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LEAN, PREMIXED, PREVAPORIZED
FUEL COMBUSTOR CONCEPTUAL DESIGN STUDY

-FINAL REPORT-

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United Technologies Corporation
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16. Abstract

Four combustor concepts have been designed for the NASA/P&WA Energy Efficient Engine (E^3) in a 9-month conceptual design study program to identify and analytically evaluate lean, premixed prevaporized (LPP) combustors. The designs utilize variable geometry or other flow modulation techniques to control the equivalence ratio of the initial burning zone. Lean conditions are maintained at high power to control oxides of nitrogen while near stoichometric conditions are maintained at low power for low CO and THC emissions. Each concept has been analyzed and ranked for its potential in meeting the goals of the program. Although the primary goal of the program is a low level of NO_x emissions (≤ 3g/kg fuel) at stratospheric cruise conditions, both the ground level EPA emission standards and combustor performance and operational requirements typical of advanced subsonic aircraft engines are retained as goals as well. Based on the analytical projections made during this study, two of the concepts offer the potential of achieving the emission goals. However, the projected operational characteristics and reliability of any concept to perform satisfactorily over an entire aircraft flight envelope would require extensive experimental substantiation before engine adaptation can be considered.

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FOREWORD

This document describes the work conducted and completed by the Commercial Products Division, Pratt & Whitney Aircraft Group of United Technologies Corporation during Lean Premixed Prevaporized Fuel Combustor Conceptual Design Study Program. This final report was prepared for the National Aeronautics and Space Administration Lewis Research Center in compliance with the requirements of Contract NAS3-21256.

The authors of this report wish to acknowledge the guidance and assistance of Dr. Edward J. Mularz, NASA Project Manager of the LPP Fuel Combustor Conceptual Design Study Program. The authors would also like to thank all the investigators of the Stratospheric Cruise Emission Reduction Program for providing useful LPP combustor design informations, and Drs. G. J. Sturgess and S.A. Syed of the Combustor/Turbine Durability Powerplant Analysis Group of Pratt & Whitney Aircraft for their assistance on the feasibility of aerodynamic air modulation.

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SUMMARY

This report presents the results of a nine-month design study to
identify and analytically evaluate lean, premixed, prevaporized (LPP)
fuel combustor concepts utilizing variable geometry and other advanced
flow control techniques. Although the primary goal of this program was
low oxides of nitrogen (NO_x) at stratospheric cruise conditions, both
the currently proposed ground level EPA emission standards and
combustor performance and operational requirements typical of advanced
subsonic aircraft engines were retained as goals as well.

Four combustor concepts were designed for the NASA/Pratt & Whitney
Aircraft Energy Efficient Engine (E^3) envelope and cycle. The Energy
Efficient Engine is configured as a high bypass ratio (6.5:1) engine in
the 190,000 Newton thrust class with a cycle pressure ratio of approxi-
mately 38:1 at cruise and a combustor exit temperature in excess of
1600K at sea level takeoff conditions. The combustor designs developed
are applicable to other advanced aircraft engines, and one of the con-
cepts was selected for adaptation to the JT9D engine cycle and enve-
lope. The basic design philosophy underlying all the concepts consider-
ed was that of lean, premixed, prevaporized combustion utilizing axial-
flow full annular designs constrained to the current E^3 configura-
tion. Achieving the NO_x emission goals will require equivalence
ratios between 0.5 and 0.6 at reduced residence times, while at low
power a significantly higher equivalence ratio must be maintained to
ensure high combustion efficiency and low emissions of carbon monoxide
(CO) and total hydrocarbons (THC). This stoichiometry must be control-
led while maintaining acceptable combustor pressure drop, stability,
temperature distribution and structural integrity.

The four designs selected allow evaluation of three variable geometry
techniques used in various combinations with advanced burner designs.
The techniques include both primary and dilution zone control as well
as aerodynamic methods for varying combustor inlet velocity profile.
Mechanical devices were designed to modulate combustor areas while a
diffuser wall bleed technique serves as the aerodynamic control.

Each of the four designs has been analyzed for its potential in meeting
the emission, performance and operational goals of the program and then
compared for the purpose of ranking the designs. Based on the analyti-
cal projections made during this conceptual design study, two of the
concepts offer the potential of achieving the emission goals while
nearly satisfying all of the performance requirements. However, the
projected operational characteristics and reliability of any of these
concepts to perform satisfactorily over an entire aircraft engine enve-
lope require extensive experimental substantiation before engine
adaptation can be considered.

INTRODUCTION

Previous technical efforts have focused on the reduction of aircraft pollution in the vicinity of airports. Additionally, recent studies have indicated there may be potential problems associated with the introducion of nitric oxides into the stratosphere. The consequences of depletion of the ozone layer have been studied by the U. S. Department of Transportation under the Climatic Impact Assessment Program (CIAP), and the report of findings (Ref. 1) from this study concluded that the control of oxides of nitrogen at high altitude may be required in the future.

As a result of the findings of the CIAP, it has been recommended to the Department of Transportation that research and development be aimed toward a reduction in the emission of oxides of nitrogen by a factor of 10 within the next decade, and that the research program be aimed at substantial further improvement in emissions to be realized in practical engines during the ensuing decade.

In response to these needs, NASA initiated the Stratospheric Cruise Emission Reduction Program (SCERP) to develop lean, premixed, prevaporized (LPP) combustor technology capable of reducing critical exhaust emissions over the full range of aircraft operation. The initial phase of a four-phase program was begun in 1976 to examine various aspects of LPP combustion which required more understanding and to establish design criteria for concepts having the potential of meeting program objectives.

This report describes the results of an initial Phase I study program to identify, design and evaluate LPP combustor concepts utilizing variable geometry and/or other flow control techniques. The primary goal of this program is the significant reduction of emissions of nitrogen oxides at stratospheric cruise conditions.

A summary of the plan and goals of the subject program is provided in Section 1.0. Section 2.0 contains a description of the reference engine (E^3) and combustor used as a basis for the program work and the criteria considered for the design work. Section 3.0 presents the aerodynamic and mechanical design features and Section 4.0 describes the engine feasibility criteria. Section 5.0 evaluates the conceptual designs for their probability of meeting the design requirements and program goals and Section 6.0 presents the concluding remarks.

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1.0 PROGRAM DESCRIPTION

1.1 GENERAL DESCRIPTION

The overall objective of this conceptual design study was to identify promising lean premixed-prevaporized combustor designs which incorporate variable geometry, and examine their potential for meeting performance, emissions, and operational requirements of advanced aircraft gas turbine engines. The ultimate goal is to reduce the emissions of oxides of nitrogen at stratospheric cruise conditions. The specific objectives of this study were to:

o   Design four combustors selected by NASA from concepts previously presented

o   Evaluate the predicted performance and emissions characteristics of these combustors

o   Evaluate their potential to meet engine operational requirements as well as their compatibility with current engine designs

o   Identify design problems associated with the application of variable combustor geometry

To accomplish these objectives a nine (9) month technical effort was undertaken. The schedule for this program is shown in Figure 1-1. The program approach involved an initial design task where the combustor envelope (diffuser, fuel system, combustor contour, variable geometry mechanisms) were defined. This was followed by a design analysis task in which the concepts were evaluated for performance and operational characteristics, potential for meeting the emissions goals and problem areas peculiar to the variable geometry features. The third task involved the rating of the four candidate concepts from the results of the previous task.
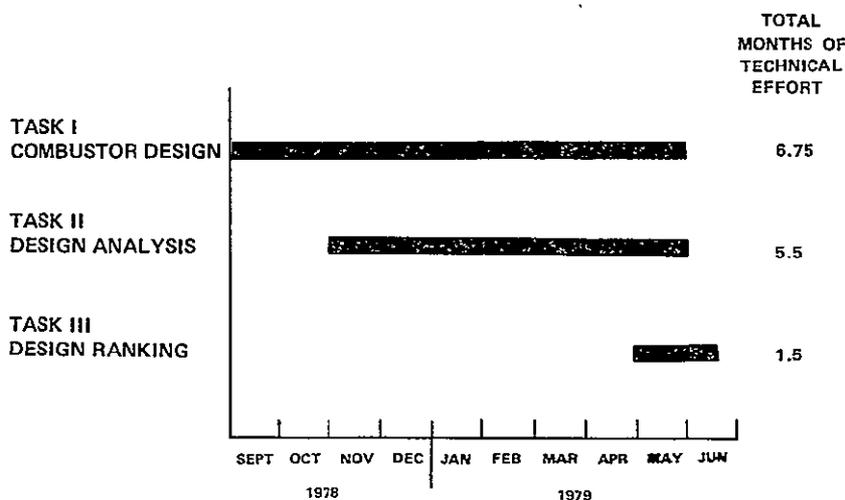
Figure 1-1   Program Schedule

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1.2 PROGRAM PLAN

1.2.1 Task I - Combustor Design

The combustor design was an axial flow annular type. During the Task I effort, preliminary flow paths and splits were defined. Flameholder and/or swirler sizing as well as fuel introduction method and schedule were determined, and the variable geometry mechanisms specified.

The designs included the combustor and all other necessary components such as the diffuser, fuel premixing components, variable geometry devices, etc. Design features and major components of the fuel system were specified and fuel injection and distribution techniques identified. Techniques for actuating the variable geometry hardware were indicated, including supports and pivot points, linkages, actuators and seals. All combustor materials and combustor liner cooling techniques were shown.

The combustor concepts were constrained to the current Energy Efficient Engine configuration. However, the advanced energy efficient turbofan engines were considered sufficiently long term so that the geometry of the burner and diffuser cases, including combustor section length, limiting radii and diffuser configuration could be altered if found either desirable or necessary.

The design layouts included enough detail to indicate how the various parts would assemble. Both a cross-sectional view across the combustor annulus at the combustor centerline as well as one or more circumferential views were given to provide sufficient information to completely define the combustor geometry. The location and sizes of all air passages, including dilution holes, film cooling slots, and convective cooling passages were specified.

1.2.2 Task II - Design Analysis

Each of the combustor designs developed in Task I was analyzed and evaluated for the potential for meeting the combustor performance goals as well as for feasibility for development into a practical engine system. The designs were analyzed for each of the following factors over the full range of combustor operation.

(a) Performance - including predictions of

- o   pressure loss
- o   combustion efficiency
- o   combustion stability
- o   exit radial temperature profile
- o   pattern factor
- o   autoignition or flashback characteristics

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(b) Emissions - including predictions of

    o NO_x, CO, THC emissions as well as smoke for the EPA landing takeoff cycle and altitude cruise conditions

(c) Operational considerations - including predictions of

    o   altitude relight
    o   transient behavior
    o   starting performance
    o   sensitivity to bleed flows

(d) Control requirements - including assessment of

    o   impact of variable geometry on engine control system
    o   control system input requirements
    o   need for new or additional sensing techniques

(e) Mechanical integrity/reliability - including predictions of

    o   combustor hardware temperatures
    o   potential fuel coking
    o   potential liner failure

(f) Cycle considerations - including evaluation of impact of burner design on

    o   engine cycle
    o   engine performance
    o   engine weight

In those portions of the analyses where a significant tradeoff existed between two or more parameters tradeoffs were identified and the results evaluated. Also included in the analyses was an elementary failure analysis to identify potential failure modes.

1.2.3 Task III - Design Ranking

Following the completion of Task II, each of the combustor designs were rated in each of the categories identified in Section 1.2.2 items (a) through (f), according to their probability of meeting the design requirements. The following rating criteria were used:

Rating   Description

  1.1   Exceeds requirements

  1.0   Likely to meet requirements

  0.7   Needs more work to meet requirements

0.3   Needs considerably more work

0.1   Very little chance of meeting requirements

0   Will not meet requirements

The four combustor concepts studied in Tasks I and II were ranked according to their relative development risk, i.e., the ability to convert the combustor concept into an operational engine combustor. The most promising design was selected and adapted to the JT9D-7 engine envelope and operating conditions.

1.3 PROGRAM GOALS

1.3.1 Emissions Goals

Design emissions goals for the study were as follows:

o NO_x EI $\leq$ 3 g/kg at subsonic cruise

o   1984 EPA emissions standards for T-2 thrust class aircraft over the landing – takeoff cycle

        CO EPAP $\leq$ 25 g/kNewton
        THC EPAP $\leq$ 3.3 g/kNewton
        NO_x EPAP $\leq$ 33 g/kNewton
        Smoke No. $\leq$ 20

1.3.2 Performance Goals and Design Requirements

Design requirements and performance goals for the study were as follows:

o   combustion efficiency:
            $\eta_b \geq$ 99.9 percent at sea level takeoff
            $\eta_b \geq$ 99.5 percent at engine idle
            $\eta_b \geq$ 99 percent at all other operating conditions

o   total combustor pressure loss, $\Delta P/P \leq 5.5$ percent at all operating conditions except idle.

o   altitude relight capability $\geq$ 10.7 km

o   all combustor designs were to have adequate cooling and structural integrity to be representative of aircraft engine combustors.

2.0 DESIGN STUDY

2.1 INTRODUCTION

Gas turbine engine combustors must satisfy many functional requirements
simultaneously. The combustor must be capable of burning all the fuel
efficiently while constraining exhaust pollutants to stringent limits.
The mean temperature of the gases leaving the combustion section has to
be commensurate with cycle efficiency requirements, but the maximum
local temperature and temperature radial distribution (profile) must be
compatible with turbine material limitations. All functions must be
performed with minimum pressure loss, since such losses represent a
reduction in available energy to the cycle.

The combustor must ignite the fuel-air mixture easily and be capable of
maintaining it lit over wide ranges of fuel temperature, ambient air
temperature and ambient pressure. It must not be subject to blowouts
resulting from either too rich or too lean fuel-air mixtures, and it
must retain its efficiency over the required operating range of the
engine. Off-design temperature rise capability has to be compatible
with the rotating machinery characteristics such that smooth accelera-
tion of the engine can be achieved. Response of the combustor to throt-
tle movements must be rapid to permit safe flight operations.

The combustion section is required to perform all these functions while
containing a high temperature combustion process and not compromising
the durability of the engine. All combustion chambers, whatever their
principle of operation or geometric arrangement, must conform to the
basic requirements described above.

A typical current service aircraft engine combustor utilizing conven-
tional techniques is shown in Figure 2-1. This combustor is designed to
satisfy all the above requirements.

