cooling flow levels usually result in higher values for the combustor exit temperature pattern factor and may also result in higher levels of pollutant emissions.

Analytical and experimental studies to assess the effects of fuel property variations on the performance of gas turbine combustion systems have been conducted by the Government and within industry for more than 20 years. For most of the early studies, considerable emphasis was placed on the use of cheap, lower grade fuels for stationary and marine applications.

In this study, a detailed evaluation of the effects of anticipated fuel property changes was made for current production aircraft engine combustion systems and for a selection of combustor concepts that are expected to be used in advanced aircraft engines.

3.0 DISCUSSION OF DESIGN STUDY CONSIDERATIONS AND RESULTS

3.1 FUEL PROPERTIES AND SPECIFICATIONS

Specifications of the fuels considered for this program are presented in Table 1. In general, the broad specification (ERBS)* fuels have more aromatics, higher boiling points, and higher viscosity levels than the standard Jet A fuel.

Experience has shown that combustors not specifically designed to handle highly aromatic fuels tend to generate more smoke and higher combustor liner temperatures when burning them. Tests of full-scale combustors using a wide variety of fuels (Reference 2) have also shown that conventional laboratory tests of fuel combustion characteristics; e.g., smoke point and luminometer number, do not correlate well with combustor liner temperatures whereas a fundamental property, hydrogen content, correlates very well. This correlation has been shown to apply not only to General Electric combustors but also to those manufactured by other engine manufacturers (Reference 3).

Fuel properties are interrelated to some degree. For example, the higher boiling point fuels are generally more viscous and have higher freezing points, while minimum flash point is generally related to the initial boiling point.

A correlation can be shown between hydrogen content and aromatic content (Figure 1). These data were secured from References 4, 5, 6, 7, and 8. The correlation is approximate since aromatic content is not the only factor affecting hydrogen content. Molecular weight and molecular structure also have significant effects. Another factor is that some degree of ambiguity is associated with the determination of aromatic content. Several procedures are available for aromatic determinations such as silica gel absorption, mass spectroscopy, and gas chromatography. However, each of these has some restrictions which makes the procedure not universally applicable. In addition, uncertainties arise due to imprecise definition of aromatics, such as the classification of molecular structures containing five-member unsaturated

*Experimental Referee Broad Specification (tentative specification as of November 1978), see Reference 1.

Table 1. Preliminary Estimates of Alternative Aviation Turbine Fuel Specifications.

Specifications	ASTM Jet A	Broad-Specification Fuel*
Composition		
Aromatics (Vol. %)	(Max.) 20	35 (Reference Only)
Sulfur Mercaptan (Wt. %)	(Max.) 0.003	(Max.) 0.003
Sulfur, Total (Wt. %)	(Max.) 0.3	(Max.) 0.3
Nitrogen, Total (Wt. %)	-	0.010 (Kjeldahl)
Hydrogen (Wt. %)	13.5 Typ.	13.0 ± 0.1 (NMR)
Ratio Monocyclic to Polycyclic Hydrocarbons	(Report)	(Report)
Volatility		
Distillation, Temp. ° F		
IBP	(Report) 340	300 (Report)
10%	(Max.) 400	400 (Report)
50%	(Max.) 450	460 ± 10
90%	(Report) 470	560 (Report)
Final B.P.	(Max.) 550	600 (Report)
Residue (%)	(Max.) 1.5	1.5 (Report)
Loss (%)	(Max.) 1.5	1.5 (Report)
Flashpoint, ° F	(Min.-Max.) 105-150	110 ± 10
Gravity, API (60° F)	(Min.-Max.- 39-51	36-38 (Report)
Gravity, Specific (60/60° F)	(Min.-Max.) 0.7753-0.8299	0.7753 (Report)
Fluidity		
Freezing Point, ° F	(Max.) -40	-20 ± 2
Viscosity at -30° F, cs	(Max.) 15	-
at -10° F, cs	-	12 ± 4
Combustion		
Net Heat of Comb., Btu/lb	(Min.) 18,400	(Min.) 18,400 (Bomb Calorimeter)
Thermal Stability		
Coker Pressure (in. Hg)		
at 300/400° F	(Max.) 12	
at 250/350° F		(Max.) 12
Coker Tube Color Code		
at 300/400° F	(Max.) 3	
at 250/350° F		(Max.) 3
JFTOT	-	500° F (Breakpoint Temperature)

*Reference 9

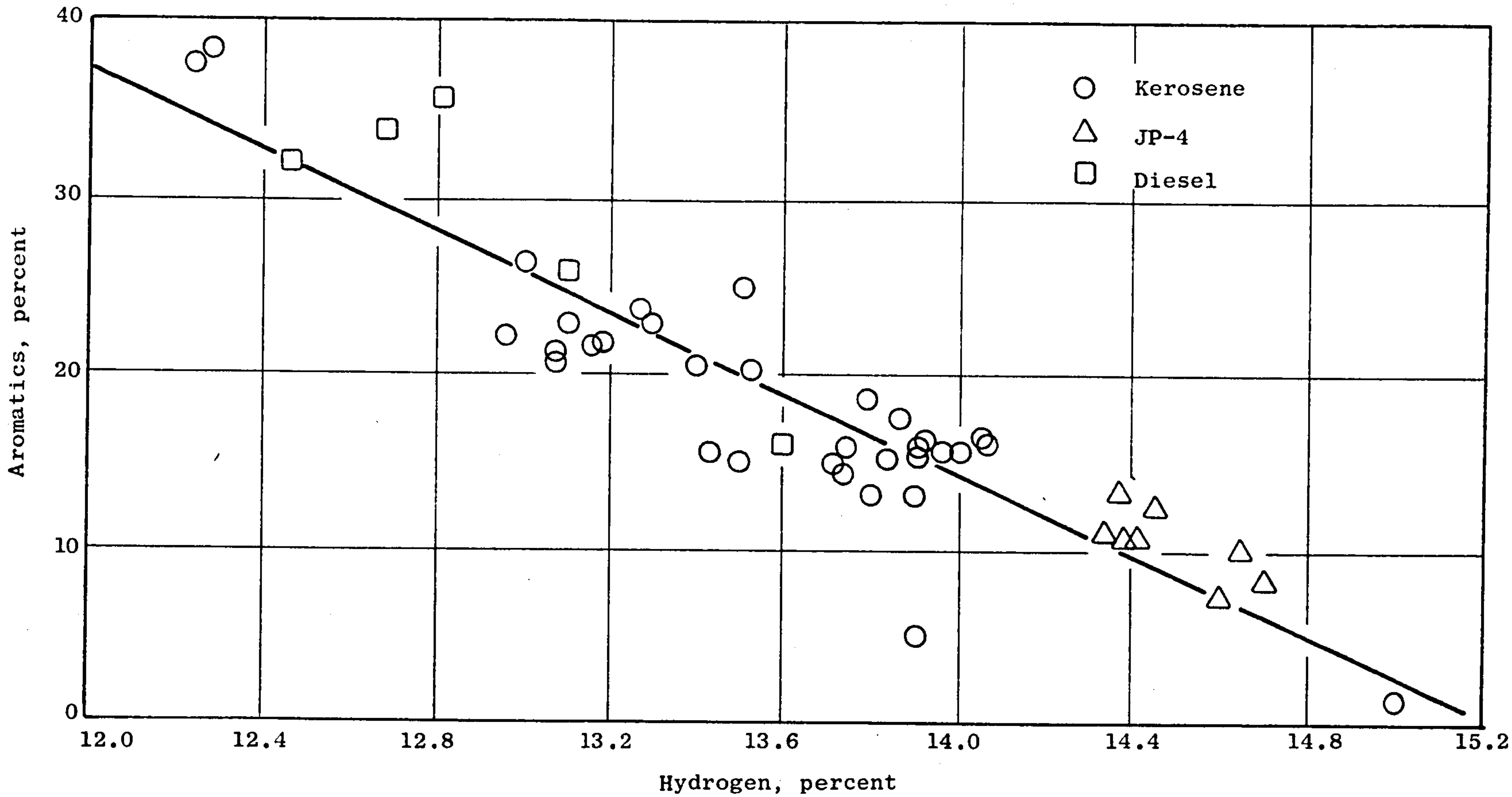

Figure 1. Correlation of Aromatics and Hydrogen Content of 50 Fuels.

rings, cyclo-paraffinic structures, or paraffinic side chains. To circumvent these problems, classification by hydrogen content appears to offer a unique solution since it is a basic property and can be standardized against pure compounds.

In addition to the effects of fuel composition on combustor liner temratures, there are indications that the type of aromatics, monocyclic versus dicyclic, as well as the final boiling point of the fuel have an effect on some exhaust emissions (Reference 4). It is also likely that fuels with lower hydrogen content will dissolve more water (Reference 10). Such fuels may, therefore, require higher concentrations of fuel system icing inhibitor to prevent the formation of ice crystals at low temperatures.

Figure 2 shows the relationship between flash point and initial boiling point of 61 samples of Jet A fuel (from Reference 11). The trend is obvious but the correlation is not very good. This is due, in part, to the difficulty involved in determining the initial boiling point. Significantly, all of the samples had flash points far above the current requirement of 105° F minimum for Jet A fuel and also above the proposed requirement of 100° F minimum for ERBS fuel.

3.2 SELECTED TURBOFAN ENGINES AND ENGINE CYCLE OPERATING CONDITIONS

For these combustion system design studies, two engines were selected: the CF6-50 engine, and an advanced energy efficient engine (E^3) which is based on information presented in Reference 12. Both of these engines are high bypass turbofans with high cycle pressure ratios. The E^3 design presented in Reference 12 is smaller in size than the CF6-50 (62.6 kg/sec versus 119 kg/sec airflow at SLS conditions) and represents more advanced component design technology. Cycle operating conditions for the CF6-50 combustion system are presented in Table 2; cycle conditions for the E^3 combustion system are presented in Table 3.

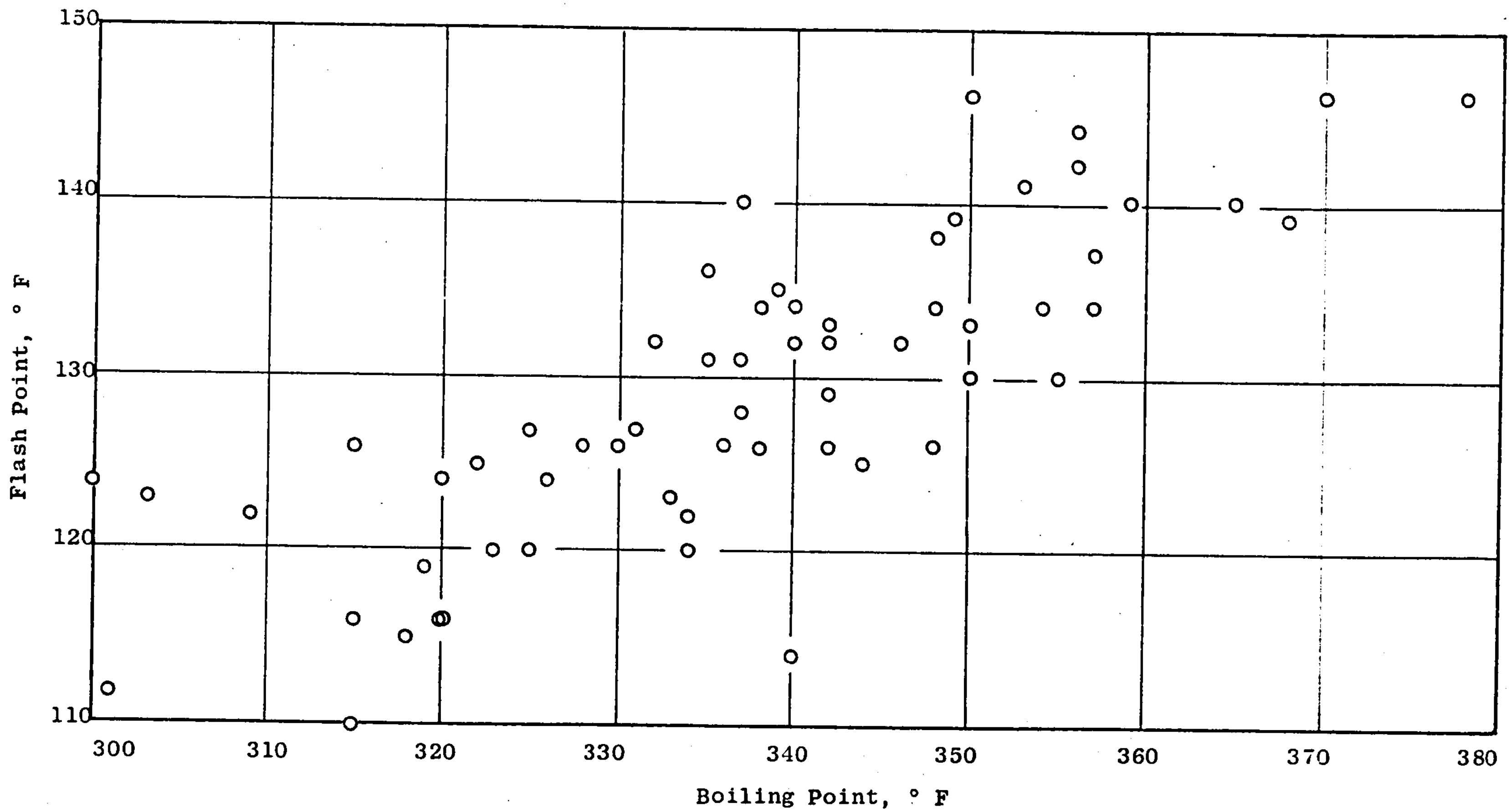

Figure 2. Flash Point Versus Initial Boiling Point - 61 Samples of Jet A Commercial Aviation Kerosine - 1977 Domestic Production.

Table 2. CF6-50C Combustor Operating Conditions.

	6% Idle	Approach	Climb	Takeoff	Maximum* Cruise
Percent of takeoff power	6.0	30.0	85.0	100.0	N.A.
Inlet total pressure - Atm.	4.13	11.84	25.78	29.46	11.90
Inlet total temperature - K	477	631	791	826	738
Exit total temperature - K	857	1135	1523	1615	1495
Total combustor airflow - kg/sec	19.3	48.1	90.7	101	42.3
Fuel-air ratio - g/kg	9.5	13.4	21.1	23.2	21.9
Compressor exit velocity - m/sec	129	149	160	160	149
Compressor exit Mach number	0.295	0.298	0.288	0.283	0.277
Engine Thrust - kN	13.5	67.3	191	224	49.6

*Maximum Cruise at 10,670 m, 0.85 Mach No.

Table 3. E^3 Combustor Operating Conditions.

	6% Idle	Approach	Climb	Takeoff	Maximum* Cruise
Percent of takeoff power	6.0	30.0	85.0	100.0	N.A.
Inlet total pressure - Atm.	4.05	11.84	26.00	29.80	12.93
Inlet total temprature - K	488	635	786	819	757
Exit total temperature - K	943	1137	1528	1617	1531
Total combustor airflow - kg/sec	9.66	25.8	49.0	54.9	24.5
Fuel-air ratio - g/kg	11.5	13.3	21.5	23.6	22.5
Compressor exit velocity - m/sec	127	151	161	163	156
Compressor exit Mach number	0.288	0.302	0.291	0.289	0.287
Engine Thrust - kN	9.14	45.7	129	152	36.1

*Maximum Cruise at 9144 m, 0.80 Mach No.

3.3 CONCEPTUAL COMBUSTOR DESIGNS

The production combustor design and five-conceptual combustion systems were designed for the CF6-50 engine cycle. Six similar conceptual combustion systems were designed for the E^3 cycle conditions. The following combustor concepts were selected for these studies:

1. Baseline Single Annular Combustor
2. Short Length Single Annular Combustor
3. Annular Slot Combustor with Premixing Fuel Injection
4. NASA/GE ECCP Double Annular Combustor
5. NASA/GE ECCP Radial/Axial Combustor
6. Premixing, Prevaporizing Variable Geometry Combustor

The CF6-50 combustor concepts were designed to meet the requirements of the current production version of the CF6-50 engine with no change in the compressor rear frame structure and no change in engine length. The E^3 combustor concepts were designed to meet the requirements of the General Electric version of the NASA/GE E^3 engine design. The compressor exit dimensions and turbine inlet dimensions are typical for this series of advanced engine designs and the maximum combustion system length for the E^3 concepts was selected to preclude the necessity of making a drastic change in the engine frame structure.

3.3.1 Combustor Design Requirements

The key combustion system design requirements selected for this study are generally representative of the design requirements of both the CF6-50 and the E^3 combustion systems, although in the case of the existing CF6-50 engines less stringent emissions requirements apply. Performance design requirements are presented in Table 4A and emissions requirements are presented in Table 4B.

In addition to these requirements, the combustion system design program would also have requirements for altitude relight capability and for the combustor exit radial temperature profile. The altitude relight requirement

Table 4A. Combustor Performance Requirements.

	CF6-50	E^3
Minimum Combustion Efficiency - at High Power Conditions	99.6%	99.6%
Maximum Total Pressure Loss	5.0%	5.0%
Maximum Exit Temperature Pattern Factor*	0.25	0.25
Carbon Formation on Swirl Cup Parts	None	None
Life Cycle Goal	5000 Cycles	9000 Cycles

*Pattern Factor $= \dfrac{T_{max} - T_{avg}}{\Delta T}$

Table 4B. Combustor Emissions Requirements.

	Current EPA Standards lb/1000 lb-Thrust-hr	Proposed New EPA Standard for Previously Certified Engines lb/1000 lb-Thrust	Proposed New EPA Standards for Newly Certified Engines lb/1000 lb-Thrust
CO	4.30	0.35	0.245
HC	0.80	0.06	0.0324
NO_x	3.00	0.38	0.324

is usually specified as an altitude at which the combustor must be able to achieve a windmilling start with cold fuel. This altitude is usually about 9140 meters (30,000 ft). The combustor exit radial temperature profile is specified by the turbine designers and this requirement is achieved during the combustor component test period by adjustments to the secondary dilution hole patterns and trim holes in the aft sections of the combustor liners. Sufficient trim and dilution airflow must be provided in the initial combustor design to enable the combustor designer to meet the temperature profile requirements.

