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LEAN, PREMIXED-PREVAPORIZED (LPP) COMBUSTOR CONCEPTUAL DESIGN STUDY

FINAL REPORT

By

GENERAL ELECTRIC COMPANY

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NASA-Lewis Research Center

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FOREWORD

The work described herein was conducted by the General Electric Aircraft Engine Group under Contract NAS3-21255. The work was performed under the direction of the NASA Project Manager, Mr. E.J. Mularz, USARTL Propulsion Laboratory (AVRADCOM), NASA-Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135.

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Dr. P.V. Heberling of the GE Corporate Research and Development Center, Schenectady, New York, served on a consulting basis to assist in the definition and analysis of the LPP combustor fuel-air mixing techniques and analyses.

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1.0 SUMMARY

The Lean, Premixed-Prevaporized (LPP) Combustor Conceptual Design Study Program was conducted to evaluate the feasibility of employing LPP combusion technology in aircraft gas turbine engines to achieve control of the emission of oxides of nitrogen (NO_x) for subsonic, stratospheric cruise aircraft operation.

This design study effort involved the conceptual design of five full-annular combustors using LPP techniques. The objective of this design study program was to identify promising LPP combustor designs that have the potential to meet several specific emissions and performance goals. One of these goals is the attainment of very low NO_x emission levels, $\leq$ 3 g/kg fuel, at subsonic cruise conditions, in addition to meeting the 1981 EPA landing/takeoff emissions standards for Class T_2 aircraft engines, while also meeting commercial engine operational and durability requirements. The NO_x emission index of $\leq$ 3 g/kg fuel represents an 85% reduction relative to typical contemporary commercial gas turbine engine combustors. The designs generated in this effort incorporate advanced lean, premixed-prevaporized technology, together with advanced combustor aerothermodynamic and mechanical design features for fuel and airflow scheduling.

In this program, LPP combustor design concepts were defined and analyzed. Four designs were sized specifically for the NASA/GE Energy Efficient Engine (E^3) design, but the technology is applicable to other advanced high pressure ratio aircraft turbofan engines as demonstrated by the fifth design which was sized for the CF6-50C commercial aircraft turbofan engine and embodies the design features of one of the concepts sized for the E^3. Both engines have cycle pressure ratios of approximately 30:1 and combustor exit temperatures greater than 1500 K.

Results of this effort indicate that combustion systems employing LPP techniques and variable geometry to control the airflow distributions provide promising means for achieving the low NO_x emission goals of this program. These low NO_x emission goals appear to be achievable with all of the concepts analyzed.

2.0 INTRODUCTION

Since 1976, NASA-Lewis has been conducting studies to increase understanding of various aspects of lean, premixed-prevaporized (LPP) combustion concepts through the Stratospheric Cruise Emission Reduction Program (SCERP). Some of the expected results and benefits of this program are an improvement in the turbine nozzle temperature distribution, an increase in combustor liner life, and a combustion system which meets the current 1981 EPA emissions standards, and achieves low NO_x emissions at engine cruise conditions. This advanced technology could be applied to future aircraft engines for improved performance and life; and if aircraft emissions are found to pose a threat to the composition of the stratosphere, this technology could significantly reduce this threat.

Two combustor design approaches show promise for meeting these stringent NO_x emission goals: catalytic combustion and lean, premixed-prevaporized (LPP) combustion. Programs to provide the technology for the design of these advanced low NO_x emission combustors have advanced rapidly in recent years. General Electric recently completed a NASA-sponsored design study program, Advanced Low Emissions Catalytic Combustor Program - Phase I (Contract NAS3-20820), to evaluate the feasibility of employing catalytic combustion technology in aircraft gas turbine engines.

The purpose of the LPP Combustor Conceptual Design Study Program was to identify and define promising lean, premixed-prevaporized combustor designs for use in advanced subsonic aircraft gas turbine engines and to assess their potential for meeting the performance, emission, and operational requirements of such engines. The primary intent of these advanced combustor designs was to attain very low NO_x emissions levels (less than 3 g/kg) at subsonic cruise operating conditions. Another important emissions goal was that these designs be capable of meeting the current 1981 EPA emissions standards which are prescribed for a landing-takeoff mission cycle involving ground and near-ground level engine operating modes.

At cruise, these advanced combustor designs were to include provisions for providing premixed-prevaporized fuel-air mixtures upstream of the combustion zone, along with features for operating with lean combustion zone equivalence ratios (0.6 or less). To permit operation over the entire range of required engine power settings, these LPP combustors were to include variable geometry or other features for modulating the combustor airflow distribution. An important aspect of the LPP program was an assessment of the design and operational problems associated with the use of such features for the modulation of combustor airflow distribution.

Each of the LPP combustor design concepts generated as a part of this program was rated and ranked in terms of criteria established to assess development risk. The intent of these assessments was to indicate which designs provide the most promise for meeting the program emissions, performance, and installation goals.

Results of this LPP design study effort have indicated that combustors incorporating LPP combustion techniques, combined with airflow mdulation capability, can achieve low NO_x emissions levels at aircraft subsonic cruise operating conditions. Cruise NO_x emissions levels below 3 g/kg are possible with little additional impact on engine control requirements. Providing adequate fuel-air ratio uniformity without autoignition problems remains the major challenge in applying LPP concepts to practical aircraft combustion systems.

3.0 PROGRAM DESCRIPTION

Four LPP combustor concepts were selected from General Electric Proposal P78-39, dated April 10, 1978. These four concepts were applied to the design of combustors sized to meet performance, operating, and installation requirements of the NASA/GE Energy Efficient Engine (E^3) which was being developed under Contract NAS3-20643. Also, one concept was sized to meet performance, operating, and installation requirements of the CF6-50 turbofan engine. Both of these engines have cycle pressure ratios of 30:1 and combustor exit temperatures greater than 1500 K.

The program was composed of four elements. Brief descriptions of the specific work accomplished in each element are presented in the following discussion.

Element 1.0 - Combustor Design

Five combustor designs selected from the conceptual design approaches described in General Electric Proposal P78-39, and approved by the NASA Project Manager, were prepared. Each of these combustor designs incorporated premixed-prevaporized fuel-air mixture preparation features, together with fuel staging and airflow modulation devices, as a means of meeting the challenging program goals for emission, performance, and engine operating characteristics. Layout drawings of each of these designs were prepared which define the entire combustion system from the compressor exit plane to the turbine inlet plane. Each design layout drawing contains sufficient detail to define all major assemblies including fuel injectors, airflow modulation devices, and cooling liners. Four designs were sized for the Energy Efficient Engine. The fifth design was sized for the CF6-50 engine.

Element 2.0 - Design Analysis

The combustor designs were further analyzed and evaluated to determine their potential for meeting the combustor performance goals and their feasibility for development into practical combustion systems. These studies included aerothermodynamic analyses to define the performance, emission, and operational characteristics of each design, together with control system studies to assess the impacts of fuel and airflow modulation devices on the existing engine control system and to determine the need for new sensing techniques. In addition, aeromechanical studies were conducted to predict metal temperatures and estimated combustion system life characteristics, as well as to define the required airflow modulation systems and associated control devices. Further, the impact of combustor design features such as size and weight on the overall engine cycle performance was assessed. Finally, an elementary failure analysis of each combustor design was made to identify potential failure modes and estimate the probability and impact of each mode.

Element 3.0 - Design Ranking

The combustor designs were rated and ranked in terms of criteria established to assess development risk. The intent of these assessments was to indicate which design showed the most promise for meeting the program emission, performance, and installation goals.

Element 4.0 - Reports and Records

Monthly progress reports were prepared in accordance with the contract requirements. This document constitutes the final report.

3.1 PROGRAM GOALS

The objective of the Lean, Premixed-Prevaporized Conceptual Design Study Program was to identify combustor designs that have the greatest potential for obtaining low cruise NO_x emissions and to meet combustor operating requirements. The specific goals were as follows:

- $NO_x \leq 3$ g/kg at subsonic cruise
- Combustion Efficiency

  $\eta_b \geq 99.9$ percent at sea level takeoff

  $\eta_b \geq 99.5$ percent at idle

  $\eta_b \geq 99.0$ percent of all other operating conditions

- The combustion system must be capable of meeting all current Environmental Protection Agency emissions standards for the engine class T2 over the landing - takeoff cycle
- Total combustor pressure loss $\Delta P/P \leq 5$ percent over all operating conditions except idle
- The combustion system must be capable of meeting altitude relight requirements of the reference engine

The specific requirements are as follows:

- Each combustor design is to incorporate an adaptation of the premixed-prevaporized combustion technique
- Each combustor design shall incorporate an airflow modulation technique
- The airflow and fuel flow distribution and schedules are to be specified over the operating range of the combustor

- All combustors are to be designed within the flowpath geometry of the respective reference engine
- All combustors are to be designed to have adequate cooling and structural integrity
- All concepts are evaluated assuming the use of Jet A fuel

3.2 REFERENCE ENGINE DESCRIPTIONS

Five combustor designs were developed in the LPP Design Study. Four designs (Concepts 1 through 4) were sized for the NASA/GE Energy Efficient Engine, and one design was intended for operation over the cycle conditions and within the combustor envelope of the CF6-50 turbofan engine. A description of these reference engines including selected operating cycle points considered during analysis follows.

3.2.1 NASA/GE Energy Efficient Engine

The engine selected as the reference engine for Concepts 1 through 4 is the NASA/GE Energy Efficient Engine (E^3) that is typical of the advanced high pressure ratio, high bypass ratio engines that will be developed for commercial aviation service within the next 10 to 20 years. This reference engine (CFX18) is a direct-drive fan, mixed-exhaust flow version of a series of turbofan engines evaluated as a part of the NASA/GE Energy Efficient Engine Preliminary Design and Integration Study Program conducted under Contract NAS3-20627. An engine layout drawing is shown in Figure 1.

A major objective of the E^3 program is to obtain a 12 percent reduction in specific fuel consumption at cruise conditions. This objective is referenced to the CF6 family of engines which represents the most efficient engines currently in commercial service.

Low specific fuel consumption values at cruise conditions are achieved by efficiency improvements in its various components and by an increase in cycle pressure ratio at cruise conditions. At sea level static conditions, the overall pressure ratio is the same as that of the CF6-50 engine (30:1), but at maximum cruise conditions, cycle pressure ratio is 35.8:1, versus 31.0:1 for the CF6-50 engine, resulting in considerbly higher combustion system inlet pressures and temperatures at these conditions.

The E^3 cycle is especially appropriate as a reference engine cycle for the LPP program because the high combustor inlet air pressures and temperatures of this cycle at cruise conditions are indicative of the trend of future commercial engine development. As a consequence of these high combustion system pressures and temperatures, the achievement of low NO_x emission at cruise conditions becomes more difficult to accomplish and the design of practical LPP combustion systems becomes a greater challenge.

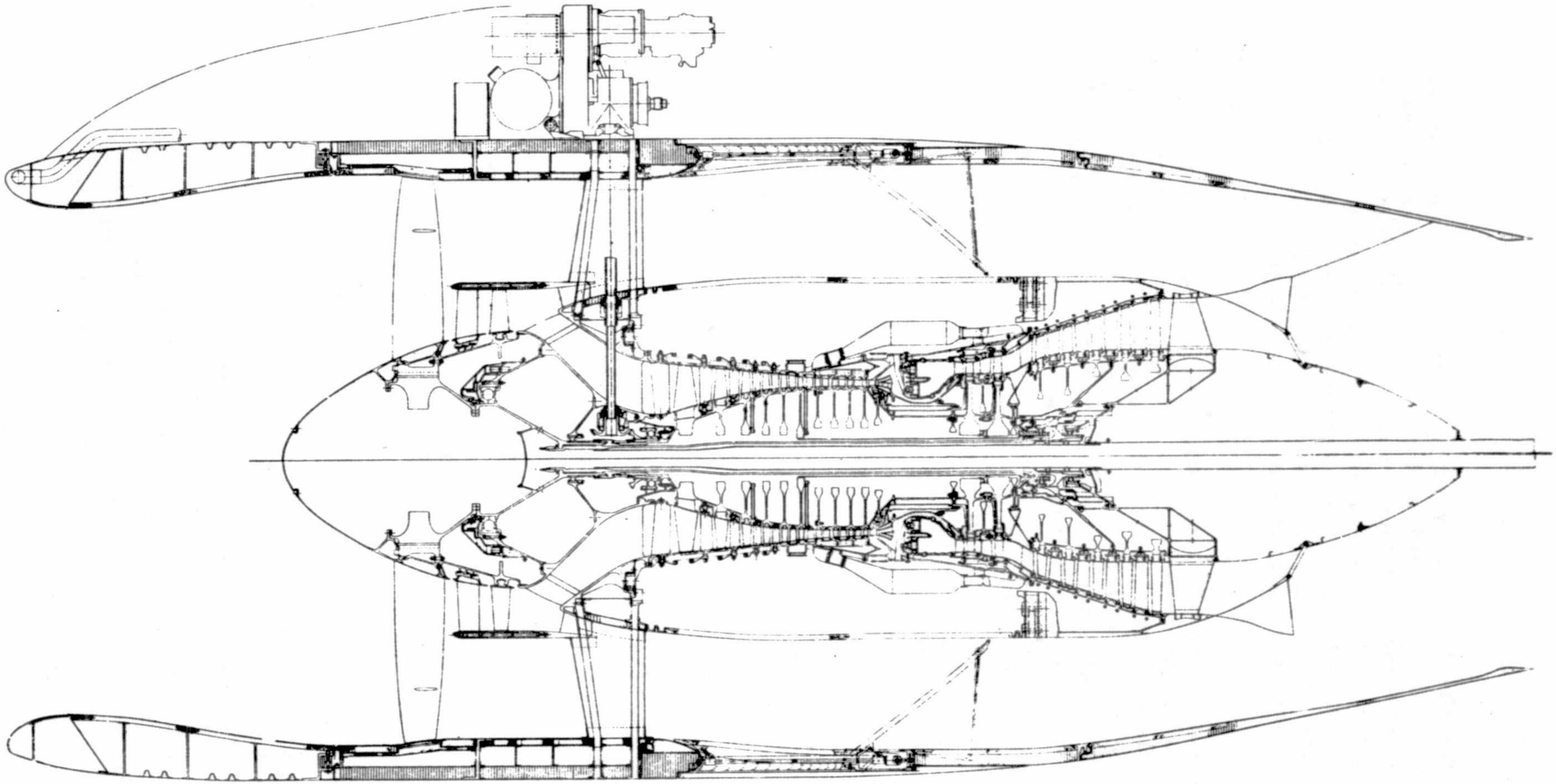


Figure 1. NASA/GE Energy Efficient Engine Layout Drawing.

Cycle parameters for the E^3 at 10 cycle operating conditions are presented in Table I. Key engine cycle and combustor operating parameters are presented for the four operating conditions required to calculate takeoff/landing cycle emissions and performance as specified in Reference 1 (with two possible idle settings); for hot-day takeoff operating conditions, where conditions are most severe in terms of autoignition and durability; and for a range of cruise conditions where ultralow NO_x emissions levels are being sought.

The preliminary design of the E^3 combustor is illustrated in Figure 2. This combustor consists of a short-length, low emission, double-annular combustor design which is based on the results of the NASA/GE Experimental Clean Combustor Program (Reference 2 and 3). The double-annulus design features 30 fuel nozzles that each have injection points for both the pilot and main stages. Therefore, there are 30 nozzles with 2 injection points each for a total of 60 fuel injection points. Early in the conceptual design of the LPP combustors, it was recognized that the combustion systems under consideration would require additional length not available within the E^3 preliminary design combustor envelope. Therefore, in the design of these LPP combustion systems, it was assumed that the combustor envelope could be lengthened to accommodate these systems. All conceptual and preliminary designs were sized to match the compressor exit and turbine inlet dimensions shown in Figure 2. Combustor inner and outer casing dimensions were allowed to vary according to requirements of each of the combustor designs, but in all cases combustor casings were contoured to avoid interference with fixed components.

3.2.2 CF6-50C Engine

Concept 5 of the LPP Design Study was designed to operate over the cycle conditions and within the combustor envelope of the CF6-50 engine. Th CF6-50 is currently in use on the McDonnell-Douglas DC-10, Airbus Industrie A300, and Boeing 747 aircraft.

This reference engine is an advanced, twin-spool, high bypass turbofan. Major engine components include a variable stator compressor, an annular combustor, a two-stage, film-cooled high pressure turbine which drives the compressor, and a low pressure turbine which drives the front fan and low pressure compressor. The high bypass turbofan concept permits a superior thrust-to-weight ratio at 25 percent improvement in fuel economy relative to earlier engines.

The CF6-50 engine combustor is a high performance design that has been developed to have low exit temperature pattern/profile factors, low pressure loss, high combustion efficiency, and low smoke emission levels at all operating conditions. The key features of this combustor design are its low pressure-loss step diffuser, swirl-cup dome design, carbon-free fuel injectors, and short burning length. The short burning length reduces the amount of liner cooling air required which, in turn, improves the exit temperature pattern factor and profile relative to earlier engine combustion systems. The

Table I. NASA/GE Energy Efficient Engine (E^3) Reference Engine Cycle Parameters.

Combustor Pressure Drop = 5%

Cycle Point	4% Idle	6% Idle	30% Approach	85% Climb	100% Takeoff	Hot Day Takeoff	Very Hot Day Takeoff	Max. Cruise	Normal Cruise	Min. Cruise
Ambient Conditions	Std Day	Std Day	Std Day	Std Day	Std Day	+15K	+35K	+10K	+10K	+10K
h_o, Flight Altitude, km	0	0	0	0	0	0	0	10.7	10.7	10.7
M_o, Flight Mach No.	0	0	0	0	0	0	0	0.80	0.80	0.80
F_N, Installed Net Thrust, kN	6.49	9.74	48.70	138.04	162.36	162.39	137.29	37.47	29.98	14.99
W_3, Compressor Exit Airflow, kg/s	8.66	10.70	28.76	55.20	61.69	60.06	51.71	26.99	23.95	17.74
W_{36}, Combustor Airflow, kg/s	7.71	9.53	25.58	49.12	54.93	53.48	46.04	24.04	21.32	15.79
P_{T3}, Compressor Exit Total Pressure, MPa	0.320	0.401	1.183	2.626	3.020	3.007	2.589	1.306	1.121	0.774
T_{T3}, Compressor Exit Total Temperature, K	447.9	485.0	632.6	781.6	813.8	851.3	864.3	782.1	745.1	676.9
T_{T4}, Combustor Exit Total Temperature, K	896.4	940.3	1135.3	1528.7	1617.7	1693.1	1691.8	1595.1	1488.4	1289.4
W_f, Fuel Flow, kg/s	0.0896	0.1136	0.3546	1.0948	1.3399	1.3867	1.1752	0.5887	0.4680	0.2743
f_{36}, Combustor Fuel-Air Ratio, g/kg	11.6	11.9	13.9	22.3	24.3	25.9	25.5	24.5	22.0	17.4
M_3, Compressor Exit Mach No. (1)	0.273	0.281	0.296	0.286	0.283	0.282	0.285	0.281	0.282	0.289

(1) Assumes A_{e3} = 314.4 cm^2

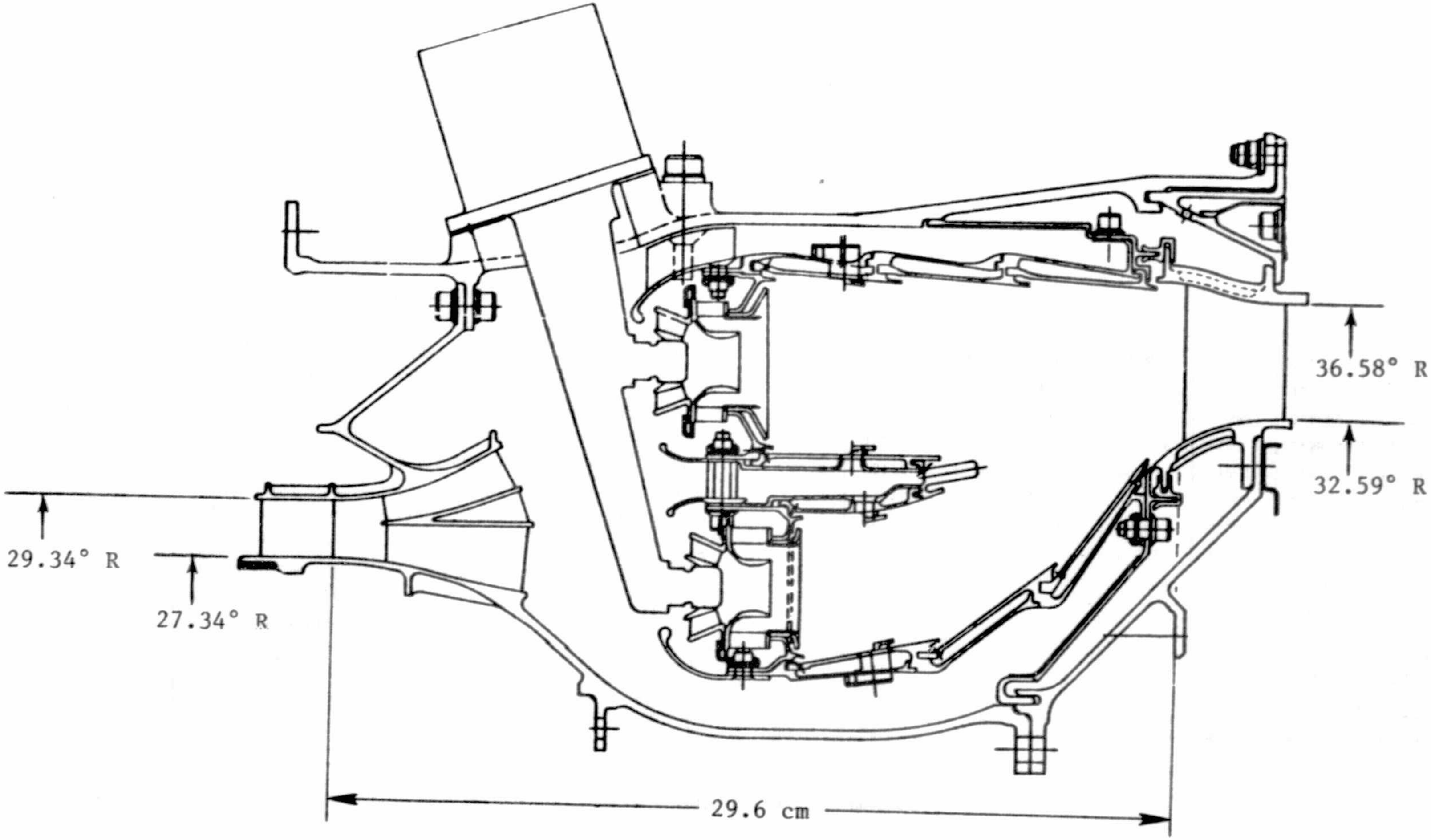


Figure 2. NASA/GE Energy Efficient Engine (E^3) Reference Engine Combustion System.

step diffuser design provides a very uniform, steady airflow distribution into the combustor.

Combustor cycle parameters for the current production CF6-50C engine at the four flight conditions specified in the EPA landing/takeoff cycle and at the cruise condition are presented in Table II. These data are typical of values obtained with the CF6-50C2 and CF6-50E2 engines which will be produced for the next several years.

The CF6-50C combustor contains 30 axial-flow swirl cups, concentric with each fuel nozzle. The combustor consists of four major sections which are riveted together into one unit and spot-welded to prevent rivet loss: the cowl assembly, the dome, and the inner and outer cooling liners. The combustor assembly is mounted at the cowl assembly by 30 equally spaced radial mounting pins. Mounting the combustor at the cowl assembly provides accurate control of the diffuser dimensions and eliminates changes in the diffuser flow pattern due to axial thermal growth. The inner and outer cooling liners each consist of a series of circumferentially stacked rings which are connected by resistance welded and brazed joints. The liners are film cooled by air which enters each ring through closely spaced circumferential holes. This combustor has three axial planes of dilution holes on the outer liner and four planes of dilution holes on the inner liner.

A photograph of the CF6-50 combustor assembly is presented in Figure 3. The combustor is designed to operate with a Mach number of 0.28 at the compressor discharge plane. This high velocity flow is diffused through an area ratio of 2.0 in an area-ruled prediffuser. This design is illustrated in the combustion system flowpath drawing shown in Figure 4 which includes envelope dimensions. Ten frame struts pass through the diffuser near the aft end of the prediffuser passage. The prediffuser walls are contoured to area-rule the passage around these airfoil-shaped strut sections. This area ruling minimizes strut wakes and strut wall interference effects. The passage area is then held constant for a distance of about 5.08 cm downstream of the strut trailing edges to mix out any remaining strut wakes. This design approach has proved to be very successful. Test results show that the diffuser pressure losses are very low and the strut wakes cannot be detected in the inner and outer passage airflows or in the temperature distributions at the combustor exit plane.

The Concept 5 combustor configuration was sized for the CF6-50 envelope with no length or diameter changes of the combustion casings.

Table II. CF6-50C Reference Engine Cycle Parameters.

Cycle Point	3.3% Idle	5% Idle	Approach	Climb	Takeoff	Hot Day Takeoff	Cruise
h_o, Flight Altitude, km	0	0	0	0	0	0	10.7
M_o, Flight Mach Number	0	0	0	0	0	0	0.85
F_N, Uninstalled Thrust, kN	7.4	11.2	67.3	190.5	224.2	224.2	48.1
W_3, Compressor Exit Airflow, kg/s	16.5	20.6	57.3	108.0	119.6	117.0	49.5
W_{36}, Combustor Airflow, kg/s	13.9	17.3	48.2	90.8	100.6	98.4	41.8
P_{T3}, Compressor Exit Total Pressure, MP_a	0.30	0.37	1.20	2.62	2.98	2.98	1.16
T_{T3}, Compressor Exit Total Temperature, K	437	463	632	792	826	863	733
W_f, Fuel Flow, g/s	152.6	178.2	664.5	1953.0	2376.0	2443.0	878.0
F_{36}, Combustor Fuel-Air Ratio	0.0110	0.0103	0.0138	0.0215	0.0236	0.0248	0.0210

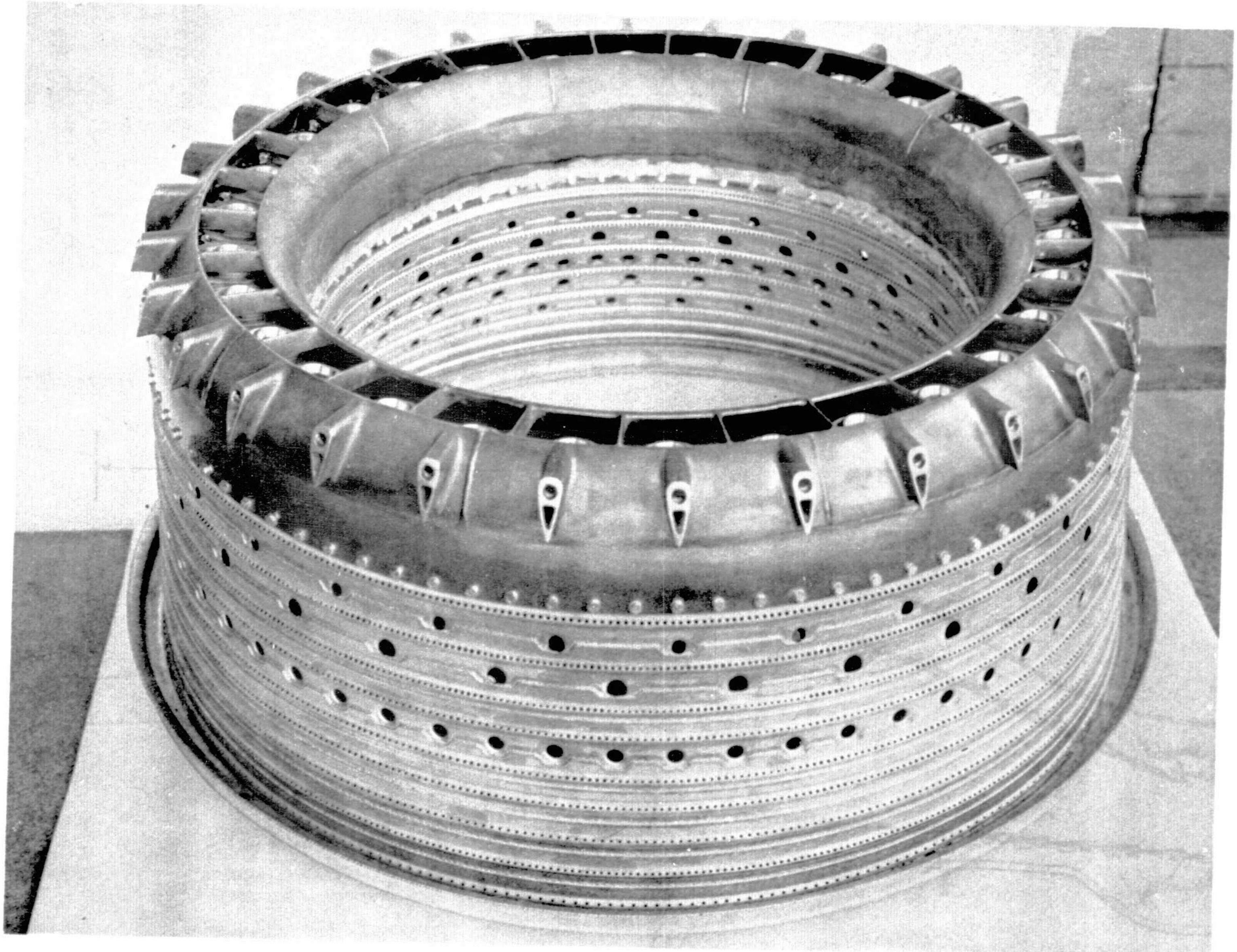


Figure 3. CF6-50 Combustor Assembly.

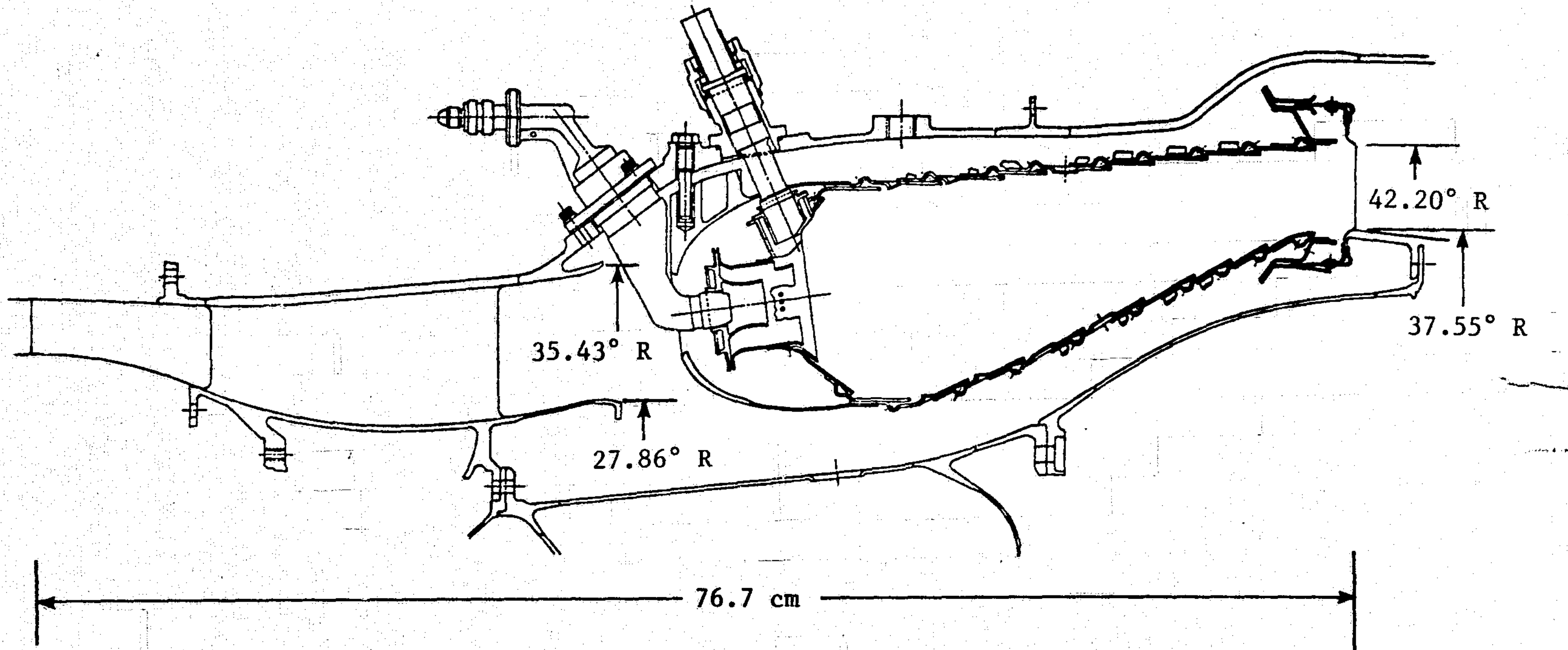


Figure 4. Production CF6-50 Engine Combustor.

4.0 GENERAL LPP COMBUSTOR DESIGN CONSIDERATIONS

In recent years, a number of experimental programs have been conducted to determine whether LPP combustion techniques can be utilized in aircraft gas turbine engines to reduce the emission levels of NO_x at high altitude cruise. The principles of LPP combustion are well understood and, as expected from chemical kinetic calculations, these experimental programs have shown that very dramatic reductions in NO_x emissions levels can be achieved, at least under ideal laboratory test rig conditions. However, these experiments have also pointed out that there are several key problems which must be solved before these techniques can be incorporated into practical combustor designs. These key problems are discussed in the following sections.

4.1 AUTOIGNITION AND FLASHBACK

One of the key considerations in the design of LPP combustor fuel preparation systems is the inherent possibility of autoignition of the fuel-air mixture upstream of the flame stabilization region. Autoignition occurs if the residence time of the fuel-air mixture exceeds the time for precombustion reactions to accelerate into the high heat release regime. A related design consideration is the possibility of flashback of flame from the flame stabilization region into the upstream fuel-air mixture. Flashback can occur if the velocity in any region of the combustible mixture is below the turbulent flame speed and if this low velocity region has access to the normal flame stabilization region. Either of these phenomena can cause major hardware damage, so the fuel preparation system must be designed to have adequate safety margin to prevent autoignition and flashback at all operating conditions.

Several references which are pertinent to autoignition in main combustor fuel preparation systems have recently appeared in literature. The scope of three investigations (References 4 through 6) which were considered most applicable to the LPP combustor design concepts and the combustor inlet conditions of the reference engine cycles is summarized in Table III. Predicted autoignition delay times based on results of these studies are shown for the key operating conditions of the reference engines in Table IV. Of the three autoignition investigations reported in the above cited references, Marek's apparatus and test conditions most resemble the LPP combustor designs of the current study. Based on the data reported in this reference, a minimum autoignition delay time of 3.9 ms is predicted for the reference engines at hot-day takeoff conditions. Stringer's tests, which were generally diesel engine oriented, were very comprehensive and his results are in general agreement with Marek's. Spadaccini employed a centered co-stream simplex atomizer mounted in a diverging test section, probably producing peaked fuel-air ratio and velocity profiles which would reduce the apparent autoignition delay times. He also found a very large pressure effect (1.8 power versus 1.0 in the other two studies), and his tests were limited to about 1.6 MPa. However, his results are in general agreement with those of Marek and Stringer, particularly at the lower pressure and temperature conditions.

Table III. Summary of Autoignition Test Apparatus and Conditions.

Reference	Fuel Injector/Duct Description	Fuel Types	Range of Test Conditions (Approx)				
			Air Velocity (m/s)	Air Temp (K)	Air Press. (MPa)	Equiv. Ratio	Delay Time (ms)
Marek, et al (4)	Upstream centered Simplex Atomizer in 10.2-cm dia. x 66-cm duct.	Jet A Ambient T.	10 to 40	590 to 833	0.5 to 2.5	$\leq$0.7	5 to 100
Stinger, et al (5)	Wall flush-mounted diesel injector in 4 x 4 x 36-cm duct.	Avtur (Jet-A) Avtag (JP-4) Diesel, 18 other pure, commercial & mixed fuels. Ambient T.	$\leq$21	770 to 980	3.0 to 6.0	0.2 to 7.0	0.6 to 5.0
Spadaccini (6)	Downstream centered simplex and air assist atomizers in 11.4-cm diameter diverging duct	JP-4, #2 & #6. Heating oils 305 to 450 K.	10 to 34	670 to 870	0.7 to 1.6	$\leq$0.15	6 to 50

Table IV. Comparison of Autoignition Delay Time Predictions at Reference Engien Design Conditions.

Reference Engine	Reference Engine Operating Conditions	T_3, K	P_3, MPa	F_{36}, g/kg	Autoignition Delay Time, milliseconds		
					Marek (Jet A) (Ref 4)	Stringer (Jet A or JP-4) (Ref 5)	Spadaccini (JP-4) (Ref 6)
E^3	Hot Day, Max Cruise	782	1.31	24.5	11.3	9.6 to 16.1	12.7
	Std Day Climbout	782	2.63	22.3	5.6	5.4 to 8.1	3.7
	Very Hot Day Takeoff	864	2.59	25.5	4.4	2.5 to 3.2	2.8
	Std Day Takeoff	814	3.02	24.3	4.4	3.3 to 4.7	2.4
	Hot Day Takeoff	851	3.01	25.9	3.9	2.4 to 3.1	2.2
CF6-50	Max Cruise	756	1.30	21.9	12.4	15.2 to 22.8	18.4
	Std Day Climbout	792	2.62	21.5	5.5	4.7 to 7.1	3.5
	Std Day Takeoff	826	2.98	23.6	4.3	3.0 to 4.2	2.4
	Hot Day Takeoff	863	2.98	24.8	3.9	2.3 to 2.8	2.1

Based on the above autoignition delay results, the LPP combustors were designed to have a maximum fuel-air mixing zone residence time of less than 2.0 ms.

Flashback characteristics are even more difficult to generalize than are autoignition characteristics. The tendency will, of course, increase with mixture flame speed, which depends upon pressure, temperature, equivalence ratio, turbulence level, and fuel type. Mixture flow velocity must certainly exceed the flame speed or flashback will occur. In practice, however, the nominal mixture velocity must be well above the flame speed in order to avoid flashback because of spatial and time fluctuations in stream properties.

Plee (Reference 7) has recently published a review of flashback reported in LPP combustors and has concluded that, to date, classical flashback, which is defined as flame propagation through the boundary layer, has not been observed in noncatalytic combustors burning jet fuels and propane. According to this reference, upstream combustion which has beeen intepreted as flashback has been the result of autoignition, particularly in separated flow regions, or flame propagation through reverse flow fields. These observations indicate the importance of avoiding diverging sections, and obstructions within the premixing tube which can cause flow separation. Because of the strong effects of details of the premixing tube geometry, a general correlation for flashback could not be developed.

In the current program, results of a series of flashback tests conducted at General Electric in conjunction with the F101 engine combustor development program were used in the design of the LPP combustor fuel preparation systems. These results are summarized in Figure 5. These data were used in the design of the NASA/GE ECCP radial/axial staged combustor, which provided many hours of flashback-free operation.

4.2 FUEL-AIR MIXING AND VAPORIZATION

NO_x formation rates vary exponentially with flame temperature, and in lean mixtures flame temperature is directly proportional to equivalence ratio (and inlet temperature). Because of this nonlinear relationship between NO_x formation rates and equivalence ratio, the NO_x emissions levels of real liquid-fueled combustors are highly dependent upon the effectiveness of the specific fuel-air injection/mixing devices as well as global operating conditions. Therefore, one of the key LPP combustor design problems is to identify and incorporate fuel-air preparation systems which provide a high degree of fuel vaporization and mixedness while also meeting other design requirements including autoignition delay criteria, space limitations imposed by the reference engine combustor envelope, and system reliability and durability requirements.

