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ADVANCED LOW-EMISSIONS CATALYTIC COMBUSTOR PROGRAM PHASE I FINAL REPORT

by
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Prepared for

National Aeronautics and Space Administration
NASA Lewis Research Center
and
United States Air Force
Engineering Services Center

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UNITED TECHNOLOGIES CORPORATION
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16. Abstract

In Task I of the Phase I program, six catalytic combustor concepts were defined. Analysis and evaluation of these six concepts were made under Task II. Major design considerations included low emissions, performance, safety, durability, installations, operations and development. On the basis of these considerations the two most promising concepts were selected. Refined analysis and preliminary design work was conducted on these two most promising concepts in Task III.

The selected concepts were required to fit within the combustor chamber dimensions of the reference engine. This is achieved by using a dump diffuser discharging into a plenum chamber between the compressor discharge and the turbine inlet, with the combustors overlaying the prediffuser and the rear of the compressor. To enhance maintainability, the outer combustor case for each concept is designed to translate forward for accessibility to the catalytic reactor, liners and high pressure turbine area. The catalytic reactor is self-contained with air-cooled canning on a resilient mounting.

Both selected concepts employed integrated engine-starting approaches to raise the catalytic reactor up to operating conditions. Advanced liner schemes are used to minimize required cooling air.

The two selected concepts respectively employ fuel-rich initial thermal reaction followed by rapid quench and subsequent fuel-lean catalytic reaction of carbon monoxide, and, fuel-lean thermal reaction of some fuel in a continuously operating pilot combustor with fuel-lean catalytic reaction of remaining fuel in a radially-staged main combustor.

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FOREWORD

This document was prepared by the Commercial Products Division of the Pratt & Whitney Aircraft Group of United Technologies Corporation, East Hartford, Connecticut, to describe the catalytic combustor preliminary design work accomplished under the National Aeronautics and Space Administration-sponsored Advanced Low Emissions Catalytic Combustor Program, Phase I, Contract NAS3-20821. The work was performed under the direction of National Aeronautics and Space Administration Project Manager, Mr. Andrew J. Szaniszlo. Additional support was provided by the United States Air Force Project Officer, Major J. A. Martone, HQ AFESC/RDVC, Tyndall AFB, Florida.

Key Commercial Products Division contributors to this program were: Dr. Geoffrey J. Sturgess, Technical Program Manager and Principal Investigator; Dr. Vito J. Sarli, Powerplant Analysis; and Mr. John H. Tweet, Preliminary Engine Design.

Subcontract support in catalytic reactor performance was furnished by United Technologies Research Center, a Division of United Technologies Corporation; key United Technologies Research Center contributor was Dr. Pierre J. Marteney. Consultations on catalytic operation were provided through United Technologies Research Center by Dr. William Pfefferle, private consultant.

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1.0 SUMMARY

National Aeronautics and Space Administration and the Air Force are co-sponsoring a two-phase program to evaluate the feasibility of catalytic combustion techniques to achieve low levels of aircraft gas turbine engine exhaust emissions at take-off and high-altitude, subsonic-cruise operation.

This report describes the Phase I Design Study effort involved in the conceptual design of six combustors using catalytic techniques, followed by evaluation, subsequent selection and detailed preliminary design of the two most promising concepts. The objective was to identify catalytic combustor designs that have the greatest potential to meet specific emissions and performance goals. One of these goals is to attain very low NO_x emission levels ($\leqslant 1$ g/kg) at subsonic cruise conditions in addition to meeting the 1979 Environmental Protection Agency landing/takeoff emissions standards for Class T_2 aircraft engines, while meeting commercial engine operational requirements.

The National Aeronautics and Space Administration/Pratt & Whitney Aircraft Energy Efficient Engine has been used as a reference design in this program. The technology is applicable to other high by-pass ratio aircraft gas turbine engines.

In Phase I, six preliminary combustor designs were conceived and evaluated. All the designs utilized catalytic reaction of all or some of the fuel, satisfying the emissions requirements while providing low exhaust emissions of oxides of nitrogen (NO_x) during stratospheric, subsonic cruise operation. Based on the evaluation of predicted performance, emissions and maintainability, two concepts were selected for further study.

Results of the Phase I design effort indicate that catalytic combustion is a means for obtaining low NO_x emissions at cruise. Levels below 4.0 g/kg appear to be obtainable. The application of catalytic combustion to practical aircraft combustion systems presents several major development challenges.

2.0 INTRODUCTION

Catalytic-combustor systems have shown the potential for producing low NO_x levels. The need for reducing the NO_x pollutant-emission levels has been assessed in recent studies conducted by the U.S. Department of Transportation (Climatic Impact Assessment Program, Reference 1) and the National Academy of Science (Reference 2) to determine the possible physical, biological, social, and economic effects of aircraft exhaust emissions. Other studies have indicated the need for pollutant emissions reduction, particularly within or near airports (Reference 3). The U.S. Environmental Protection Agency has promulgated standards for aircraft smoke and gaseous emissions in the vicinity of airports (Reference 4). Although no cruise standards have been proposed, it was recommended that new technology be developed to reduce NO_x pollutant-emission levels by a factor of ten within the decade of 1978-1988.

In response to the recommendations, the Advanced Low-Emissions Catalytic-Combustor Program is being undertaken to evolve catalytic combustor system designs which can provide low NO_x levels at stratospheric cruise operating conditions while meeting ground-level emission standards. The normal-cruise emission goal for this program is to obtain a NO_x emission index of less than one gram NO_x per kilogram of fuel. The normal-cruise operating conditions are representative of advanced technology engines with pressure ratios of approximately 34 to 1 and with turbine-inlet temperatures of about 1700 K at sea-level takeoff conditions. This goal represents more than an order-of-magnitude decrease from levels obtained with current technology engines ($\sim$30 g NO_x/kg fuel).

The objective of this Phase I analytical study was to define and evaluate several aircraft gas-turbine catalytic combustor designs as a means for achieving low NO_x levels at stratospheric cruise conditions. Preliminary design and performance results for each catalytic combustor concept and selection of the two most promising concepts are reported here.

3.0 PROGRAM DESCRIPTION

The Advanced Low-Emissions Catalytic-Combustor Program was initiated to acquire technology and demonstrate combustor designs that provide low exhaust emissions through catalytic combustion, while maintaining performance. This effort is planned in two phases, consisting of a design study, and screening tests and combustor refinement. The Phase I design study, which is described in this report, consisted of three tasks.

Task I. Conceptual Design Studies, involved definition of six catalytic combustor concepts

Task II. Analysis and Evaluation, where each of the six conceptual designs was analyzed and evaluated for the potential for meeting the combustor performance and emissions goals, as well as for the feasibility of development into a practical engine system

Task III. Preliminary Design, an effort was conducted to refine the analysis of their performance and emissions characteristics and provide more detailed preliminary design of the selected concepts, following the selection of the two most promising concepts.

3.1 Program Goals

Phase I specific program pollutant-emission and combustor-performance goals are as follows:

1. $NO_x \leqslant 1$ g/kg at subsonic cruise.

2. Combustion efficiency of 99.9 percent at sea-level takeoff, 99.5 percent at engine idle and 99.9 percent at all other operating conditions.

3. Capable of meeting the U.S. Environmental Protection Agency 1979 emissions standards for T_2 aircraft over the landing-takeoff cycle for altitudes less than 915 meters (Reference 4).

4. Combustor total pressure loss, $(\Delta P/P)_T$ = 5.75 percent over all operating conditions.

5. Capable of meeting engine performance requirements, including ignition, pattern factor, and stability requirements.

6. Capable of meeting practical operating requirements. In the evaluation of the combustor conceptual designs, good overall performance and feasibility for engine development were weighted heavily compared to emissions reduction potential. All concepts were evaluated assuming the use of Jet A fuel.

3.2 Reference Engine Description

The engine selected as the reference engine for this program is the National Aeronautics and Space Administration/Pratt & Whitney Aircraft Energy Efficient Engine, which is typical of the high bypass, high-pressure ratio engines to be developed in the next two decades for commercial service.

The reference engine (STF 505M-7B) is part of the current National Aeronautics and Space Administration/Pratt & Whitney Aircraft Energy Efficient Engine program conducted under study contract NAS3-20646.

In Figures 1 through 5, the sea-level performance is given. The information is for a flight inlet and drags, bleed and horsepower extraction. Figure 6 gives the relationship between core engine speed and thrust. Table I summarizes performance of the reference engine at some altitude operating points.

Reference-engine combustor envelope. - The envelope for the reference engine which must contain the catalytic-combustion section is shown in Figure 7.

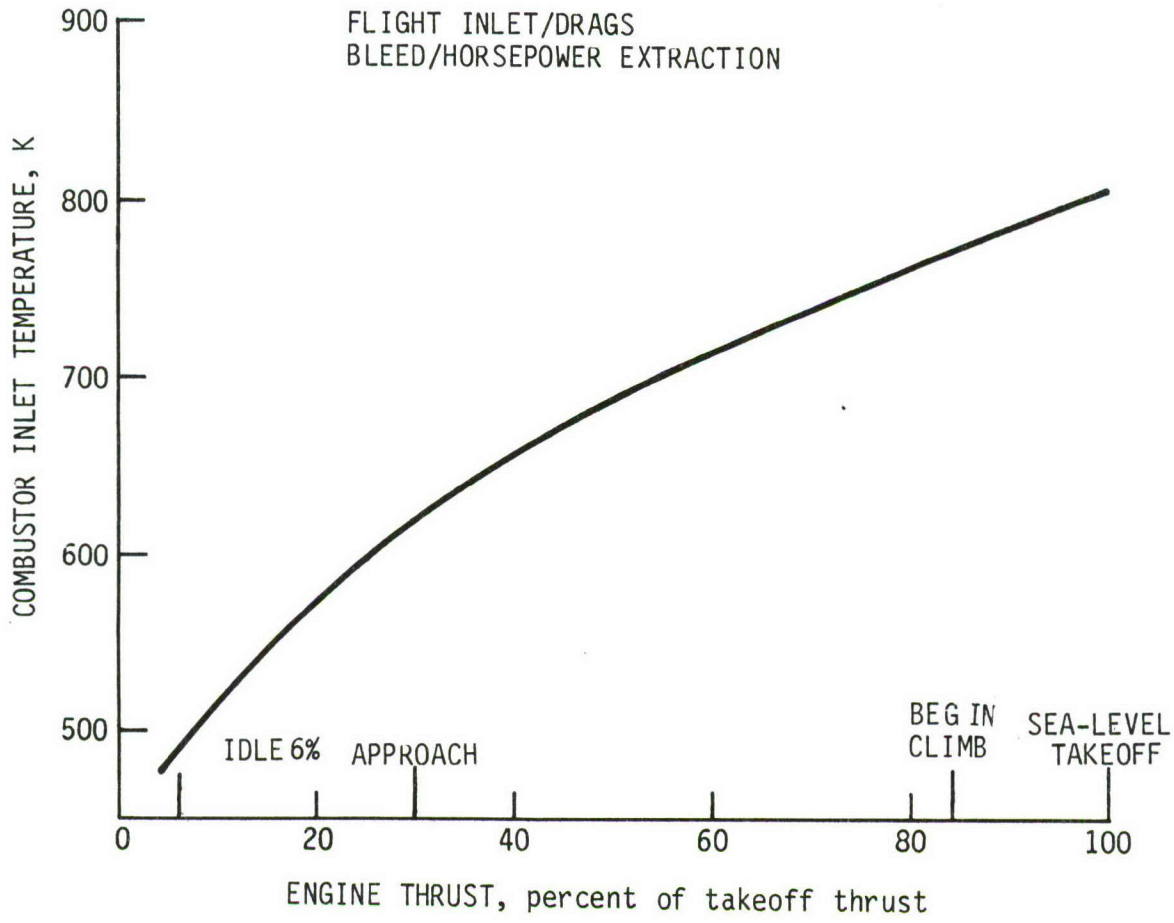


Figure 1 Reference-Engine Combustor Inlet Temperature Dependence on Engine Operating Mode

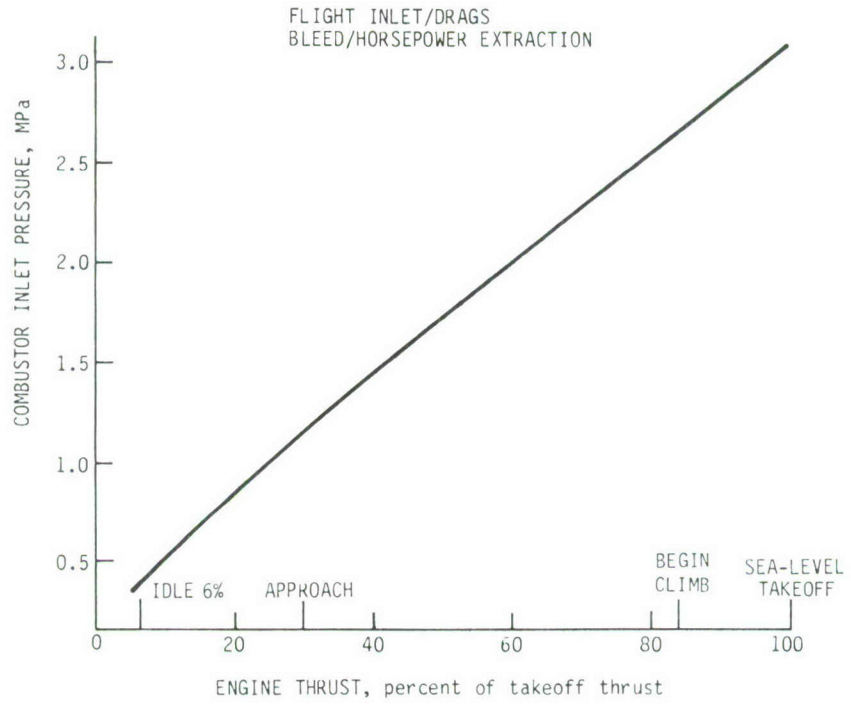


Figure 2 **Reference-Engine Combustor Inlet Pressure Dependence on Engine Operating Mode**

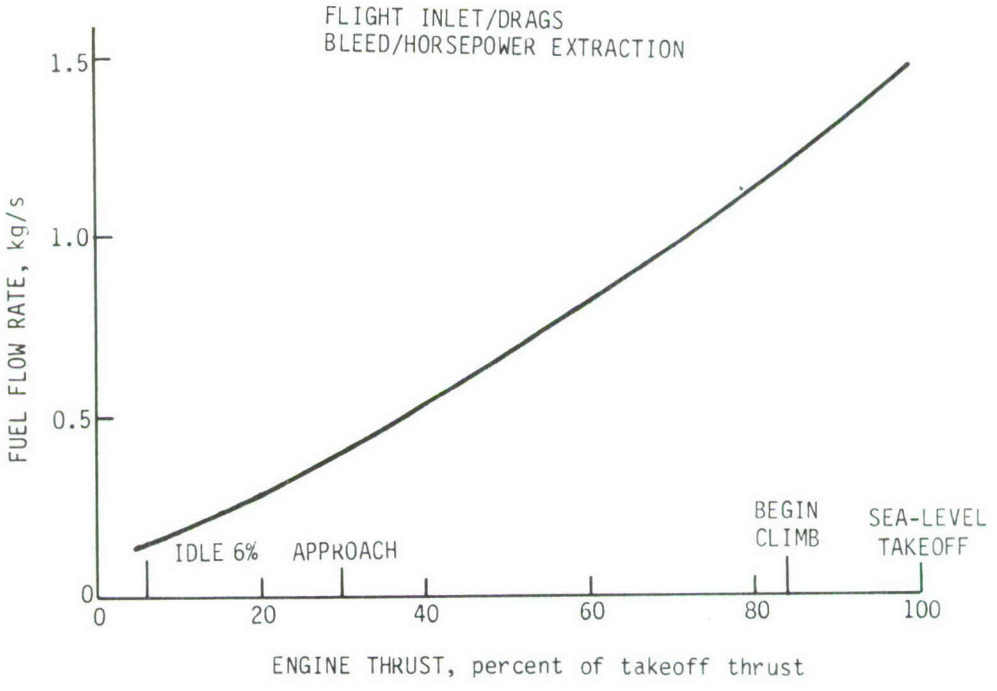


Figure 3 **Reference-Engine Combustor Fuel Flow Dependence on Engine Operating Mode**

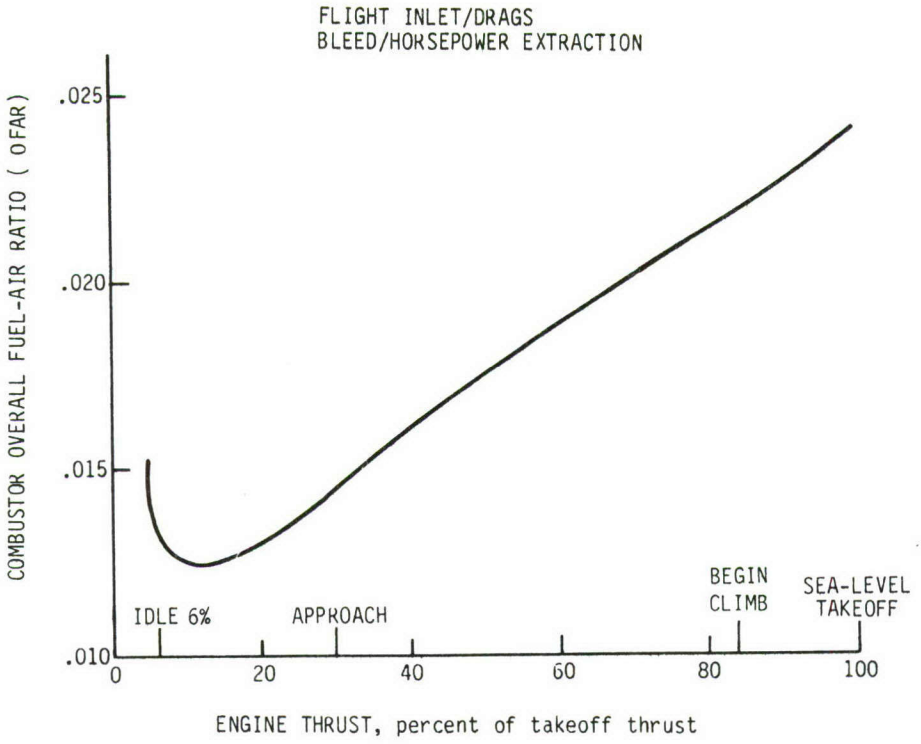


Figure 4 **Reference-Engine Combustor Overall Fuel-Air Ratio (OFAR) Dependence on Engine Operating Mode**

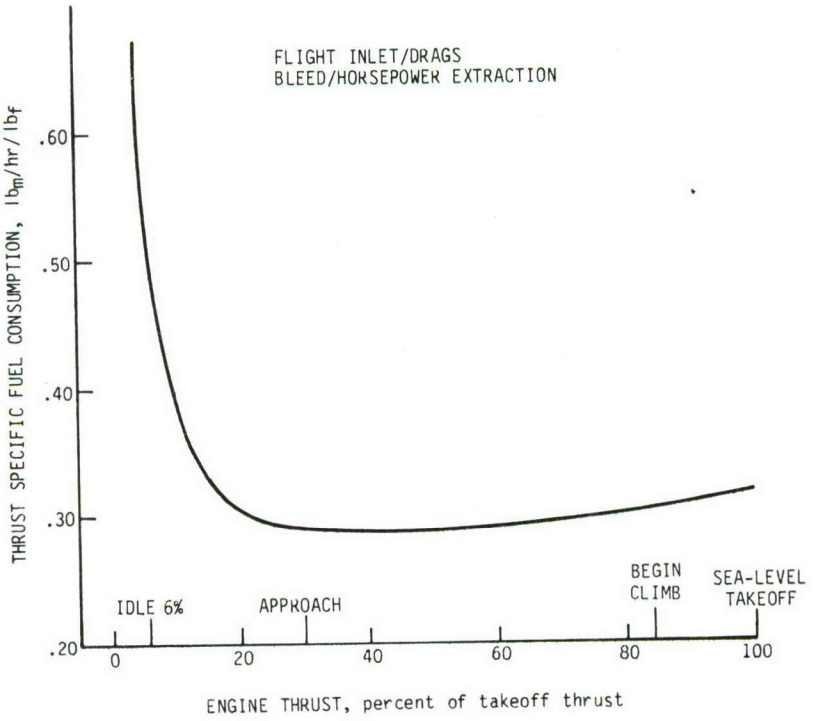


Figure 5 **Reference-Engine Thrust Specific Fuel Consumption Dependence on Engine Operating Mode**

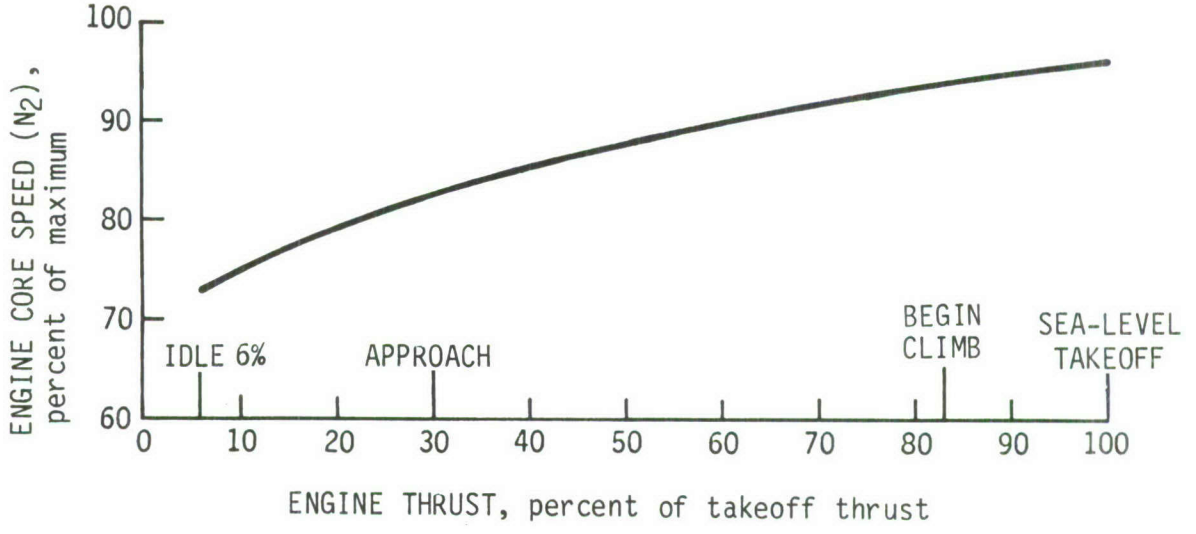


Figure 6 Relationship Between Reference-Engine Core Speed and Engine Thrust

TABLE I

REFERENCE ENGINE PERFORMANCE AT ALTITUDE

Altitude (km)	Mach No.	Engine Operating Mode	Compressor Exit $T_{T3.0}$* (K)	Compressor Exit $P_{T3.0}$ (MPa)	Engine Core Speed N_2 (% max)	Fuel Flow Rate (kg/s)	Overall Fuel-Air Ratio OFAR
10.668	0.8	max. climb, end climb	782	1.5286	94.51	0.727	0.02459
10.668	0.8	max. cruise	756	1.4017	92.75	0.641	0.02311
10.668	0.8	85% max. cruise	727	1.2541	90.73	0.543	0.02125
10.668	0.8	82% max. cruise	722	1.2245	90.34	0.524	0.02090
11.887	0.8	max. climb, end climb	780	1.2757	94.34	0.608	0.02465
11.887	0.8	max. cruise	753	1.1714	92.55	0.537	0.02318
11.887	0.8	95% max. cruise	743	1.1287	91.87	0.509	0.02257
11.887	0.8	87% max. cruise	728	1.0625	90.77	0.465	0.02156
0.457	0.39	end take-off	836	3.2735	97.84	1.508	0.02429
0.457	0.39	begin climb	835	3.2847	97.97	1.526	0.02443
6.096	0.7	mid. climb, max. climb	802	2.2904	95.76	1.063	0.02402
6.096	0.7	flight idle	492	0.3106	72.67	0.078	0.00937
10.668	0.8	flight idle	501	0.3101	73.59	0.078	0.00942

*Subscript T denotes total values

Subscript 3.0 denotes compressor delivery values.