3.3.2 Conceptual Designs

The current production combustor configuration for the CF6-50 engine is shown in Figure 3.

An advanced, conceptual short single annular combustor concept designed for CF6-50 engine cycle conditions is illustrated in Figure 4. This concept embodies several recently evolved combustor design technology features. Counterrotating swirl cups create strong shear gradients that increase turbulence levels and provide more rapid mixing of the fuel and air in the primary combustion zone. Impingement cooling of the combustor liner provides more uniform cooling of the liner with reduced levels of cooling flow. The increased mixing and reduced cooling flow permits the use of a smaller size combustor with no reduction in performance levels. The combustor length for this design is 25.4 cm (10.0 in.) which is 9.65 cm (3.8 in.) shorter than the length of the baseline single annular design.

An annular slot combustor design concept for the CF6-50 engine is illustrated in Figure 5. In this design concept, the fuel is introduced into a circumferential row of premixer ducts that is uniformly spaced around the dome of the combustor. These ducts are curved to introduce the premixed fuel and air into the combustor dome with a steep circumferential swirl angle. A top view of the premixer duct design is shown in Figure 5.

As is illustrated in Figure 5, additional dome air is introduced into the combustor through two sets of swirl vanes that are concentric with the premixer swirler and positioned radially inside and outside of the premixer annulus. The flow through these air swirlers is swirled in the opposite

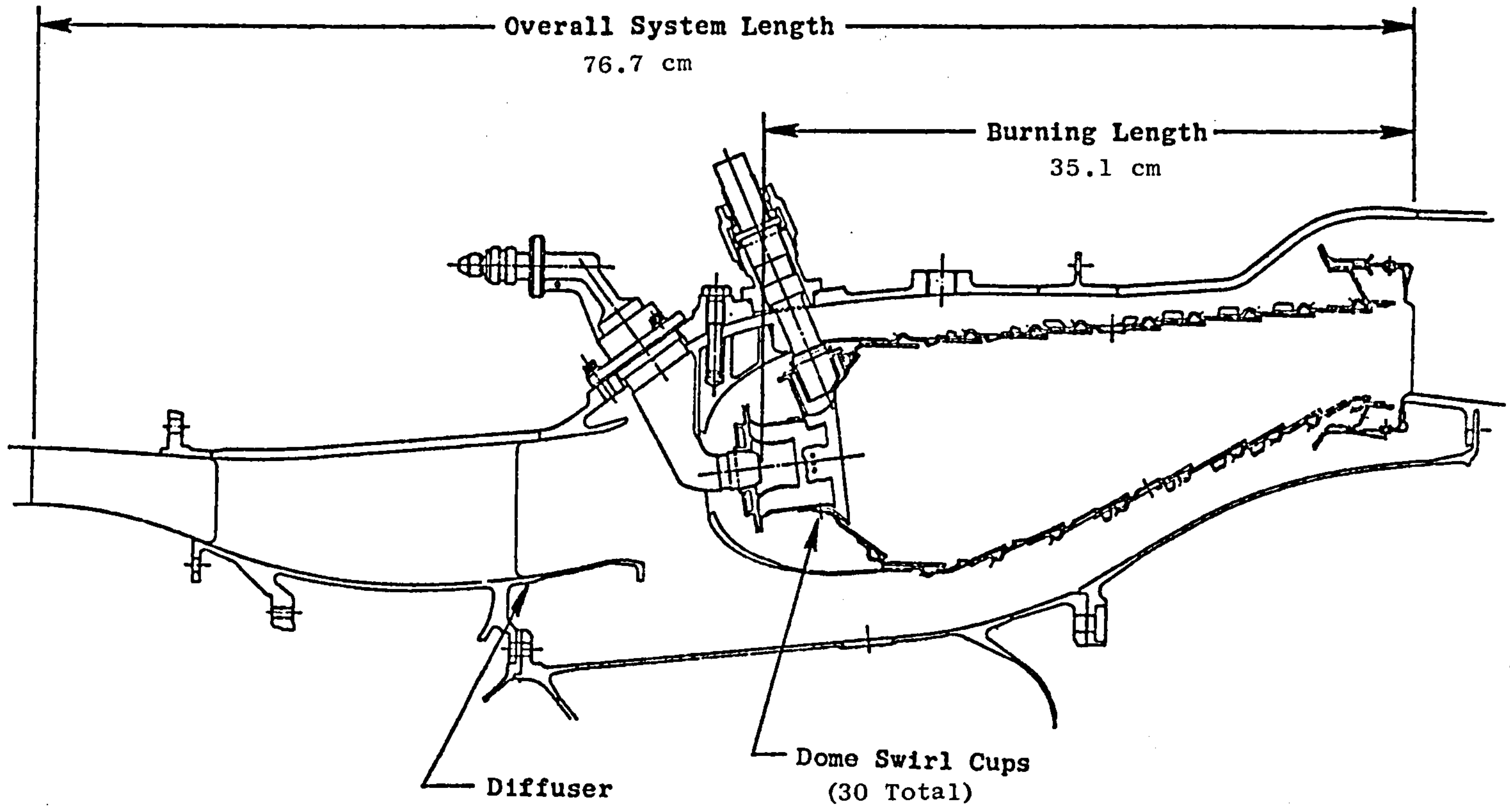

Figure 3. Production CF6-50 Engine Combustor.

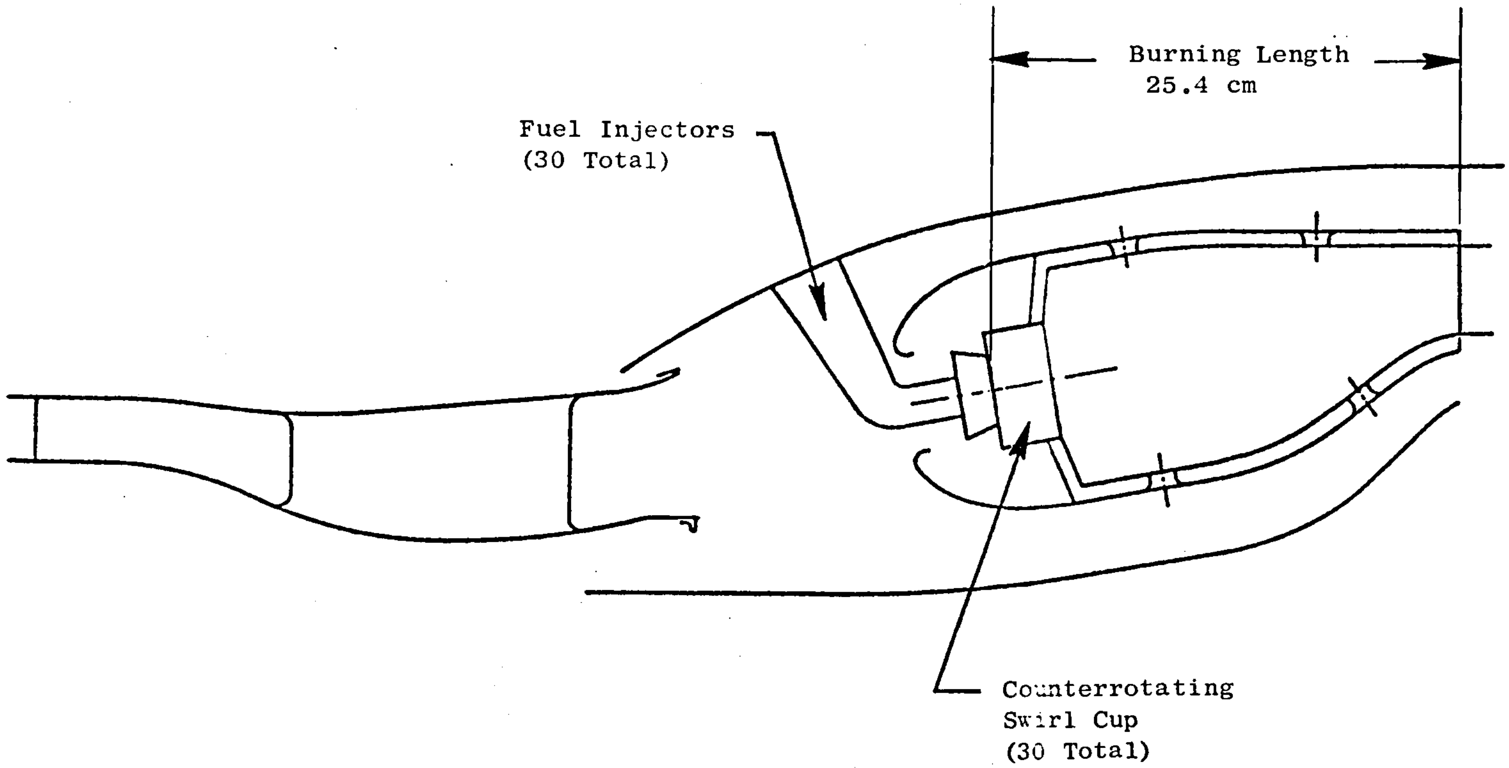

Figure 4. Short Single Annular CF6-50 Combustor Conceptual Design.

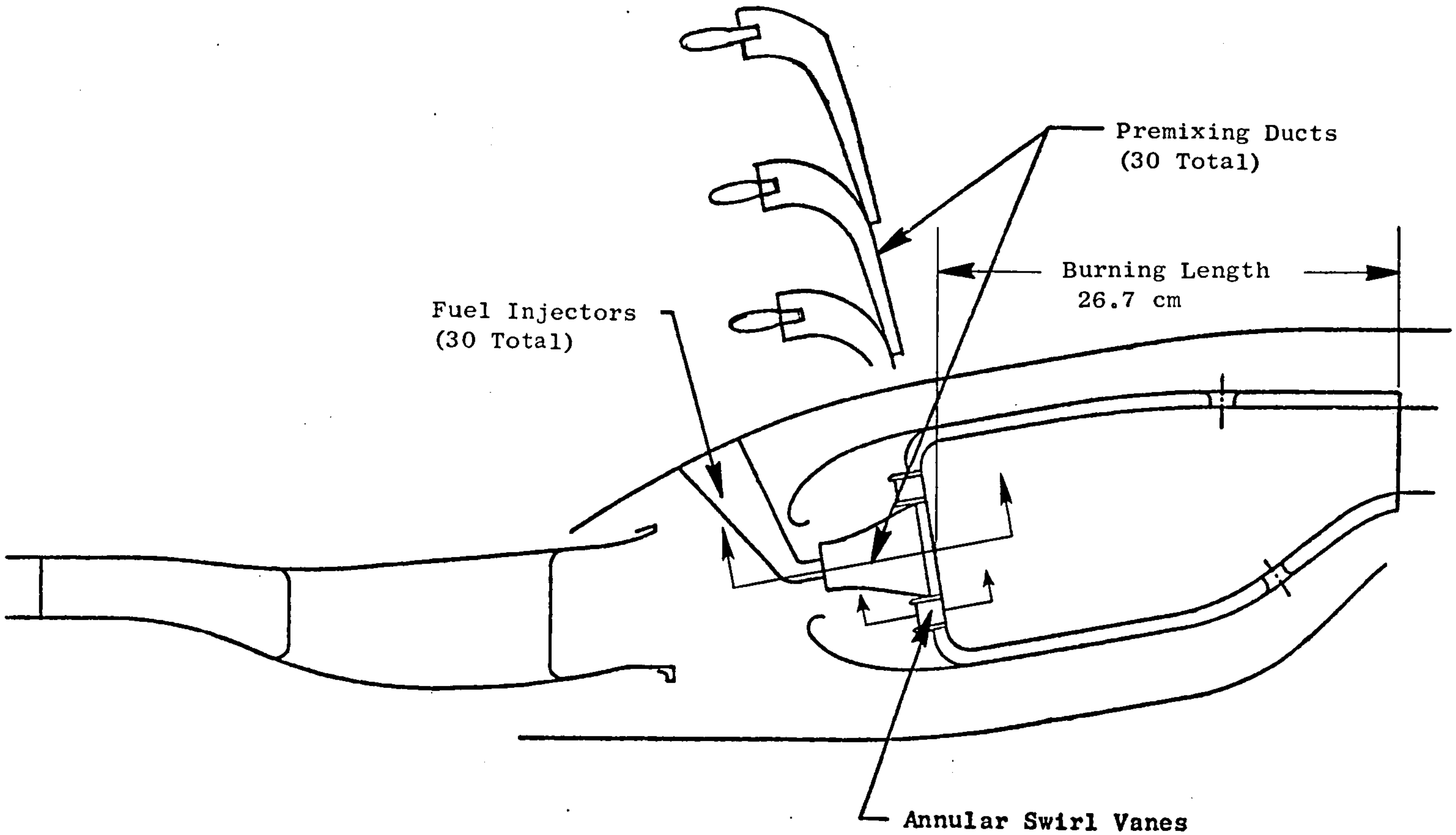

Figure 5. Annular Slot CF6-50 Combustor Conceptual Design.

direction with respect to the premixer flow resulting in very rapid mixing of the dome flow and a very uniform and stable flameholding pattern in the dome region of the combustor. The mixing pattern is very uniform in the circumferential direction around the combustor dome which results in highly uniform circumferential temperatures. This uniform circumferential temperature distribution is expected to eliminate the repetitive hot-cold streaks that normally occur in a conventional combustor. These hot streaks are the principle cause of reduced liner life and durability in conventional combustion systems. With broad specification fuels that have higher flame temperatures and higher emissivity levels, it is especially important that hot streaks are eliminated or minimized as much as possible.

A double annular combustion system for the CF6-50 engine developed under a prior NASA/GE Experimental Clean Combustor Program (ECCP) (References 13 and 14) is illustrated in Figure 6. An isometric view of an early version of the double annular design is illustrated in Figure 7. This concept incorporates two burning zones consisting of two concentric annular domes separated by an annular centerbody. At lightoff and low engine power operating conditions, all of the fuel is injected into the outer annulus dome, which utilizes about 13% of the total airflow. Near-stoichiometric fuel-air ratios are maintained in the low velocity and long residence time outer dome region, resulting in high combustion efficiency and low CO and HC emissions at low power conditions. The inner annulus dome utilizes about 55% of the total airflow. At high power engine operating conditons (over 30% power), increasing percentages of fuel flow are supplied to the inner annulus dome with corresponding reductions in outer annulus fuel. At full engine power conditions, about 85% of the total fuel flow is supplied to the inner annulus. Consequently, lean combustion is maintained in both annuli, and very short residence times exist in the high velocity inner annulus dome. As a result of the lean combustion and short residence times, low NO_x and smoke levels are produced at these conditions.

Figure 8 illustrates a radial/axial combustor concept that was designed for the CF6-50 engine as a part of the NASA/GE ECCP. An isometric view of this design is presented in Figure 9. This combustion system has two stages. An upstream pilot stage generates hot gases for the main stage which burns a

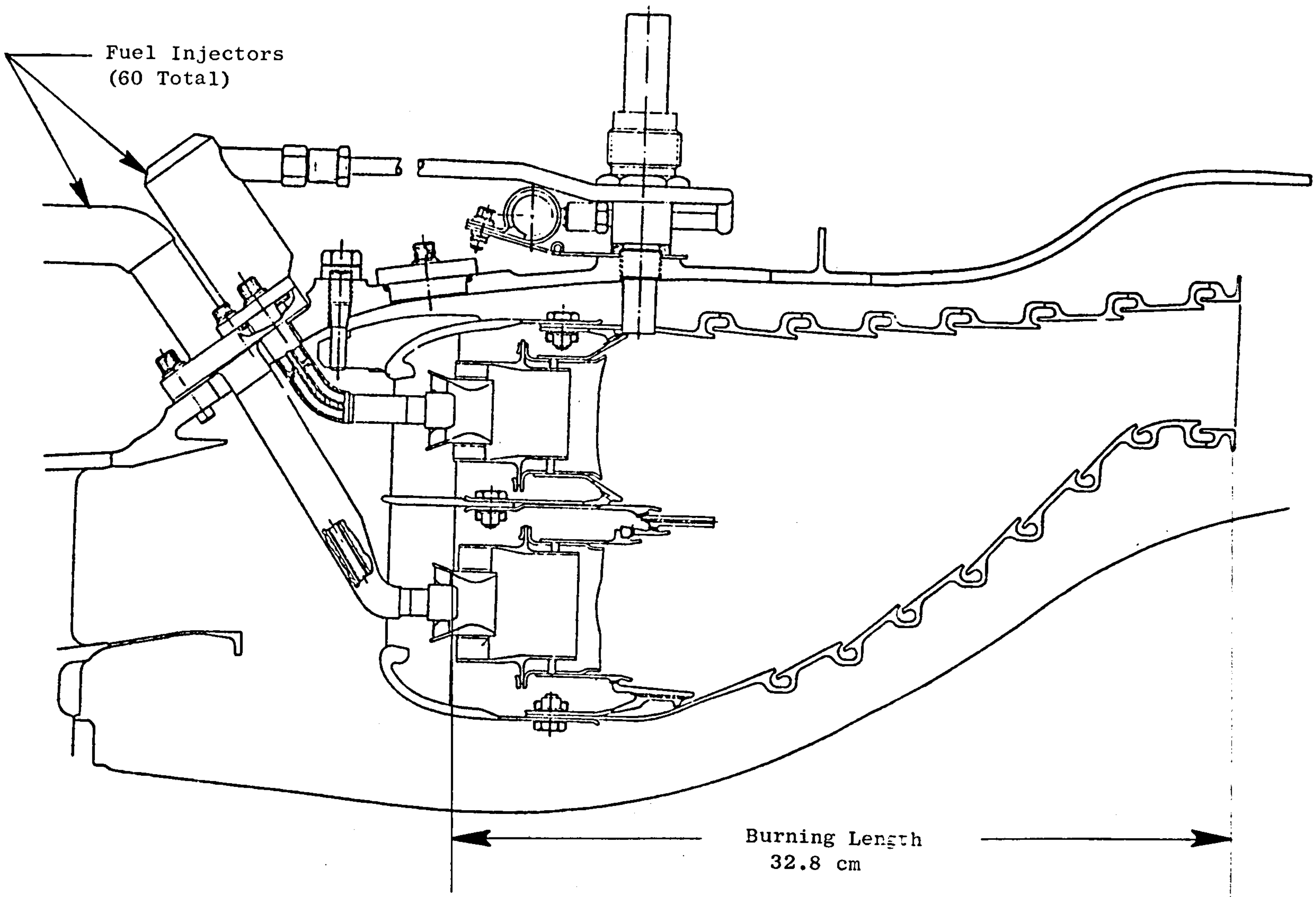

Figure 6. Double Annular CF6-50 Combustor Design.