2.2 REFERENCE ENGINE

The lean premixed-prevaporized combustor conceptual components were
designed for the cycle and performance parameters anticipated for the
Energy Efficient Engine (E^3), currently being developed under a
contract with NASA. The E^3 is configured as a high bypass ratio
(6.5:1) engine in the 190,000 Newton thrust class, with a pressure
ratio of about 38:1 at the cruise design point. Representative operat-
ing conditions for the Energy Efficient Engine for the design points of
the landing/takeoff cycle and for maximum rated cruise are presented in
Table 2-I.
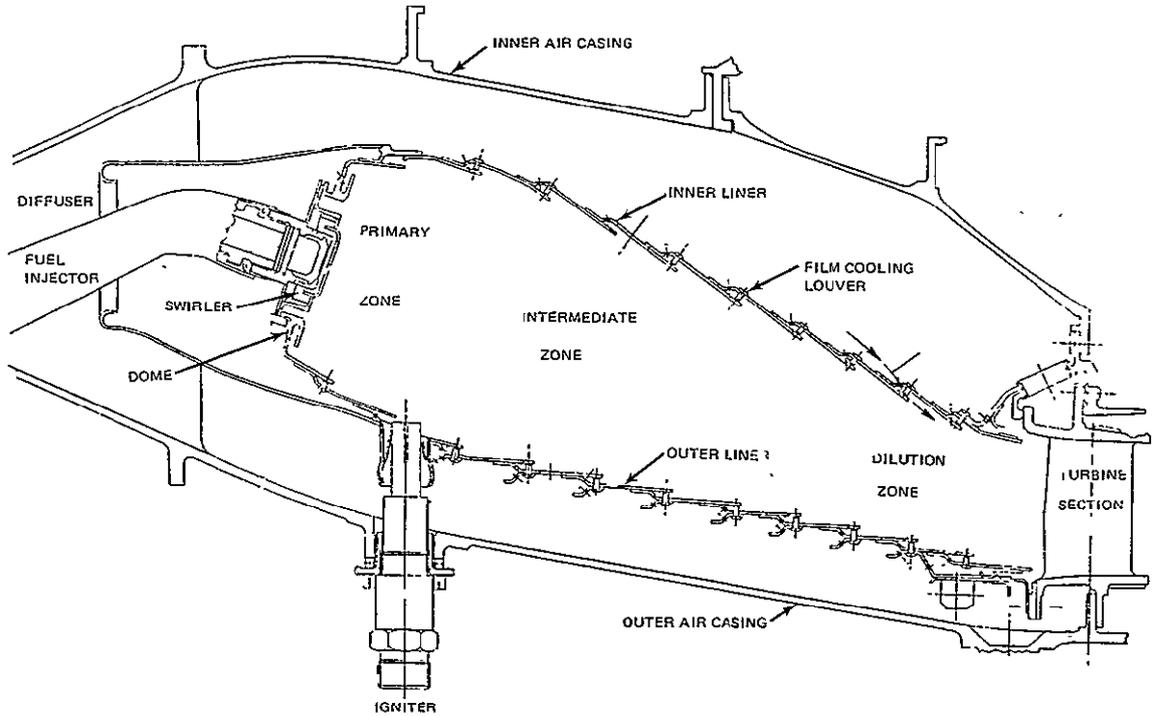
Figure 2-1   Layout of JT9D-70 Combustor

TABLE 2-I

REPRESENTATIVE OPERATING CONDITIONS FOR THE
ENERGY EFFICIENT ENGINE

	Ground[a]			Sea-Level	Max[b]
	Idle	Approach	Climb	Takeoff	Cruise
Combustor Inlet Temperature (K)	473	621	777	810	754
Combustor Inlet Pressure (atm)	4.4	11.7	27.0	31.2	13.8
Air Flow Rate (kg/sec)	14.0	31.6	62.4	70.2	31.7
Combustor Exit Temperature (K)	815	1118	1522	1611	1533
Combustor Exit Pressure (atm)	4.1	11.0	25.5	29.5	13.1
Fuel Flow Rate (kg/sec)	0.13	0.43	1.38	1.68	0.74
Overall Fuel-Air Ratio	0.009	0.0137	0.0221	0.0240	0.023

[a] Std. Day - uninstalled (7% power)

[b] Alt = 10.7 km, Mn = 0.8

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2.3 LPP COMBUSTOR DESIGN CONSIDERATIONS

2.3.1 Introduction

The ideal variable geometry LPP combustor would be designed to modulate
the combustor air flow, mix and vaporize the fuel in air in proper
proportions for each engine operating condition, and burn the control-
led homogeneous mixture efficiently, thereby minimizing exhaust pollut-
ants. The successful application of LPP combustion to practical engine
combustors imposes a number of considerations that often result in
contradictory requirements. Some of these factors, such as the charac-
teristics of the compressor discharge flow field, fuel preparation and
vaporization, autoignition and flashback, flame stability, and cooling
and dilution air requirements will be discussed in Sections 2.3.2
through 2.3.7.

2.3.2 LPP Combustor Phenomena

The conclusion to be drawn from the numerous emission reduction
programs conducted by Pratt & Whitney Aircraft and from other investi-
gations (Refs. 2, 3, 4, 5) is that the lean, premixed, prevaporized
(LPP) combustion technique offers the best potential of meeting all of
the program goals. Both theoretical and experimental studies (Ref. 2,
3) have shown that the concentration of nitrogen oxides produced by the
oxidation of atmospheric nitrogen during combustion is nearly exponen-
tially dependent on flame temperature (Figure 2-2). Furthermore, it has
been shown in these studies that above 1900K the gas phase reactions
are fast enough to produce significant amounts of NO_x. Therefore, if
the combustor were to operate such that the local fuel-air ratio was
below approximately 60 percent stoichiometric everywhere, then the
production of NO_x would be negligible.

The implications of lean combustion in minimizing NO_x emissions are
quite evident. The desired uniformity and control of the fuel-air mix-
ture in the combustion zone precludes droplet burning. The fuel must be
premixed and prevaporized prior to introduction into the primary zone
of the combustor. The exhaust emission reduction potential, particular-
ly that for NO_x reduction, of lean premixed-prevaporized (LPP) com-
bustion has been demonstrated in laboratory experiments (Ref. 2, 4).
Figure 2-3 (from the data of Ref. 2) shows the interrelationship of
combustion residence time, equivalence ratio and combustion efficiency
and the impact of these parameters on NO_x emissions from an LPP
system. It illustrates that NO_x emissions may be reduced by reduc-
tions in equivalence ratio and/or residence time while maintaining high
levels of combustion efficiency. However, it must be recognized that
these controlled rig tests represent, at best, the simulation of a
fixed operating condition in the overall engine cycle. In order to
exploit its full potential, and to broaden its useful operating range,
the LPP system requires some form of variable geometry. Considerable
basic technology and component development is necessary to optimize the
LPP type combustor from a performance as well as a emission reduction
viewpoint over the entire operating range of the gas turbine engine.

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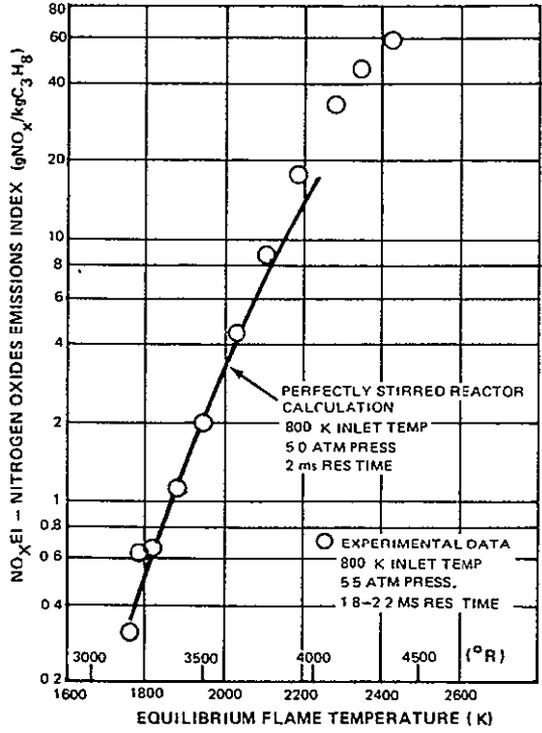
Figure 2-2   Variation of NO_x Emissions with Flame Temperature
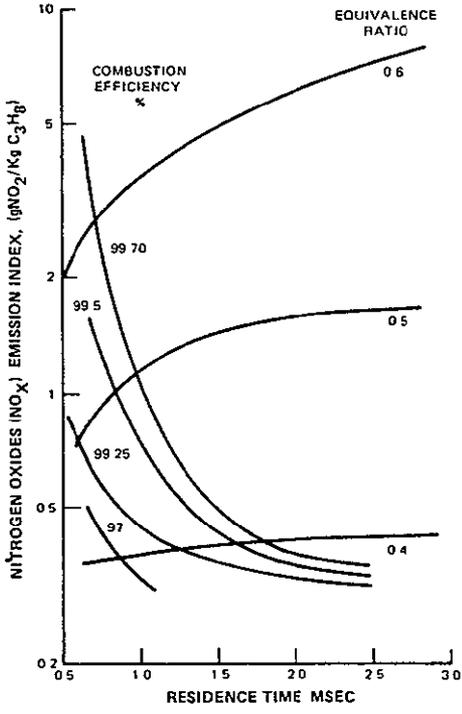
Figure 2-3   Effect of Residence Time on NO_x Emissions. Inlet mixtu
temperature, 800K; inlet pressure, 5.5 atm; reference
velocity 25 and 30 m/sec (from Ref. 2)

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Before an LPP combustor concept can be designed for a practical advanced aircraft engine, serious consideration and concern must be given to the basic factors that follow.

2.3.3 Fuel-Air Preparation

It is recognized that even in the ideal case of a uniform flow field feeding the premixing passages, fully premixed and prevaporized mixtures may not be obtainable over the entire engine operating range. In the absence of an external vaporizer, some of the factors that influence fuel vaporization are air temperature and pressure, combustor inlet turbulence level (and possibly scale), fuel droplet size and distribution, and premix passage length and residence time. Figure 2-4 (from Ref. 5) shows analytical predictions of fuel droplet evaporation as a function of pressure. When the ignition delay characteristics of Jet-A fuel (from Ref. 6) are superimposed, it can be seen that vaporization will be limited by premix passage autoignition restrictions. The limits imposed by autoignition on passage length makes it imperative that optimum atomization and distribution be achieved. A spray evaporation model developed during the PWA/NASA Catalytic Burner Program (Ref. 7) was used to calculate the degree of fuel vaporization for parametric variations in passage length, velocity and droplet size. The results of this analytical investigation as shown in Table 2-II point out the importance of ultra fine atomization at the design conditions for high pressure ratio advanced gas turbine combustors. New approaches to fuel atomization aimed at the production of very small droplets ($\leq 40 \mu$SMD) should be explored. The fuel injector must be designed with as many injection sources as practical, without impinging fuel on liner walls and with no wakes where fuel could be entrained and possibly exceed autoignition limits.
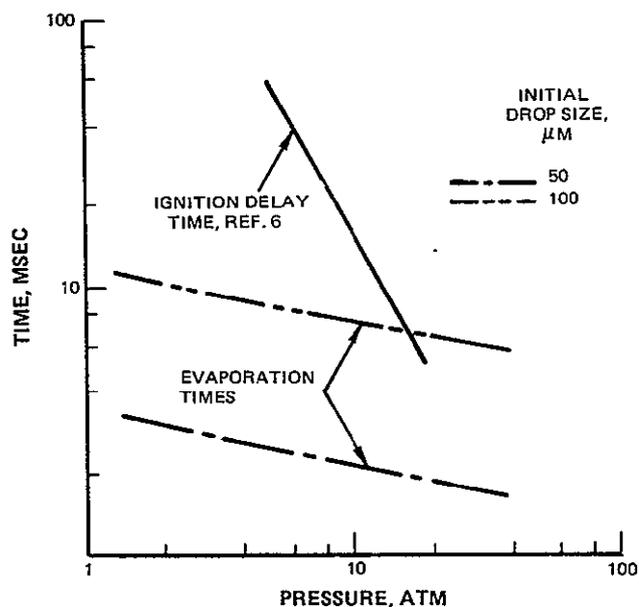
Figure 2-4   Effect of Pressure on Ignition Delay and Vaporization Times for JP-4. Inlet air temperature, 833K (from Ref. 5)

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TABLE 2-II

PARAMETRIC STUDY ON DEGREE OF VAPORIZATION

Premix Passage Length	7.6 cm			10.2 cm		
Air Velocity	61 m/s	91 m/s	122 m/s	61 m/s	91 m/s	122 m/s
Residence Time	1.25 ms	0.83 ms	0.63 ms	1.67 ms	1.11 ms	0.83 ms
SMD*	Percent Vaporized					
10 μ	80.7%	77.9%	75.9%	83.0%	80.2%	78.1%
20 μ	70.3%	67.5%	65.4%	72.6%	69.7%	67.7%
40 μ	60.0%	57.1%	55.1%	62.2%	59.3%	57.3%

Inlet Pressure 31.2 atm. Temperature 810K.

* initial injector droplet size (Sauter mean diameter)

An analytical prediction (Ref. 8) showing the effect of burning zone uniformity on the rate of NO formation is presented in Figure 2-5. It is apparent that the NO_x emission characteristics should be assessed for those engine operating conditions which result in deviations from homogeneous fuel mixing and vaporization.
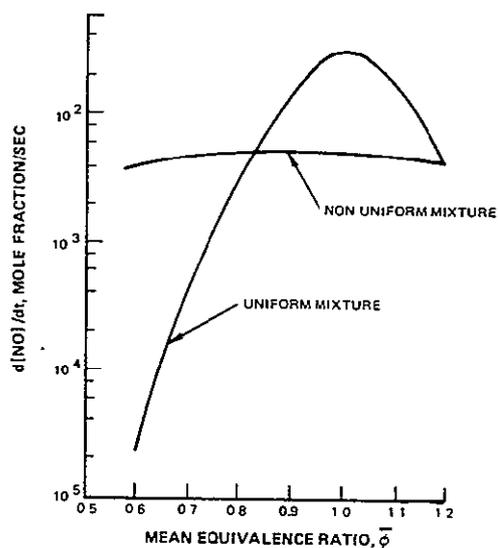
Figure 2-5   Effect of Mixture Uniformity on Rate of Formation of Nitric Oxide (from Ref. 8)

2.3.4 Autoignition and Flashback

Perhaps the most formidable obstacles to the successful application of the LPP combustor in advanced aircraft engines is the phenomena of autoignition and flashback. Many of the experimental rig programs including those sponsored by NASA have experienced autoignition or flashback problems (Ref. 4). Autoignition occurs when the residence time of the fuel-air mixture in the premixing passage exceeds the ignition delay time. Flashback occurs when the flame propagation velocity exceeds the mixture velocity, enabling the flame to detach from the intended flameholder and propagate into the premixing passage. In either case, autoignition or flashback, burning takes place in the premixing/prevaporizing passage, resulting in potential damage to the combustor and possibly the entire engine.

Autoignition delay data reported in the literature require careful interpretation with respect to the test apparatus and measurement method used. Some results are contradictory. All experimenters have had difficulty in rapidly obtaining a uniform fuel-air mixture and in determining the extent of fuel vaporization.

The autoignition characteristics of Jet-A fuel, as reported in Ref. 9, are presented in Figure 2-6. Some of the E^3 operating temperatures and pressures are superimposed on the figure. Clearly SLTO operating condition is the power setting that allows minimum margin for autoignition. In designing the premixing passages for the LPP system, precautions have to be taken to minimize and/or avoid potential flow problems, such as wakes behind variable geometry devices or fuel injectors, which could increase the residence time of fuel-air mixture in the premixing passage. If flow distortions resulting from variable geometry devices are unavoidable, the design should attempt to restrict these problems to operating conditions corresponding to lower pressures and temperatures, e.g., idle. Incomplete mixing/vaporization, hence higher NO_x emissions at SLTO power conditions, must be weighed against providing adequate margin to avoid autoignition.
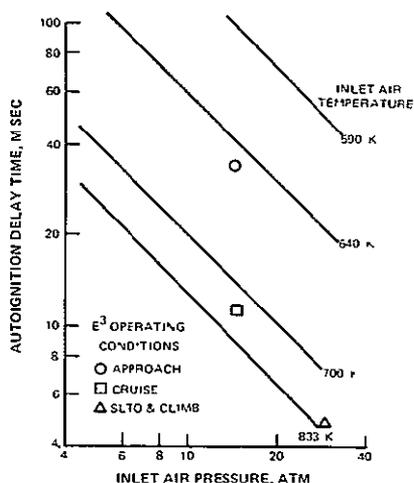
Figure 2-6   Autoignition Delay Times as Function of Inlet Air Pressure and Temperature (from Ref. 9)

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Flashback is another performance constraint on the LPP combustor that requires serious design concern (Reference 10). Two major types of flashback that must be avoided are: (1) flashback occurring in the free stream, and (2) flashback occurring through the low velocity flow in the boundary layer along the surfaces of the flameholder, any support struts, and the walls of the premix/prevaporized passage.

The most obvious free stream mechanism would involve flashback due to a flow reversal in the bulk flow through the combustor. This reversal could be a result of compressor surge, or combustion instability. Flashback can also occur in the absence of flow reversal if the turbulent flame speed through the gas in the premixing passage is greater than the local bulk velocity. While lean combustion tends to reduce flame speeds, other factors associated with the engine cycle, such as high temperatures, pressure, turbulence levels and preignition reactions due to applicable residence times at high temperature levels, cause increased flame speed.