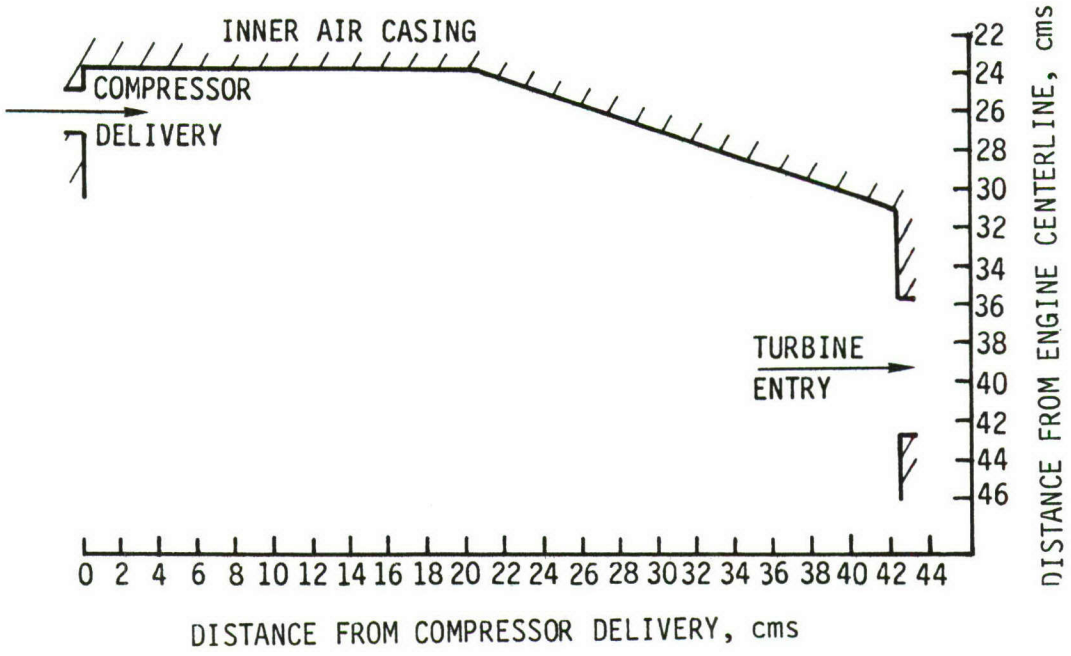


Figure 7 **Reference-Engine Combustion Section Dimensions**

4.0 GENERAL AEROTHERMODYNAMIC AND MECHANICAL DESIGN STUDIES

4.1 Combustion Concepts

Concept requirements and design considerations. - The catalytic combustor has a number of special requirements that must be met for satisfactory operation, which include starting, low and high-power emissions, combustion stability, response rate, durability, and maintainability.

Starting

When starting a catalytic combustor, a strong dependency on initial temperature is expected. In order for reaction of the fuel/air mixture delivered to the reactor to become self-sustaining, it has been suggested that it is necessary to preheat the catalytic reactor to 590 to 640 K (Reference 5). Aging of the catalytic could exert significant influence on the light-off temperature. It is apparent that temperatures in excess of 600 K will be required for startup.

Consideration of Figure 8 shows that 600 K corresponds to almost the sea-level approach power of a typical modern engine. It is evident that present day catalytic combustors will not be self-starting.

The inability to self-start requires a separate starting procedure. One possible system would be an auxiliary combustor to start and accelerate the engine to a speed where the combustor air inlet temperature is above the catalyst extinction temperature. Another would be to electrically preheat the catalyst directly to above the extinction temperature, and then start the engine.

Whatever auxiliary system is selected, it must be capable of starting the engine on a cold day with cold fuel, and at high altitudes.

Low and High Power Emissions

Combustors now have to be designed with regard for the Environmental Protection Agency emissions standards. The implications of these standards is that combustion efficiency be at least 99.5 percent at ground idle.

The catalytic combustor has not yet been conclusively shown capable of achieving such efficiencies at conditions equivalent to a typical ground idle. Blazowski and Walsh (Reference 6) showed that such efficiencies were not achieved for JP4 fuel until the exhaust temperature reached 1350 K with an inlet temperature of 650 K. Similiar results were obtained in Reference 7 for propane and air mixtures. Figure 8 shows that these conditions do not correspond to a typical engine ground idle point. Although the pressure in an engine at idle is greater than that used in Reference 6 (almost by a factor of two), Blazowski and Walsh demonstrated that combustion efficiency was insensitive to pressure at these conditions.

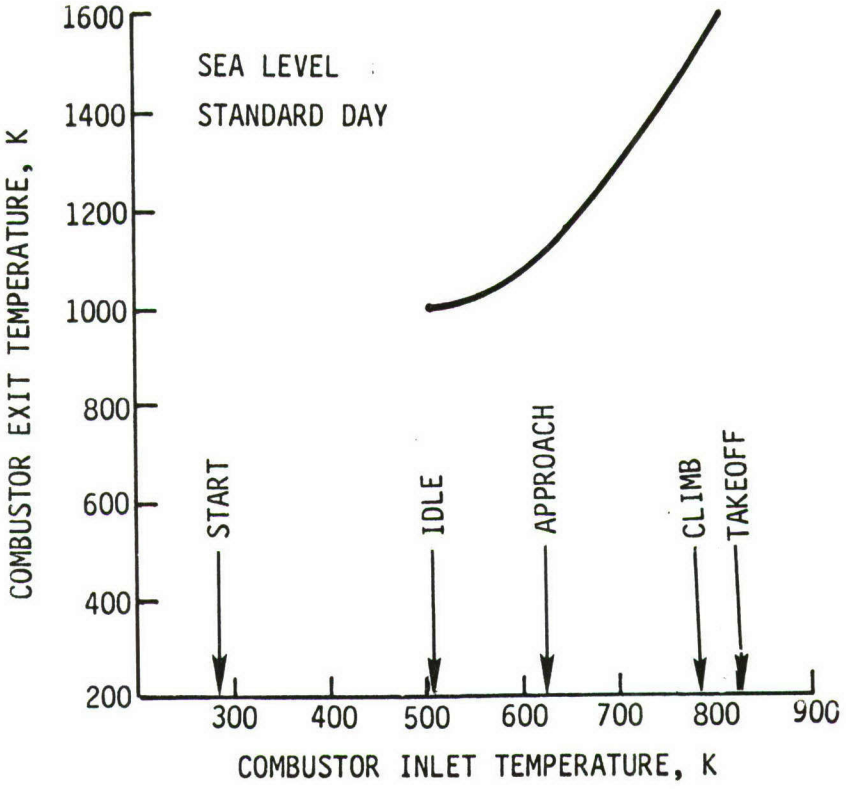


Figure 8 Typical Engine Combustor Exit-Temperature Dependence on the Inlet Temperature

It is apparent that even if starting can be accomplished, the catalytic combustor alone is unlikely to be used at ground-idle conditions due to inadequate combustion efficiency. Considerations of combustion inefficiency, therefore, will determine the way the catalytic combustor is used in an engine system.

A major advantage of the catalytic combustor is the capability of oxidizing the fuel without generating large amounts of oxides of nitrogen. This can be achieved because the axial temperature through it increases monotonically to the combustor exit temperature. This distribution contrasts to that of the conventional combustor which usually exhibits a temperature peak above the exit temperature. A high-temperature region exists because a near-stoichiometric region is needed to stabilize the flame. The stoichiometric region contributes the major portion of the oxides of nitrogen produced in the combustor. Typical temperature distributions in a conventional combustor are illustrated in Figures 9 and 10.

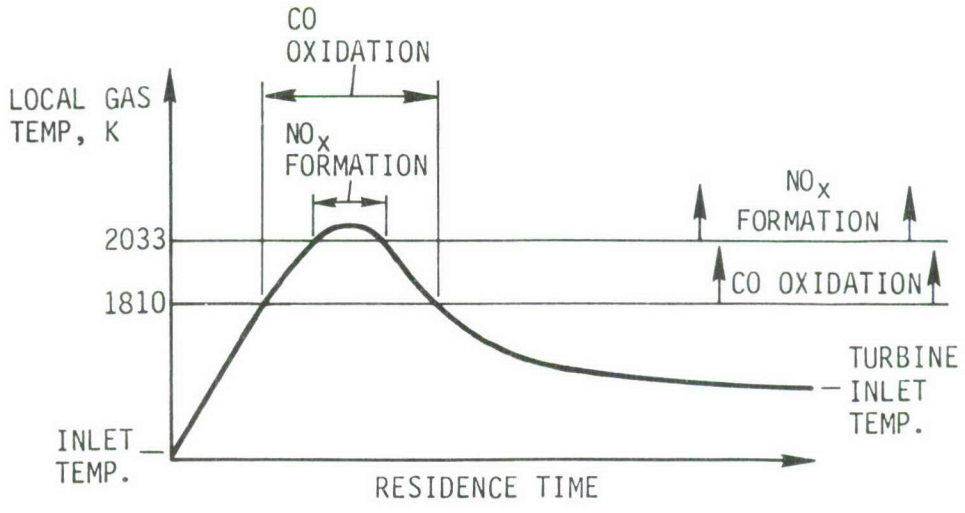


Figure 9 Relative Activity of CO and NO_x at Idle Power in Conventional Combustor

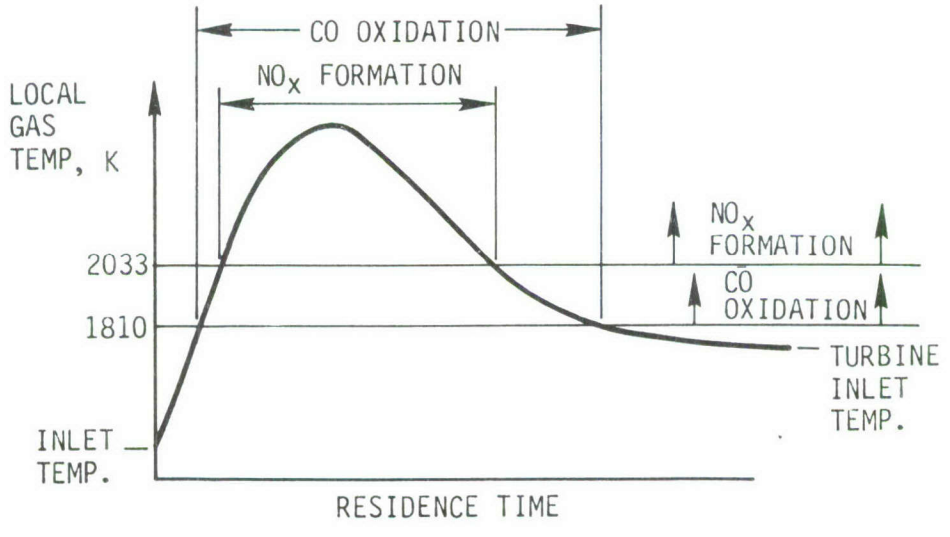


Figure 10 Relative Activity of CO and NO_x at High Power in Conventional Combustor

Combustion Stability

The catalytic combustor supports self-sustaining reactions once the catalyst temperature exceeds its extinction value. The catalyst will then tend to remain self-sustaining even if the inlet-air temperature temporarily falls below the extinction temperature. Most of the catalyst will operate at a temperature close to the theoretical adiabatic flame temperature for the fuel-air mixture entering it. This feature of catalytic combustors means that fuel-air mixtures normally outside the flammability limits of the mixture can be reacted. The familiar problems of lean and rich blow-outs associated with conventional combustors are potentially ameliorated for the catalytic combustor.

A related stability-mode to be considered is breakthrough. Breakthrough results when gas-phase reactions within the catalytic reactor are extinguished due to an excessive throughput for the reactor.

Blowout results when increases in mass flow cause the surface-reaction heat release rate to be less than the heat losses due to convection, conduction and radiation in the reactor. To control blowout, it is desirable to reduce the convective heat transfer coefficient in the passages at the front of the reactor.

Response Rate

Thermal inertia of the catalytic reactor causes the reactor temperature to remain close to the entering mixture theoretical adiabatic flame temperature. This can introduce a temperature phase-lag to throttle movements. The phase lag can be corrected to some extent by minimizing the size of the catalytic reactor and designing a fuel control system to vary fuel flow for temperature level and temperature rate-of-change control.

Mounting

Differences in the coefficient of thermal expansion between ceramics and metals introduce difficulties of mounting a ceramic substrate catalytic reactor in an engine. It is therefore necessary to devise a soft-mounting that will allow thermal incompatibilities to be taken up.

Fabricability and Maintainability

Any catalytic-combustor should be designed so that it can be fabricated and assembled easily and inexpensively.

The major new component is the catalytic reactor. The reactor could take a number of different forms varying from packed beds to thin-walled honeycomb. Two characteristics of the honeycomb make it a natural choice. The honeycomb structure has been demonstrated to have a relatively low pressure loss (Reference 7). In addition, the honeycomb form is amenable to forming by extrusion, making it reasonably inexpensive.

The layout of a combustor involving a catalytic reactor should be chosen such that the reactor can be inspected, and readily removed. For an annular configuration combustor in a large diameter engine, modular construction of the catalytic reactor is desirable.

Catalyst reactivity considerations. - A catalytic reaction can schematically be broken down into the following steps:

1. diffusion of the reactants to the catalyst surface
2. physical adsorption
3. chemisorption
4. actual reaction of the reactants to products
5. desorption
6. diffusion of the reaction products away from the catalytic surface

The catalytic reactivity of a catalyst for a particular reaction may depend on any one of these steps, or on any two or more of these steps.

It can be shown that in the gas-turbine combustor application, activity in the reactor is physically controlled. For a physically controlled process, changes in catalyst reactivity will not significantly influence fuel conversion. Therefore, a catalyst may be chosen primarily for its durability, and for its reactivity only secondarily. Starting, of course, is not a consideration.

Catalysts that have been investigated in combustion systems include platinum, palladium, iridium, cobalt oxide (CoO), chromia (Cr_2O_3), ceria (CeO_2), and nickel oxide (NiO). All have been shown to be effective in promoting combustion while minimizing emissions. Mixed metal oxides have been found to be more effective than single metal oxides, such as zinc-cobalt spinels and "chromates" (CuO + Cr_2O_3, MgO + Cr_2O_3, and MnO_2 + Cr_2O_3) and "hopcalities" (CuO + MnO_2 plus promoters). The most active are the noble metals. These unfortunately exert considerable vapor pressure at the temperature of interest and, therefore, are not likely to be durable in the aircraft gas-turbine combustor.

It has been found (References 8 and 9) that the mass transfer limitation to reaction can be overcome at high temperatures by preheating through heat transfer from the reactor of the diffusing fuel-air mixture before it actually reaches the catalytic surface. This preheating leads to thermal ignition of the mixture. Eventually, as the mixture passes through the reactor, homogeneous reactions dominate and at the rear of a reactor, no contact with the catalyst is necessary for complete reaction (Reference 10). By this means, the required fuel conversion rates can be achieved with acceptable reactor sizes.

4.2 Combustor Cooling Concepts

Liner cooling concepts selected. - Any new cooling technique proposed for an advanced application should be capable of maintaining the temperatures currently achieved in liners while maintaining or reducing the coolant flux. While many problems remain to be dealt with, the combined impingement/inclined multi-hole cooling scheme emerges as being extremely attractive on a thermal basis. This scheme was selected. The principle is illustrated in Figure 11.

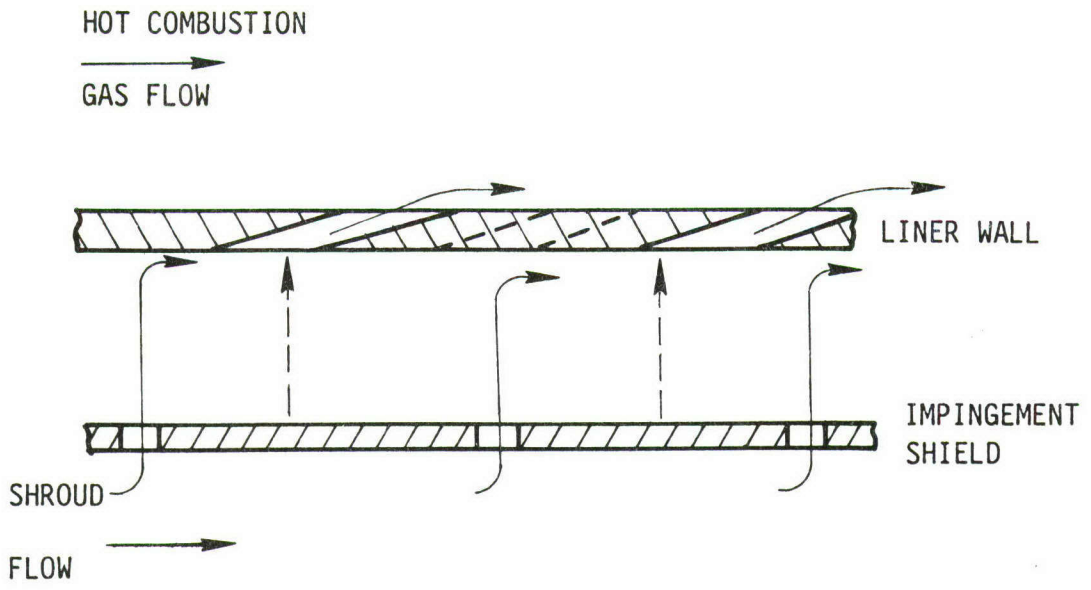


Figure 11 Schematic of Combined Impingement/Multi-Hole Liner Cooling Scheme

Liner material selection. - Hastelloy X was selected as the baseline liner material, with Inconel 617 chosen as the alternative. For an adequate life, a liner maximum average temperature of 1088-1116 K is stipulated for Hastelloy X material. Inconel 617 was taken to be capable of giving the same life as Hastelloy X with a permissible liner temperature increase of 30 K.

Catalytic-reactor substrate material. - Among the factors to be considered in selecting a substrate are maximum operating temperature, pressure drop, compressive strength, resistance to thermal shock and capability of retaining a large surface-area wash coat of refractory oxides.

Table II compares the characteristics of some potential substrate matrix materials and clearly shows only one suitable candidate - zirconia (ZrO_2).

TABLE II

CHARACTERISTICS OF SUBSTRATE MATERIALS

Material	Axial Strength	Transverse Strength	Shock Resistence	Temperature Limit, K
Cordierite	high	moderate	moderate	1590 - 1700
Alumina	high	moderate	low	1700 - 1810
Silicon carbide	low	very low	low	1810 - 1922
Zirconia	high	moderate	high	1922 - 2033
Metals (e.g. Ni)	very high	high	very high	1590 - 1700

Catalytic-reactor mounting. - Zirconia has been selected for the substrate material. Interface problems between metal and ceramic have been encountered and solved by using soft mounting methods (Reference 11). The catalytic reactor will be supported on a resilient pad which takes up incompatibilities between the ceramic and the surrounding support structure. This approach leaned heavily on earlier work (Reference 12) and on the experience of Pratt & Whitney Aircraft with turbine ceramic outer air seals.

A graded ceramic intermediate layer would be used to attach a Feltmetal^{R} pad to the reactor. By varying the composition of the attachment layer, the different coefficients of thermal expansion of the Feltmetal and the zirconia can be matched up so that the attachment does not fail under temperature transients.

Catalytic-reactor cooling. - Cooling must be incorporated into the catalytic-reactor canning. FINWALL is a very efficient form of cooling which has been developed by Pratt & Whitney Aircraft. FINWALL lends itself very well to the present application because relatively long axial runs can be used without the need to vent spent coolant.

Figure 12 illustrates, in cross-section, how FINWALL would be used to provide cooling of the Feltmetal and the interface with the reactor.

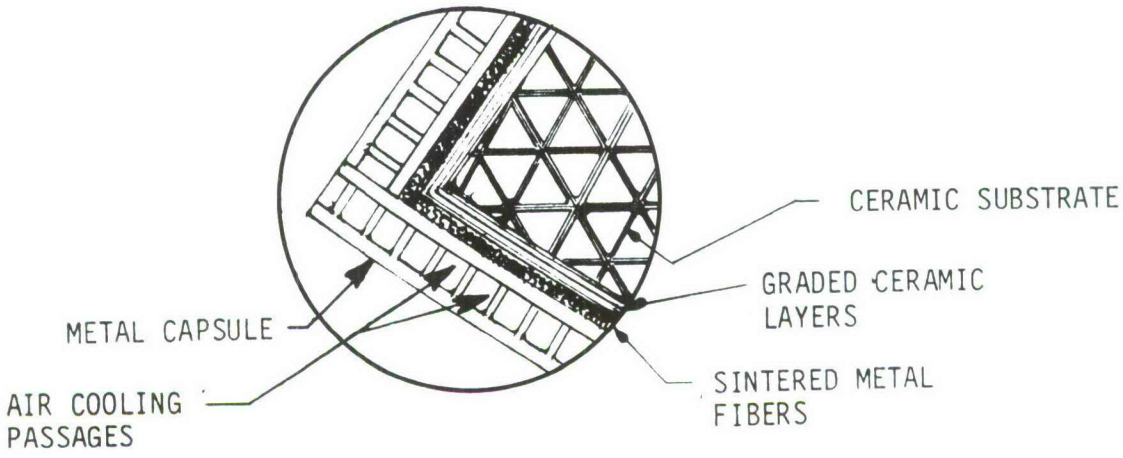


Figure 12 Canning of ZrO_2 Catalytic Reactor

Mounting of the Catalytic Reactor

The load carrying struts in the diffuser dump section also serve as the mounting for the catalytic reactor. With the self-contained reactor canning and cooling system, it becomes easy to design a catalyst reactor that is annular in overall form consisting of a number of equal segments individually carried between the load-bearing struts.

5.0 CONCEPT DESIGN AND OPERATION

5.1 Identification of Concepts

Candidate concepts for an aircraft engine combustion chamber must take into account the special requirements of the catalytic reactor, and must also satisfy all the demands made on a combustor by the application.

The required six concepts evolved by following these tenets.

Concept 1: Base-line pure catalytic combustor (Figure 13)

The pure catalytic combustor was selected to provide the sole means for reacting all the fuel supplied to the engine. It was felt necessary to consider an ideal catalytic reactor to ascertain exactly what compromises the application would impose. The pure catalytic combustor would then act as a baseline. The pure catalytic combustor also serves as a design to which auxiliary systems associated with external starting and fuel preparation may be applied for study purposes.

Total-Pressure Loss Breakdown

The overall combustion-section pressure-loss at take-off conditions was specified as 5.75 percent of the combustion section inlet total pressure. This overall loss was broken up according to Table III.

TABLE III

TOTAL-PRESSURE LOSS BREAKDOWN

Component	$(\Delta P/P_T)_{3.0}$, percent
Diffuser	2.00
Combustor liner	2.00
Catalytic reactor	1.60
Miscellaneous	0.15
Total	5.75

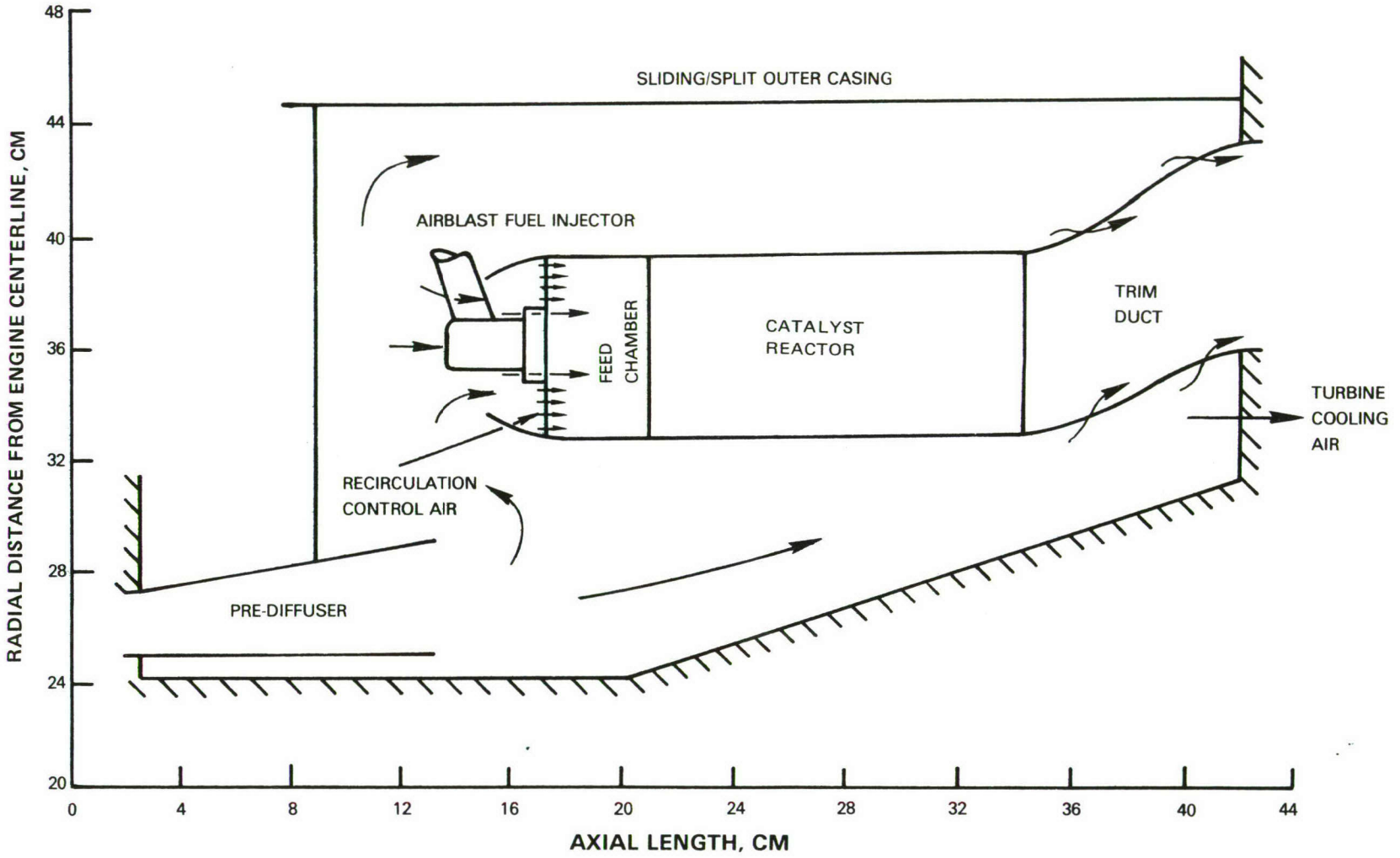


Figure 13 Revised Preliminary Flowpath for Concept 1 (With Airblast Fuel Injectors)

Diffuser Design

The pressure-loss assignment for the diffuser was 2.0 percent of the compressor delivery total pressure. The flow Mach number at the compressor exit at take-off was 0.26. A dump diffuser was chosen in the interests of desensitizing flow splits to changes in the compressor-exit velocity profile, and to minimize strut wakes.