Several recent studies have been conducted which indicate the strong dependence of NO_x emission on the degree of fuel evaporation and fuel-air

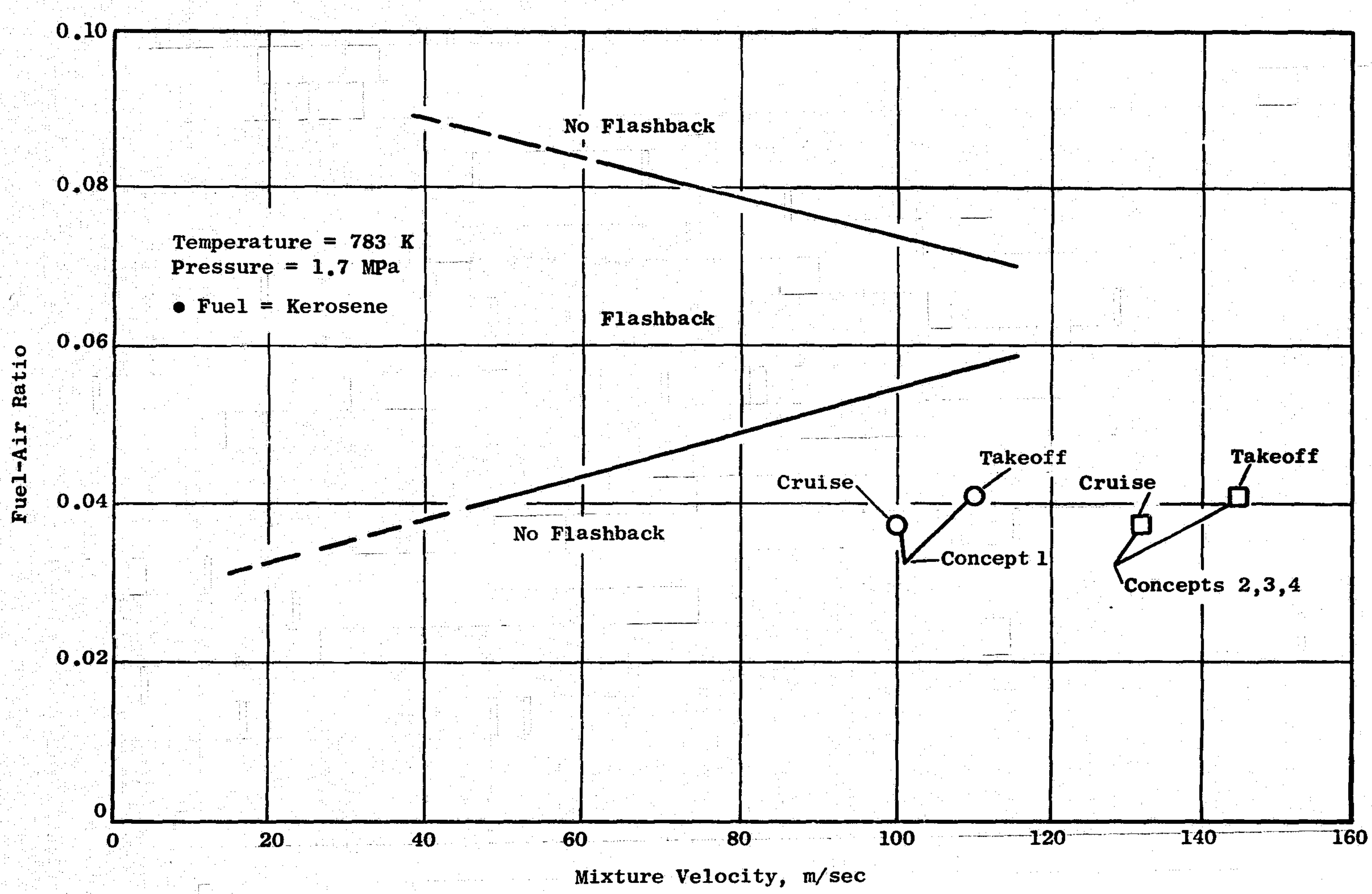


Figure 5. General Electric Flashback Test Data, Premixing Combustor.

mixture uniformity. Key results of two studies conducted by Roffe (References 8 and 9) are shown in Figure 6. These results have been corrected to the normal cruise operating conditions of the reference engine using correction factors based on parametric test data found in References 9, 10, 11, and 12, which show the effects of combustor residence time and inlet temperature and pressure. As shown in Figure 6, variations in fuel injection/mixing technique can result in more than an order of magnitude change in NO_x emission levels. In these tests, the best results (labeled curve b, 12-orifice wall ring injector in an 8.9-cm diameter duct with 53-cm mixing length) were very close to the theoretical (thoroughly premixed) emission levels. Shortening the mixing length to 33 cm (curve c) with otherwise the same system nearly tripled the NO_x emission levels. The NO_x levels, however, were still comfortably below the proposed program goals. Injection techniques which utilized pressure-atomizing spray nozzles (curves d, e, and f) probably provided better fuel atomization relative to the single-wall jets, but the NO_x levels were much higher, indicating less fuel penetration and/or spreading.

The explicit dependence of NO_x emission on fuel-air mixture uniformity has recently been demonstrated by Lyons (Reference 13). In her tests, Jet A fuel was burned in a flame tube having a multiple conical tube fuel injector and a perforated-plate flameholder. Nonuniform fuel-air mixtures were produced by fueling selected tubes of the injector, and both fuel-air profile and NO_x emissions were measured. Resulting mass-weighted average NO_x emission indices are shown in Figure 7 as a function of inlet air temperature and a fuel-air nonuniformity parameter, s, which is the standard deviation of the equivalence ratio profile. As indicated by this figure, at all temperatures, the NO_x emission index was doubled as the fuel-air nonuniformity parameter was increased to a value between 0.07 and 0.09.

Another recent experimental investigation has been conducted by Cooper (Reference 14) to determine the effect of fuel vaporization on CO and NO_x emissions from a lean premixing-prevaporizing combustion rig. In these tests, Jet A fuel injected through multiple jet cross-stream and multiple conical tube injectors was burned downstream of a perforated-plate flameholder. NO_x and CO emissions as a function of equivalence ratio, inlet temperature, and degree of vaporization are shown in Figure 8. As indicated by this figure, the degree of fuel vaporization had very little effect on NO_x emission at an equivalence ratio of 0.72. At a lower equivalence ratio (0.6), the effect was stronger but was still significantly weaker than that of mixture nonuniformity. The effect of vaporization on CO emissions varied depending on distance downstream of the flameholder. Close to the flameholder (48 cm), CO decreased with increasing vaporization, but further downstream (79 cm), vaporization had little effect. It is estimated that at the upstream measurement point, combustion residence times were on the order of 4 ms. Since practical LPP combustors for aircraft applications are expected to provide residence times of about 2 ms, it is probable that the effect of incomplete vaporization on CO emissions will be somewhat stronger than that shown in Figure 8(b).

		L_{mix} (cm)	D_{mix} (cm)	$\left(\frac{L\sqrt{N}}{D}\right)_{mix}$
(a)	Thoroughly Premixed Calculation	---	---	---
(b)	12-Point Wall Ring Injector (Normal)	53	8.9	20.6
(c)	12-Point Wall Ring Injector (Normal)	33	8.9	12.8
(d)	4-Point Wall Nozzles (Normal)	49	7.65	12.8
(e)	1-Point Centered Nozzle (Upstream)	57	8.9	6.4
(f)	1-Point Centered Nozzle (Downstream)	48	8.9	5.4

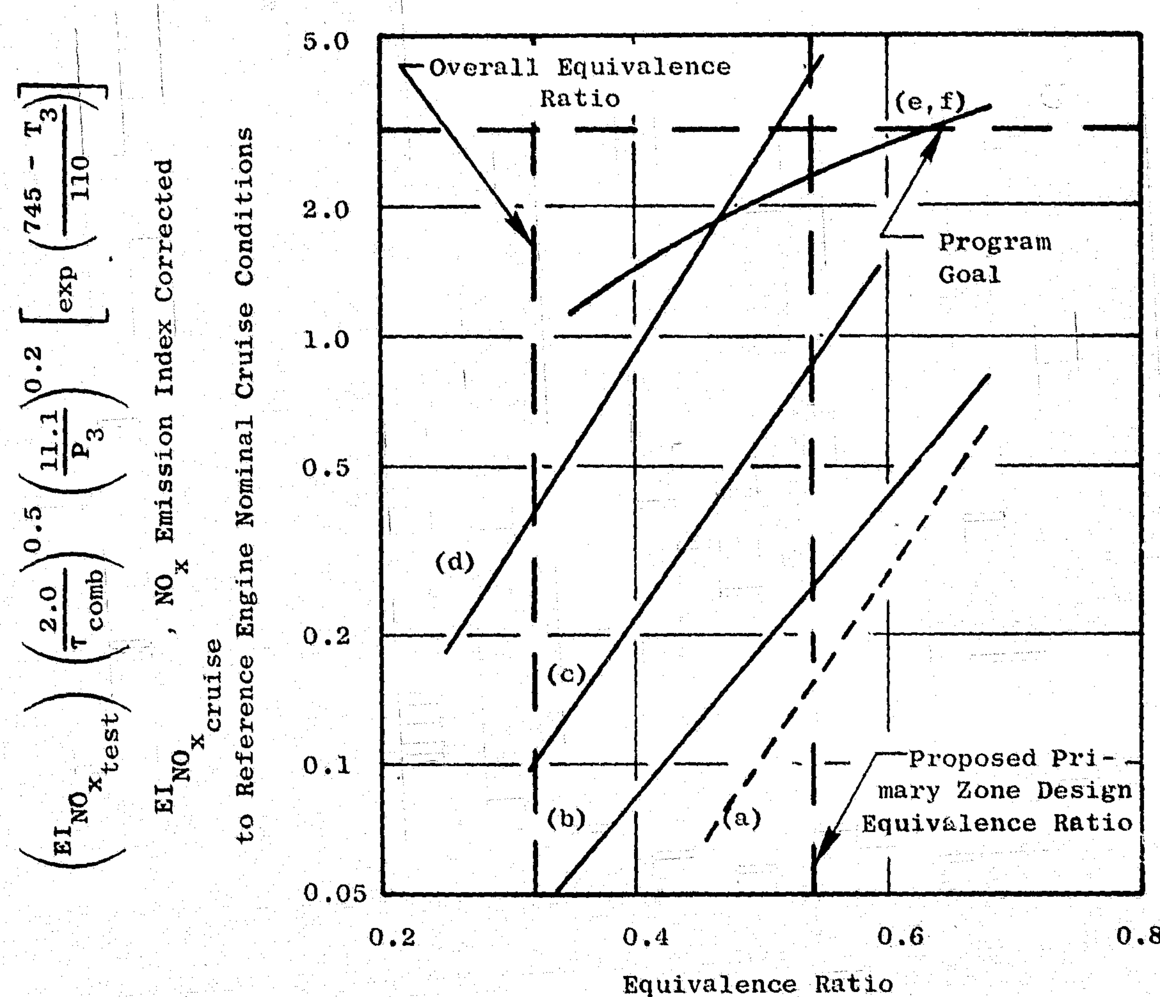


Figure 6. Effect of Fuel-Air Premixing on NO_x Emission Levels.

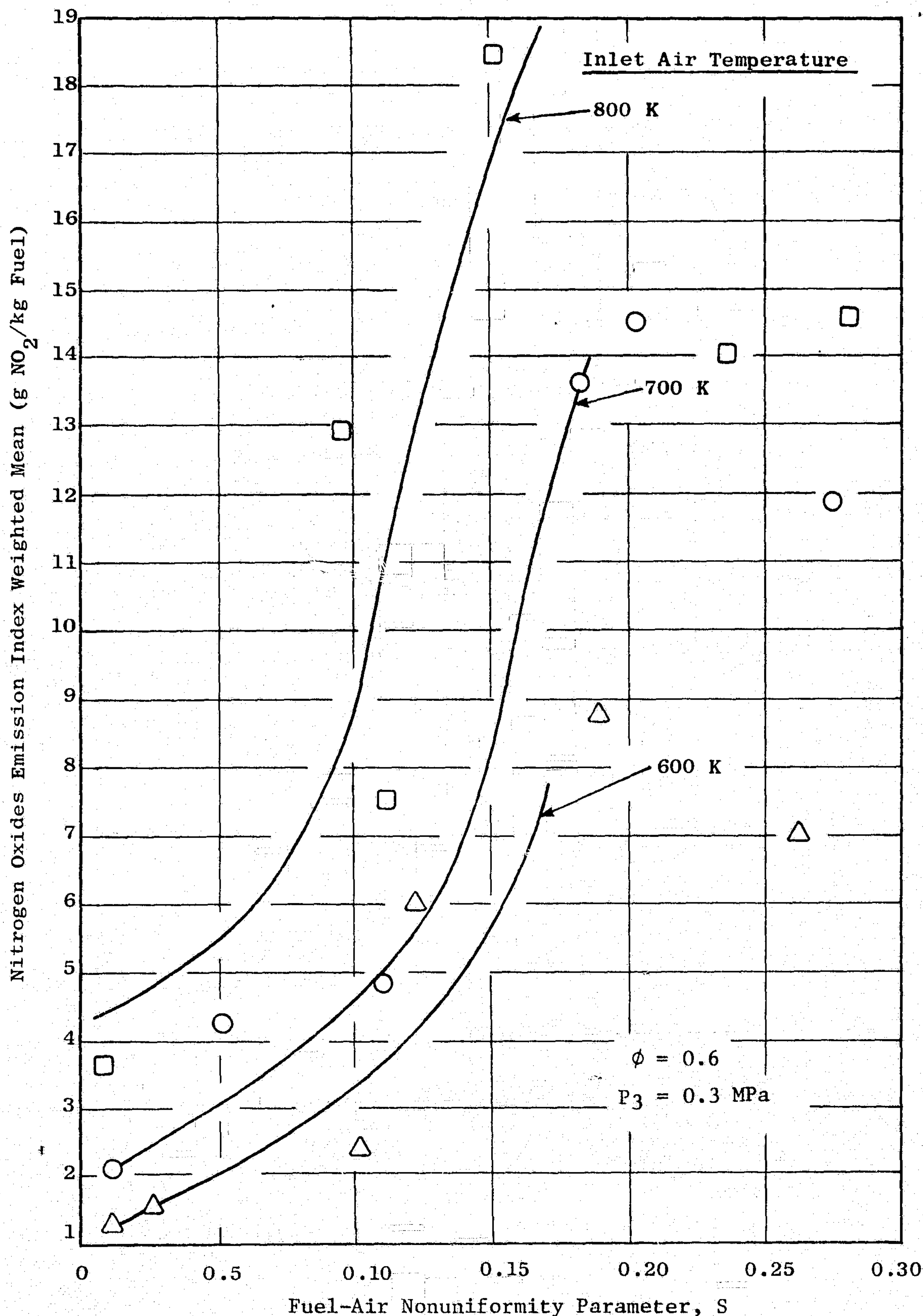
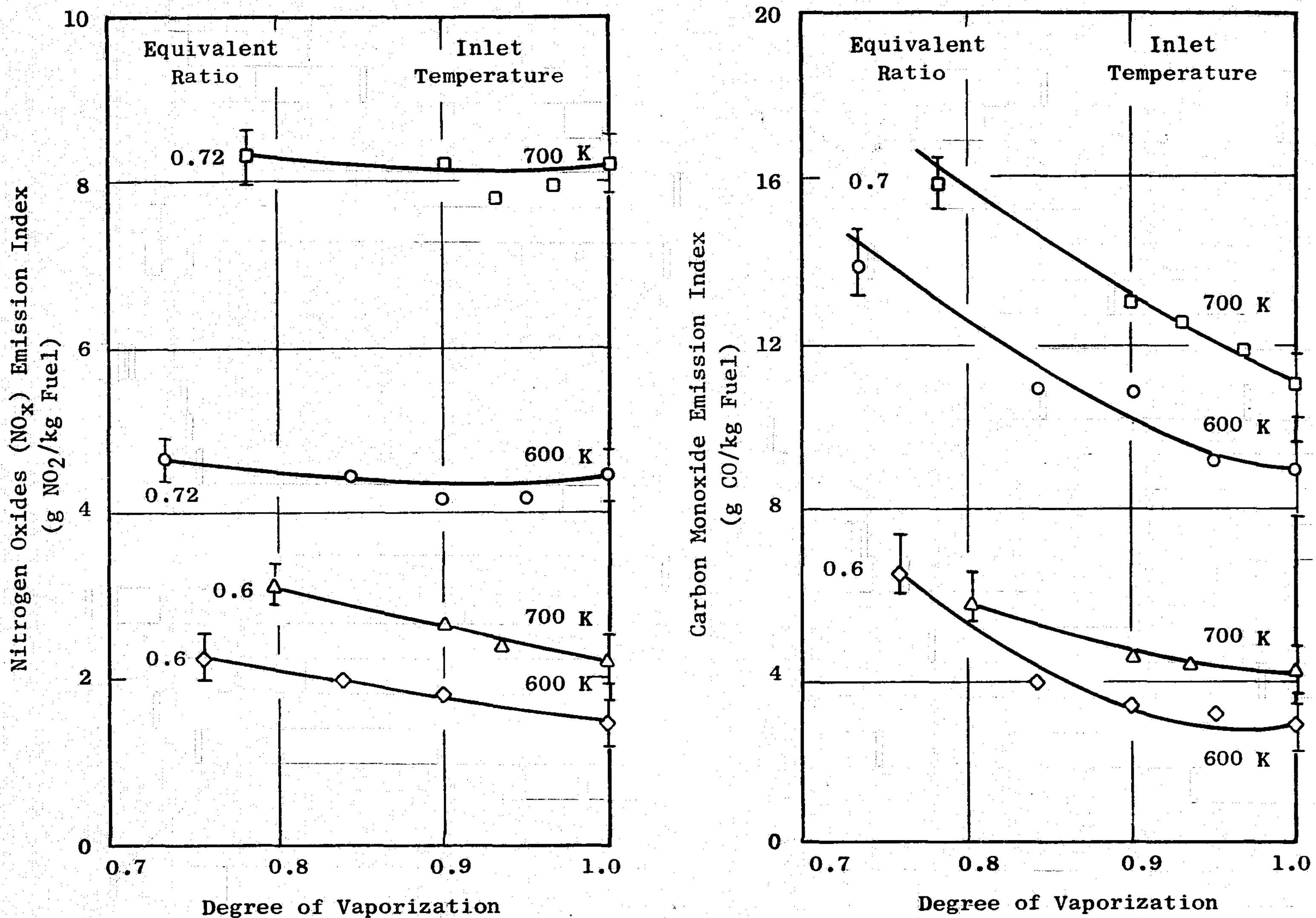


Figure 7. Effect of Fuel-Air Nonconformity and Inlet Temperature on NO_x Emissions.



(a) Oxides of Nitrogen

(b) Carbon Monoxide (Probe Position = 48 cm)

Figure 8. Effect of Vaporization on NO_x and CO Emissions.

Precise a priori prediction of evaporation and fuel-air mixture uniformity for a given fuel preparation system is difficult because of the complexity of the evaporation and mixing processes in turbulent flows containing multiple-component fuel droplets having time and space varying sizes and relative velocities. Therefore, several recent experimental investigations have been conducted to develop premixing fuel-air preparation systems. Two of these efforts, which were specifically aimed at the development of fuel preparation systems for gas turbine catalytic combustors, are summarized in References 15, 16, and 17. In these references, mixer outlet velocity and fuel-air ratio profile data are presented.

Roffe (Reference 15) met program goals and obtained best results with an air-assist spray nozzle/compound swirler system. The data suggest that the swirler configuration was a more important ingredient than was the air-assist atomization feature. By varying the swirl angle form hub to tip, Roffe was able to obtain very flat fuel-air ratio and velocity profiles in quite short mixing lengths ($L \sqrt{N}/D = 6.0$ where L is the duct length, D the duct diameter, and N the number of injection points) relative to those used in References 8 and 9, and the pressure drop was still less than 1 percent.

Tacina (Reference 16) investigated pressure and air atomizers with swirlers (not compound) and simple multiple jet spraybars with normal and contra-stream injection. He obtained best results with a 28-point cross-stream injection in a 7.6-cm-diameter duct with a mixing length of 39.4 cm ($L \sqrt{N}/D = 27.4$). He also obtained very uniform profiles, high degrees of vaporization, and a very low pressure drop (less than 0.5 percent).

In a similar study (Reference 17), Tacina investigated three airblast atomizers and an air-assist nozzle in a 12-cm duct with mixing lengths between 12.7 and 25 cm. Best results in this study were obtained with a multiple conical tube injector in which 21 cones were used to provide increased atomizing air velocity and straighten the inlet airflow. With this injector, uniform profiles and nearly complete fuel vaporization were obtained with mixing lengths greater than 17.8 cm ($L \sqrt{N}/D = 6.8$). Total pressure loss was less than 1.0 percent. Tacina's operating conditions were far less severe with respect to autoignition than those of the proposed reference engine. Cross-stream wall-mounted spraybars (for example: the ones used in the multiple conical tube injector) would form wakes which would be accentuated by the diverging mixing duct. Therefore, in the LPP combustor designs prepared for the current program, axially mounted spraybars and converging mixing sections were used wherever practical.

For the current study, estimates of fuel evaporation and fuel-air mixture uniformity were obtained using correlations presented in References 18, 19, 20, 21, and 22. Estimates of fuel evaporation were obtained with a computer program which provides an iterative solution to the droplet evaporation equations of El Wakil, Uyehara, and Meyers (Reference 18) using initial drop sizes calculated and a correlation from Ingebo and Foster (Reference 19). Fuel spreading was estimated based on experimental results reported by Bahr (References 20 and 21) and theoretical considerations contained in Reference 22 (Longwell and Weiss).

In addition to fuel evaporation and fuel-air mixture uniformity, other considerations in the design of fuel injection systems for aircraft gas turbine LPP combustion systems include practical limitations on fuel injector size, quantity of fuel injection points, and combustion system inlet distortion and turbulence. Ideally, a very large number of very thin fuel injectors would be used to uniformly dispense the fuel with a minimum disturbance to the airflow. However, in order to avoid fouling of the internal fuel injector passages, it is desirable to insulate a major portion of the injector by using double-wall construction. Thus, careful design is required to provide aerodynamically clean injector profiles. Similarly, although a very large number of fuel injection orifices would be desirable to provide uniform dispersion of the fuel, the quantity of fuel injection points is limited by fuel orifice size and pressure drop. Previous experience at General Electric indicates that orifice diameters should be larger than 0.5 mm and minimum orifice pressure drop should be above about 0.1 MPa to provide uniform fuel distribution while avoiding orifice plugging. This limits the allowable number of orifices to 150 for injection of all of the fuel at the minimum cruise condition for the reference engine cycle. Although the number of fuel injection points, and therefore the density of injection points, is limited by the above considerations, fuel-air mixing in an actual engine application could be significantly improved by the high turbulence levels of the air exiting the compressor. On the other hand, careful diffuser and injector design are required to minimize the effects of nonuniform compressor exit velocity and temperature profile on mixture and uniformity.

4.3 FLAME STABILIZATION

The mechanism by which flame propagates through a fuel-air mixture is the forward transport of hot gas containing free radicals from behind the flame front to mix with and ignite the unburned mixture ahead of the flame front. The gas transport is accomplished basically by molecular diffusion. If the unburned mixture is turbulent, the gas transport is augmented by turbulent diffusion so that the flame propagation speed is greater. With very lean mixtures, the chemical reaction rates that release the heat are slowed and may fall behind the turbulent mixing rates, resulting in a quenching process that prevents flame propagation. At still leaner conditions, the burned gases have insufficient energy to ignite the unburned mixture at any mixing rate. The flame speed is sensitive to the temperatures of the unburned and burned gases.

Flame propagation speeds, even augmented by turbulence, are generally much less than the through-flow velocity of practical combustion systems. To maintain stable combustion in a flow duct, a flame stabilizer must be used. The flame stabilizer generally provides a sheltered region in which burned gases recirculate to mix with and ignite the incoming fuel-air mixture. Generally, flame stabilization devices which have been employed in gas turbine combustion systems are basically perforated plates, screens, swirlers, vee-gutters, or combinations of these devices.

The reported lean stability limits in terms of combustor equivalence ratio for a perforated-plate flameholder investigated in Reference 23 are shown as a function of combustor inlet air temperature in Figure 9. These limits are typical of lean stability characteristics obtained in several LPP combustor programs in which either cones or perforated-plate flameholders were employed. Also indicated in this figure is the maximum equivalence ratio permissible to obtain NO_x emissions of less than 2 g/kg, which provides some margin relative to the program goal. These NO_x emission data (reported in Reference 24) were obtained in the same test rig, again utilizing a perforated-plate flameholder. As indicated in this figure, lean stability limits of these systems were very near the selected design point stoichiometry. This is a problem the combustor designer has encountered before, particularly in the design of augmentors.

The traditional approach for increasing the margin between the design operating point and the stability limits has been to increase either the combustor equivalence ratio or the size of the stabilizer recirculation zone. In the case of the LPP combustor, where NO_x emission levels are of prime concern, it would be desirable to increase the recirculation zone size rather than the equivalence ratio. However, even this approach must be carefully applied, since NO_x emission levels are dependent upon combustor residence time as well as equivalence ratio. One example of the tradeoff between stability limits and NO_x emission levels is contained in Reference 12, which is reported in Figure 10. Lean blowouts were significantly lowered as the flameholder recirculation zone size (and hence residence time) was increased. NO_x emission levels, however, increased by factors of two to three. Presumably, this comparison was made at a constant bulk residence time in the combustor primary zone which was probably 2 ms. Most of the perforated-plate flameholder data indicate that this time is sufficient to attain the target combustion efficiency levels (99.9 percent), but these tests have not included actual combustor secondary zone dilution. In the case of flameholders with increased recirculation zone residence time, it may be possible to shorten the bulk residence time and, hence, provide a more favorable tradeoff between stability margin and NO_x emission levels. On the other hand, flame stabilizers with small recirculation zones are most often selected to increase flame spreading rates and thereby reduce residence time required to achieve the target combustion efficiencies.

A more recent experimental study sponsored by NASA (Reference 25) indicates that the effects of flameholder geometry may be weaker with thoroughly premixed systems than is indicated in Figure 10. In this study, several different types of flameholders were tested to evaluate their emission and performance characteristics. The types of flameholders tested included wire grid, perforated-plate, single and multiple cone, vee-gutter, and swirler configurations having blockage values between 60 and 83 percent. Tests indicated that at 800 K and 1 MPa inlet conditions the lean stability limit corresponds to an adiabatic flame temperature of 1700 K, and that the lean stability limit is not strongly affected by flameholder geometry. It was reported that CO, NO_x, and HC emissions all tend to decrease with increasing pressure drop, but that details of flameholder geometry which do not affect

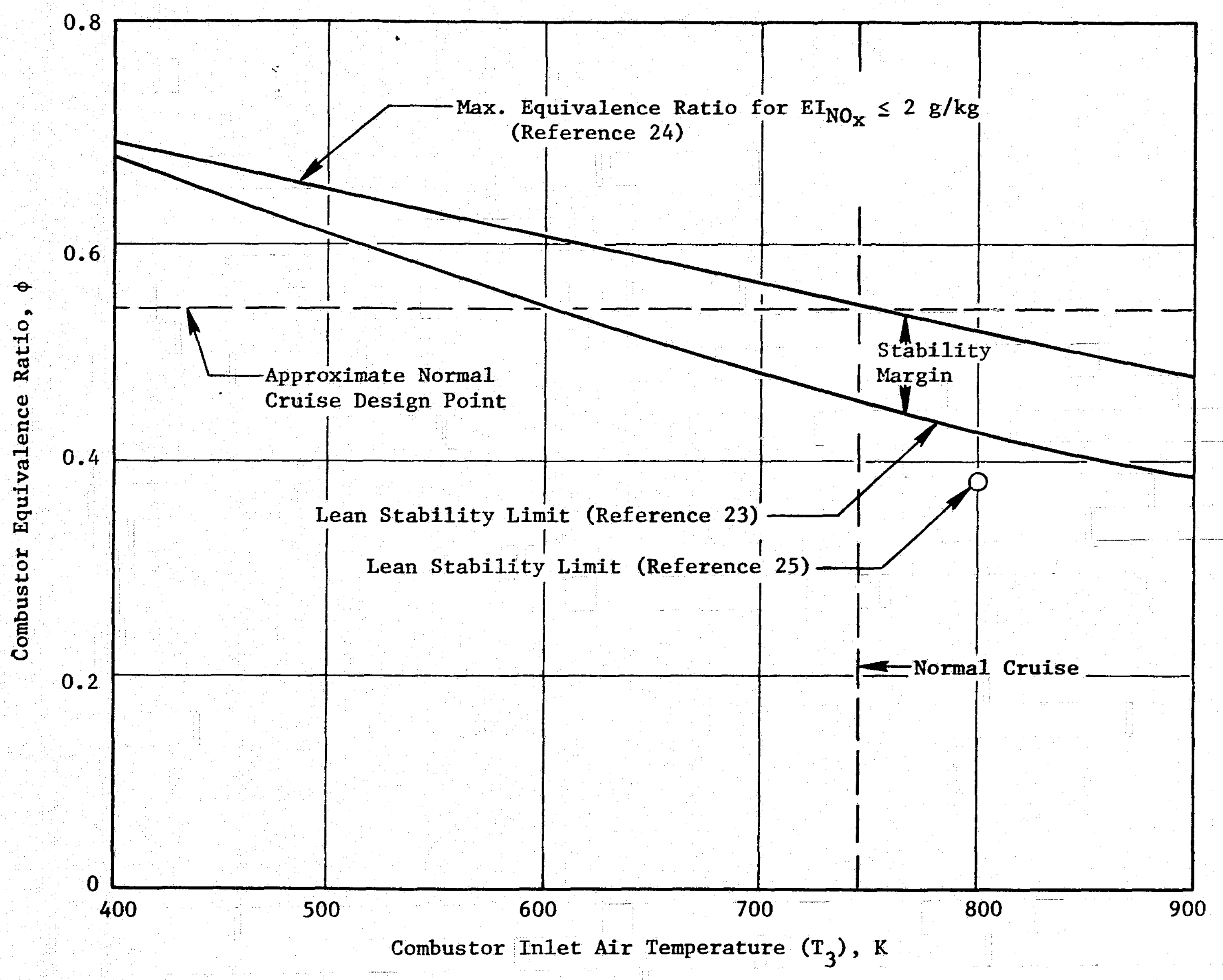
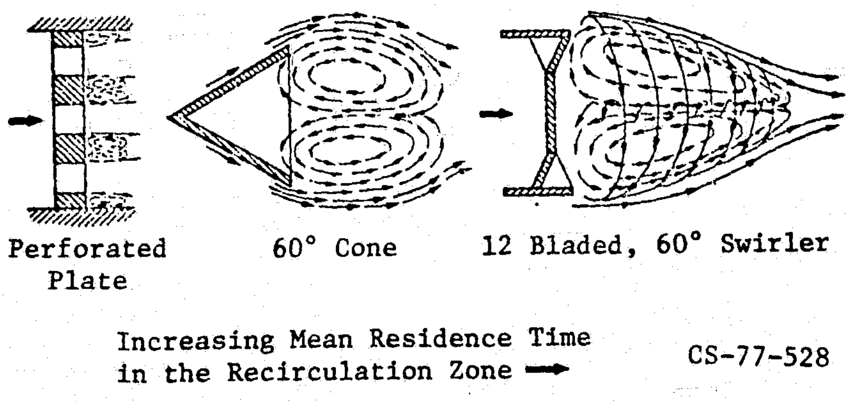


Figure 9. Research LPP Combustor Lean Stability Limits.



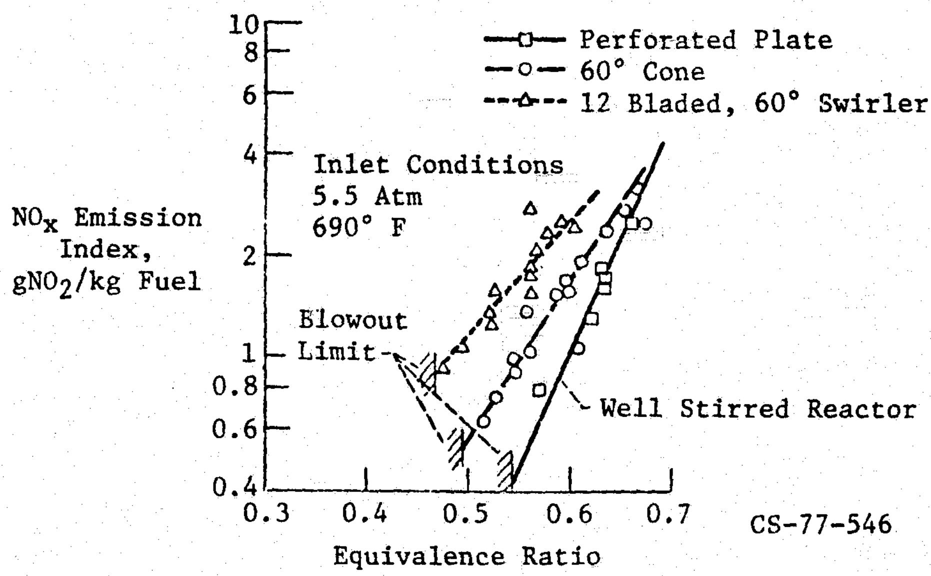


Figure 10. Effect of Flameholder Geometry on LPP Combustor Lean Blowout Limits and NO_x Emission Levels (Reference 9).

pressure drop are of second order importance. Duerr (Reference 26) tested a conical flameholder that was positioned to provide either 56 or 80 percent blockage. With very lean mixtures (adiabatic flame temperatures less than 1900 K), he reported reduced NO_x emissions with increased blockage, which is in agreement with trends reported in Reference 25. At flame temperatures above 1900 K, however, NO_x emissions increased with increasing blockage, apparently as a result of increased recirculation zone length and residence time. As indicated by the above discussion, there is still some question about the effect of flameholder geometry on emissions and performance. Therefore, for the current design study, flameholder configurations were selected based primarily on mechanical design considerations (strength, flameholder cooling, and ease of manufacture) and on combustor pressure drop requirements. A study of the effects of flameholder geometry in practical LPP combustion systems will be conducted as part of a subsequent combustor development program.

As described above, LPP combustor operation close to the lean stability limit is required to meet the program NO_x goals. In order to meet these goals and also meet the full-range operational requirements of the reference engine, it would be desirable to extend the lean stability limit through some form of lean combustion augmentation.

One of the most positive techniques for stability augmentation without incurring a significant NO_x emissions penalty is fuel modification, preferably through hydrogen enrichment. A considerable number of internal combustion engine studies have been made of this approach, including development of techniques for on-board generation of hydrogen from liquid fuels. Further, Anderson has conducted experiments in the same LPP combustor rig used in Reference 11 which clearly show the benefits of even very small quantities of hydrogen injection (Reference 27); however, the complexity of a hydrogen system makes it undesirable.

Another technique for stability augmentation which often has been considered is to increase the combustion mixture inlet temperature by regeneratively heating either the air or fuel. Marek (Reference 28) observed that the added stability induced by increasing the inlet air temperature to a premixed burner permitted the equivalence ratio to be reduced enough to more than compensate for the increased NO_x emission caused by the higher temperatures. Further, if the fuel were prevaporized, a more uniform mixture should be easier to obtain. Fuel heating and/or complete vaporization is, however, difficult to accomplish throughout the needed operating range without encountering thermal stability problems which cause fuel system gumming and plugging. Also even small degrees of preheat aggravate the autoignition problem.

Another method which has been proposed to improve lean stability limits is to reduce the heat loss from the flame zone by increasing the flameholder and/or adjacent liner surface temperatures, possibly by the use of thermal-barrier coatings. Flameholders constructed from silicon carbide or ceramic composites might allow even higher surface temperatures. Presumably, if reduced heat loss improves lean stability limits, then heat addition through the use of a catalyzed flameholder surface would provide further improvement. However, in recent tests reported by McVey (Reference 29), no significant improvement in blowout limits was obtained with a catalyzed tube flameholder.

In McVey's study, in which self-piloting, catalytic, and piloted flameholders were evaluated for their ability to augment lean combustion, only the piloted flameholder provided an appreciable reduction in lean stability limit. In this design, a portion of the fuel was injected directly into the combustion zone through orifices in the flameholder. This direct injection technique is similar to the use of a pilot burner, a technique which has long been used in afterburners and duct burners, and more recently in multistage low-emission combustors. In the case of low-emission main combustors, a pilot stage is needed for lightoff and low-power operation with all of the fuel supplied to it, but the function at high-power operating conditions can vary somewhat. For example, in a parallel-staged combustor, the pilot and main stages are essentially independent. Stable combustion can be maintained with all of the fuel supplied to either stage, or with the fuel split between the stages. Conversely, in a series-staged combustor, the pilot stage is used to stabilize the main stage by providing a continuous ignition source.

If a pilot stage is fueled at high-power operating conditions, it must be designed to operate at conditions which not only provide the desired stability augmentation but also do not compromise the NO_x emission levels. For example, if 10 percent of the fuel is supplied to the pilot stage and its NO_x emission index is 10 g/kg, then the other 90 percent of the fuel which is supplied to the main stage must produce a NO_x emission index of 2.2 g/kg or less in order to meet the overall NO_x emission goal of 3.0 g/kg for the LPP combustor design program.

In this program, both parallel and series-staged LPP combustor designs were investigated. These designs are described in Section 5.0.

4.4 AIRFLOW MODULATION

Although LPP combustor lean stability limits can be augmented by the techniques described in the preceding section, none of the techniques mentioned are sufficient to meet the program emission, performance, and operational capability requirements over the full range of combustor operation without additional airflow modulation or fuel flow distribution control. Additional control is required to maintain local stoichiometry between the lower limit set by lean blowout and the upper limit required to meet the NO_x emission goals. As indicated in Tables I and II, combustor fuel-air ratio is more than doubled between the idle and takeoff operating conditions of the reference engines. Even between the approach and takeoff conditions, which is the required range of operation for the LPP stage of a multistage combustor having a conventional pilot, fuel-air ratio can increase by a factor of over 1.8. In a design without airflow modulation of fuel distribution control, an LPP stage equivalence ratio of about 0.5 or greater would be required for stable operation at approach conditions (Figure 9, T_3 = 633 K).

The resulting equivalence ratio would be about 0.9 at standard day takeoff, and about 0.8 at normal cruise. Under these conditions, NO_x emission would be well above the program goals.

One method to obtain LPP stage stoichiometry within acceptable limits is through the use of devices to modulate airflow to the various zones within the combustor. This airflow modulation is used to control local stoichiometry within the combustor, so that both the pilot zone and the premixed reaction zone are sufficiently rich to provide low CO and HC emissions yet lean enough to avoid high NO_x emission.

Airflow modulation devices can be classified both by physical makeup and position and by operational characteristics. Physically, airflow modulation features can be either: (1) mechanical variable geometry systems in which vanes, pistons, or other devices are used to vary flow-metering areas of the combustor, or (2) fluidic devices in which bleed is used to control the direction of a high velocity airstream. Airflow modulation features can be incorporated into the inlet diffuser, combustor dome, premixing ducts, or liner dilution or cooling holes.

In terms of operational characteristics, airflow modulation systems can be either compensated, where an area or pressure reduction in one region of the combustion system is accompanied by an area or pressure increase in another region to maintain constant pressure drop, or uncompensated, where overall combustor pressure drop is allowed to vary. Finally, these devices can be designed to provide either continuous or discrete modulation. Generally, it is desirable in terms of combustor performance to use a compensated system having continuous modulation capability. However, such a system is likely to be mechanically complex.