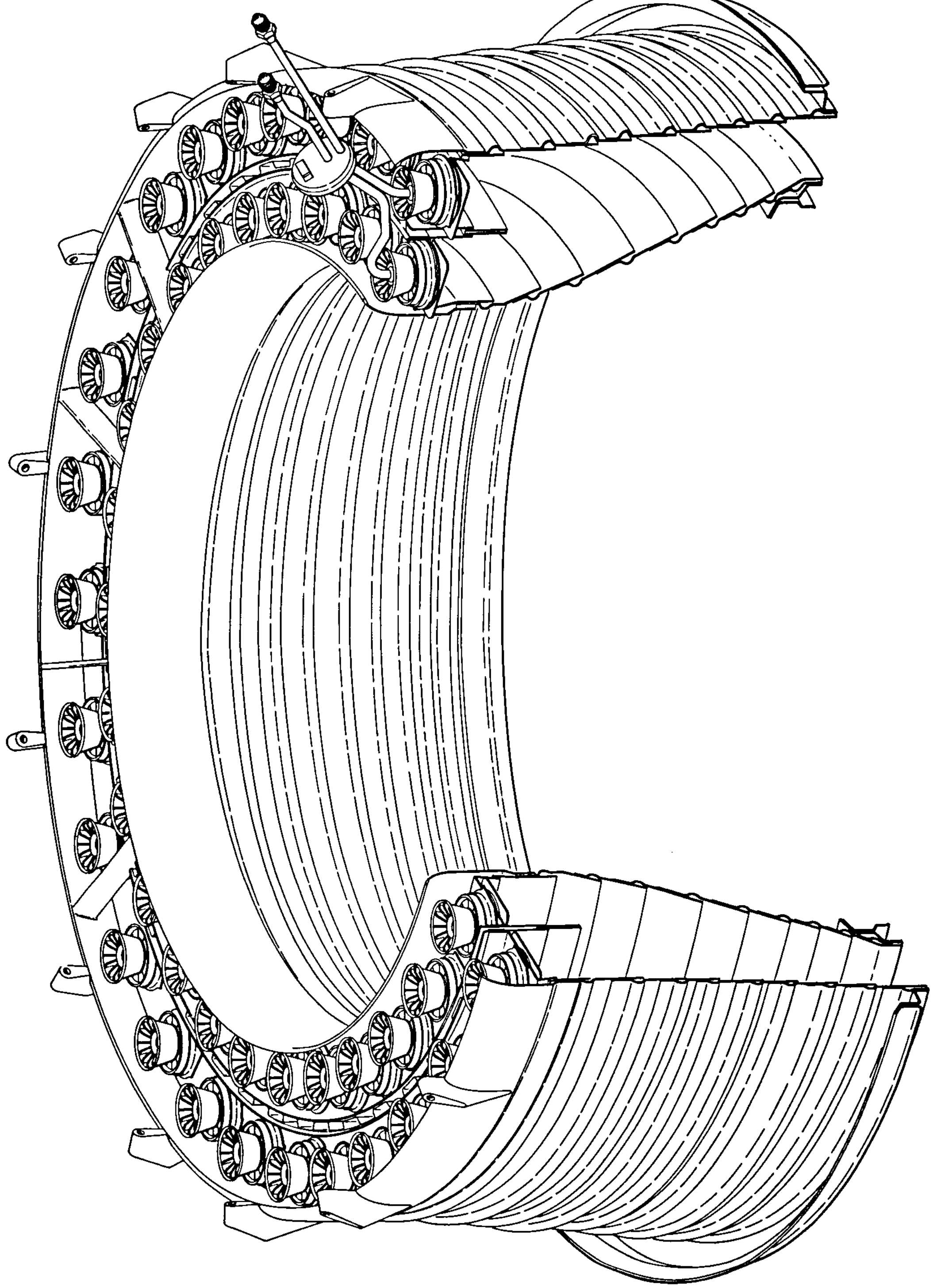

Figure 7. Double Annular Combustor.

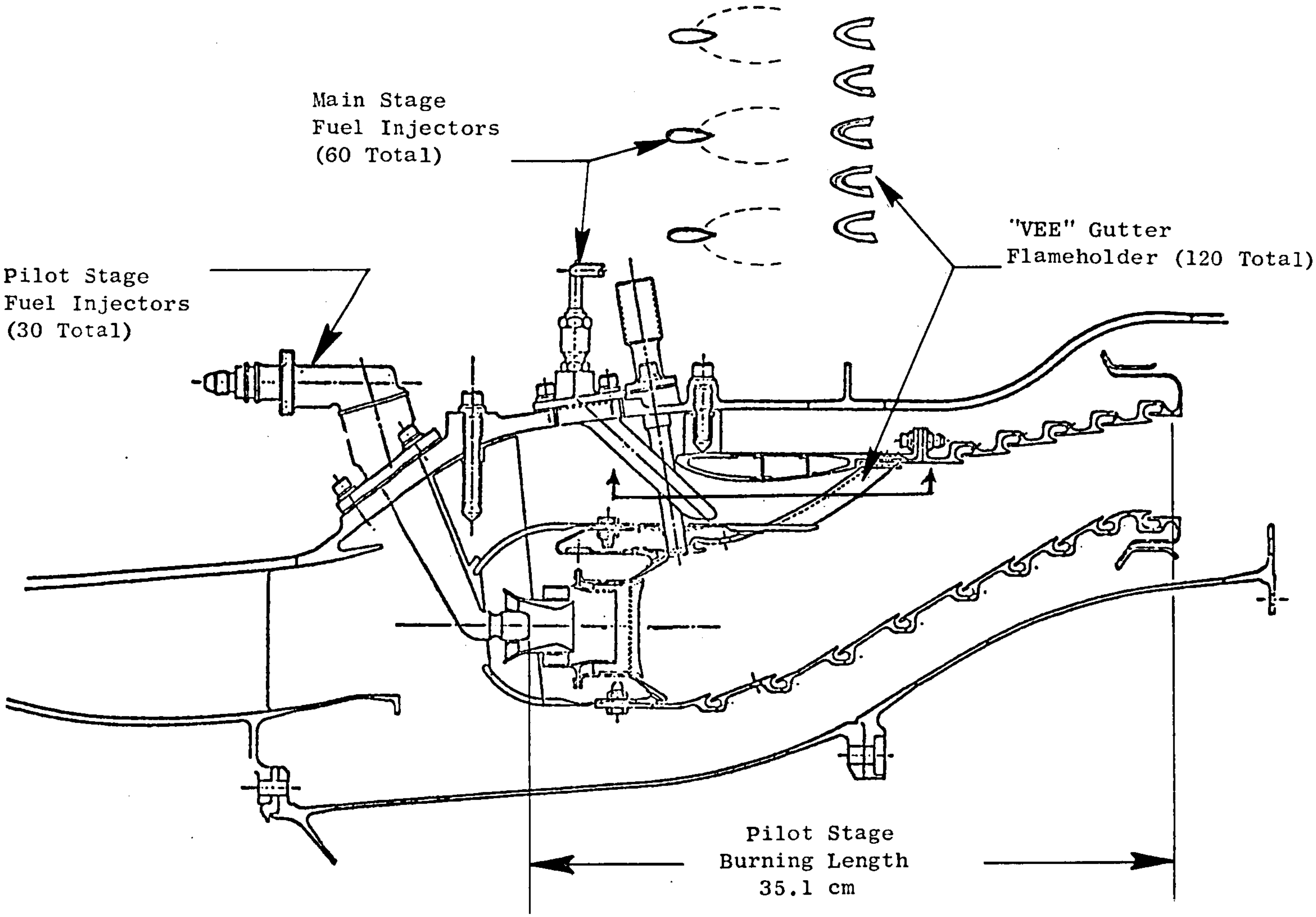

Figure 8. Radial/Axial Staged CF6-50 Combustor Design.

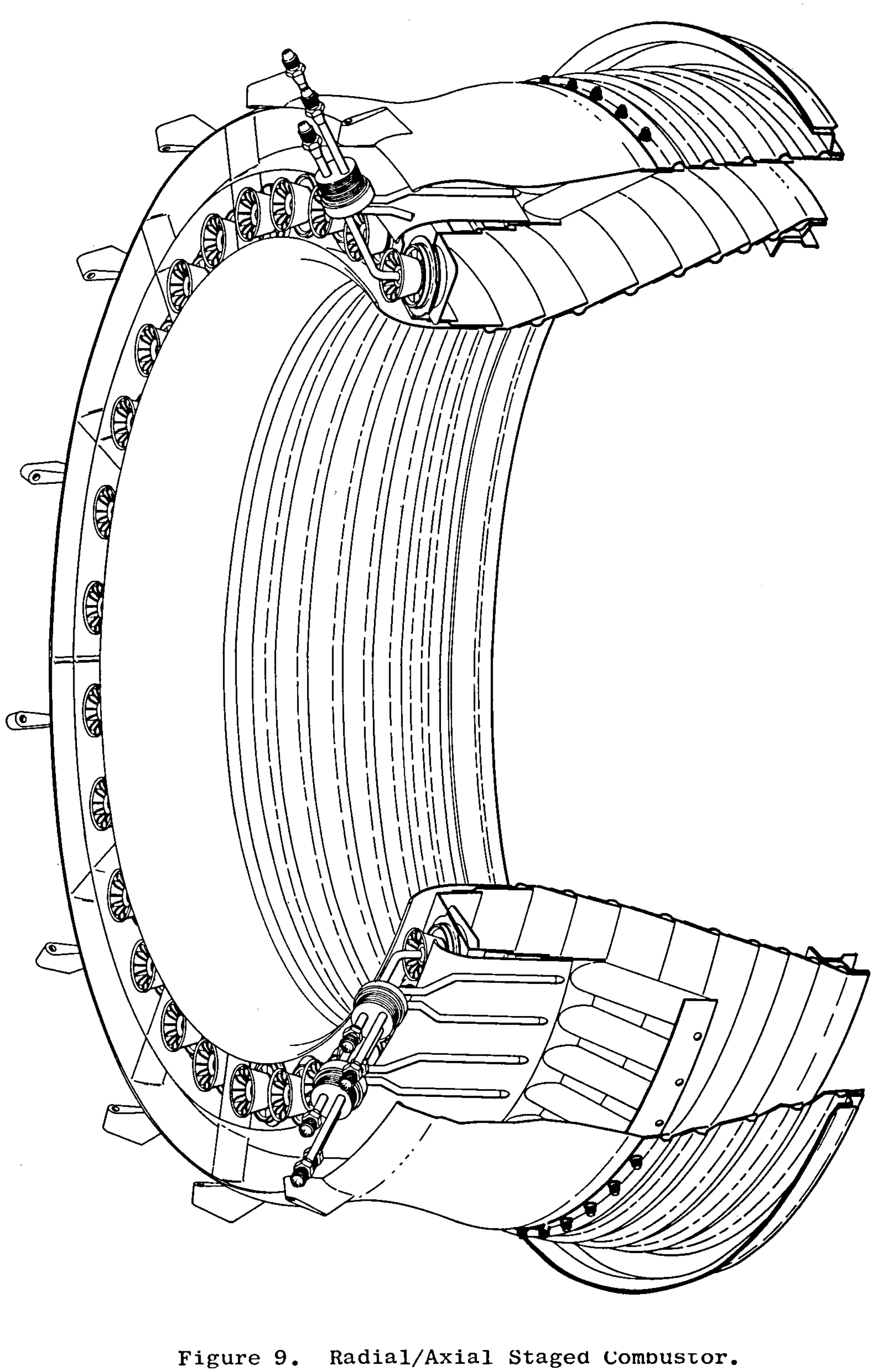

Figure 9. Radial/Axial Staged Combustor.

premixed and prevaporized fuel-air mixture that is supplied by an annular premixing duct upstream of the main stage flameholders. Fuel staging is similar to the double annular design.

The radial/axial staged combustor is similar in several respects to the double annular combustor. However, where the two stages of the double annular combustor are essentially parallel and independent, the two stages of the radial/axial staged combustor are more nearly in series and highly interdependent. The airflow splits and the fuel scheduling between stages of the radial/axial staged combustor are generally similar to those in the double annular combustor. Only the pilot stage, which utilizes 13% of the combustor airflow is fueled from lightoff through ground idle power. With this low airflow, high local fuel-air ratios and low air velocities are maintained in the pilot stage, promoting high combustion efficiency and corresponding low CO and HC emission levels at low power operating conditions. At high power engine operating conditions, a high proportion of the fuel is supplied upstream of the main stage flameholder array where it is premixed with about 50 to 60% of the total combustor airflow. Combustion of this mixture is stabilized by the hot gases exhausting from the pilot stage. Because of the premixing feature of the second stage, leaner mixtures (compared to the double annular combustor) are obtained in the second stage since the fuel is more thoroughly mixed with all of the available second stage airflows. As a result, very low NO_x levels have been achieved with this combustor design.

A variable geometry, premixed, prevaporized combustion system concept for the CF6-50 engine is illustrated in Figure 10. In this design, the fuel and dome airflow are premixed in cylindrical ducts spaced around the dome of the combustor. These premixer ducts are long enough to prevaporize a large proportion of the fuel at high engine power conditions. Variable swirl vanes are concentric with the fuel injectors at the entrance of each of the premixer ducts. At lightoff, idle, and other low engine power conditions, the variable swirl vanes are closed down to provide a rich fuel-air ratio mixture in the dome region. With the resulting high dome pressure drops, final atomization of the fuel is accomplished by a second set of swirler vanes that is concentric

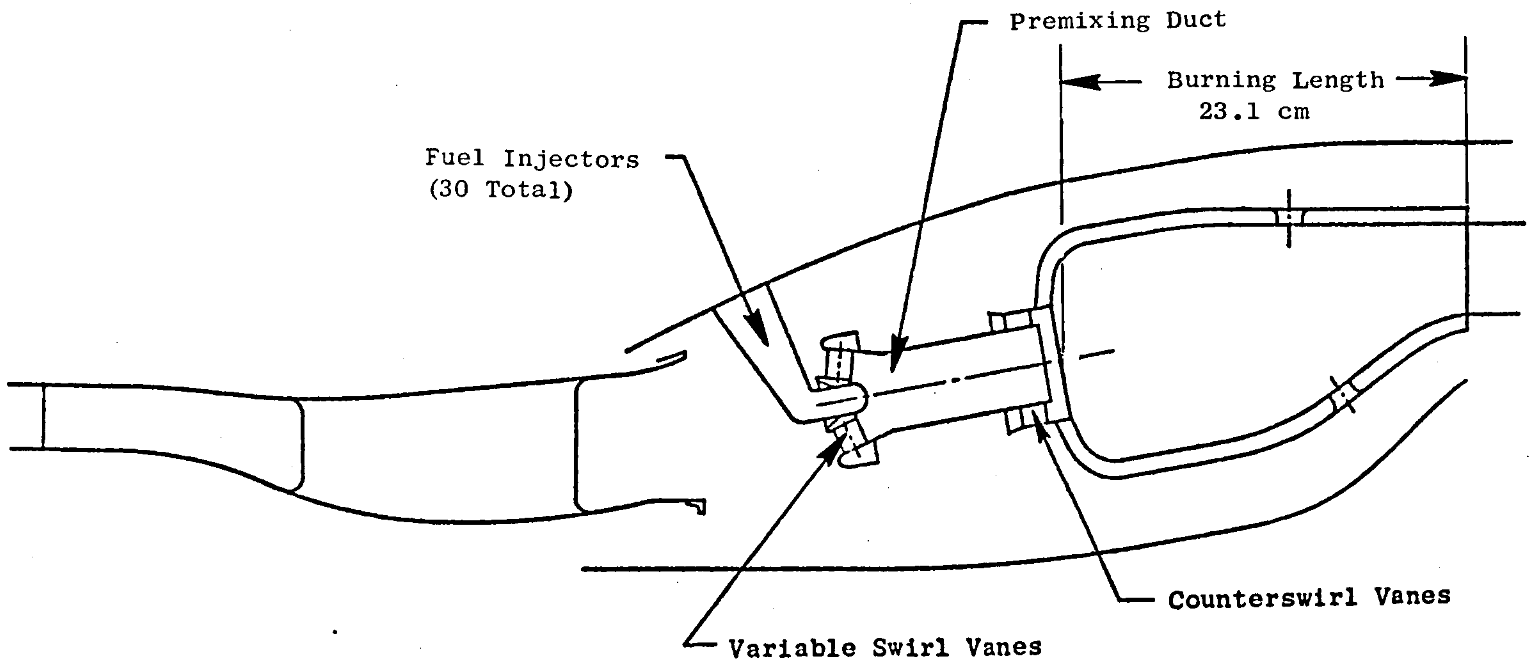

Figure 10. Premixed-Prevaporized CF6-50 Combustor Conceptual Design.

with the premixer ducts at the dome end of the ducts. This fine atomization of the fuel, coupled with the relatively rich mixtures and low dome velocities, is expected to produce low levels of CO and HC emissions at the low engine power operating conditions. As the engine power level is increased, the variable swirl vanes are opened up resulting in leaner fuel-air ratios in the dome of the combustor and higher velocities and reduced residence times in the primary zone. Consequently, at high power engine operating conditions, the NO_x emissions from this combustion system will be very low.

The E^3 version of the baseline single annular combustor concept is illustrated in Figure 11. This single annular concept is based on the most recent General Electric combustor design technology.

An ultra-short single annular combustor concept for the E^3 is illustrated in Figure 12. This high space rate, high velocity concept is designed for very small values of hot gas residence time to reduce NO_x emissions levels at high engine power conditions. However, this concept, which is 3/4 of the length of the baseline design, will require a considerable amount of development effort to meet pattern factor and low power emissions requirements.