A strutless prediffuser was selected, with struts to carry loads from the inner case to the outer case being placed in the dump region as a support for the catalytic reactor. A strutless prediffuser and dump section was designed that would meet the assigned pressure-loss goals with the specified inlet Mach number and velocity profile. The resulting prediffuser design had the following characteristics:

Axial length/inlet height, N/W	6
Area ratio	1.74
Included angle, deg	6.993
$\Delta P/P_{T3.0}$, percent	1.66

An asymmetric prediffuser configuration was used with the dump forming a plenum chamber containing a combustor parallel to the engine centerline and displaced radially outwards from the compressor exit elevations. Such an asymmetric prediffuser was outside normal engine experience so checks for flow separation were made using TSTALL, a diffuser computer deck (Reference 13).

No separation of any kind was perceived on the nondiverging inner wall. On the outer diverging wall, only the shape factor indicated separation, and that is intermittent. Since TSTALL does not account for the boundary layer re-energizing from the compressor-generated turbulence and a Pratt & Whitney Aircraft diffuser deck indicates an acceptable trade between prediffuser length and overall total pressure losses (0.1-0.2% $P_{T3.0}$ per 2.54 cms. length), the design is considered satisfactory.

Turning losses from the end of the prediffuser have been estimated at 0.6 percent of $P_{T3.0}$. Consideration of Table III indicates that the overall loss goal can be met.

Fuel Preparation

Two aviation fuels were considered for this study: D.Eng.R.D. 2494 and JP5. D.Eng.R.D. 2494 is fuel to a British specification and represents a low-flash kerosine roughly equivalent to ASTM-A1. JP5 is a high-flash kerosine. These two fuels were considered representative of the likely range of fuels to be encountered in current commercial service. Leading properties of the two fuels are given in Table IV.

TABLE IV

FUEL SPECIFICATIONS

Fuel Type	D.Eng.R.D. 2494	JP5
Viscosity, $m^2/s \times 10^6$, (max.)	6.0 at 255.4 K	16.5 at 238.7K
Final boiling pt., K	573	-
Flashpoint, (min.), K	311	333
Freezing pt., (max.)	223K	233K
Specific gravity at 289/289 K		
min.	0.775	0.788
max.	0.830	0.845
Aromatics, V% (max.)	20.0	25.0
Olefins, V% (max.)	5.0	5.0
Sulphur, W%, (max.)	0.2	0.40
Mercaptan sulphur, W%. (max.)	0.001	0.005
Net heat of combustion, J/g	42,800	42,600
Smoke pt. (min.)	20	19
Distillation V% (min.)	20 at 473 K	10 at 478K
End pt. (max.), K	561	561
Residue V%	1.5	1.5
Loss, V%	1.5	1.5

Figure 14 shows the effects of fuel type on evaporation at reference engine takeoff conditions. The calculations were made for 20 fuel injectors, typical of current usage, each with a 20 micrometer (μm) mean-diameter spray which represents a considerably improved atomization quality over current JT9D engine injectors. As a consequence of the evaporation performances shown in Figure 14, the evaporation studies were concentrated on JP5, the less volatile fuel.

In Figure 15, the effect of spray mean droplet size is shown; the fuel is JP5 and 20 fuel sources are used. The separation of droplet size and the number of fuel sources in this fashion is somewhat artificial since the two are connected. The figure, therefore, really represents a variable injector design. However, the tremendously powerful effect of spray mean droplet size is illustrated. For mean droplet sizes greater than 15 μm, very large distances are required for greater than 90 percent spray evaporation.

Spray mean droplet sizes less than 20 μm appear to be necessary. Such values cannot be achieved with conventional dual-orifice pressure atomizers, as Figure 16 illustrates.

Prefilming airblast atomizing fuel injectors are expected to have the superior performance required. The performance of prefilming airblast atomizers has been described in Reference 14 in terms of a characteristic dimension, which depends on prefilmer diameter and film thickness.

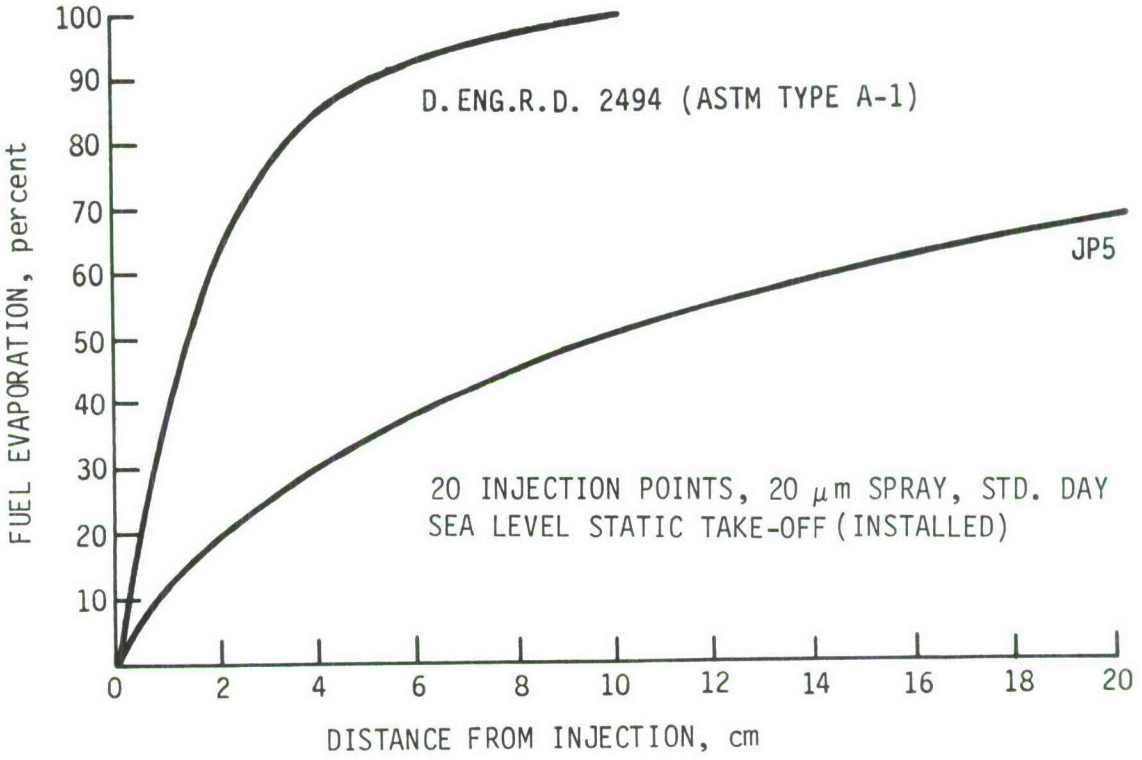


Figure 14 Fuel Spray Evaporation Dependence on Fuel Type and Distance from the Injection Point

Figure 17 shows how the characteristic dimension D influences the spray Sauter Mean Diameter at take-off conditions over a range of equivalence ratios.

The injector atomization performance is translated into terms of JP5 evaporation in Figure 18 for 20 injectors. This figure indicates that the characteristic dimension should be less than 2.35 cm. Figure 19 shows the benefit to be obtained from increasing the number of injectors to 30 from 20 at a characteristic dimension of 2.35 cm.

The number of 30 prefilming airblast atomizing fuel injections with a characteristic dimension less than 2.35 cm has been selected. At take-off, such injectors would produce atomized JP5 fuel sprays of about 15 μm Sauter Mean Diameter in size. About 85 percent of this fuel would be evaporated within 5 cm of the injectors. This is the best performance that can be expected at the present time.

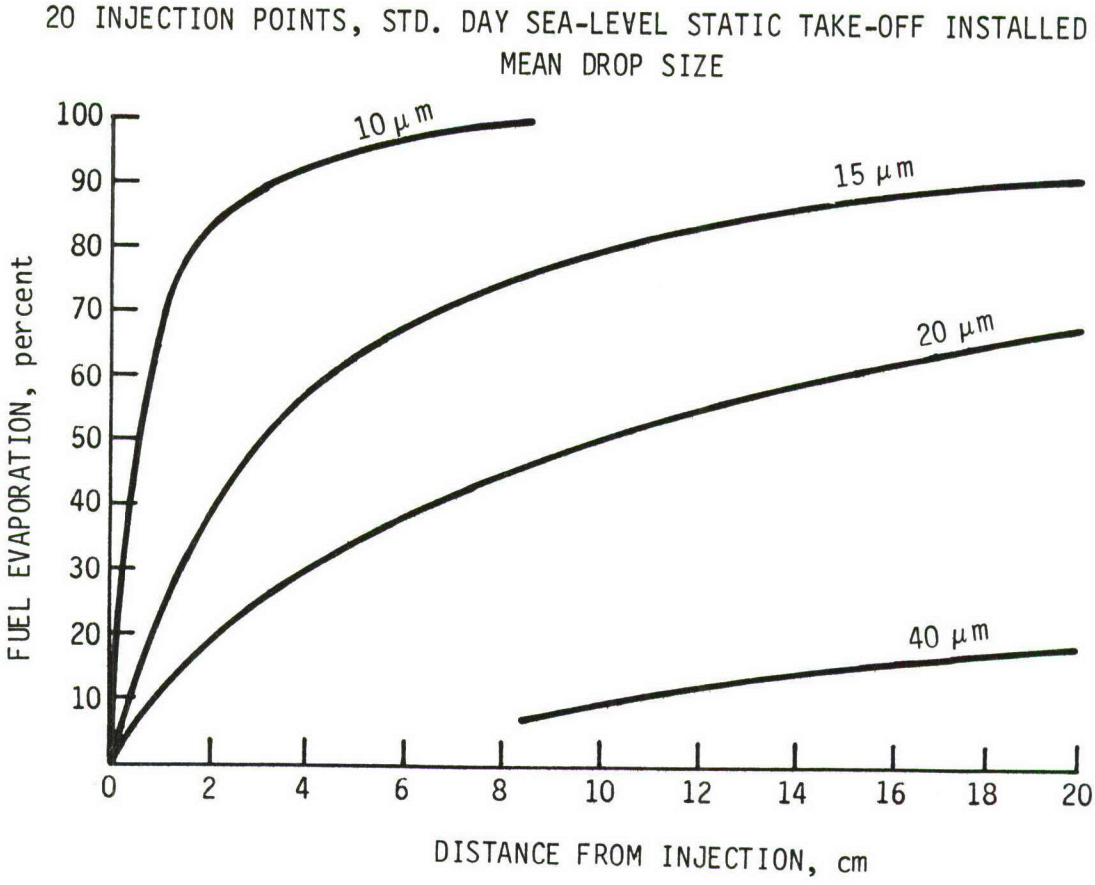


Figure 15 Effect of Mean Drop Size on JP5 Fuel Evaporation with Distance from the Injector Plane

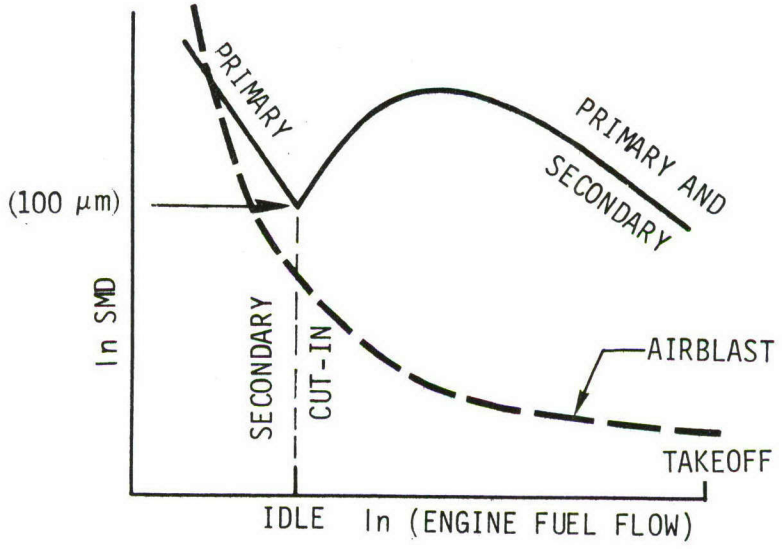


Figure 16 Atomization Performance of a Typical Dual-Orifice Pressure Atomizing Fuel Injector

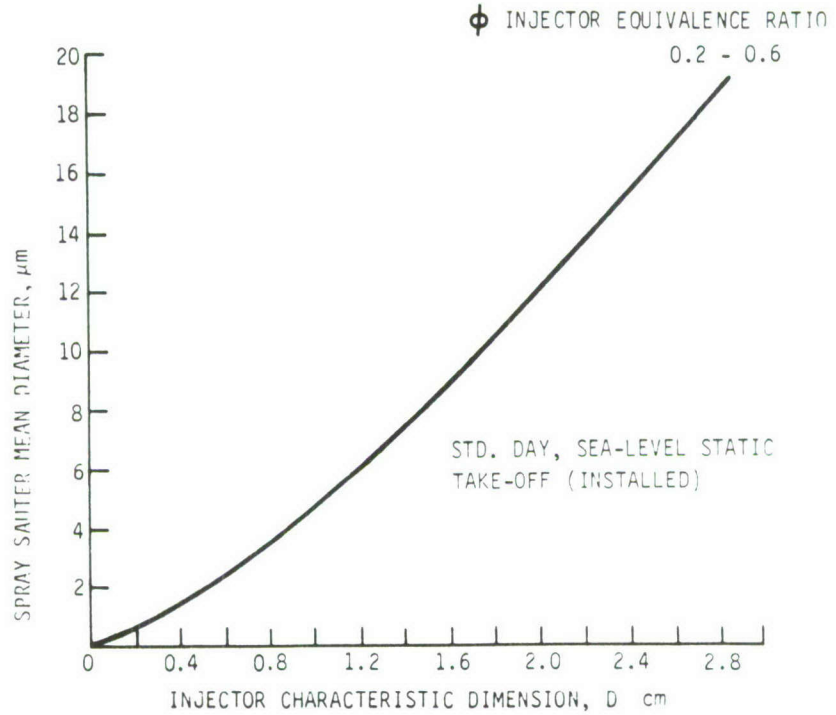


Figure 17 **Spray Sauter Mean Diameter Dependence on Prefilming Airblast Atomizing Characteristic Dimension**

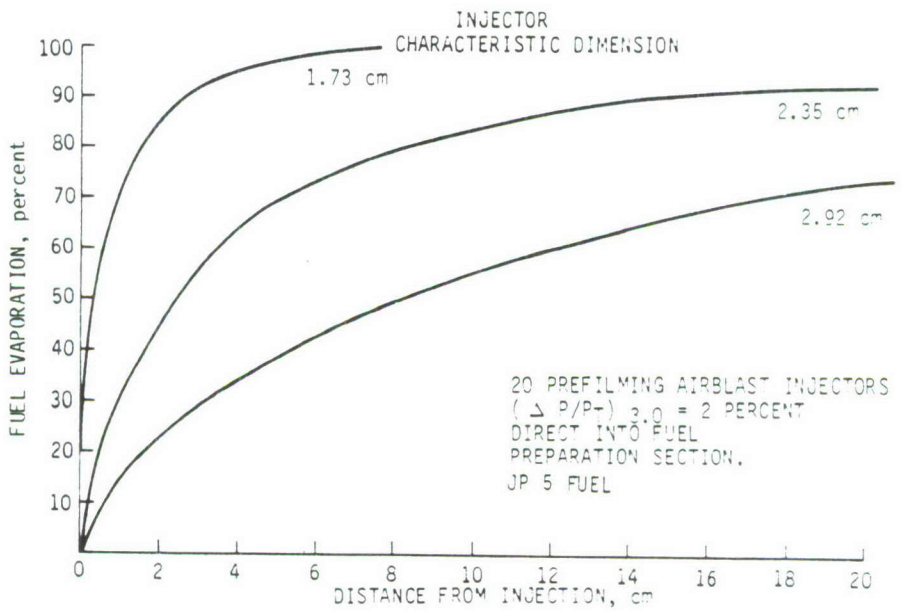


Figure 18 **Effect of Injector Characteristics Dimension on JP-5 Fuel Evaporation with Distance from Injection Plane**

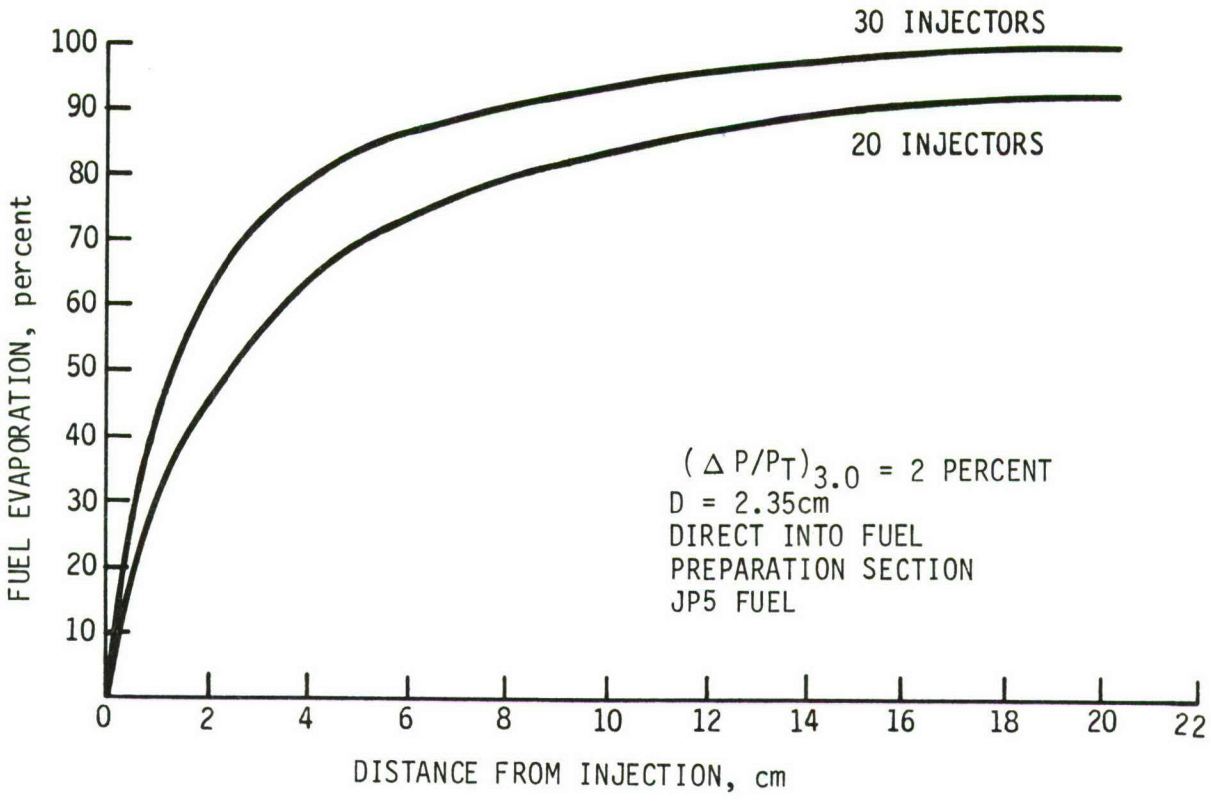


Figure 19 Effect of Prefilming Airblast Injector Number on JP-5 Fuel Evaporation Dependence with Distance from the Injection Plane

Limits on the Fuel Preparation Section

Figures 18 and 19 show that spray evaporation with a sufficient number of correctly designed prefilming airblast atomizing fuel injectors would present no difficulties if adequate length could be made available for the evaporation process.

There are two restrictions which limit the length available for fuel preparation. The first of these is a rather obvious one associated with the reference-engine combustor-envelope length (Figure 7). The second is caused by the autoignition characteristics of the fuel and air mixture flowing through the fuel preparation section. At the pressure prevailing inside the combustor at reference-engine take-off conditions, the residence time in the fuel preparation zone must not exceed 1.2 milliseconds. This time represents an autoignition safety factor of two (Figure 20). Design of the fuel preparation section consists of matching this maximum residence time with section dimensions that will allow sufficient length for the discharge from individual fuel injectors to become mixed uniformly at the catalytic-reactor face.

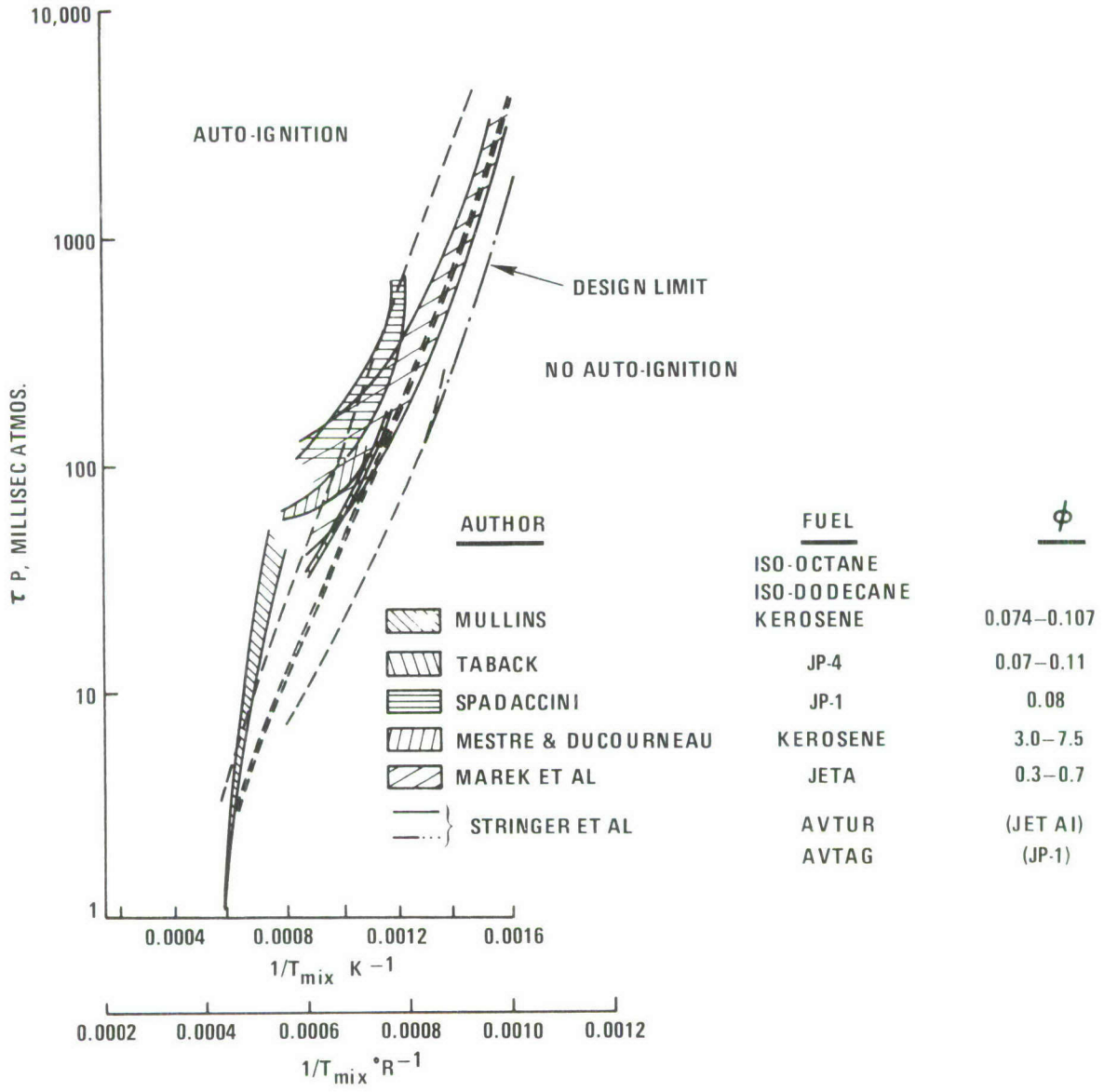


Figure 20 Autoignition of Liquid Hydrocarbon Fuel Sprays in Air

The total residence time of 1.2 milliseconds has two components: time spent in the fuel injector forming the spray, and time spent evaporating the spray and mixing with air. The time spent in forming the spray cannot be counted in the spray evaporation time, but does count towards the autoignition delay. It is part of the mixing time because the spray is formed by airblast.