Although the influence of these factors is qualitatively known, there is an inadequate amount of data on the quantitative effect these parameters have on flashback for aircraft fuels over the operating regime of the LPP combustor. Control of the flashback phenomenon can be approached by controlling wall temperatures, reducing equivalence ratios near surfaces, and by the application of free stream pressure gradient.

2.3.5 Stability

The combustor front end airflow required to establish lean combustion during high power operation may result in flame blowout at lower power conditions. There are two approaches to alleviate this design problem. The first, which is a part of this program, is to employ variable geometry to modulate the airflow in order to meet the stability requirements over a wide range of operating conditions. The second approach is to utilize a pilot combustor incorporated into the LPP system. The pilot combustor would be used for starting, ground idle and altitude relight; the LPP system would be staged in the power conditions above idle. This would require a smooth transition between the pilot and LPP stages to ensure proper acceleration and deceleration characteristics. This may necessitate more complex fuel injector and flameholder designs that have hitherto been contemplated.

Studies have been made (Ref. 11) to evaluate the effect of flameholder geometry on blowout limits and methods of enhancing stability characteristics through flameholder design. The results of this program will provide data required in the subsequent design of lean combustor concepts. An additional design concern in the application of fuel staging is fuel nozzle coking, which can result after a particular stage has been shutdown during a change in engine operating condition.

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2.3.6 Cooling and Dilution Air Requirements

Current high bypass ratio commercial engines, such as the JT9D, employ annular combustors constructed with Hastelloy-X material. The liners are fabricated from a series of cylindrical louvers which are film cooled. Thermal barrier coatings, such as magnesium zirconate, are applied to the hot gas side of the liner to reduce the maximum metal temperature and approximately forty-five percent of the combustor air-flow is required to cool the JT9D liners. The effect of utilizing large quantities of air in the front end of the lean premixed combustor on cooling/dilution air requirements is shown in Figure 2-7.
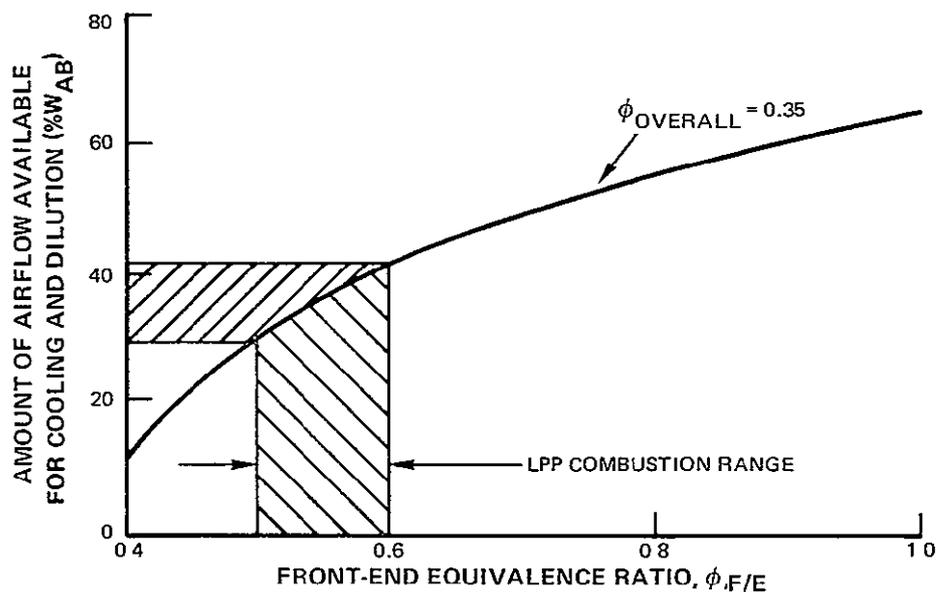
Figure 2-7   Cooling and Dilution Airflow Requirements of Lean
               Combustion

Control of combustor exit temperature pattern factor and radial profile will continue to require approximately the amount of dilution air that is used in current engines. The implication is that only 25 percent of the combustor airflow is left to cool the premixed combustor designed with a front end equivalence ratio of 0.55. The result of a study to define wall temperatures when louvers are employed in LPP conceptual designs is presented in Section 4.1.1. Lower primary zone gas tempera-tures and flame radiation, and most importantly, a significantly short-er burner liner all contributed towards maintaining liner wall tempera-tures at satisfactory levels with only 25 percent combustor airflow for film cooling. To achieve the desired liner durability in the more severe operating environment of future aircraft engines, and also to reduce liner cooling air requirements and thereby release combustor air for exit temperature distribution and emissions control, more efficient cooling techniques must be applied to the liner design.

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Pratt & Whitney Aircraft has been developing, through analytical and experimental investigations, advanced combustor liner configurations which will require less than half of the air required for the current conventional film cooling liner. Candidate cooling configurations include Counter-Flow Film cooling, Counter-Parallel FINWALL® (CPFW), Impingement Transpiration cooling, and Impingement-Film cooling. The effect of applying one of these advanced cooling schemes (CPFW) to one of LPP conceptual designs is shown in section 4.1.1.

2.3.7 Cycle and Performance Constraints

The successful application of LPP combustion to practical engine com-bustors imposes a number of considerations that often result in contra-dictory requirements. Some of these factors such as fuel preparation and vaporization, autoignition and flashback, flame stability and cool-ing and dilution air requirements have already been discussed.

Since premixed-prevaporized fuel combustors have demonstrated the potential for significant reduction in NO_x emissions via lean burn-ing, one method of obtaining efficient combustion throughout the engine operating spectrum is to employ LPP combustion in conjunction with variable geometry features. Variable geometry (or continuous air stag-ing) offers the possibility of smooth variation in combustor stoichio-metry relative to fuel staging, or it could be employed together with fuel staging to optimize a combustor for serveral operating conditions as opposed to the two-stage combustor. The utilization of variable geo-metry, though desirable from a combustor performance viewpoint, intro-duces significant complexity and difficulty with respect to combustor design. A typical single-stage combustor operating at stoichiometric fuel-air ratio at idle power setting would require approximately 15 percent of the total combustor airflow in the front end. The same stage at cruise or SLTO power setting would require approximately 65 percent of the combustor airflow to maintain an equivalence ratio of 0.55. Therefore, efficient and viable techniques of diverting up to 50 per-cent of combustor airflow from one operating condition to another must be evolved if the full potential of the LPP combustor is to be exploi-ted. Fuel staging would reduce the amount of air to be staged. Movement of air of such magnitude will influence the combustor section pressure drop characteristics at different operating conditions. Some form of additional coordinated variable geometry is needed in order to vary the amounts of air employed in liner wall cooling and dilution so as to maintain a constant liner pressure drop. Utilization of 65 percent of the available combustor airflow in the front end premixing process leaves only 35 percent for dilution and liner cooling.

The anticipated design problems with variable geometry features are their control, operational characteristics and durability. The complex air staging techniques will require sophisticated control systems and sensors in order to keep the combustor stoichiometry at desired levels for various flight conditions. The challenge presented to the control

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system designer is to meet desired engine performance requirements with the least complex system possible. Minimizing complexity enhances the potential of meeting the ever present goals of high reliability and low weight, cost and maintainability.

The major types of control systems are (1) on-off control, (2) openloop modulating control and (3) closed-loop modulating control. The on-off control is the simplest approach of the three types and provides the lowest degree of control. The output control element, a bleed air valve for example, would be in the open or the closed position as a function of an activation signal. The open-loop modulating control system is more complex and provides more precise control than the on-off control system. In an open-loop modulating system, the output control element, such as a bleed air valve, would be capable of being positioned at any location between full open and full closed. The third type of control system, a closed-loop modulating control, is the most complex system and maximizes the engine performance benefits. This type of control could utilize, for example, a modulating bleed air valve, with the position of the valve being set at whatever location is required to obtain the desired effect.

A major factor that must be addressed in determining control requirements is the impact that the precision of the variable geometry setting has on engine performance. If the performance benefit is very sensitive to clearance, a closed-loop modulating system will probably be required. If the benefit is much less sensitive, on-off control will probably be acceptable.

There are a number of actuating mechanisms for variable geometry devices that can be adopted. Prime concerns in selecting the proper approach include compatibility with the engine control system, weight, complexity, and reliability. Specific devices are described in detail in Section 3.0. Nevertheless, for the purpose of defining the general types of activating mechanisms that can be considered, the following categories are listed: (1) hydraulic; (2) mechanical; (3) electromechanical; (4) air and vacuum systems; (5) burner pressure drop driven systems; and (6) bimetallic movement.

The influence of the control system in the overall operation of the engine will have to be evaluated. The variable geometry system should be designed such that if it fails, it will not impact the safe operation of the engine.

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3.0 CONCEPTUAL DESIGNS AND ANALYSIS

3.1 INTRODUCTION

Four concepts were selected for design, analysis and evaluation as potential lean premixed prevaporized configurations. The concepts selected allowed the evaluation of three variable geometry techniques used in various combinations with advanced burner designs. In order to ensure the ultimate adaptability of the proposed designs to actual engine hardware, it was necessary to restrict the selection process as described below:

(1) Simultaneous control of IBZ (Initial Burning Zone) and dilution zone airflow would be required in order to maintain a nearly constant combustor section pressure loss at all operating conditions. Although increasing the complexity significantly, the variation in pressure loss resulting from individual control was felt to be intolerable.

(2) Any attempt to control airflow upstream of the IBZ injection plane would have to be carefully designed to minimize wakes.

(3) The variable geometry mechanism would have to be designed for fast response.

(4) A safety factor of about 2.5 would be applied to autoignition residence time data.

3.2 CONCEPT 1

3.2.1 Concept Description

The design of the first concept is presented in Figure 3-1. The concept features 24 premix passages each equipped with a translating centerbody that provides both the desired area modulation between idle and SLTO and a bluff body recirculation zone for stability. The design evolved from a desire to meter front end airflow at the IBZ injection plane and accelerate the flow in order to minimize the possibility of flashbacks.

The conical flameholder is based on a design evaluated in a NASA program, Ref. 12, that demonstrated low NO_x emissions and overall good stability. The reference design was used to establish the overall cone size and shape based on a desired degree of blockage, while the number of passages, 24, was selected for compatibility with the 24-strut design of E^3. The outer contour of the passage was sized to allow the annulus area to vary as required for equivalence ratio control. At idle conditions an IBZ equivalence ratio of 1.0 is maintained to ensure high combustion efficiency and low emissions of carbon monoxide and unburned hydrocarbons, while at high power the equivalence ratio is reduced to 0.55 to control oxides of nitrogen. The test

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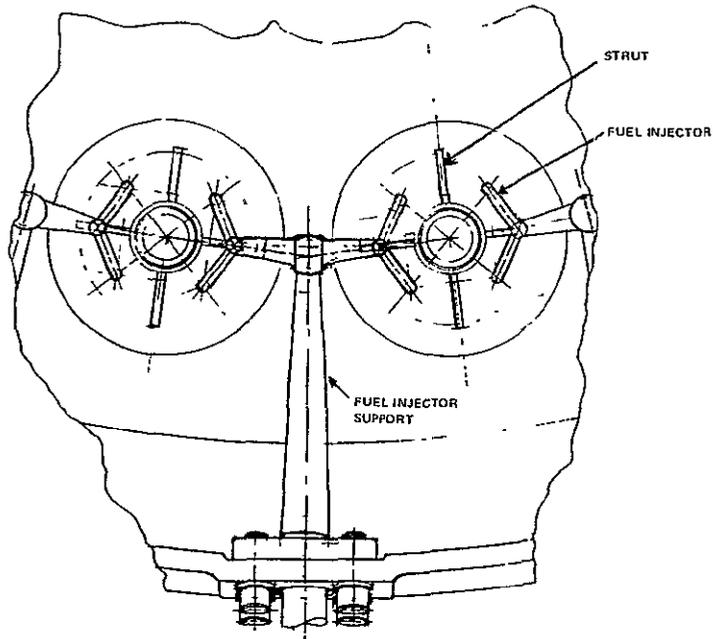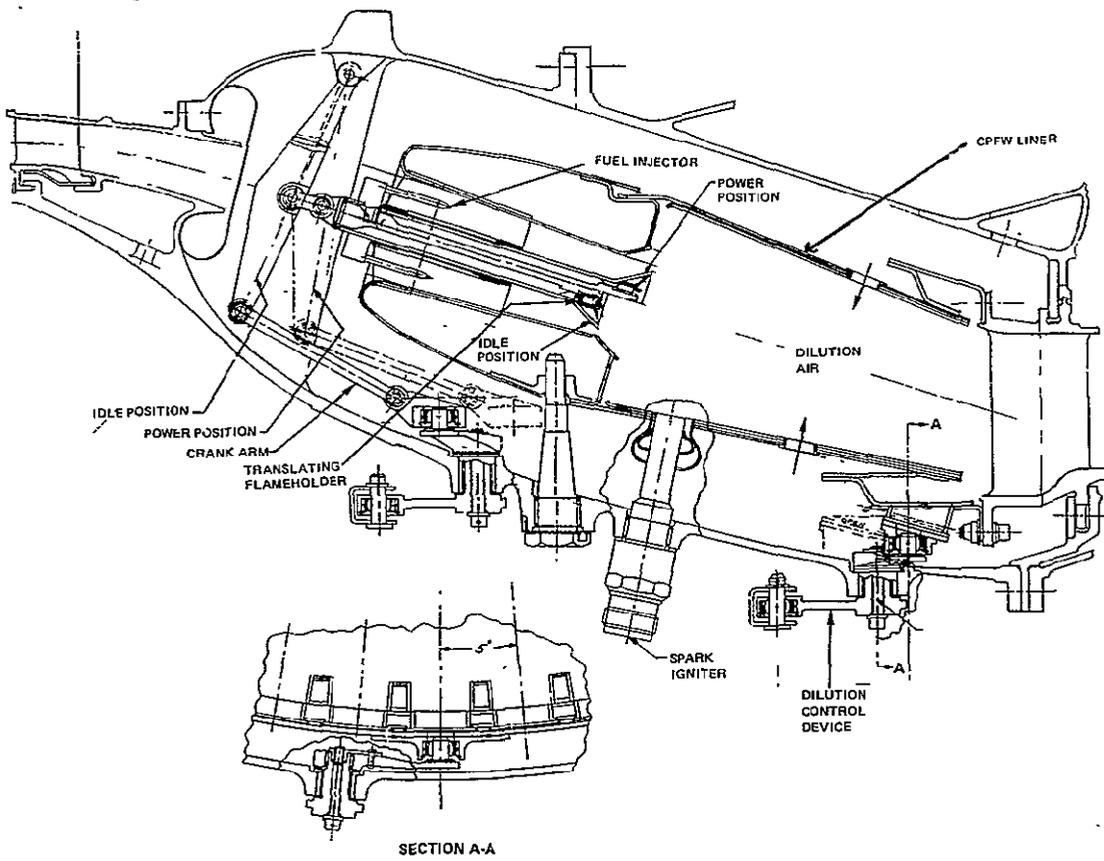
Figure 3-1   Variable Geometry LPP Combustor - Concept 1

results from previous low emissions combustor programs, Refs. 13 and 14, were used in selecting an idle IBZ of 1.0 while the experiment premix data of Anderson, Ref. 2, were used in selecting a value of 0.55 for high power operation.

As shown, the 24 premix passages are located downstream and between the diffuser case struts. The translating centerbody is centered in each passage, guided by impregnated graphite sleeve bearings at each end of a center tube supported by four struts. Movement of the plug is accomplished by the ball jointed linkage shown which is connected to the axially translating internal ring. A set of crank arms on the forward end of the combustor case connects the internal ring to the external unison ring which is rotated by an appropriate actuation system. The outer crank arm shaft is inserted through the case bearing bushing into a splined connection with the inner crank arm and secured with a radial bolt. The bearing bushing is lined with low friction impregnated graphite on the ID and the inner flange face. The inner torque arms engage ball joint assemblies set in bosses on the OD of the translating ring to convert rotation of the unison ring into translation of the inner ring to move the nozzle plugs.