An E^3 version of the annular slot combustor concept is illustrated in Figure 13. This combustion design concept is very similar to the CF6-50 annular slot combustor concept and is also expected to eliminate the repetitive hot-cold streaks that limit the liner life and durability of conventional combustion systems.

A double annular combustor concept for the E^3 is illustrated in Figure 14. This concept is similar to the CF6-50 double annular design. The combustion system length is reduced to 29 cm to meet E^3 engine requirements. However, flow velocities are lower in the E^3 concept and the bulk residence times are almost the same as those in the CF6-50 concept.

The E^3 version of the radial/axial concept is illustrated in Figure 15. The operating principles for this design are the same as those for the CF6-50 radial/axial design. However, there are some differences in the premixing

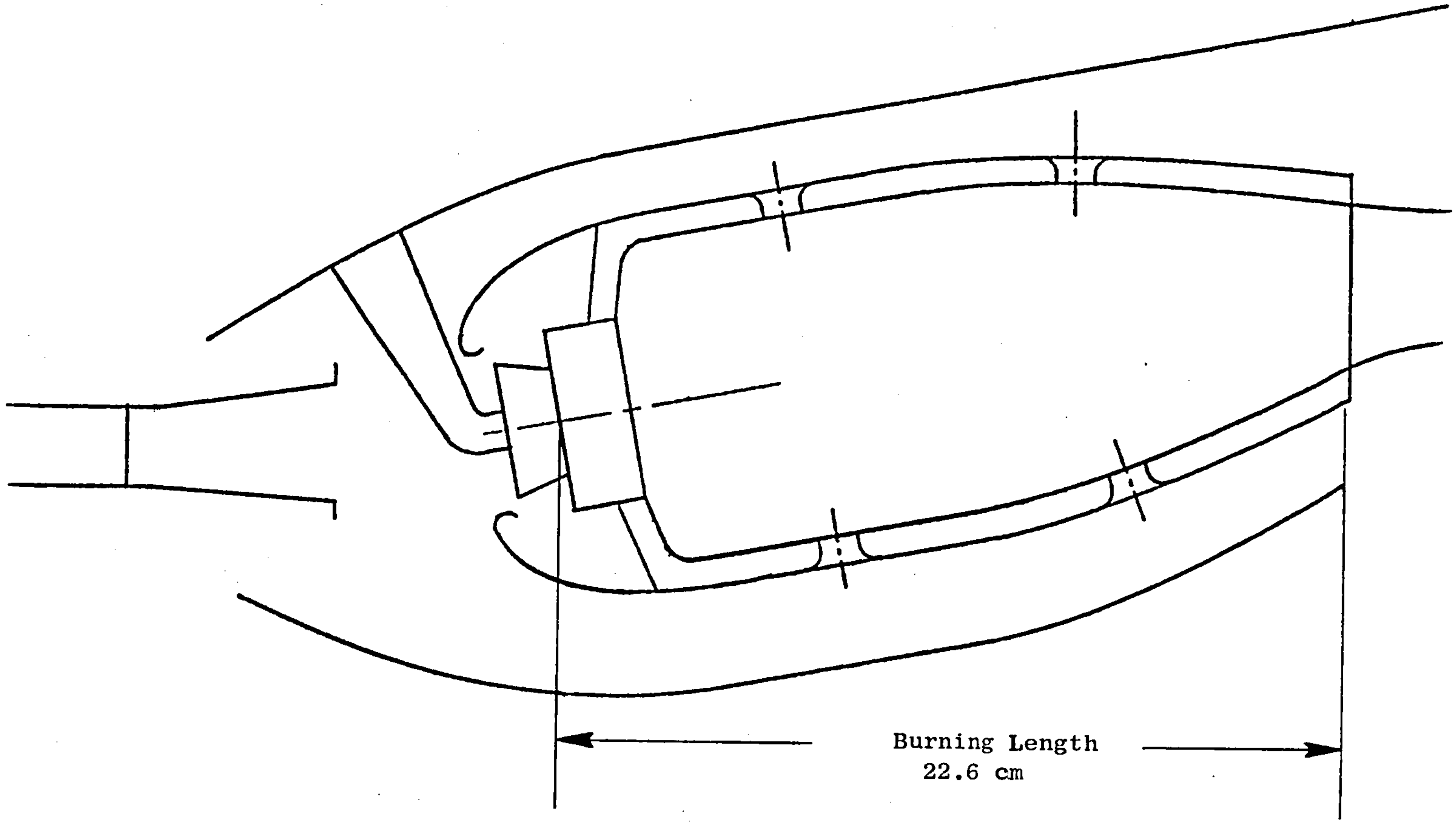

Figure 11. Single Annular E^3 Combustor Conceptual Design.

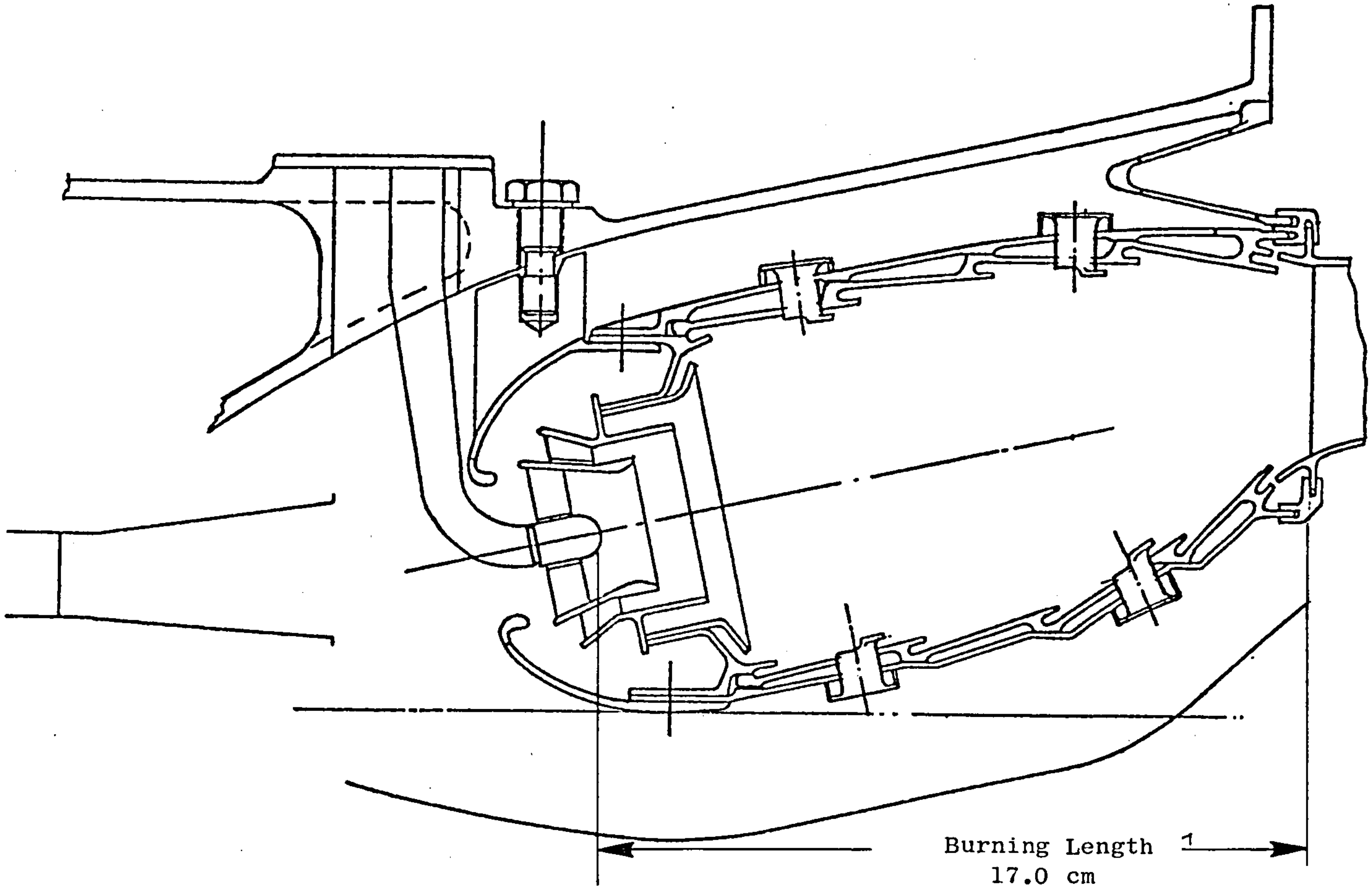

Figure 12. Ultra-Short Single Annular E^3 Combustor Design.

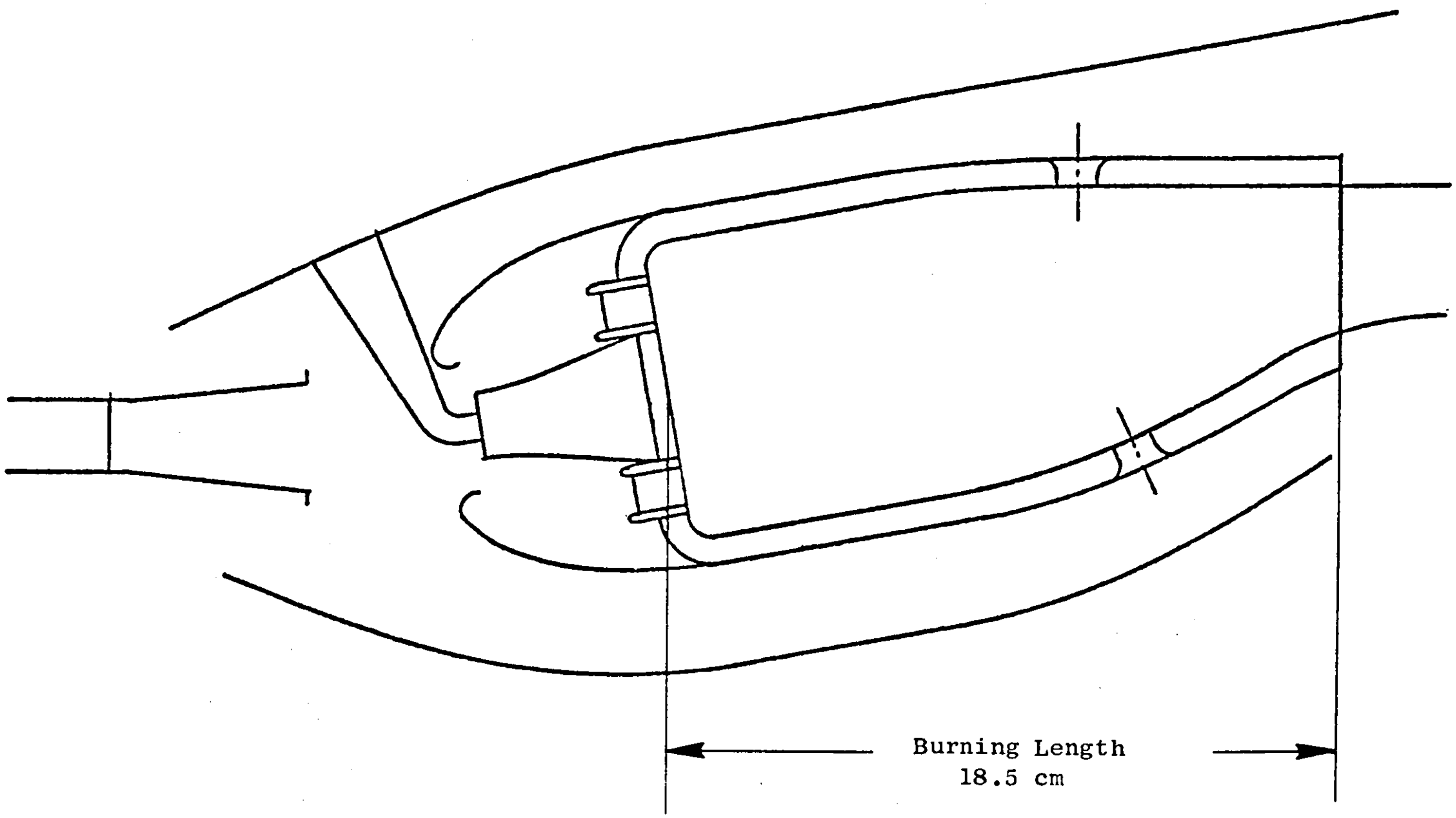

Figure 13. Annular Slot E^3 Combustor Conceptual Design.

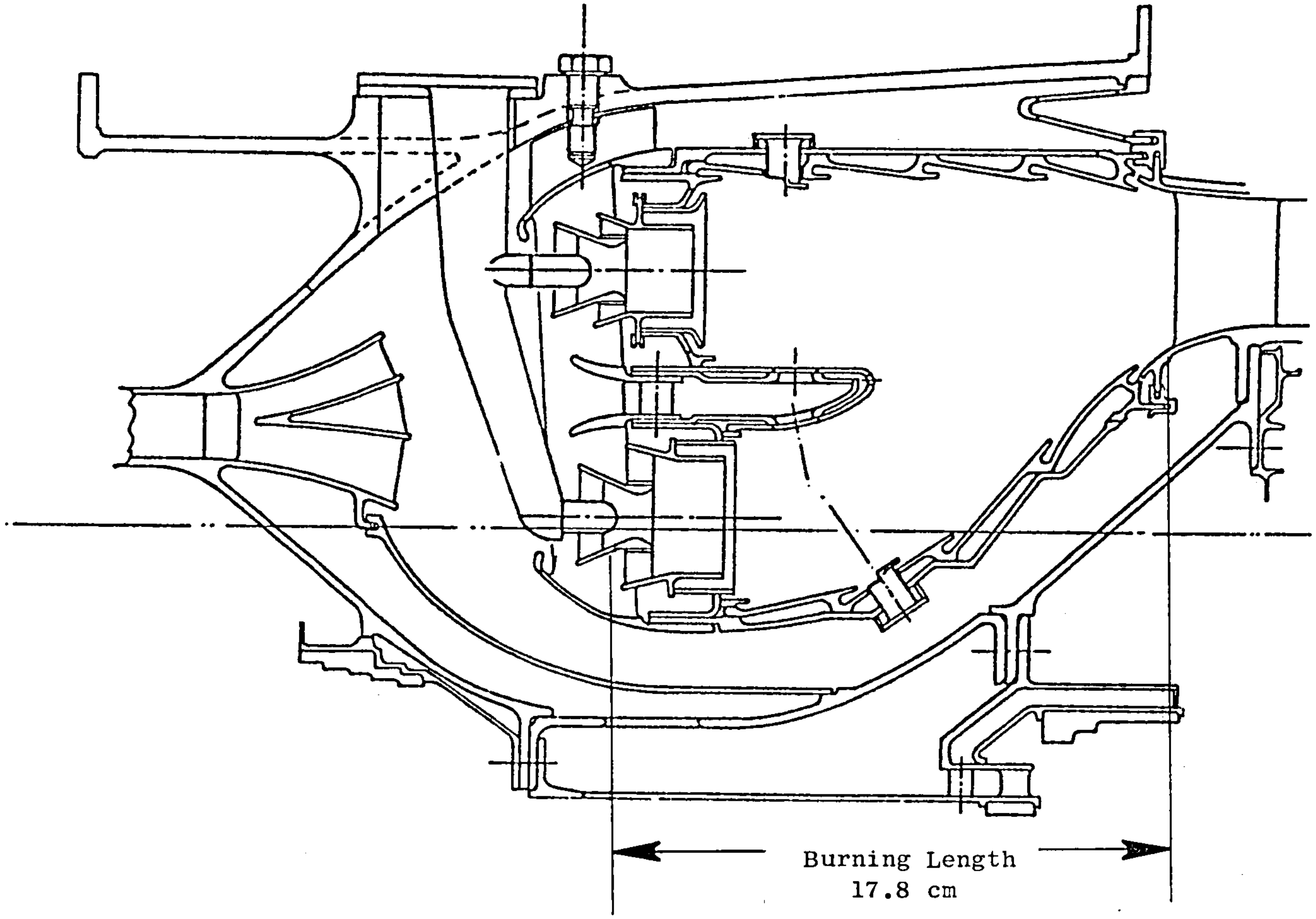

Figure 14. Double Annular E^3 Combustor Design.