Another method for control of local stoichiometry is the use of fuel distribution control. In an annular combustor, local fuel-air ratio can be controlled by admitting fuel through injectors in a partial sector of the annulus, thus increasing the local fuel-air ratio in the fueled sector. With this method, local fuel-air ratio is inversely proportional to the size of the fueled sector, so that a high degree of control is possible. One limitation placed upon sector burning concepts is that the maximum temperature limits for the turbine must not be exceeded. Therefore, at maximum engine power conditions where the turbine inlet and cooling air temperatures are at their maximum values, only full-annular burning is utilized. At reduced power conditions where temperature margins exist because of lower temperature and fuel-air ratios, sector burning can be used advantageously to improve local fuel-air ratios for improved combustion performance. Various forms of sector burning have been demonstrated on several General Electric engines. One form of sector burning used in production engines is a configuration where alternate fuel injectors are not fueled at some reduced power conditions. This arrangement is utilized on the F101 and the CF6 engines. Another form of sector burning involves burning with groups of adjacent nozzles. Examples of this type of sector burning that have been successfully used include 180° sector burning and 270° sector burning (270° of dome fueled, 90° unfueled). These arrangements have both been demonstrated in cyclic engine endurance tests and in flight tests.

4.5 ENGINE CONTROL REQUIREMENTS

The major consideration in the design and development of control systems for engines incorporating LPP combustion systems with variable geometry for airflow control is the requirement for additional control functions to maintain combustor stoichiometry within acceptable operating limits during both steady-state and transient operation. Precise control of fuel and air flows to the various combustor stages will be essential to ensure stable operation and exploit the inherent advantages of the LPP combustion system.

In multistage LPP combustor designs, the combustor fuel flow must be divided and controlled to each combustor stage. Under low-power conditions, the control system must direct the fuel to the pilot burner. As power demand is increased, the control system must automatically direct the fuel to the LPP combustor and reduce the fuel to the pilot burner.

Where airflow modulation is employed, the engine control system must properly position the LPP combustor variable geometry for airflow control. At low power during operation on the pilot burner, the air valve is closed. As power is increased, the air valve is opened to allow LPP combustor operation. The air valve modulation must be integrated with the fuel flow control. Additional airflow control is also necessary for regulation of the burner pressure drop in designs having compensated variable geometry.

In addition to control requirements for steady-state operation, the control system must include provisions for transient operation, including engine acceleration and deceleration, and recovery from blowout and compressor stall.

Acceleration fuel metering in conventional fuel controls depends upon simple relationships between compressor discharge static pressure and total pressure at the choked turbine diaphragm. The requirements of LPP combustors will upset this relationship so the control logic will have to accommodate this change. Present decelerations are performed against rather simple fuel limits. It is anticipated that major changes in this area are required since the LPP combustor emphasizes combustion under minimum fuel-air ratio conditions. Present control practice for setting minimum fuel limits is based on combustor pressure and fuel flow and does not consider inlet temperature or local conditions within the combustor. Therefore, more sophisticated minimum fuel-limiting logic is required for operation of the LPP combustor designs.

Another important transient which must be considered is the control action required for initiation of an "air start" following a blowout. For instance, it may be necessary to perform a modified start sequence including repositioning the variable geometry and use of the pilot burner. The in-flight sequence would be different from the ground-starting sequence because it is desirable to perform it as rapidly as possible and at as high an rpm as possible without waiting for stable conditions.

The NASA/GE E^3 design, which served as a reference engine for this program, includes full authority digital electronic control of all engine variables. This type of system has more-than-adequate capability to meet the control requirements of the LPP combustor.

5.0 LEAN PREMIXED-PREVAPORIZED COMBUSTOR CONCEPTS

During this LPP design study program, five combustor designs were selected for preliminary design and performance analysis. Each of these combustor designs incorporates premixed-prevaporized fuel-air mixture preparation features together with fuel staging and airflow modulation devices. These features provide means of optimizing the combustion parameters, such as fuel-air ratios, velocities, etc., in the combustion zone to meet the very challenging program goals for emission, performance, life, and engine operating characteristics. Four of the concepts, sized for the GE/NASA E^3, were designed to the same overall combustion length of 36.83 cm from the compressor outlet guide vane trailing edge to the turbine nozzle diaphragm leading edge. This combustion length is 7.24 cm longer than the standard E^3 combustor length. This small extra length was deemed necessary to incorporate fuel premixing and variable geometry devices.

The fifth design incorporates the same features as Concept 1 but was sized for the existing length and flowpath of the CF6-50 engine. This latter study demonstrates the scaling of an LPP combustor design to another size engine.

Drawings of all five of these combustors were generated and are presented in Figures 11 through 15.

5.1 SWIRL TUBE COMBUSTOR WITH VARIABLE AREA SWIRLERS - CONCEPT 1

The swirl tube combustor, Concept 1, is shown in Figure 11. This combustor is shown as sized for the E^3 cycle and envelope (except for the length increase indicated above). This swirl tube combustor has 28 conical premixing tubes spaced around the combustor dome annulus. Variable-vane primary swirlers control the airflow into each of the premixing tubes, and dual-orifice pressure-atomizing fuel nozzles are centered in each of the primary swirlers at the inlet plane of the tube. Fixed-vane counterrotating (direction of the swirl is opposite to that of the primary swirlers) secondary swirlers are concentric with the premixing tubes at the dome end of the combustor. The combustor is a short-length, single-annular design with one stage of dilution flow.

At cruise and takeoff operational conditions, the primary swirl vanes are at the maximum open position, which admits about 47 percent of the compressor discharge airflow into the premixing tubes with a swirl angle of about 15°. The premixing tube equivalence ratio at takeoff conditions is about 0.67, and the swirl angle is small to minimize the mixing time by avoiding nonuniform velocity profiles in the premixing tubes.

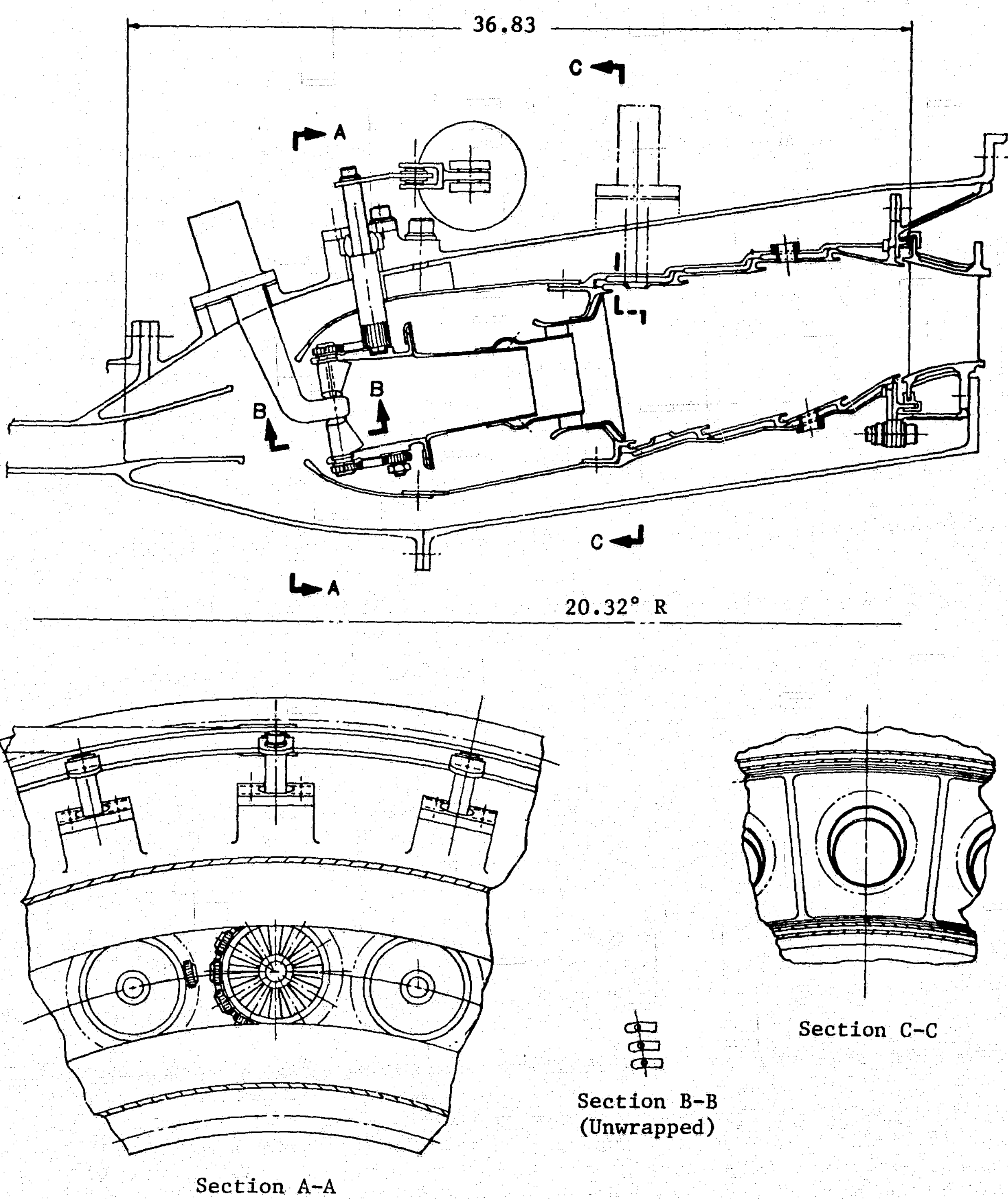


Figure 11. Swirl Tube Combustor with Variable Area Swirlers - Concept 1.

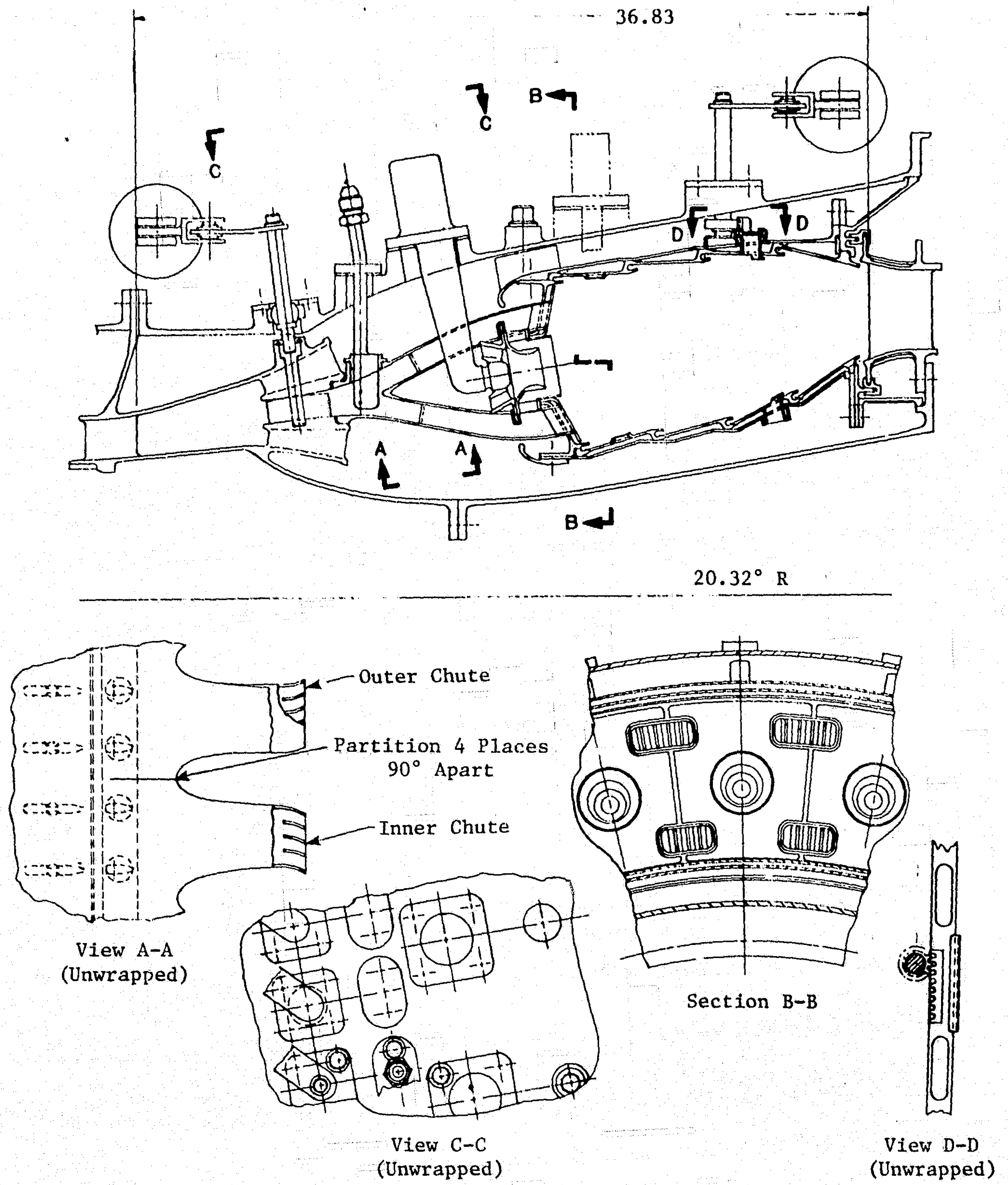


Figure 12. Multiple Duct Combustor with Variable Vane Annular Premixer - Concept 2.

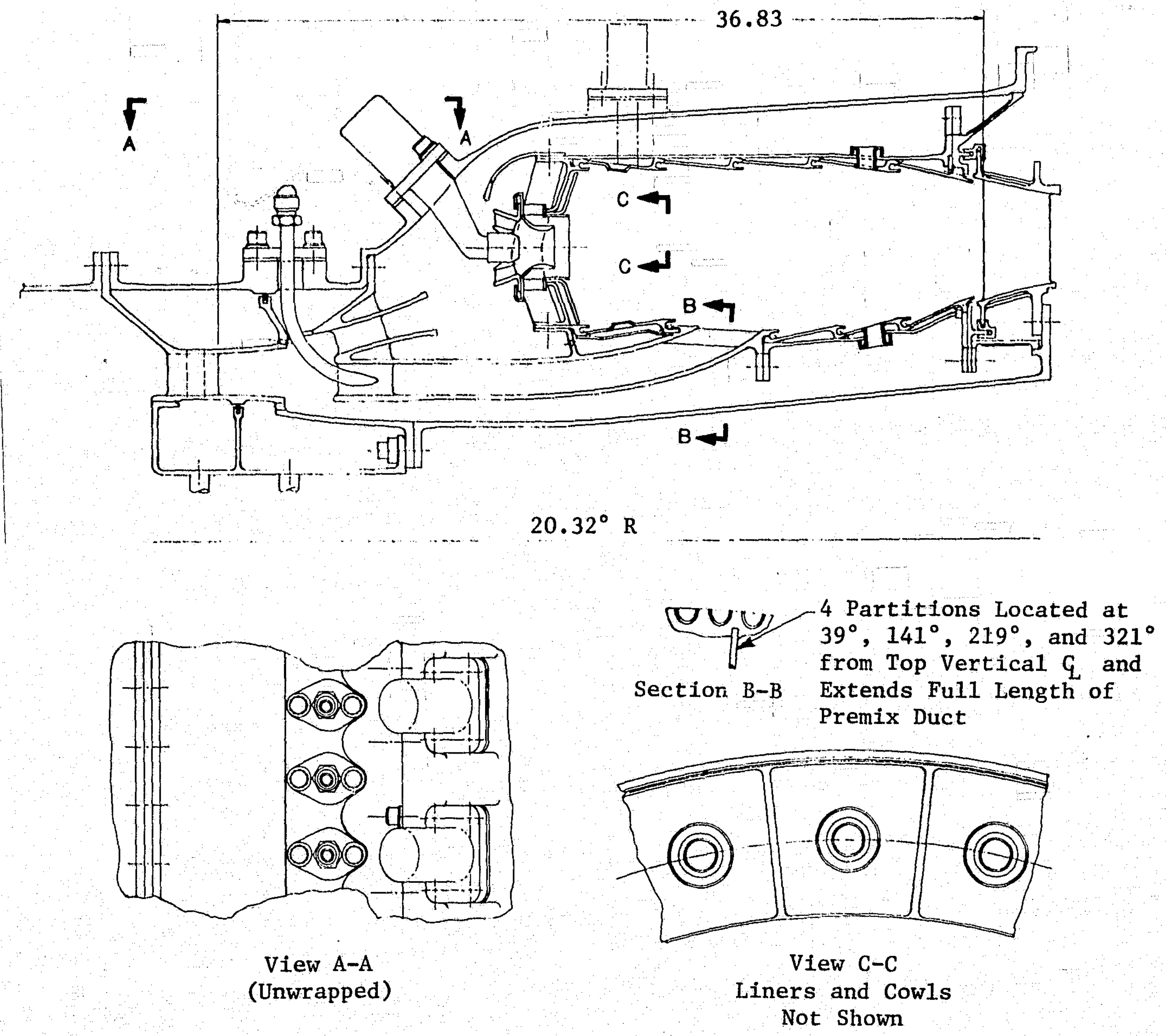


Figure 13. Series Staged LPP Combustor with Fluidic Flow Control - Concept 3.

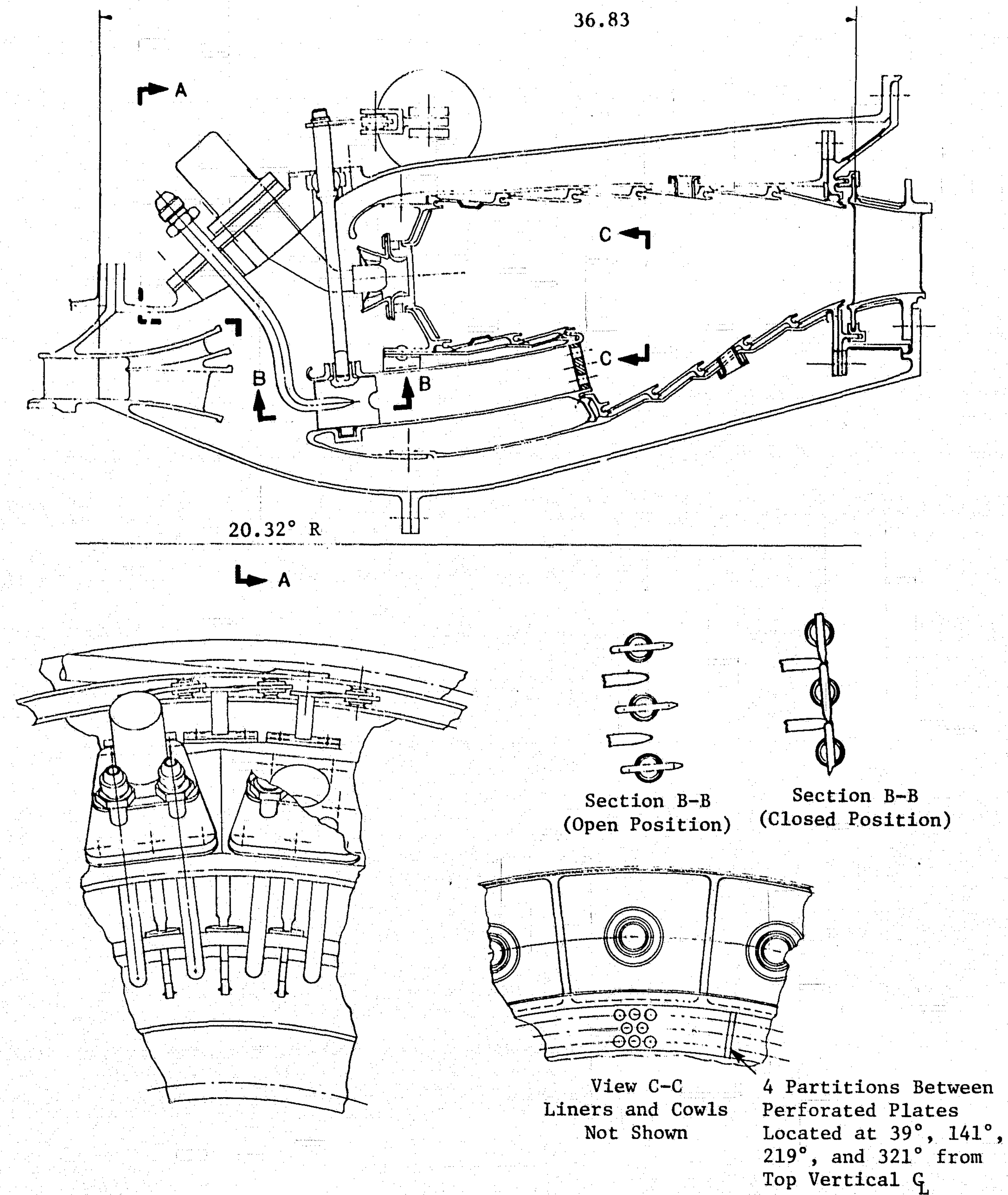
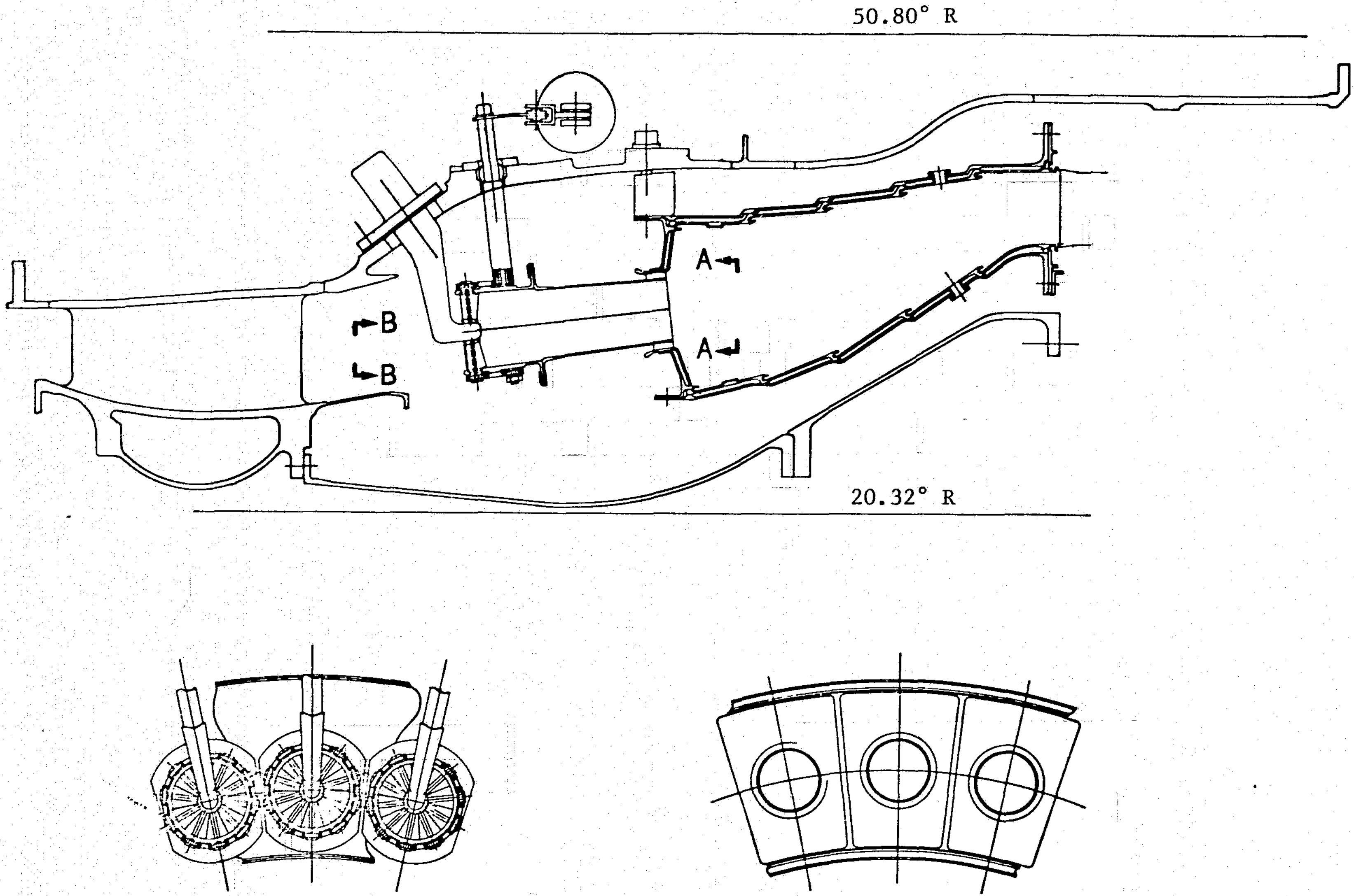


Figure 14. Parallel Staged LPP Combustor with Variable Annular Premixer Duct - Concept 4.



View B-B

View A-A
Liners Not Shown

Figure 15. Swirl Tube LPP Combustor with Variable Swirl Vanes Sized for CF6-50C Envelope - Concept 5.

As engine power is reduced from high-power conditions, the primary swirler vanes are held in the maximum open position until the cruise condition is reached. At this point, the overall fuel-air ratio for the combustion system is 0.021 and the equivalence ratio in the premixing tubes is 0.61, which is the desired range for low NO_x emissions at cruise conditions. The equivalence ratio, including secondary swirler flow at cruise conditions, is 0.55, which is the intended design stoichiometry. It is not clear at this point whether emissions will be determined by the premixing tube equivalence ratio or by the combined premixing tube/secondary swirler equivalence ratio. During the normal development cycle for a concept of this type, the optimum flow rates for the primary and secondry swirlers would be determined.

Below the normal cruise operating condition, the primary swirler vanes are closed down as the power is decreased to hold the premixing tube equivalence ratios well above the combustor blowout conditions. At engine idle conditions, the primary swirler vanes are closed to the minimum flow position which admits about 7 percent of the compressor discharge airflow through the premixing tubes. The maximum secondary reverse swirler flow at these conditions is about 6.5 percent of the compressor discharge flow which, combined with the primary swirler air, provides the correct combustor stoichiometry and dome velocity for low CO and HC emissions at idle conditions. At these conditions, the function and performance of the dome swirlers are similar to those of the conventional General Electric counterrotating swirl cup designs that are used on several production and development engines. The equivalence ratio at the secondary swirlers exit is a little over 1.0. After addition of the primary zone dilution and cooling air, the equivalence ratio is approximately 0.6 for good CO consumption.

It has been shown in other experimental programs (Reference 30) that idle emissions can be improved considerably by minimizing film cooling air in the primary zone. Therefore, impingement cooling at the engine primary zone including the dome is used to minimize the quantity of cooling required. In addition, the dome cooling air is admitted in a manner to promote mixing with the primary zone gases. This is illustrated in Figure 16. A typical dual-orifice pressure atomizing fuel nozzle that would be employed with Concept 1 is illustrated in Figure 17. This nozzle has two concentric orifices located in the tip. The lower-flowing orifice is located on the inside of the high-flow orifice. The low-flow orifice is connected directly to the inlet fuel supply and is pressurized by the fuel pressure in the fuel manifold. A pressure-activated valve is used in series with the high-flow orifice. This valve opens at a predetermined differential fuel pressure to admit fuel to the large orifice and then controls the fuel flow as a function of differential pressure above the valve opening pressure. Different spray angles are used for the two orifices. This provides for flexibility in achieving the desired fuel-air profiles in the premixing tube. These nozzles embody numerous features to reduce heat transfer to the fuel to assure long life and minimization of gum deposits caused by excessive heating of the fuel at the wetted wall surfaces in the nozzles. These features include an external heat shield in the nozzle stem, insulating tubes within the fuel flow passages in the stem, insulating air gaps around the nozzle tip, etc. The valve body also includes a screen to filter the incoming fuel.

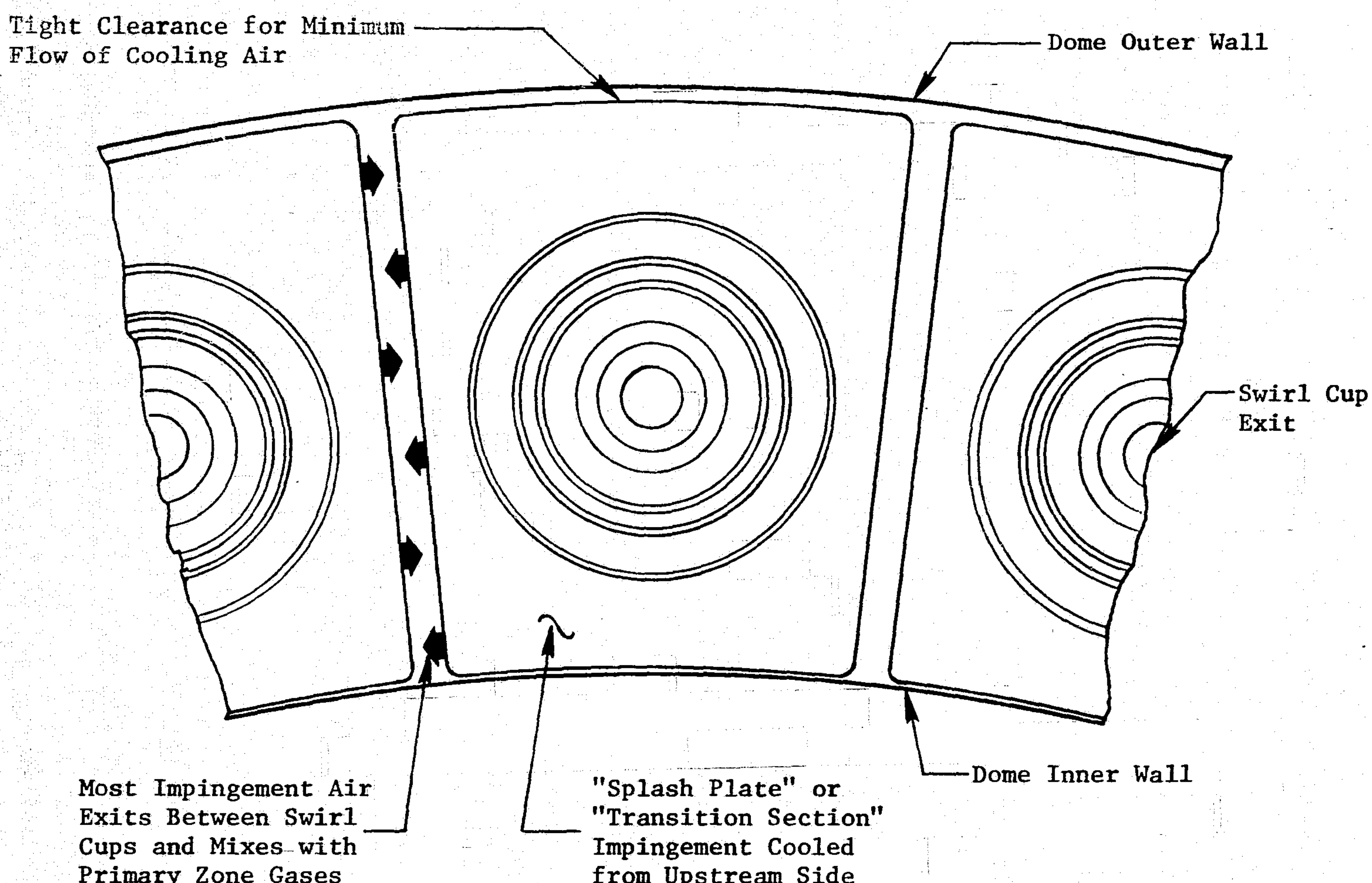


Figure 16. Combustor Dome Arrangement for Improved Mixing of Dome Cooling Air in Primary Zone.

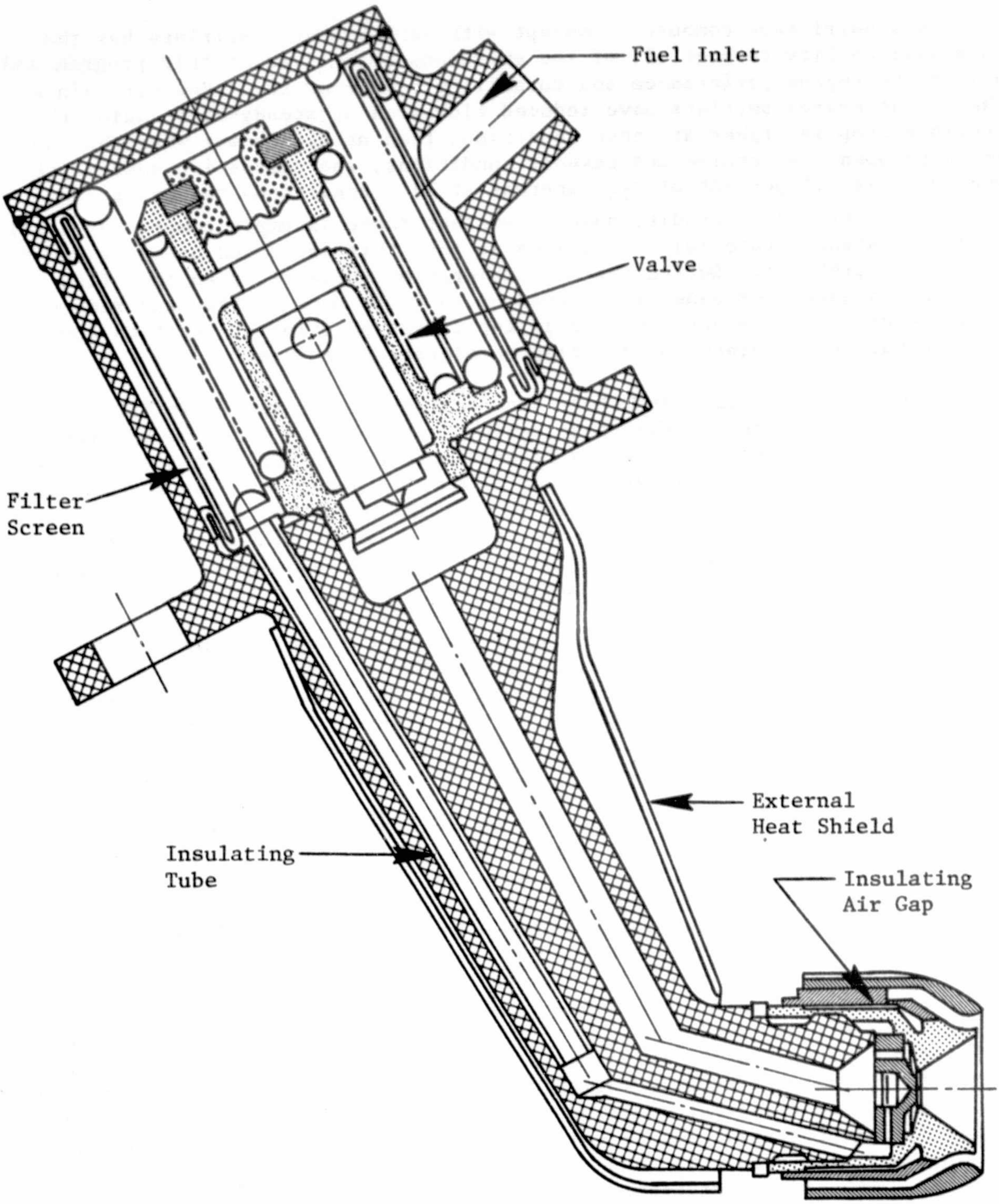


Figure 17. Dual Orifice Fuel Nozzle Cross Section.

This swirl tube combustor concept with variable-area swirlers has the potential ability to meet all of the emissions objectives of this program and all of the engine performance and durability requirements. However, since the variable-area swirlers have reduced flow area at steady-state idle, the pressure drop is higher at these conditions than at high power when the vanes are wide open. At cruise and takeoff conditions, the combustion system pressure drop is 5.1 percent of P_{T_3}, whereas at idle conditions the pressure drop is 9.7 percent. Studies have shown that there is ample compressor stall margin at steady-state idle conditions so that this increased pressure would present no problems. During engine acceleration, however, when fuel flow rates are higher, the vanes are opened up to admit more airflow and reduce pressure drop. The vanes are also in the closed position at ignition conditions but are modulated open during acceleration to idle.

A summary of design parameters for Concept 1 is presented in Table V, along with parameters for the other concepts and several other combustion systems for comparison. The variable-area swirlers for Concept 1 are illustrated in Figure 11. Each swirler has 12 movable vanes. In the maximum open position, the vane angle and the air swirler angle are approximately 15°. For lightoff and idle conditions, the vanes are in the minimum area position and the swirl angle is approximately 35°. The vanes are positioned by pinion gears on each vane and a ring gear. The ring gear for each swirler is actuated by a radial drive rod that has a ball-joint seal for flexibility at the juncture with the combustion casing. The combustor is mounted by radial support pins which are located in proximity to the variable-area swirler drive rods to minimize misalignment of the rods due to differential thermal growth between the liner and casing. The drive rods are connected to a unison ring by levers. The unison ring is operated by a hydraulic actuator of the type that is used for variable compressor stator vanes.

The combustor liner cooling wall construction is the double-wall, impingement-cooled shingle liner. Figure 11 shows a schematic representation of the shingle liner construction. The outer wall which is completely sheltered from heat transfer directly from the hot gases provides the structural support. The inner surface is impingement cooled on the back side and film cooled on the hot gas side.

The swirl tube combustor concept has several features which make it particularly promising. Only one stage of fuel injection is used, which results in reduced cost and weight relative to a system with two fuel injection stages. In addition, the continuously variable swirl vanes provide great flexibility in achieving the desired combustion zone equivalence ratios over the entire engine operating range. This flexibility of controlling both fuel flow and air flow may also result in reduced engine development time for problem solving. Combustion conditions could be varied over a wide range of conditions without physical hardware modifications.

Table V. Combustor Design Parameters.

	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	E^3 Double	CF6-50	ECCP** Double Annular
Combustor Length, cm	16.5	18.5	22.4	22.9	25.9	17.8	35.1	32.8
Dome Height, cm Inner/ Outer	7.1	8.1	7.6	6.6	10.0	5.6/ 6.1	11.4	6.1/ 6.9
Length/Dome Height, Inner/ Outer	2.3	2.3	2.9	3.5	2.6	3.2/ 2.9	3.1	5.4/ 4.8
Number of Injectors, Inner/ Outer	28	60/ 30	60/ 30	60/ 30	30	30/ 30	30	30/ 30
Injector Spacing, cm Inner/ Outer	6.9	3.3/ 6.6	3.0/ 7.1	2.8/ 6.9	6.7	5.6/ 7.1	6.9	6.1/ 7.9
Length/Spacing, Inner/ Outer	2.4	2.8	3.1	3.3	3.9	3.2/ 2.5	5.0	5.4/ 4.2
Pressure Loss, % P_{T_3}, T.O./ Idle	5.1/ 9.7	4.1/ 5.0	5/ 4.8	5.3/ 9.6	4.5/ 9.1	5/ 4.5	4.6	4.8
Reference Velocity, m/s	23.8	21.0	18.3	20.4	27.1	16.8	26.2	22.9
*Dome Velocity, m/s Inner/ Outer	7.3	7.3	6.7	8.2	9.4	19.5/ 5.5	10.7	26.5/ 9.8
Passage Velocity, m/s T.O./ Idle	39.6/ 54.9	36.6/ 51.8	40.7/ 30.5	33.5/ 45.7	36.6/ 54.9	42.7/ 42.7	51.8	45.7
Number Fuel Stages	1	2	2	2	1	2	1	2
Dome Flow/Combustor Flow In/ Out	0.25	0.28	0.26	0.27	0.22	0.33/ 0.27	0.31	0.39/ 0.20
Space Rate, M_{cal}/sec-Atm-m^3	22.3	19.5	15.1	14.1	20.5	19.8	14.3	15.1
Premix Dwell Time, ms	1.4	1.2	2.0	1.9	1.5	---	---	---
Variable Geometry Type	Vanes (Continuously Variable)	Vanes (Open-Closed)	Fluidic	Vanes (Open Closed)	Vanes (Continuously Variable)	---	---	---
Bulk Residence Time, ms	2.4	2.8	3.7	3.6	2.6	2.0	3.5	2.5
Overall Length, cm	36.8	36.8	36.8	36.8	76.7	29.6	76.7	76.7

*Calculated at Idle Flow Splits with Takeoff Density.