Figure 3-1 shows the fuel injectors and supports. Each of the 24 premixing passages contains four fuel injectors each with two fuel injection holes at the injection plane spraying fuel toward the support struts for the air nozzle plug. These struts serve as splash plates or a filming surface if any atomized fuel droplets impinge on them.

Because of the importance that fuel spray quality plays in the vaporization process, the design of the fuel injector must be considered as a critical design item. The fuel injection system for Concept 1 represents an attempt to maximize the number of fuel source locations to obtain the highest possible degree of vaporization.

A dilution control device that meets the design objective of controlling a large quantity of airflow has been incorporated in the Concept 1 design. The design shown in Figure 3-1 utilizes a valving arrangement to bypass combustor inlet air at low power operation. The valve is closed during high power operation and can be partially open at part power to modulate the flow of bypass air. The valve consists basically of a conical ring which is translated axially by a set of crank arms around the combustor outer case. The outer arm of each set is connected to a unison ring rotated by an appropriate actuation device. To allow for tolerances and distorton, individual conical inserts are loosely attached to the conical ring by means of the rectangular spacers and retaining plates at each side of each insert. In operation, the conical ring moves rearward until the "high" points of the assembly engage. Inserts which are still loose are then forced into contact with their seats on the ends of the bypass ports by the combustor air pressure differential across the liner.

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An analysis was conducted to determine if the 25 percent of combustor airflow available for cooling was sufficient to permit a conventional JT9D film cooled louver design with magnesium zirconate (MgZr) coating. A thermal analysis computer program was used to calculate surface temperatures for several IBZ equivalence ratios at the E^3 SLTO condition. The Counter Parallel FINWALL® (CPFW) cooling scheme was also evaluated to assess the effects of an advanced cooling scheme on an LPP fuel combustor. Based on the results of this analysis which are presented in Section 4.1.1, CPFW was selected for this concept and all other concepts. CPFW is the most promising cooling scheme for E^3 currently being developed by Pratt & Whitney Aircraft.

3.2.2 Concept Assessment

The results of a performance and emissions analysis for Concept 1 are summarized in Table 3-I and where applicable, the method of analysis applied to each parameter is discussed in detail below:

o Pressure loss: the burner was sized to operate at a pressure loss of 5.5 percent at all operating conditions.

o Combustion Efficiency:

   The combustion efficiencies were estimated using an air loading correlation. In this correlation an air loading parameter (ALP) approach was applied to collected performance and emissions data from a large number of engines using annular combustors. Empirical curves of combustion efficiency as a function of ALP and equivalence ratio were plotted where:

$$ALP = \frac{3.72 W_a}{P^{1.8} \ V \ 10^{0.000794 \ T}}$$

   W_a = Burner Air Flow
   P = Burner Inlet Pressure
   V = Burner Volume
   T = Burner Inlet Temperature

o Stability

   The stability of concept 1 was assessed based on the empirical stability correlation of Ozawa (Ref. 15) and a study performed in-house on bluff body stabilization of premixed prevaporized flames. In Ref. 15 an empirical stability curve was generated by correlating data from a numerous different geometry flameholders. Figure 3-2 shows the predicted stability characteristics of concept 1 compared with experimental results for a similar 90° cone flameholder. The stability parameter of concept 1 was evaluated at the worst altitude relight condition estimated from JT9D informa-

TABLE 3-I

CONCEPT 1 DESIGN ANALYSIS

EMISSIONS

	Goal	Estimation*	Comment
CO EPAP (g/kN)	≤ 25.0	12	
THC EPAP (g/kN)	≤ 3.3	1.7	
NO_x EPAP (g/kN)	≤ 33.0	≤ 33.0	
NO_x EI at CRUISE (g/kg fuel)	≤ 3.0	3.1 to 3.9	
Smoke Number	≤ 20.0	≤ 10.0	

* Engine to engine variability not included in emission estimate.

PERFORMANCE

	Goal	Estimation	Comments
Pressure Loss	$\leq 5.5\%$	$\leq 5.5\%$	
Combustion Efficiency			Based on ALP correlation
At Idle	$\geq 99.5\%$	$\geq 99.6\%$	
At Take Off	$\geq 99.9\%$	$\geq 99.9\%$	
At Other Operating Conditions	$\geq 99.0\%$	$\geq 99.0\%$	
Stability			Satisfactory
Autoignition			Safety factor of 2.5 applied.
Pattern Factor at Takeoff & Cruise	≤ 0.25		Premix passage sizing and control critical.
Temperature Profile Factor at Takeoff & Cruise	≤ 0.15		Premix passage sizing and control critical.
Maximum Combustor Liner Temperature			See analysis in Section 4.1.1
Altitude Relight	≥ 10.7 km		Satisfactory
Starting			Satisfactory
Transient Behavior			Could be a problem.

tion since windmilling flight characteristics for the E^3 were not yet available. The predicted stability at the worst altitude relight condition was reassessed using the in-house stability study of the premixed prevaporized flames, as shown in Figure 3-3. The stability of concept 1 appears to be satisfactory in both correlations.

o   Autoignition:

Autoignition time was estimated based on the design curve of Ref. 7. In Ref. 7, a number of autoignition data for JP fuels were displayed on an Arrhenius plot, and a design limit line was drawn to allow a safety factor of about 2.5. The plot is shown in Figure 3-4. Based on the design limit, the autoignition delay time is evaluated to be 0.8 Msec. at the E^3 SLTO condition and 3.1 Msec. at the cruise condition.

o   Emission Estimates:

CO and THC emissions were estimated from the combustion efficiency correlation described above. A CO to THC ratio of 7 to 1 at idle was assumed based on several prior experimental emissions programs. CO and THC were then back-calculated from the efficiency relationship.

$$\eta_c = 100 - 100 \ \frac{4343 \ (CO) + 21500 \ (HC)}{18.4 \times 10^6}$$
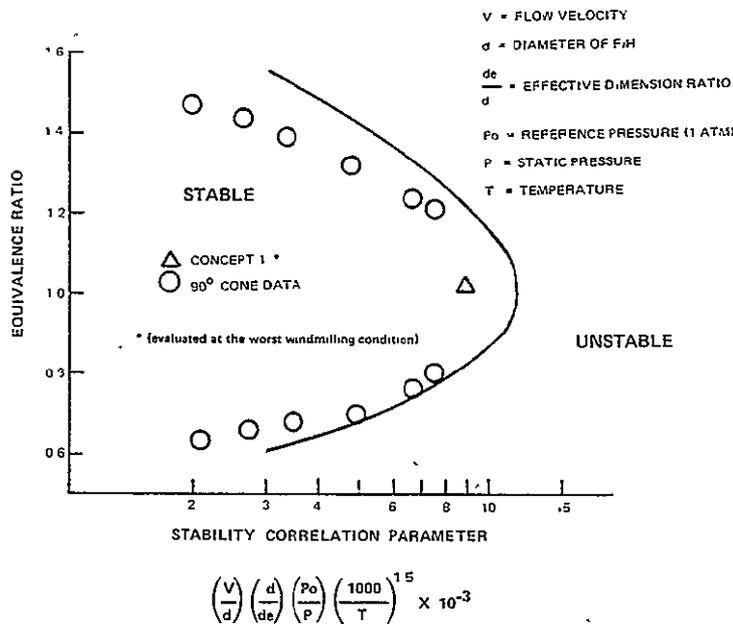
Figure 3-2   Flame Stability Curve

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EQUIVALENCE RATIO

STABLE

UNSTABLE

△ CONCEPT 1 *
* (EVALUATED AT THE WORST
WIND MILLING CONDITION)

V = FLOW VELOCITY
D = DIAMETER OF F/H
Cd = DRAG COEFFICIENT
($\Delta PT/\frac{1}{2}\rho V^2$)

P = PRESSURE
θ = T ($^{\circ}$K)/755°K

STABILITY PARAMETER ($\dfrac{V}{D\,Cd\,p\,\theta^{3/2}}$)
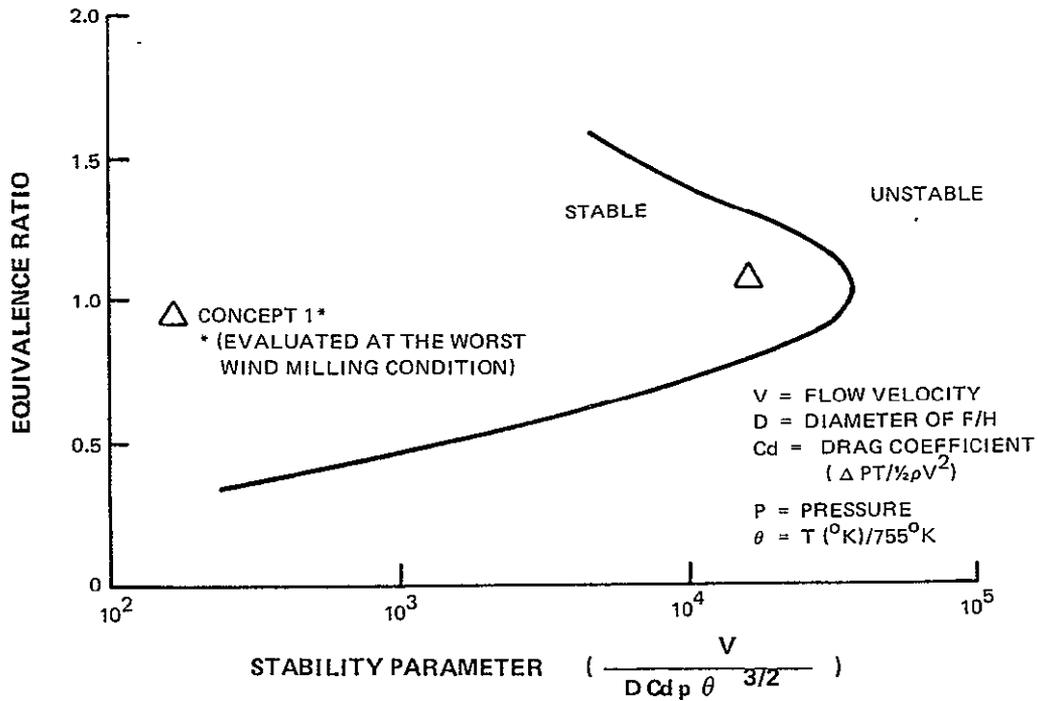
Figure 3-3   Stability Correlation Curve

AUTO IGNITION

DESIGN LIMIT

NO AUTO IGNITION

τ P, MILLISEC ATMOS

AUTHOR	FUEL	ϕ
	ISO-OCTANE	
	ISO DODECANE	
MULLINS	KEROSENE	0 074–0 107
TABACK	JP-4	0 07–0 11
SPADACCINI	JP-1	0 08
MESTRE & DUCOURNEAU	KEROSENE	30–75
MAREK ET AL	JETA	0.3–07
STRINGER ET AL	AVTUR	(JET AI)
	AVTAG	(JP-1)

1/T_{mix} K^{-1}

1/T_{mix} °R^{-1}
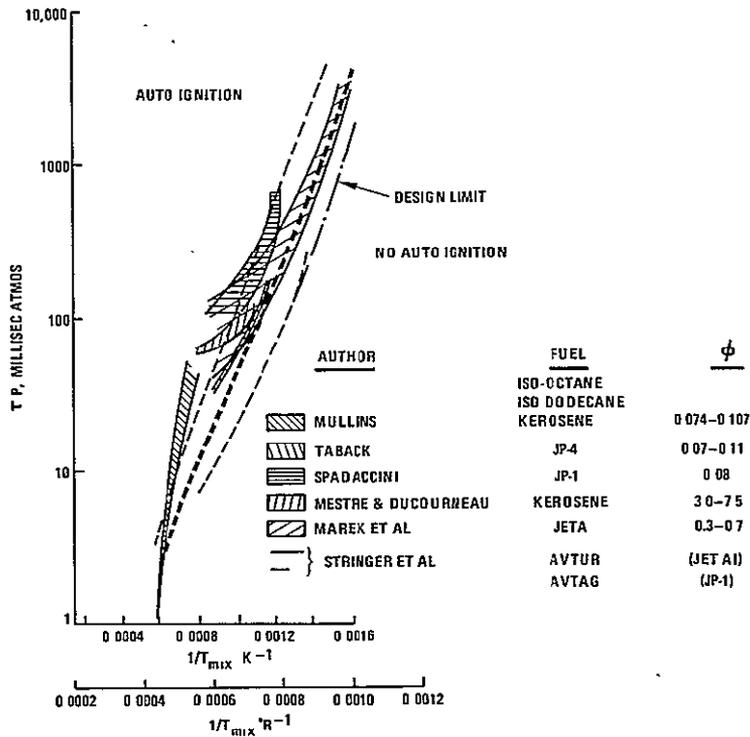
Figure 3-4   Autoignition of Liquid Hydrocarbon Fuel Sprays in Air

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Although the ability to estimate emissions in this manner is questionable, past experience has shown that most combustors can achieve very low CO and THC emissions if operated at a high IBZ equivalence ratio at idle. Since variable geometry air staging provides the ability of richening the primary zone to desired levels, achieving the low power emission goals should be possible.

Although significant research has been conducted in the area of NO_x formation in homogeneous premixed flames, Refs. 2 and 16, the ability to accurately predict NO_x emissions in an engine environment requires some knowledge on the effect of non-homogenity resulting from incomplete vaporization and mixing. In the present study, NO_x emissions at cruise were estimated by two methods, the first used data generated in a recent NASA program, Ref. 17, to account for the effect of incomplete vaporization. Using data from this study a NO_x EI at cruise of 3.1 was predicted for the Concept 1 configuration operating at approximately 70 percent vaporization.

The effect of the incomplete vaporization was also estimated by comparing the results obtained with a premix burner design that was evaluated in a Pratt & Whitney Aircraft engine test program (Ref. 13). In the reference program the combustor premix passage was operated at an equivalence ratio of approximately 0.65 and a calculated vaporization of 45 percent. By assuming that the difference between the measured NO_x and the predicted value for 100 percent vaporization and perfect mixing was due to the unvaporized fuel, an estimate was made of the emissions for the Concept 1 configuration operating at 70 percent vaporization with some droplet burning. At the cruise condition the NO_x emissions index was estimated at 3.9 using this approach.

Since this second estimate is based on actual engine data, it is probable that the higher value is the result of poor fuel/air preparation. It is likely that the value for the Concept 1 configuration when tested at E^3 condition will be somewhere in between.

o   Smoke Level

    Based on previous in-house programs with premixed combustors, smoke should be well below the goal value.

o   Altitude Relight and Starting:

    Both of these operational requirements are difficult to assess for this new front end design. Ignitor location will be critical and the optimum ignitor location for good relight and starting should be determined through testing.

o   Transient Behavior:

This is considered a critical area in LPP variable geometry design.
The very lean IBZ ϕ at high power operation makes the designs sus-
ceptible to lean blowouts on snap decels. In addition, snap accel-
erations may cause unanticipated problems such as flashback in the
combustor system. Since it is not easy to conduct transient test-
ing, burner stability should be evaluated at steady state off-design
conditions to investigate transient behaviors.

o   Exit Temperature Pattern Factor

A significant side benefit of lean premixed combustion is a reduc-
tion in the potential for hot streaks and, hence, improved pattern
factor. The Concept 1 configuration will require careful premix
passage and control system design since any induced variations in
airflow through the individual passages will affect pattern factor.
Furthermore, with 65 percent of the combustor airflow entering
through the premix passages, new techniques will be required for
tailoring exit temperature radial profile with the remaining small
amount of dilution air available.