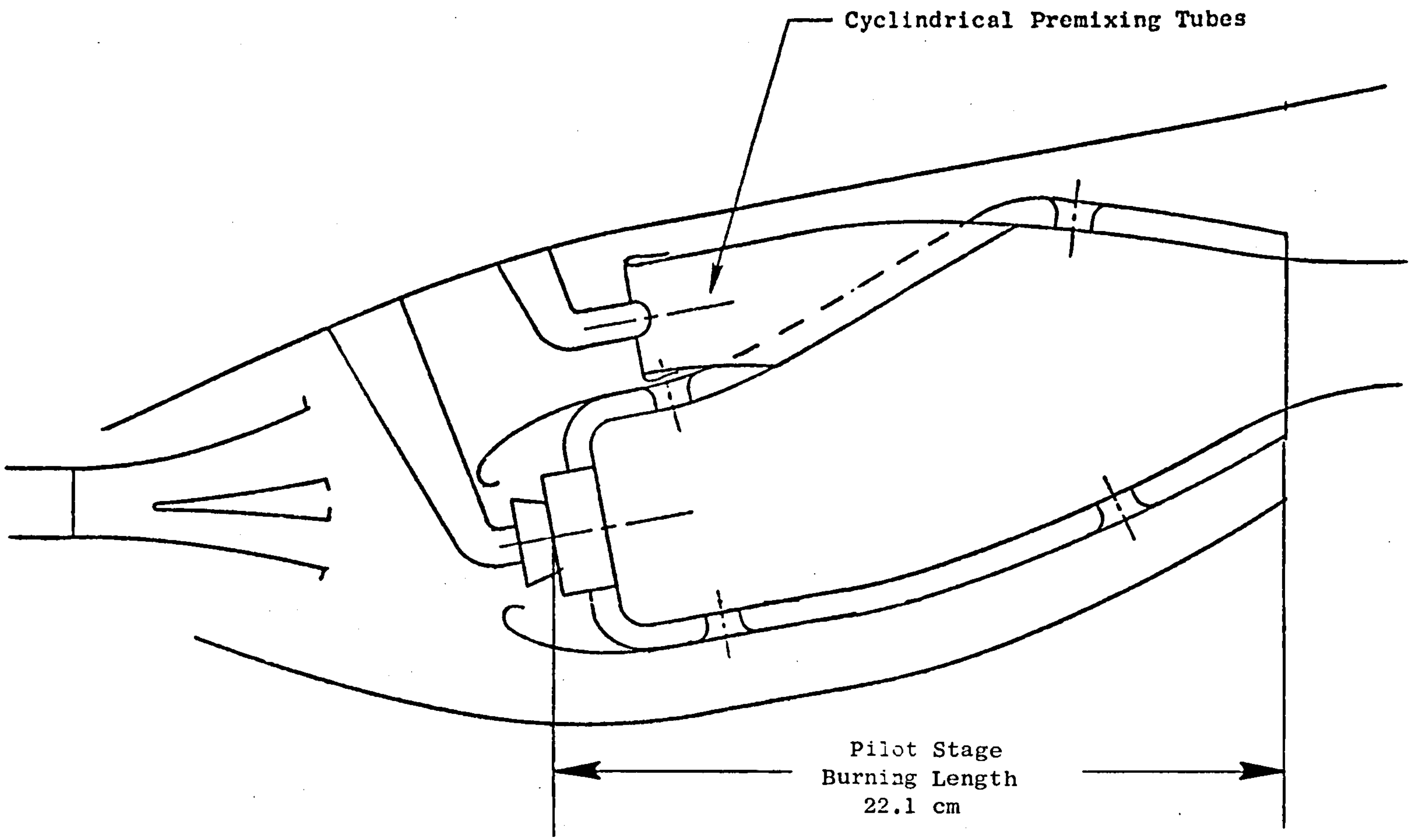

Figure 15. Radial/Axial Staged E^3 Combustor Conceptual Design.

duct arrangement. For the CF6-50 radial/axial design the second stage premixing duct is a high velocity annular passage. For the E^3 design, a parallel row of cylindrical tubes is used for the premixing ducts. These tubes are sized for very high velocity flow to minimize the possibility of autoignition in the premixed region. These tubes transition into narrow rectangular slots that intercept the outer combustor liner wall about midway along the length of the liner.

A premixing, prevaporizing variable geometry combustor concept for the E^3 engine is illustrated in Figure 16. This concept is very similar to the CF6-50 premixing, prevaporizing concept and is expected to have very low emissions levels at all of the engine operating conditions.

The CF6-50 baseline single annular concept has the current production engine combustor liner construction and the CF6-50 double annular and radial/axial concepts have the "rolled ring" liner construction used for the NASA/GE ECCP double annular combustor design. All of the other concepts have an advanced impingement plus film liner construction. This impingement cooled, double wall construction is illustrated in Figure 17.

All of these concepts except the CF6-50 baseline design use counterrotating dome swirlers to provide rapid mixing of the combustor dome air with the fuel spray. A typical counterrotating dome swirler is illustrated in Figure 18.

3.3.3 Design Parameters

Combustion system design parameters for the six CF6-50 and six E^3 combustor designs are presented in Table 5. Several of these parameters are closely interrelated. The combustor length and dome height parameters are selected to provide the best combination of length to dome height ratio, space rate, dome velocity, and bulk residence time. These parameters must fall within acceptable limits for a particular configuration to meet the design requirements of the engine system.

In Table 5 the number of fuel injectors is the total number required for the combustion system. For instance, the radial/axial combustor designed for the CF6-50 engine requires 30 fuel injectors in the pilot dome annulus and 60

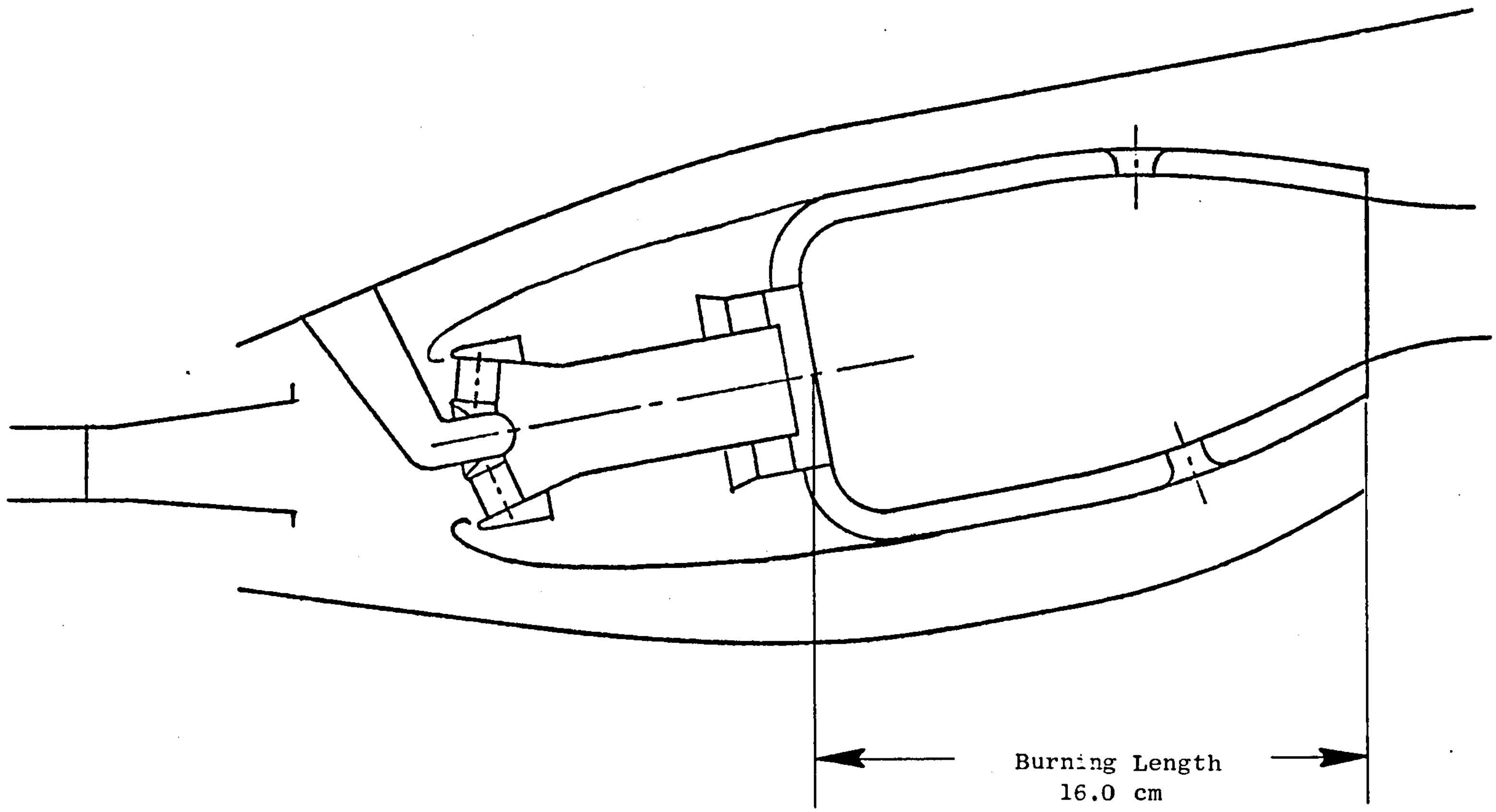

Figure 16. Premixed-Prevaporized E^3 Combustor Conceptual Design.

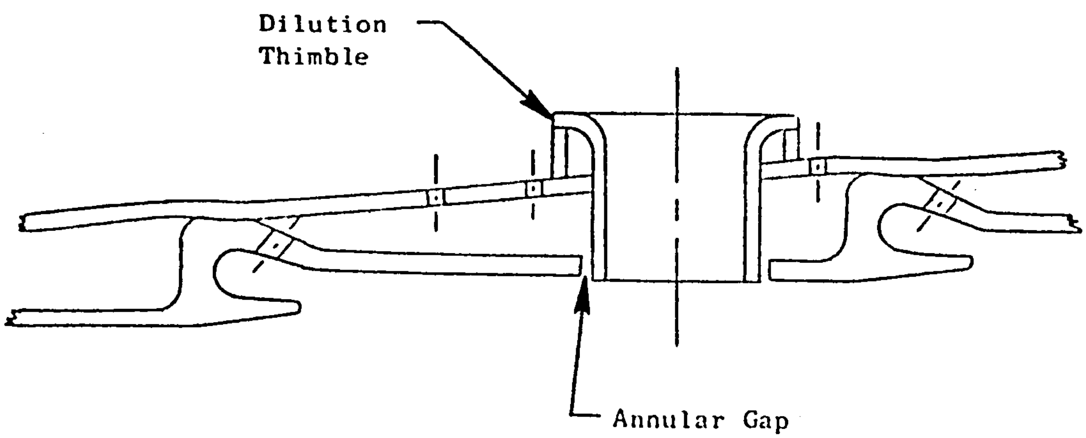

Figure 17. Impingement-Cooled Panel with Double Wall Construction and Dilution Hole.

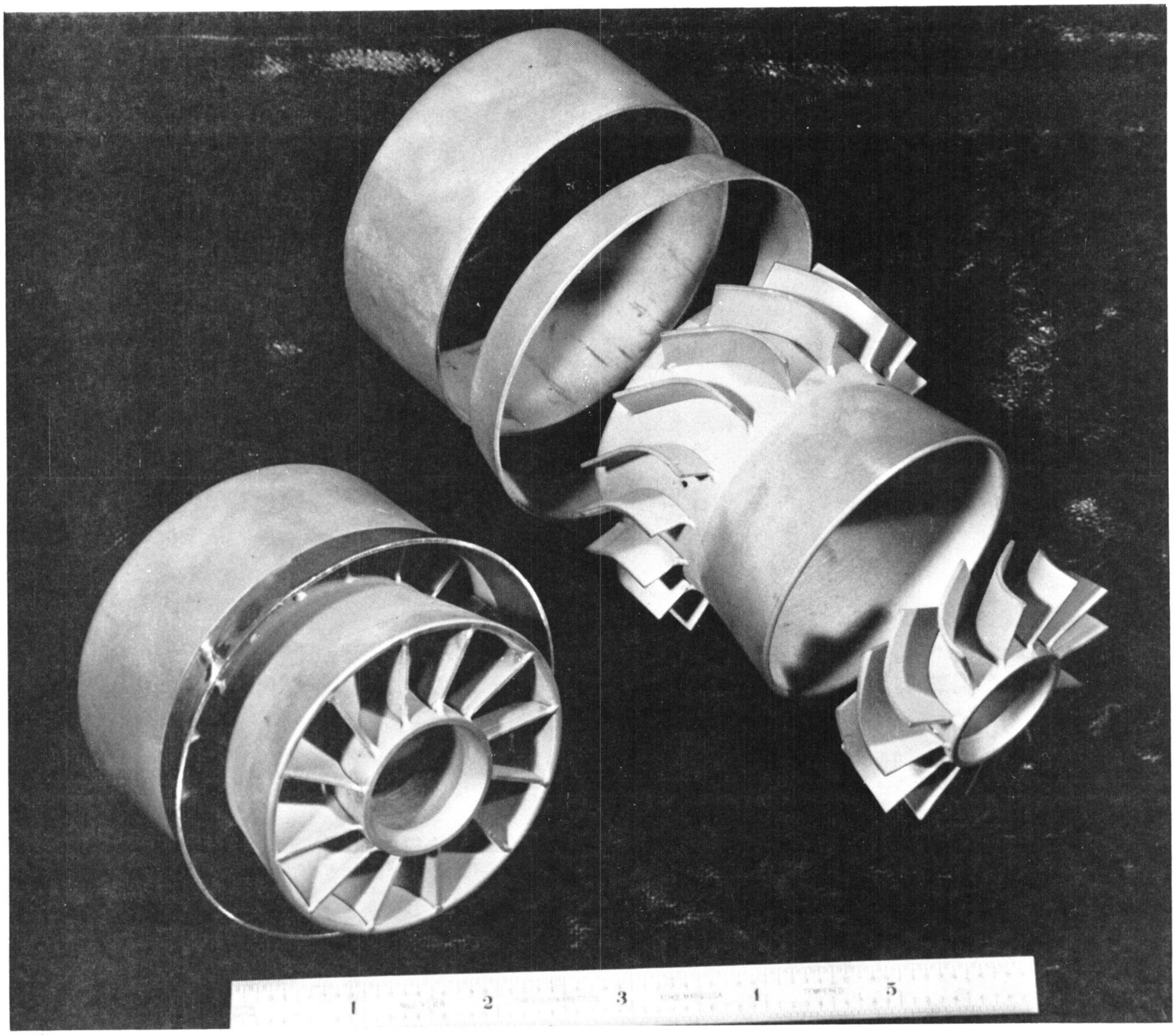

Figure 18. Typical Combustor Dome Swirlers.

Table 5. Combustor Design Parameters for the CF6-50 Engine Cycle.

	Single Annular	Short Single Annular	Annular Slot	Double Annular	Radial Axial	Premixed Prevaporized
OA Length, cm	76.7	76.7	76.7	76.7	76.7	76.7
Burner Length, cm	35.1	25.4	26.7	32.8	35.1	23.1
Dome Height*, cm	11.4	11.4	11.4	6.9	7.4	11.4
Length/Height	3.1	2.2	2.3	4.8	4.9	2.0
No. Fuel Injectors	30	30	30	60	90	30
Length/Injector Space	5.0	3.5	3.7	4.2	5.3	3.1
Ref. Area, cm^2	3697	4310	4245	4245	3774	4335
V_{Ref}, m/sec	26	23	23	23	25	22
$V_{Passage}$, m/sec	52	43	43	46	30	30
V_{Dome}, m/sec	11	8	8	10	12	8
Comb. Volume, m^3	0.058	0.044	0.045	0.055	0.039	0.040
Space Rate, mcal/sec-atm-m^3	14.3	18.8	18.3	15.1	21.3	20.5

Combustor Design Parameters for the E^3 Engine Cycle.

	Single Annular	Short Single Annular	Annular Slot	Double Annular	Radial Axial	Premixed Prevaporized
OA Length, cm	34.3	27.9	33.5	29.2	35.6	35.6
Burner Length, cm	22.6	17.0	18.5	17.8	22.1	16.0
Dome Height*, cm	9.1	7.9	8.1	6.1	6.1	8.1
Length/Height	2.5	2.2	2.3	3.0	3.6	2.0
No. Fuel Injectors	28	28	28	56	84	28
Length/Injector Space	3.5	2.6	2.8	2.4	3.6	2.3
Ref. Area, cm^2	2542	2277	2490	2910	2374	2581
V_{Ref}, m/sec	19	22	20	17	20	19
$V_{Passage}$, m/sec	43	43	43	43	43	43
V_{Dome}, m/sec	8	7	7	7	10	6
Comb. Volume, m^3	0.027	0.018	0.024	0.023	0.024	0.022
Space Rate, mcal/sec-atm-m^3	16.3	25.5	18.3	19.8	18.8	20.8

*Outer dome height for double annular concept.

fuel injectors in the lean stage premixing annulus, all equally spaced around the annulus. The length to fuel injector spacing ratio parameter, in each case, is based on the pilot dome or primary zone fuel injector circumferential spacing.

3.3.4 Flow Distribution

Combustor liner airflow distributions and fuel-air equivalence ratios are presented in Tables 6, 7, 8, 9 and 10 for the six CF6-50 combustor concepts and for the six E^3 combustor concepts. These flows are presented as a percentage of the total combustor airflow. The dome equivalence ratio is the ratio of the dome fuel-air ratio to the stoichiometric fuel-air ratio, which is 0.0676, and the dome flow is the sum of the dome swirler flow and the dome cooling flow.

A detailed panel-by-panel heat transfer analysis of all of the combustor liner configurations was performed to determine the liner cooling flows required for these systems. This analysis was made for Jet A fuel and for the ERBS broad specification fuel. The cooling flows were calculated for each concept to limit maximum liner temperatures. This analysis was based on engine combustion system test data and on component test rig data for dome and liner constructions similar to those analyzed.

In the single annular concepts, higher liner and dome cooling flows are required with the ERBS fuel because the flame radiation levels are higher with this fuel. For these designs, the aft dilution flow is reduced to provide the higher liner cooling flows. This could result in an increased pattern factor for the single annular designs with ERBS fuel since aft dilution is the method employed to reduce pattern factor.

The dome temperatures of the standard CF6-50 single annular design are not life limiting with Jet A fuel; and for the same level of dome cooling flow, the dome temperatures will increase by about 20 K with ERBS fuel, which is still not life limiting. Therefore, for this design, the dome cooling flow was not increased for the ERBS fuel version. For the other concepts, the

Table 6. CF6-50 Single Annular Conceptual Combustor Designs - Airflow Distribution and Dome Equivalence Ratios with Jet A and Broad Specification (ERBS) Fuels.

(Airflow in Percent of W_{comb})

	CF6-50 Single Annular		CF6-50 Short Single Annular		CF6-50 Annular Slot	
Fuel	Jet A	ERBS	Jet A	ERBS	Jet A	ERBS
Swirler Flow	17.0	17.0	13.0	12.0	20.5	20.0
Dome Cooling	14.1	14.1	10.3	11.3	3.5	4.0
Forward Dilution	16.8	15.7	26.0	25.0	26.0	26.0
Outer Aft Dilution	7.0	6.0	13.2	12.5	11.9	10.9
Inner Aft Dilution	12.3	11.3	15.3	14.6	13.9	12.6
Outer Liner Cooling	17.0	18.5	12.3	13.7	13.4	14.7
Inner Liner Cooling	15.8	17.4	9.9	10.9	10.8	11.8
Total Flow	100.0	100.0	100.0	100.0	100.0	100.0
* ϕ_{Dome} at Idle	0.45	0.45	0.60	0.60	0.59	0.59
* ϕ_{Dome} at Takeoff	1.11	1.11	1.48	1.48	1.43	1.43

* ϕ_{Dome} - Fuel-Air Equivalence Ratio in the Combustor Dome Region

Table 7. E^3 Single Annular Conceptual Combustor Designs - Airflow Distribution and Dome Equivalence Ratios with Jet A and Broad Specification (ERBS) Fuels.