Ideally, the length of a mixing section should not be less than one half the annular height of the section in order to permit adequate jet spreading for uniform feed to the reactor. It would be desirable if the catalytic-reactor

face area could be sized for optimum reactor performance. However, with the exceedingly short autoignition time, the reactor annular height has to be determined to meet mixing time requirements.

The velocity appropriate to forming the spray is that due to the air pressure drop across the injector, i.e., 96.9 m/s. A catalytic-reactor annular height of 6.35 cm with an inner radius of 32.7 cm was taken (see Figure 7) to define the catalytic-reactor face area. The mixture velocity at the reactor face was found from conservation of mass with the volume of unvaporized fuel being neglected. A value of 31.0 m/s was obtained. With these conditions, the length of the fuel preparation section was set as 3.18 cm and the spray formation length was found to be 1.78 cm. Hence,

spray formation length, cm	1.78
evaporation length, cm	3.18
mixing length, cm	4.95
Total fuel-preparation length, cm	9.91

The total length with Figure 19 suggests liquid fuel will enter the catalytic reactor at take-off power. However, with good fuel injector design, the amount of unevaporated fuel should be less than 10 percent of the total fuel flow rate, and should be well mixed with air, thereby minimizing any potential hot-streaking problems.

Catalytic-Reactor Size

The reactor was sized using the United Technologies Research Center Catalytic Kinetics Computer program. The input conditions were the reactor face area of 1431 cm^2, and the mixture approach velocity of 31.0 m/s. The characteristics of several actual catalytic reactors were used to provide a feel for sensitivity of required volume to these characteristics. With the annular height of 6.35 cm and inner radius of 32.7 cm, the calculated volumes were translated into reactor axial lengths. Table V shows the results of the calculation; reactor characteristics were taken from References 15 and 16.

TABLE V

CALCULATED CATALYTIC-REACTOR LENGTHS FOR COMPLETE FUEL CONVERSION

Type	Manufacturer	Ref. 15 Identification	Required Length, cm
1	Englehard	-	16.5
2	W. R. Grace	KT	15.5
3	General Refractories	JH	13.6
4	General Refractories	HH	13.8

Catalytic-Reactor Total Pressure Losses

A total pressure loss breakdown for the combustion section was given in Table III, where 1.6 percent of $P_{T3.0}$ was available for the reactor. Figure 21 shows the calculated total pressure loss variation of the four reactors as a function of axial length at take-off conditions for the inlet velocity and face area previously selected. The reactor length requirements from Table V are superimposed on this figure, together with the pressure loss value from Table III.

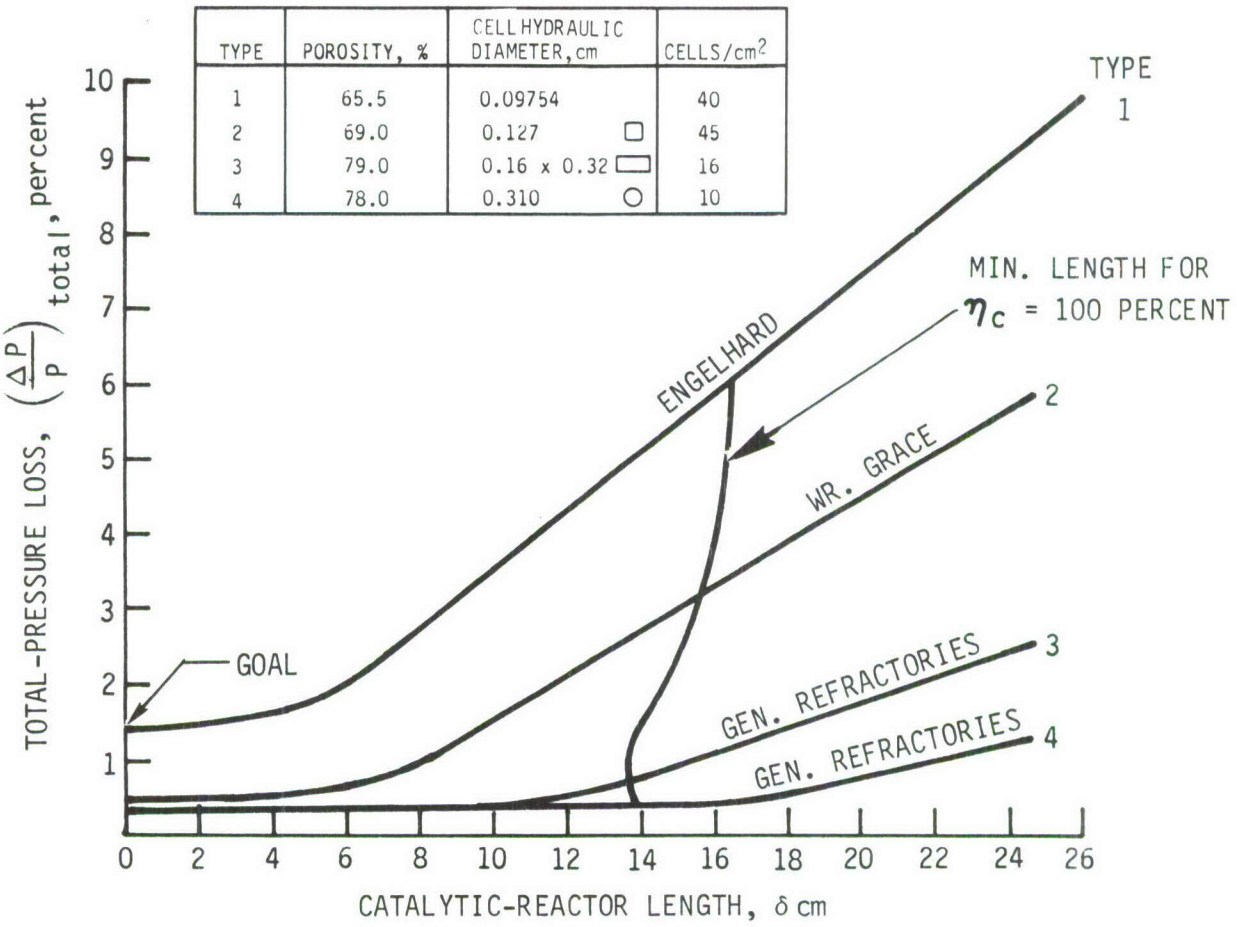


Figure 21 Concept 1: Effect of Catalytic Reactor Type on Total-Pressure Loss Variation with Reactor Length -- Standard Day Sea-Level Take-off Conditions (Installed)

It can be seen from Figure 21 that only the General Refractories reactors satisfy all the goals. The charactertistic responsible for this is the substrate porosity, which has to be about 80 percent.

Catalytic-Reactor Heating Requirements

Some preheating of the catalytic reactor is necessary for self-sustaining reaction conditions to be established. It was suggested that preheating above 600 K would be necessary for the reactor to become self-sustaining at idle ($T_{T3.0}$ = 483 K). The energy for this condition to be achieved has been estimated. The reactor volume was found from the reactor dimensions. The substrate properties of specific heat, density and thermal conductivity were taken from an American Lava Corporation bulletin for a zircon/mullite reactor with a porosity range of 65 to 72 percent.

A commercial gas-turbine engine is required to start, accelerate, and reach idle within 60 seconds in normal operation. Therefore, the preheating period cannot be long. A preheating period of one minute was assumed so that the total engine starting time was 2 minutes, which is probably acceptable. The energy requirement to achieve 600 K reactor temperature on a standard day was 44.4 kw without losses. On a cold day with losses, this requirement rises close to 100 kw, which presents unacceptable energy demands.

Concept 2: Rich front-end hybrid combustor (Figure 22)

The rich front-end hybrid combustor employs upstream thermal reaction of some of the fuel to start the engine and vaporize and partially react the remaining fuel, prior to the fuel-air mixture entering the downstream catalytic reactor.

The upstream thermal reactor may be designed to achieve high combustion efficiencies at engine idle conditions so that the downstream catalytic reactor is preheated to its extinction temperature at idle. High combustion efficiency is achieved by operating at a mixture strength close to stoichiometric, as Figure 23 shows. Since flow to the upstream thermal reactor is unmodulated, it will operate on the rich side of stoichiometric equivalence ratio at engine powers above idle. Rich operation will confer low NO_x generation, as indicated by Figure 24.

Downstream of the conventional thermal reactor and before the catalytic reactor, a rapid-quench zone can be used to add sufficient air to lower the equivalence ratio of the mixture entering the catalytic reactor to be considerably less than stoichiometric. Operation of the reactor at low equivalence ratio would give low NO_x, as Figure 24 also suggests.

A rapid-quench introduces large amounts of relatively cool dilution air to freeze chemical reactions so that NO_x generation due to "thermal soak" between the reactors would be minimized. With frozen reactions, the process is one of reducing residence time between reactors, as illustrated in Figure 25. Consideration of Figure 9 and Figure 10 demonstrates that a rapid-quench is only practical due to the presence of the downstream catalytic reactor.

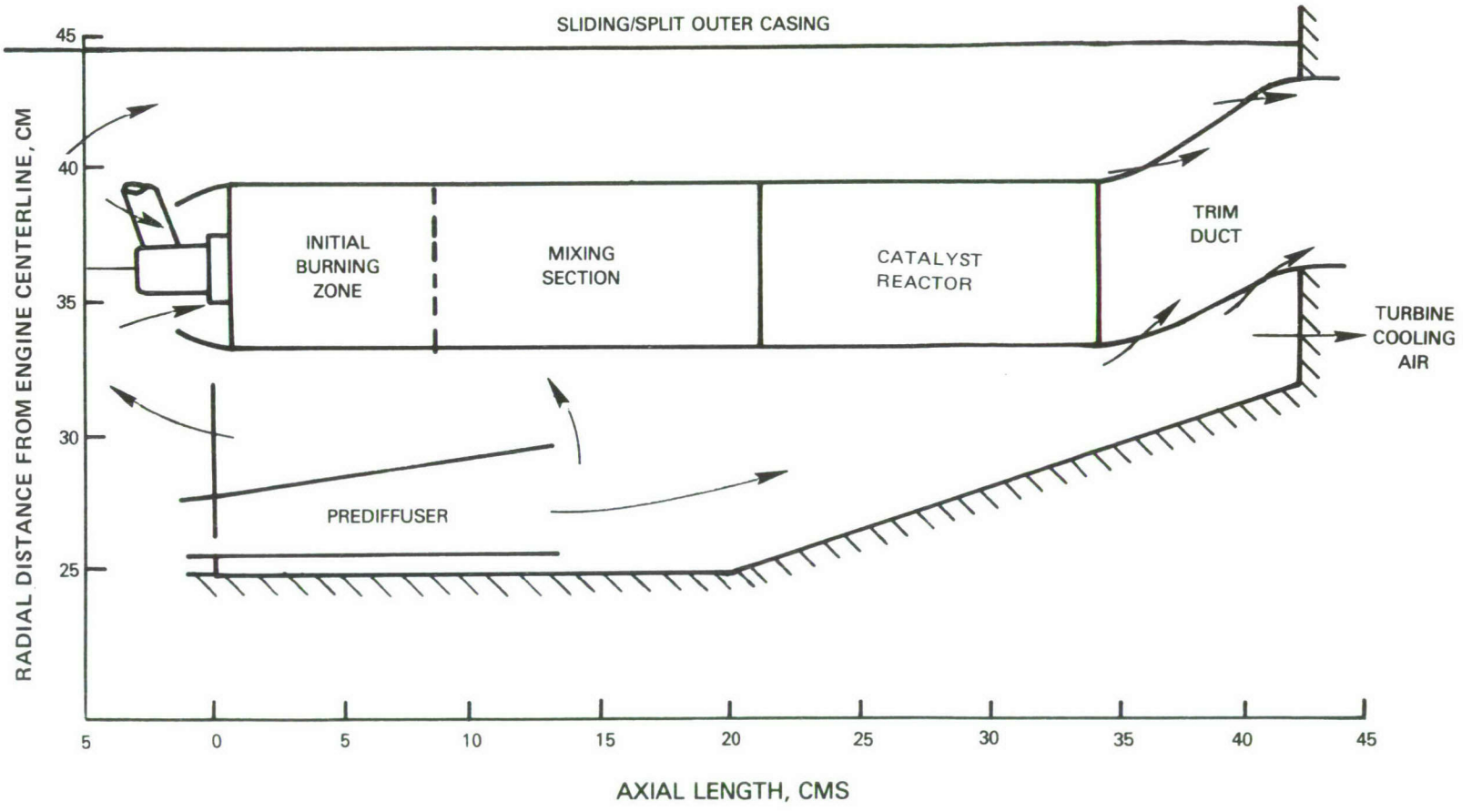


Figure 22 Preliminary Flowpath for Concept 2 - Rich-Front-End Hybrid

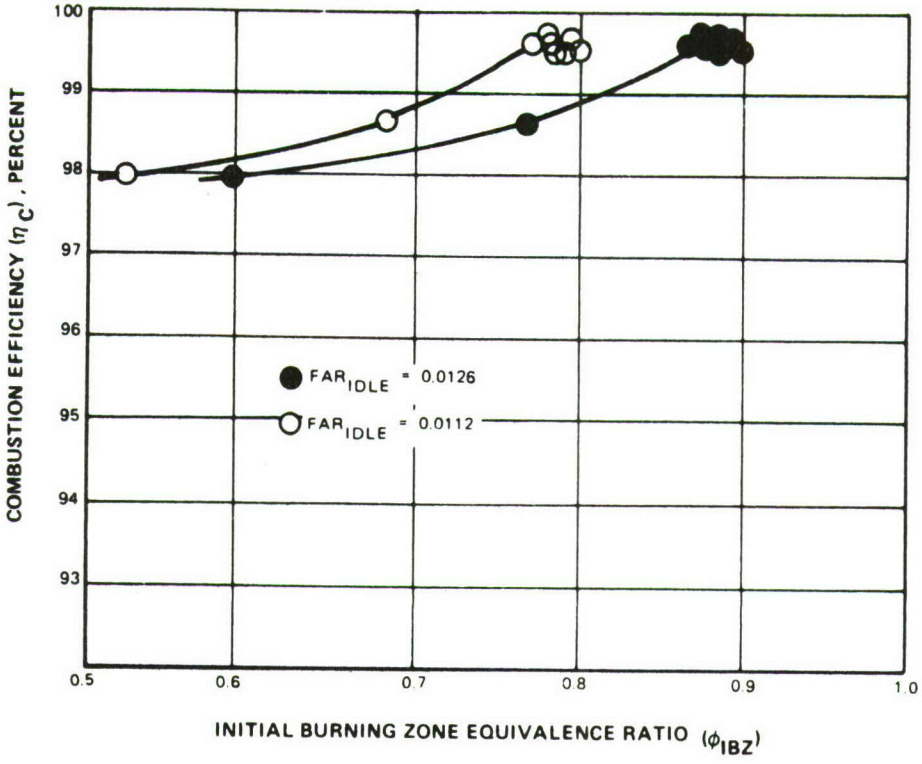


Figure 23 Dependence of Idle Combustion Efficiency on Equivalence Ratio for a Modern, Large Turbofan Engine

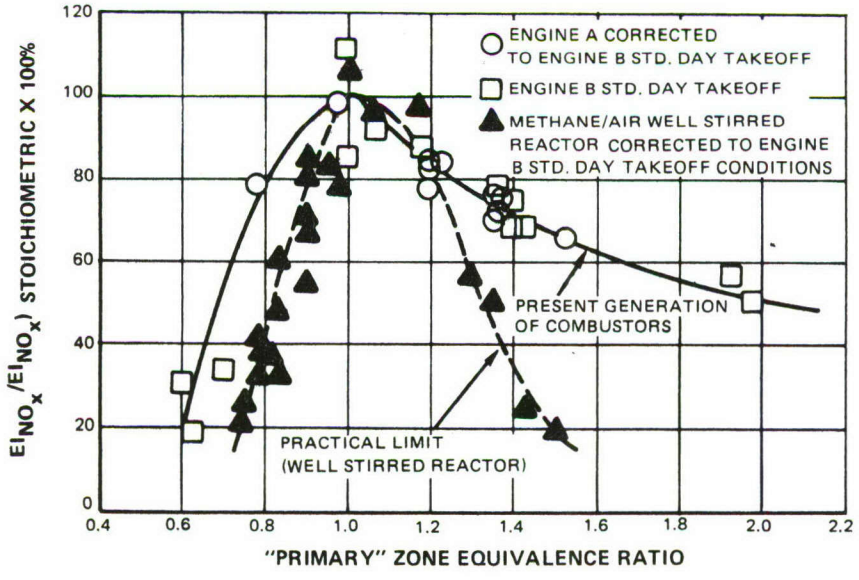


Figure 24 Conventional Combustor NO_x -Equivalence Ratio Relationship

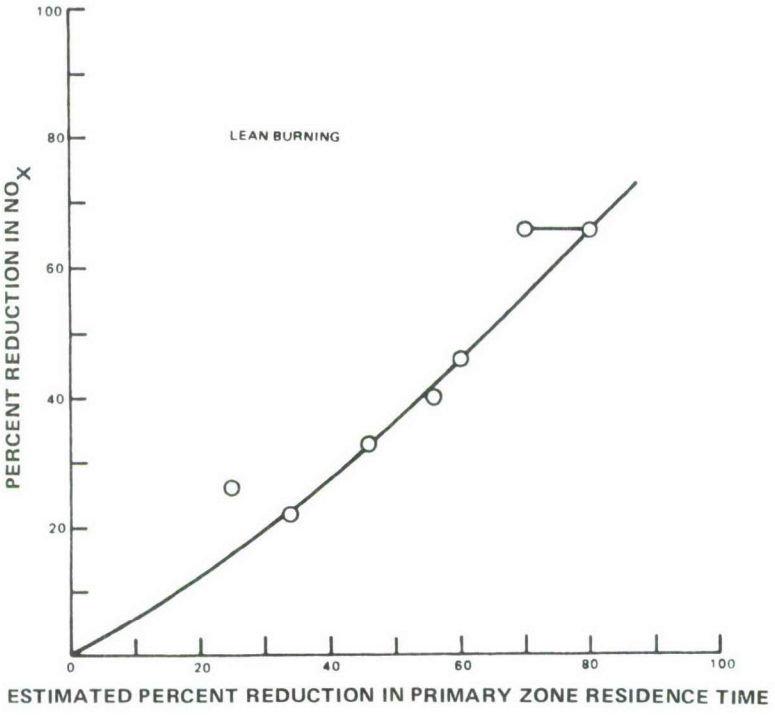


Figure 25 Reduction in NO_x Emission by Residence Time - Information Based on Experimental Data

Total-Pressure Loss Breakdown

The pressure loss breakdown given in Table III was maintained for this concept.

Diffuser Design

The diffuser design devised for Concept 1 was considered acceptable.

Design of Initial Burning Zone

The initial burning zone portion of the hybrid combustor has to be designed to satisfy the 1979 Environmental Protection Agency emissions regulations for CO and UHC at idle power. This involves sizing of the initial burning zone, so sufficient volume is provided to result in a combustion efficiency greater than 99.5 percent at all steady-state operating conditions. No reliance on the catalytic combustor for fuel conversion at idle conditions is made. The initial burning zone has also to perform other duties such as relighting easily at altitude in windmilling flight. The limiting parameter here is the initial burning zone mean throughput velocity. The combustion approach was decided as conventional swirl-stabilization.

Design of the quench-zone involves matching its characteristics with those of the initial burning zone to achieve the best combination of the following:

a) a mixed-gas temperature at idle that permits some catalytic reaction,

b) a mixed-gas temperature at takeoff that is low enough not to damage the catalytic reactor,

c) avoidance of autoignition of the quenched gases while mixing and flowing into the catalytic reactor,

d) a matching which permits catalytic reaction of the majority of the total engine fuel flow.

Consideration of the temperature of the mixed initial burning zone gases and the quench air entering the catalytic reactor shows that over wide ranges of initial burning zone idle equivalence ratio, some reliance can be placed on the catalyst to oxidize some unreacted fuel. This represents an improvement on the original assumption that the full 99.5 percent combustion efficiency required for regulation compliance had to be attained in the initial burning zone alone, and provides margin for meeting the regulations. This is illustrated in Figure 26. Lines are shown representing perfect mixing, and for hot and cold streaks due to imperfect mixing. No combustion was assumed in the quench zone. In addition, 9 percent of combustion air was used for profile trim and 3 percent was used for trim duct cooling. An arbitrary value of 0.35 was taken for pattern factor, and accords with currently achieved mixing performance.

Shown on Figure 26 is the approximate maximum extinction temperature for aged catalysts from Reference 16. At idle conditions, all the temperatures of the gases entering the reactor are above the extinction temperature. Some catalytic activity may be expected, therefore, if the initial burning zone is not as efficient as required. This permits some flexibility on deciding the actual initial burning zone idle equivalence ratio.

Figure 27 shows the possible variation of the inlet gas temperature entering the catalytic reactor at take-off conditions. Two significant temperatures are shown: the limit for a zirconia substrate, and the minimum temperature for significant CO conversion.

It is concluded from Figure 28 that autoignition of the combustibles in the quench zone at take-off power is not likely to take place even around the dilution air jets, provided that the initial burning zone idle equivalence ratio is less than 1.2 and the hydrogen in the initial burning zone products is well-dispersed through the mixture. Consequently, the quench zone will, indeed, be substantially reaction-free, and with a sufficient length to introduce the dilution air in a suitable pattern to achieved a rapid quench.