3.3   CONCEPT 2

3.3.1   Concept Description

The second concept, shown in Figure 3-5, employs fuel staging in addi-
tion to variable geometry in an attempt to improve transient stability.
Basically the design consists of 24 premixing tubes, each with concen-
tric inner and outer fuel/air mixing passages. The inner passage, which
has fixed geometry and is supplied with fuel through an aerating noz-
zle, serves as the pilot stage while the outer annular passage, which
is equipped with a variable geometry sleeve, serves as the main stage.
Swirling flows generated within each passage act to enhance vaporiza-
tion and mixing of the fuel air mixture and also stabilizes the flame
in the combustion zone. The concept is based on a design that demon-
strated significant reduction in high power NO_x emissions in Pratt &
Whitney Aircraft IR&D low emissions program. Variable geometry was
simulated in back-to-back emissions tests by using blockage rings to
modulate outer passage airflow. The results of that testing are presen-
ted in Section 3.3.2, where emissions estimates for Concept 2 are
discussed.

TRANSLATING
SECONDARY AIR VALVE
OPEN
CLOSED

MAIN
FUEL INJECTION

MAIN
PREMIX PASSAGE

CPFW LINER

PILOT
PREMIX
PASSAGE

DILUTION
AIR

AERATING
NOZZLE TIP

SWIRL
VANES

SPARK IGNITER

DILUTION
CONTROL
DEVICE

SECTION B-B

SECONDARY
AIR VALVE
POSITION
CLOSED
OPEN

SECTION BETWEEN
PREMIX PASSAGES

Figure 3-5   Variable Geometry LPP Combustor – Concept 2

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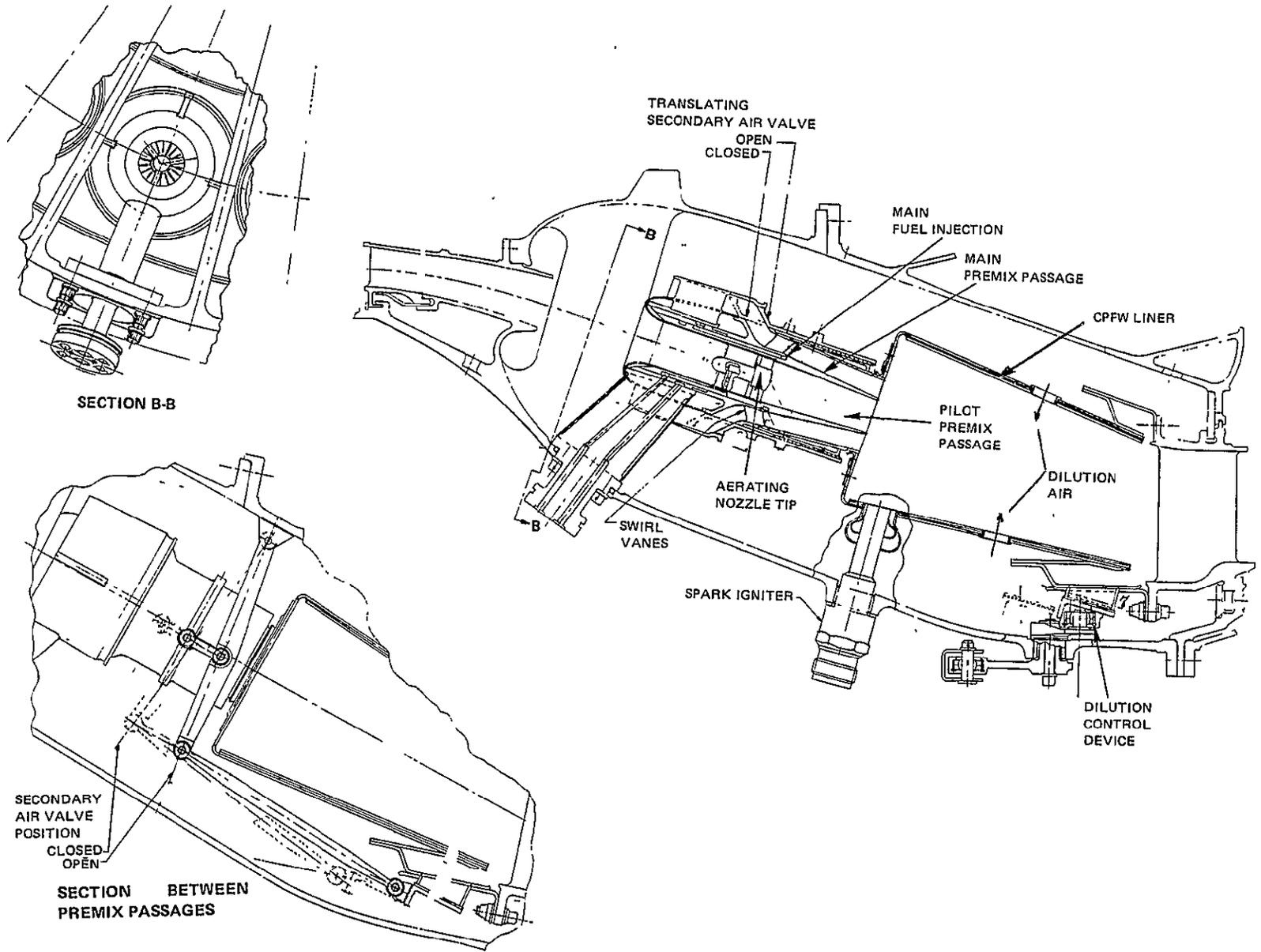
A preliminary fuel schedule for the pilot and main stage for Concept 2 is presented in Figure 3-6. As shown, the fuel and air schedules are adjusted for stoichiometric combustion at idle for high combustion efficiency and low levels of THC and CO while lean conditions are maintained at high power to reduce flame temperature and limit NO_x production. At idle, fuel and air are supplied through only the inner passage while the outer passage is closed off to both except for a small amount of purge air to prevent recirculation of combustion gases into the tube. At the approach condition both inner and outer passages are fueled with the majority of fuel still supplied through the inner passage. At this condition, passage airflow is low to keep the equivalence ratio sufficiently high for good CO and THC emissions. At the high power conditions most of the fuel is supplied through the outer tube and the air passage is near full open such that the equivalence ratio will be close to the desired 0.55. During high power operation, the primary zone equivalence ratio will be maintained above 0.55 to provide protection against lean blowouts during snap deceleration. Since the percentage of fuel supplied through the pilot is low at these conditions, the pilot contribution and hence the increase in overall NO_x level will be small.
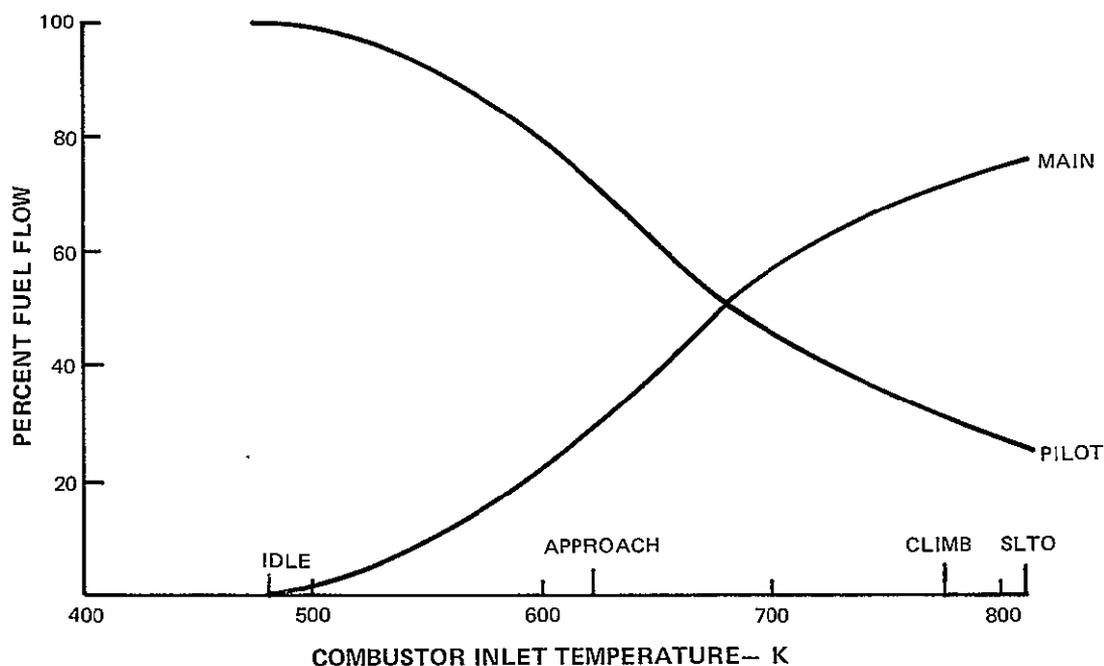
Figure 3-6   Preliminary Fuel Schedule for Concept 2

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As shown in Figure 3-5 heat shields surround the support structure of the premix tube assemblies and provide an aerodynamic ram inlet fairing for the primary and secondary air inlets. The central primary air tube contains an aerating nozzle and swirl vane assembly supported by three struts. Primary and secondary fuel passages in the main support strut feed circular manifolds.

The secondary ram air inlet hood is supported by the main strut and by three short struts. An axially sliding sleeve with a conically diverging forward end opens and closes the circumferential secondary mixing tube inlet. Eighteen swirl vanes also support the outer secondary mixing tube and the cylinder on which the graphite liner for the sliding sleeve is mounted. The aft end of the secondary mixing tube engages a sliding seal which permits axial and radial displacements of the premix tube assemblies relative to the combustor front bulkhead.

Actuation of the sliding sleeves is provided by the ball jointed linkages shown in the figure, which are connected to the exit bypass valve ring. External actuation of the circumferential unison ring rotates 12 crank arm assemblies to provide axial translation of the exit valve ring. The linkage is designed so that the secondary air premix tube valve is open when the exit bypass valve is closed and vice versa.

Two ignitors are provided. Their final axial and circumferential locations can only be determined during a test program. Axial support of the combustor is provided at the aft end of the inner liner, with a sliding joint at the end of the outer liner. Brackets may be added at the front end of the outer liner to engage case mounted radial pins similar to the design for Concept 1 should the need arise.

The Concept 2 design incorporates the same dilution control device as described for Concept 1 in Section 3.2.1.

3.3.2 Concept Assessment

The assessment of the Concept 2 design is summarized in Table 3-II. Except for the expected improvements to stability by the addition of a pilot fuel stage, the performance characteristics of Concept 2 are essentially the same as for Concept 1. The discussion of these items presented in Section 3.2.2 for Concept 1, therefore, applies to Concept 2. This section will concentrate on the emission estimates for Concept 2.

Emission Estimates

The emission levels predicted for Concept 2 were estimated from the results of a Pratt & Whitney Aircraft rig test program directed at evaluating the configuration from which Concept 2 has been modeled. Variable geometry was simulated by utilizing blockage rings in back-to-back rig tests to vary the airflow through an outer passage which served as the main combustor stage. At idle conditions, fuel and air were supplied through just the inner pilot stage, while at high power condition, the blockage rings were removed and both the inner and outer passages were fueled. Although testing during this program was limited in scope, the results did demonstrate the excellent potential of this concept toward NO_x emission reduction.

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TABLE 3-II

CONCEPT 2 DESIGN ANALYSIS

EMISSIONS

	Goal	Estimation*	Comment
CO EPAP (g/kN)	≤ 25.0	24.0	Significant reduction should result with aerating pilot nozzle.
THC EPAP (g/kN)	≤ 3.3	0.5	
NO_x EPAP (g/kN)	≤ 33.0	≤ 33.0	
NO_x EI at Cruise (g/Kg fuel)	≤ 3.0	2.4	
Smoke Number	≤ 20.0	≤ 10.0	

* Engine to engine variability not included in emission estimate.

PERFORMANCE

	Goal	Estimation	Comments
Pressure Loss	≤ 5.5%	≤ 5.5%	
Combustion Efficiency			Based on ALP correlation
At Idle	≥ 99.5%	≥ 99.6%	
At Takeoff	≥ 99.9%	≥ 99.9%	
At Other Operating Conditions	≥ 99.0%	≥ 99.0%	
Stability			Satisfactory
Autoignition			Safety factor of 2.5 applied.
Pattern Factor At Takeoff & Cruise	≤ .25		Premix passage sizing and control critical
Temperature Profile At Takeoff & Cruise	≤ .15		Premix passage sizing and control critical
Maximum Combustor Liner Temperature			See analysis in Section 4.1.1
Altitude Relight	≥ 10.7 Km		Satisfactory
Starting			Satisfactory
Transient Behavior			Pilot zone should be beneficial at both steady state and transient operation.

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The low power emissions obtained at various IBZ equivalence ratios are shown plotted in Figures 3-7 while high power NO_x emissions are shown plotted in Figure 3-8. When extrapolated to E^3 operating conditions, THC and NO_x emissions meet the program goals while CO exceeds the goal as shown in the table. The incorporation of an aerating pilot nozzle in the Concept 2 design should reduce CO levels by reducing droplet size and improving fuel air preparation. Other results obtained in the rig program were a demonstrated smoke number of 6 at the design SLTO condition and the fact that CO and THC emissions were very low at high power conditions. Quite often low NO_x levels at high power conditions are compromised by high CO and THC levels which can be construed as a sign of impending instability.

3.3.3 Concept 2 Adaptation to JT9D

3.3.3.1 Concept Description

The adaptation of the concept 2 design to the JT9D engine is shown in Figure 3-9. Although the two designs are very similar, the lower high power operating temperatures and pressures of the JT9D engine allow an expanded premix passage length which should benefit vaporization and mixing of fuel and air. The lower combustor inlet temperatures and pressures also permit the conventional film cooling louver with MgZr coatings to be employed as a liner cooling scheme. The number of premix passages was also changed from 24 to 20 to be compatible with the 10-strut design of the JT9D engine. Except for these modifications the description presented earlier in section 3.3.1 for the E^3 design is applicable.

3.3.3.2 Concept Assessment

The performance and mechanical/operational characteristics of the two engine designs were judged to be essentially the same and the discussion presented in section 3.3.2 for the E^3 design applies for the JT9D adaptation. This section will concentrate on the differences in estimated emissions between the two designs.

Emission Estimates

A comparison of the estimated emission and smoke levels for the two engine designs is presented in Table 3-III. As shown, the JT9D design should produce significantly lower NO_x emission at the cruise condition chiefly due to the reduced operating pressure and temperature. At low power condition the reduced temperature and pressure would result in a slight increase in both CO and THC emission levels. The large increases shown in the table is mostly the result of the differences in EPAP coefficients, the E^3 being 50 percent less due to an improved idle engine efficiency. Smoke for both designs should be well below the goal levels.