(Airflow in Percent of W_{comb})

Fuel	E^3 Single Annular Jet A	E^3 Single Annular ERBS	E^3 Short Single Annular Jet A	E^3 Short Single Annular ERBS	E^3 Annular Slot Jet A	E^3 Annular Slot ERBS
Swirler Flow	19.0	18.0	13.1	12.1	20.5	20.0
Dome Cooling	11.9	12.9	11.9	12.9	3.5	4.0
Forward Dilution	14.4	14.4	26.0	26.0	26.0	26.0
Outer Aft Dilution	15.2	13.5	14.3	13.0	13.0	11.3
Inner Aft Dilution	17.3	16.0	16.0	14.9	15.1	13.5
Outer Liner Cooling	12.5	14.2	10.1	11.4	12.2	14.2
Inner Liner Cooling	9.7	11.0	8.6	9.7	9.7	11.0
Total Flow	100.0	100.0	100.0	100.0	100.0	100.0
$^*\phi_{Dome}$ at Idle	0.55	0.55	0.68	0.68	0.71	0.71
$^*\phi_{Dome}$ at Takeoff	1.13	1.13	1.40	1.40	1.46	1.46

$^*\phi_{Dome}$ - Fuel-Air Equivalence Ratio in the Combustor Dome Region

Table 8. Double Annular Conceptual Combustor Designs: Airflow Distributions and Dome Equivalence Ratios with Jet A and ERBS Fuel.

	Airflow in Percent of W_{comb}	
	CF6-50 Double Annular	E^3 Double Annular
Outer Swirler Flow	13.3	13.3
Inner Swirler Flow	29.0	34.2
Outer Dome Cooling	7.2	7.7
Inner Dome Cooling	5.5	4.5
Outer Liner Dilution	4.3	4.5
Centerbody Dilution	0	8.0
Inner Liner Dilution	11.6	6.5
Outer Liner Cooling	12.0	8.3
Centerbody Cooling	4.8	3.5
Inner Liner Cooling	12.3	9.5
Total Combustor Flow	100.0	100.0
** ϕ_{Dome} at Takeoff	0.62	0.59
** ϕ_{Dome} at Idle*	0.72	0.81

*Outer Annulus Only

** ϕ_{Dome} – Fuel-Air Equivalence Ratio in the Combustor Dome Region

Table 9. Radial/Axial Conceptual Combustor Designs: Airflow Distributions and Dome Equivalence Ratios with Jet A and ERBS Fuel.

	Airflow in Percent of W_{comb}	
	CF6-50 Double Annular	E^3 Double Annular
Main Stage Airflow	50.0	50.0
Pilot Stage Swirler Flow	12.2	16.9
Dome Cooling	11.1	7.7
Pilot Stage Dilution	4.5	4.0
Outer Aft Dilution	1.2	1.0
Inner Aft Dilution	2.7	3.0
Outer Liner Cooling	8.0	7.9
Inner Liner Cooling	10.3	9.5
Total Combustor Flow	100.0	100.0
$^{**}\phi_{PM}$ at Takeoff*	0.48	0.49
$^{**}\phi_{Pilot}$ at Takeoff*	0.44	0.43
$^{**}\phi_{Pilot}$ at Idle	0.60	0.69

*70/39 Fuel Flow Split at Takeoff.

$^{**}\phi_{Dome}$ - Fuel-Air Equivalence Ratio in the Combustor Dome Region

Table 10. Premixed-Prevaporized Conceptual Combustor Designs: Airflow Distributions and Dome Equivalence Ratios with Jet A and ERBS Fuel.

	CF6-50 Variable Geometry		E^3 Variable Geometry	
	Idle	Takeoff	Idle	Takeoff
Premixer Airflow	5.0	50.2	4.0	50.9
Reverse Swirler Flow	6.7	3.5	7.8	4.0
Dome Cooling	11.4	6.0	11.7	6.0
Forward Dilution	0	0	0	0
Outer Aft Dilution	16.8	8.8	17.8	9.1
Inner Aft Dilution	20.6	10.8	22.1	11.3
Outer Liner Cooling	21.9	11.5	19.8	10.1
Inner Liner Cooling	17.6	9.2	16.8	8.6
Total Combustor Flow	100.0	100.0	100.0	100.0
$^*\phi_{Dome}$	0.61	0.58	0.72	0.57

$^*\phi_{Dome}$ - Fuel-Air Equivalence Ratio in the Combustor Dome Region swirler flow is reduced by the same amount that the dome cooling flow is increased for the ERBS fuel. This change does not affect the dome equivalence ratio, but the reduced swirler flow will result in a small increase in emissions.

Dome airflows which include swirler flow plus dome cooling flow for the production version of the CF6-50 single annular design concept and for the baseline E^3 single annular design concept are based on standard design practice. These combustors will have relatively high NO_x emission levels due to their high dome equivalence ratios at takeoff conditions. Emissions at idle conditions for these concepts will be controlled by "sector burning" techniques. With these relatively lean burning designs, smoke emissions will be very low.

The CF6-50 and E^3 short single annular and annular slot design concepts have relatively low dome flows and, consequently, high dome equivalence ratios at takeoff conditions. These rich mixtures in the dome regions will result in lower values for NO_x at takeoff conditions than the production combustors. Relatively high values for airflow through the forward dilution holes provide a "quick quench" of the rich dome mixtures down to an equivalence ratio of about 0.7 where the NO_x generation is also very low. This quick quench design feature, combined with the short length and low residence times for the short single annular and annular slot design concepts, will result in relatively low NO_x emissions for these designs. However, the quick quench design feature could increase CO and HC emissions at idle conditions. This tendency is reduced somewhat by the high values for dome equivalence ratios at idle conditions, and considerable reductions in idle emissions can be achieved by careful control of the dome cooling flow and the first liner panel film cooling flow.

At high engine power conditions the double annular, radial/axial, and premixed, prevaporized concepts (Concepts 4, 5, and 6) operate with very lean equivalence ratios in the dome regions to achieve low NO_x emissions levels at these conditions. For these lean dome designs, combustion system test results (Reference 4) indicate that flame radiation levels with ERBS fuel are nearly the same as those with Jet A fuel. Consequently, the liner cooling and dome cooling flows have not been increased with the ERBS fuel. The same flow distributions are used for both fuels with these lean dome concepts.

As shown in Table 8, the flow distribution for the E^3 double annular design concept is similar to that for the CF6-50 double annular design. However, the E^3 design has centerbody dilution flow, which was not possible with the CF6-50 design because of combustor casing size restrictions. Centerbody dilution flow in the E^3 design will improve the dilution flow mixing in the combustor dome regions, resulting in reduced emissions and reduced combustor exit pattern factors. At high power engine operating conditions, both the outer and inner stages of the double annular combustors operate with low equivalence ratios, which results in low NO_x emissions at these conditions. At idle conditions, the outer pilot stage is operated with relatively high dome equivalence ratios, resulting in low CO and HC emissions at these low power conditions.

Main stage airflows and fuel flows for the CF6-50 and E^3 radial/axial design concepts, as presented in Table 9, were selected to provide very lean equivalence ratios in the premixing duct. These lean mixtures will result in very low NO_x emissions levels at the high power engine operating conditions. The CF6-50 pilot dome equivalence ratio at idle conditions is less than that of the E^3 because the idle fuel-air ratio is lower for the CF6-50 engine cycle.

Table 10 shows the airflow distributions and dome equivalence ratios at idle and at takeoff conditions for the CF6-50 and E^3 premixed, prevaporized, variable geometry combustor concepts. Airflow distributions for the CF6-50 and E^3 versions of this design are very similar. At high power engine operating conditions, the variable premixer inlet swirler vanes are opened up. This results in high dome airflow and accompanying low NO_x emissions. At low power engine operating conditions, the swirler vanes are closed down to increase the dome equivalence ratios which reduce the dome velocities and result in low CO and HC emissions. The dome equivalence ratios remain relatively constant throughout the engine operating range. At idle conditions with the vanes closed down, the combustor effective open area is reduced and the percent pressure loss of the combustor is increased. At low power conditions, this increase in combustor pressure loss will have very little effect on the operating characteristics of the engine and will probably have a beneficial effect on combustion system performance.

3.3.5 Fuel Injection Systems

Two basically different fuel injector types are used for the CF6-50 and E^3 conceptual combustion systems: high pressure and low pressure injectors. The high pressure simplex and dual orifice spray atomizing fuel nozzles have been used for many years in gas turbine combustion systems. A typical high pressure dual orifice fuel nozzle flow characteristic curve is presented in Figure 19. For the combustor concepts that use high pressure fuel injection systems, a dual orifice system is usually required for single annular designs and for the pilot stage of two stage designs because the ratio of maximum fuel flow to minimum fuel flow is too large to achieve the desired degree of atomization at light-off conditions with simplex injectors. However, simplex injectors may be used in the second stage of two stage concepts. Two stage combustion systems that use high pressure simplex fuel injectors in the main stage must use an injector flow characteristic similar to that presented in Figure 20. More recently, low pressure injectors have been developed for systems that use premixing ducts or air blast atomizers. A flow characteristic curve for a typical low pressure injector is also presented in Figure 20. Airflow energy is used to achieve a high degree of fuel atomization in the low pressure fuel injection systems.

The fuel injector types and numbers required for the CF6-50 and E^3 concepts are presented in Table 11. To achieve the very fine atomization required in the premixing duct of the No. 6 concept, high pressure dual orifice atomizer with air assist may be needed. Air assist atomization results in very small droplets that evaporate quickly. However, this technique requires an external air compressor to supply atomizing air at a pressure level above the engine compressor exit pressure. The annular slot concept (No. 3) has low pressure injectors that simply dump the fuel into the inlets of the premixer ducts. The fuel injection technique for this concept is not very

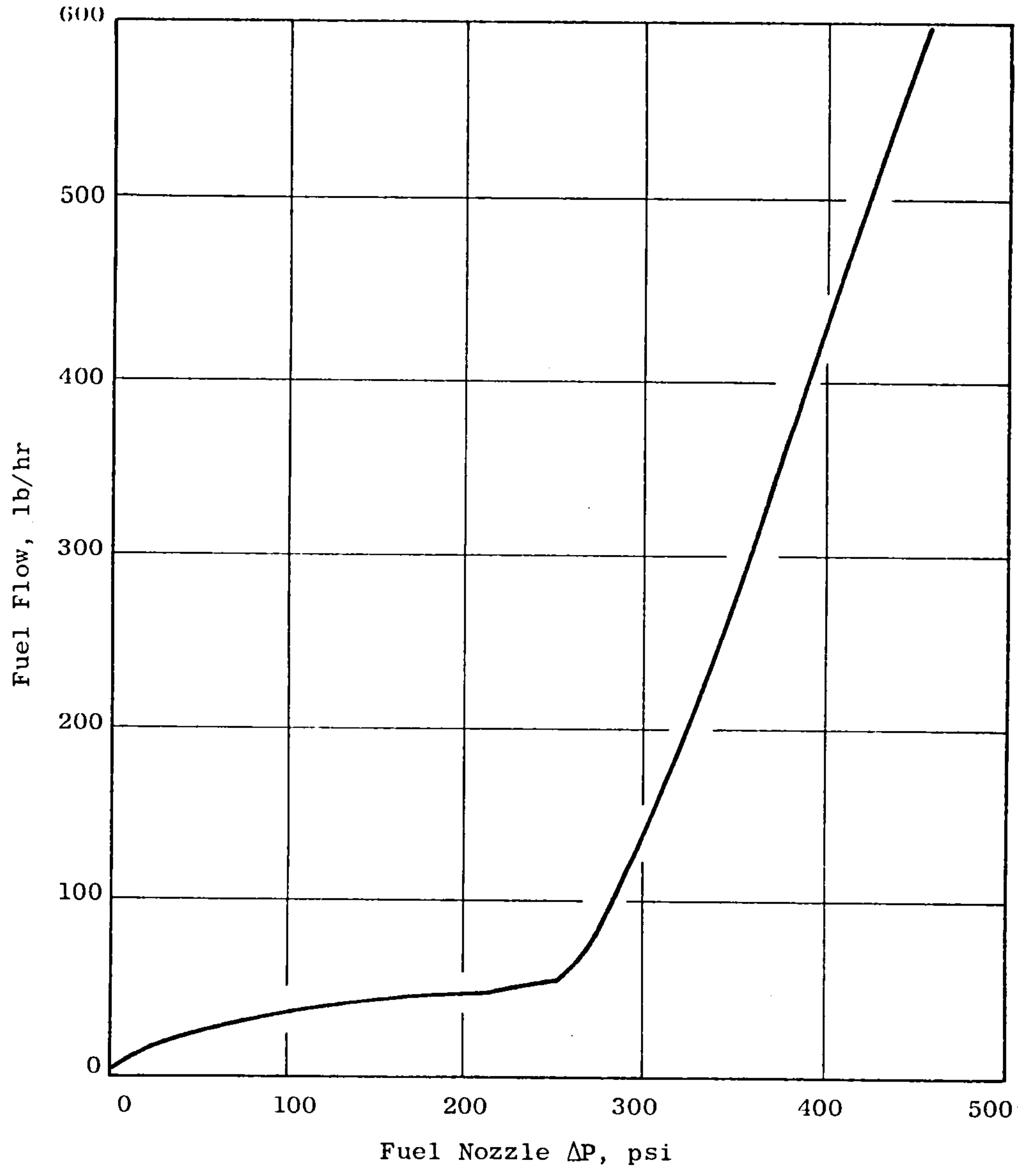

Figure 19. Typical Dual Orifice Fuel Nozzle Flow Characteristics.

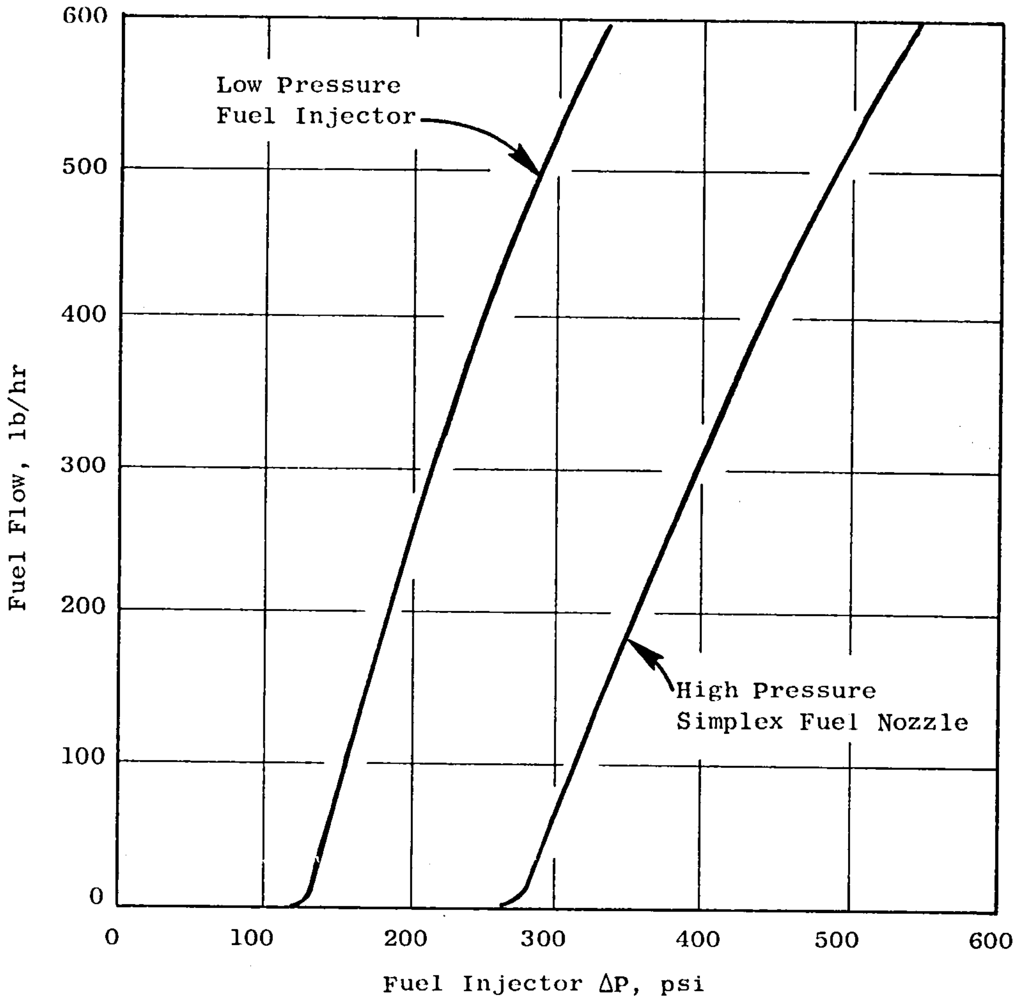

Figure 20. Typical Fuel Injector Flow Characteristics.

Table 11. Conceptual Combustor Designs - Fuel Injector Type and Operating Characteristics.

	Baseline Single Annular	Short Single Annular	Variable Geometry LPP	Annular Slot	Double Annular		Radial/Axial	
					Main Stage	Pilot Stage	Main Stage	Pilot Stage
CF6-50 Concepts:								
Injector Type	30	30	30	30	30	30	60	30
Injector Type	Dual Orifice	Dual Orifice	Dual Orifice with Air Assist	Low Pressure	Simplex	Dual Orifice	Low Pressure	Dual Orifice
E^3 Concepts:								
Number of Fuel Injectors	28	28	28	28	28	28	56	28
Injector Type	Dual Orifice	Dual Orifice	Dual Orifice with Air Assist	Low Pressure	Simplex	Dual Orifice	Low Pressure	Dual Orifice

critical. The piloted radial/axial concept (No. 5) has close-coupled low pressure main stage fuel injectors. These injectors introduce the fuel through small holes that are sized and spaced to provide a relatively uniform distribution of the fuel in the premixing ducts. The remaining three concepts (Nos. 1, 2, and 4) use conventional high pressure dual orifice or simplex fuel injectors.