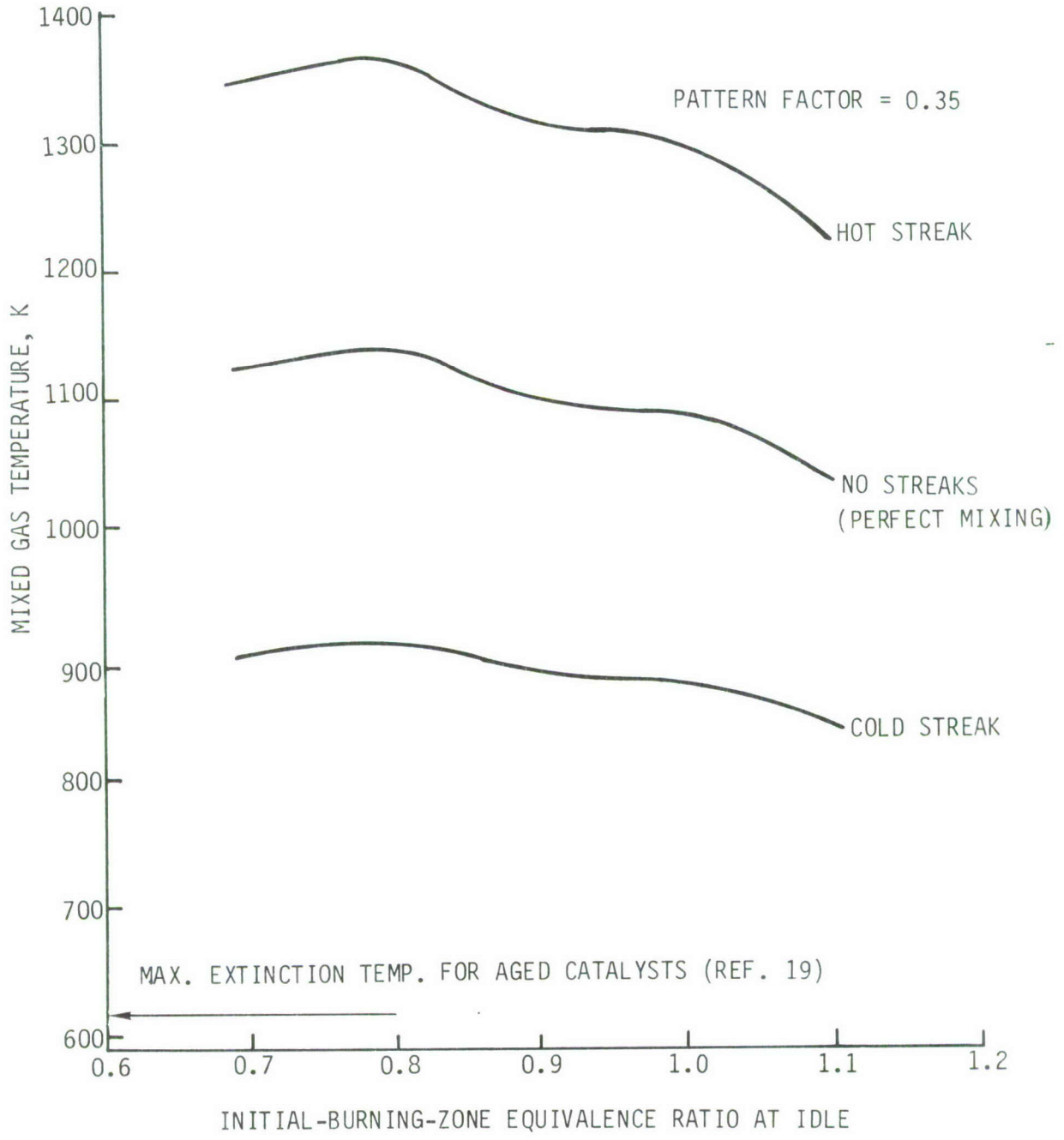


Figure 26 **Effect of Mixing, Hot or Cold Streaks, on the Catalytic-Reactor Inlet-Gas Temperature Variation with the Initial-Burning-Zone Equivalence Ratio (Concept 2)**

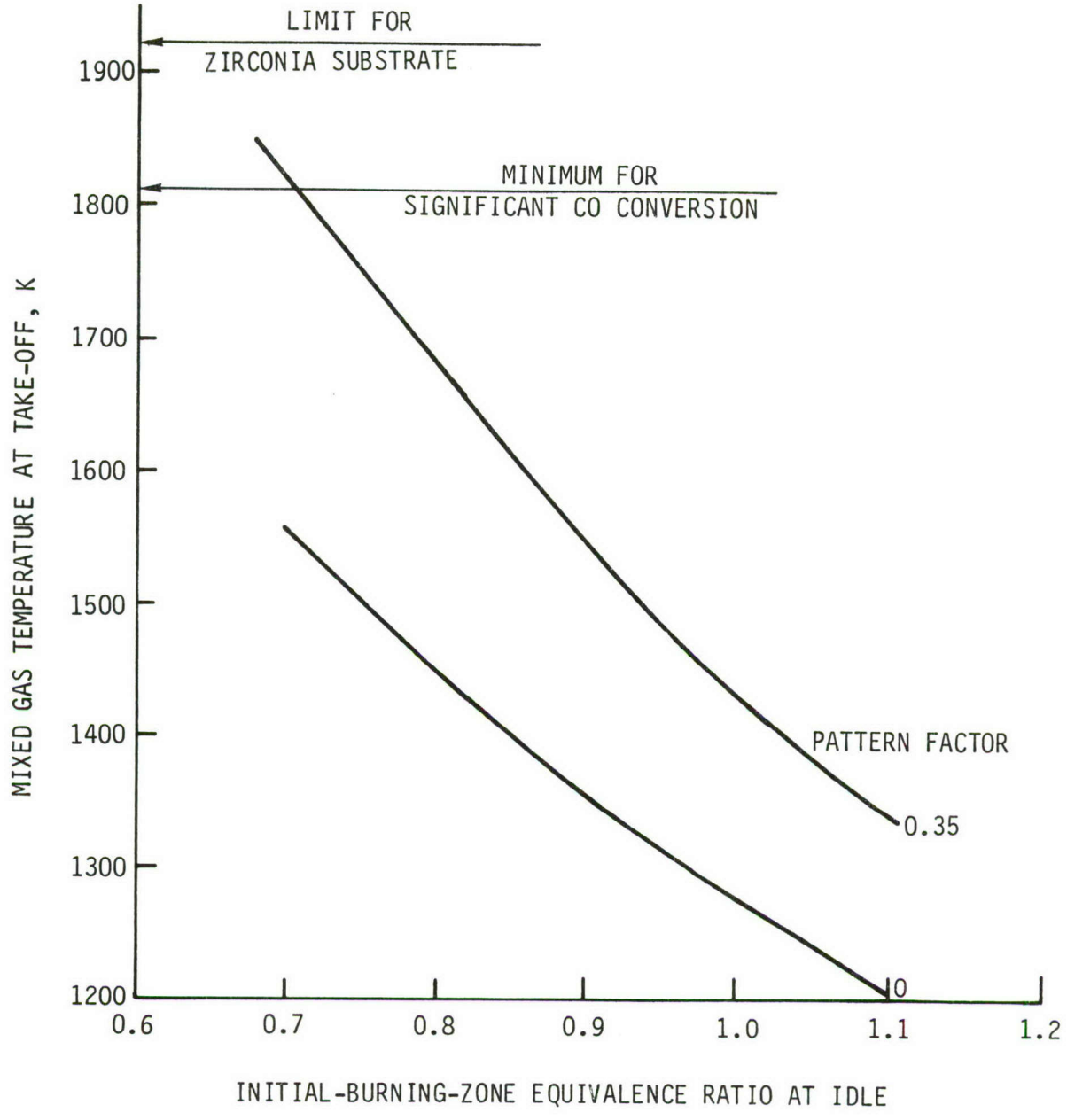


Figure 27 **Effect of Pattern Factor on the Catalytic-Reactor Inlet-Gas Temperature Variation with the Initial-Burning-Zone Equivalence Ratio**

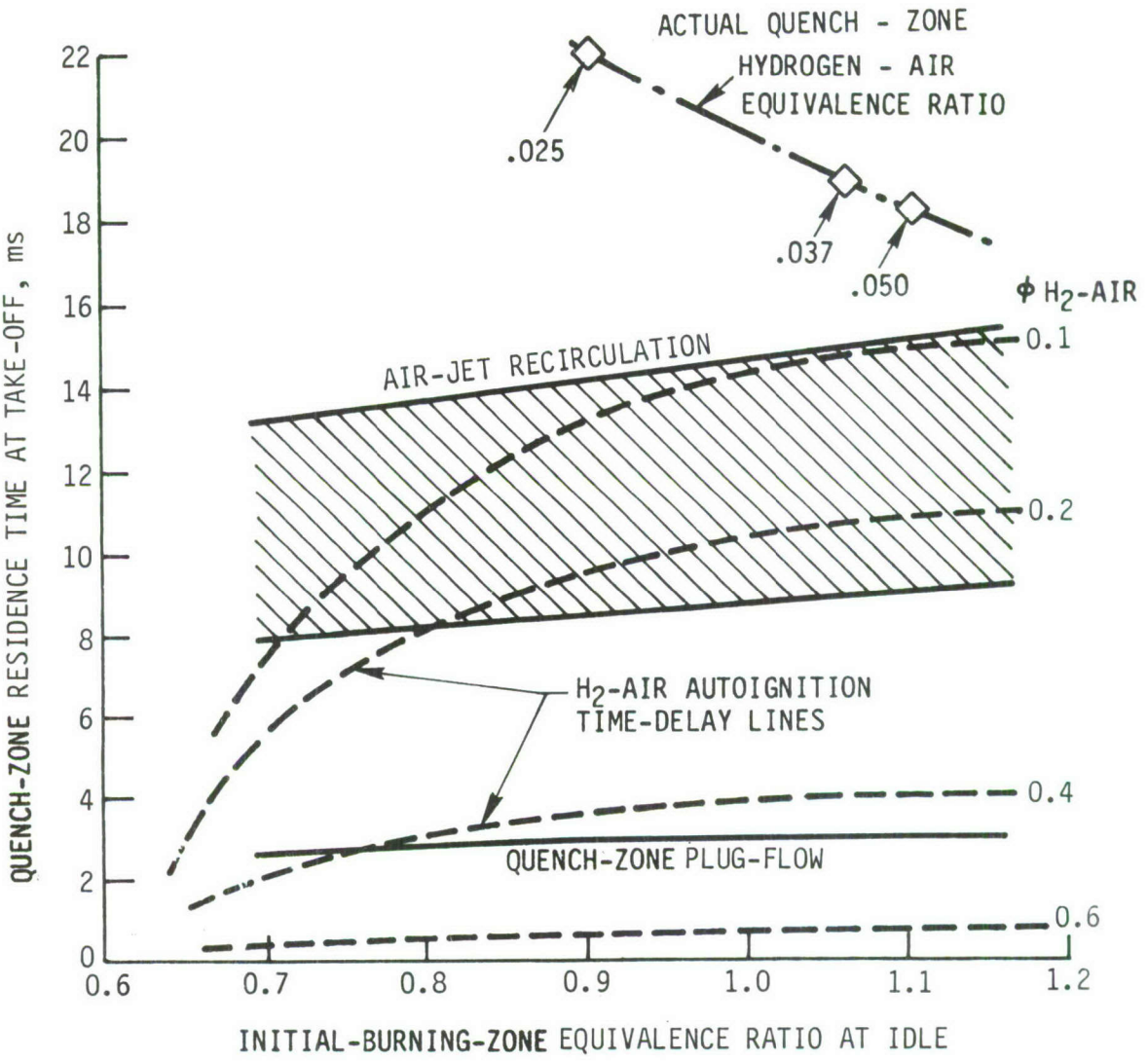


Figure 28 Quench-Zone Residence Time Dependence on Flow Field Type Compared to H_2-Air Autoignition Times for Different Equivalence Ratios

Matching of Initial Burning Zone and Quench Zone

A number of conditions linking the initial burning zone and quench zone have been studied through the link of the initial burning zone equivalence ratio at idle. These are summarized in Table VI.

TABLE VI

MATCHING OF INITIAL BURNING ZONE AND QUENCH ZONE

Initial burning zone ϕ , idle	0.7	0.8	0.9	1.0	1.1	1.2
Initial burning zone ϕ , takeoff	1.0773	1.223	1.375	1.518	1.674	1.83
Flametemp, take-off, K	2612	2529	2406	2291	2171	
Mixed temp, 0.35 Pattern Factor, idle, K	1811	1683	1544	1433	1339	
Emissions index NO_x take-off, gm/kg	35.2	5.73	0.577	0.05	0.0003	
Smoke, take-off	ok	ok	ok	ok	probably ok	problem
Mixing zone H_2 autoignition take-off	no	no	no	possible	probable	yes
Local hot gas ignition, take-off	likely	possible	?	ok	ok	possible
CO oxidation, take-off	slow	quenched	quenched	quenched	quenched	quenched
Catalyst extinction, idle	no	no	no	no	no	perhaps
Reactor durability, takeoff	marginal	ok	ok	ok	ok	ok

In Table VI, limiting lines are drawn to illustrate a possible design window for the initial burning zone idle equivalence ratio. Within this window, all initial burning zone and quench zone criteria are satisfied. Two values of initial burning zone idle equivalence ratio are possible -- 0.9 and 1.0, respectively. Accordingly, final choice between these two values will be determined by catalytic-reactor length and pressure-loss considerations.

Catalytic-Reactor Sizing

Catalytic reactors have been sized for the most promising initial burning zone idle equivalence ratios from Table VI. Sizing was done by means of the United Technologies Research Center catalyst kinetics computer program. The input conditions to this program are given in Table VII. The reactor face area was 1431 cm^2 for an annular height of 6.35 cm and an inner radius of 32.69 cm. Table VIII gives the resulting reactor lengths along with the calculated total-pressure loss for the catalytic-reactor characteristics given in Figure 21.

TABLE VII

INPUT FOR CATALYTIC-REACTOR SIZING PROGRAM AT TAKEOFF

Initial burning zone ϕ idle	0.9	1.0
Fuel to be reacted, kg/sec	0.417	0.517
Reacted products from initial burning zone, kg/sec	15.631	13.939
Quench airflow, kg/sec	38.759	40.261
Reactor mean inlet temperature, K	1355	1283

Table VIII shows negligible difference in reactor length with either equivalence ratio or different reactor geometries. Reactor length is much less sensitive to reactor geometry than was the case for the Concept 1 design. This is because of the increased inlet temperature to the reactor.

TABLE VIII

CONCEPT 2: REACTOR LENGTHS AND PRESSURE LOSSES

Reactor Type No.	1		2		3		4	
Initial burning zone ϕ idle	0.9	1.0	0.9	1.0	0.9	1.0	0.9	1.0
Reactor length, cm	14.0	13.5	13.5	13.3	13.5	13.3	13.5	13.3
Take-off pressure loss, % $P_{T3.0}$	10.19	8.88	6.92	6.14	3.15	2.86	1.7	1.41

Catalytic-Reactor Pressure Losses

The pressure losses for Concept 2 essentially have the same sensitivity to reactor geometry as was found for Concept 1, except the total-pressure loss level is elevated due to the higher temperature and velocity input conditions. The loss goal level for the reactor given in Table III is reduced by the initial burning zone heating loss and the quench-zone mixing losses. The loss goal for the reactor is 1.5 percent of $P_{T3.0}$. Table VIII shows only Reactor No. 4 with its high porosity meets this goal.

Fuel Injector Selection

The design of the fuel injectors is not critical for this concept. Thirty (30) airblast injectors were chosen. Injector pitch to dome height ratio is 1.18.

Concept 2: Design Summary

Dome height, cm	6.35
Dome inner radius, cm	32.69
Initial burning zone length, cm	7.94 (1.25 H_d)
Quench zone length, cm	12.7
Reactor length, cm	13.3
Reactor face area, cm^2	1431
Reactor characteristics:	
Cell hydraulic diameter, d_H, cm	0.31
Cell density, cells/cm^2	10
Porosity, percent	78
Idle ϕ, initial burning zone	1.0
Take-off ϕ, initial burning zone	1.518
Take-off ϕ, Reactor	0.19 (fuel treated as CxHy)
Total-pressure losses at takeoff, percent	
Diffuser	1.66
Turning	0.60
Liner	2.00
Initial burning zone and quench zone	0.10
Reactor	1.41
	5.77 (close enough to overall section loss)
Initial burning zone exit temp. at takeoff, K	2291 (perfect mixing)
Reactor inlet temp. at takeoff, K	1278 (perfect mixing)
(% $\dot{m}_{a3.0}$) entering downstream of reactor	12.7
No. initial burning zone fuel injectors	30
Fuel injector type	airblast

Concept 3: Radially-staged pilot and catalytic main combustor (Figure 29)

Concept 3 consists of separate homogeneous and heterogeneous reactors arranged as radial stages, with the homogeneous reactor acting as a continuously operating pilot and the catalytic main combustor only being turned on when the compressor delivery air temperature is above the extinction temperature of the catalyst reactor. An inboard pilot helps to reduce radial temperature profile problems. The durability of the catalytic reactor is considerably improved since it is not exposed to direct thermal reaction, or to a particularly severe starting shock.

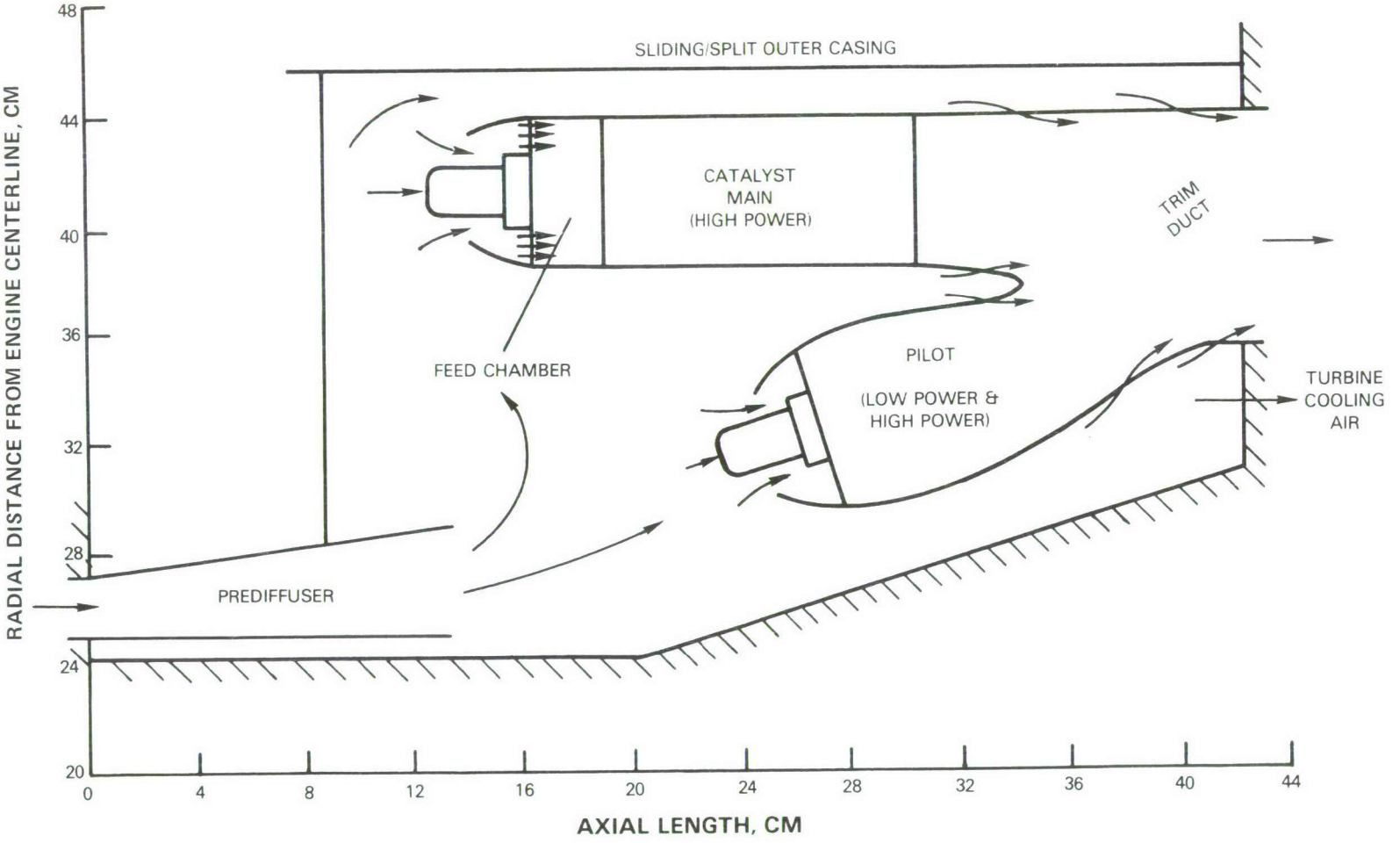


Figure 29 Preliminary Flowpath for Concept 3 - Radial Staging

Fuel staging can be arranged such that both combustors operate at the same lean equivalence ratio at take-off conditions. Lean reaction at take-off power in both reactors assures low NO_x emissions. Low CO and UHC at idle can be controlled by sizing the pilot correctly and operating close to stoichiometric mixture, according to Figure 23, when only the pilot is fueled.

Concept 3 suffers from the fact that it is extremely difficult to separately optimize the performance of the thermal pilot and catalytic main combustors with fuel staging as the only variable. To avoid a lean blowout of the pilot when fuel is introduced to the catalytic main combustor, fuel may only be supplied to the latter at very low rates. This would initially give very low main-combustor equivalence ratios. Catalytic combustors tend to produce extremely poor emissions of CO and UHC under such operating conditions. In addition, although at maximum power the temperature of the gases exiting from both combustors will be the same, this is not the case at lower powers. At powers less than take-off, the output from the pilot will always be hotter than from the main combustor. Depending on the arrangement of the pilot and main combustors, this might present a problem to the turbine.

Pressure-Loss Breakdown

The total-pressure loss breakdown given in Table III was maintained.

Diffuser Design

The diffuser design devised for Concept 1 was considered acceptable.

Design of Homogeneous Pilot Combustor

With a parallel-staged system, the engine is to idle on the pilot combustor. Therefore, the pilot combustor has to be designed to satisfy the 1979 Environmental Protection Agency low-power emissions regulations entirely on its own.

The minimum idle combustion efficiency required to satisfy the emissions is 99.5 percent. The initial burning zone study carried out for Concept 2 indicated that the best choice for idle equivalence ratio was unity. This value was, therefore, selected for the pilot combustor of Concept 3. The pilot volume necessary to satisfy the minimum combustion efficiency was determined to be $0.010 m^3$.

Swirl-stabilized combustion was selected for the conventional pilot. The dome height needed to satisfy the windmilling flight altitude relight requirements was determined to be 5.84 cm. Primary-zone inlet area was calculated as 81.68 cm^2. Fifteen percent of the total combustion air was taken for trim duct air. The pilot and main combustor were operated at the same equivalence ratio, 0.4084, for sea-level take-off conditions. Conventional guidelines were used to determine the number of fuel injectors. A near-optimum number of 30 was selected. The resulting injector pitch to dome height ratio is 1.17.

Fuel Scheduling of Catalytic Main Combustor

The main combustor cannot be fueled until the temperature of the compressor delivery air exceeds the extinction temperature ($\geqslant$600K) of the catalytic reactor. In addition, fueling cannot begin at any normal steady-state operating point of the engine.

The extinction temperature for aged present-day catalytic reactors has been previously shown to occur in the range 600-650 K. Figure 1 shows that the upper end of this temperature range occurs at about 38 percent of sea level take-off thrust, and the lower end at 24 percent. In between these thrust values is a 30 percent steady-state operating point -- an approach condition. This point has been defined as a condition at which emissions measurements are to be taken (Reference 4). Also, from a safety point of view, it is undesirable to make an approach on the pilot combustor only. Consequently, it was decided to commence fueling the main combustor at 25 percent sea-level takeoff thrust (81 percent maximum N_2) which is not a steady-state point.

Figure 30 shows the fuel-flow curves for both combustors as a function of engine core speed (N_2). The fuel-flow split is shown in Figure 31. At takeoff, three-quarters of the total fuel flow is reacted catalytically. Figure 32 shows the equivalence ratio characteristics of the two stages. At takeoff, all the fuel is reacted lean, so that NO_x emissions are minimized.