**Reference 31.

5.2 MULTIPLE DUCT COMBUSTOR WITH VARIABLE VANE, ANNULAR PREMIXING SYSTEM - CONCEPT 2

The multiple duct combustor concept shown in Figure 12 features a multiple annular duct main stage with variable inlet vanes and conventional counter-rotating fixed-area swirlers in the pilot stage. At cruise conditions, the duct inlet vanes are full open for lean, low NO_x operation. The main stage has 60 low pressure drop injectors for introducing fuel into the annular premixing duct. Each of the injectors sprays fuel into both the upper and lower passages and from both sides of the injector (four ports per injection tip). A sketch of the low pressure drop injector is presented in Figure 18. This injector has an airfoil shape for minimum wake generation in the premixing duct air stream. It also employs double-wall construction up to the fuel exit ports to minimize heating of the fuel and gum deposits. This injector type has a single inlet tube connected to shutoff valves mounted on the fuel manifold. The shutoff valves prevent the manifold from draining during operation on the pilot stage. This minimizes full time for the main stage fuel system and results in rapid response times during a transient from pilot only to pilot plus main stage operation. Uniform fuel distribution of the fuel and air mixture at the entrance to the dome is an important objective of the fuel injection system and mixing duct design. Fuel will be introduced into the main stage only when the vanes are in the full-open position.

At high-power operating conditions, when autoignition and flashback into the premixing duct are important considerations because of the high inlet temperature conditions, the residence time of the mixture in the premixing duct has been set at 1.2 ms. The fuel and air mixture from the main stage enters the dome region through ports located between the pilot stage swirlers, as illustrated in Figure 12, View B-B. The ports at the exit of the premixing ducts have turning vanes to inject the mixture at an angle to the combustor axial centerline and in a direction opposite to that of the pilot secondary swirlers for good mixing. The swirl angle of these vanes is approximately 35° and is in the opposite direction for the inner and outer ducts. Excellent piloting of the main stage fuel-air mixtures is expected for this arrangement because of the proximity of the main stage air stream exit to the pilot swirlers.

At low-power operating conditions, the primary zone airflow is reduced by closing the inlet vanes and all of the fuel is introduced through conventional pressure-atomizing nozzles of the type illustrated in Figure 17. Airflow for the pilot swirlers enters the region between the inner and outer premixing ducts through pylons or splitters in the premixing ducts. These pylons, which also provide access for the pilot stage fuel nozzle stems, are illustrated in Figure 12, View A-A.

For Concept 2, variable-area dilution ports on the outer aft combustor liner are employed. These compensate for the flow area reduction when the premixing duct vanes are closed so that no significant combustor pressure drop change occurs when the system is changed from one mode of operation to another (vanes open or closed). The dome flow rates with the vanes in the

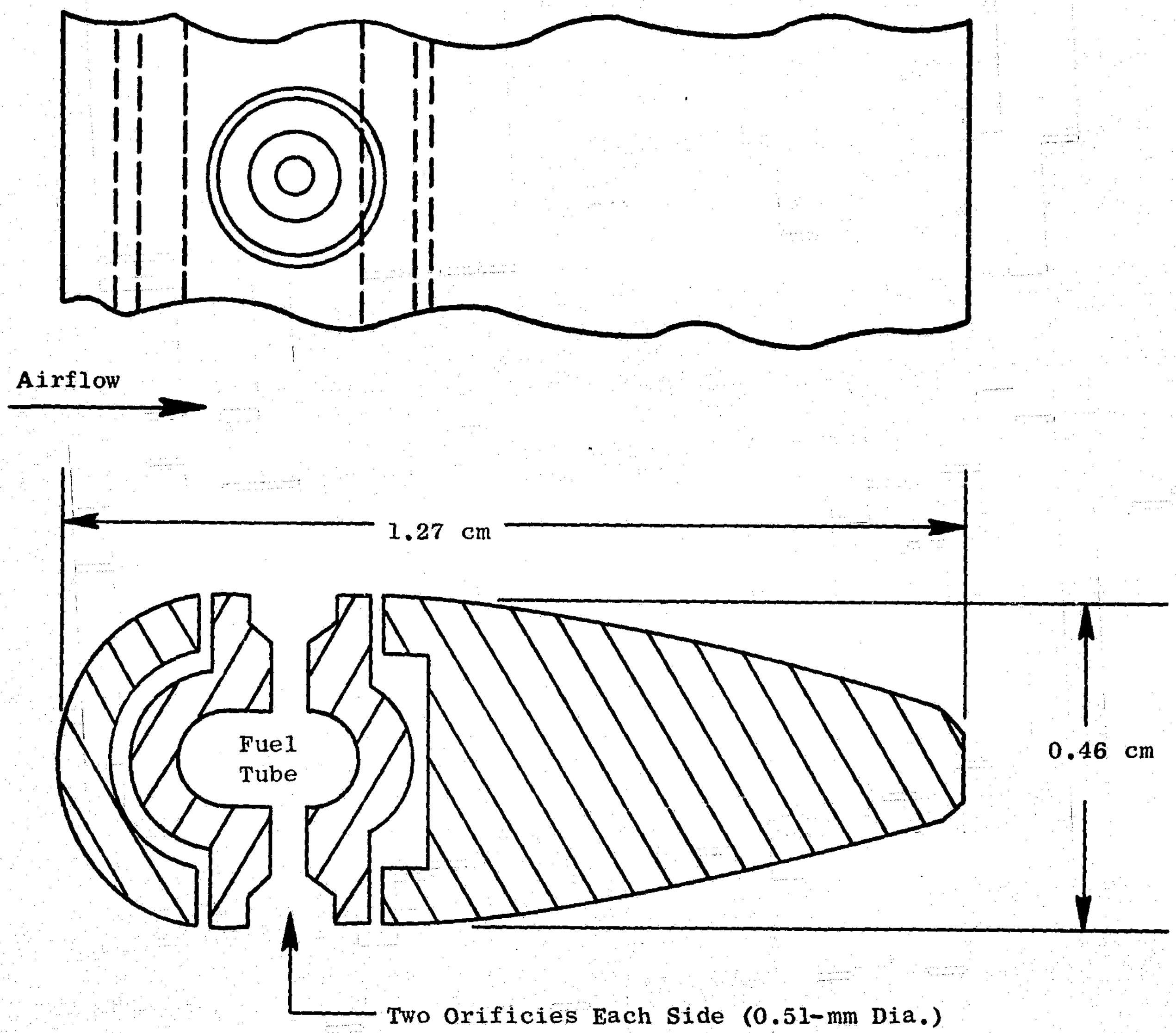


Figure 18. Fuel Injector Tip Configuration for Combustor Concept 2 Premixing Duct.

closed position have been set for optimum stoichiometries and low velocities in the dome for very low emissions of CO and HC. Even though the inlet vanes are closed, some airflow is admitted to the premixing ducts via leakage around the vanes. This is to assure no recirculating flow from the dome back into the premixing ducts.

The main stage vanes are also used in the full-closed position during lightoff and acceleration to idle. The low velocity dome conditions with the vanes closed should result in excellent starting characteristics for this concept.

At operating conditions between idle and cruise when the main stage air vanes are first opened, the engine fuel flow rates are low and would result in lean, inefficient combustion if the entire main stage airstream was fueled. Therefore, at these intermediate power conditions, sector burning of the main stage is employed. During this condition, only half of the main-stage injectors are fueled and the local fuel-air ratios are doubled. The sector burning is accomplished by fueling two 90° sectors on opposite sides of the engine, rather than fueling one 180° sector. Two sectors are used for improved symmetry of the combustor exit temperature patterns with the engine (two opposed fueled sections rather than one section on one side of the engine). As fuel flow increases, the other two main stage 90° sectors are fueled. At cruise conditions and all higher power conditions, full-annular burning is employed.

In order to prevent fuel from migrating into the region that is not to be fueled during sector burning, four partitions 90° apart are used on the leading edge of the flow splitters in the main stage premixing duct as illustrated in Figure 12, Section A-A.

The main stage air control vanes are butterfly-type airfoil sections and 60 are employed for symmetry with the 60 fuel injectors. The vanes are actuated by 60 rods that penetrate the combustion casing forward of the fuel injector. Ball-joint seals are used to provide some flexibility for thermal differential growth between elemnents of the diffuser and the casing. The 60 drive rods are attached to a unison ring with individual levers. The unison ring is positioned by an hydraulic actuator as is typically used for variable compressor stators.

The variable-area dilution ports for the aft dilution holes consist of a perforated ring actuated by a rack and pinion system, as illustrated in Figure 12, View D-D. The perforations in the rotatable ring can be made to coincide with the dilution ports in the liner or cover the dilution ports depending on the selected position for the ring. The ring is controlled in a fashion similar to that for the premixing duct vanes, but in a manner to compensate for area changes in the premixing ducts.

Double-wall shingle liner construction is employed for this concept as for Concept 1.

Attractive features for Concept 2 include excellent piloting of the main stage by the pilot stage and constant pressure drop at all operating conditions as a result of the compensating variable-area geometry.

5.3 SERIES-STAGED COMBUSTOR WITH FLUIDIC FLOW CONTROL DIFFUSER - CONCEPT 3

The series-staged LPP combustor with fluidic flow control diffuser is shown in Figure 13. This combustor was sized for the NASA/GE E^3 cycle and envelope. This concept is an adaptation of the NASA/GE/ECCP radial/axial combustor design (Reference 3), which incorporates a high velocity annular premixing duct located inboard of the combustor dome and a fluidic flow valve to control flow into the premixing duct. For this concept, which has two stages of fuel injection, the compressor exit flow is directed into the premixing duct at high-power operating conditions and cruise flight conditions. At these conditions, a proportion of the flow goes into the pilot stage dome and both stages are operated to provide low NO_x emission levels and efficient combustion. Fuel enters the pilot stage through pressure-atomizing spray nozzles (Figure 17), and a multiple cross-stream injector arrangement is used for the introduction and uniform dispersion of the fuel into the annular premixer duct. Figure 19 illustrates details of the fuel injector tip construction. No fuel is admitted to the main stage until the flow is completely switched to the mode with high main stage flow. At engine power levels between idle and cruise, sector burning of the main stage is employed with this concept to maintain the desired fuel-air ratios for efficient, stable burning as was done for Concept 2 (Section 5.2). Sector burning with two 78° sectors of the main stage is employed with this concept. At cruise and higher power levels, full-annular burning is used in the main stage. Full-annular burning of the pilot stage is used at all power conditions.

At idle and other low-power operating conditions, the compressor exit flow is directed into the pilot stage dome and all of the fuel is introduced through the pilot fuel nozzles. The pilot stage dome has 30 counter-rotating swirlers concentric with the fuel nozzles. This dome is designed to provide very low CO and HC emissions levels at the low-power operating conditions because of the selected dome velocities and stoichiometries.

The compressor exit flow passes through a short prediffuser to reduce the velocity head to a value that will provide the desired flow distribution. At the end of the prediffuser, the flow enters a larger passage area that is initiated by backward-facing steps on the outer and inner wall surfaces. In the absence of bleed, the flow would separate from both wall surfaces at this point and form an annular jet. This jet flow can be controlled by bleed flow from the step regions. If bleed is applied to the outer step region, the low pressure in this region causes the jet flow to curve outward and attach to the outer wall surface, leaving much larger separated region on the inner wall surface. With bleed from the outer step region at low engine power conditions, the jet flow is directed into the pilot dome of the combustor through a diffusing passage that provides sufficient pressure recovery to ensure an adequate pressure drop across the pilot dome and combustor liner. A small proportion of this flow enters the premixer duct and provides the required cooling and dilution flow for the premixing duct at these conditions. Either inner or outer bleed is employed at all times for this concept.

At high-power operating conditions and at cruise conditions, the bleed flow is switchd to the inner step region which causes the jet flow to curve

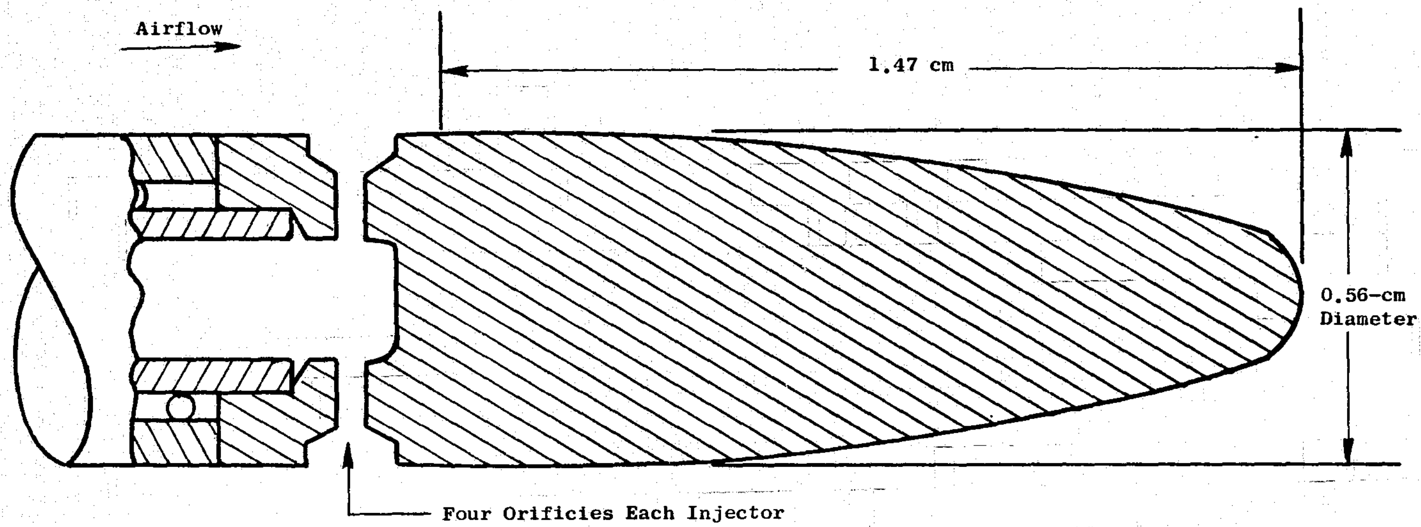


Figure 19. Fuel Injector Tip Configuration for Combustor Concepts 3 and 4.

inward and attach to the inner wall surface, leaving a large separated region on the outer wall surface. This flow enters the premixing duct and provides a uniform, high velocity flow in the premixing duct at these conditions. A considerable proportion of the jet flow also enters the outer flowpath to provide the flow required by the pilot dome and outer combustor liner at the high-power operating conditions.

The compressor exit bleed flow required for this concept is used for turbine cooling. Bleed from the outer step region is manifolded and piped through hollow compressor exit guide vanes and into another manifold and then through a diverter valve to the turbine for cooling. The inner bleed flow is manifolded and ducted to the diverter valve. The diverter valve is used to switch the bleed from one step region to the other.

At high-power operating conditions, the lean fuel-air mixture in the premixing duct enters the combustor through an array of U-gutter flameholders that causes rapid mixing of this flow with the hot gases from the pilot burner. This rapid mixing results in good flame stability and high combustion efficiency.

The use of the fluidic flow control system is promising in that it is self-compensating, so that pressure loss is not increased at low-power operating conditions, and because variable-area mechanical devices are not required within the combustor flowpath region.

5.4 PARALLEL-STAGED COMBUSTOR - CONCEPT 4

The LPP combustor concept illustrated in Figure 14 is a parallel staged design with an annular premixing duct and an annular flameholder array at the end of the premixing duct. This design is an adaptation of the NASA/GE ECCP double-annular combustor design (Reference 31) and is sized for the E^3 cycle and envelope. This combustor utilizes a pilot dome with fixed-area counter-rotating swirlers.

Flow through the premixing duct is controlled by an array of variable vanes near the inlet plane of the premixing duct. At high-power operating conditions and cruise conditions, the variable vanes are open and a large proportion of the compressor discharge airflow enters the premixing duct. A uniform fuel-air mixture is provided by a multiple spraybar array (Figure 19) that distributes finely atomized fuel droplets uniformly into the high velocity airflow. The fuel is vaporized by the high-velocity, high-temperature airflow, and the resulting lean fuel-air mixture passes through an annular flameholder array that consists of a metallic plate with a large number of closely spaced small holes. The inlet to each of these holes is contoured to promote smooth acceleration without separation in order to avoid flashback.

The variable vanes are closed down at idle and other low-power operating conditions, diverting more of the airflow into the pilot dome of the combustor. At these conditions, all of the fuel is injected into the pilot dome through pressure atomizing spray nozzles that are concentric with reverse-flow central injection swirl cups equally spaced around the pilot dome annulus. This pilot dome is designed to provide low CO and HC emission levels at the low-power operating conditions and at idle conditions. Because compensating variable geometry is not used in this concept, idle pressure drop increases to about 9 percent. During lightoff, acceleration to idle, and operation above idle, the variable vanes are positioned in the full-open position. This reduces the pressure drop and also provides excellent lightoff characteristics for this design (low dome flow with vanes open). Since the main stage airflow enters the dome at a downstream position, it has no adverse effect on the pilot operation when the vanes are open. With this system, the premixing duct vanes must be opened completely before the main stage can be fueled. Sector burning of the main stage (two 78° sectors) at operation between idle and cruise is employed to achieve the desired local fuel-air ratios in the main stage. At cruise and above, full-annular burning is used.

With this parallel-staged design, the main and pilot stages are independent. Pilot stage operation at high-power conditions is not required to stabilize the main stage flame. Therefore, the pilot stage fuel flow can be minimized at high-power conditions. This minimizes the pilot stage NO_x contribution. Theoretically, the pilot stage could be completely extinguished, but this would require a pilot stage relight sequence during deceleration to idle.

5.5 SWIRL TUBE COMBUSTOR FOR CF6-50 ENVELOPE - CONCEPT 5

The swirl tube combustor with variable-area swirlers designed for the CF6-50 engine envelope and cycle is shown in Figure 15. This combustor is designated Concept 5.

The operational characteristics and physical description of this combustor are the same as for those of the swirl tube combustor, Concept 1, designed for the E^3 (Section 5.1).

This design study demonstrates the scaling of the swirl tube combustor from one size engine, E^3, to another larger size engine, the CF6-50. The combustor was designed to fit within the existing overall combustion length of 76.7 cm. The overall combustion system length is defined as the distance from the compressor outlet guide vane trailing edge to the leading edge of the turbine nozzle diaphragm. The combustor length from the fuel nozzle tip to the turbine nozzle diaphragm leading edge is 25.9 cm.

Concept 5 is shown in Figure 15 with the double-wall impingement-cooled-type liner that was utilized for the other four combustor concepts. An alternative approach would be to use the standard CF6-50 liner wall design since the life requirements are less stringent than those specified for the E^3 engine. In this case the size, performance, and emission predictions for Concept 5 would be unchanged although the life capability would be reduced. The design parameters for this concept are presented in Table V.

6.0 LPP COMBUSTION SYSTEM DESIGN ANALYSIS

This section presents the results and brief discussions of design studies and analyses conducted to define the five LPP combustor concepts described in Section 5.0 and to predict the performance, life, and emission characteristics of these combustor concepts.

6.1 FUEL AND AIRFLOW SCHEDULING

Fuel and airflow schedules were defined and developed for each of the conceptual designs through an iterative process, with consideration for a variety of design requirements and goals. Initial flow splits for all concepts were selected to meet program emission goals and durability requirements at the idle and normal cruise operating conditions. Primary considerations in these studies were as follows:

- Pilot-stage dome airflow with the variable-geometry features in the idle mode position was selected to provide a pilot dome equivalence ratio of about 1.0 at idle conditions. This value was selected to obtain low CO emission, based on results of the NASA/GE low emissions combustor programs discussed in References 3 and 32. An example of the effect of dome equivalence ratio on CO emission is shown in Figure 20.

- As discussed in Section 4.2 (Figure 6), a premixing duct equivalence ratio of about 0.55 was selected at normal cruise conditions to meet the program emission goal while providing lean blowout margin. With this equivalence ratio, NO_x levels of about 2 g/kg are expected to be produced in the LPP combustion stage. This provides a safety margin for NO_x emission in Concepts 1 and 5, and also provides for additional pilot-stage NO_x emission contributions in Concepts 2, 3, and 4. It is expected that a slightly leaner premixing duct equivalence ratio could eventually be employed in Concepts 2 and 3 because of improved lean stability due to piloting in these designs. However, additional data on this piloting effect will be needed to determine the optimum stoichiometry. These data would be obtained during combustor development efforts.

- Liner cooling airflows were selected to provide adequate impingement and film cooling to produce peak linear temperatures below 1150 K at all operating conditions. Initial flows were scaled from the Baseline E^3 combustor as described in Section 6.6.

- Combustors were sized to meet the 5 percent combustion system pressure drop goal at the normal cruise operating condition. Idle pressure drop was increased as required to obtain the selected idle flow splits by actuation of the flow modulation features. Airflow splits at idle and cruise operating conditions for each concept considered are presented in Tables VI through X.

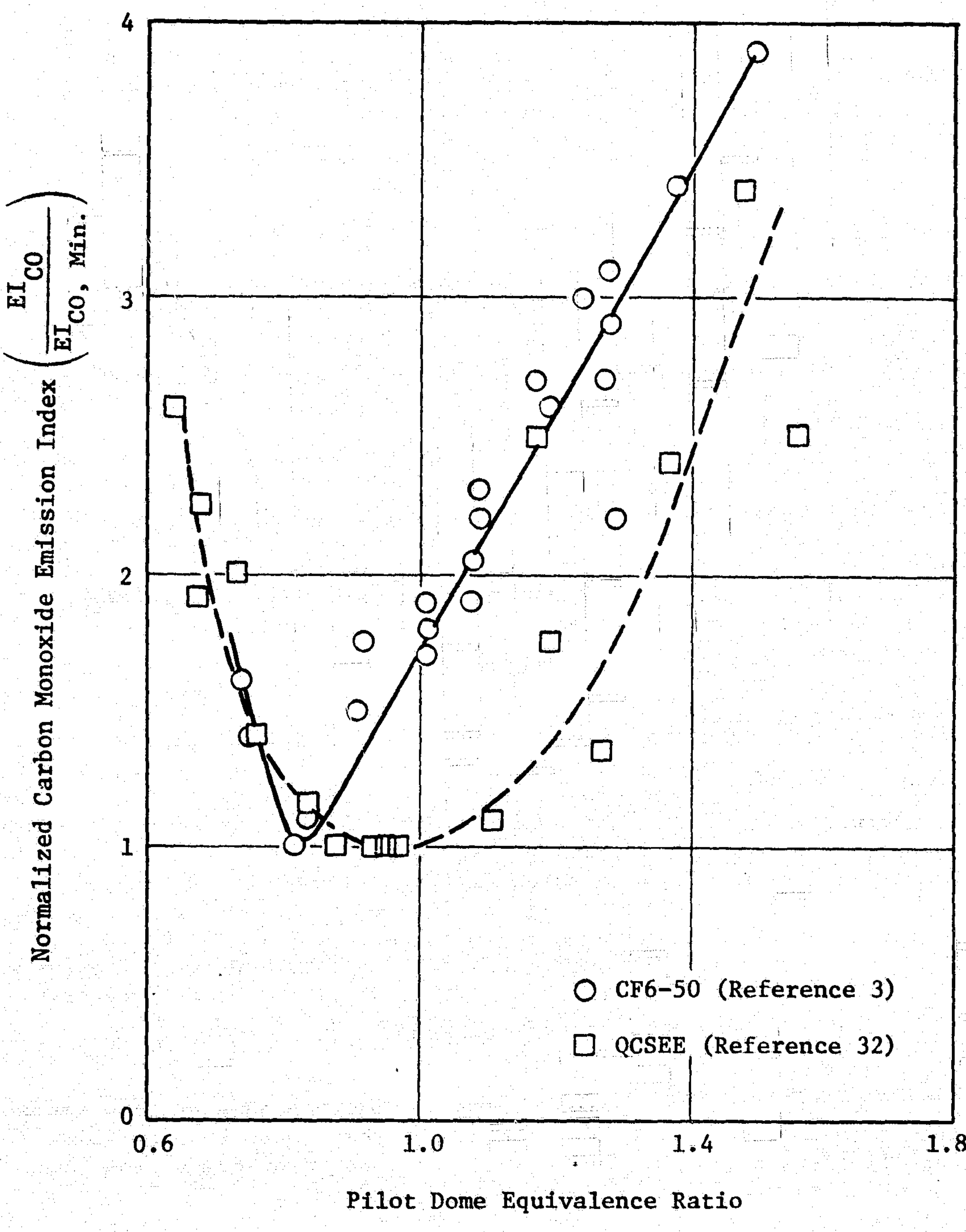


Figure 20. Effect of Pilot Dome Equivalence Ratio on CO Emission.

Table VI. Airflow Splits for Concept 1 - Swirl Tube Combustor with Variable Vanes.

	Percent of W_3	
	Idle	Cruise
Premix Tubes	6.1	47.4
Reverse Swirlers	9.1	5.1
Dome Cooling	7.0	3.9
Outer Dilution	7.7	4.3
Inner Dilution	10.9	6.1
Outer Cooling	22.2	12.5
Inner Cooling	17.5	9.8
Out Turbine Bleed	10.0	5.6
In Turbine Bleed	9.5	5.3
	100.0	100.0

Table VII. Airflow Splits for Concept 2 Multiple Duct with Variable Vanes and Compensating Variable Dilution.

	Percent of W_3	
	Idle	Cruise
Premix Duct	6.1	46.0
Swirler	9.0	9.0
Dome Cooling	5.5	5.5
Outer Dilution	42.1	2.2
Inner Dilution	2.9	2.9
Outer Coolng	13.5	13.5
Inner Cooling	10.0	10.0
Outer Turbine Bleed	5.6	5.6
In Turbine Bleed	5.3	5.3
	100.0	100.0

Table VIII. Airflow Splits for Concept 3 Series Staged with Fluidic Flow Control.

	Percent of W_3	
	Idle	Cruise
Swirler	15.2	10.7
Dome Cooling	8.0	5.6
Outer Cooling	14.8	10.4
Outer Dilution	4.5	3.2
Inner Cooling (Fore)	3.0	2.1
Outer Turbine Bleed	7.8	5.5
Subtotal	53.5	37.5
Premix Duct	36.3	45.2
Inner Cooling (Aft)	4.8	7.9
Inner Dilution	2.3	3.9
Inner Turbine Bleed	3.3	5.5
Subtotal	10.4	17.3
Total	100.0	100.0

Table IX. Airflow Splits for Concept 4 - Parallel Staged with Variable Annular Premix Duct.

	Percent of W_3	
	Idle	Cruise
Premix Duct	17.8	45.2
Swirlers	15.1	10.1
Dome Cooling	8.2	5.5
Outer Dilution	3.2	2.1
Inner Dilution	4.6	3.1
Outer Cooling	16.5	11.0
Inner Cooling (Fore)	5.6	3.7
Inner Cooling (Aft)	12.6	8.4
Out Turbine Bleed	8.4	5.6
In Turbine Bleed	8.0	5.3
	100.0	100.0

Table X. Airflow Splits for Concept 5 - Swirl Tube Combustor with Variable Swirl Vanes - CF6-50 Size.

	Percent of W_3	
	Idle	Cruise
Premix Tubes	4.6	43.5
Reverse Swirler	7.3	4.3
Dome Cooling	6.9	4.1
Outer Dilution	9.3	5.5
Inner Dilution	9.1	5.4
Outer Cooling	20.1	11.9
Inner Cooling	16.6	9.9
Out Turbine Bleed	9.5	5.6
In Turbine Bleed	8.3	4.9
Rotor Cooling Bleed	8.3	4.9
	100.0	100.0

At conditions other than idle and normal cruise, flow schedules for concepts having two fuel stages (Concepts 2, 3, and 4) were selected based on the following additional considerations:

- Pilot-stage fuel flow at all conditions was selected to maintain pilot-stage fuel-air ratio slightly above the lean stability limit. The required pilot-stage fuel-air ratio is shown as a function of combustor inlet temperature in Figure 21. This figure was derived from lean blowout data which is currently used for transient fuel flow scheduling in the CF6-50 engine. Low thermal NO_x production is obtained by scheduling pilot stage fuel and airflow to provide pilot-stage fuel-air ratio close to the lean stability limit.

- After establishing pilot-stage air and fuel flow requirements, sector burning is utilized as required to maintain LPP stage stoichiometry above the lean stability limit and to produce acceptable emission levels. The size of the fueled sector is determined by the stability limit and pattern factor considerations at the various operating conditions as discussed in Section 6.3 (Aerothermo Performance).

- In Concept 4, increased pressure drop is obtained when the variable-geometry vanes are in the idle position. To minimize the performance decrement due to increased pressure loss in these designs, transition to the cruise position is scheduled to occur slightly below the approach operating condition (30 percent of rated thrust). In Concepts 2, 3, and 4, early transition to cruise mode operation is used to minimize the amount of fuel required to obtain stable pilot stage operation, thereby reducing the relatively high NO_x contribution of the pilot stage.

- The two-position airflow modulation devices used in Concepts 2, 3, and 4 were not designed to allow main-stage burning during idle mode operation. Therefore, during transition from idle to cruise mode operation, it was assumed that the main stage could not be fueled until actuation was completed and cruise mode airflow splits are established.

Fuel and airflow schedules typical of Concepts 2, 3, and 4 are shown in Figure 22. As indicated in this figure, schedules are directly keyed to overall combustor fuel-air ratio rather than engine power level. This approach was used so that the schedule would be applicable to acceleration and deceleration fuel flow schedules, as well as on the steady-state operating line. Fuel-air ratios corresponding to steady-state values at the idle, approach, cruise, and takeoff conditions are also shown on this figure. As indicated by Figure 22, low-power operations are conducted with the airflow modulation feature in the idle mode and all fuel supplied to the pilot stage fuel injectors. As power (fuel-air ratio) is increased between the idle and approach operating conditions, the airflow modulation is switched to the cruise mode. Immediately after cruise airflow splits are established, a majority of the combustor fuel flow is routed to the LPP main stage. During operation at

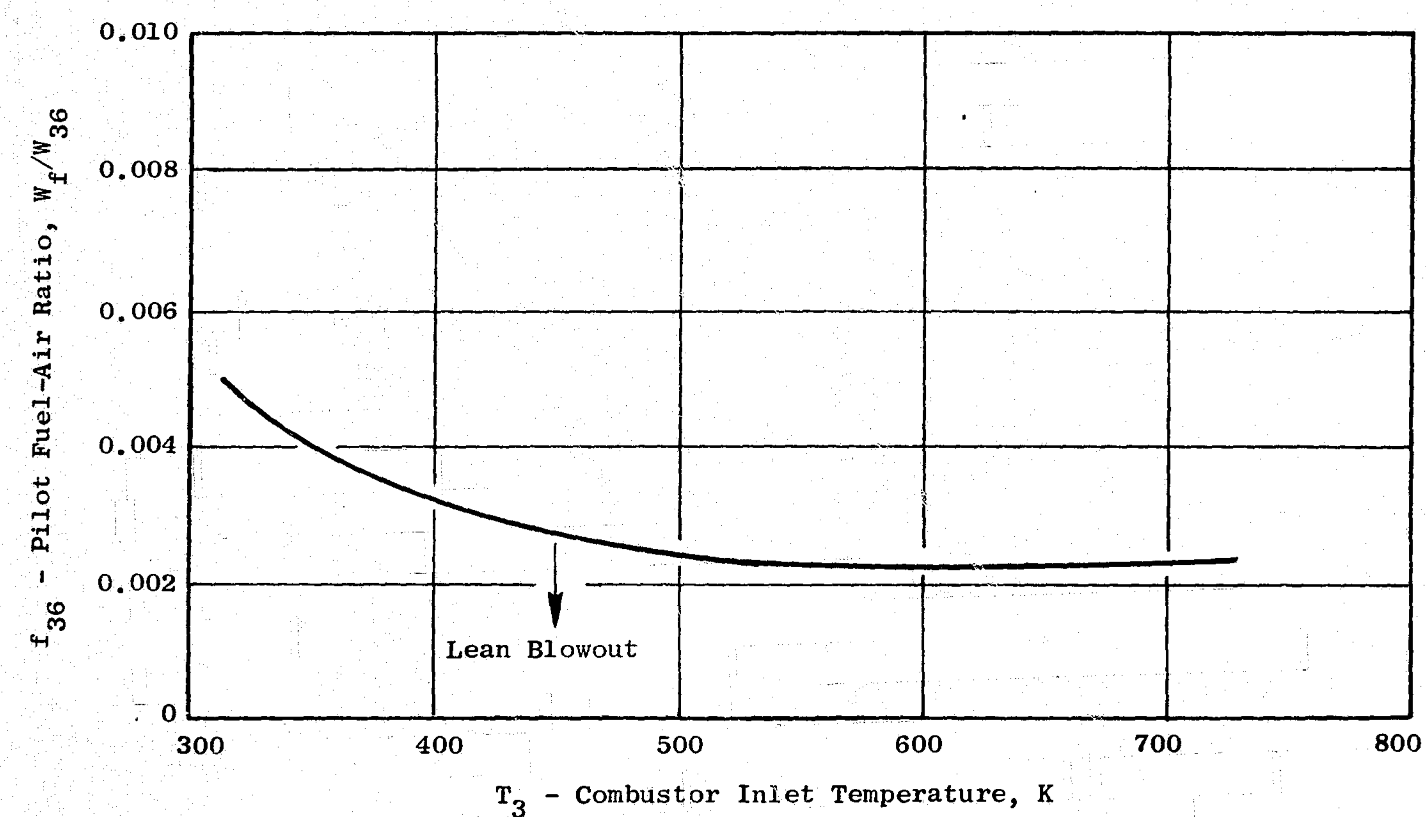


Figure 21. LPP Pilot Stability Limits as a Function of Combustor Inlet Temperature.

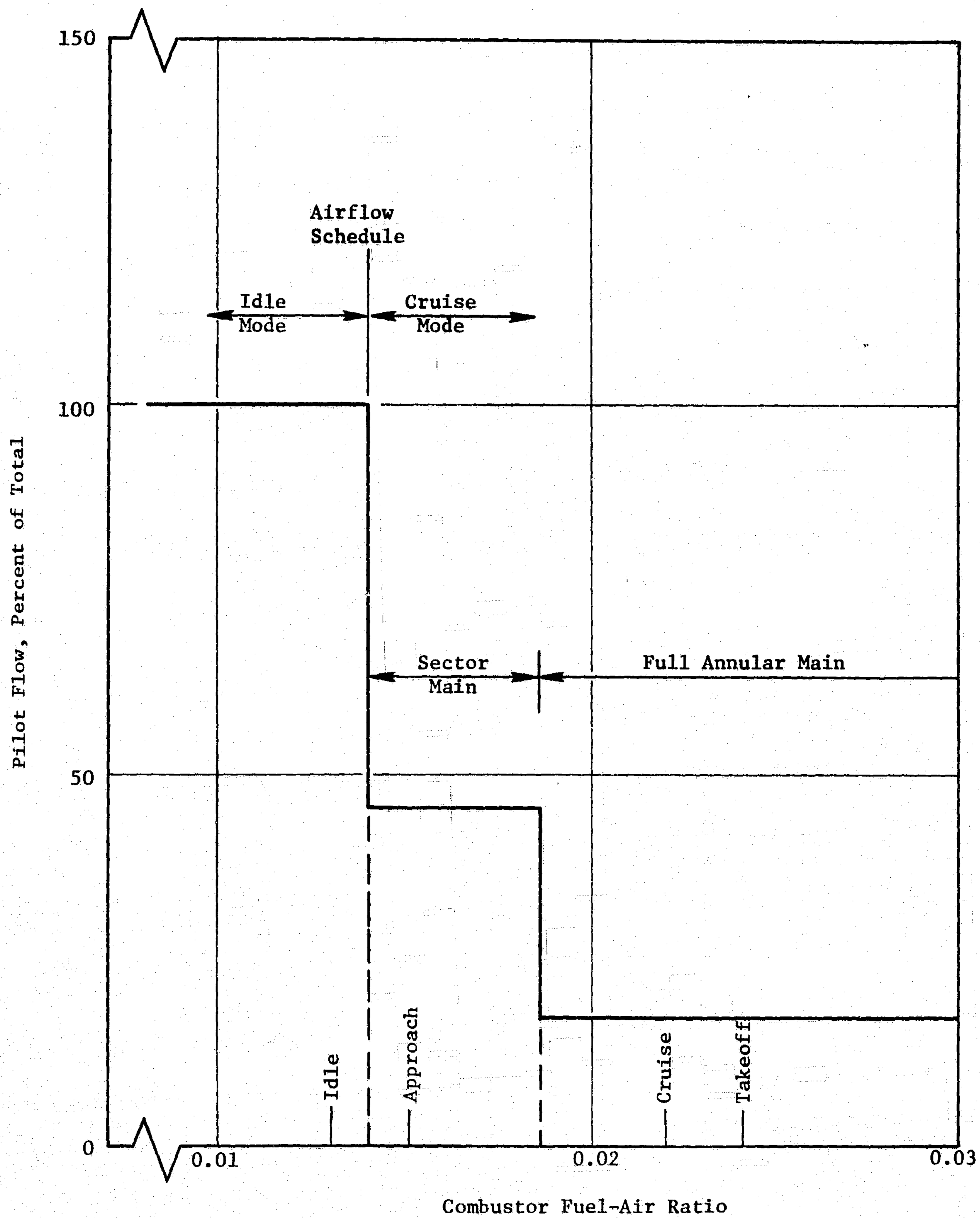


Figure 22. LPP Combustor Fuel and Airflow Schedules - Concepts 2, 3, and 4 (Typical).

midrange power levels (fuel-air ratios between about 0.014 and 0.019), the overall combustor fuel-air ratio is insufficient to obtain both pilot- and main-stage fuel-air ratios above their respective lean stability limits if both stages are uniformly fueled. Therefore, main-stage sector burning is employed to increase local main-stage fuel-air ratio during operation in this range (uniform pilot-stage burning is employed at all times). At high power levels, both the main and pilot stages are uniformly fueled.

In Concepts 1 and 5, which have only one stage of fuel injection, combustor stoichiometry is controlled by airflow modulation alone. This is possible because of the use of continuously variable airflow modulation devices in these swirl tube designs, which permits precise selection of combustor dome flow. Sector burning is not required. In these concepts, operation very near the lean stability limit (with maximum possible swirl tube flow) is utilized to provide low NO_x emission and minimize combustor pressure drop at all operating conditions above idle.

The tentative fuel and airflow schedules and key local equivalence ratios at key engine operating conditions are presented for each of the LPP combustor conceptual designs in Tables XI through XV. These flow schedules, which represent a starting point for combustor development, provided the basis for the emission, performance, and operational characteristic studies discussed in the following sections.

6.2 FUEL-AIR PREPARATION

Fuel-air preparation system design studies considered autoignition and flashback, evaporation and mixture uniformity, fuel injector reliability (resistance to coking), and sensitivity to inlet distortion. A summary of fuel-air preparation system design parameters is presented in Table XVI. (Because of the similarity between Concepts 1 and 5, only parameters for Concept 1 are shown.)