CF6-50 engine fuel flow schedules for the two stage double annular and radial/axial concepts (Nos. 4 and 5) are presented in Figure 21. As the engine thrust level increases above the 35% power condition, the main stage fuel is introduced and the pilot stage fuel flow is sharply decreased to maintain a uniform increase in total fuel flow to the combustion system. Fuel flow schedules for the E^3 two-stage conceptual designs would be the same as those of Figure 21, but scaled down to the E^3 engine fuel flows.

All of the fuel injection system characteristics would be the same with both Jet A and ERBS fuel. However, test results show that the ERBS fuel will have much smaller autoignition delay times. This presents a critical problem for the premixing concepts. The autoignition delay time is the residence time required for a fuel-air mixure at a particular temperature and pressure level to initiate reaction, as indicated by a small temperature rise. If a significant amount of reaction occurs in a premixing duct upstream of the combustor inlet station, the combustor may be severely damaged. Experimental results for autoignition delay times (from Reference 15) for JP-4 fuel, which is similar to Jet A, and for No. 2 fuel oil, which is similar to ERBS, are presented in Figure 22. Using these curves and assuming hot day, sea level takeoff conditions, the predicted autoignition delay times, corrected for the E^3 engine combustor inlet pressure level, is about 2.1 milliseconds for JP-4 fuel and about 0.70 millisecond for No. 2 fuel oil For a premixing duct velocity of 100 meters/sec, which is rather high, and using a 2-to-1 safety margin, the maximum premixing length would be 10.5 cm (4.1 in.) for Jet A fuel and only 3.5 cm (1.4 in.) for ERBS fuel.

It would be feasible to accomplish the uniform dispersion and partial evaporation of the fuel within a length of 10 cm, but to do this within a length of only 3.5 cm would be very difficult. From this analysis, the use

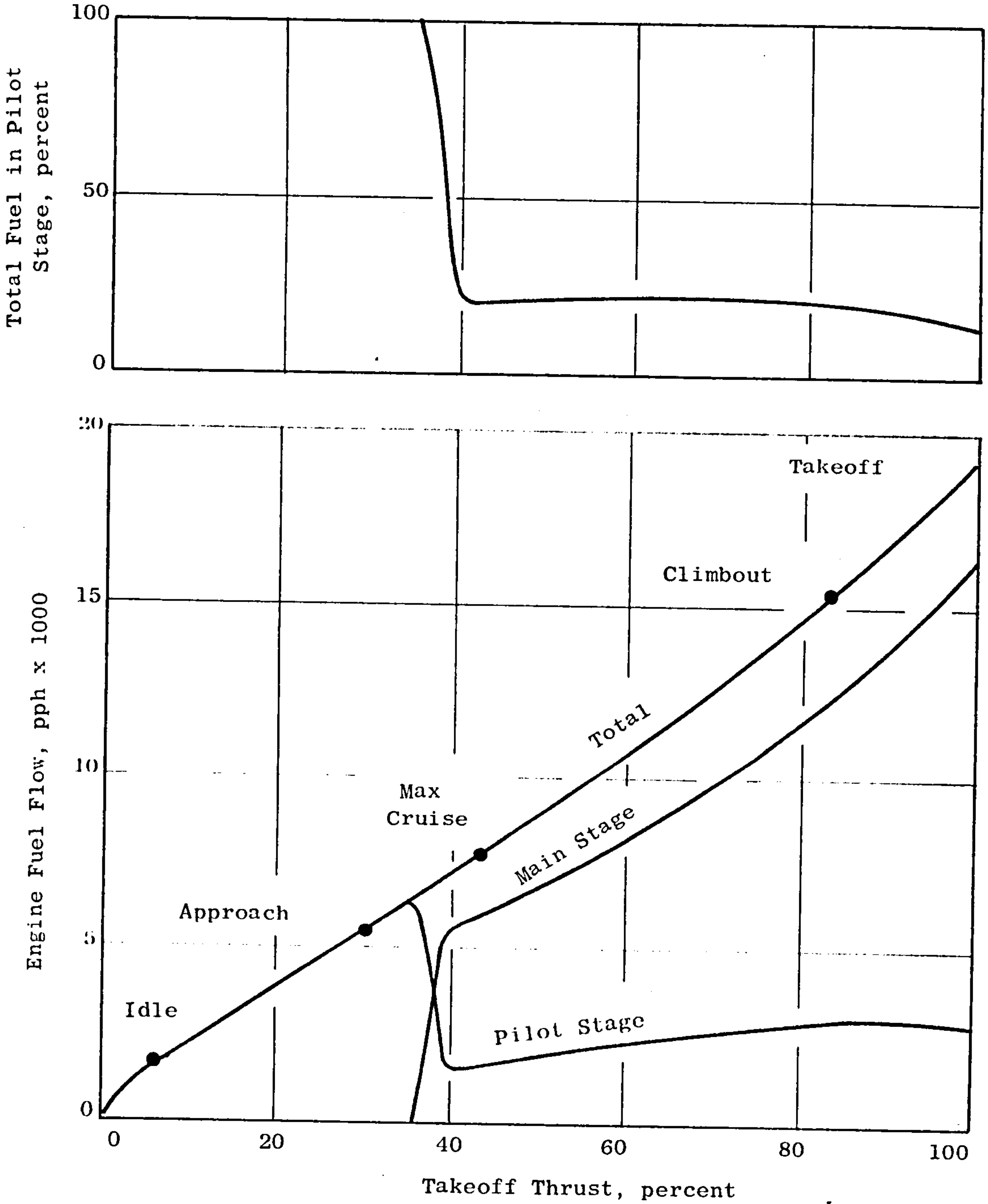

Figure 21. Preliminary CF6-50 Fuel Flow Schedule with a Two-stage Combustion System.

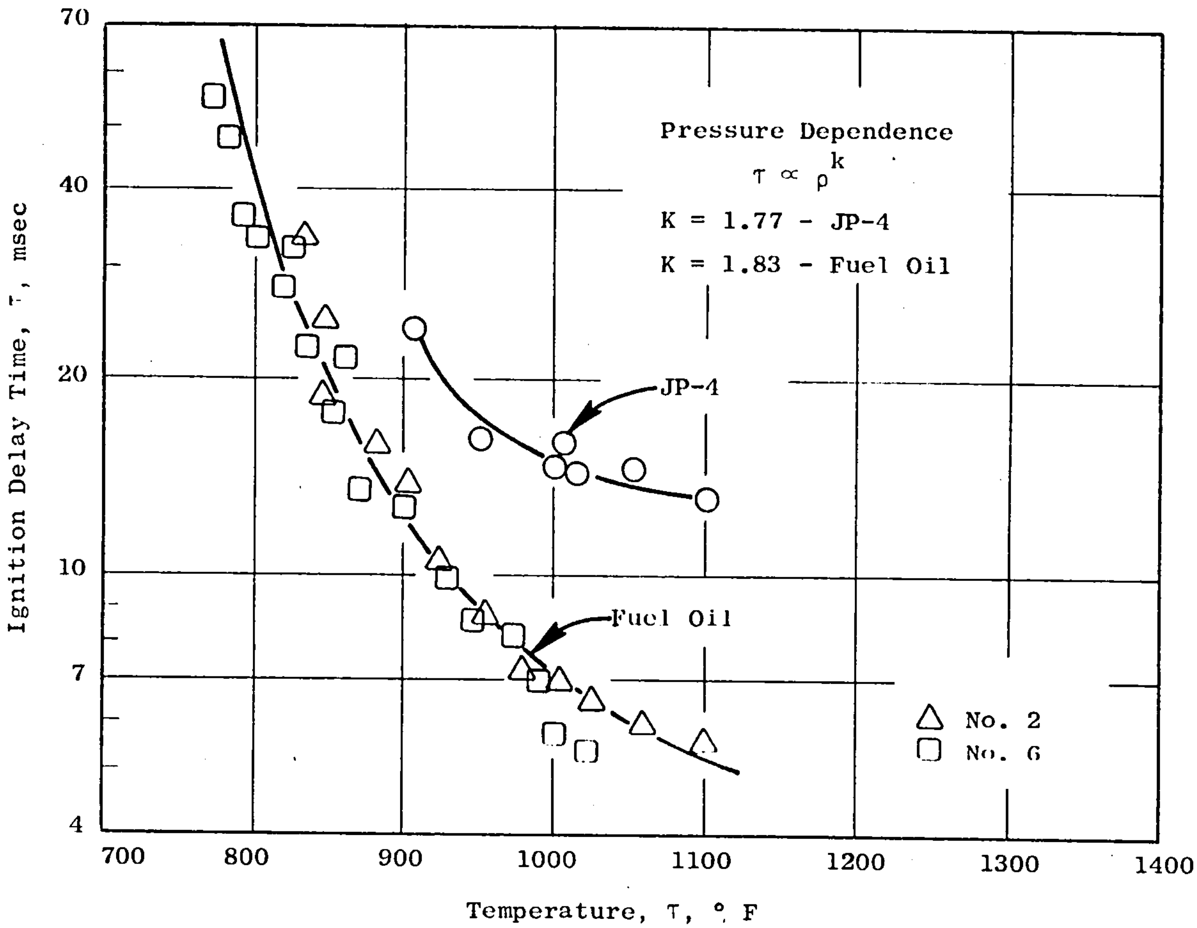

Figure 22. Ignition Delay Times for JP-4, No. 2 Fuel Oil, and No. 6 Fuel Oil in Air.

of ERBS fuel in a premixed prevaporized combustion system does not appear to be practical for an engine that has a design pressure ratio of 30 atmospheres or higher.

The maximum allowable fuel temperature at the inlet to the engine fuel manifold with Jet A fuel is 408 K. If the fuel temperature should increase to 422 K, gum formation and seizure of the fuel metering valves could occur within about 200 hours of engine operation. The maximum allowable fuel temperature may be lower than 408 K with the ERBS broad specification fuel. Studies are currently underway to determine the temperature stability characteristics of ERBS fuel.

3.4 PREDICTED PERFORMANCE

Broad specification fuels are expected to have very little effect on overall combustor performance. For the test conditions reported in Reference 4, no discernible effects of fuel type on combustor pressure loss or combustor exit temperature distributions were observed. Combustion efficiency levels at simulated takeoff conditions were virtually 100% with all of the fuels tested. However, exhaust pollutant emission levels will be somewhat higher for fuels with reduced hydrogen content and higher boiling points. These effects are discussed in greater detail in the following paragraphs.

3.4.1 Pressure Losses

The results of comprehensive diffuser design analysis studies and combustion system pressure loss estimates for the six CF6-50 conceptual designs and for the six E^3 conceptual combustor designs are presented in Table 12. All of the CF6-50 combustor concepts use the standard CF6-50 prediffuser design. This prediffuser is a long, high area ratio (2.20) design that has very low pressure losses, which, for a fixed value for the total combustion system pressure loss, results in relatively high pressure drops across the combustor liners. The total system pressure loss for the CF6-50 baseline single annular design is the same as that for the production combustion system (4.60%), and the total system losses for the CF6-50 double annular and radial/axial concepts are the design values for the engine version of

Table 12. Conceptual Combustor Designs - Predicted Pressure Losses.

(Pressure Loss in Percent of P_{T3} at SLS Conditions)

Combustor Design	Baseline Single Annular	Short Single Annular	Double Annular	Radial Axial	LPP Variable Geometry	Annular Slot
CF6-50 Concepts:						
Maximum Passage Loss	1.15	1.10	1.39	1.40	1.76	1.10
Dome Flow Loss	0.63	0.73	0.63	0.63	0.63	0.63
Mass Weighted Diffuser Loss	1.01	1.03	1.01	0.99	1.19	1.00
Combustor Liner Loss	3.59	3.97	3.79	3.81	3.81	4.00
Total System Loss	4.60	5.00	4.80	4.80	5.00	5.00
E_3 Concepts						
Maximum Passage Loss	1.80	1.73	2.68	2.02	2.27	1.72
Dome Flow Loss	0.55	0.55	0.55	0.55	0.55	0.55
Mass Weighted Diffuser Loss	1.46	1.47	1.33	1.38	1.34	1.47
Combustor Liner Loss	3.54	3.53	3.67	3.62	3.66	3.53
Total System Loss	5.00	5.00	5.00	5.00	5.00	5.00

these concepts as designed for the NASA/GE Experimental Clean Combustor Program (4.80%). The other three CF6-50 combustor concepts and all of the E^3 concepts are designed for a total combustion system pressure loss of 5.0 percent.

Short length is an important requirement for the E^3 engine; and to meet this requirement, a short length prediffuser with an area ratio of 1.6 has been selected for the E^3 conceptual combustor designs. Tradeoff studies of engine length versus combustor pressure loss with a compressor exit Mach number of 0.28 show that the optimum prediffuser area ratio is about 1.6. However, with this short length prediffuser, the diffuser passage pressure losses for the E^3 combustor concepts are somewhat greater than those for the CF6-50 designs.

These diffuser pressure loss studies revealed that the passage pressure losses for the original E^3 lean premixing-prevaporizing (LPP) variable geometry combustor concept would be 3.11% which is unacceptably high. High pressure losses in the combustor passages reduce the pressure drop available for first stage turbine nozzle vane cooling. As a result of these studies, cowlings were designed for the E^3 LPP concept to enclose the combustor dome region and reduce the dumping losses of the passage flow. These cowlings, as illustrated in Figure 16, reduce the passage pressure losses of this combustor concept to 2.27% which is in the acceptable range of passage losses. The CF6-50 LPP conceptual design does not require a cowling because this concept has a high area ratio prediffuser which results in relatively low passage dumping losses.

3.4.2 Estimated Combustion Performance Characteristics

The minimum steady state operational combustion efficiency, maximum altitude relight capability, structural durability in terms of maximum life cycles, and combustor exit temperature pattern factors were estimated for the six CF6-50 and six E^3 conceptual combustor designs.

The estimated performance parameters for each of the combustor concepts is presented in Table 13. The minimum combustion efficiency (using the ERBS fuel) is for the engine idle operating condition. At all of the other

Table 13. Predicted Combustor Performance Characteristics.

	Percent Minimum Efficiency (Idle)	Maximum Relight Altitude km (ft x 10^{-3})	Maximum Life-Cycles	Pattern Factor (Takeoff)
CF6-50 Concepts:				
Baseline Single Annular	97.0	10.7 (35.0)	1500	0.28
Short Single Annular	99.5	11.0 (36.0)	2100	0.21
Annular Slot	99.4	10.8 (35.5)	4600	0.20
Variable Geometry LPP	99.5	11.0 (36.0)	2100	0.20
Double Annular	99.7	7.5 (24.5)	2100	0.20
Radial/Axial	99.7	6.9 (22.5)	2100	0.20
E^3 Concepts:				
Baseline Single Annular	99.5	9.9 (32.5)	2000	0.21
Short Single Annular	99.2	7.9 (26.0)	2100	0.25
Annular Slot	99.5	9.1 (30.0)	4600	0.20
Variable Geometry LPP	99.6	9.3 (30.5)	2100	0.24
Double Annular	99.7	8.2 (27.0)	2100	0.21
Radial/Axial	99.7	7.8 (25.5)	2100	0.20

operating conditions, the combustion efficiency for all of the concepts is 99.9% or greater. The maximum relight altitude for each concept is based on a correlation that includes the effects of combustor dome height and dome velocity.

Combustor structural durability is presented in terms of the maximum number of operating cycles for the operational life of the combustor. Liner cooling flows were calculated for each concept to maintain a maximum liner temperature of 1090 K. However, the CF6-50 and E^3 annular slot concepts are not expected to have the hot streaks that characterize all of the other concepts. Therefore, the maximum liner temperature of the annular slot concept is estimated to be about 1047 K, which results in a larger number of life cycles for this concept.

Pattern factor estimates for these combustor concepts are based on combustor severity correlations that include the effects of space heat release rate, liner cooling flow, combustor pressure loss, combustor length-to-dome-height ratio, and number of fuel nozzles. The practical minimum pattern factor for any combustor concept is assumed to be 0.20. All of the pattern factor estimates are for combustors using ERBS fuel. Pattern factors for combustors designed to use Jet A fuel would be somewhat lower than these values because, with Jet A fuel, the liner cooling flows are lower with correspondingly more air available for pattern factor control.

Altitude relight limits are expected to be strongly affected by fuel viscosity and fuel volatility at the relight conditions. Usually, combustion system altitude relight capability is specified for a fuel temperature at the fuel nozzle of 256 K (0° F). This temperature is near the freezing point for the ERBS fuel listed in Table 1. Obviously, the ERBS fuel must be heated to a higher temperature to provide sufficiently low viscosity for good atomization at relight conditions. The altitude relight tests reported in Reference 4, however, were conducted with fuel and air temperatures close to the ambient values; and for these conditions, the altitude relight limits were approximately the same for all of the configurations tested and for all of the test fuels.

3.4.3 Estimated Pollutant Emissions Characteristics

The exhaust emissions of concern from an air pollution standpoint consist of carbon monoxide (CO), unburned or paritally oxidized hydrocarbons (HC), oxides of nitrogen (NO_x), and carbon smoke particulate matter. Both CO and HC emissions are products of inefficient combustion which occurs mainly at idle and other low power engine operating conditions. At low power operating conditions, the combustor inlet air temperature and pressure levels are relatively low, the overall combustor fuel-air ratios are generally low, and the quality of the fuel atomization and its distribution within the primary combustion zone are usually poor because of the low fuel and airflows. More viscous fuels and those with higher final boiling points would be expected to have atomization and vaporization characteristics that are worse than those for Jet A fuel. Test results (Reference 3) indicate that idle CO and HC emissions levels for several different combustor configurations are influenced by both fuel hydrogen content and fuel volatility as defined by the final boiling point. Although the absolute levels of CO and HC emissions at idle operating conditions were highly configuration dependent, these levels, for a particular design at these conditions, seemed to have a linear relationship to the final boiling point of the fuel and an inverse relationship to fuel hydrogen content.