31
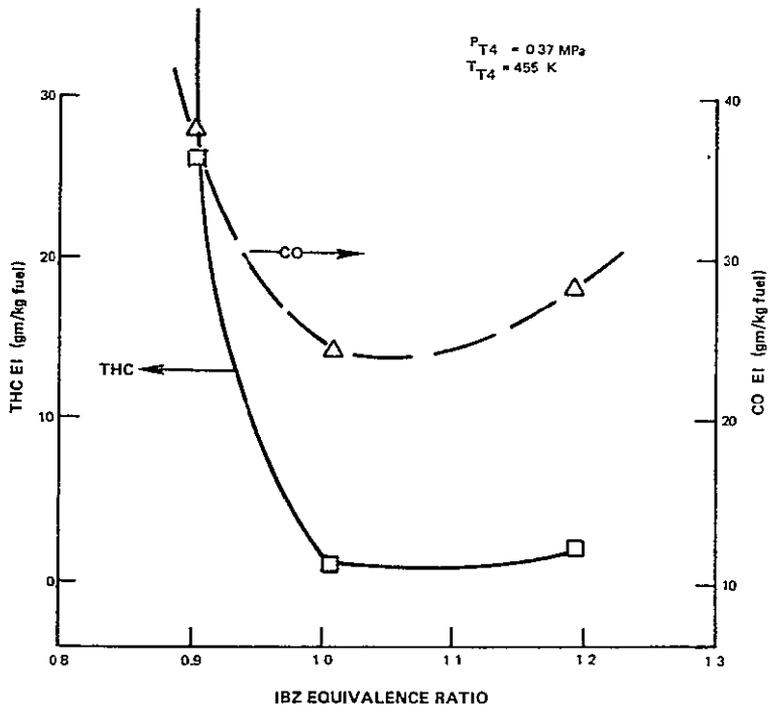
Figure 3-7   CO and THC Emissions at Idle for Various IBZ Equivalence
Ratios
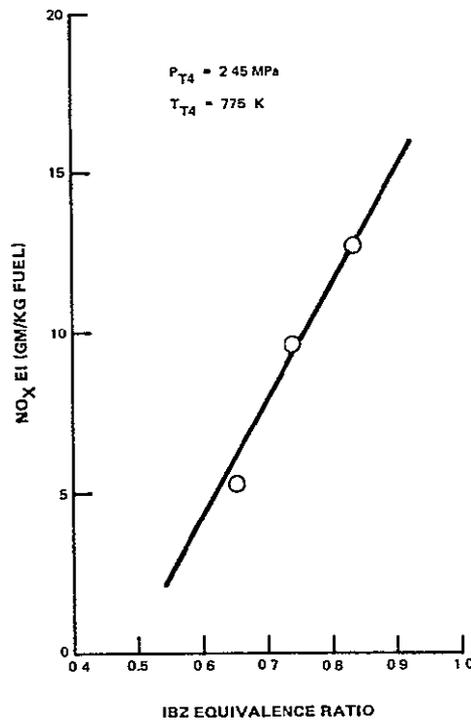
Figure 3-8   NO$_x$ Emissions at SLTO for Various IBZ Equivalence Ratios

MAIN FUEL
INJECTION

CLOSED   OPEN
POSITION POSITION

MAIN
PREMIXING PASSAGE

PILOT
PREMIXING PASSAGE

DILUTION AIR

AERATING
NOZZLE TIP

20 NOZZLES

SPARK IGNITER

DILUTION CONTROL DEVICE
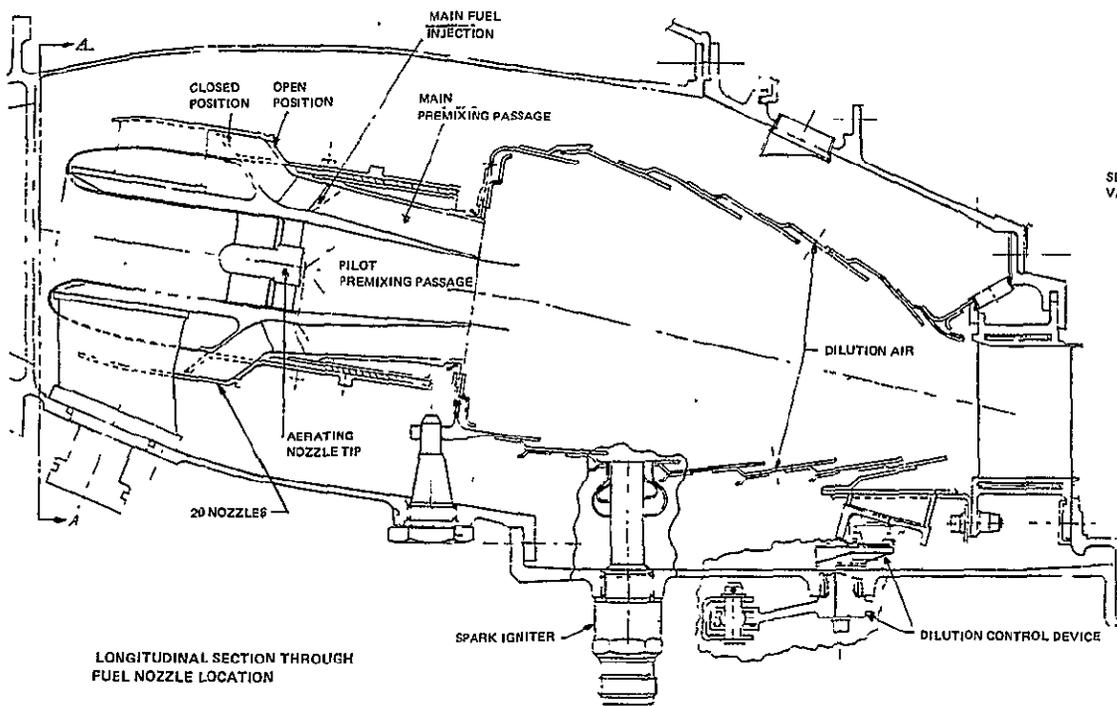
LONGITUDINAL SECTION THROUGH
FUEL NOZZLE LOCATION
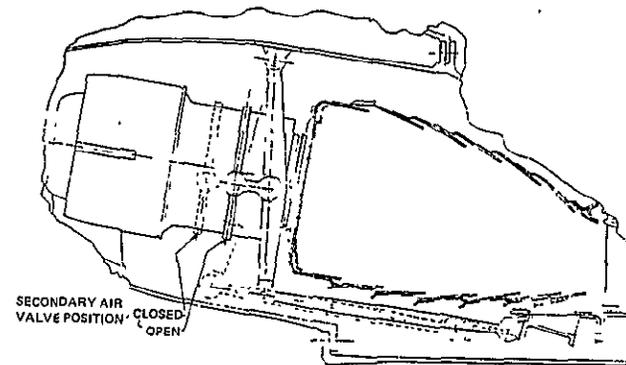
SECONDARY AIR
VALVE POSITION CLOSED
OPEN

LONGITUDINAL SECTION BETWEEN FUEL NOZZLES

UPSTREAM STRUT
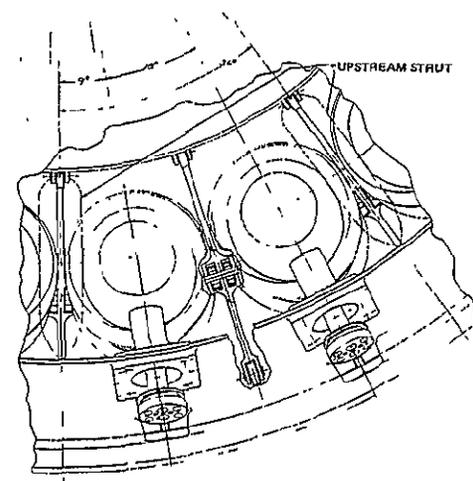
SECTION A A

Figure 3-9   Concept 2 Adapted to JT9D Engine

TABLE 3-III

COMPARISON OF CONCEPT 2 EMISSION ESTIMATES
FOR E^3 AND JT9D ENGINE APPLICATION

Emission Estimate*	E^3	JT9D	Goal
Cruise NO$_x$ EI (g/kg fuel)	2.4 (13.8 atm. 754 K)	1.7 (10 atm. 710 K)	$\leq$ 3.0
CO EPAP (g/kN)	24	43	$\leq$ 25.0
THC EPAP (g/kN)	0.5	0.9	$\leq$ 3.3
Smoke	$\leq$ 10	$\leq$ 10	$\leq$ 20

* Engine-to-engine variability not included in emission estimate.

3.4   CONCEPT 3

3.4.1   Concept Description

The Concept 3 configuration as shown in Figure 3-10 is a radially
staged burner design incorporating an aerated nozzle fueled, swirl
stabilized pilot zone, located inboard and upstream of a premixed/pre-
vaporized main zone. The main zone premix passage is separated into 24
compartments that occupy approximately 70 percent of the available
burner inlet circumferential area. The remaining area between passages
is used for structural support to allow a free floating flameholder
design.

Several flameholder types were evaluated before selecting the V-gutter
design presented in Figure 3-10. Each compartment contains four indivi-
dual V-gutters that are free to expand in the longitudinal direction in
order to minimize stresses and distortions. The size and spacing within
each compartment were selected from the results of a previous NASA
program, Ref. 12, in which a conical V-gutter flameholder was evaluated
for stability and emissions. Forty-eight pressure atomizing fuel
nozzles mounted on the primary nozzle supports supply the main zone
with fuel.

SEAL (TIG)

I D BLEED THRU STRUTS

BLEED
FENCE

BLEED
SLOT

PILOT FUEL
NOZZLES (24)

CPFW LINER

V-GUTTER
FLAMEHOLDER

DILUTION
AIR

SEAL (REAR END)

DIFFUSER EXIT
BLEED MANIFOLD

MAIN FUEL
NOZZLES (48)

BYPASS TUBE

LONGITUDINAL SECTION THROUGH
FUEL NOZZLE LOCATION

STRUT
COMPARTMENT
SIDEPLATES

SUPPORT PINS

SPARK IGNITER

LONGITUDINAL SECTION THROUGH
DIFFUSER CASE STRUT LOCATION

FUEL NOZZLE C

DIFFUSER STRUT C

SECTION B-B

V-GUTTER FLAMEHOLDER

Figure 3-10 LPP Combustor - Concept 3

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The concept differs from the previous designs in the method in which front end airflow and stoichiometry are controlled. Instead of a mechanical type of area modulation diffuser wall bleeding is used to vary the inlet air velocity profile. Both inner and outer wall bleeds are used to divert airflow from the burner front end at only the approach condition. The design is based on a variable geometry combustor evaluated as part of a research program directed at determining the feasibility of controlling exhaust emissions in a purely aerodynamic manner, Ref. 18. How the airflow is modulated by bleeds is schematically shown in Figure 3-11. The vortex formed by bleeding acts in the manner of a roller bearing, guiding flow to bypass the front end smoothly over a sudden step. Without bleeds the airflow ignores the step and leaves the diffuser as a high velocity jet.

Prior to adopting this system an analytical investigation was conducted to evaluate a more simple approach of controlling velocity profile with diffuser bleed alone. The feasibility of a simple aerodynamic control to modulate airflow distribution was studied using the computer flow calculation deck (TEACH), which handles two-dimensional incompressible viscous flow. Bleed was applied to a 2-D sudden expansion flow and parametrically run changing the bleed flow rate, and position. Study results indicate that without downstream blockage, bleeding can change airflow distribution but modulation is limited to off/on, and that the flow is not sensitive to the position of bleed. The analysis was repeated with downstream blockage simulating a combustor in size and location. With the blockage diffuser bleeding was not successful in shifting airflow significantly regardless of bleed position or flow rate. Hence the more complex system tested and reported in Ref. 18 was adopted.

3.4.2 Concept Assessment

The assessment of the concept 3 design is summarized in Table 3-IV. Except for an improvement in mechanical complexity/reliability resulting from the absence of any area modulation hardware, the performance and operational characteristics of concept 3 are essentially the same as for concept 1. The discussion of these items presented in Section 3.2.2 therefore applies. This section will concentrate on the emission estimates for concept 3.

Emission Estimates

During the preliminary analysis of concept 3 it was evident that the degree of front end airflow modulation available with a diffuser bleed control was critical in estimating emission levels. The analysis was therefore conducted for three different values of airflow diverted from the combustor front end. Specifically values of 25, 40 and 50 percent were considered even though most of the test data in Ref. 18 indicated that a maximum of 25 percent diffuser airflow could be diverted with 7 percent bleeds.

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TABLE 3-IV

CONCEPT 3 DESIGN ANALYSIS

Emissions

	Goal	Estimation*	Comment
CO EPAP (g/kn)	≤ 25.0	21	
THC EPAP (g/kn)	≤ 3.3	3.9	
NO$_x$ EPAP (g/kn)	≤ 33.0	< 33.0	
NO$_x$ EI at Cruise (g/kg fuel)	≤ 3.0	30	
Smoke Number	≤ 20	< 10	

* Engine to engine variability not included in emission estimate.

Performance

	Goal	Estimation	Comment
Pressure Loss	≤ 5.5%	≤ 5.5%	Based on ALP correlation
Combustion Efficiency			
at Idle	≥ 99.5%	≥99.7%	
at Takeoff	≥ 99.9%	≥99.9%	
at Other Operating Conditions	≥ 99.0%	≥99.0%	
Stability			Satisfactory
Autoignition			Safety factor of 2.5 applied
Pattern Factor at Takeoff and Cruise	≤ 0.25		Premix passage sizing and control critical
Temperature Profile Factor at Takeoff and Cruise	≤ 0.15		Premix passage sizing and control critical
Maximum Combustor Liner Temperature			See analysis in Section 4.1.1
Altitude Relight	≥10.7 Km		Satisfactory
Starting			Satisfactory
Transient Behavior			Could be a problem
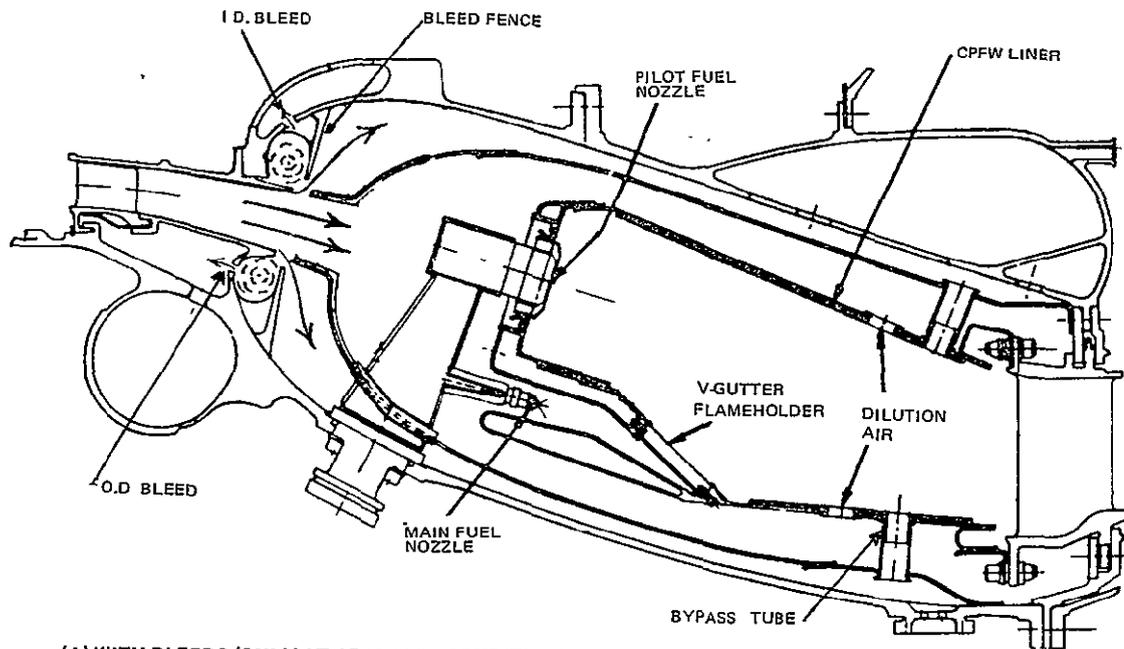
(A) WITH BLEEDS (ONLY AT APPROACH CONDITION)
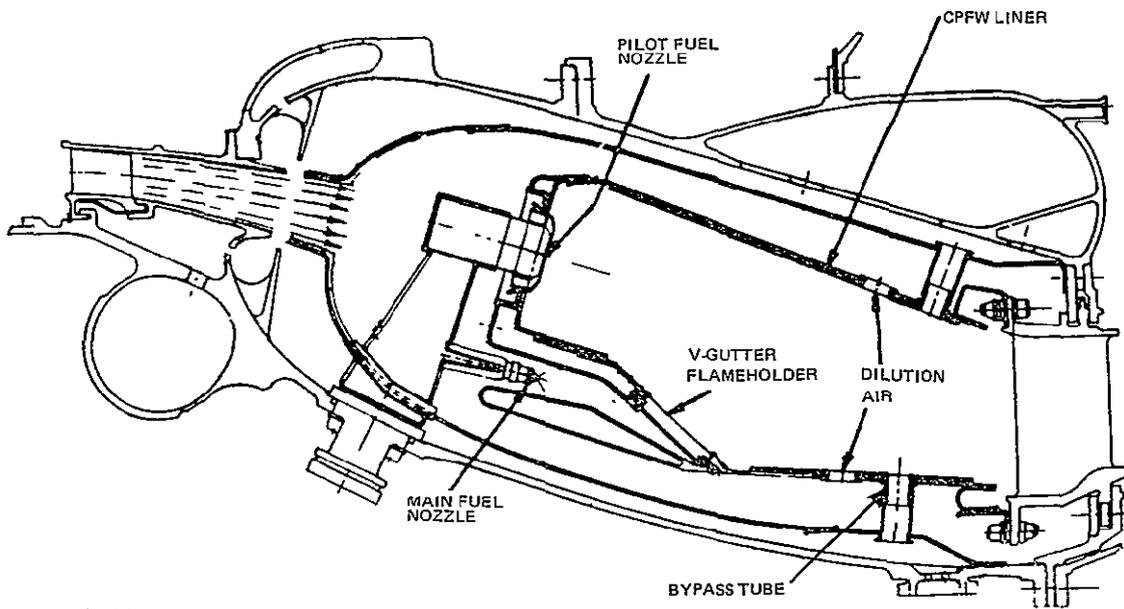
(B) WITHOUT BLEEDS

Figure 3-11   Schematic of Airflow Modulation by Bleeds

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The flow distribution within the combustor was determined by setting
the equivalence ratio at approach with bleed sufficiently high to
ensure a combustion efficiency of 99.0 percent. The test results from
previous emission program (Ref. 13) presented in Figure 3-12, were used
in establishing a value of 0.70 at approach. The unbled equivalence
ratios at cruise were then back-calculated for each bleed condition
being analyzed and NO_x emission levels at cruise were estimated
following the same theoretical procedure used for concept 1 and descri-
bed in Section 3.2.2. The results of the analysis are presented in
Table 3-V and as shown, unless a very high percentage of flow can be
diverted, this method does not have much potential for NO_x reduction.