In the initial design and sizing of the fuel-air preparation systems for the LPP combustor concepts, the primary design guidelines were to meet the autoignition and flashback limits discussed in Section 4.1, and to remain within the combustor envelopes specified in Section 3.2. In combustor Concepts 1, 2, and 5, the fuel-air mixture is admitted at the forward end of the combustion chamber. Therefore, in these concepts, available premixing length was limited by the total combustion system length (envelope). Thus, premixer dwell time in these concepts is limited to between 1.2 to 1.4 ms at the takeoff conditions. In Concepts 3 and 4, premixer dwell time was limited to between 1.9 to 2.0 ms at takeoff conditions in order to meet the autoignition criteria discussed in Section 4.1. In all designs, flow was accelerated between the axial plane of fuel injection and the entrance to the combustion chamber in order to prevent flow separation within the premixing ducts. Similarly, streamlined, axially-mounted fuel injectors were used in Concepts 3 and 4 to minimize wakes and flow separation associated with radially inserted injectors (however, radially inserted injectors were used in Concept 2 to facilitate combustor assembly).

Table XI. Swirl Tube Combustor (Concept) Flow Schedules.

Operating Condition	Main Stage Fuel Flow,* % W_f	Premixing Tube Airflow, % W_3	Local Equivalence Ratio			
			Premixing Tube	Premixed Lean Stability Limit**	Pilot Swirler	Pilot Swirler Lean Stability Limit**
6% Idle	100	6.1	2.56	N/A	1.03	0.23
30% Approach	100	22.6	0.80	0.54	0.61	N/A
85% Climb	100	47.4	0.62	0.44	0.56	N/A
100% Takeoff	100	47.4	0.67	0.42	0.61	N/A
Normal Cruise	100	47.4	0.61	0.45	0.55	N/A

*Single fuel injection stage.

**Pilot lean stability limit applies at idle - premixed limit applies at all other operating conditions.

Table XII. Multiple Duct Combustor (Concept 2) Flow Schedules.

			Local Equivalence Ratio			
Operating Condition	Main Stage Fuel Flow, % W_f	Premixing Duct Airflow, % W_3	Premixing Tube	Premixed Lean Stability Limit	Pilot Swirler	Pilot Swirler Lean Stability Limit
6% Idle	0	6.1	0	N/A	**1.74	0.23
30% Approach (Vanes Closed)	0	6.1	0	N/A	2.03	0.21
(Vanes Open)	0	46.0	0	N/A	3.72	0.21
	*68	46.0	*0.61	0.54	0.65	0.21
85% Climb	88	46.0	0.55	0.44	0.41	0.21
100% Takeoff	88	46.0	0.61	0.42	0.44	0.21
Normal Cruise	88	46.0	0.55	0.45	0.40	0.21

*Two 78° main stage sectors fueled.

**ϕ = 1.0 including premixing duct airflow.

Table XIII. Series Staged Combustor (Concept 3) Flow Schedules.

			Local Equivalence Ratio			
Operating Condition	Main Stage Fuel Flow, % W_f	Premixing Duct Airflow, % W_3	Premixing Tube	Premixed Lean Stability Limit	Pilot Swirler	Pilot Swirler Lean Stability Limit
6% Idle	0	36.3	0	N/A	1.03	0.23
30% Approach (Fluidic Switch in Idle Mode)	0	36.3	0	N/A	1.20	0.21
(Fluidic Switch in Cruise Mode)	0	45.2	0	N/A	1.71	0.21
	75*	45.2	0.59*	0.54	0.65	0.21
85% Climb	85	45.2	0.55	0.44	0.4	0.21
100% Takeoff	85	45.2	0.61	0.42	0.4	0.21
Normal Cruise	85	45.2	0.54	0.45	0.4	0.21

*Two 78° main stage sectors fueled.

Table XIV. Parallel Staged Combustor (Concept 4) Flow Schedules.

			Local Equivalence Ratio			
Operating Condition	Main Stage Fuel Flow, % W_f	Premixing Duct Airflow, % W_3	Premixing Tube	Premixed Lean Stability Limit	Pilot Swirler	Pilot Swirler Lean Stability Limit
6% Idle	0	17.8	0	N/A	1.03	0.23
30% Approach (Vanes Closed)	0	17.8	0	N/A	1.21	0.21
(Vanes Open)	0	45.2	0	N/A	2.0	0.21
	75*	45.2	0.61*	0.54	0.65	0.21
85% Climb	85	45.2	0.55	0.44	0.4	0.21
100% Takeoff	85	45.2	0.61	0.42	0.4	0.21
Normal Cruise	85	45.2	0.54	0.45	0.4	0.21

*Two 78° main stage sectors fueled.

Table XV. CF6-50 Swirl Tube Combustor (Concept 5) Flow Schedules.

Operating Condition	Main Stage Fuel Flow,* % W_f	Premixing Tube Airflow. % W_3	Local Equivalence Ratio			
			Premixing Tube	Premixed Lean Stability Limit**	Pilot Swirler	Pilot Swirler Lean Stability Limit**
6% Idle	100	4.7	2.52	N/A	1.00	0.25
30% Approach	100	21.3	0.80	0.54	0.63	N/A
85% Climb	100	43.5	0.61	0.44	0.56	N/A
100% Takeoff	100	43.5	0.67	0.42	0.61	N/A
Normal Cruise	100	43.5	0.60	0.45	0.55	N/A

*Single fuel injection stage.

**Pilot lean stability limit applies at idle - premixed limit applies at all other operating conditions.

Table XVI. Fuel-Air Preparation System Design Parameters.

Parameter	Design Value (Takeoff/Cruise)			
Combustor Concept	1	2	3	4
Injector Type	Pressure Atomizing	Radial Multiple Orifice	Axial Multiple Orifice	Axial Multiple Orifice
Number of Injectors (n)	28	60	60	60
Number of Orifices	28	240*	240*	240*
Injector Spacing, cm	6.9	3.3	3.1	2.8
Premixing Length (L), cm	10.9	10.3	16.3	11.4
Annulus Height or Tube Diameter at Injector, cm	4.3	1.0 (2 ea)	1.5	2.3
Premixer Dwell Time, ms	1.4/1.3	1.2/1.1	2.0/1.8	1.9/1.7
Air Velocity at Injector, m/s	83/76	60/55	82/74	55/50
Mixture Velocity Entering Combustor Chamber, m/s	110/100	146/133	146/133	146/133
Orifice Fuel Velocity, m/s	---	45/13	45/13	45/13
Jet Penetration, cm**	---	0.84/0.66	0.64/0.48	0.91/0.71
Estimated Evaporation, %	100/100	97/100	100/100	100/100
Pressure Drop Across Fuel Injection Orifice, MPa	3.45/0.42	0.79/0.06	0.79/0.06	0.79/0.06

*0.51 mm sharp edged orifices.

**Estimated using correlation of Reference 33.

Flashback potential was evaluated using the criterion shown in Figure 5 based on takeoff equivalence ratio and mixture velocity at the inlet to the combustion chamber. As indicated in Table XVI, the mixture velocity entering the combustor in all designs was above 110 m/s at the takeoff operating condition. This meets the bulk-flow flashback criterion (at an equivalence ratio of 0.6) with a wide safety margin. The cruise and takeoff conditions are plotted with the flashback test data on Figure 5. The flashback limit for $\phi = 0.6$ as indicated by Figure 5 is approximately 50 m/s which is less than half the LPP mixture velocities. Concept 2 presents a slightly higher flashback risk than Concepts 3 and 4 because of the use of turning vanes at the inlet to the combustion chamber, but the safety margin is expected to be sufficient with careful turning vane design to avoid any serious threat of flashback. The swirlers in Concepts 1 and 5 will also require careful development to avoid wakes and recirculation which could lead to autoignition or flashback. The probability of flashback due to recirculation in these designs is considered to be remote because of the acceleration of the mixture in the converging premixing tubes and the low angle (~15°) of the swirl vanes.

General fuel evaporation studies were conducted for a typical LPP combustor airblast fuel injection system operating at pressures and temperatures corresponding to several key reference engine combustor operating conditions. These studies utilized empirical correlations for evaporation of Jet A or kerosene injected from a multiple conical tube injector (Reference 34), a simple contrastream injector (Reference 35), and an airblast atomizer (Reference 36), and a computer model which uses the correlation of Reference 19 to calculate the mean diameter of injected droplets (cross-stream injection of Jet A) and provides an iterative solution to the droplet evaporation equations of Reference 18. This computer model accounts for variation in drop size and relative velocity with time, as well as changes in fuel properties as a function of droplet temperature; however, droplet size distribution, variation in fuel properties as the lighter fuel fractions are evaporated, and local turbulence levels are not included in the calculation. Results of these studies, shown in Figure 23, indicate that more than 80 percent evaporation can be obtained throughout the LPP operating range, and that levels above 90 percent can be obtained at power levels above about 70 percent or rated thrust. General agreement between levels predicted using the different methods is good considering the fact that the correlations were developed for several different airblast injector configurations, and that significant extrapolation of pressure and residence time effects was required. Evaporation levels for LPP combustor Concepts 2, 3, and 4 at the takeoff and normal cruise operating conditions were calculated with the computer model and are shown in Table XVI. As indicated, essentially complete evaporation (97 percent or greater) is expected to be obtained. Drop sizes predicted for the pressure atomizing nozzle of Concept 1 (70 to 130μ) were larger than those predicted for the airblast injector (~30μ), indicating the possibility of less-than-complete fuel evaporation, particularly at the normal cruise conditions where fuel injector pressure drop is relatively low; however, it is thought that evaporation will be improved due to the high intensity turbulence within the swirl tubes. If necessary, this concept could be adapted during development to use an airblast injector design.

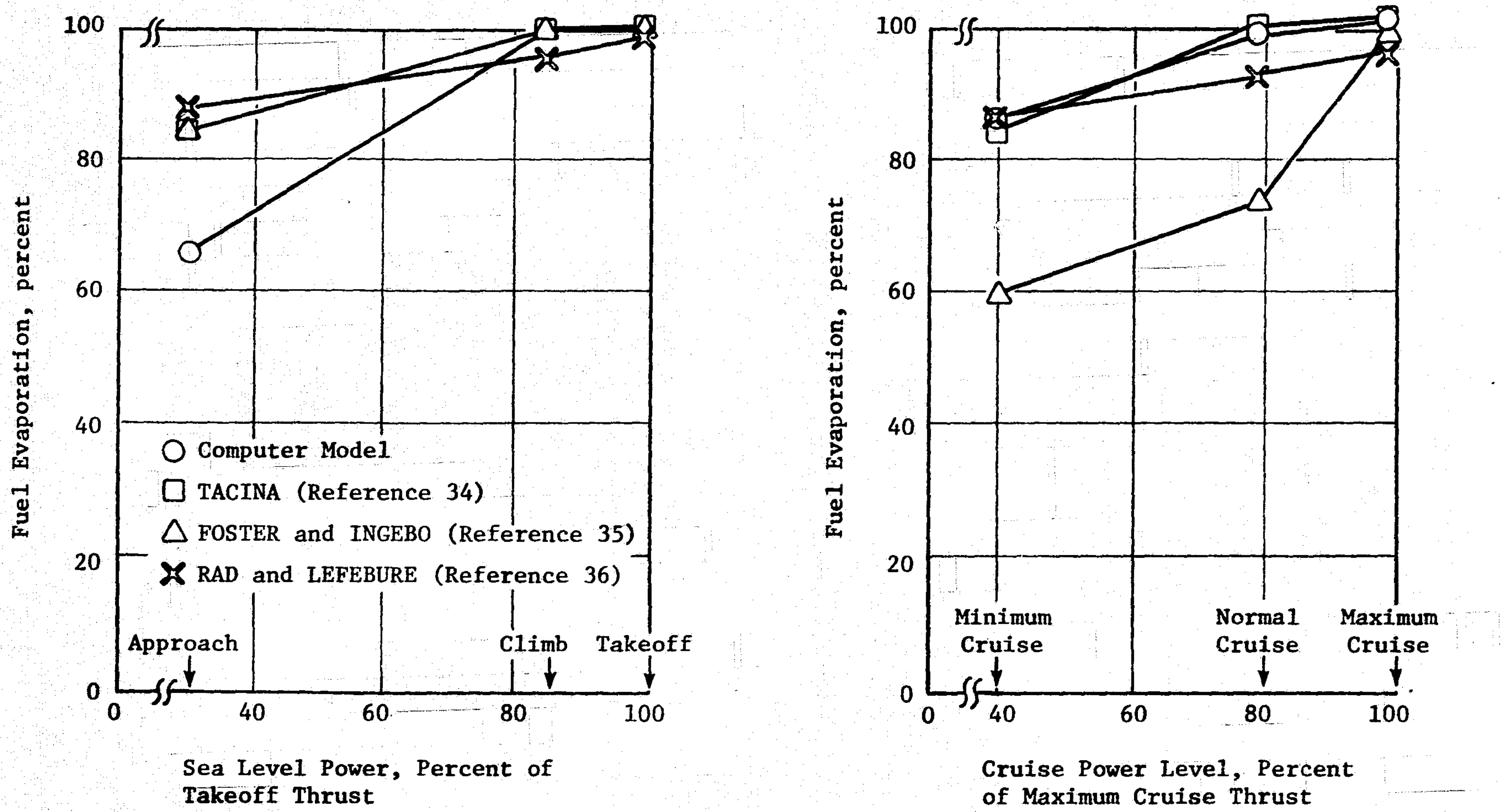


Figure 23. Comparison of Evaporation Predictions for a Typical LPP Fuel Injection System (Airstream Velocity = 61 m/s, Fuel Orifice Diameter = 0.635 mm, Evaporation Length = 10.2 cm).

As indicated in Section 4.2, methods for analytical prediction of mixture uniformity have not been perfected because of the complexity of the mixing process in two-phase turbulent flow with a simultaneous phase change. Therefore, fuel spreading studies were limited to rough estimation of mixture uniformity using correlations and analysis techniques reported in the literature.

Considerable development is expected to be required to obtain uniform fuel-air mixture and to perfect any premixing system.

The fuel-air preparation system geometry of Concepts 1 and 5 is very similar to a system which was experimentally evaluated in Reference 15, except that pressure atomizing nozzles and converging premixing tubes are used. In that study, very uniform fuel-air ratio and mixture velocity profiles were obtained in a duct having a length-to-diameter ratio of about 6.0 with a swirler having a pressure drop of less than one percent. The length-to-diameter ratios for Concepts 1 and 5 are about 3.0, based on the average premixing tube diameter, indicating that some additional development will be required to obtain uniform mixtures with these systems. However, these systems should be capable of improved performance relative to the design evaluated in Reference 15 because of high turbulence levels obtained with the increased swirler pressure drop (about 2.5 percent $\Delta P/P$), and the use of converging premixing tubes. Also, the fuel injectors have dual core tips with different spray angles possible for the two spray cones. This provides for an additional degree of flexibility during the development effort. Although additional development may be required, the swirl tube concept can be developed in relatively simple and inexpensive tests of a single swirl tube.

Evaluation of fuel spreading in Concepts 2, 3, and 4 utilized experimental and analytical techniques described in Reference 22 and experimental results reported in References 20 and 21. The general method used, which is described in Reference 37, was to model the fuel injection orifices as a square array of point sources with spacing S between adjacent sources. The fuel-air mixture uniformity then depends on the ratio of the square of the source spacing (S^2) to a spreading index (m), which is determined from References 22, 20, or 21. In order to obtain mixture uniformity with ±10 percent, the ratio S^2/m must be less than about 2.6.

Predicted uniformity depends to a large degree on the length scale applied. An example of possible length scales is shown for an injection system typical of Concepts 3 and 4 in Figure 24. If fuel penetration is ignored, the appropriate length scale is S1, which is the spacing between the fuel injectors. With fuel penetration, the appropriate length is the largest of S2, S3, S4, and S5 (length S5 assumes that the source is reflected at the wall, which is the procedure recommended in Reference 22). Assuming no fuel jet penetration, more than 100 percent nonuniformity is predicted (peak fuel-air ratio is more than twice as high as the mean) using a spreading index based on the correlation of Reference 20. However, much better results are predicted if fuel jet penetration is considered. Nonuniformity is minimized when S2 = S3 and S4 = S3. These relationships can be obtained by adjusting the angle of injection relative to the direction of the airflow (α_1) to reduce effective fuel jet penetration, and the orifice spacing (in Concept 2) or

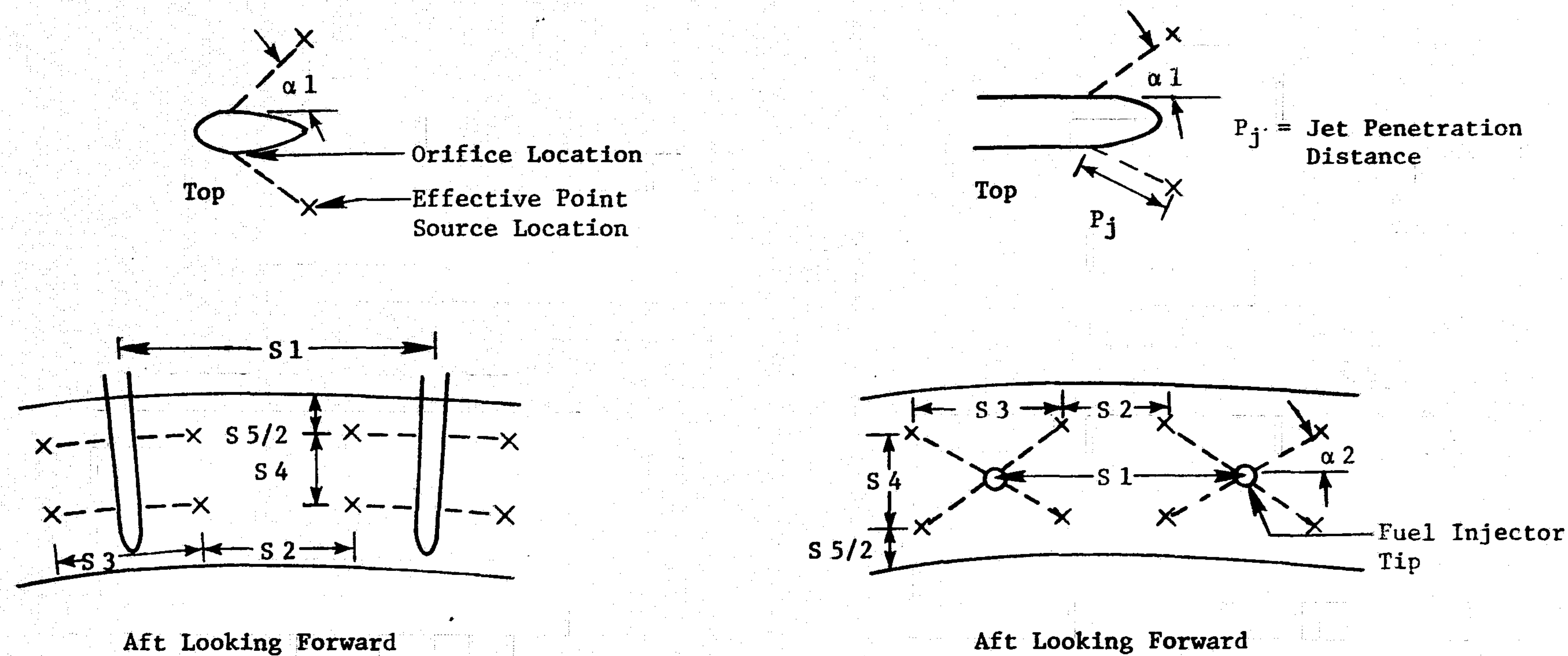


Figure 24. Concepts 2, 3, and 4 Fuel Injector Design Parameters.

angle of injection relative to the fuel injection duct pitchline (α_2) to set the radial spacing between the effective point sources. Predicted optimum values for α_1, and α_2 for concepts 2, 3, and 4 (based on predicted penetration at the takeoff operating condition) are presented in Table XVII. With these injection angles, nonuniformity of less than ±10 percent is predicted for all three concepts, assuming that airstream velocity profiles are perfectly uniform and that exactly equal amounts of fuel flow through each orifice.

As indicated previously, there is a good deal of uncertainty in the above spreading estimates. Therefore, it is unlikely that the predicted fuel-air mixture uniformity could be obtained without significant development. However, these studies do indicate that good mixture uniformity can probably be obtained in Concepts 2, 3, and 4 while also meeting autoignition and combustor size requirements.

Fuel injectors in each concept were designed with double-wall construction, as shown in Figures 17, 18, and 19, to prevent coking and gumming. Results of elementary heat transfer analyses on the injector stems indicate the internal wall temperatures will be well below maximum levels specified by standard General Electric design practice. The pressure atomizing fuel nozzle tips used in Concepts 1 and 5 are also very similar to conventional designs, so no coking problems are expected. The probability of injector coking in Concepts 2, 3, and 4 is slightly increased due to the small values used for orifice size (0.51-mm diameter) and orifice pressure drop at minimum cruise conditions (0.06 MPa) which were selected in order to maximize the number of injection points (for improved mixture uniformity). Although no major durability problems are expected, further investigation of the tradeoff between injector durability and mixture uniformity would be included in the combustor development process.

The final consideration in fuel-air preparation studies was sensitivity to inlet temperature and velocity distortion. Both mixture uniformity and autoignition tendency can be affected by inlet distortion. If fuel is uniformly distributed across the premixing duct at the fuel injection plane, the local fuel-air ratio will be inversely proportional to local velocity (mass flux effect) and proportional to local temperature (density effect). Similarly, autoignition tendency will be increased in locally low velocity regions (increased dwell time) and high temperature regions (decreased autoignition delay time).

Design factors which affect sensitivity to inlet velocity distortion include diffuser shape, boundary layer effects, and distortion attenuation by blockage upstream of the fuel injectors. The use of a curved diffuser tends to produce thickening of the boundary layer on the inside of the turn, resulting in an outboard peaked radial velocity profile. In the conceptual designs, required turning is accomplished in a constant area passage prior to diffusing the flow in order to avoid this problem. Boundary layer effects are also minimized in the conceptual designs by drawing premixing duct flow from the central portion of the diffuser, using the low velocity boundary layer flow

Table XVII. Concepts 2, 3, and 4 Fuel Injector Design Values.

Concept	Injection Angle Relative to Flow Direction (α_1), degrees	Injection Angle Relative to Annulus Pitchline (α_2), degrees
2	41	0
3	66	27
4	49	39

to feed the pilot dome and inner and outer combustor passages. Sensitivity to inlet distortion is reduced by placing a blockage at the inlet to the premixing duct, as is the case with the variable swirlers in Concepts 1 and 5. In these concepts, the pressure drop across the swirlers is about two-and-one-half times as large as the average velocity head at the diffuser exit. This pressure drop tends to distribute the flow uniformly among the swirl tubes.

Engine test measurements of temperature and velocity profiles within the diffuser of an advanced combustion system, both with a clean compressor inlet and with a 180° screen to force compressor inlet distortion, indicate temperature distortion of less than ±30K and velocity distortion of less than 30 percent (except in the boundary layer) as indicated in Figure 25. This level of temperature distortion would reduce autoignition delay time by 30 percent (using the correlations of Reference 5), and the local premixer dwell time would be increased by up to 30 percent by the velocity distortion. The system tested utilizes a short, curved, single-passage diffuser. It is expected that reduced distortion levels obtained with the multiple-passage diffuser designs used in LPP Combustor Concepts 2, 3, and 4 will be acceptable in terms of these effects on both autoignition and mixture uniformity.

In summary, obtaining uniform fuel-air mixtures without autoignition or flashback and with adequate fuel injector durability and tolerance to inlet distortion appears to be possible with all concepts. Considerable development effort will be required to fully assess the tradeoffs among system performance (evaporation and mixture uniformity), reliability (resistance to coking), and safety considerations (autoignition and flashback). Of the combustor concepts studied, the swirl tube combustors (Concepts 1 and 5) appear to have the lowest design risks based primarily on injector durability and sensitivity to inlet distortion.

6.3 AEROTHERMO PERFORMANCE

A series of aerothermo analyses were conducted to predict performance for the purpose of evaluating each of the five LPP low-emission combustor concepts over the engine operating range. Analysis was conducted at appropriate cycle points specified in Section 3.0. Aerothermo performance analyses were conducted to determine combustion efficiency predictions, combustor pressure drop estimates, exit temperature profiles, pattern factors, and combustor stability.

Combustion Efficiency

Combustion efficiency is a function of combustor inlet conditions, main-stage and pilot stoichiometry, residence time, dilution rates, flameholder geometry, and piloting features. For combustor Concepts 1 through 5, the combustion efficiencies are very high at all of the typical steady-state operating conditions, including idle. The method employed to obtain combustion

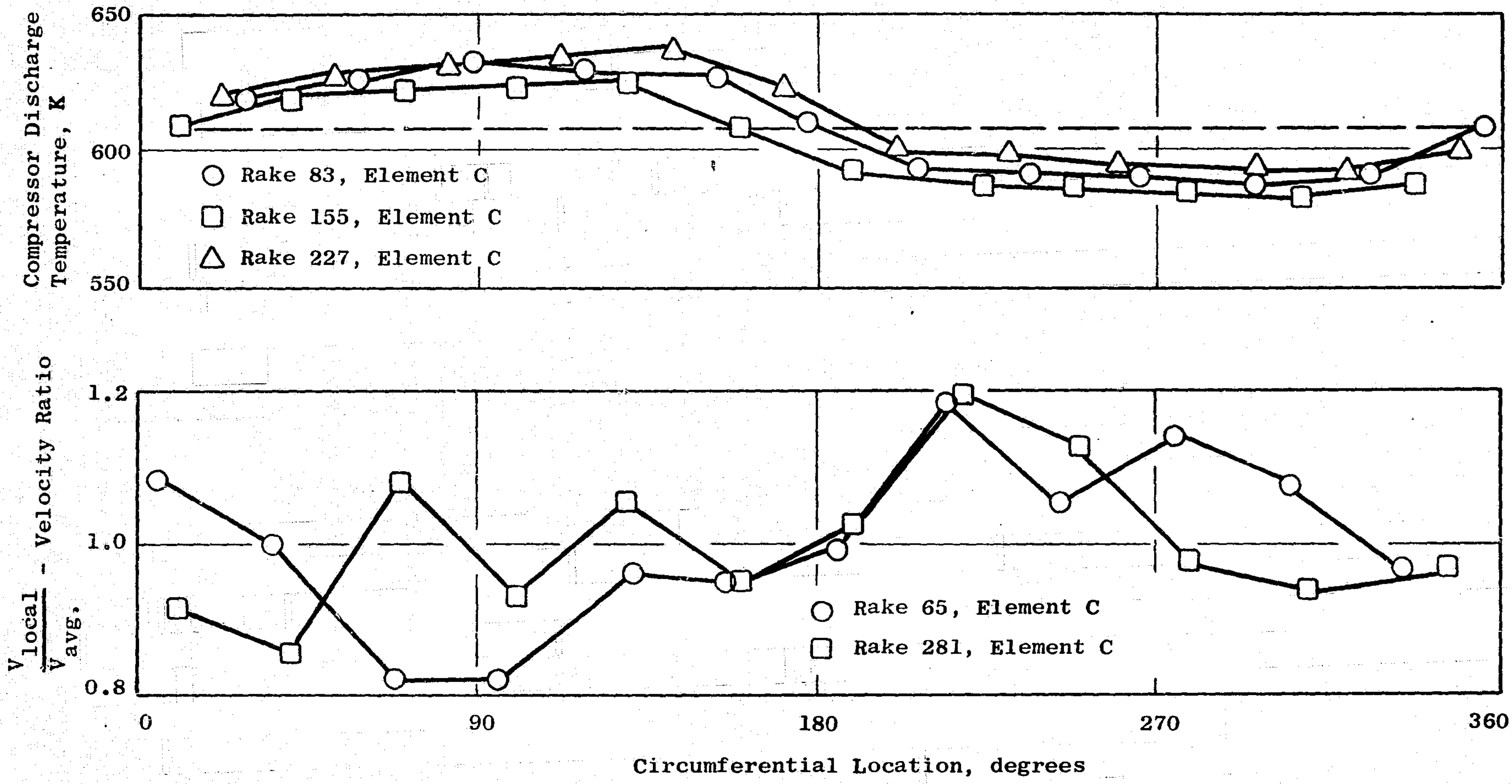


Figure 25. Circumferential Velocity and Temperature Variation for an Advanced Compressor with a 180° Distortion Screen.

efficiencies was to first predict the system emission levels (reference Section 6.5) and then calculate the efficiency levels using the emissions indices. The following relationship was used:

$$\eta b = 100 - 0.1\ EI_{HC} - 0.02334\ EI_{CO}$$

The systems all meet the goals of 99.9 percent at takeoff, 99.5 percent at idle (6 percent thrust idle assumed), and 99 percent at all other operating conditions.

Combustor Pressure Loss

Pressure drop for each of the LPP conceptual designs was predicted based on an incompressible flow analysis. Special consideration was made for these LPP concepts since all include airflow modulations. Also, interface with the turbine and the requirements needed for proper turbine vane cooling were considered. The principle design considerations included in this analysis were:

- Prediffuser losses
- Dump losses
- Turbine cooling backflow margin
- Airflow modulation position
- Passage static pressure recovery
- Variable vane and injector losses

The five combustor concepts all employ some form of dump or step diffuser. The diffuser pressure loss was estimated using the static pressure recovery curves of Figure 26. An additional dumping loss due to flow separation (with no static pressure recovery) at the diffuser step was added for airflow which was not directed into a cowling surrounding a dome.

In general, the combustor system pressure loss is a weak function of temperature rise but a strong function of geometry; i.e., effective flow area. The relationship used for calculating the pressure drop across the domes and liners was of the form:

$$\Delta P = \frac{W^2\ RT_3}{2\ A_e^2\ P^2}$$

where $\Delta P/P$ = the element pressure drop (liner, dome, etc.) divided by the local upstream pressure

W = airflow rate

R = gas constant

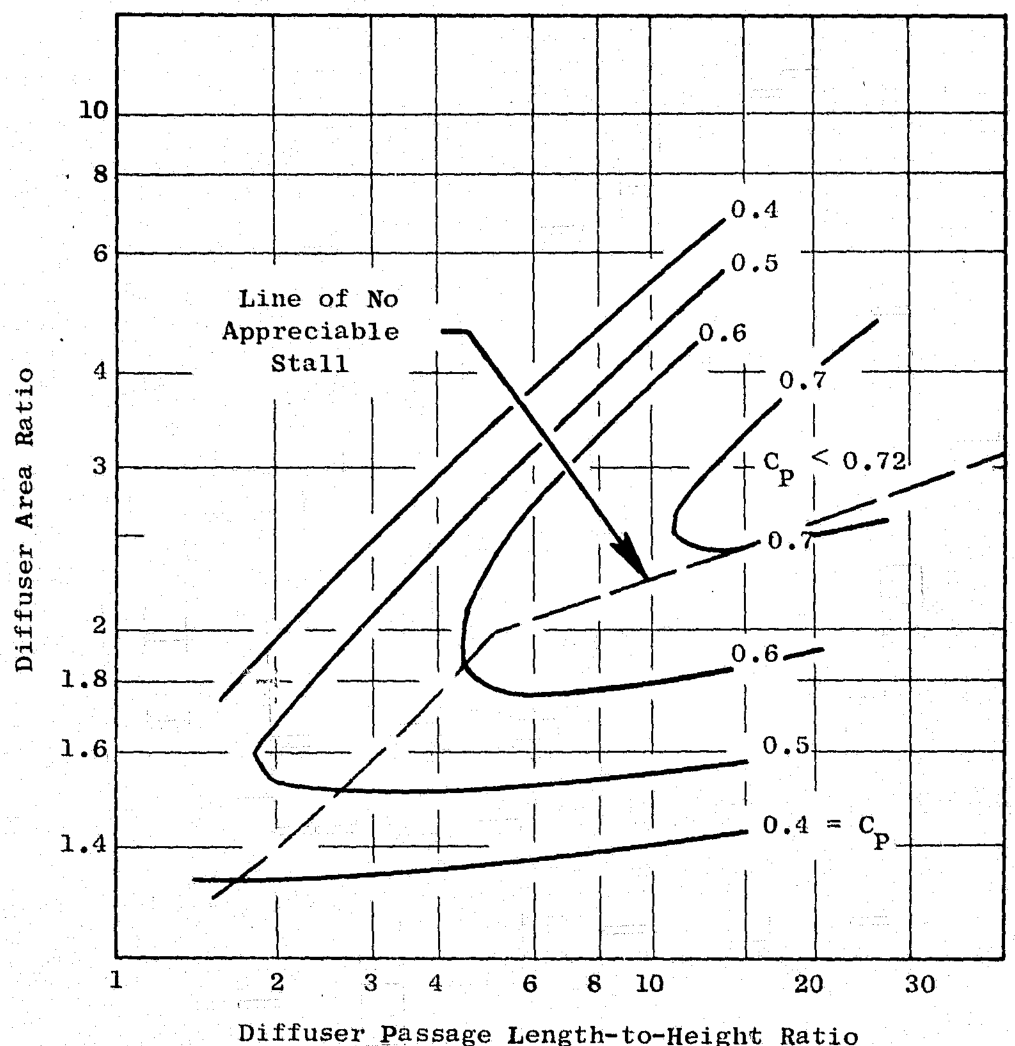


Figure 26. Two-Dimensional Diffuser Pressure Loss (Reference 31).

T_3 = combustor inlet temperature

A_e = effective flow area

P = pressure

For these LPP combustors that employ airflow modulation, the modulation technique and selected mode of operation have a dramatic effect on pressure loss. The variable-geometry vanes in these analyses were modeled as variable orifices. The flow/pressure drop relation is the same as the equation above except that the effective area is a variable depending on the selected operating mode. For Concept 4, with an open-closed vane position actuation system and no compensating variable geometry, pressure loss is largely dependent on vane position. The effective flow area is sized for approximately 5 percent pressure drop for open vane position when operating at high power settings and a higher loss (9.6 percent) for closed vane positions when operating at idle with reduced effective flow area.

Concept 2, however, employs a system that automatically increases effective area simultaneously with variable vane closure. In contrast, Concepts 1 and 5 have continuously variable-vane systems and, therefore, a wide range of pressure loss possibilities. At idle (steady state), the pressure loss is 9.7 percent. At approach the loss is 7.5 percent. At cruise and above, it is 5.1 percent.

Concept 3 employs a fluidic control airflow modulation system. It has been designed such that the combustion system has essentially constant pressure loss independent of the mode selection. The potential advantage of this airflow modulation technique is mechanical simplicity since no actuation system and effective area compensating system is required. Combustor pressure loss predictions for each of the five conceptual designs are included in Table V. See Section 6.8 for combustor pressure loss effects on the cycle.

Combustor Exit Temperature Distribution

Two measures of combustor exit temperature distribution are generally of concern. One of these is the pattern factor, which is a measure of the highest single temperature at the combustor discharge. The other is the radial temperature profile factor, which is a measure of the radial distribution of the temperature. The pattern factor is defined as

$$P.F. = \frac{T_{T4\ max} - T_{T4\ avg}}{T_{T4\ avg} - T_{T3}}$$

where $T_{T4\ max}$ = the highest single temperature at the combustor exit

$T_{T4\ avg}$ = the average temperature at the combustor exit

T_{T3} = the average temperature at the compressor exit

The pattern factor is used in the cooling design for the turbine stator. Since the one local hot spot may occur anywhere in the annulus the entire stator must be designed to be capable of the temperature defined by the pattern factor. The radial profile factor has a similar definition:

$$\mathrm{Pr.\ F.} = \frac{T_{T4\ peak} - T_{T4\ avg}}{T_{T4\ avg} - T_{T3}}$$

where T_{T4} = highest temperature of the temperature profile. The requirement for the E^3 engine combustor is illustrated by Figure 27. The profile curve to the left is the desired or design profile. However, since profiles will vary from engine to engine, a locus of possible peaks is also used and is the profile limit. Any profile which is to the left of the limit curve is acceptable. The turbine rotor is designed for the limiting curve.

Temperature distribution capabilities for the four combustor concepts were predicted based on test results for similar combustors. Concept 1 should function in a manner similar to that of many previous standard single-annular combustors developed at General Electric. In fact, premixing of the fuel and air should provide some improvement in terms of hot spots caused by streaks of liquid fuel in the domes of conventional combustors. Therefore pattern factors on the order of 0.2 or less and normal profiles are anticipated for Concept 1. The same performance would be expected for Concept 5.

Concept 2 should have normal profile shape capability. The design has one more degree of flexibility for trimming profiles than do standard combustors. This is the possibility of modifying the profile by adjusting the fuel flow split between the inboard and outboard premixing ducts. Therefore, normal profiles should be achievable. The premixing ducts for the main stage present an unknown; however pattern factors of approximately 0.20 are predicted.

The pattern factor of Concept 3 will be dependent upon achievement of uniform fuel/air distribution in the main-stage premixing duct. Quite uniform fuel distribution at the inlet to the combustion section is anticipated. Note that in a standard combustor design, all of the fuel is introduced into the dome region in a number of discrete fuel jets. Twenty-eight fuel injectors are used in Concept 1, for example. For Concept 3, 240 individual fuel jets are planned for the 60 main-stage injectors. With development, uniform fuel profiles should be attainable with this concept; and pattern factors on the order of 0.20 are expected. The radial profile goals for Concepts 3 and 4 were based on experience from the NASA/GE ECCP double-annular combustor program where several double-annular combustors were designed and tested. For Concept 3, excellent penetration and mixing of the main-stage and pilot gases are expected with the arrangement as shown in Figure 13. The penetration of the main-stage gases into the primary zone gases can be controlled by adjustments to the V-splitter slopes and opening sizes. Therefore, excellent profiles are anticipated with development.

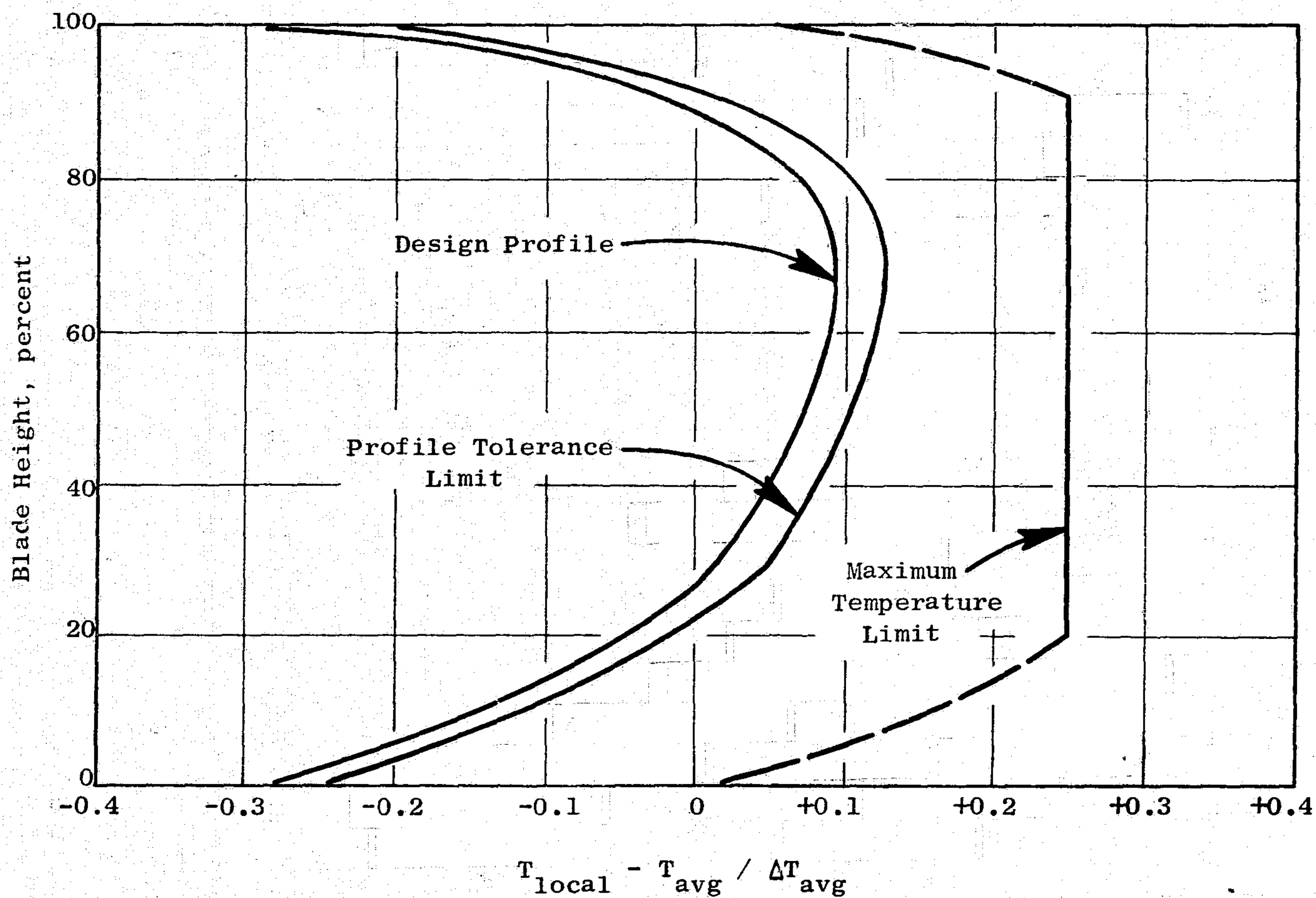


Figure 27. E^3 Turbine Inlet Radial Temperature Profile.