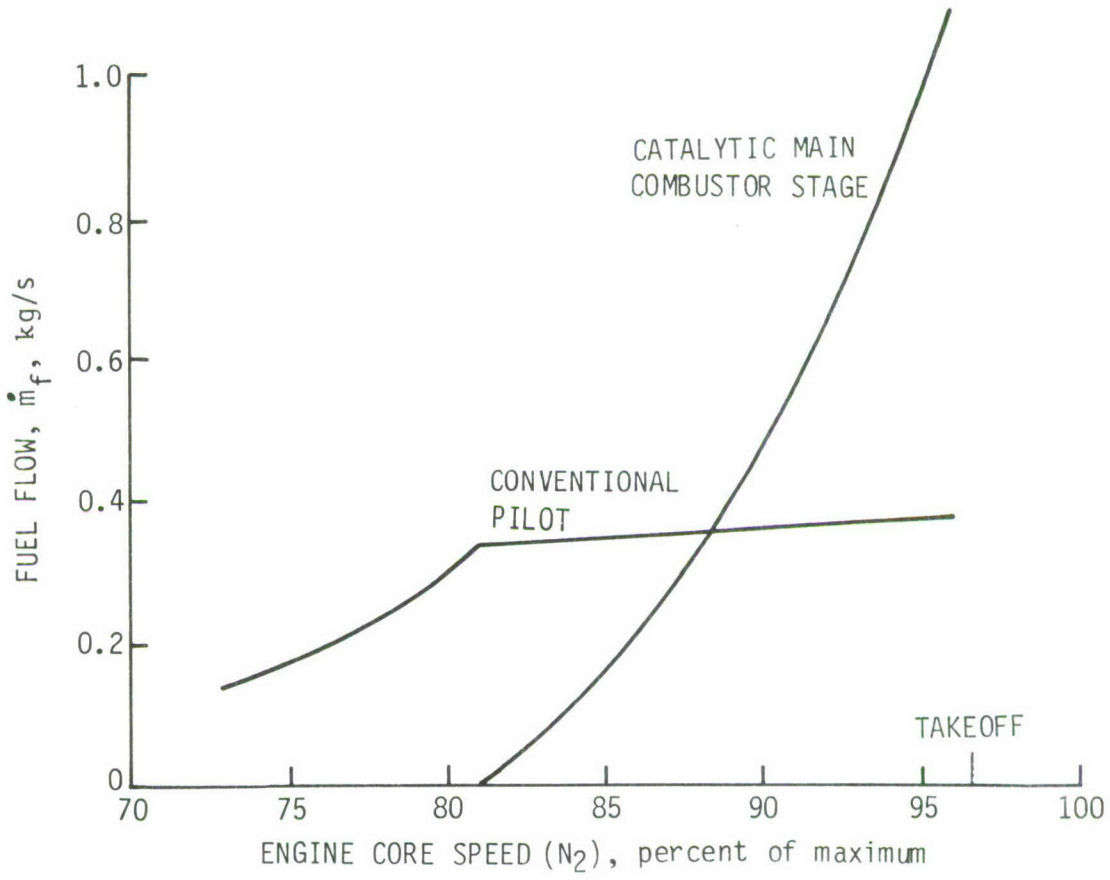


Figure 30 Concept 3: Main Combustor and Pilot Combustor Fuel Flow Variation with Engine Core Speed

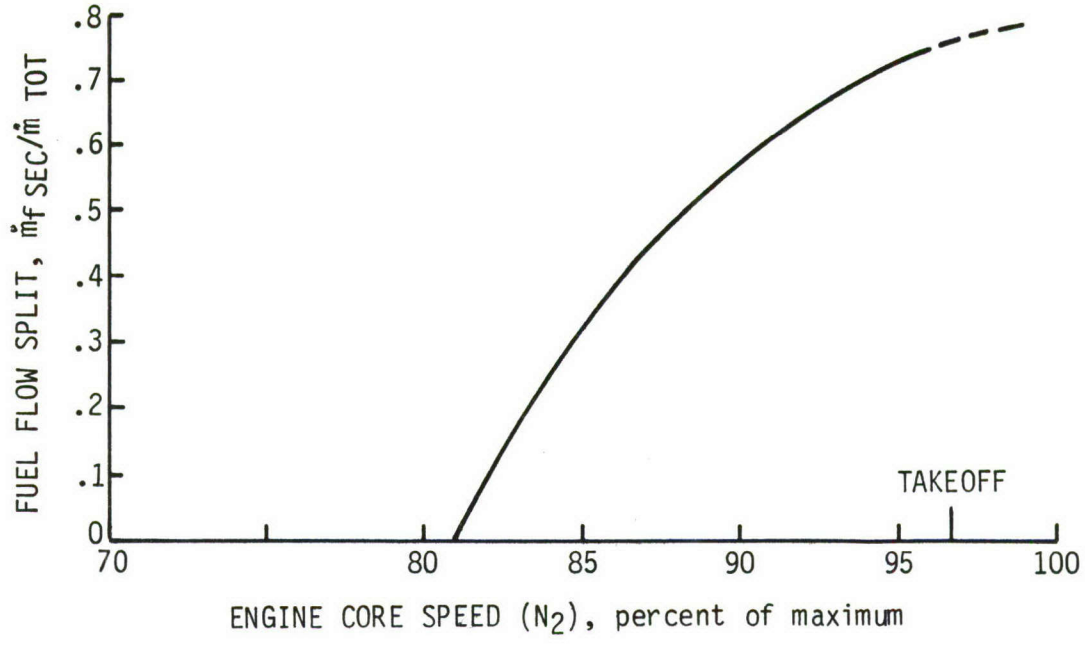


Figure 31 Concept 3: Main Catalytic-Combustor Stage Fuel Flow Fraction Dependence on Engine Core Speed

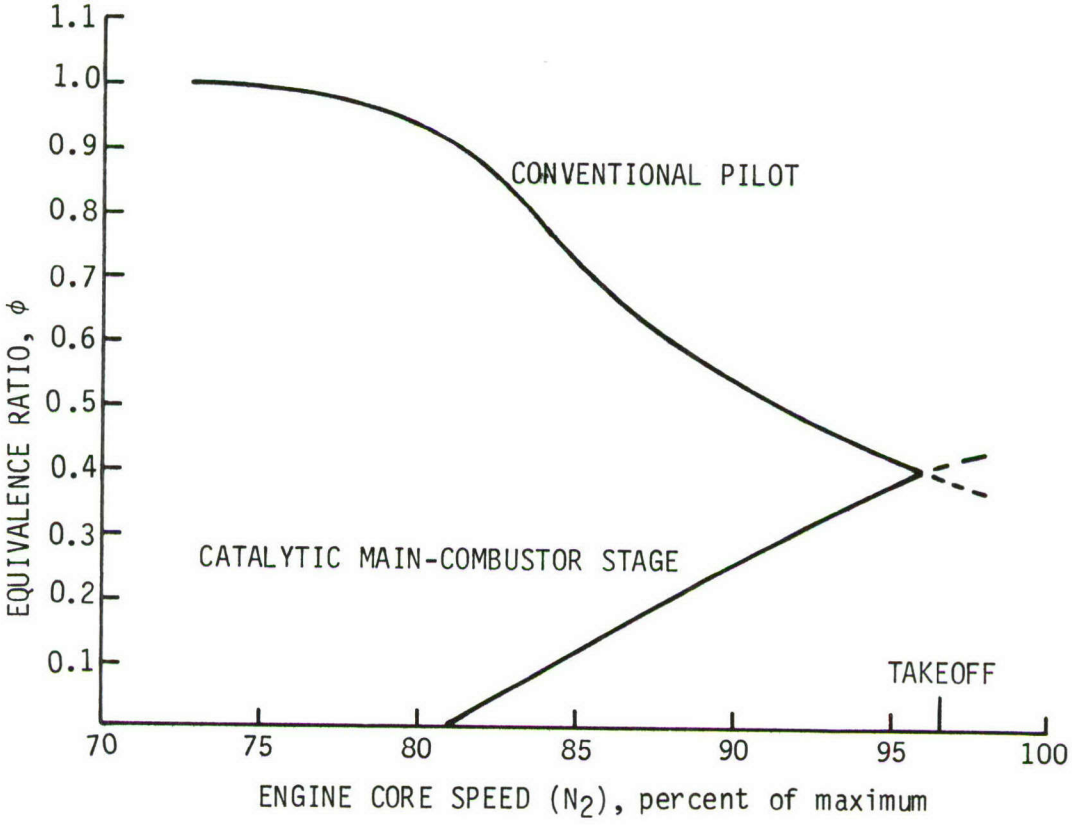


Figure 32 Concept 3: Equivalence-Ratio Variation with Engine Core Speed for Each Combustor Stage

The ramp-function fueling used for the main combustor, Figure 30, results in extremely low equivalence ratios in the catalytic reactor, as Figure 32 shows. Anderson (Reference 17) and others have found that the combustion efficiencies of reactors operated at these types of conditions tend to be low. This might constitute a CO and UHC emissions problem at the approach condition.

Catalytic Main-Combustor Design

With the catalytic-reactor equivalence ratio of 0.4084 at takeoff and the fuel-flow split of Figure 30, the maximum reactor temperature at take-off with an assumed 0.35 pattern factor is 2043 K. This temperature is approximately equal to the upper temperature limit for the substrate. It is therefore required that the fuel-air preparation section produce a pattern factor less than 0.35.

The autoignition delay at take-off conditions is 1.2 milliseconds for JP5. This fixes the length of the fuel preparation section. For a right cylindrical form of the annular combustor a relationship can be developed linking the relevant parameters, i.e.

$$H_d L = \frac{\tau \dot{m}}{2\pi \rho \bar{r}}$$

where,

τ	=	autoignition delay
$\dot{m}$	=	gaseous mass flow rate in fuel preparation section
H_d	=	dome height (annular height of fuel preparation section)
$\bar{r}$	=	mean radius of fuel preparation section
L	=	length of fuel preparation section
ρ	=	density of gases flowing

A reasonable value for r is 41.28 cm. The maximum value of H_dL would then be 14.307 cm. The minimum practical value for L is 1/2 H_d so that the maximum H_d is 5.36 cm and the evaporation distance would be 2.68 cm.

Prefilming airblast fuel injectors were selected. Figure 17 shows that a prefilming injector with a characteristic dimension less than 2 cm can produce a spray at take-off conditions with an Sauter Mean Diameter less than 12 micrometers (μm). Calculation shows that sixty such injectors would result in 92 percent evaporation of JP5 in the distance of 2.68 cm.

The catalytic reactor was sized using the United Technologies Research Center Catalytic Kinetics Computer program. The major input conditions were the reactor inlet-face area of 1317 cm^2 and the mixture approach velocity of 24.12 m/s. The reactor length produced by the program was 11 to 12 cm for the four reactor internal geometries considered.

Catalytic-Reactor Pressure Losses

The total-pressure losses through the reactor were made for a 11.5 cm length and four different internal geometries. Table IX gives the results of the calculations.

TABLE IX

CONCEPT 3: REACTOR PRESSURE LOSSES

Reactor No.	1	2	3	4
Porosity, %	65.5	69.0	79.0	78.0
Cell hydraulic dia., cm	0.09754	0.127	0.213	0.310
Cell Density, cells/cm^2	40	45	16	10
Total-pressure loss, percent	2.28	1.34	0.46	0.47

The pressure loss goal is 1.6% $P_{T3.0}$, from Table III. Therefore, reactors 2, 3 and 4 would all be suitable for this concept. This flexibility is worthwhile in view of the potential emissions problem at approach as discussed in the section entitled "Fuel Scheduling of Catalytic Main Combustor".

Concept 3 Design Summary

Pilot combustor:

Dome height, cm	5.84
Primary-zone volume, m^3	0.010
Primary-zone mean radius, cm	32.56
Primary-zone length, cm	10.16
Idle ϕ primary-zone	1.0
Take-off ϕ primary-zone	0.4084
No. fuel injectors	30
$\dot{m}_f$, (max), kg/s	0.38

Main combustor:

Dome height, cm	5.36
Fuel prep. length, cm	2.68
No. fuel injectors	60
Type fuel injectors	airblast, prefilming
Fuel injector characteristic dim., cm	<2
Reactor mean radius, cm	41.28
Reactor length, cm	11.5
Idle ϕ	0
Take-off ϕ	0.4084
$\dot{m}_f$, (max), kg/s	1.098
Core speed at fuel cut-in., percent max N_2	80
Reactor face area, cm^2	1317
Reference velocity, m/s	24.12

Total-pressure losses at takeoff, percent

Diffuser	1.66
Turning	0.60
"Liner"	2.00
Bed	1.34
Mixing	0.10
	5.70 (close enough to overall section loss)
Total combustion air for exit temperature profile trim, percent	15

Concept 4: Modulated airflow, axially-staged hybrid combustor

A variable geometry version of Concept 2 was selected as the basis for this concept. Air-modulation is used to give an initial burning zone which is at or near stoichiometric mixture strength at engine idle, but is made lean at high power. A diagramatic representation is illustrated in Figure 33. To achieve the required low NO_x emissions at take-off, the equivalence ratio has to be far removed from stoichiometric. The resulting high air loading of the thermal reactor is likely to result in reduced combustion efficiency. However, high emissions of CO and UHC at take-off would not be expected to become a problem since the downstream catalytic reactor acts as a clean-up device.

This concept is unlike the others. Only a small fraction of fuel is reacted catalytically. The variable geometry must be applied in such a fashion to ensure a constant combustor pressure drop/flow relationship.

Pressure-Loss Breakdown

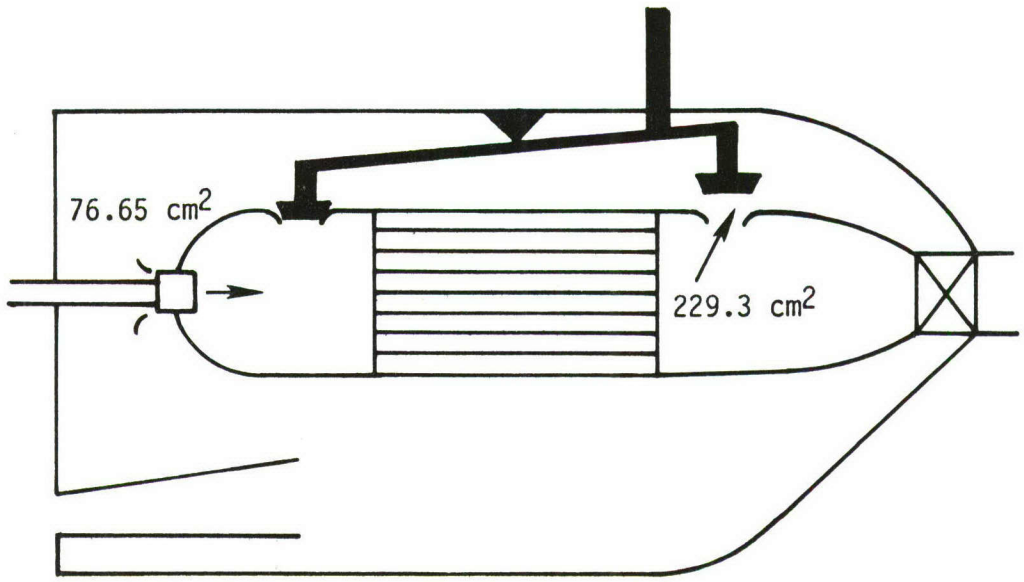
The total-pressure loss breakdown given in Table III was maintained for this concept.

Diffuser Design

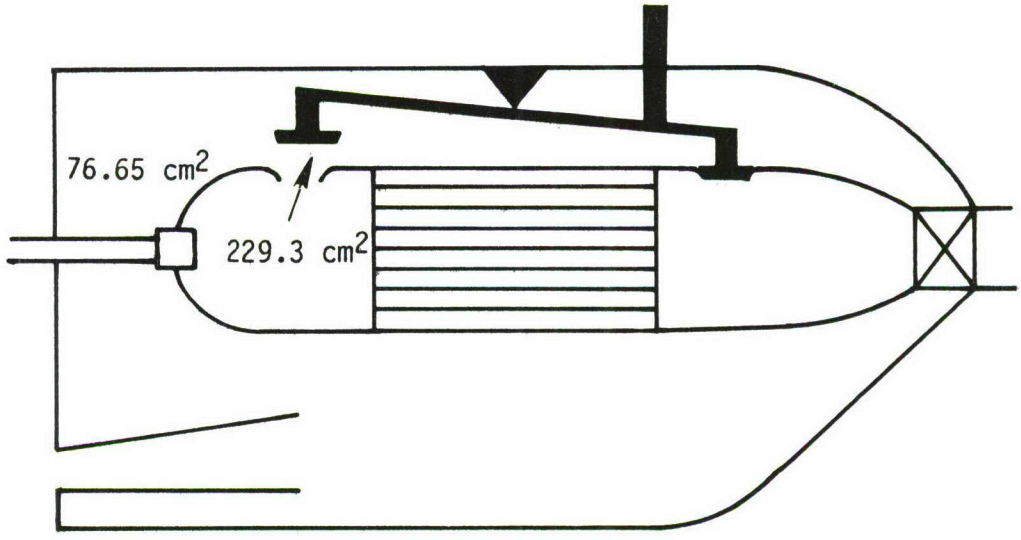
The diffuser design devised for Concept 1 was considered acceptable.

Variable Geometry

It is desirable to have a constant pressure loss relationship with flow function for the combustor. The implication is that when a flow area is opened or closed in one part of the combustor, a compensating flow area is closed or opened in another part of the combustor. This requires a differential variable geometry system such as the simple, two-position system illustrated in Figure 33.



IDLE



TAKE-OFF

Figure 33 Diagrammatic Representation of Concept 4: Two-Position, Variable-Geometry Operation

To avoid possibilities of a lean blow-out, it was necessary to select a partially modulating variable geometry rather than a two-position device. The total inlet area variation required was large, and equal to 229.3 cm^2. From a safety point of view, it was advantageous to split this total variation into two parts by a major movement of the geometry that separated idle powers from flight power levels. The major portion of movement could be executed in a single movement at a particular engine setting as with a simple, two-position system, while the portion prior to and following this could be carried out as a continuous change with varying setting.

Elimination of the quench zone used in Concept 2 exposes the catalytic reactor to potentially high inlet temperatures. To minimize this problem at altitude, it was necessary to control the variable geometry operation on a basis of percent maximum engine core speed (N_2) rather than thrust, and also, to reduce the initial burning zone equivalence ratio at idle from unity to 0.684. In fact, it was necessary to design the variable geometry prior to the major shift, for a constant flame temperature below the substrate limit of 2000 K.

Figure 34 shows the initial burning zone inlet-area variation as a function of speed. Operation consists of continuous variation to maintain constant initial burning zone flame temperature (1978 K), and a step-shift, followed by continuous variation to maintain constant equivalence ratio. Figure 35 shows the operation in terms of combustor loading. It can be seen that the constant flame temperature requirement reduces idle combustion efficiency to 98 percent.

Also shown on Figure 35 is a variable geometry operation that achieves the same results in terms of emissions without the need for a catalytic reactor.

Altitude Operation of Variable Geometry

With engine speed control of the variable geometry, the variation of catalytic reactor inlet temperature during a typical climb is shown in Figure 36. This temperature increases slowly from the take-off value of 1718 K to 1772 K at 10,668 meters altitude at 0.8 flight Mach number. These values are well within the capability of the substrate material. The catalyst extinction temperature is exceeded, although initial burning zone combustion efficiency is always greater than 99 percent.

Note that the temperatures have been presented in terms of thrust rather than speed. This is a matter of convenience in plotting, as Figure 6 will explain. The calculated variation however, does depend on speed and not thrust.

Typical cruise behavior is shown in Figure 37. From a maximum reactor inlet temperature of 1772 K at the end of climb, cruise reduces this temperature to the range 1742 to 1693 K, depending on the actual cruise point. These temperatures are perfectly acceptable to the reactor substrate material.

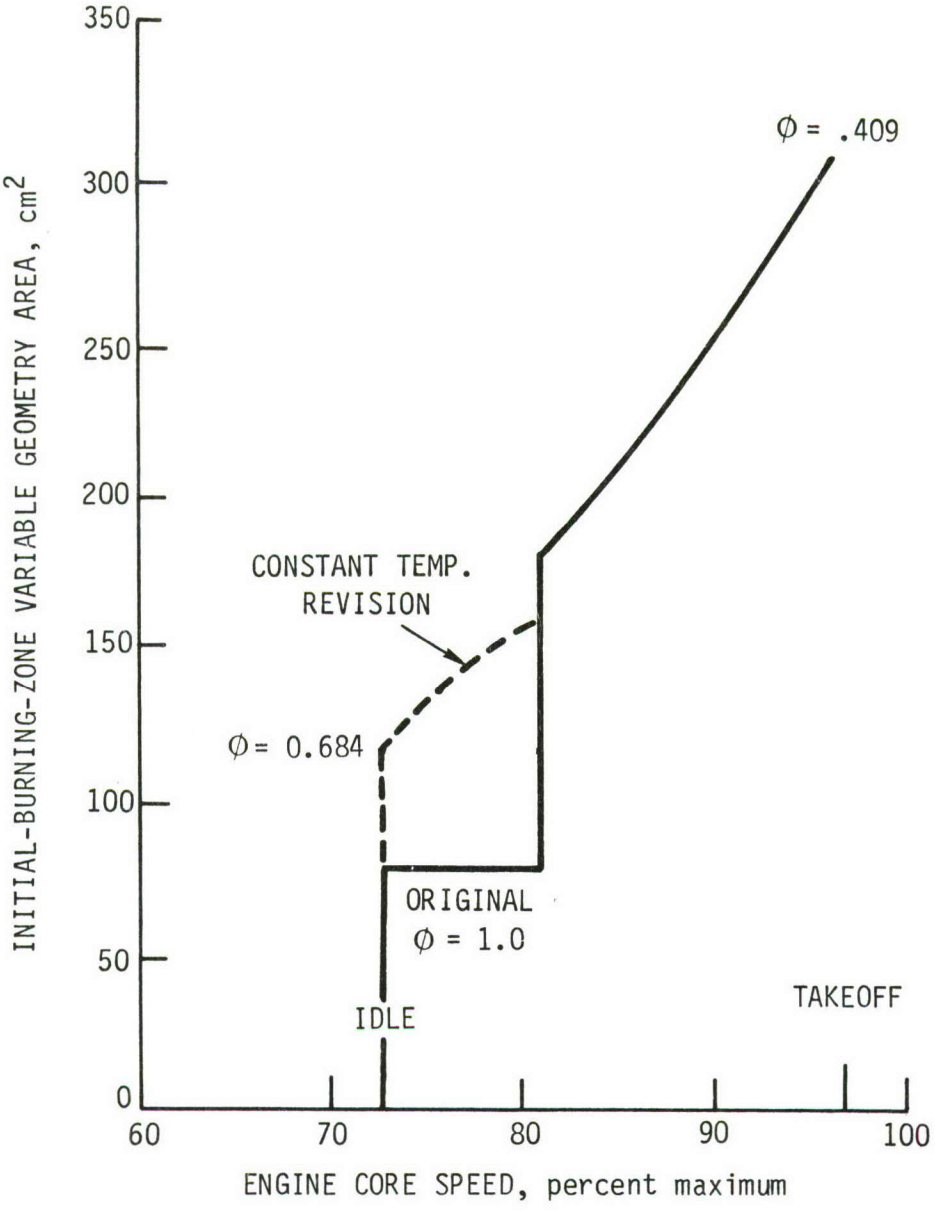


Figure 34 Concept 4: Relationship between Initial Burning Zone Variable Geometry Area Variation and Engine Core Speed

Although the catalyst is active at these temperatures, the initial burning zone combustion efficiency remains above 99 percent at all cruise points.

Figure 38 shows the lean blow-out stability margins in the initial burning zone during cruise conditions. The stability margin is represented by the difference in equivalence ratio between the operating value and the limiting value for lean blow out. A negative value would indicate a lean blowout, and zero on unstable flame. Sufficient margin exists for safe operation.