The rates at which NO_x is formed in a combustion system are highly dependent on flame temperature level and increase very rapidly as flame temperature is increased. Further, these rates also increase as the pressure level of the combustion gases is increased, because of the direct effects of pressure on the chemical kinetics of the formation processes for NO_x. However, because these NO_x formation rates are generally far slower than the fuel combustion reactions, the quantities of NO_x emissions generated in typical combustion systems are limited by the short residence times of the hot combustion gases within the engine combustors. Because of the strong dependence of the NO_x formation rates on the initial combustion air temperature and pressure levels, the quantities of NO_x generated in the combustor are highest at takeoff and other high engine power operating conditions. Broad specification fuels with higher levels of aromatics would be expected to have higher flame temperatures which would result in higher formation rates for NO_x. The test results of Reference 4 show that the NO_x emission levels for several different combustion system configurations correlate quite well with the inverse ratio of fuel hydrogen content. As shown in Figure 1, fuels with higher levels of aromatics generally have lower percentages of hydrogen. These test results also show that final boiling point has no discernible effect on NO_x emissions levels, but high levels (813 ppm) of fuel-bound nitrogen did produce a measurable effect. NO_x emissions were also highly configuration sensitive. Lean burning, short residence time combustors have reduced NO_x emissions levels. The trends with fuel type were, however, the same for all of the configurations tested in Reference 3.

The smoke emission levels were generally very low for all of the configurations and all of the fuels tested in Reference 4. The highest levels were produced by the standard production CF6-50 combustor at idle operating conditions with No. 2 diesel fuel. In all the other tests, smoke levels were virtually zero with any fuel. Advanced low-smoke combustors appear to be very tolerant of fuel properties. However, higher aromatic contents (lower hydrogen contents) always result in higher smoke levels in any given combustor. Thus, smoke levels with ERBS fuel will be slightly higher than those with Jet A fuel.

Exhaust emissions levels, using Jet A fuel and the broad specification ERBS fuel, were estimated for the six CF6-50 and the six E^3 conceptual combustor designs. The emissions levels, expressed as an EPAP value for the EPA landing and takeoff cycle, and as the maximum smoke number (SAE 1179) at the takeoff condition, are presented in Table 14 for the CF6-50 combustor concepts and in Table 15 for the E^3 combustor concepts. Correction factors for the CO, HC, NO_x and smoke emissions, using ERBS fuel, were calculated using the emissions correlations for broad specification fuels presented in Reference 4. For each of the pollutants and for each combustor concept, the emission levels, using the ERBS fuel, range from 4 to 12% higher than the emission levels with Jet A fuel. This increase in emission levels is due to the lower hydrogen content and higher final boiling point of the ERBS fuel.

Table 14. CF6-50 Concepts - Estimated Emissions.

EPA Parameters - 6% Idle Conditions

Concept No.	1	2	3	4	5	6	EPA Requirement
			Jet A Fuel - Current EPA Standards (lb/1000 lb-Thrust-hr)				
CO	7.78	2.89	3.33	1.44	2.47	2.89	4.30
HC	2.05	0.07	0.14	0.08	0.04	0.07	0.80
NO_x	6.85	4.07	4.24	3.80	3.80	2.36	3.00
			ERBS Fuel - Current EPA Standards (lb/1000 lb-Thrust-hr)				
CO	8.71	3.24	3.73	1.61	2.77	3.24	4.30
HC	2.24	0.08	0.15	0.09	0.04	0.08	0.80
NO_x	7.14	4.24	4.42	4.00	4.00	2.46	3.00
			Jet A Fuel - Proposed New EPA Standards* (lb/1000 lb-Thrust)				
CO	0.69	0.26	0.30	0.13	0.22	0.26	0.35
HC	0.18	0.01	0.01	0.01	0.003	0.01	0.06
NO_x	0.61	0.36	0.38	0.34	0.34	0.21	0.38
			ERBS Fuel - Proposed New EPA Standards* (lb/1000 lb-Thrust)				
CO	0.77	0.29	0.33	0.14	0.25	0.29	0.35
HC	0.20	0.01	0.01	0.01	0.004	0.01	0.06
NO_x	0.63	0.38	0.39	0.36	0.36	0.22	0.38
SAE Smoke No. with Jet A	12.0	20.6	14.3	10.0	10.0	10.0	
SAE Smoke No. with ERBS	13.0	22.0+	15.5	11.0	11.0	11.0	

*Proposed New EPA Standards for Previously Certified Engines.

Table 15. E^3 Concepts - Estimated Emissions.

EPA Parameters - 6% Idle Conditions

Concept No.	1	2	3	4	5	6	EPA Requirement
			Jet A Fuel - Current EPA Standards (lb/1000 lb-Thrust-hr)				
CO	2.42	3.63	2.42	1.20	2.02	2.23	4.30
HC	0.10	0.12	0.10	0.07	0.03	0.03	0.80
NO_x	4.37	3.37	3.45	3.03	3.03	2.07	3.00
			ERBS Fuel - Current EPA Standards (lb/1000 lb-Thrust-hr)				
CO	2.71	4.07	2.71	1.34	2.26	2.50	4.30
HC	0.11	0.13	0.11	0.08	0.03	0.03	0.80
NO_x	4.55	3.51	3.60	3.16	3.16	2.16	3.00
			Jet A Fuel - Proposed New EPA Standards* (lb/1000 lb-Thrust)				
CO	0.21	0.32	0.21	0.11	0.18	0.20	0.245
HC	0.01	0.01	0.01	0.01	0.003	0.003	0.0324
NO_x	0.39	0.30	0.31	0.27	0.27	0.18	0.324
			ERBS Fuel - Proposed New EPA Standards* (lb/1000 lb-Thrust)				
CO	0.24	0.36	0.24	0.12	0.20	0.22	0.245
HC	0.01	0.01	0.01	0.01	0.003	0.003	0.0324
NO_x	0.40	0.31	0.32	0.28	0.28	0.19	0.324
SAE Smoke No. with Jet A	1.7	4.9	2.9	1.2	1.2	1.2	
SAE Smoke No. with ERBS	1.8	5.3	3.2	1.3	1.3	1.3	

*Proposed New EPA Standards for Newly Certified Engines.

The emissions levels for the CF6-50 baseline single annular production engine are corrected to the 6% idle conditions. Emission estimates for the E^3 baseline single annular CF6-50 and E^3 short single annular, annular slot, and variable geometry LPP concepts are based on CFM56 engine test results, modified, as appropriate, for residence time, rich or lean burning conditions, dome velocity, and cycle conditions. The emission estimates for the CF6-50 and E^3 double annular and radial/axial concepts are based on the NASA/GE ECCP test results for the ECCP Phase II double annular and radial/axial combustion systems.

The EPAP numbers for the E^3 combustor concepts are generally lower than those for the CF6-50 combustor concepts because the sfc for the E^3 cycle is lower than the CF6-50 engine sfc and the EPAP number is the product of the emissions index (EI), which depends on the combustor design, and the engine sfc. Also, the E^3 smoke numbers are much less than those for the CF6-50 engine. The E^3 is a mixed-flow engine system; the fan flow mixes with the core engine flow ahead of the exhaust nozzle, and the smoke from the core engine is diluted by the much larger fan stream. The CF6-50 is a separated-flow engine, and the smoke numbers for this engine are for the unmixed core engine flow.

3.5 COMPARATIVE EVALUATION OF THE CONCEPTUAL DESIGNS

The six CF6-50 and six E^3 combustor concepts designed and analyzed for this study were compared and evaluated to determine the relative ability of each concept to use broad specification fuels. Rating factors have been assigned to each concept for each of the evaluation criteria and comparative overall ratings were used to select those concepts that are expected to have the greatest fuel handling flexibility with the least amount of development work.

3.5.1 Evaluation Criteria

Initially, comparisons of the combustor concepts and evaluations were made in terms of the following criteria:

1. Fuel flexibility (flexibility to handle current and broad specification fuels)

2. Combustion performance
3. Exhaust pollutant emissions
4. Design complexity
5. Reliability
6. Maintainability
7. Durability and operating life
8. Effect on overall engine weight
9. Effect on overall engine fuel consumption

Each of the CF6-50 concepts and each of the E^3 concepts were judged to be about equal in terms of the effect of the concept on overall engine weight and on overall engine fuel consumption. There are small differences in the overall combustion system lengths of the E^3 concepts, but these differences have a very small effect on engine weight and none of the E^3 concepts exceed the maximum system length. Consequently, the last two items of the evaluation criteria were eliminated from further consideration.

Rating Factors

For each of the other evaluation criteria in the above list of criteria, a rating factor was assigned to each of the six CF6-50 concepts and to each of the six E^3 concepts. These rating factors are defined as follows:

3 - Expected to meet design goals with normal development.

2 - Additional development effort will probably be required to meet design goals.

1 - Major additional development effort required to meet goals.

3.5.2 Comparative Ratings

The rating factor values for each of the concepts are presented in Table 16. As shown in this table, increased design risk is expected in the following areas:

Table 16. Evaluation of Conceptual Combustor Designs.

Concept No.	CF6-50 Concepts 1	2	3	4	5	6	E^3 Concepts 1	2	3	4	5	6
Fuel Flexibility	2	2	2	3	1	1	2	2	2	3	1	1
Performance	3	3	2	3	2	2	3	2	2	3	2	2
Emissions	1	3	3	3	3	3	2	2	3	3	3	3
Complexity	3	3	2	2	2	1	3	3	2	2	2	1
Reliability	3	3	2	3	2	1	3	3	2	3	2	1
Maintainability	3	3	3	3	3	2	3	3	3	3	3	2
Durability	2	2	3	2	2	1	2	2	3	2	2	1

Concept Designation:

1 - Baseline Single Annular
2 - Short Single Annular
3 - Annular Slot
4 - Double Annular
5 - Radial/Axial
6 - Variable Geometry

Rating Factors:

3 - Expected to meet design goals with normal development.
2 - Additional development effort required.
1 - Major additional development effort required.

- Fuel Flexibility - As fuel aromatic contact is increased and percent hydrogen decreased, the single annular concepts (1, 2, and 3) are expected to have increased emissions and increased combustor liner temperatures (Reference 4). The radial/axial and variable geometry concepts (Concepts 5 and 6) would have reduced autoignition delay times in their premixing ducts. The double annular concept (Concept 4) is expected to have relatively low sensitivity to fuel specifications.

- Performance - Concepts 3, 5, and 6 are expected to require additional development effort to achieve performance goals because these concepts have not been subjected to intensive development efforts in the past. The E^3 ultra-short single annular concept may require extra development to achieve pattern factor goals.

- Emissions - NO_x emissions requirements may be impossible to achieve with the CF6-50 baseline single annular concept. The short single annular concepts may also require additional development effort to meet emissions goals.

- Complexity - Concepts 3, 4, and 5 are more complex (and more expensive) than Concepts 1 and 2. Concept 6, with variable geometry linkage and mechanisms, would require major additional development effort.

- Reliability - Reliability ratings are similar to complexity ratings with the exception of Concept 4, which has the advantage of considerable development effort.

- Maintainability - The variable geometry mechanism of Concept 6 may be difficult to maintain.

- Durability - Concepts 1, 2, 4, 5, and 6 may have "hot streaks" that limit combustor liner life, while Concept 3 is not expected to have hot streaks. Major additional development effort may be required to improve the durability of the variable geometry feature of Concept 6.

On an overall basis, the double annular concept, Concept 4, is expected to have the greatest flexibility to handle broad specification fuels. This concept is also expected to require the least amount of development effort to achieve the combustion system design goals.

3.6 DISCUSSION OF POSSIBLE RELAXATION OF FUEL PROPERTIES

There are three major requirements of the ASTM Jet A specification which, if relaxed, would yield significantly greater potential fuel availability:

1. Flash point

2. Freezing point

3. Aromatics content

The flash point could be lowered to well below room temperature, until the fuel actually had a front-end volatility similar to JP-4 in which case the volatility would be controlled by a vapor pressure limit of 3 psi maximum. This would increase the potential fuel availability substantially and have no adverse effect on engine performance.

The major disadvantage of this relaxation of flash point requirement is the possible increased fire hazard in the event of a fuel spill.

Although reducing the flash point is a technically valid means of increasing potential fuel availability, this is not being realized because of legal restraints. The flash point of ASTM Jet A fuel has now been reduced to 311 K (100° F) minimum, but most such fuels have flash points over 322 K (120° F) because of state laws controlling the flash point of kerosine-type fuels.

If reduced flash point is to be considered (it has already been adopted in Canada), then a review of state laws must be made and efforts begun to modify them as required.

Fuel freezing point could be raised from 233 K (-40° F) to possibly 244 K (-20° F), yielding a significantly greater potential fuel availability with no adverse effect on engine performance. Studies already completed under NASA sponsorship (Reference 9) have shown that such fuels could be used in current aircraft without modifications in short range flights and could be used under all conditions in long range flights through the use of aircraft modifications.

Fuel aromatic content could be raised to about 30% maximum or to the equivalent hydrogen content of 13.1% minimum. This should significantly increase potential fuel availability. It is doubtful that additional lowering of the hydrogen content could yield much more fuel unless the crude source was changed from petroleum to coal-derived liquids.

It is unlikely that a significant increase in potential fuel availability could be achieved by lowering the fuel thermal stability requirements, since these are seldom limiting and no refining process is specifically applied to the fuels to make them meet the requirements. In other words, the fuels "naturally" meet the requirements with no extra effort being applied.

Estimates of how far ASTM Jet A fuel specifications could be relaxed without degrading the production CF6-50 turbofan engine or the E^3 turbofan engine combustion system performance depend on the combustor design concept being considered as a candidate engine design. The CF6-50 baseline single annular design, Concept 1, has high emission levels with Jet A fuel, and any relaxation of the specifications for this fuel that has the effect of reducing hydrogen content or increasing the final boiling point of this fuel will increase these emission levels. Also, the pattern factor of this concept will increase beyond acceptable limits as the fuel specifications are relaxed beyond those for Jet A fuel, because the combustor liner cooling flow requirements will increase with no corresponding change in operating life as the fuel specifications are relaxed.

Although all of the other CF6-50 concepts have predicted emission levels that are much closer to the EPA requirements, all but Concept 6, the LPP design, have NO_x emissions levels that are above the current EPA requirements using Jet A fuel. If the specifications of this fuel are relaxed, the NO_x emissions levels of these concepts will further increase.

The E^3 baseline single annular design (Concept 1) has predicted NO_x emissions levels that are above the EPA requirements with Jet A fuel, and E^3 Concept 2 has predicted CO emission levels that are above the EPA requirements with Jet A fuel. All of the other E^3 conceptual designs (Concepts 3, 4, 5, and 6) meet the EPA emission requirements with Jet A fuel and also meet these requirements with the broad-specification (ERBS) fuel. E^3 Concept 3 is close to the maximum requirement levels for CO and NO_x, however, and any further relaxation of the fuel specification beyond the ERBS values would increase the emissions of this concept above the EPA requirements.

The CF6-50 and E^3 radial/axial and variable geometry designs (Concepts 5 and 6) have premixing-preevaporizing systems for the introduction of the fuel at high power conditions. With allowance for a reasonable autoignition safety margin, the mixing distance, with ERBS fuel, is judged to be too short for a practical design. Therefore, if a premixing-prevaporizing combustion system is to be used at CF6-50 or E^3 cycle conditions, the fuel specifications cannot be relaxed beyond those for Jet A fuel.

Of all the conceptual designs considered in this study, only the E^3 double annular design (Concept 4) is predicted to meet all engine performance and emission requirements with a significant relaxation of fuel specifications. Also, if the idle power setting for the E^3 cycle is reduced below the 6% level considered for this study, the idle emissions of all of the conceptual designs would increase; and the CO emission level for all of the concepts, except that for the double annular design, would exceed the EPA emission requirements. For a fuel that has a final boiling point the same as that specified for the ERBS fuel, the hydrogen content could be reduced to a level below 13% of the fuel weight without exceeding the EPA requirements for NO_x emissions if the double annular combustion system design is used.

If the combustion system is designed to meet the performance and emissions requiremnts of the wide body turbofan engine applications, there does not appear to be any fuel property in the ERBS fuel specification that might limit the use of this fuel in these applications. The higher freezing point of this fuel may require the use of fuel heaters in some applications, but these heaters would be a part of the airframe or ground supply fuel system.

3.7 EVALUATION OF CONCEPTUAL DESIGN COMPLEXITIES AND ENGINE INTEGRATION PROBLEMS

Several problems are associated with integrating two of the six CF6-50 and six E^3 conceptual designs with Jet A and ERBS fuel with the production CF6-50 turbofan engine and the E^3 turbofan engine. Concepts 1, 2, 3, and 6 would use a conventional single annular fuel system arrangement which would not present any new problems. However, Concept 4 (the double annular design) and Concept 5 (the radial/axial design) would require a larger number of fuel injectors and two separate fuel manifolds with special engine control features to select the fuel manifolds and fuel flows to the manifolds over the range of engine operating conditions. However, these problems were addressed as a part of the NASA/GE Experimental Clean Combustor Program (References 13 and 14) and satisfactory approaches to this problem were identified.

As fuel specifications are relaxed from those of Jet A fuel to those of ERBS fuel, additional design complexity may be required for only two of the six conceptual design configurations to achieve the performance objectives (not including emissions) of the CF6-50 or E^3 engines. The rich burning designs (Concepts 1, 2 and 3) will require higher levels of liner cooling flow which is detrimental to pattern factor. The CF6-50 baseline design (Concept 1) and the E^3 short single annular design (Concept 2) have predicted pattern factors that are approaching the upper limit of acceptability. For operation with broad specification fuels, these combustors may require higher pressure losses, revised dilution hole patterns, or more complex liner cooling designs to achieve the required pattern factor levels.

3.8 SIGNIFICANT PROBLEM AREAS AND RECOMMENDATIONS FOR FUTURE STUDY

For the six conceptual designs considered in this study, most of the problem areas related to the relaxation of fuel specifications are amenable to normal development efforts. However, the most significant problem area caused by the relaxation of fuel specifications is the drastically reduced autoignition delay times for lean premixing-prevaporizing (LPP) systems. The LPP designs (Concepts 5 and 6), analyzed as part of this study, are predicted to have good performance and very low NO_x emission levels. However, the autoignition delay times are so short with ERBS fuel that Concepts 5 and 6 would not be practical if this fuel, or any fuel with specifications relaxed beyond those for Jet A, is to be used in the engine application. Autoignition characteristics of various fuel types represent a very significant problem area for LPP combustor designs. Experimental studies are needed to determine the critical fuel properties that affect autoignition characteristics and to determine how these characteristics may be modified to improve the acceptability of broad specification fuels for LPP combustor designs.

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