The profile goals for Concept 4 will be the most difficult of the four concepts to achieve based on previous experience with double-anular combustors. For this concept, more aft dilution air has been provided for Concept 4 versus 2 percent for the reference test combustor (ECCP). In addition, the airflow split between the pilot-stage dome and the main stage has been shifted in favor of the main stage at high power conditions on this concept (relative to earlier tested combustors). This minimizes the contribution of the pilot dome and should result in improved radial profiles. With development, it is anticipated that acceptable radial profiles should be achievable with this concept.

For Concepts 2, 3, and 4, sector burning is employed to avoid very low fuel-air ratios in the main stages during low fuel flow conditions. The sector burning is utilized only at low-power conditions when fuel flows are low so that considerable margins in profile and pattern factor exist at these conditions. Nevertheless, temperature distribution is a consideration. For the studies completed, the maximum local temperatures with sector burning were limited to less than or equal to those that occur at the takeoff condition with uniform burning. The selection of the sector size thus became a compromise between emission levels and temperature distribution. Additional comments on sector burning are presented in Sections 6.1 and 6.7.

Table XVIII presents a summary of the results of this study on pattern factor and profile for high-power conditions without sector burning. The same maximum temperature limitations were used in establishing the sector burning configurations.

Combustion Stability

Combustion stability can be divided into two categories: lean blowout and combustion-generated oscillations. Although these phenomena are related, they are generally treated separately in the design and development of combustion systems. Lean blowout characteristics have been well documented and were discussed in Sections 4.3 and 6.1. Oscillation predictions are, on the other hand, more difficult to handle analytically.

Various methods exist for the purpose of maintaining lean blowout stability on LPP combustors. All LPP concepts of this study employ swirl vanes (either fixed or variable in the pilot stage) to anchor or stabilize the flame. Concepts 1 and 5 use swirl vanes exclusively. Concept 2 features a nested pilot, i.e., the pilot swirl cup is surrounded by the premixed fuel-air mixture as it enters the primary combustion zone. The purpose of this pilot design is to provide an ignition and flame stabilization system for the main stage. Concept 3 also employs a main-stage piloting concept. But in this design, hot pilot gases are intermixed with the main-stage fuel-air mixture in layers. This action is provided by the U-gutter arrangement at the premix duct discharge plane. In contrast, Concept 4 uses a perforated-plate flameholder for the main-stage flame stabilization which is capable of stabilizing the flame without the aid of a pilot dome. Theoretically, the pilot could be shut off at high-power conditions on Concept 4. This is not done because of profile effects and transient operation considerations.

Table XVIII. Predicted Temperature Distribution Summary/Comparison.

	Concept 1	Concept 2	Concept 3	Concept 4
Pattern Factor	Predicted PF $\leq$ 0.2 based on severity parameter correlation. (0.2 = goal) This prediction is believed conservative as premixed system will provide some benefits relative to dome generated hot streaks.	PF $\approx$ 0.2 Dome slot presents unknown but not expected to present any significant problems.	PF $\approx$ 0.2 Will be dependent on main stream f/a uniformity.	PF $\approx$ 0.2 Dependent on main stream f/a uniformity.
Turbine Inlet Temperature Profile	Normal profile. Anticipated (similar to conventional combustors). No problem expected.	Normal profile. Can trim by adjusting main stream flow split as well as by normal trimming methods.	More difficult to achieve profiles, however penetration of main stream with pilot stage can be controlled by adjustments to "V" splitter openings and slope.	Most difficult of three designs to achieve profile shape. However, more dilution air avail and less pilot flow than for previous double annular combustion tested (ECCP).

The lean blowout limit for pilot swirlers (Concepts 2, 3, and 4) was presented as Figure 21. This limit applies to Concepts 1 and 5 as well when operating in the idle mode. Premixed main-stage lean blowout limits have been presented as Figure 9 based on the experimental results of Reference 23. More recent data reported in Reference 25 and also contained in Figure 9 present an improved lean blowout prediction. It should be pointed out that those data were taken at 800 K/1MPa only and may not apply directly over a wide range of combustor inlet temperatures. Several flameholder types were tested with no pilot stabilization; little variation was reported in lean blowout limits. For Concepts 2 and 3, this is probably conservative, but it applies directly to Concepts 1, 4, and 5 during high-power operation.

Another stability consideration when designing LPP combustors is combustion oscillation or combustion instability. Combustion oscillation is a dynamic coupling of the fuel-air system, combustion chamber acoustic properties, and flame characteristics. It is a function of combustor geometry and operating conditions (especially gas temperature) and the dynamic characteristics of the fuel system and combustion process. Analytical techniques for the prediction of this phenomenon are not refined and developmental testing is required to determine if and at what conditions instability exists. Concepts 1 and 5 are quite similar to conventional combustion systems except that considerably more dome airflow is utilized at high power operating conditions. In combustion testing of a high dome flow combustor (ECCP combustor with direct fuel injection), no problems with combustion instability were noted. High dome flow combustion systems represent a significant deviation from conventional combustors so that combustion dynamic pressure characteristics would deserve considerable attention during development testing of these combustion systems. Concept 2 also employs high dome flow at high power; however, the pilot swirlers may present some advantages in promoting flame stability at the high dome flow operating conditions. Concepts 3 and 4, on the other hand, have similarity to the radial/axial and the double-annular combustors of the ECCP. No instability problems of any consequence were noted (References 2 and 3) during the testing of the ECCP. This testing included extensive sea level engine operation. Concept 3, however, has fluidic flow control that depends on diffuser flow separation for airflow modulation. This represents an unknown; however, dump, or step, diffusers are in extensive use in the industry today and are not believed to result in any increase in the tendency toward combustion system instabilities. The step diffusers have a region of separated airflow by intent.

In general, experience indicates that no particular problem of combustion instability would be anticipated for any of the systems evaluated. However, because of the unknowns introduced with advanced combustion systems, considerable attention will be devoted to measuring and analyzing combustion dynamic pressures for these systems during development.

6.4 CONTROL SYSTEM CONSIDERATIONS

A study was conducted to assess the impact of LPP combustion concepts on the engine control system; specifically, to evaluate the impact of the required fuel flow control and airflow modulation control on the reference engine system and to evaluate the need for additional or new sensing techniques.

Control requirements can be summarized as:

- Fuel flow must be scheduled between the pilot and premix fuel stages to provide the splits described in Section 6.1 (applies to Concepts 2, 3, and 4 only).

- Fuel flow to the premixed stage must be selected for either sector or full-annular burning as described in Section 6.1 (applies to Concepts 2, 3, and 4).

- Airflow modulation must be selected for starting, idle, and all cycle points.

- Airflow modulation must be sequenced with fuel flow and staging to provide smooth continuous operation over the cycle envelope for transient operation for both accelerations and decelerations.

The fuel control system incorporating the above criteria is shown in Figure 28. Fuel flow from the engine fuel pump is filtered, metered, and then split as required between the pilot and premixed main stages (sector and full-annular). The three fuel valves and the airflow modulation are controlled by the fuel servo systems which in turn are closed-loop controlled by the digital electronic control. All the logic, schedules, and computation is accomplished within the Full Authority Digital Electronic Control (FADEC). A logic diagram applicable to Concept 4 is shown in Figure 29. Logic diagrams for Concepts 2 and 3 would be similar with slight variations. Figure 30 shows a model of the FADEC with a typical large-scale integrated circuit substrate included. The FADEC is an advanced concept control system that controls electronically in contrast to hydromechanical systems commonly in use on modern production engines. The FADEC is being developed for demonstration on the Joint Technology Demonstrator Engine scheduled for test in late 1979 and is planned for use on the NASA/GE Energy Efficient Engine. If LPP concepts incorporated in these combustor designs were to be implemented on the existing CF6-50 engine, then an additional control system would be required to supplement the existing control to accommodate the additional requirements of airflow modulation or fuel staging.

Fuel flow dividing valves required to schedule fuel for staging and sector burning as required for Concepts 2, 3, and 4 are depicted in Figure 31. The use of the digital control for scheduling fuel flow splits provides great versatility. It can readily provide splits as a function of total flow, percent core speed, compressor discharge pressure or temperature, or other measured parameters in any combination. It can also modify splits during transients to prevent blowout and ensure smooth continuous operation.

One concern item would be carbon or gum formation within the unfueled injectors during sector burning. Based on experience with commercial jet engines which employ fuel injectors that do not flow fuel at all operating conditions, no problems are expected and purging of the nonflowing fuel injectors is not proposed. Current commercial engines employ fuel systems for

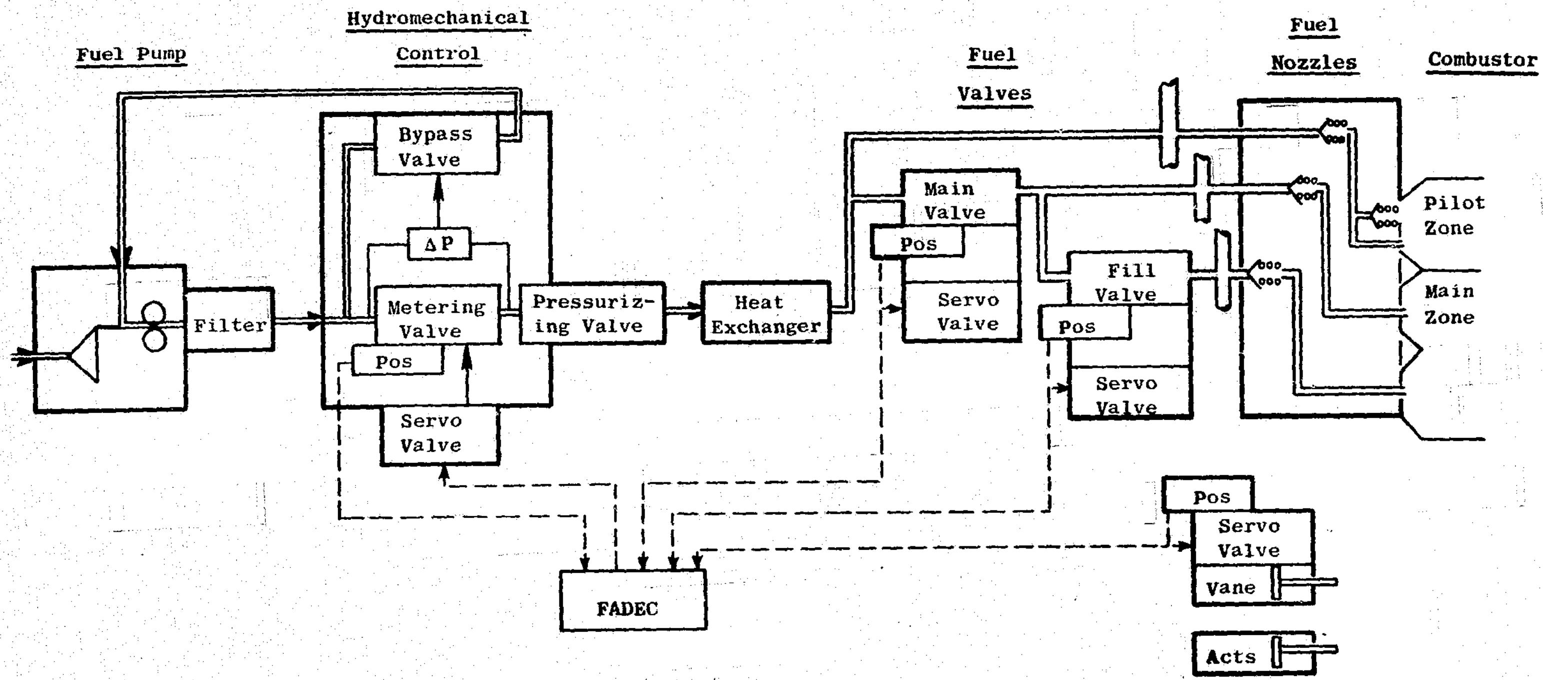


Figure 28. Fuel Control System Schematic.

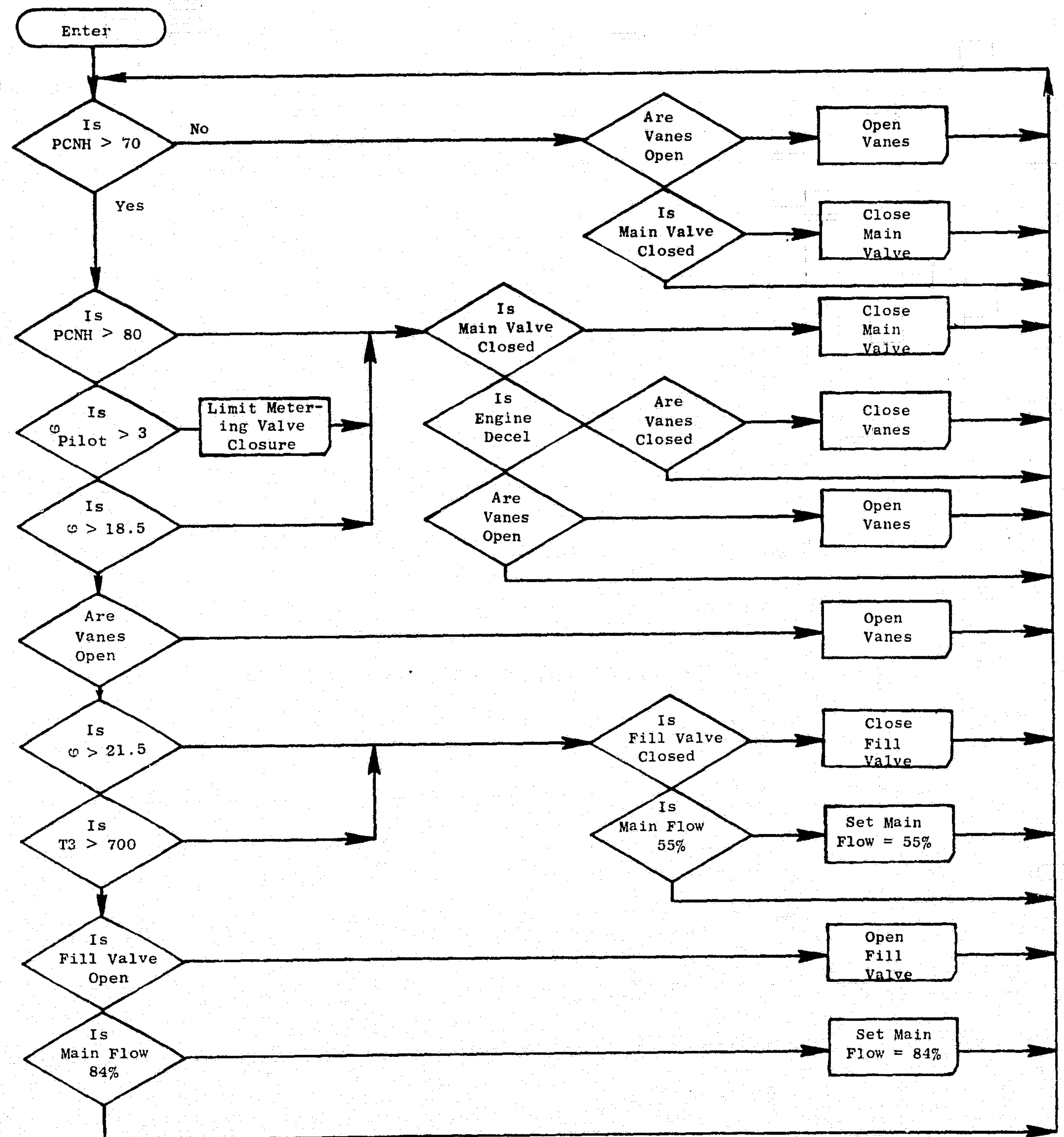


Figure 29. Logic Diagram for LPP Combustor Control.

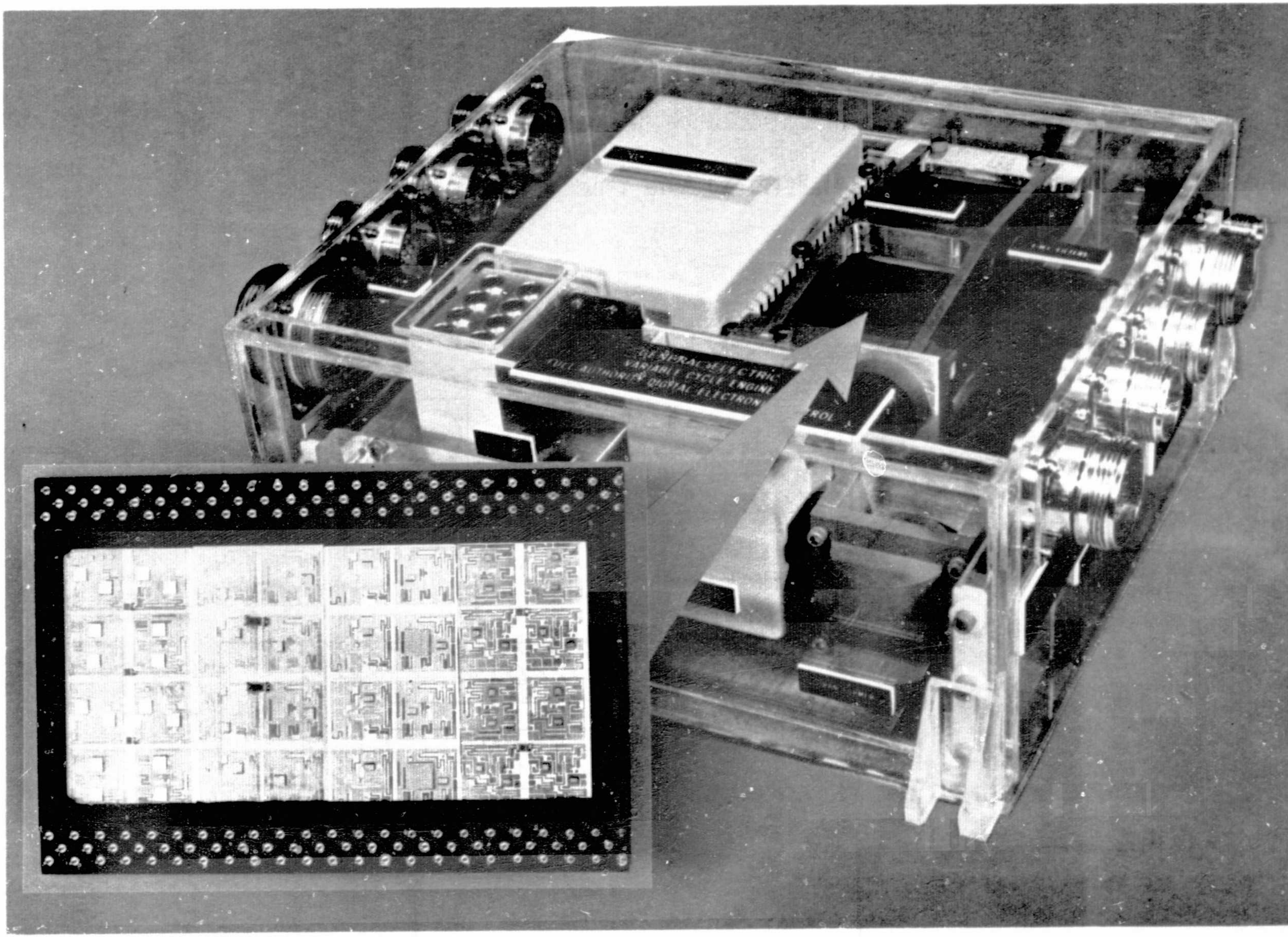


Figure 30. Full Authority Digital Electronic Control (FADEC) Model and Typical Hybrid Substrate.

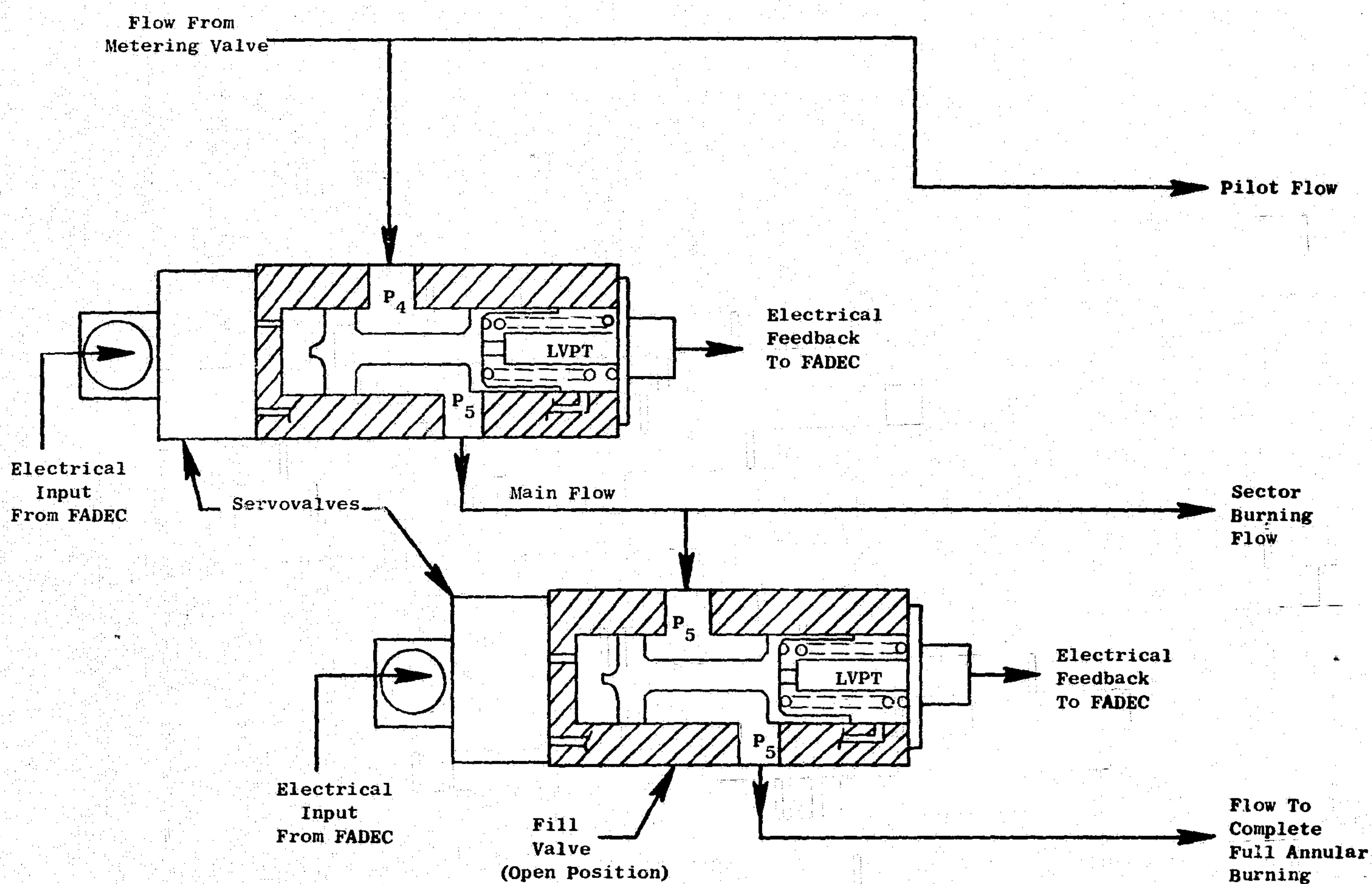


Figure 31. Fuel Flow Dividing Valves.

which a portion of the injectors are not fueled at all times. No carboning within the fuel injector spray tips has been encountered with these systems with Jet A fuel; therefore, no purging of the LPP fuel injectors is proposed during or after sector burning.

Airflow modulation in Concepts 1, 2, 4, and 5 is accomplished by scheduling the position of multiple vanes at the inlet of the premix ducts. The vanes will be actuated to full open or full closed position with no intention of operation in intermediate positions for Concepts 2 and 4. Concepts 1 and 5, however, require proportional modulation depending on power setting and accel and decel parameters. In either case, the means of actuating these systems takes advantage of proven technology used in variable-stator mechanisms employed on General Electric aircraft gas turbines.

Each combustor air vane is rotated by a radial shaft extending out through the combustor casing (Figure 32). Lever arms that connect the pivot of each shaft to an actuation ring are rotated through an adjustable linkage by a master lever which is moved by hydraulic actuators. The bearing-mounted adjustable linkage provides for rigging the air vanes at open or closed position to the actuator end stroke position. It also allows for small axial movements of the actuation ring as the lever arms rotate. Vane actuation synchronization is achieved through the inherent rigidity of the actuation linkage.

The variable combustor vane actuators are fuel-operated, double-acting hydraulic cylinders. The full stroke length is a critical rigging dimension, creating a baseline for the combustor variable vanes in the open or closed position. The actuator head and rod ports are supplied through the inner section of double-walled fuel lines, the outer chamber of which protects against port fitting leakage and provides a path to overboard for interseal drainage. A Teflon wiper installed in the end cap keeps the rod clean to avoid seal damage. These features are important when operating fuel devices near hot sections of the engine. Since vane air loading can be balanced, only linkage friction needs to be overcome. Based on the loads of standard CF6-type variable compressor stator actuators which position several stages of stator vanes, only one combustor vane actuator is required. Two smaller actuators located 180° apart are desirable to provide balanced actuation forces.

The FADEC computes the scheduled air vane position based on sensed parameters and provides an electrical signal to an electrohydraulic servovalve. The servovalve controls the pressurized fuel to the head and rod ports of the actuators (Figure 32). A closed-loop system is accomplished by sensing the actuator linear position using a linear-variable-phase transformer (LVPT), providing a digital, compatible, electrical signal feedback to FADEC.

The time required to actuate a vane system or switch the fluidic flow control is of interest because of the impact on acceleration or deceleration times. The control system has millisecond delay times and, therefore, does not affect transient time requirements. Transient times will be affected, however, by the actuation time which is a function of load requirements. A practical actuation time for a vane system is estimated to be less than 0.5 seconds and even less for the fluidic flow control.

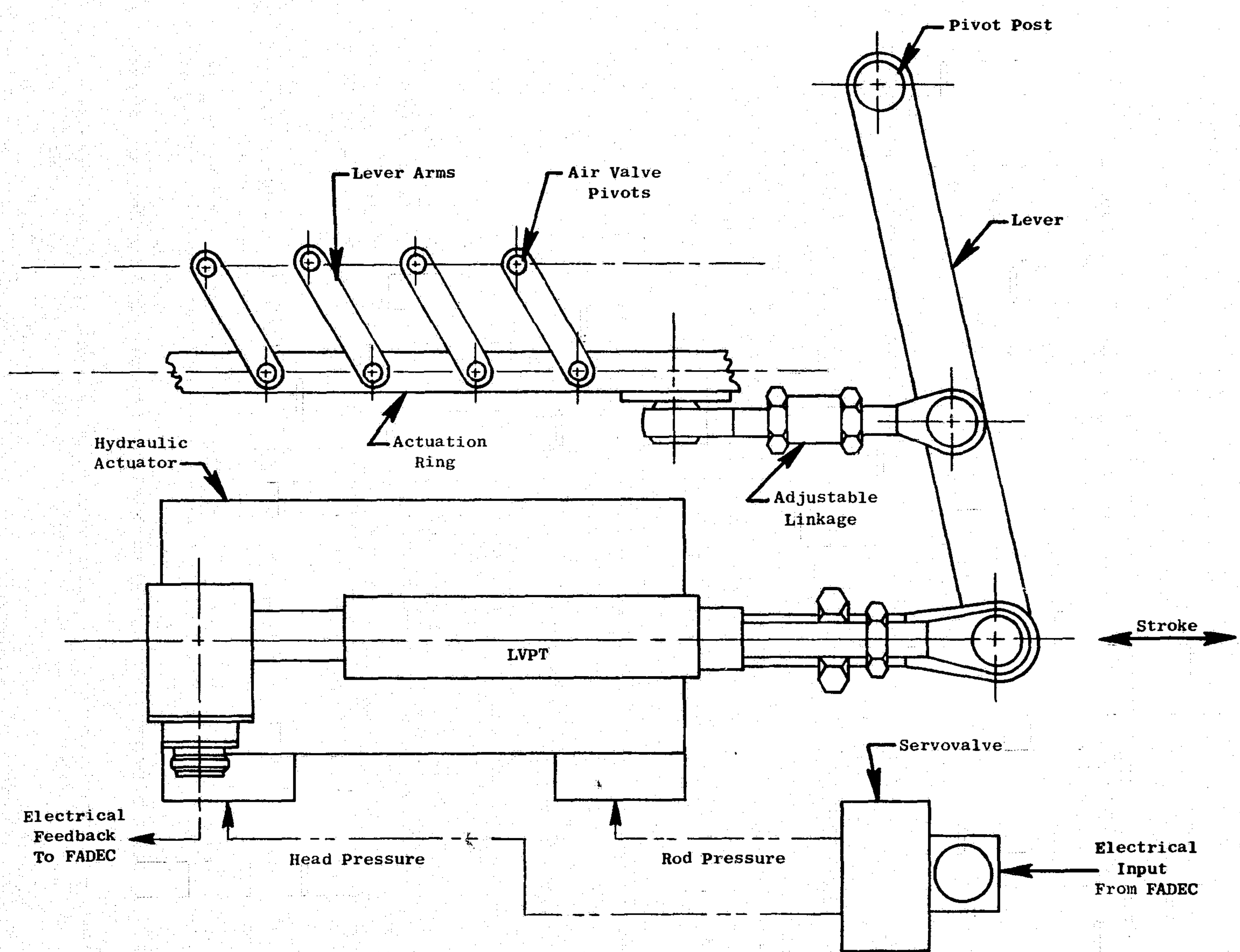


Figure 32. Combustor Airflow Modulation Means.

Airflow modulation for Concept 3 is accomplished by a fluidic diffuser. It is designed to be bistable in airflow modulation, i.e., two stable modes of operation much like a two position (open-closed) vane system. Control is accomplished by selecting either inner or outer bleed ports with a remotely actuated valve located near the engine centerline between the combustor and the turbine rotor. Bleed air will be used for turbine rotor cooling. Therefore, it is functionally identical to Concepts 2 and 4 from a controls point of view.

The LPP combustor control requires that the FADEC provides two additional torque motor servovalve drives and two linear variable-phase position feedback transducer interface circuits. The impact on a FADEC designed specifically for the NASA/GE E^3 which includes custom LSI circuitry would be to add about 8 cm^2 or about 3 percent to the overall hybrid board area and about 0.5 kg to the overall weight of the control.

The LPP control strategy is estimated to be about 10 percent of the overall engine control strategy, or about 500 words of program memory. The FADEC will have sufficient spare memory capacity to perform the additional functions without configuration hardware change to the FADEC memory.

To summarize, it is concluded that the fuel flow splits and airflow modulation can be appropriately controlled using conventional digital electronic control systems with very little additional circuitry requirements beyond those of the reference engine. It is further concluded that the need for additional sensing requirements is limited to those required for fuel valve and airflow modulation position feedback and that no new sensing technique need be employed with the present program goals.

6.5 EMISSION PREDICTIONS

Emission predictions were conducted using the following general approach. Idle operation on pilot burners was treated separately from the main-stage or premixed operation. Total emission indices were appropriately weighted averages based on fuel flows to the respective stages when applicable.

Idle Operation on Pilot Burners

Baseline emission data obtained from state-of-the-art combustor component and engine testing were selected, modified, and corrected to the appropriate reference engine cycle for pilot burners (Concepts 3 and 4) or for idle operation in single-annular (Concepts 1 and 2). Specific sources of baseline data are listed in Table XIX. Compressor discharge temperature and pressure corrections were made using the relationship.

Table XIX. Emission Prediction Baseline Data Sources.

Idle Concept	Source
1 and 2	F101 Engine Test (Reference 39)
3	ECCP Phase II Radial Axial (Reference 3)
4	ECCP Phase II Double Annular (Reference 3)
5	CF6-50 Sector Burning Component Tests
Pilot Concept	**Source**
2, 3, and 4	ECCP Phase I Pilot Only (Refrence 2)
Main Stage Concepts	
1 through 5	Fundamental Flame Tube Data (Reference 24)

$$\frac{E_I}{EI_{base}} = \left(\frac{P_3}{P_{3\ base}}\right)^{\alpha} \ \mathrm{Exp}\left(\frac{T_3 - T_{3\ base}}{\tau}\right)$$

where the parameters α and τ are dependent on combustor design and were determined from correlations of state-of-the-art combustor emissions data selected to be representative of the particular LPP concept being considered. Table XX presents the numerical values for the parameters α and τ for each concept. The technique was exactly identical to that used to correct emission predictions on Reference 38.

Pilot-produced NO_x at cruise, climb, and takeoff conditions was predicted from pilot-only test data reported in Reference 2 and modified as presented in Figure 33.

Premixed Operation/Main Stages

Premixed main-stage emissions predictions are based on fundamental studies conducted under NASA contracts supported by the Stratospheric Cruise Emission Reduction Program (SCERP). The primary source is Reference 24 with modifications as required and corrections applied similar to those used on the pilot burners. These results are the only extensive measurements made at conditions which match those of the reference engine. However, Roffe used propane as a fuel in these studies, as opposed to Jet A which is the fuel being considered in this study. Therefore, the effect on NO_x emissions of using propane instead of kerosene is of interest. Calculations of equilibrium flame compositions and temperatures were done for both fuels, and the results were used to calculate the thermal NO production rate. These results, in terms of the ratio of the rate for propane divided by the rate for kerosene, are given in Table XXI.

Table XXI. Propane NO_x Production Rate Normalized by Kerosene NO_x Production Rate as a Function of Inlet Temperature and Equivalence Ratio.

	NO_x (ppm)/NO_x (ppm, kerosene)	
T_{inlet}-K	$\varphi = 0.5$	$\varphi = 0.7$
600	1.60	1.45
800	1.45	1.31
1000	1.32	1.22

Table XX. LPP Emission Correlation Constants.

$$\frac{EI}{EI_{base}} = \left(\frac{P_3}{P_{3\ base}}\right)^{d} \ \mathrm{Exp} \left(\frac{T_3 - T_{3\ base}}{\tau}\right)$$

Combustor Concept	CO		HC		NO_x	
	α	τ	α	τ	α	τ
1, 2, 5	-1.0	-250	-2.0	-100	0.37	345
4	-1.0	-250	-1.7	-136	0.37	345
3	-1.1	-230	-2.1	-76	0.37	345

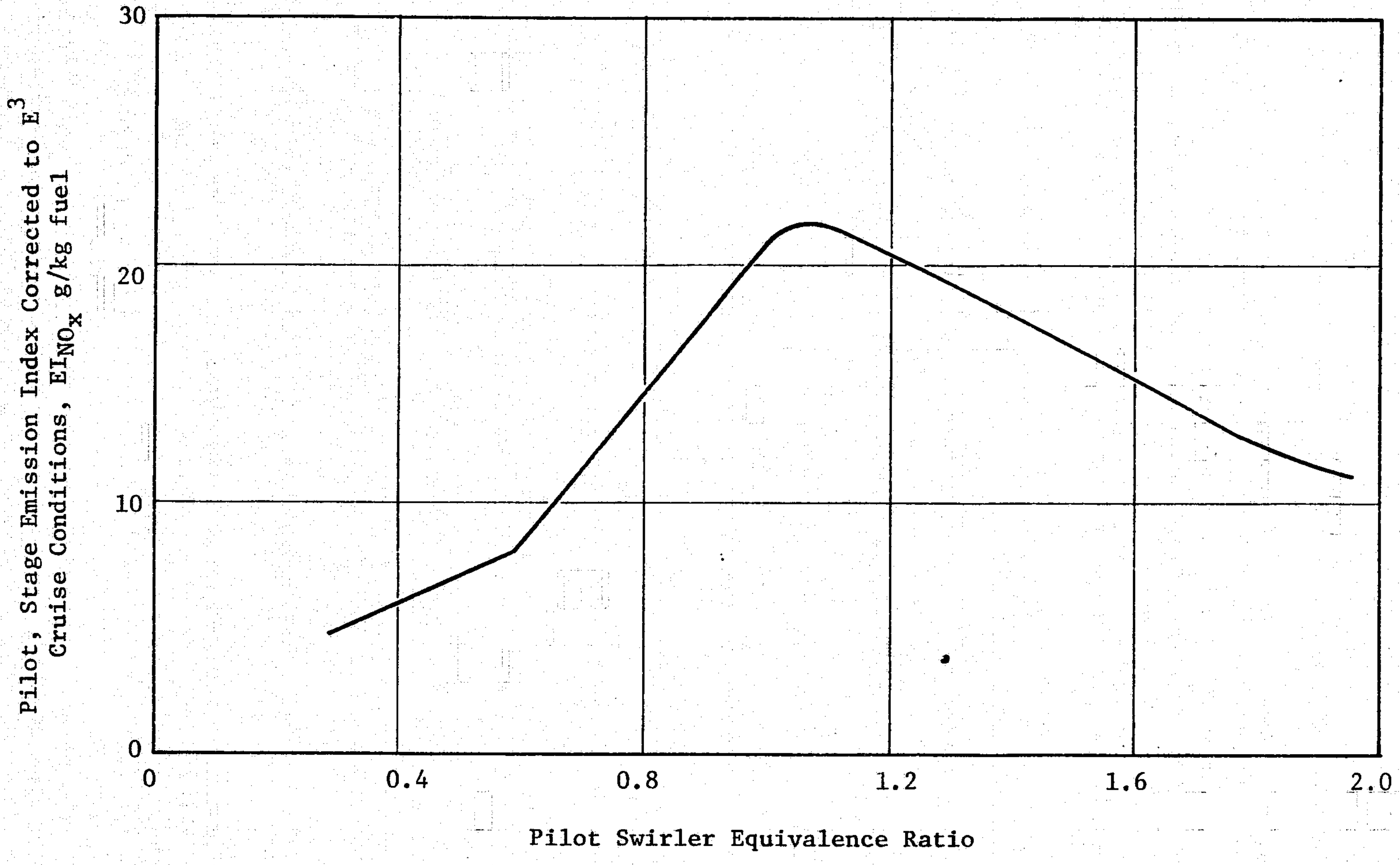


Figure 33. Pilot Emission Index Corrected to E^3 Cruise Condition Versus Equivalence Ratio.