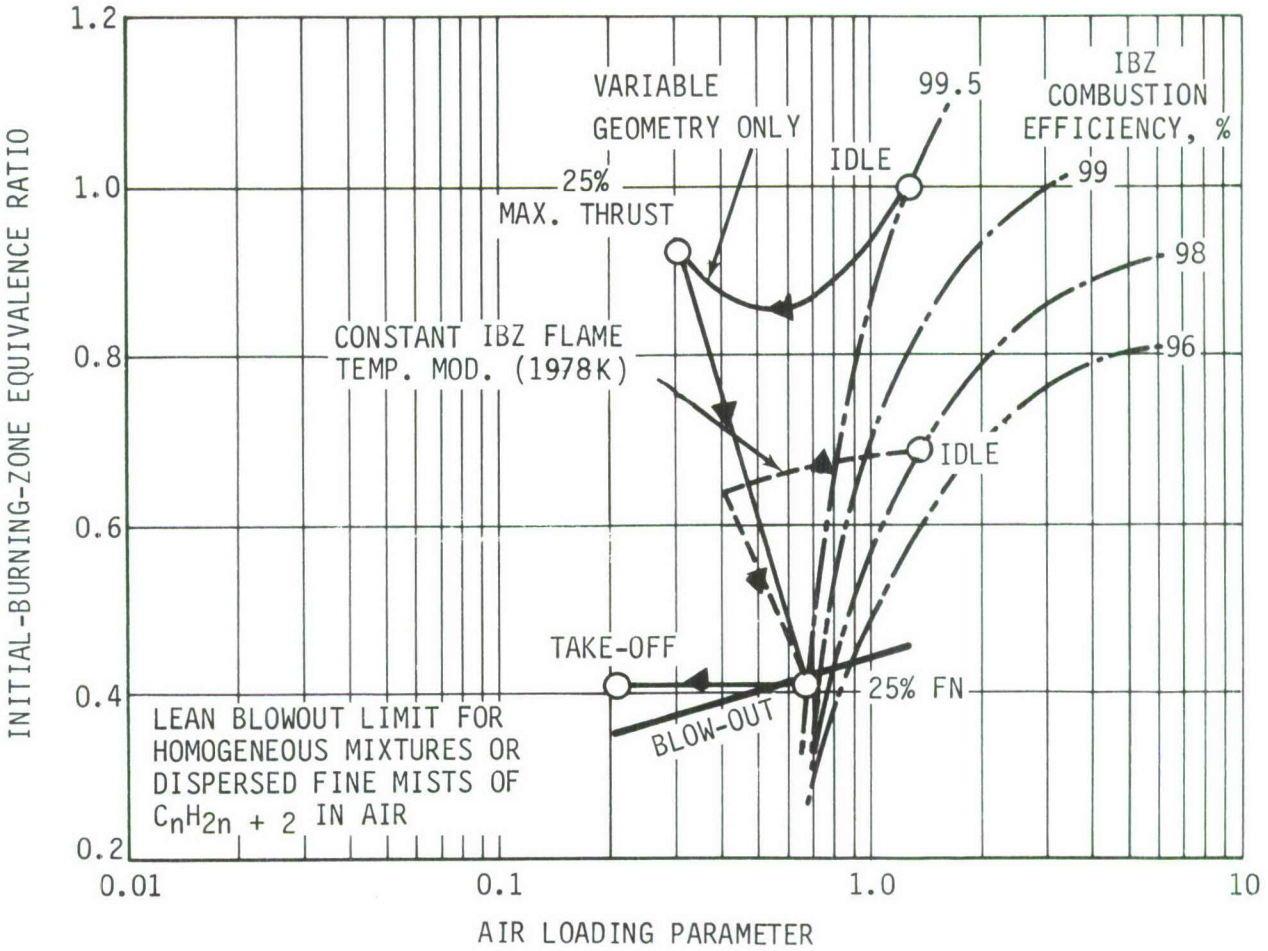


Figure 35 Concept 4: Revised Modulating Variable Geometry Initial Burning Zone Equivalence Ratio Dependence on the Air Loading Parameter

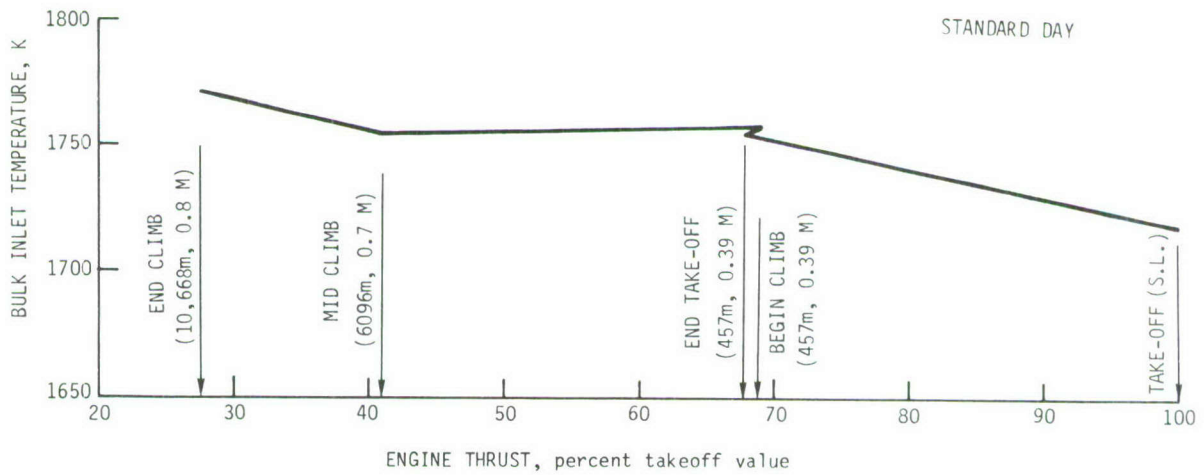


Figure 36 Concept 4: Reactor Bulk Inlet Temperatures During Typical Climb with Engine Speed-Controlled Variable Geometry

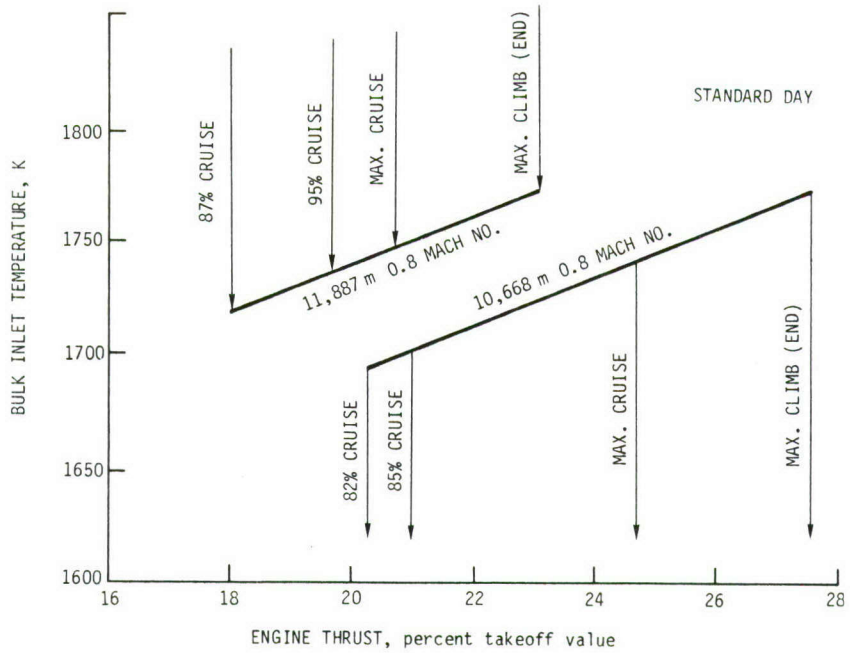


Figure 37 Concept 4: Reactor Inlet Bulk Temperature Dependence on Cruise Conditions for Engine-Speed Controlled Variable Geometry

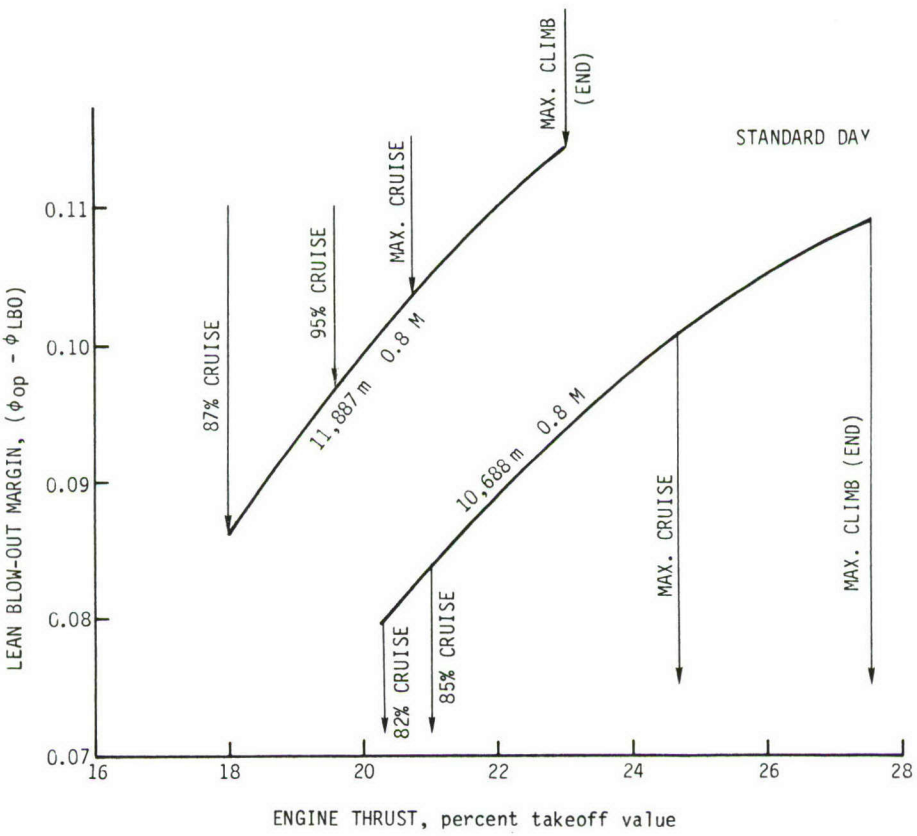


Figure 38 Concept 4: Combustion Stability Margin Dependence on Cruise Conditions for Engine Speed-Controlled Variable Geometry

On idle descent from altitude cruise, initial burning zone temperatures fall very considerably, as does combustion efficiency. With swirl-stabilized combustion in the initial burning zone, lean blow outs should not occur. (However, there is no real margin for reducing the initial burning zone equivalence ratio at ground idle.) Combustion efficiency is less than 90 percent at some conditions on a descent, but as reactor inlet temperatures remain over 1400 K, the overall combustion efficiency should remain high due to the catalytic effect.

Catalytic-Reactor Sizing

It can be realized from the foregoing that the catalytic reactor is somewhat redundant with this concept. At idle, the reactor is needed only because the initial burning zone equivalence ratio cannot be optimized due to temperature limitations on the reactor. However, at idle, and at approach, it does act as a clean-up device to raise the overall combustion efficiency to satisfy the emissions regulations. During idle descent from altitude cruise, the reactor acts as a clean-up device to improve the reduced initial burning zone combustion efficiency. However, there are no emission regulations governing the descent mode of flight operations. At no point is a significant quantity of fuel reacted catalytically. Where it does contribute to overall combustion efficiency, the reactor only serves in the clean-up role.

The fuel to be reacted catalytically is shown in Figures 39 and 40. Figure 39 expresses the fuel in terms of the mass fraction of unburned fuel components entering the reactor at sea-level power. Figure 40 shows the mass fraction of unburned fuel at the cruise conditions, where again, there are no emissions regulations or recommendations concerning CO or UHC. During idle descent from altitude cruise, the mass fraction of unburned fuel entering the reactor is in the range 0.001 to 0.002. Although the amount of fuel to be reacted catalytically at idle is twenty times that at take-off, it is still a small amount.

The design point for sizing the reactor was the take-off condition with an assumed initial burning zone combustion efficiency of 98.5 percent. This represents the worst combination of circumstances. The input conditions to the United Technologies Research Center computer code were as follows:

Reactor face area	=	1431 cm^2	(Reactor annular height = 6.35 cm with inner radius of 32.69 cm)
Inlet temperature	=	1711 K	
Inlet pressure	=	2.945 MPa	
Reference velocity	=	63.7 m/s	

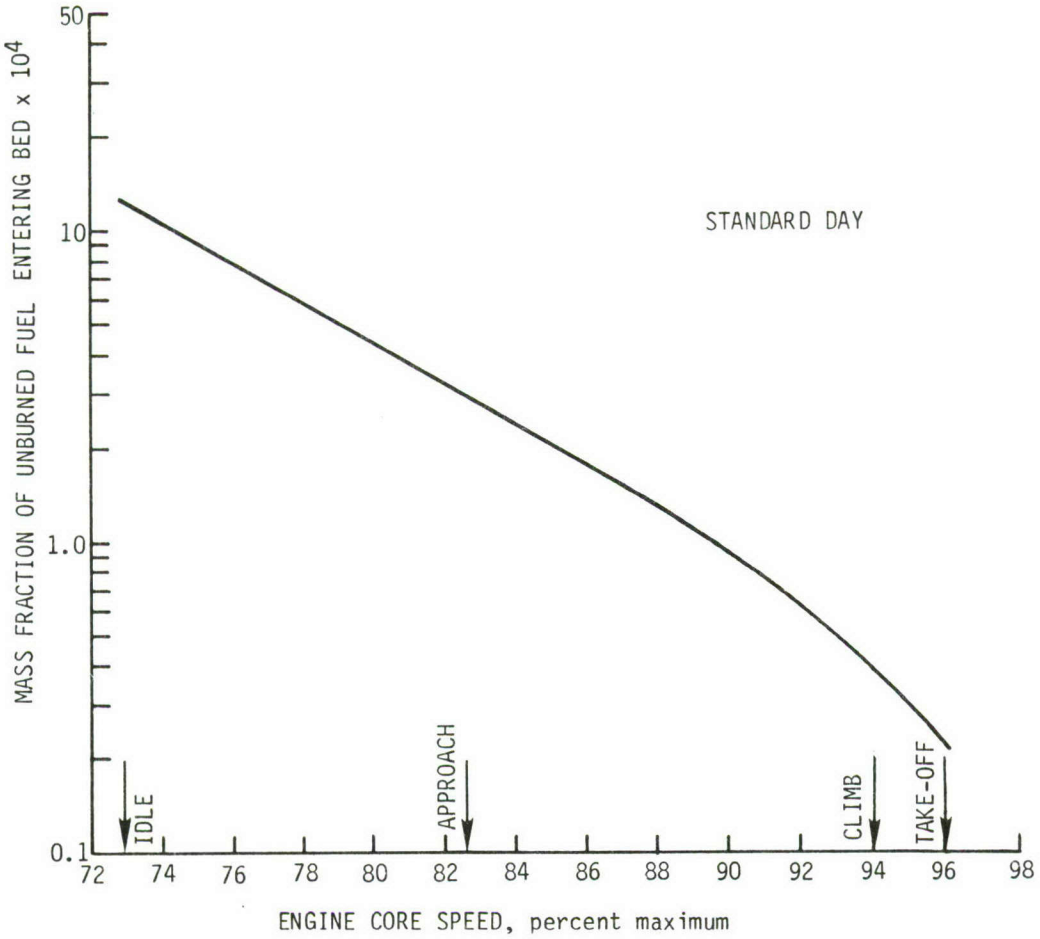


Figure 39 Concept 4: Mass Fraction of Unburned Fuel Entering the Catalytic Reactor at Sea Level

Composition of entering gases in unit time (simple treatment):

Component	Mass fraction	
O_2	0.1349	
N_2	0.7468	
H_2O	0.0342	
CO_2	0.0836	
$C_{12}H_{24}$	0.00041	(note that this is somewhat higher than that given in Figure 39)

The resulting reactor length for the types considered earlier is 9 cm. While shorter than the reactor lengths for earlier concepts, this length appears high for a clean-up device. The reason for this is the short residence time reflected in the high value of reference velocity.

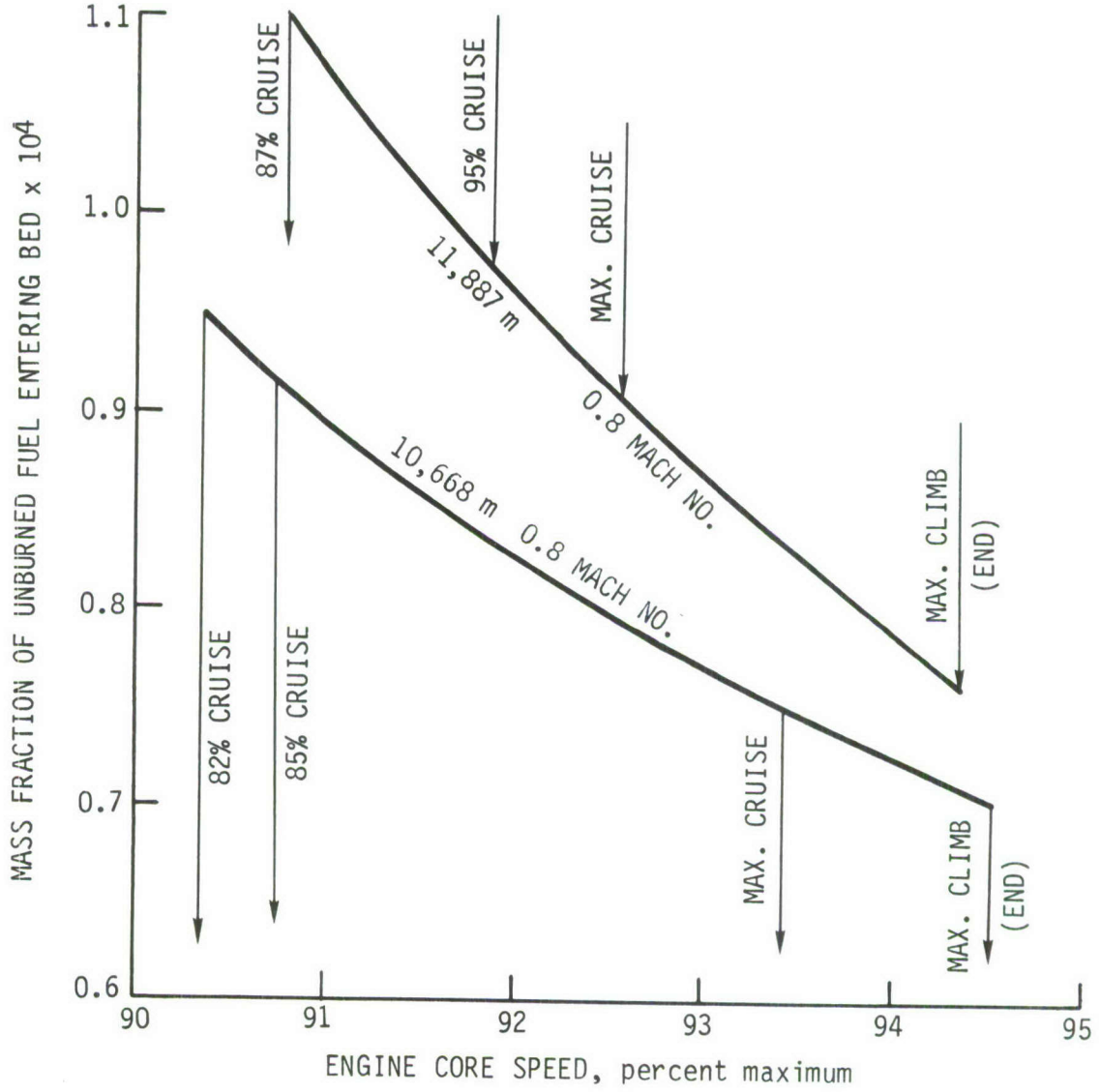


Figure 40 Concept 4: Mass Fraction of Unburned Fuel Entering the Catalytic Reactor at Cruise

Catalytic-Reactor Pressure Losses

The total-pressure losses through the 9 cm length reactor are given in Table X.

TABLE X

CONCEPT 4: REACTOR PRESSURE LOSSES

Reactor No.	1	2	3	4
Porosity, %	65.5	69.0	79.0	78.0
Cell hydraulic dia., cm	0.09754	0.127	0.213	0.310
Cell density, cells/cm^2	40	45	16	10
Total-pressure loss, percent	2.28	1.34	0.46	0.47

With the pressure-loss goal of 1.6 percent $P_{T3.0}$, reactors 2, 3 and 4 would all be suitable for this concept. The losses of these reactors are less than those for Concept 2 (Table VIII). This arises from the shorter length of the present reactors, and also because the contribution of heat release losses to the total loss are negligible.

Concept 4: Design Summary

Dome height, cm	6.35
Dome inner radius, cm	32.69
Initial burning zone volume, m^3	0.010
Initial burning zone length, cm	6.35 (min. to satisfy volume)
Initial burning zone idle ϕ	0.684
Initial burning zone take-off ϕ	0.4085
Initial burning zone exit-temp. at idle, K	1978
Initial burning zone exit-temp. takeoff, K	1718
Initial burning zone fixed inlet area, cm^2	16.77 (effective) reflecting the change
Initial burning zone total inlet area, cm^2	309.68 (effective)
Variable geometry operation	continuous from idle
No. fuel injectors	30
Catalytic reactor face area, cm^2	1431
Catalytic reactor thickness, cm	9
Catalytic reactor characteristics	Nos. 2, 3, 4

Concept 5: Modulated airflow, radially-staged pilot and catalytic main combustor (Figure 41)

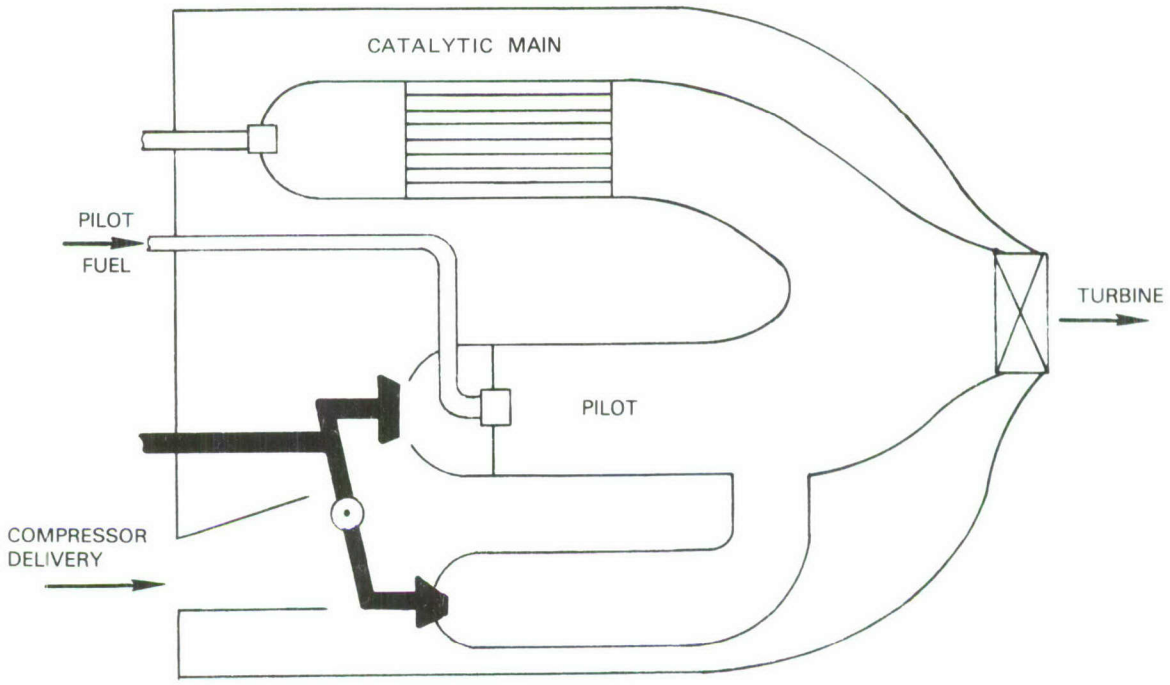
Concept 5 is a variable geometry version of Concept 3, where fuel staging and pilot combustor-air management are controlled to give equal equivalence ratios in the two combustors at all operating conditions. Use of air modulation in the pilot combustor allows a step increase in fuel flow to the main combustor to reduce starting and low flight-power efficiency problems anticipated with Concept 3.

Pressure Loss Breakdown

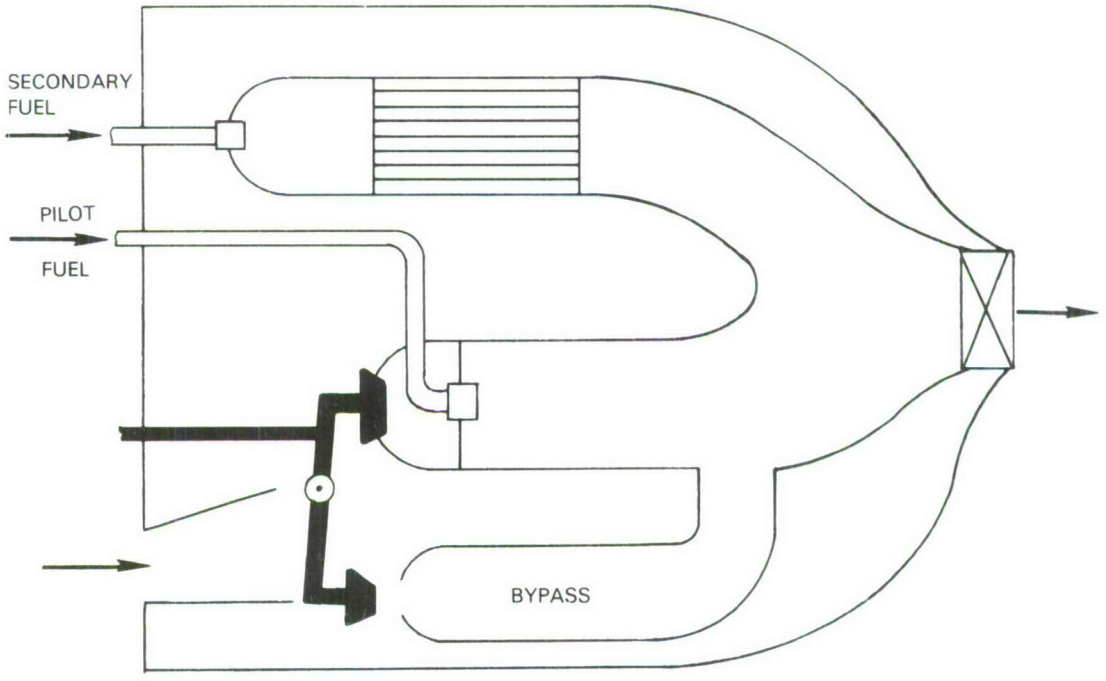
The total-pressure loss breakdown given in Table III was maintained.