CO and THC emissions at idle and approach were estimated from the effi-
ciency correlation described in Section 3.2.2. For this concept the
approach contribution to the CO and THC EPAP were significant.
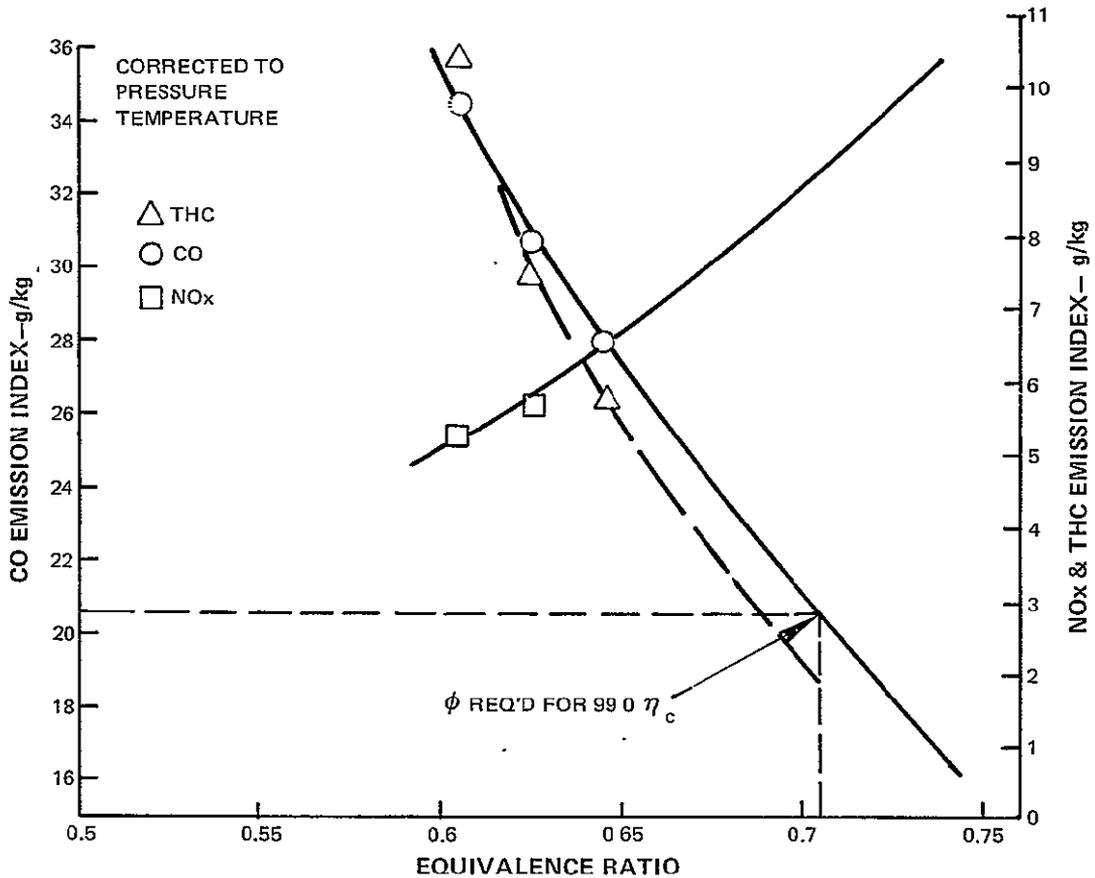
Figure 3-12 Emissions Estimates for Concept 3

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TABLE 3-V

ESTIMATED NO$_x$ EMISSIONS AT CRUISE

Front End Flow Diversion %	Equivalence Ratio Cruise Unbled	NO$_x$ Cruise EI g/kg
25	0.89	30
40	0.70	11.7
50	0.59	4.8

3.5 CONCEPT 4

3.5.1 Concept Description

The fourth concept shown in Figure 3-13 was patterned after a promising design developed during the Catalytical Combustor Program, Ref. 7. Valves located in the combustor OD shroud area are used to modulate airflow between the primary and dilution zones to allow stoichiometric burning at idle for high combustion efficiencies and low levels of CO and THC, and very lean combustion at high power conditions for reduced NO$_x$ emission levels.

The size and location of the air control valves introduced several mechanical design problems. Physical size restraints required both an outward expansion of the burner case to accommodate the valve assembly and a recontouring of the diffuser to provide an aerodynamically clean feed to the valve inlet tubes. Furthermore, the resultant "one sided" combustor could introduce penetration and mixing deficiencies that would adversely effect both emission and exit temperature distribution. Providing additional air control valves in the ID shroud area was considered as a possible fix, but since it would result in a drastic increase in complexity without eliminating the physical size problems it was not incorporated in the design.

In the concept 4 design the two valves are mounted on the same drive shaft to ensure simultaneous control of primary and dilution zone air-flows. At the idle condition the inner valves are closed and the outer ones are open. This prevents air entering the primary zone through the side ports allowing stoichiometric burning for high combustion effi-ciencies and low levels of CO and THC. At high power conditions the outer valves are closed and the inner ones are open, allowing the combustion air to enter through the side ports, providing very lean combustion for reduced NO$_x$ emission levels.

SECTION A – A

AIRBLAST FUEL INJECTOR

DIFFUSER STRUT

CPFW LINER

SPLIT DIFFUSER

DILUTION AIR

FINGER SEAL

COMBUSTION AIR

DILUTION AIR   DILUTION AIR

BURNER SUPPORT

BUTTERFLY VALVES

SPARK IGNITER

FRONT VIEW LOOKING AFT
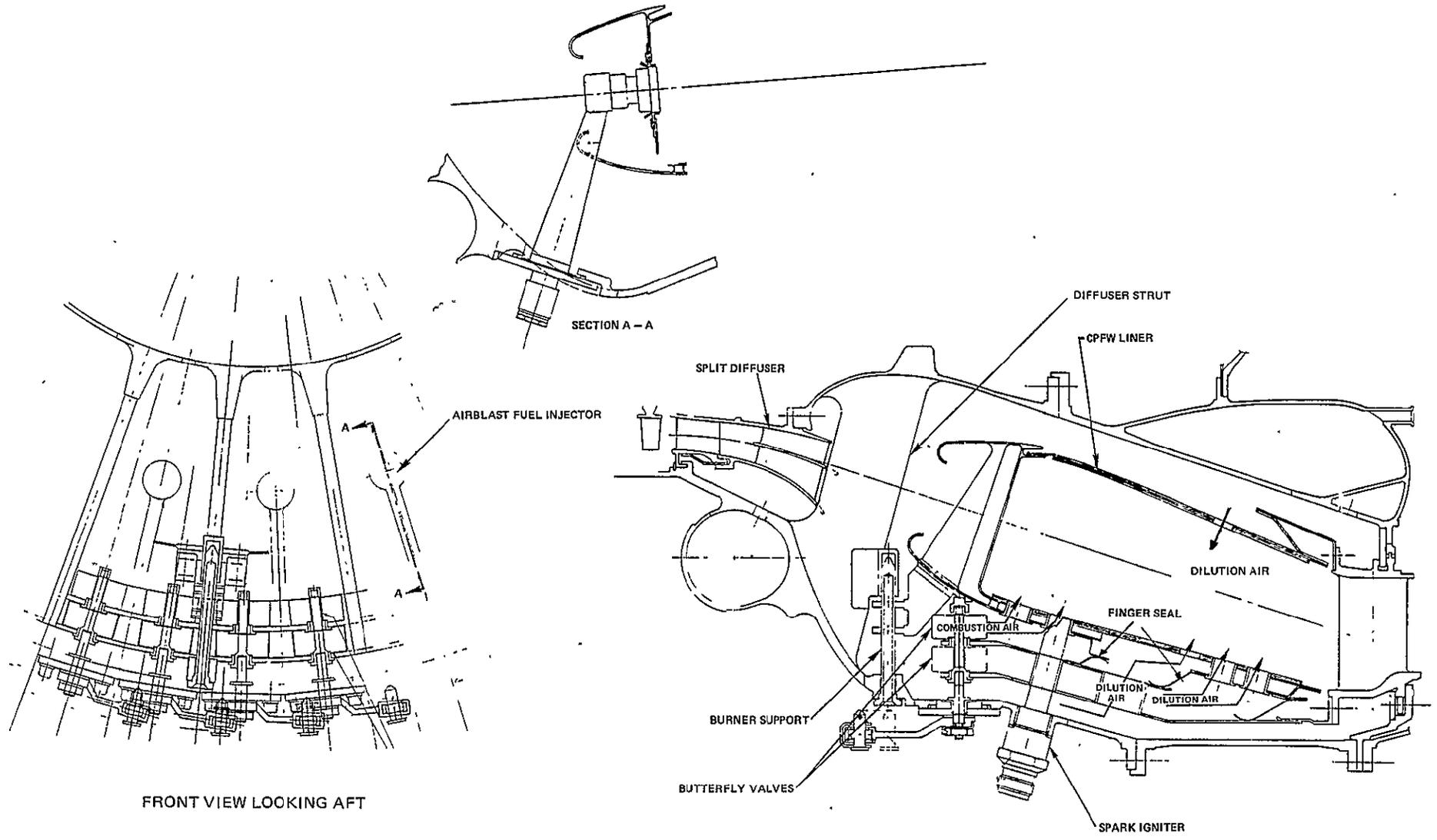
Figure 3-13   LPP Combustor – Concept 4

A split diffuser is used to give the desired flow split between ID and OD shroud. To ensure adequate cooling of the front end combustor outer liner at all conditions, cooling airflow is provided by double wall construction, with the resultant annulus feed from inside the hood. A separate annulus passage is provided between the outer valves and the outer diffuser case to supply both cooling air necessary for the combustor outer liner aft section and dilution air for temperature distribution control. The outer contour of the Energy Efficient Engine diffuser case was modified to incorporate the variable geometry and three independent annulus air passages in the OD shroud area. Twenty four airblast fuel injectors are provided in a conventional, externally removable arrangement, as shown in Figure 3-13 (section A-A). The number of valves (96, 48 inner valves and 48 outer valves) and the number of fuel injectors (24) were selected for compatibility with the 24- strut design of the Energy Efficient Engine.

3.5.2   Concept Assessment

The assessment of the concept 4 design is summarized in Table 3-VI. Except for pattern factor and radial temperature profile which are considered worry items with the concept 4 design, the performance and operational characteristics of Concept 4 have been judged the same as those for concept 1 and the discussion in Section 3.2.2 is applicable. This section will concentrate on the emissions estimates.

Emissions Estimate

CO and THC emissions for concept 4 were estimated from the combustion efficiency method described for concept 1 in Section 3.2.2. The estimated values were then compared to results obtained with a low emission JT9D-7 combustor being developed at Pratt & Whitney Aircraft. The low emissions combustor which serves to provide backup data support to the calculation procedure employs a bulkhead type front end containing aerated fuel nozzles similar to those for Concept 4. The results from an experimental JT9D-7 engine program corroborate the calculated values for concept 4 tabulated in Table 3-VI.

NO_x emissions were estimated based on an assumed 50 percent variation in IBZ equivalence ratio due to poor mixing and were calculated from pollutant measurements taken from partially mixed turbulent flames during a flame tube study at Pratt & Whitney Aircraft (Ref. 19).

Based on previous in-house programs with premixed combustors and exper- ience with the JT9D-7 low emissions combustor, smoke should be well below the goal.

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TABLE 3-VI

CONCEPT 4 DESIGN ANALYSIS

EMISSIONS

	Goal	Estimation*	Comment
CO EPAP (g/kN)	≤ 25.0	12.0	
THC EPAP (g/kN)	≤ 3.3	1.7	
NO$_x$ EPAP (g/kN)	≤ 33.0	24	
NO$_x$ EI At Cruise (g/kg Fuel)	≤ 3.0	7.5	NO$_x$ emission will depend on the degree of mixedness. This estimate is based on 50% varia-
Smoke Number	≤ 20.0	≤15.0	tion in IBZ equivalence ratio due to poor mixing.

* Engine to engine variability not included in emission estimate.

PERFORMANCE

	Goal	Estimation	Comments
Pressure Loss	≤5.5	≤5.5%	
Combustion Efficiency			Based on ALP correlation
At Idle	≥ 99.5%	≥99.7%	
At Takeoff	≥ 99.9%	≥99.9%	
At Other Operating Conditions	≥ 99.0%	≥99.0%	
Stability			Satisfactory
Autoignition			Safety factor of 2.5 applied.
Pattern Factor At Takeoff & Cruise	≤0.25		One sided combustion will re- quire evaluation at test.
Temperature Profile Factor at Takeoff & Cruise	≤0.15		One sided combustion will re- quire evaluation at test.
Maximum Combustor Liner Temperature			See analysis in Section 4.
Altitude Relight	≥10.7 Km		Satisfactory
Starting			Satisfactory
Transient Behavior			Could be a problem.

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4.0 ENGINE FEASIBILITY CRITERIA

Aircraft engine component design, as opposed to conceptual design
studies, requires that criteria in addition to those of emissions and
performance already discussed be considered as well. Specifically,
factors such as mechanical integrity, reliability, weight, cost and
time to develop are also prime considerations. Although it was beyond
the scope of this conceptual design study program to develop designs in
sufficient detail to permit an accurate assessment of these factors,
estimates of the relative strengths and weaknesses of the four concepts
were made and are presented in the following sections.

4.1 MECHANICAL INTEGRITY/RELIABILITY

This section includes a comparative analysis of combustor hardware
temperatures and reliability characteristics of each design.

4.1.1 Thermal Analysis

This section presents an analysis conducted to determine if the 25
percent of combustor airflow available for cooling was sufficient to
permit a conventional JT9D film cooled louver design with magnesium
zirconate coating. A thermal analysis computer program was used to cal-
culate surface temperatures on each concept for several IBZ equivalence
ratios at the E^3 SLTO condition. The Counter Parallel FINWALL ^{R}
(CPFW) cooling scheme was also evaluated on concept 1 to assess the
effects of an advanced cooling scheme on an LPP fuel combustor. The
results of this analysis are shown in Figure 4-1. The figure shows
that the surface temperatures of concepts 1 and 2 are below the desired
maximum temperature of 1150K (1600°F) at the design high power equiv-
alence ratio of 0.55 if uniform (premixed) combustion is achieved,
while concept 3 and 4 are slightly over the desired surface tempera-
ture. The prediction also shows that the surface temperatures for CPFW
cooling are about 100K cooler than the film cooled louver temperatures
of concept 1.