The ratio is greater than one indicating that using Roffe's results for propane will give conservative estimates for the thermal NO_x emissions from kerosene. No corrections were made for the theoretical difference in NO production rate; the predictions included in this report are therefore believed to be somewhat conservative.

NO_x data from Reference 24 corrected to the E^3 cruise condition are presented in Figure 34. The average equivalence ratio calculated for this premix duct was not used to enter the graph, but an equivalence ratio distribution was assumed to account for nonuniform fuel-air mixing. The distribution assumed was that half the fuel-air mixture was 10 percent leaner than average and half was 10 percent richer than average. This assumption was applied to all predictions made from the fundamental data of Reference 24.

Combined Emission Predictions

Total emission predictions, i.e., predictions based on the additive effects of both pilot and main stages (where applicable) were calculated as weighted averages. Weighting was dependent on fuel splits as determined by the airflow splits and the desired stoichiometry for each burner contributing to the combined prediction. That is:

$$EI_{total} = \frac{EI_{pilot}\, W_{fpilot} + EI_{pre}\, W_{fpre}}{W_{fpilot} + W_{fpre}}$$

where:

EI = Emission Index, g/kg fuel

W_f = Fuel Flow, kg/s

Emission indices predicted for each of the five concepts at each cycle point are presented as Table XXII. All concepts investigated were predicted to meet the cruise NO_x goal of 3 g/kg and the cruise efficiency goal of 99 percent. The emission results expressed in terms of the Environmental Protection Agency Parameter (EPAP) as defined by Reference 1, are presented as Table XXIII. From these tables it is observed that all five concepts meet the program goal of 3 g/kg NO_x at cruise. Also, all concepts meet the EPAP goals, with a 6 percent idle thrust. Concept 4 even meets the EPAP goals with a 4 percent idle thrust.

Because the techniques used in predicting these emission levels are conservative, it is believed that these levels would be achieved and improved upon in the development of any of the five combustor concepts. Also there appear to be some margins in NO_x emissions which could be used for further advancements in other areas such as reduced CO. Their tradeoff should be done during a development program. Therefore, these LPP combustor concepts represent very promising approaches for meeting very low emissions levels for advanced engines.

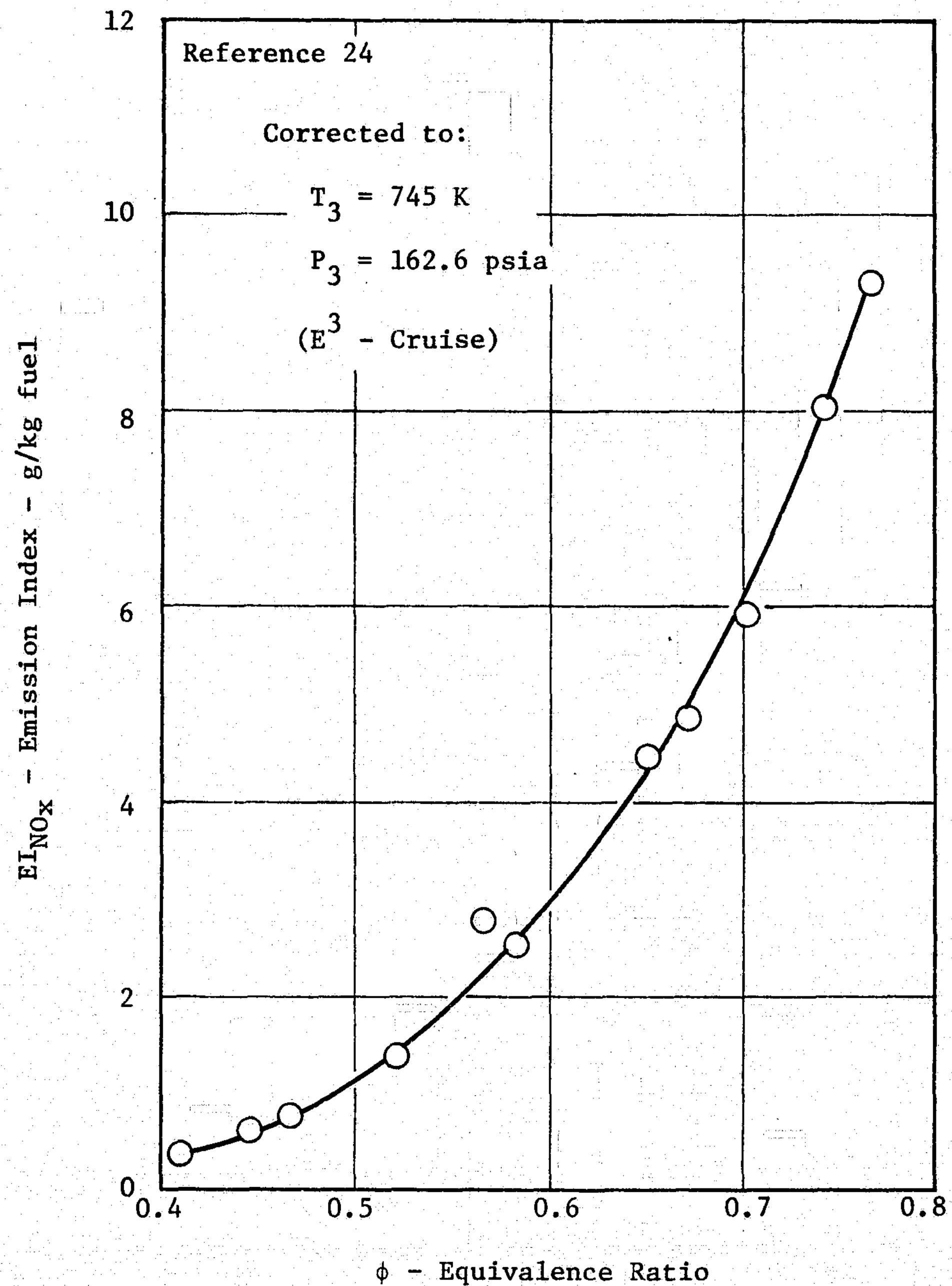


Figure 34. Mainstage Emission Index Corrected to E^3 Cruise Condition Versus Equivalence Ratio.

Table XXII. LPP Emission Predictions at Cycle Points.

	4% Idle*				6% Idle				Approach			
	Emission Indices g/kg Fuel			Combustion Efficiency, %	Emission Indices g/kg Fuel			Combustion Efficiency, %	Emission Indices g/kg Fuel			Combustion Efficiency, %
Concept	CO	HC	NO_x		CO	HC	NO_x		CO	HC	NO_x	
1	25.8	2.3	3.6	99.2	15.4	0.5	4.7	99.6	2.5	2.8	1.8	99.7
2	25.8	2.3	3.6	99.2	15.4	0.5	4.7	99.6	6.5	2.4	3.1	99.6
3	19.9	0.2	3.4	99.5	11.4	0.1	4.6	99.7	7.2	2.3	3.3	99.6
4	14.9	1.0	3.7	99.6	8.9	0.4	4.9	99.8	7.0	2.3	3.2	99.6
5	25.0	1.0	3.4	99.3	13.4	0.3	4.7	99.7	2.5	2.8	1.8	99.7
Program Goal	---	---	---	99.5	---	---	---	99.5	---	---	---	99.0

	Climb				Takeoff				Cruise			
	Emission Indices g/kg Fuel			Combustion Efficiency, %	Emission Indices g/kg Fuel			Combustion Efficiency, %	Emission Indices g/kg Fuel			Combustion Efficiency, %
Concept	CO	HC	NO_x		CO	HC	NO_x		CO	HC	NO_x	
1	6.5	0.4	3.5	99.8	5.5	0.2	6.0	99.9	13.5	2.4	2.0	99.4
2	5.9	0.4	4.4	99.8	5.0	0.2	6.8	99.9	12.3	2.1	2.5	99.5
3	5.7	0.4	4.5	99.8	4.9	0.2	6.9	99.9	12.1	2.1	2.6	99.5
4	5.8	0.4	4.5	99.8	4.9	0.2	6.9	99.9	12.2	2.1	2.6	99.5
5	6.0	0.3	3.7	99.8	5.1	0.2	6.4	99.9	14.3	2.8	1.9	99.4
Program Goal	---	---	---	99.0	---	---	---	99.9	---	---	3.0	99.0

*3.3% Idle for Concept 5.

Table XXIII. LPP Emission Predictions EPAP Summary.

Concept	EPAP - lbm/1000 lbf thrust-hr-cycle					
	4% Idle*			6% Idle		
	CO	HC	NO_x	CO	HC	NO_x
1	3.82	0.47	1.13	2.85	0.27	1.24
2	3.99	0.45	1.35	3.00	0.25	1.44
3	3.39	0.22	1.35	2.54	0.19	1.45
4	2.86	0.30	1.38	2.24	0.23	1.48
5	4.61	0.38	2.14	2.97	0.25	2.12
Program Goal:						
Newly Certified	3.0	0.4	3.0	3.0	0.4	3.0
Newly Manufactured	4.3	0.8	3.0	4.3	0.8	3.0

*3.3% Idle for Concept 5.

6.6 MECHANICAL DESIGN AND HEAT TRANSFER

Each of the LPP combustors employs the double-wall, impingement-cooled shingle liner concept. The combustors are shown schematically in Figures 11 through 15. The selection of the liner design is dictated by the ambitious life goals of the reference engine (E^3) which are 9000 hours and 9000 cycles. The advanced liner construction also allows for minimization of cooling air requirements. Low liner cooling flow rates are desirable for reduced emissions and greater allocation of air for profile trim dilution air.

The shingle liner design selected utilizes high temperature/high strength materials which avoid the high thermal stresses often associated with these advanced materials in a combustor application. The shingle combustor uses segmented panels as heat shields to protect the load-carrying support structure. The shingles are cooled both by impingement jets and by film cooling. The shingle design mechanically decouples the hot, segmented panels from the relatively cool support structure, thereby reducing the thermal stresses and improving the liner cyclic life. The excellent durability of this combustor liner approach has been demonstrated on the ATEGG GE14 and GE23 engines and in combustor component cyclic endurance tests.

In this design concept, the support liner consists of a 360° load-carrying structure that doubles as an impingement liner. Each inner panel of the liner is composed of individual shingles that are slipped into place and locked into the support structure by retention rings. Film-cooling slots are formed at the junction of adjacent shingles. Leakage between shingles is minimized by a captive seal, as shown in Figure 35. Also shown in this figure is the shingle inner liner assembly. Figure 36 shows a shingle outer liner closeup. The formation of the film slot can be seen in this figure. Note that the shingle split lines are staggered from row to row to prevent a buildup of air from between the shingles.

In the shingle liner design approach, the shingle is relieved from carrying large pressure loads because approximately 50 percent of the pressure loss occurs across the support structure. This member is also used to impinge cooling air on the back side of the shingles; impingement patterns can be specifically tailored to concentrate cooling on any highly stressed shingle areas. The impingement air is collected and used for film cooling the shingles.

The materials for the liners were selected based on the following considerations:

- Low Thermal Stress Coefficient - Thermal stress associated with a thermal gradient in a part is directly proportional to the material properties. A low thermal stress coefficient ratio is desirable to minimize the thermal stress.

- High Rupture Strength - Although a majority of the liner stress is due to thermal gradients, the liner is subjected to an aerodynamic pressure loading, therefore, high rupture strength is desirable to produce long life.

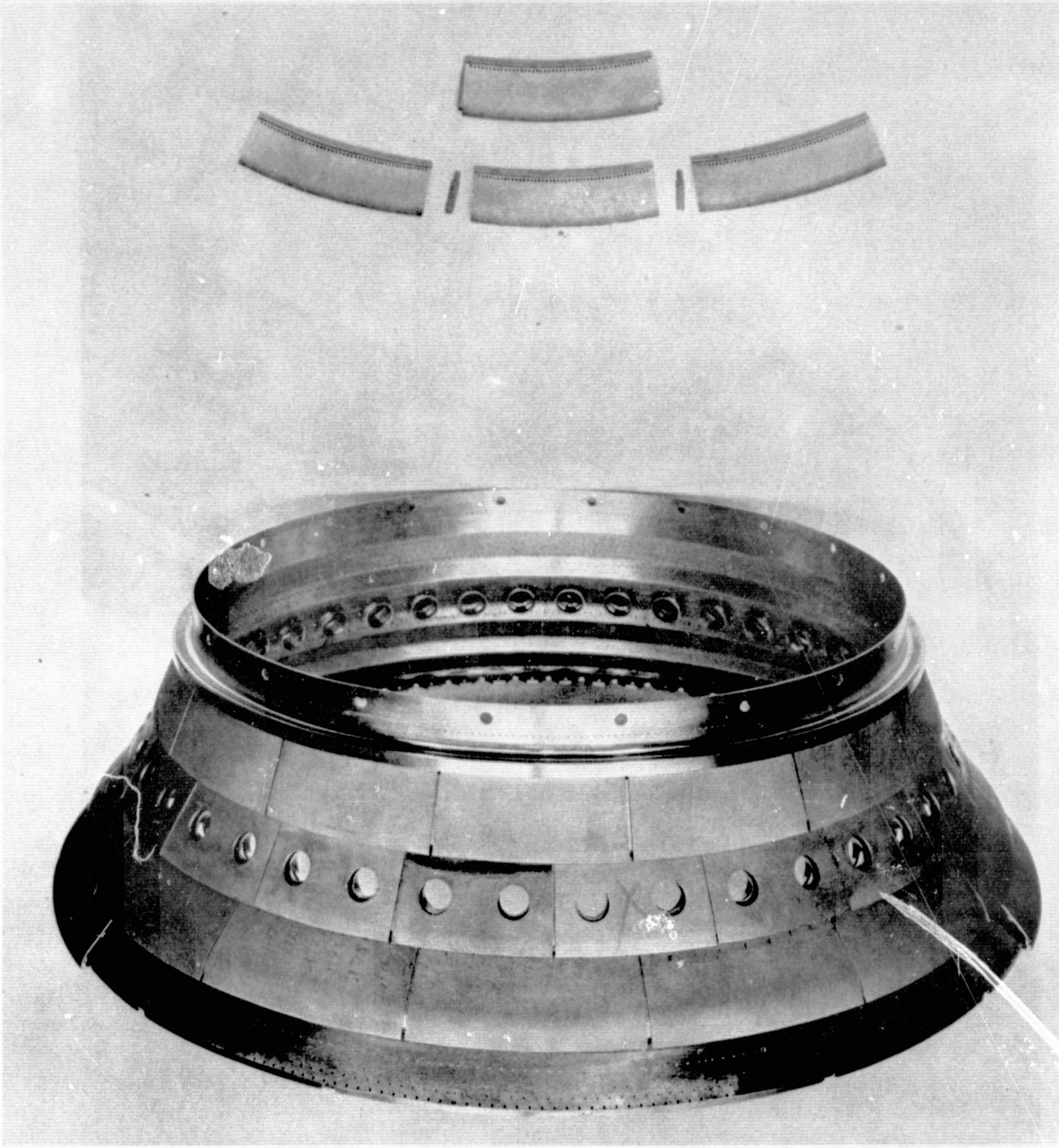


Figure 35. Shingle Combustor Inner Liner Assembly.

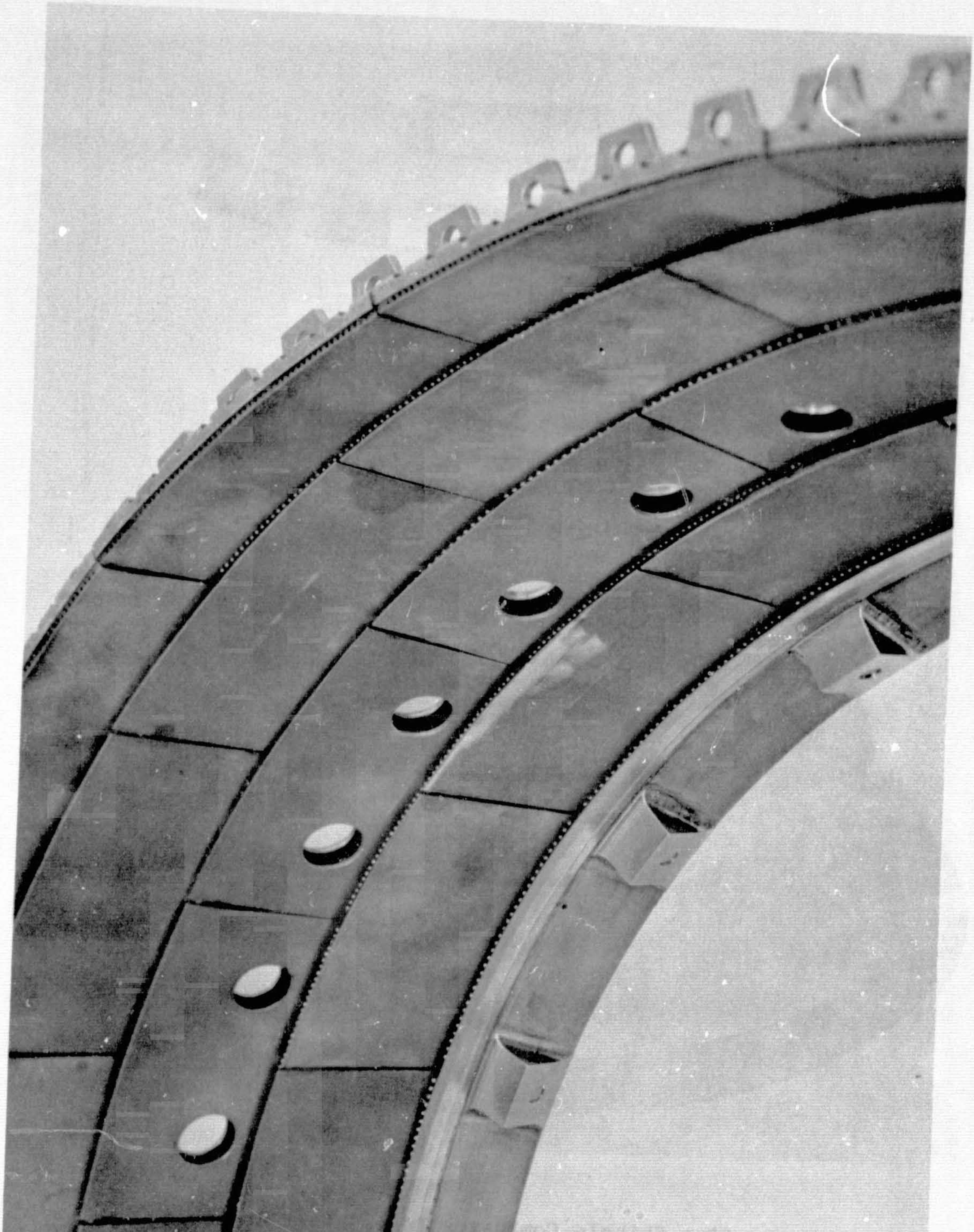


Figure 36. Outer Shingle Liner Closeup.

- Thermal Shock and Corrosion Resistance - Due to the operating environment of the combustor, a material that exhibits a high degree of corrosion and thermal shock resistance is desirable.

- Compatibility with Adjoining Structures.

- High Burnout Temperature - Considering circumferential temperature variations in combustors, an alloy with a high burnout temperature is desired.

Based on these considerations, the following materials were assumed for the LPP combustor concepts:

- Impingement/Support Liner - Inconel 625

- Shingles - X-40

- Dome Structure - Hastelloy X

- Cowls - Hastelloy X

- Dilution Thimble Inserts - Hastelloy X

Concept 5, which was sized for the CF6-50 engine, could also possibly employ other types of liner construction because the CF6-50 life requirements are considerably less stringent than the goals for the E^3 combustor. One possibility would be to use the stacked-ring-type construction which consists of brazed and spot-welded overlapping panels. This type of liner construction is illustrated in Figures 3 and 4.

Heat transfer analyses were conducted on four of the LPP concepts. Concept 5 was not analyzed in detail since it is a CF6-size Concept 1 and is, in many respects, similar to Concept 1 from a heat transfer perspective. Standard design practice procedures were used to determine flame radiation levels, film temperatures and heat transfer coefficients. The cooling flow rates were selected based on the reference engine's rates previously established. The calculations were made at takeoff conditions for each concept and at the sector-to-annular burning transition point for Panel 1 outer of Concept 3. These conditions are summarized below:

	Takeoff	Transition
T_3 - K	814	711
P_3 - MPa	3.02	1.90
W_c - kg/s	54.9	36.75
W_f - kg/s	1.34	0.68

One-dimensional calculations were made on representative panels of each of the four LPP concepts over a range of film cooling flows. The calculations were made for average conditions and for a maximum condition which was assumed to have a gas velocity twice that of the average. Nonluminous flame radiation levels were used for all calculations. This is based on radiation measurements made on many combustion systems that have shown that recent smokeless combustors have radiation signatures approaching nonluminous characteristics. With premixing and prevaporization systems, the radiation signatures should be even closer to nonluminous conditions. An additional benefit of LPP combustion is the reduced possibility of fuel streaking and, therefore, the local heat spots that accompany poor fuel distribution. The impingement heat transfer coefficient was calculated using 50 percent of the available pressure drop across the impingement baffle. Figure 37, for Panel 1 of Concept 1, is typical of the results of this one-dimensional analysis. The maximum liner panel temperature predicted just upstream of the cooling slot for the nominal cooling flow selected was 964 K. This is well below the 1150 K goal. The cooling slot overhang would be 80 to 100 K higher in temperature; however, this also is well within life goals.

A two-dimensional analysis was conducted on selected panels on Concepts 1 and 3. Assumptions made for this analysis were similar to those of the one-dimensional calculations. The major difference was that the two-dimensional case accounted for axial conduction which was neglected in the one-dimensional case. This was accomplished by dividing the combustor liner into nodes of unit depth small enough to be assumed at the same temperature and applying a numerical relaxation technique to balance heat flux. The two-dimensional profiles for Panels 4 and 5 of Concept 3 are presented in Figure 38 and are representative of the other LPP concepts being considered.

Heat transfer calculations were also made on the flameholder of Concept 4. The perforated plate located at the aft end of the premix duct was assumed to be 0.51-cm thick with 0.51-cm-diameter holes spaced 0.76 cm on center for a porosity of 40 percent. The entrance region of the holes was considered to be shaped for smooth, attached flow resulting in high flow coefficients and high heat transfer coefficients in the bore of the holes. This smooth attached flow would also reduce the possibility of flashback into the separated flow region that could cause localized material failure as cited in Reference 25.

The major consideration in the calculation of the flameholder temperature was the convective load on the downstream surface of the plate. The convective heat transfer coefficient was calculated using a flat plate correlation based on a short boundary layer length (2.5 mm) and one half of the perforated plate flameholder exit jet velocity was assumed for the velocity of the hot gases scrubbing the downstream side of the flameholder. With these assumptions, a heat transfer coefficient for the hot side of 678 cal/s-m^2-K was calculated. The corresponding metal temperature was 1117 K. In an attempt to calculate an extreme upper limit on the metal temperature, the heat transfer coefficient was doubled (1357 cal/s-m^2-K). With this assumption, the calculated flameholder surface temperature was 1250 K on the hot

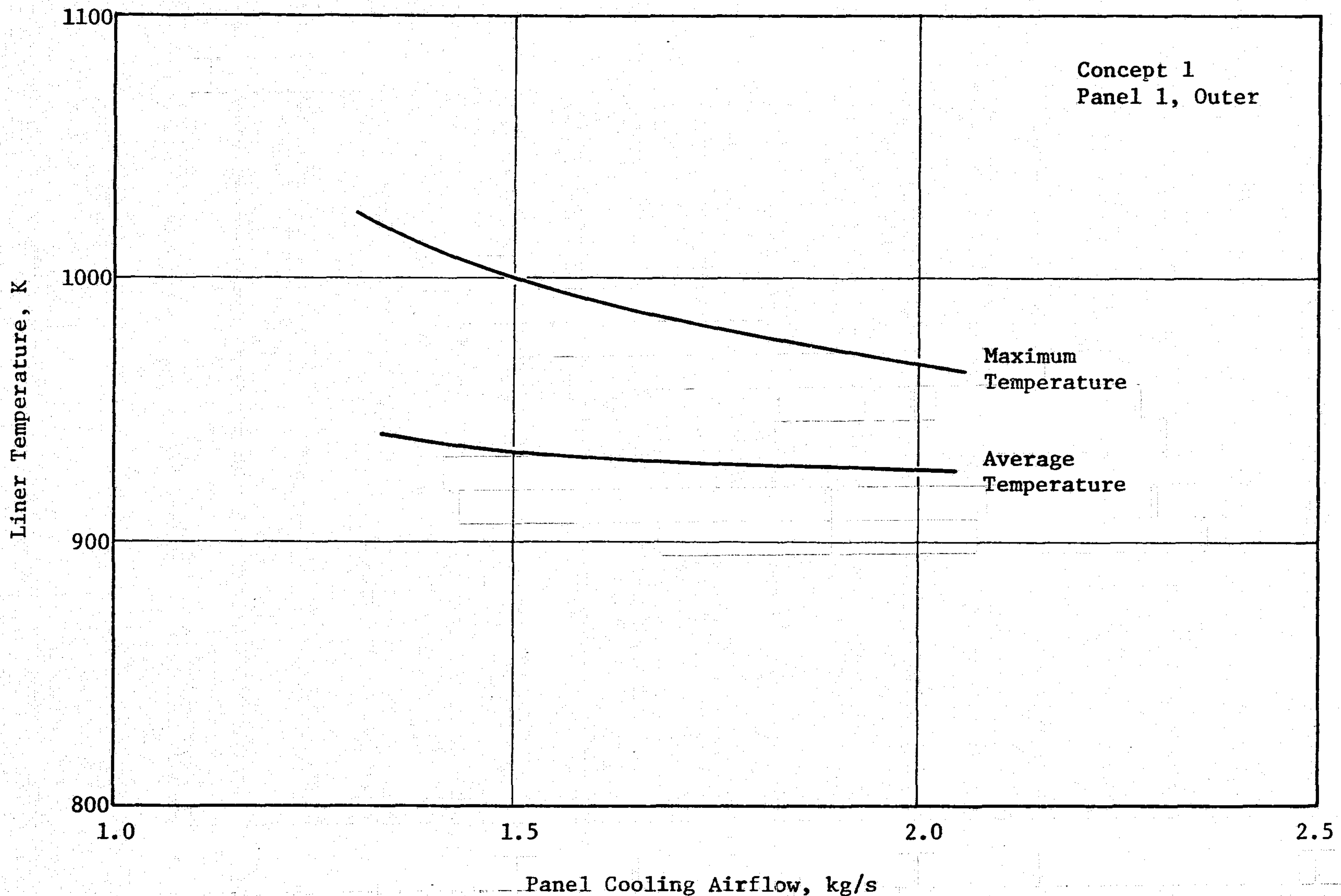


Figure 37. Typical LPP Cooling Liner Peak Temperature Predictions as a Function of Cooling Flow.

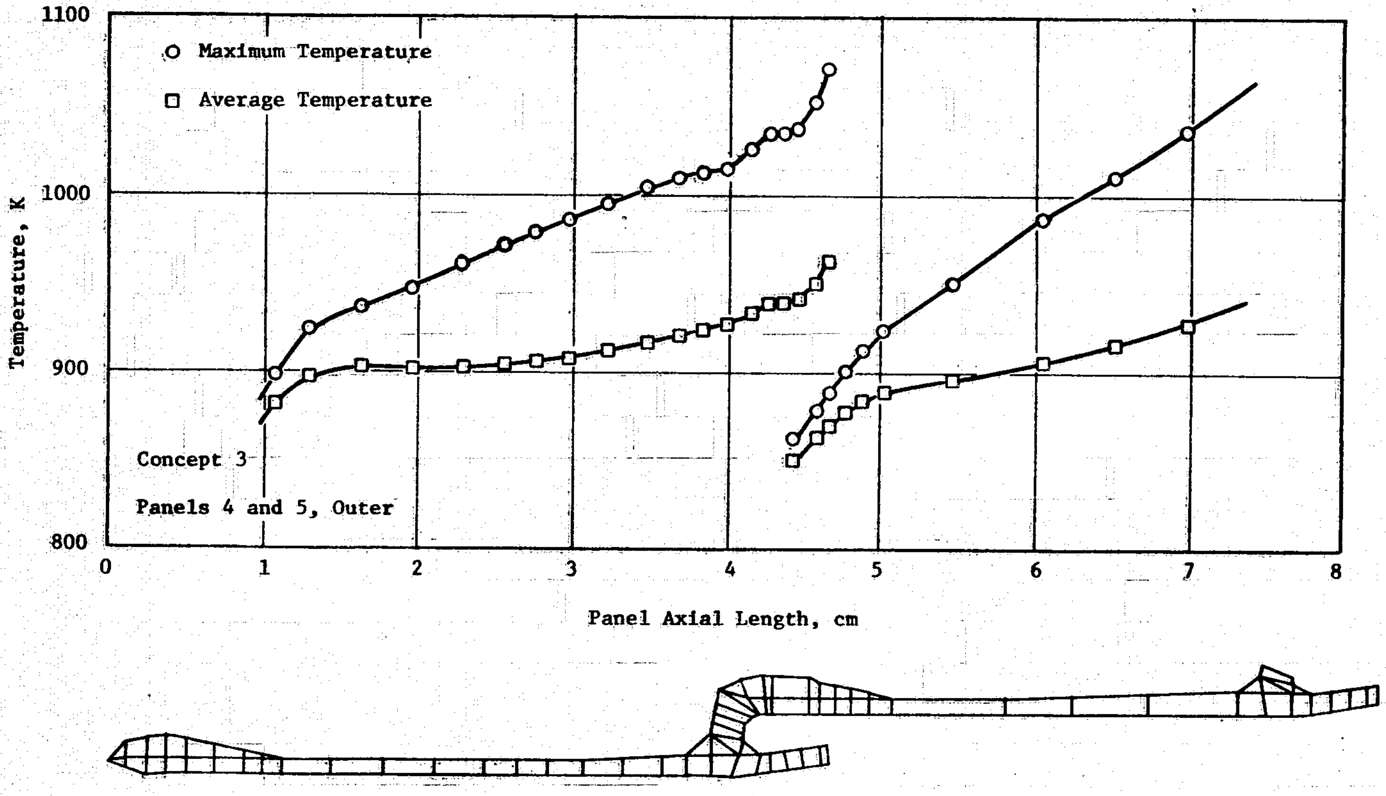


Figure 38. Typical LPP Cooling Liner Axial Temperature Distribution.

side and 960 K on the cold side. Considering the conservatism of this calculation, the flameholder metal temperature is expected to be in an acceptable range in actual practice. These conservative temperatures (highest) were input into the Shell Numerical Analysis Program (SNAP) computer code, which has been developed for the analysis of shells of revolution with axisymmetric loading. The resulting stress levels from this computer program were about 340 MPa, which indicates life capability within program goals.

In these LPP combustor designs, the secondary dilution air is introduced through a port design like that shown in Figure 39. This thimble design uses a tight diametral fit into the impingement liner to limit leakage. A gap around the thimble at the film liner is necessary for tolerance stackup and thermal growth between liner parts. Hot areas generally exist on liners downstream of the dilution holes as a result of the protective film air being disrupted by the dilution jet. In this design, a portion of the spent impingement air that enters the combustor through the dilution annulus is used to reenergize the dilution-stripped, liner cooling film aft of the dilution ports. This method has been used and proved to be effective on combustors designed as a part of the ATEGG Demonstrator.

The impingement cooling patterns in the liners were designed using the same criteria which were successfully used in previously designed General Electric combustors. These criteria include the following:

- Utilize approximately 50 percent of the available pressure drop across the impingement liner.
- A minimum impingement hole diameter of 1.27 mm.
- A spacing (between load carrying liner and shingles) to diameter (z/D) ratio of approximately 4.
- Minimize the spacing (center-to-center distance between impingement holes) to diameter ratio (x/D) at the aft end of the panel.

Also, the film cooling metering holes were designed using a similar criteria described as the following:

- Spacing to diameter ratio approximately 2
- Web thickness greater than 1.27 mm
- Hole diameter greater than 1.02 mm but less than 2.03 mm

The detailed impingement and metering hole designs for each panel and the dilution hole sizes for Concept 1 are presented as Table XXIV and are representative of hole size design for the other LPP combustor concepts. In summary:

- The calculated liner and overhang temperatures are within limits.

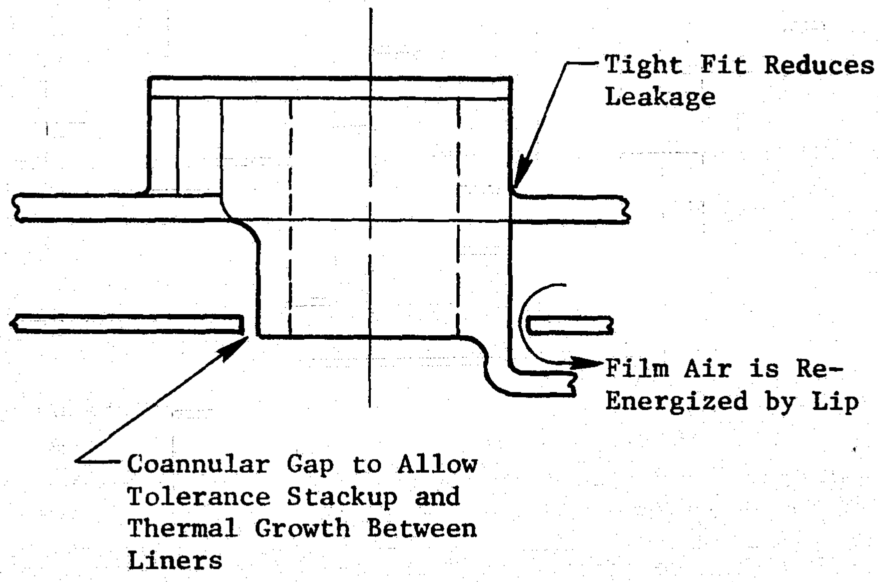


Figure 39. Combustor Dilution Thimble Design.

Table XXIV. LPP Concept 1 Liner Cooling, Dome Cooling, and Dilution Hole Sizing.

	Cooling Flow/ Combustor Airflow, %	Effective Area, cm^2	Physical Area, cm^2	Number of Holes	Hole Diameter, cm	Number of Hole Rows	Hole Spacing, cm	Spacing to Diameter Ratio	Web Thickness, cm
Impingement Cooling									
Outer Panel 1	3.72	19.35	24.84	1500	0.145	5	0.767	5.30	0.622
2	3.72	19.42	24.90	1500	0.145	5	0.777	5.40	0.632
3	3.30	17.29	22.19	1200	0.152	4	0.787	5.20	0.635
4	3.30	17.35	22.26	1200	0.152	4	0.792	5.20	0.640
Inner Panel 1	2.90	15.10	19.35	1125	0.147	5	0.795	5.40	0.648
2	2.89	15.10	19.35	1125	0.147	5	0.808	5.50	0.635
3	2.27	11.87	15.23	900	0.147	4	0.831	5.60	0.683
4	2.97	15.68	20.13	1125	0.147	5	0.859	5.80	0.711
Film Cooling									
Outer Panel 1	1.86	14.06	18.00	800	0.137	1	0.282	2.06	0.145
2	3.72	21.74	27.87	800	0.211	1	0.284	1.35	0.074
3	3.30	18.58	23.81	800	0.193	1	0.292	1.51	0.099
4	2.31	12.39	15.87	800	0.160	1	0.292	1.83	0.132
Aft	0.99	4.13	5.29	560	0.109	1	0.417	3.81	0.307
Inner Panel 1	1.45	10.97	14.06	600	0.173	1	0.297	2.40	0.124
2	2.89	16.90	21.68	600	0.213	1	0.305	1.43	0.091
3	2.27	12.77	16.39	600	0.185	1	0.312	1.68	0.127
4	1.98	10.58	13.55	520	0.183	1	0.368	2.01	0.185
Aft	0.99	4.52	5.81	520	0.119	1	0.381	3.19	0.261
Primary Dilution									
Outer	1.86	12.19	13.55	28	0.785	1	8.100	10.30	7.320
Inner	1.45	9.61	10.71	28	0.699	1	6.450	9.22	5.770
Trim Dilution									
Outer	4.83	27.16	28.58	28	1.140	1	8.380	7.35	7.240
Inner	6.85	38.52	40.52	28	1.356	1	6.730	4.96	5.380
Splashplate Cooling	4.38	14.00	17.94	80	0.102	2	0.638	6.28	0.536

- The perforated-plate flameholder temperatures appear to be in an acceptable range even with the most pessimistic assumptions.

- Stress levels including those of the perforated-plate flameholder are within the range required for the long life goals of the E^3 combustor.

- A proven design concept which provides film replenishment has been selected for the dilution hole thimbles.

- No major life problems are anticipated for the combustor concepts and the liner construction concept selected for the LPP combustor designs.

6.7 OPERATIONAL CHARACTERISTICS

Operational characteristics considered in analyzing the LPP combustor concepts included ground start, altitude relight, sensitivity to bleed, transition to premixed or main stage operation, and transient behavior during engine accelerations and decelerations. Since all LPP design concepts incorporate airflow modulation, transitional behavior is influenced by the technique and type of airflow modulation employed.

Altitude relight and ground start characteristics are influenced by dome geometry and velocity, igniter location, and dome and combustion system pressure drops. The pilot dome of each concept was designed in accordance with General Electric design practice to provide good ignition characteristics under normal operating conditions. Therefore, any ignition problems with the LPP combustors are expected to be a result of idle pressure drop differences resulting from airflow modulation.

Increased pressure drop at idle for Concepts 1, 4, and 5 would be expected to affect ignition characteristics; however, airflow modulation can be adjusted to aid lightoff conditions. Generally speaking, LPP combustors have rich pilot equivalence ratios at low power and are therefore similar to older generation combustors which have excellent demonstrated relight characteristics. Concept 2 is unaffected by pressure drop since it features compensating variable dilution. Concept 3 also exhibits normal pressure drop and should be unaffected in lightoff characteristics. Concepts 3 and 4 are similar to the ECCP combustor reported in Reference 3 which had adequate ground start and altitude relight characteristics.

Transient operation requirements for all five concepts include the ability to accelerate from ground idle to 95 percent of rated thrust in 5 seconds, and to decelerate from 100 percent thrust to 20 percent in 6 seconds. One concern of meeting this requirement is the time delay introduced during accelerations due to airflow modulation actuation. For autoignition prevention, fuel injection into the premix duct will not be permitted until airflow modulation transition is completed for two-position (open-closed) systems such as Concepts 2, 3, and 4. This does not apply to Concepts 1 and 5. This requirement will add approximately 0.5 seconds to the acceleration times of Concepts 2 and 4 to allow for vane actuation. It is expected to lengthen the acceleration time required by Concept 3 by approximately 0.2 seconds. Deceleration times will be unaffected.

Fuel and airflow scheduling requirements for transition to premixed operation for LPP concepts have been established in Section 6.1. Transition for Concepts 1 and 5 (refer to Table XXV) is quite straightforward since fuel staging is not required and the variable vanes are simply adjusted to the desired position for any given condition. This is a distinct advantage for continuous modulation. Transition for Concepts 2, 3, and 4 requires both fuel staging and two-position (open-closed) airflow modulation. Sector burning is required in the main stages of Concepts 2, 3, and 4, as indicated in the operational analyses of Tables XXVI through XXVIII. Pilot stages employ full-annular burning at all times for Concepts 2, 3, and 4. To help understanding of the operation of Concepts 2, 3, and 4, a detailed description of Concept 4 operation (both steady-state and transient) follows. Operationally, Concepts 2, 3, and 4 are very similar differing mainly in the actual fuel and airflow splits. Also, from an operational point of view, the fluidic flow control of Concept 3 is similar to two-position vane (open-closed) airflow modulation.