4.1.2 Reliability

Each of the four conceptual designs was reviewed and analyzed relative
to its potential impact on engine reliability. Previous combustor and
engine component hardware reliability experience was used as the
criterion for judging the relative importance of the major LPP fuel
combustor features. Reliability may be expected to be the inverse of
the complexity of the total combustor system, with reduced reliability
associated with movable components. The three major features considered
in order of importance were:

1. Mechanical Linkages:

    o   Quantity - the more joints the more likelihood of binding.
    o   Location - support at the burner front end is considered
         structurally weaker than support by the outer shoud area.

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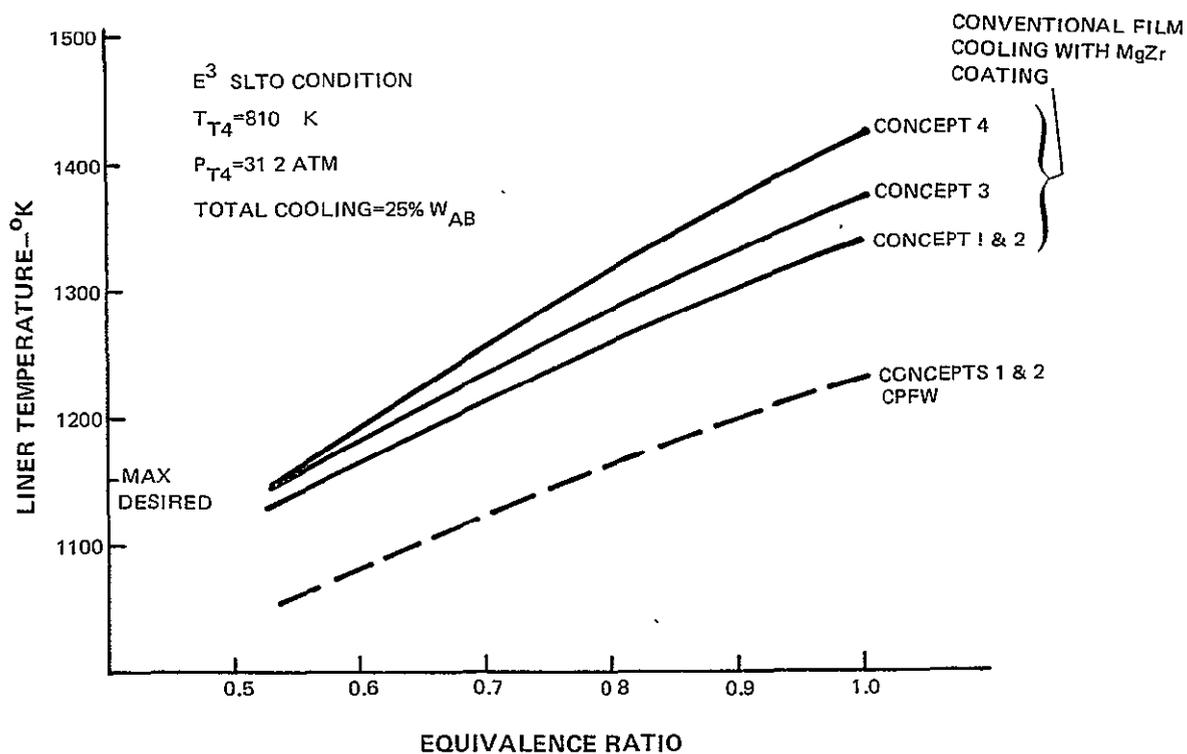
Figure 4-1   Thermal Analysis Results

o   Execution – the push/pull type scheme with a large area of
     contact is considered worse than a translating ring.

2. Fuel System

Based on experimental engine experience, aerating fuel nozzles are
considered to be less troublesome than pressure atomizing fuel
nozzles. In addition, concepts utilizing two fuel stages are
complex and more susceptible to coke formation.

3. Burner Complexity

Attaching ducts to the burner liner or other features that impact
the engine hot section envelope seriously increases complexity.

The relative ranking of the four concepts for each of the evaluation features considered was as follows:

Feature	Relative Feature Value	Ranking			
		Best	+	+	Worst
Linkages	3	#3	-	#4	#(1, 2)
Fuel System	2	#4	#1	#2	#3
Burner Liner Complexity	1	-	#(1, 2)	#3	#4

Each concept was scored 4 for best in a particular category, 2 or 3 for mid-range and 1 for worst. These relative values were multiplied by the relative feature value, and added to obtain a total ranking value for each concept. The results of this comparative ranking for reliability is shown below. Unfortunately, the two concepts ranked lowest in reliability have the highest potential of meeting the emission and performance goals.

	Concept No.	Point Total
Best	3	(16)
	4	(15)
	1 .	(12)
Worst	2	(10)

4.2 COST AND TIME TO DEVELOP

Until fabrication drawings are available and construction, testing and final refinements to the combustor hardware have been accomplished, no meaningful estimates can be made of the time and cost to develop one of the LPP fuel combustor conceptual designs into an operational engine combustor. The overall SCERP schedule indicates the information necessary for an accurate time/cost estimate to be several years away during the Phase IV (Engine Demonstration) Program.

The major combustor system components required which contribute towards complexity and subsequently cost and time to develop are itemized below.

Concept No.	Variable Geometry	Fuel System	Additional Complexity
1	Front and dilution air staging	1-stage	
2	Front and dilution air staging	2-stage	

| 3 | Aerodynamic control by diffuser bleed | 2-stage | May require fuel nozzle purge system. |
| 4 | Front and dilution air staging | 1-stage | Requires expansion of burner case and recontouring of the diffuser. |

4.3 WEIGHT RANKING

Since the design work carried out for each concept is not sufficiently detailed to permit reliable absolute weight estimates, only a relative weight ranking of the concepts was made; this is shown below.

Concept No.	Order (Lightest = 1)
1	2
2	3
3	1
4	4

Concept 4 is considered to be the heaviest because of the expanded diffuser case to incorporate the butterfly valves and three annulus ducts in the OD shroud area. Concept 3 is projected to be the lightest of the designs because it utilizes aerodynamic air modulation rather than mechanical variable geometry hardware which requires crank arms, linkages and unison rings.

Concept 2 is estimated to be slightly heavier than concept 1 because of a bulkier fuel injector system necessary for good structural integrity of a dual fuel stage.

4.4 FAILURE ANALYSIS

A structural failure analysis of the four LPP conceptual combustor designs was conducted to identify potential failure modes and estimate the probability and effects of each mode. The results of this study are presented in Table 4-I.

Each of the four concepts would seriously impact existing engine systems in the areas of installation, maintainability and serviceability. The early stage of LPP fuel combustor system development makes it difficult to define all the problem areas, but it is apparent that a major redesign of any existing engine would be required should one of these concepts be incorporated.

TABLE 4-1

LPP COMBUSTOR
FAILURE ANALYSIS OF PRELIMINARY DESIGNS

Concept	Possible Failure Modes (Preliminary Design)	Likelihood of Failure as Shown	Severity of Failure if Occurs	Ease of Remedy for Final Design
1) Variable inlet mounted on bulkhead and aft bypass	1. Fuel nozzle vibration.	Minimal	Very severe - fuel leakage, burnout, streaks, etc.	Present design adequate.
	2. Translating tube vibration.	Minimal	Severe - burnout, etc.	Present design adequate.
	3. Bind up or failure of interior linkage or bind up of translating tube.	Moderate	Minimal - variable geometry would be nulled. Severe - Failure could cause high flame temperature.	Hard to design reliable system in hostile environment of burner vibration and thermal gradients.
2) Variable inlet mounted on fuel nozzle and aft bypass valves.	1. Fuel nozzle vibration.	Minimal	Very severe - fuel leakage.	Present design adequate.
	2. Bind up of translating sleeve or linkage system.	Moderate	Severe - could load up fuel nozzle and fuel leakage.	Very difficult - hostile environment sonic vibrations and severe thermal gradient.
	3. Failure of linkage system.	Minimal	Minimal - variable operation would be nulled.	Beef-up possible.
3) Inlet velocity profile control bleed.	1. Duct buckling	Likely	Moderate - Flow areas would be affected. Possibility of liner distortion via tubes.	Addition of stiffening rings is feasible and is recommended.
	2. V gutter vibration.	Moderate	Moderate to severe - burnout, aspiration, etc.	Feasible to beef-up.
	3. Seals (front tongue in groove seal and rear end seal).	Likely	Moderate to severe - burnout, etc.	Feasible to redesign.
	4. Strut plate connection fatigue.	Likely	Moderate - bulkhead alignment would be affected if enough plates fail out of the 24 total or if bulkhead distorts thermally.	Feasible to improve connections. Front end thermals more difficult to alleviate.
	5. Front end thermal distortion.			
4) Dilution air valve control.	1. Finger seal deterioration.	Likely	Minimal - zone isolation would be affected but not safety.	Very difficult - seals must be flexible for thermal gradients and assembly but be strong to resist pressure loads.
	2. Duct bulkhead bending - blowoff loads.	Likely	Moderate - bind up of butterfly valves and distortion of outer liner.	Feasible - beef-up needed.
	3. Duct buckling.	Likely	Moderate - zone isolation promised.	Easy - Rings to be added.

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5.0 COMPARISON OF CONCEPTS

5.1 CONCEPT RANKING

5.1.1 Rating Procedure

The four conceptual designs were rated according to their probability of achieving the program goals or matching the operational characteristics of the reference Energy Efficient Engine. The designs developed under Task I were evaluated and compared under the main categories of Emissions, Safety, Performance, Durability and Operation. These categories were sub-divided as follows:

1. Emissions

Gaseous emissions of carbon monoxide, unburned hydrocarbons and oxides of nitrogen over the Environmental Protection Agency specified landing and takeoff cycle, EPAP; emissions of oxides of nitrogen during high altitude cruise; particulate emissions (smoke) at sea level take- off conditions.

2. Safety

Included in this area was the susceptibility of the design to autoignition and flashback, relight capability over the flight envelope and stability during transient operation.

3. Performance

The performance criteria consisted of pressure loss, combustion efficiency, pattern factor, exit radial temperature profile, sensitivity to bleed, weight and cycle performance.

4. Durability

Included in durability were liner temperature, liner failure and susceptibility to fuel nozzle coking.

5. Operation

The operation category consisted of ground start and control requirements.

To determine the rating for each concept, a probability type analysis was first performed with each category. Using the system shown in the tabulation below, individual items were assigned a score between 0 and 1.1 based on the probability of meeting the program goals. The scores were then multiplied together to obtain the overall probability in each main category. A weighting factor appropriate to each category was then applied and the total score determined by summing the individual weighted scores.

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SCORING CRITERIA

1.1 – Exceeds requirements

1.0 – Likely to meet requirements or comparable to reference engine.

0.7 – Will require some work to meet requirements.

0.3 – Will require substantially more work to meet requirements.

0.1 – Very little chance of meeting requirements

  0 – Will not meet requirements

In establishing the weighting factors, top priority was given to emissions, because it was the prime objective of the LPP program, and safety, because of its obvious importance. Both categories were assigned a weighting factor of 40. Performance and durability were weighted equally and slightly lower at 30 while the operation category was considered to be somewhat forgiving and was assigned the lowest value of 10. Using this method a concept that meets all the goals and requirements will receive a score of 150.

5.1.2 Results

The overall ratings for the four concepts which are summarized in Table 5-I represent the average of several individual ratings obtained from key program personnel. As indicated when all categories are considered, concepts 1 and 2 are clearly superior to concepts 3 and 4 with concept 2 a slight favorite over concept 1. Concepts 1 and 2 scored very well in the emission category while concepts 3 and 4 were considered to have very little potential for satisfying the program NO_x emission goals at cruise: concept 3 because of lack of sufficient bleed capability and concept 4 because of poor fuel air mixing.

Concepts 1 and 2 were both judged fairly close in all categories except in the safety area, where concept 2 was judged superior due to an expected improvement in transient capability achieved with a dual staged fuel nozzle.

Concepts 3 and 4 were also considered inferior relative to 1 and 2 in the performance area, concept 3 due to probable variations in pressure loss and poor combustion efficiencies at approach and concept 4 indicating potentially troublesome pattern factor and exit radial temperature profile.

Although some items in the system used to rate the four concepts could ony be assessed qualitatively, it is interesting to note that the results of three individual reviews scored concept 2 the highest.

TABLE 5-I

CONCEPT RATING SHEET

Category	Concept			
	1	2	3	4
Emissions (40)	36	37	2	4
Safety (40)	10	23	20	26
Performance (30)	14	14	6	4
Durability (30)	19	15	13	15
Operation (10)	5	5	7	7
Total Score (150)	84	94	48	56

( ) Weighting Factor

The rating system used to evaluate the four LPP concepts should be considered as an initial step in the selection process. Further along in the development of LPP combustion other items such as cost, time to develop, maintainability and serviceability will have to be given serious consideration.

6.0 CONCLUDING REMARKS

Four LPP combustor concepts utilizing variable geometry and/or other flow control techniques were identified, designed and analytically evaluated for the reference Energy Efficient Engine (E^3). One of the concepts (Concept 2) was designed and sized for the JT9D engine cycle and envelope.

Based on the analytical projections made during this conceptual design study, two of the concepts (Concepts 1 and 2) offer the potential of achieving the emission goals while satisfying nearly all of the performance requirements. However, the projected operational characteristics and reliability of any of these concepts to perform satisfactorily over an entire high pressure ratio aircraft engine envelope require extensive experimental substantiation before engine adaptation can be considered.

Other fundamental SCERP Phase I activities and this design study program revealed areas of concern as well as the need for technology improvement. The LPP is based on supplying the combustion zone with well mixed and well vaporized fuel-air mixture. Both these goals may prove to be difficult to attain in practice, within reasonable combustor lengths and without incurring autoignition and/or flashback. In the design of the premixing passages for the LPP systems, precautions were taken to avoid potential flow problems, such as wakes behind variable geometry devices and fuel injectors, which could increase residence time of the fuel-air mixture in the premixing passage. Incomplete mixing/vaporization, hence higher NO_x emissions, were weighed against providing adequate margin to avoid autoignition and flashback.

It is evident that future development must concentrate on achieving uniform fuel-air mixture preparation if the full potential of this concept is to be realized. At the present time the most practical means of achieving rapid fuel vaporization would appear to be ultrafine atomization. Analysis and experimentation should be pursued to determine the time or distance needed to fully vaporize the fuel as a function of airflow properties and fuel drop size. New aproaches to fuel atomization aimed at the production of very small droplets should be explored. Allied to this is the problem of measurement of small drop sizes ($\leq 20\mu$). Every encouragement should be given to new ideas and the development of new techniques for achieving improved means of fuel atomization.

The effect of utilizing larger quantities of front end combustion air requires advanced, efficient cooling techniques to achieve the desired liner durability in the more severe operating environment of future aircraft engines. An additional design consideration is the cooling requirements of the flameholders. On the positive side, lean premixed burning should achieve lower primary zone gas temperatures and flame radiation which in turn should alleviate the cooling requirements.

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The anticipated design problems with variable geometry features are their control, operational characteristics and durability. The air staging mechanisms will require control systems and sensors somewhat more complex than those used in current engines.

Although variable goemetry introduces complexity with respect to combustor design for emissions reduction, it represents a new degree of freedom for advanced engine designs. Future engine requirements of higher thrust-weight ratios, higher temperature rise, smaller combustor volume and extended flight envelopes will make it difficult to satisfy both emission and performance requirements. Air staging offers the unique potential of significant improvement in both areas.

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