6.7.1 Concept 4

Steady-State Operation

Conventional control systems establish steady-state operation by setting combustor fuel flow to hold engine rpm. An engine using the LPP combustor uses the same steady-state engine control except for the addition of the combustor fuel flow split control and combustor variable geometry control. Table XIV shows the steady-state schedules for the LPP combustor.

Idle - For idle, all fuel flow is to the pilot zone and the combustor variable-geometry vanes are full closed. Closed vanes result in pilot-zone stoichiometry giving improved ground idle emissions. The variable-geometry vanes are controlled to either full open or full closed with no steady-state operation between.

Part Power - In the part-power regime, the vanes are scheduled to the full-open position. After full opening of the vanes, fuel is admitted to approximately one-half the main-zone annulus by modulating the main valve to give the required pilot/main flow split. Sector burning is required in the mid power range to provide locally high enough main-zone fuel-air ratios for successful lightoff and burning at the relatively low total combustor fuel flow.

High Power - For all high power conditions, i.e., takeoff, climb, and cruise, the combustor requirements are for a constant percent of total engine fuel flow (approximately 84 percent) to be delivered to the main zone. Further, it is required that the main zone be burning in the full-annular con-

Table XXV. Operational Analysis for Concepts 1 and 5.

Cycle Point	Description	Remarks
Lightoff	Vanes minimum opening, Vdome = 7.3 m/s (V = 7.6 m/s for typical combustor) $\Delta P/P$ = 9.7%	With compensating variable dilution ΔP=5%
Accel to Idle	Partially open vanes to reduce ΔP	Determine opening during development testing
Idle	Vanes minimum opening (synchronize closing with fuel decrease)	
Accel to High Power	Open vanes (synchronize with fuel increase) ΔP=5%	
Approach	Vanes 48% open; ΔP=7.5% 17% blowout margin (premix criteria)	
Accel to High Power	Open vanes (synchronize with fuel increase) ΔP=5%	
Climb, T.O., Cruise	Vanes maximum open position	
Decel	Reverse accel procedure - vane closing synchronized with fuel decrease to assure good lean blowout characteristics	Vanes close to minimum at idle

Table XXVI. Operational Analysis for Concept 2.

Cycle Point	Description	Remarks
Lightoff	Vanes closed (minimum opening); ΔP=11.7% Vdome = 5.8 m/s; ω cup = 17% W_c	ΔP=5% with variable dilution
Accel to idle	Vanes remain closed	Compressor stall margin questionable without variable dilution
Idle	Vanes closed ΔP=11.7%	ΔP=5% with variable dilution
Accel to High Power	Open vanes as fuel flow increases when f/a_{36} = 0.0139, stage fuel 82% split to 30 of 60 main fuel injectors (2-90° sectors) φ premix = 0.6; φ cup = 0.65 when f/a_{36} = 0.0185, stage fuel 93% split to full annulus	Pilot full annular burning at all times (90° sector burn at approach - f/a = 0.0139)
Climb, T.O., Cruise	Vanes open; main burner full annular	
Decel	Follow reverse schedule - sectoring as required	Close vanes at idle. Fuel permitted to main stage only when vanes are full open

Table XXVII. Operational Analysis for Concept 3.

Cycle Point	Description	Remarks
Lightoff	Fluidic switch in outer mode, Vdome = 5.2 m/s; ω cup = 17% W_c	ΔP=5% at all times
Accel to Idle	Fluidic switch remains outer	
Idle	Fluidic switch remains outer	
Accel to High Power	As fuel flow increases to f/a = 0.0139, switch to inner passage. Simultaneously, fuel staged 62% to 26 of 60 main fuel injectors (2-78° sectors) φ premix = 0.59; φ cup = 0.65. When f/a_{36} = 0.0185, stage fuel 85% to full annular main burner	Pilot full annular at all times; other other possibility is to use two step sectoring for PF considerations. Two 78° sectors at approach - f/a = 0.0139
Climb, T.O., Cruise	Inner mode; main full annular burning	
Decel	Reverse schedule - sectoring as required	Fluidic switch to outer passage at idle

Table XXVIII. Operational Analysis for Concept 4.

Cycle Point	Description	Remarks
Lightoff	Vanes open (normal ΔP = 5%) Vdome = 5.4 m/s; ω cup = 11% W_c	Rich dome, very conservative
Accel to Idle	Vanes remain open to reduce ΔP to 5.0%.	Stall margin is preserved
Idle	Vanes close ΔP = 7.8%	Synchronize with fuel schedule
Accel to High Power	Open vanes as fuel flow increases when f/a_{36} = 0.0139, stage fuel 56% split to 26 of 60 main fuel injectors (2-78° sectors) φ premix = 0.61; cup = 0.65 when f/a_{36} = 0.0185, stage fuel 82% split to full annulus	Pilot full annulus at all times; possibility is to use two step sectoring
Climb, T.O., Cruise	Vanes open; main burner full annular	
Decel	Follow reverse schedule - sectoring as required	Close vanes at idle

figuration for high power. To provide the best flow split accuracy for these conditions, the fuel nozzle flow-pressure drop characteristics will set the split. The flow characteristics of the fuel nozzles for the two zones will be selected such that when fed by a common pressure source, the flow split will be as required by the schedule. The main valve and the fill valve will both be scheduled full open for these steady-state, high-power conditions. The variable vanes, of course, are full open whenever there is any main-zone fuel flow.

Hysteresis - To assure stable operation near the defined switching points per the combustor control schedule shown in Table XIV, the control system includes hysteresis. The actual switch points are somewhat higher than the schedule when accelerating and are somewhat lower than the schedule when decelerating.

Transient Operation

Starting - For engine lightoff and acceleration to idle, the fuel will be delivered only to the pilot zone. This is accomplished by scheduling the main valve full closed. The variable vanes in the main zone will be scheduled full open during starting to lower the compressor operating line thereby giving a greater stall margin. Upon reaching 70 percent core engine rpm, the variable vanes are scheduled full closed. Steady-state idle operation is with the variable vanes full closed and with all fuel flow delivered to the pilot burning zone.

Acceleration - During engine accelerations, the conventional controls meter fuel to protect against compressor stall and turbine overtemperature. Typically, acceleration fuel flow rate is scheduled as a function of corrected core rpm and compressor discharge pressure. An engine using the LPP combustor will use the same acceleration scheduling parameters, except that schedule modifications may be needed as a function of combustor variable vane position. This schedule adjustment may be needed to accommodate the shift in compressor operating line when the vanes are moved.

The logic diagram, Figure 29, shows the steps required in combustor control when executing an engine acceleration. Upon demand for an engine acceleration, the fuel metering valve will deliver the acceleration fuel flow rate. Below 80 percent engine rpm, the main valve and the variable vanes will both be held closed. The fuel-air ratio during acceleration will exceed the equivalent of 18.5 WF/PS_3 ratio units at which point the variable vanes will be scheduled to the open position. The fuel-air ratio during acceleration will also exceed the equivalent of 21.5 ratio units. The logic requires that the variable vanes be at the full-open position, however, before moving to the next action. After exceeding this fuel-air ratio, but before the engine has accelerated sufficiently to produce 645 K T3, the fill valve is held closed and the main valve is opened to meter 55 percent of total engine fuel flow to the first sector of the main burning zone. As acceleration continues and T3 exceeds 645 K, the fill valve is opened such that main fuel flow is delivered to the full combustor annulus. The main-zone fuel flow rate is then increased to 84 percent of total flow. This flow split, it is recalled, is established by the fuel nozzle characteristics when both the main valve and the fill valve are wide open.

Deceleration - For engine decelerations, the conventional controls meter fuel to give rapid deceleration without combustor blowout. Typically, the deceleration fuel flow rate is scheduled either as a percentage of the accel schedule or as a constant level of WF/PS3 units. An engine using the LPP combustor will use similar decel schedules except that schedule modifications may be needed as a function of calculated pilot-zone fuel-air ratio. This schedule adjustment is needed to assure that pilot-zone lean blowout limits will not be reached during rapid transients.

The logic diagram (Figure 29) shows the steps required in combustor control when executing an engine deceleration. Upon demand for an engine deceleration, the fuel-metering valve will deliver the deceleration fuel flow rate. The fuel-air ratio during deceleration will be less than the equivalent of 18.5 ratio units at which point the main valve will be scheduled closed.

A test of actual engine speed versus demand speed will indicate a decel is called for and, therefore, the vanes will be held open. It is required that the vanes be full open during all decelerations to maintain maximum pilot-zone fuel-air ratio. The open vanes give higher main-zone airflow and, therefore, give lower pilot-zone airflow which results in richer pilot-zone burning.

An additional test, to preclude pilot-zone blowout, is the calculated pilot-zone fuel-air ratio. This calculated pilot-zone fuel-air ratio is used to limit the closure rate of the total metering valve during decel to keep the pilot-zone from reaching the lean blowout limits.

6.8 CYCLE CONSIDERATIONS

Various aspects of LPP combustion considered in this program have impact on the engine cycle. The most obvious effects originate with the airflow modulation features and their effect on compressor performance, combustor inlet conditions, and specific fuel consumption. Combustion efficiencies can also be affected by the lean burning techniques employed by LPP concepts necessary to achieve low NO_x production rates. These considerations have been analyzed and are included in the following discussions.

Pressure Drop Effects

The E^3 reference engine cycle parameters listed in Section 3.2 were calculated assuming a fixed airflow combustor design with 5 percent total pressure loss for the combustor. All of the LPP combustor designs analyzed and evaluated in this program employ a form of airflow modulation. The primary intent of these airflow control techniques is to regulate combustion zone airflows and hence fuel-air ratios, but in some designs the combustor pressure drop is increased at idle operating conditions. As shown in Table XXIX, increased combustor pressure loss increases the combustor inlet pressure, temperature, and fuel-air ratio, and decreases inlet Mach number and velocity. These conditions are favorable for reducing emissions at idle but result in increased specific fuel consumption. Concepts 1 and 4 are affected by this

Table XXIX. Effect of Combustor Pressure Drop at Idle on Reference E^3 Cycle Parameters.

% Thrust	4	4	4	4	6	6	6	6
$\Delta P/P$, %	5	10	15	20	5	10	15	20
W_3, kg/s	8.8	8.6	8.3	7.8	10.9	10.7	10.4	9.7
W_{3b}, kg/s	7.7	7.6	7.3	6.8	9.5	9.3	9.1	8.5
P_3, MPa	0.321	0.336	0.353	0.370	0.402	0.421	0.444	0.462
T_3, K	448	454	464	480	485	491	499	523
T_4, K	898	935	990	1091	941	971	1006	1120
W_f, kg/h	324	340	363	405	410	425	443	498
f_{36} ---	0.0117	0.0126	0.0139	0.0165	0.0120	0.0127	0.0135	0.0163
M_3(1)--	0.280	0.262	0.242	0.218	0.290	0.270	0.252	0.228

(1)Assumes $A_{E3} = 314.2\ cm^2$

consideration; but because of compensating variable dilution on Concept 2, and an inherent advantage of fluidic flow control on Concept 3, this penalty is not imposed on Concepts 2 and 3. Studies indicate that the fuel consumed for a total mission, including the EPA landing-takeoff cycle (Reference 1) and 1 hour at cruise operating condition, is increasd 0.3 percent when idle pressure drop is 10 versus 5 percent. This can be offset, however, by slightly reducing the idle power setting. The idle thrust reduction required to offset the increased fuel consumption caused by 10 percent pressure drop is 0.4 percent (from 6 to 5.6 percent of takeoff thrust). Another possible approach to offset the low power increase in fuel consumption is to reduce the overall combustor pressure drop at all power conditions. Since high-power fuel flow rates are so much greater than at idle and the portion of the time spent at high power conditions is greater, a small pressure drop reduction (~0.2 percent $\Delta P/P$) would offset the 5 percent increase (from 5 to 10 percent) in idle pressure drop due to the modulating geometry.

Although the increased fuel consumption involved in the above discussions is very small (negligible by past standards), these small tradeoffs must be considered in future energy efficient engine systems. Therefore, in any eventual application of Concepts 1 or 4 type combustors, these tradeoffs between idle thrust levels and overall combustor pressure drop versus idle pressure drop would be considered.

The use of airflow modulation techniques with the associated valves' actuation system and control components, results in some increase in the engine system weight. The estimated weights for the LPP concepts were approximately the same and were about 12 kg greater than for the E^3 double-annular combustion system. Using the differential parameter of 1 percent change in specific fuel consumption per 182 kg weight increase, this translates to a modest 0.07 percent sfc increase for introduction of the LPP low emissions design techniques.

Another aspect of the increased combustor pressure drop at idle conditions is the impact upon compressor stall margin. Typical compressor stall margins are on the order of 20 to 30 percent at steady-state conditions (i.e., idle). Therefore, the increased combustor pressure drop at idle conditions presents no steady-state concerns relative to stall. During engine accelerations, however, the stall margin is reduced because of the increased fuel flows and turbine inlet temperatures (increased turbine flow function). Therefore, during the engine acceleration, the increased combustor drop would consume an additional portion of the stall margin. To minimize this increased pressure drop during accelerations on Concepts 1 and 4, the airflow modulating vanes would be opened up to increase the combustor effective flow area and reduce the pressure drop. Since the fuel flow is much higher during acceleration, the dome airflow rate can safely be increased with no concern for lean blowout during the acceleration. For Concept 4, the added airflow (with increased vane area) is introduced downstream of the primary zone and has no influence on the dome stability.

Combustion Efficiency

As indicated in the combustor efficiency predictions in Table XXI, the program goals were met by all concepts being considered. Those goals are summarized below:

$\eta b \geq 99.9$ percent at takeoff

$\eta b \geq 99.5$ percent at idle

$\eta b \geq 99.0$ percent at all other

Since commercial aircraft gas turbine engines operate a majority of the time at cruise conditions, a large portion of the total fuel consumed is used at stratospheric cruise. Assuming the EPA landing-takeoff cycle (Reference 1) and a 1 hour cruise mission, almost 80 percent of the total fuel used is consumed at cruise. Therefore, specific fuel consumption at cruise is most important to energy efficiency. Older engines with rich domes (relative to LPP concepts) generally have combustion efficiencies on the order of 99.9 percent at cruise operating conditions. Based upon data available in the literature for predicting emissions and hence combustion efficiencies for lean premixed systems, the cruise efficiencies will be on the order of 99.5 percent (reference Table XXII). This small reduction in combustion efficiency is due to the increased levels of HC and CO emissions, which are higher for lean premixed systems. The associated difference in fuel flow consumed at cruise (0.3 percent or 15 lb of fuel for the E^3 reference engine cycle) is small but must be attributed to techniques introduced for achieving the very low NO_x emission goals of this program (very lean combustion). During the development and testing of LPP systems, the actual values for HC and CO emissions will be measured to determine if these small differences in efficiency are real. Also, some improvements or advantageous tradeoffs between CO, HC, and NO_x might be possible.

In summary, the introduction of LPP-type combustion systems into aircraft gas turbines would appear to present no major problems or impact on engine cycles or performance. However, some minor effects have been identified which would be explored during the development and testing of LPP combustion systems.

6.9 FAILURE ANALYSIS

An elementary failure analysis has been conducted for the LPP combustor Concepts 1 through 4. Concept 5 is considered to be functionally the same as Concept 1 relative to possible failure modes so that the failure analysis for Concept 1 also applies to Concept 5. In this study, attention was directed toward the new ingredients which have been introduced into these designs. These include variable geometry air control means and premixing tubes or duct operation. Other features are considered to be similar to other contemporary combustion systems.

The types of failure considered include effects resulting from the variable-geometry air control system locked in the two extreme position modes (air switched one way or the other) or in an intermediate position. For the systems utilizing variable vanes, the possibility of a portion of the vanes to be stuck partially open or closed was also considered. The possibility of main-stage flameholder overtemperature was also studied for Concepts 3 and 4. In addition, loss of parts of the variable-area vanes was considered.

Assumptions include that if the actuator is positioned closed on Concepts 2 and 4, the control system is programmed not to admit fuel to the main stage. If local vanes are closed, the control system logic is not informed and fuel could be admitted to the main stages.

The hazard classifications are defined as follows:

Class I - Safe	Condition(s) such that personnel error, deficiency/inadequacy of design, or subsystem/component malfunction will not result in major system degradation and will not produce system functional damage or personnel injury.
Class II - Marginal	Condition(s) such that personnel error, deficiency/inadequacy of design, or subsystem/component malfunction will degrade system performance but which can be counteracted or controlled without major damage or any injury to personnel.
Class III - Critical	Condition(s) such that personnel error, deficiency/inadequacy of design, or subsystem/component malfunction will degrade system performance by personnel injury or substantial damage or will result in a hazard requiring immediate corrective action for personnel or system survival.
Class IV - Catastrophic	Condition(s) such that personnel error, deficiency/inadequacy of design, or subsystem/component malfunction will severely degrade system performance and cause subsequent system loss or death or multiple injuries to personnel.

For the study, failures that could result in combustor life reduction below the normal TBO but for which the engine could continue to operate safely for a time were considered Class I. If severe damage occurred, such that the engine would have to be shut down or would suffer a loss in power capability, the failure was considered Class II.

An example of the format employed in the study analysis is shown below. The sample is for Concept 1 with the vanes assumed to be all in the full open position.

Failure Mode	Component Output Effect	System Output Effect	Engine Output Effect	Cockpit Indication	Corrective Action	Hazard Class
Vanes locked open (all)	Significantly increased airflow through premix tube during low power conditions	Lean combustion operation at low power conditions	• Increased idle emissions • Possible starting problems	• No start	Replace or correct actuation problem on effected engine	I

A summary of the results from the study is presented in Table XXX.

For Concept 1, the failure analysis indicates the most serious form of failure would be the loss of vanes locally which could enter the turbine and result in damage. In the extreme case which was assumed for this study, this could result in material loss and imbalance of the turbine rotor and necessitate an engine shutdown. For Concepts 2 and 4, two types of failure for each would result in the inability to introduce fuel into the main stage and therefore the engine could not reach full power until the malfunction was corrected. These situations could occur if for any reason the actuation system was locked in a position such that the air scheduling vanes were in the closed position. In this event, the fuel control system is programmed to prevent fuel flow to the main stage and full power could not be achieved. The airflow control systems for these concepts are similar to those employed for variable compressor stators and are in wide use and have been quite reliable in production engines. For Concept 1, it would appear that the system is amenable to innovations for applying positive retention techniques for the vanes or for the design of other swirler configurations with fewer parts. This would be an area to be given additional study and development.

Table XXX. System Failure Mode and Effects Analysis - Hazard Classification.

Failure Mode Assumed	Concept 1	Concept 2	Concept 3	Concept 4
All Vanes Failed Closed	I	II	NA	II
All Vanes Open	I	I	NA	I
All Vanes in Intermediate Position	I	II	NA	II
Some Vanes Closed	I	I	NA	I
Some Vanes Open	I	I	NA	I
Some Vanes in Intermediate Position	I	I	NA	I
Vanes at Varying Positions	I		NA	
Mechanical Failure (Loss) of Vane	II	I	NA	I
Compensating Dilution Closed	NA	I	NA	NA
Compensating Dilution Open	NA	I	NA	NA
Air Valve Such That Flow is to Mixing Duct	NA	NA	I	NA
Air Valve Such That Flow is to Pilot	NA	NA	I	NA
Air Valve Such That Flow is in Intermediate Position	NA	NA	I	NA
Main Stage Flameholder Overtemperature	NA	NA	I	I

7.0 DESIGN RANKING

Each of the combustor designs was ranked according to the probability of meeting the design requirements or goals or matching the characteristics of the reference engine based on the predictions presented in Section 6.0. Since the Concept 5 combustor employs the same design approach as Concept 1, its performance would be similar and its ranking the same as for Concept 1. Therefore, only the rankings for Concepts 1 through 4 are presented in the tables. The reference engine is the Energy Efficient Engine (E^3).

A "scorecard" format was used with the following numerical rating criteria:

10 Likely to meet requirements or goals or to be comparable to the reference engine with normal development effort.

7 Additional development effort (over and above normal) needed to meet requirements or goals or to be comparable to reference engine.

3. Major development effort needed to meet requirements or goals or to be comparable to the reference engine.

0 Will not meet requirements.

The scorecard ratings were used to rank the concepts according to their relative ability to fulfill design requirements and goals. The scorecard categories are:

- Emission Predictions (Table XXXI)
- Aerothermo Performance (Table XXXII)
- Fuel-Air Preparation System (Table XXXIII)
- Operational Characteristics (Table XXXIV)
- Mechanical Design Considerations (Table XXXV)

The overall performance ratings (Item 2.5 of Table XXXVI) resulted from averaging the aerothermo, operational, fuel-air preparation, and mechanical ratings. The average ratings in Table XXXVI were calculated based on an average of (1) emission predictions, aerothermal fuel-air preparation, operational and mechanical ratings and (2) an average of emission predictions and overall performance.

Table XXXI. Emissions Evaluation Scorecard.

Design Parameter	Goal	Concept Rating/Ranking 1	2	3	4
1. NOx Emissions - g/kg					
1.1 Normal Cruise	3.0	10	10	10	10
1.2 Ranking		1	2	3.5	3.5
2. EPA Parameter, $\frac{\text{lb}}{\text{1000 lb-Thrust-hr}}$					
2.1 CO	3.0	7	7	7	10
2.2 HC	0.4	7	7	10	10
2.3 NOx	3.0	10	10	10	10
2.4 SAE Smoke Number	20	10	7	7	7
2.5 Overtall Rating		8.5	7.75	8.5	9.25
2.6 Ranking		2.5	4	2.5	1

Table XXXII. Aerothermo Performance Evaluation Scorecard.

Design Parameter	Goal	Concept Rating/Ranking 1	2	3	4
Combustion Efficiency, %					
Takeoff	≥99.9	10	10	10	10
Idle	≥99.5	7	7	10	10
All Other	≥99	10	10	10	10
Pressure Drop, %					
Idle	<5	7	10	10	7
All Other	<5	7	10	10	10
Exit Temperature Profiles					
Profile Factor	<0.125	10	10	7	3
Pattern Factor	<0.25	10	7	7	7
Combustion Stability	Stable combustion at all conditions	7	7	7	10
Maximum Metal Temperature, %	<1150 K	10	10	10	7
Overall Rating		8.67	9.0	9.0	8.22
Ranking		3	1.5	1.5	4

Table XXXIII. Fuel-Air Preparation System Performance Evaluation Scorecard.

Design Parameter	Goal	Concept Rating/Ranking 1	2	3	4
Vaporization at Cruise	>90	10	10	10	10
Premix Dwell Time, msec	<2	10	10	10	10
Premix Duct and Injector Tip Aerodynamics		7	3	7	7
Fuel Uniformity, %	±10	7	3	7	7
Injector Coking Potential		10	7	7	7
Flashback Potential		7	7	10	10
Sensitivity to Inlet Distortion and Swirl		10	7	7	7
Overall Rating		8.71	6.71	8.29	8.29
Ranking		1	4	2.5	2.5

Table XXXIV. Operational Characteristics Evaluation Scorecard.

Design Parameter	Goal	Concept Rating/Ranking			
		1	2	3	4
Altitude Relight-m	9000	10	10	10	10
Controls Complexity		10	10	10	10
Transition to Premix Operation		10	7	3	7
Ground Start-Time to Full Propagation-sec	10	10	10	10	10
Sensitivity to Bleed		10	10	7	10
Transient Behavior - sec					
Accel (Ground Idle to 95%)	5	10	7	7	7
Decel (100% to 20% Thrust)	6	10	10	10	10
Overall Rating		10.0	9.14	8.14	9.14
Ranking		1	2.5	4	2.5

Table XXXV. Mechanical Design Scorecard.

Design Parameter	Concept Rating/Ranking			
	1	2	3	4
Weight	7	7	7	7
Mechanical Complexity	3	3	10	7
Fuel System Complexity	10	7	7	7
Actuation System Complexity	3	3	7	7
Assembly Difficulty	3	3	10	7
Initial Cost	3	3	10	7
Mechanical Risk	3	3	10	7
Overall Rating	4.57	4.14	8.71	7.0
Ranking	3	4	1	2

Table XXXVI. Overall Rating Scorecard.

Design Aspect	Concept Rating/Ranking			
	1	2	3	4
1.0 Emissions				
1.1 Curise EI_{NO_x}	10	10	10	10
1.2 EPAP and Smoke	8.5	7.75	8.5	9.25
1.3 Overall Emissions Rating	9.25	8.88	9.25	9.63
2.0 Performance				
2.1 Aerothermal	8.67	9.0	9.0	8.22
2.2 Operational	10.0	9.14	8.14	9.14
2.3 Fuel-Air Carburetion	8.7	6.71	8.29	8.29
2.4 Mechanical	4.57	4.14	8.71	7.0
2.5 Overall Performance Rating	7.99	7.25	8.54	8.16
3.0 Average (1.3 + 2.5)	8.62	8.07	8.90	8.90
4.0 Average (1.3 + 2.1 + 2.2 + 2.3 + 2,4)	8.24	7.57	8.68	8.46
5.0 Overall Ranking	3	4	1	2

7.1 EMISSION EVALUATION

The emission evaluation scorecard (Table XXXI) considers two subcategories: (1) NO_x emissions at cruise, and (2) EPA parameter. At normal cruise, all four concepts were predicted to meet the NO_x program goal of 3 g/kg and therefore all receive a rating of 10. However, the concepts were ranked based on the relative NO_x emissions predicted at cruise, as presented in Table XXII. A ranking of 3.5 was assigned to Concepts 3 and 4 since the NO_x emissions at cruise were predicted to be the same for both, yet less favorable than Concepts 1 and 2. A rating was likewise assigned to each design parameter listed in Subcategory 2, EPA parameter. An overall rating resulted as an average of each design parameter (2.1 + 2.2 + 2.3 + 2.4), and the combustor concepts were ranked accordingly.

7.2 AEROTHERMO PERFORMANCE EVALUATION

The design parameters considered in this category are listed in Table XXXII with the program goal listed at the right.

Combustion Efficiency

All concepts meet the program goals for combustion efficiency for each cycle point except idle. Concepts 1 and 2 are close but do not quite meet the goal at 4 percent idle thrust (refere to Table XX) and are therefore penalized as indicated in Table XXXII. Note, however, that all of the systems meet the goal at 6 percent idle thrust.

Pressure Drop

Concepts 2 and 3 are designed with constant pressure drop and therefore meet or exceed the program goals (Table V). Concept 1 is penalized for both idle pressure drop (9.7 percent) and approach pressure drop (7.5 percent with vanes partially closed). Concept 4 is penalized for idle pressure drop only, since the vanes are open at all other cycle points.

Exit Temperature Profiles

Concept 1 is rated high in both profile and pattern factor since this LPP concept is so similar to conventional combustors and is expected to have improved profile and pattern factor relative to conventional combustors. This is due to the anticipated benefits of premixing with the reduced tendency for hot streaking. Concept 2 is rated 10 for profile factor for similar reasons as Concept 1 but is penalized in pattern factor rating when the sector burning requirement is considered. Concept 3 is penalized for profile factor because the pilot flow and mainstream flow interface must be developed to produce the desired mainstream penetration. Sector burning is also required on Concept 3 and therefore is reflected in the pattern factor rating.

Concept 4 was more severely penalized for profile factor. This was based on the tendency of the gas stream to remain stratified in the parallel staged design so that the discharge profile is dependent upon the fuel flow split to the two stages, ECCP double-annular combustor (which also is stratified, Reference 3) experience indicates that profile control under these restrictions requires careful development. However, it should be emphasized that more dilution air is available for trim on Concept 4 than on the ECCP combustor and the Concept 4 design has less pilot flow than the previous double-annular designs tested.

Combustion Stability

Concepts 1, 2, and 3 were assessed to present developmental risk with respect to lean blowout potential and/or combustion instability. Hence, they were penalized accordingly.

Metal Temperatures

Heat transfer analysis revealed that liner cooling with the double-wall design is not a problem for any of the four combustor concepts. Experience with the NASA/GE ECCP radial/axial combustor indicates that metal temperatures on the V-gutters present no problem in the absence of autoignition in the premix duct. However, the perforated-plate flameholder of Concept 4 is difficult to analyze and represents some additional developmental risk, hence the reduced rating relative to the other concepts.

7.3 FUEL-AIR PREPARATION SYSTEM PERFORMANCE

Considerations for fuel-air preparation as applied to the four LPP combustor designs were discussed in Section 6.2. The fuel-air evaluation scorecard is presented in Table XXXIII.

Vaporization at Cruise

As indicated in Table XVI, vaporization was expected to be nearly complete for all four LPP concepts.

Premix Dwell Time

The premix dwell times for all concepts were expected to remain under the 2-ms autoignition limit for both cruise and takeoff conditions.

Premix Duct and Injector Tip Aerodynamics

All four LPP concepts were considered to have the potential for autoignition in wakes from vanes or fuel injectors and were therefore penalized in rating. Concept 2 was further penalized due to the radially inserted injectors.

Fuel Uniformity

Fuel-air uniformity predictions indicate significant development requirements for all LPP concepts. Concept 2 was further penalized because of the multiple-duct design and the reduced dwell time relative to the other concepts that do not have the benefit of swirl-vane mixing (Concepts 3 and 4). Each individual duct or chute must be fueled equally by one orifice on each of two injectors, posing additional system tolerance requirements.

Injector Coking Potential

The design of the mainstage fuel injectors for Concepts 2, 3, and 4 employs small orifices with low orifice pressure drop and therefore poses a slightly increased probability of coking. Concept 1 was not subject to penalty since it has one source of fuel injection.

Flashback Potential

Concept 1 was penalized due to the possibility of flashback in the recirculation zone generated by the variable vanes of the swirl tubes. Concept 2 was also penalized because of the possibility of flashback associated with the turning vanes at the duct exits.

Sensitivity to Inlet Distortion and Swirl

Concepts 2, 3, and 4 would be more sensitive to inlet distortion than either Concept 1 or the reference engine. Concepts 2, 3, and 4 do not have the benefit of flow distributing pressure drop upstream of the main-stage fuel injection plane.

7.4 OPERATIONAL CHARACTERISTICS EVALUATION

The design parameters considered for the operational characteristics evaluation, and the respective goals and ratings, are presented in Table XXXIV. Specifics of the analysis which provided the basis for these ratings were presented in Section 6.7.

Altitude Relight

Since all four LPP conceptual designs are expected to exhibit excellent relight characteristics, they all received ratings of 10.

Controls Complexity

As indicated in Section 6.4, very little additional control capability is required for any of the concepts considered. It was also concluded that no new measurement techniques are required, and very little additional feedback sensing is needed for control. Since no additional effort is required over and above normal, all concepts received a rating of 10.

Transition to Premix Operation

During accelerations, the LPP combustors must smoothly transition from an idle, or pilot only, mode to a high-power main-stage operation. For Concept 1, the transition is very smooth and straightforward since only one stage of fuel injection exists and the airflow modulation technique is continuously variable. Therefore, Concept 1 was rated 10. The other concepts all require three stages of burning: (1) pilot only, (2) sectored main stage, and (3) full-annular main stage. Staged burning is an additional requirement and must be coordinated with the airflow modulation; hence, the reduced rating in Table XXXIV for Concepts 2, 3, and 4. Concept 3 uses fluidic airflow modulation, which is expected to be relatively abrupt compared to the vane actuation used on Concepts 2 and 4. This resulted in an additional penalty for Concept 3.

Ground Start - Time to Full Propagation

The domes and primary zones of all of the LPP combustors were designed to have favorable airflow rates during starting conditions. This was made possible because of the variable geometry features included in all of the designs. Therefore, all of the combustors will likely exhibit acceptable propagation characteristics and consequently received ratings of 10.

Sensitivity to Bleed

The airflow modulation technique used in Concept 3 is a fluidically controlled diffuser. The mode and stability of operation depends on bleed (see Section 5.3). It is the only concept which is sensitive to bleed. Therefore Concept 3 was penalized for sensitivity to bleed.

Transient Behavior

As pointed out in Section 6.1, sector burning is utilized on Concepts 2, 3, and 4. This will lengthen the time required to acclerate due to airflow modulation requirements. During deceleration, fuel flow to the main stage can be curtailed with no time penalty.

7.5 MECHANICAL DESIGN RANKING

Each of the four LPP conceptul designs was rated and ranked mechanically. The categories chosen for this comparison and the ratings and rankings are listed in Table XXXV.

Weight

Weight was estimated for all components which differed in configuration from concept to concept. The weights of components having the same configuration in each of the four concepts was not included in the estimate. Weight was estimated using a timesharing computer program designed for this purpose. The material density used for all components was 8.2 gm/cm^3 (0.296 $lb/in.^3$). The weight predictions for all four concepts were roughly similar at about 10 percent greater than the reference engine.

Mechanical Complexity

The mechanical complexity rating of each concept was determined by considering the number of mechanical components, the complexity of the component parts, and the anticipated clearances and tolerances involved. Concept 1 uses a large number (336) of variable vanes that must be manufactured with tolerances that will permit smooth actuation without binding or excessive hysteresis. Concept 2 employs a complicated premix duct design that includes a three-passage prediffuser. Concept 4 is designed with a vane actuation system and a perforated-plate flameholder which represent additional mechanical complexity relative to the reference engine.

Fuel System Complexity

The main consideration in rating the fuel system complexity was the number of systems required. All of the designs except Concept 1 require two fuel systems, as well as sector burning, and therefore received a rating of 7.

Actuation System Complexity

This rating provides a measure of the mechanical complexity involved in the airflow modulation actuation. Rating considerations include the number of components, the method employed, and the opportunity for failure.

Assembly Difficulty

This rating attempted to quantify the relative difficulty of assembling the various concepts. The main criteria used for this rating were the total number of components to be assembled, the anticipated clearances or tolerances involved, the number and kind of unusual procedures or processes required, and the number of expected rigging problems.

Initial Cost

The four concepts were rated for cost by Value Engineering. The concepts were ranked on a relative cost basis because of the preliminary nature of the design. In doing this, the number of components and the manufacturing complexity were assessed.

Mechanical Risk

This rating was intended to provide some quantitative measure of risk involved to bring the various concepts to fruition. This rating took into account past design experience, the technology involved, and the opportunity for failure (Reference Section 6.9)

7.6 OVERALL RATING AND RANKING

Table XXXVI shows, for each concept an overall emissions rating, an overall performance rating, two average ratings, and an overall ranking. The overall emissions rating resulted from the average of the cruise NO_x rating and the combined EPAP and smoke rating. The overall performance rating was the average of the aerothermo, operational, fuel-air carburetion, and the mechanical ratings. Two average ratings were generated. The first weighted the emissions ratings equal to the sum of the performance ratings. This resulted in the ratings in part 3.0 of Table XXXVI. The other average rating weighted each of the performance parameters equal to the emissions results (part 4.0 of Table XXXVI). In one case, Concepts 3 and 4 were rated equal, with Concepts 1 and 2 rated somewhat lower. In the second case, Concept 3 rated highest with Concept 4 second. Therefore, the final overall ranking was:

1.. Concept 3 - Most likely to meet goals with least development

2. Concept 4 - The next most likely to meet the goals and very close to Concept 3 in ranking

3. Concept 1 - The next most likely to meet the goals (Concept 5 is considered the equivalent of Concept 1 in these rankings)

4. Concept 2 - Most development effort required to meet the program goals.

None of the concepts is rated as incapable of meeting the design study goals or requirements.

8.0 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions have been drawn based on the results of this design study:

- LPP combustion systems provide a viable means of achieving very low NO_x emissions at the stratospheric cruise operating conditions of aircraft gas turbine engines.
- Of the five concepts studied, all meet the NO_x program goal of 3 g/kg based on the best prediction techniques available.
- All five concepts meet the EPA-prescribed 1981 emission standards for newly certified engines, assuing a 6 percent idle thrust level.
- All five concepts also meet the progam goal for combustion efficiency assuming a 6 percent idle thrust.
- Predicted liner temperatures for all designs are low and the life goals of the reference engine (E^3) should be attainable for these LPP concepts.
- As an additional benefit besides low NO_x production, LPP fuel-air mixtures are expected to provide reduced radiant heat flux from hot gases to the liner walls and reduce hot spots caused by fuel streaking, compared with direct injection combustion systems.
- Normal levels of pattern factor and radial temperature profiles are attainable with these concepts.
- Some of the combustor concepts studied (Concepts 1, 4, 5) have increased pressure drop at idle operation conditions. Increased pressure drop for these concepts was chosen as an alternative to using compensating variable-area geometry. Compensating variable-area geometry could be used in these concepts, however. One system (Concept 2) has compensating variable geometry and therefore constant pressure loss. One of the concepts (3) does not require variable geometry to achieve a constant pressure loss coefficient.
- Based on the best estimates of performance, life, emissions, and other operational parameters, the concepts were rated in the following order relative to the ease with which the program goals cold be met:

  Concept 3 - Most likely to meet goals with minimum development.

Concept 4 - Next most likely to meet goals

Concept 1 and 5 - (5 and 1 are the same)

Concept 2 - Most development efforts required.

None of the concepts was rated as incapable of meeting the goals.

- Potential problem areas or areas that will require considerable attention during development of these LPP combustor concepts include:

  - Avoidance of autoignition or flashback into the premixing tubes of actual engine combustion system hardware over the full operating conditions encountered in flight servivce.

  - Achieving uniform fuel distributions in premixing ducts (while avoiding autoignition or flashback).

  - Achieving reliable operation of systems involving airflow modulation for distributing airflow in combustion systems.

Based upon the results of the studies conducted in this program, it is recommended that combustion development testing be conducted to demonstrate the potential of LPP combustion systems for achieving low emission of NO_x at stratospheric cruise conditions as well as meeting other normal combustion system goals. The five concepts defined in this program present excellent candidates for these proposed test programs.

SYMBOLS

Symbol		Units
A_e	Effective Flow Area	cm^2
CO	Carbon Monoxide	
C_p	Static Pressure Recovery Coefficient	
D	Diameter	cm
EI	Emission Index	g/kg
f, f/a	Combustor Fuel-Air Ratio	
HC	Unburned Hydrocarbon	
h_o	Flight Altitude	km
L	Duct Mixing Length	cm
m	Spreading Index	cm2
M	Mach Number	
NO_x	Oxides of Nitrogen	
P, P_T	Total Pressure	MPa
P.F.	Pattern Factor	
Pr.F.	Profile Factor	
R	Gas Constant for Air	m^3P_a/kg K
s	Fuel-Air Nonuniformity Parameter	
S,S1,S2,S3,S4	Fuel Injector Spacing	cm
T, T_t	Total Temperature	K
V	Velocity	m/s
W	Flow Rate	kg/s
WF/PS3	Engine Control Parameter	
Z	Impingement Liner Shingle Spacing	cm

Subscripts		Units
avg	Refers to Average	
base	Refers to Baseline	
c,36	Refers to Total Combustor Airflow	
cup	Refers to Swirl Cup	
f	Refers to Fuel	
local	Refers to Local	
max	Refers to Maximum	
pilot	Refers to Pilot Stage	
pre, premix	Refers to Premixing Stage	
total	Refers to Total of Both Stages	
3	Refers to Combustor Inlet	
4	Refers to Combustor Exit	

Greek Letters

α	Exponent of Emission Index Pressure Correction Term	
α_1	Injection Angle Relative to Flow Direction	degrees
α_2	Injection Angle Relative to Annular Pitchline	degrees
$\Delta P, \Delta P/P$	Combustor Pressure Drop	percent
η_b	Combustor Efficiency	percent
τ	Constant in Emission Index Temperature Correction Term	K
τ_{comb}	Combustor Residence Time	ms
	Equivalence Ratio	

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