Diffuser Design

The diffuser design devised for Concept 1 was acceptable.



IDLE



TAKE-OFF

Figure 41 Representation of Concept 5: Two Position Variable Geometry Radial Staging

Design of Homogeneous Pilot Combustor

As with Concept 3, the parallel arrangement of stages necessitates that the engine idle only on the pilot combustor and therefore, the pilot combustor should be designed to satisfy the 1979 low-power emissions regulations entirely on its own.

It was decided to operate the pilot and main combustors at the same equivalence ratio at takeoff, a value of 0.4085. The pilot was also to operate at an equivalence ratio of unity at idle. As with Concept 3, the aim is to catalytically react as much of the total fuel flow as possible, at a low equivalence ratio to avoid NO_x production at high power. The pilot sizing from Concept 3 was used for this concept.

Need for Variable Geometry

The engine-core speed level is chosen to control fuel flow to the catalytic combustor as is done for Concept 3 and for the same reasons. Anderson's work (Reference 17) indicates that for Jet A fuel, catalytic combustion efficiency can fall off dramatically if a catalytic reactor comes into operation with an equivalence ratio less than about 0.22, particularly when the inlet temperature is relatively low. Consideration of Figure 32 and Figure 1, together with Figure 6, reveal that this is the situation for Concept 3 at the cut-in point of the catalytic main combustor. This could create an emissions problem at the approach condition.

In order to deal with this potential problem, the ramp function fueling used for Concept 3 was replaced with a step function fueling, as shown in Figure 42. The actual equivalence ratio chosen was 0.25.

The engine must operate free from either thrust gaps or thrust jumps. The total fuel flow must increase monotonically with engine speed. Therefore, a step-function fueling of the catalytic main combustor must be accompanied by a corresponding step-function reduction in pilot combustor fuel flow, (Figure 42). This procedure would cause the lean blow out limit for the pilot combustor to be exceeded. Consequently, in order to prevent lean blow out of the pilot and to retain the good starting of the catalytic main combustor, it is necessary to resort to variable geometry.

Variable Geometry Choices

Variable geometry has been applied to the pilot combustor. As for Concept 4, the variable geometry was to be applied in such a fashion as to preserve a constant pressure loss/flow function relationship for the combustion section. The desirable variable geometry system selected is a simple, two-position device.

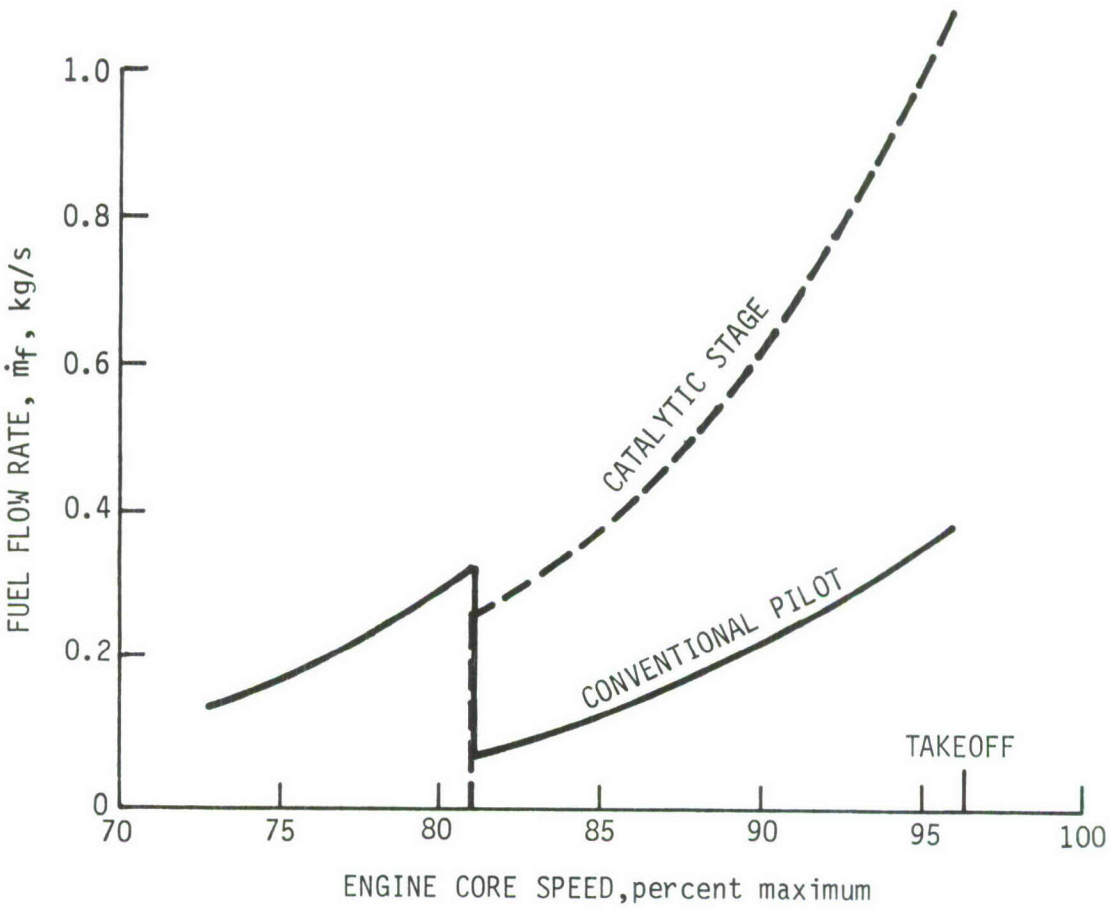


Figure 42 Concept 5: Fuel Flow Variation Dependence on Engine Core Speed

Two-Position Variable Geometry Operation

Figure 43 illustrates the performance of the pilot combustor with two-position variable-geometry operation at 25 percent sea-level thrust (81 percent maximum engine core speed).

The pilot size and equivalence ratio give 99.5 percent combustion efficiency at idle. From idle up to an engine core speed represented by 25 percent sea-level take-off thrust, the pilot operates with fixed inlet area at combustion efficiencies greater than 99.5 percent. Operation of the variable geometry simultaneously with fueling of the main combustor and consequent reduction in pilot fuel flow prevents the equivalence ratio from falling off to too low a value and also reduces the air loading parameter value. The minimum equivalance ratio is set as 0.345.

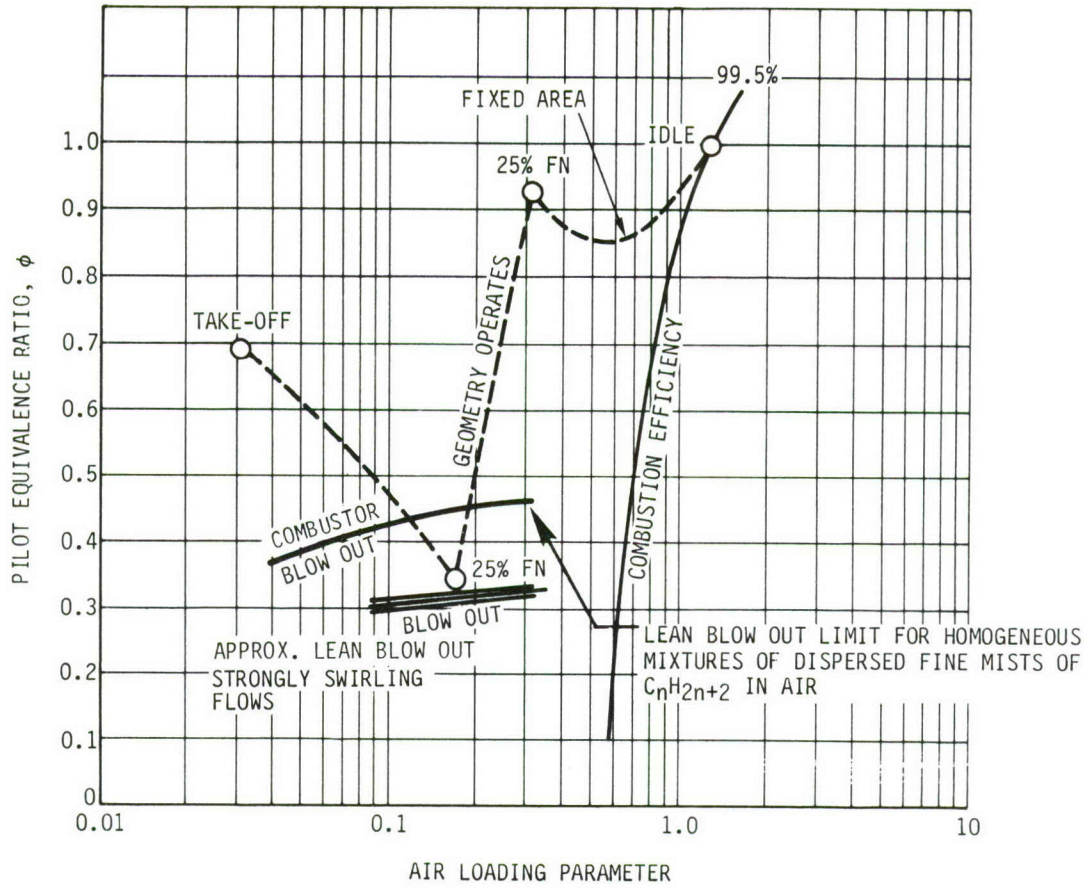


Figure 43 Concept 5: Radially Staged Combustor with Simple Two-Position Variable Geometry - Pilot Combustor Operation (Sea Level)

The air that the variable geometry excludes from the combustion process can be added downstream as dilution air to the pilot combustor. This provides dilution of the NO_x produced in the burning zone. It also results in the pilot combustor exit equivalence ratio being equal to that leaving the catalytic reactor at all speeds after the variable geometry has been operated. This makes easier control over the turbine-entry radial temperature profile than would otherwise be the case.

The equivalence ratio variation based on the fuel scheduling curves shown in Figure 42 and the end-point equivalence ratios are shown in Figure 44. The pilot effective inlet area variation is given in Figure 45. The two-position variable geometry can be seen to be a practical system for this concept.

Altitude Operation of Variable Geometry

Figure 46 shows the fuel flow split between the pilot and main combustors. Also shown is a hatched band which represents the uncertainty in the fuel split associated with realistic metering accuracy. The band represents a metering accuracy of a given flow of $\pm 1/2$ percent full scale.

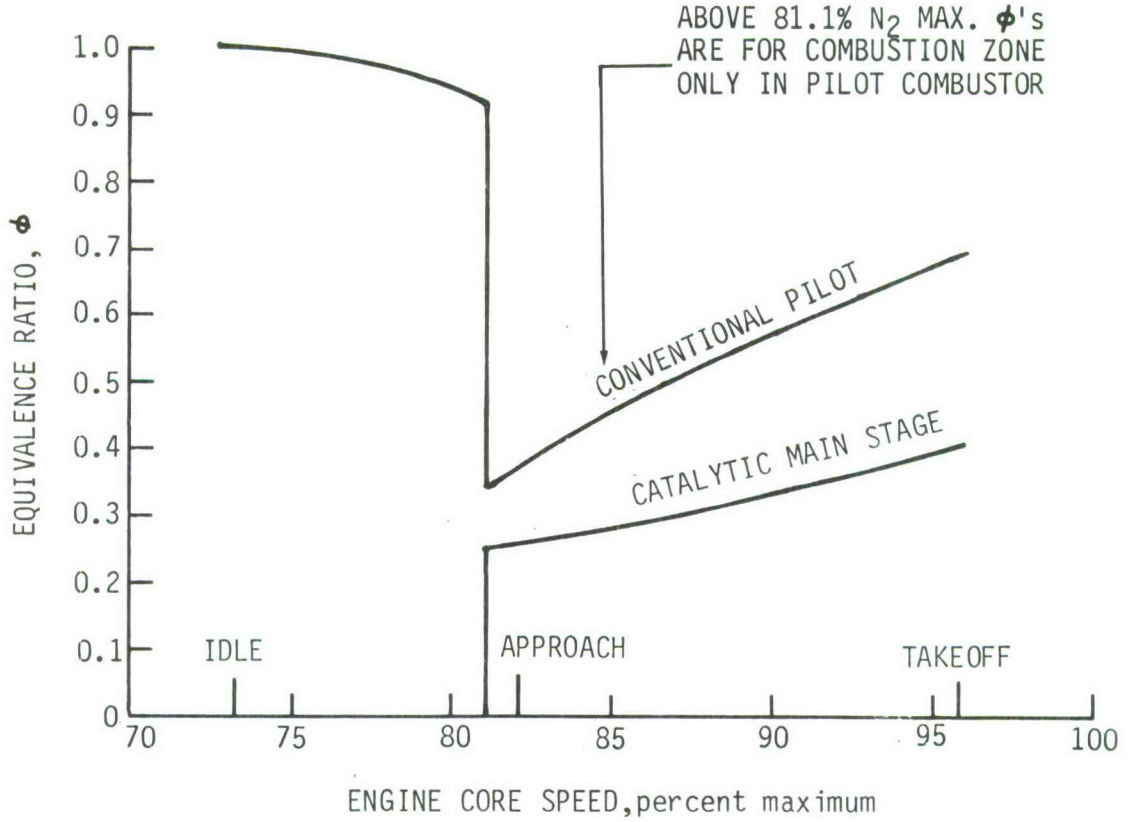


Figure 44 **Concept 5: Pilot and Catalytic Main Stage Equivalence Ratio Variation with Engine Core Speed**

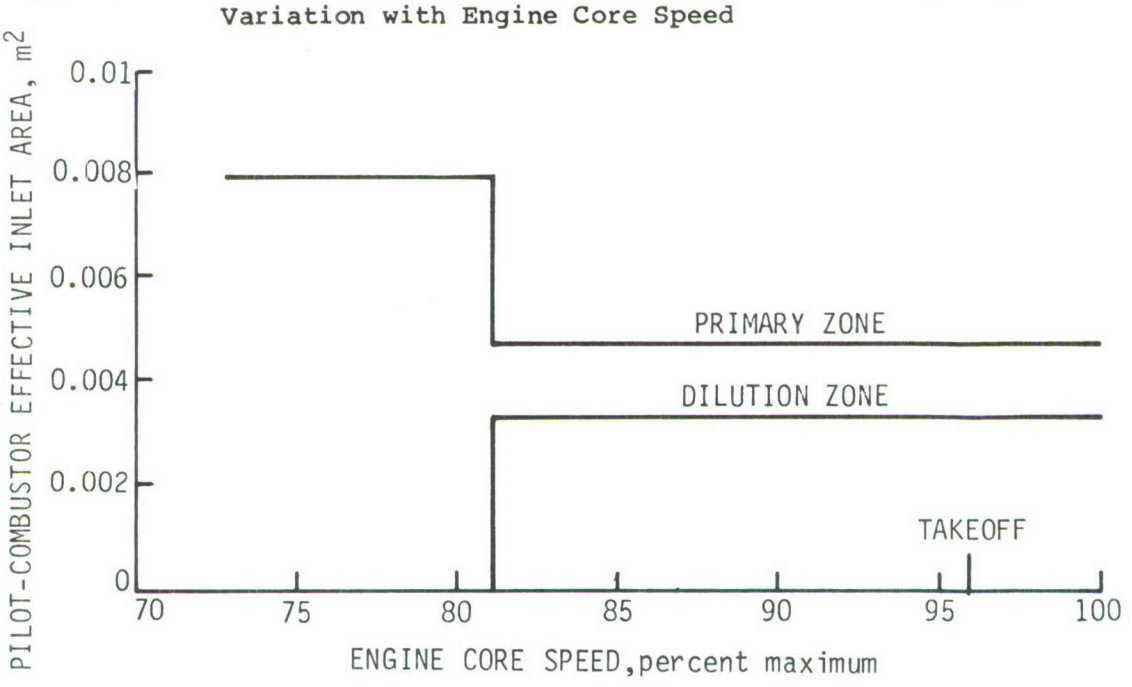


Figure 45 **Concept 5: Pilot Combustor Effective Inlet-Area Dependence on Engine Core Speed**

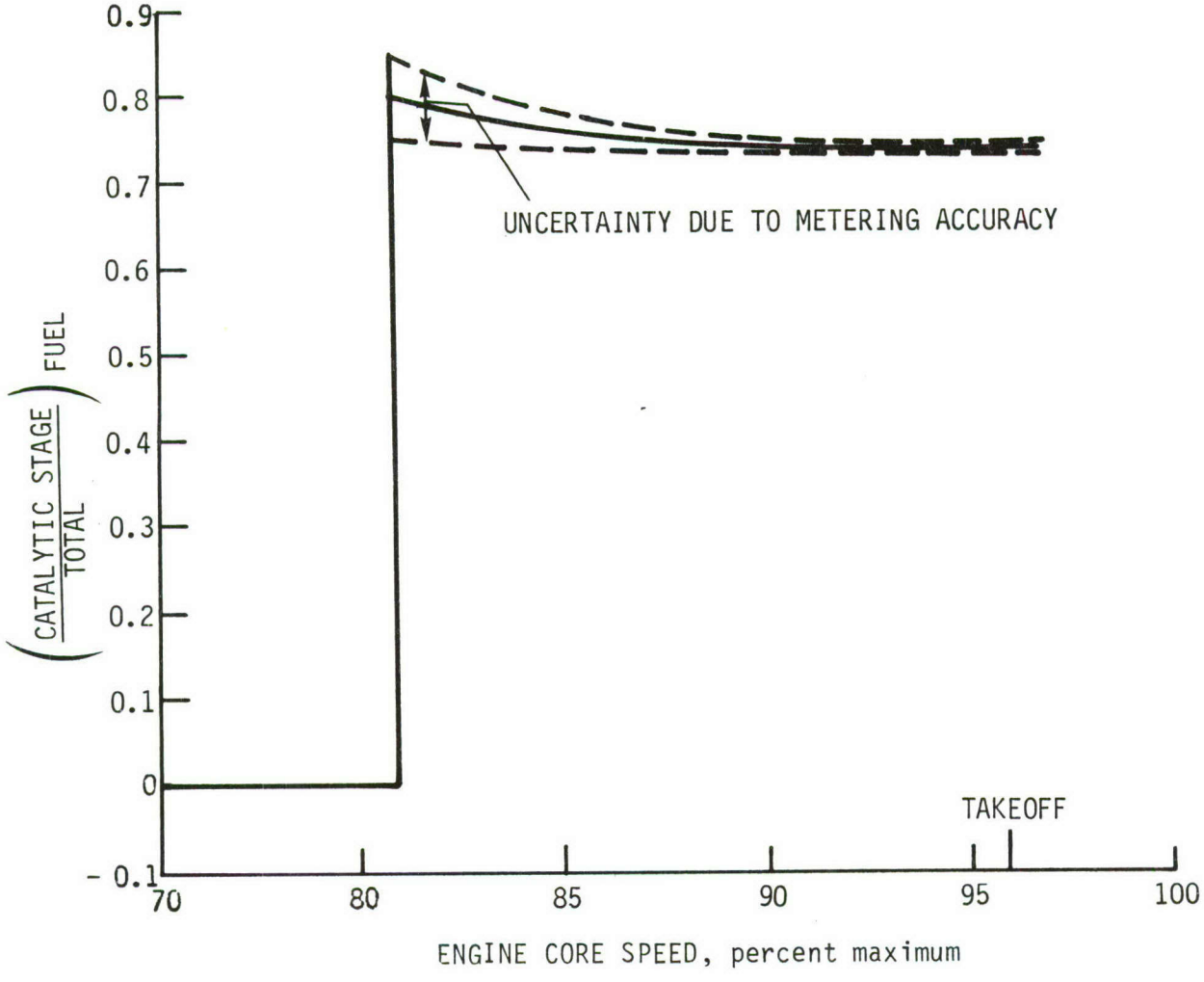


Figure 46 Concept 5: Fuel Flow Split Dependence on Engine Core Speed

The pilot-combustor exit temperatures are given for cruise operation in Figure 47. The hatched band shown represents the temperature uncertainty associated with the fuel metering inaccuracy that is shown in Figure 46. The uncertainty band width is about 55 K. As cruise power and altitude are reduced, the pilot exit temperature is also reduced. The pilot-combustor exit temperatures during a typical climb are given in Figure 48.

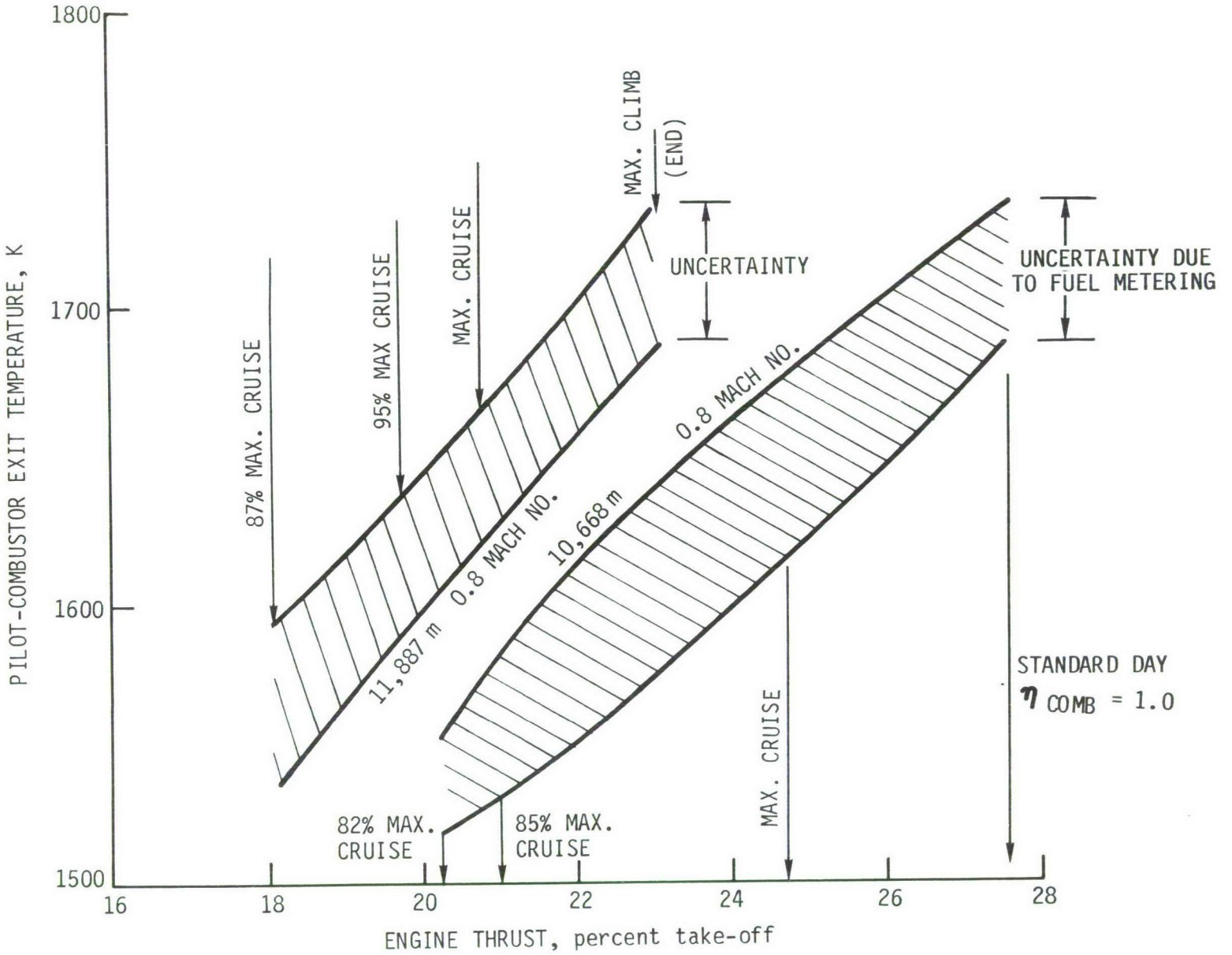


Figure 47 Concept 5: Pilot-Combustor Exit Temperatures at Cruise with Speed-Control of Fuel Staging and Variable Geometry

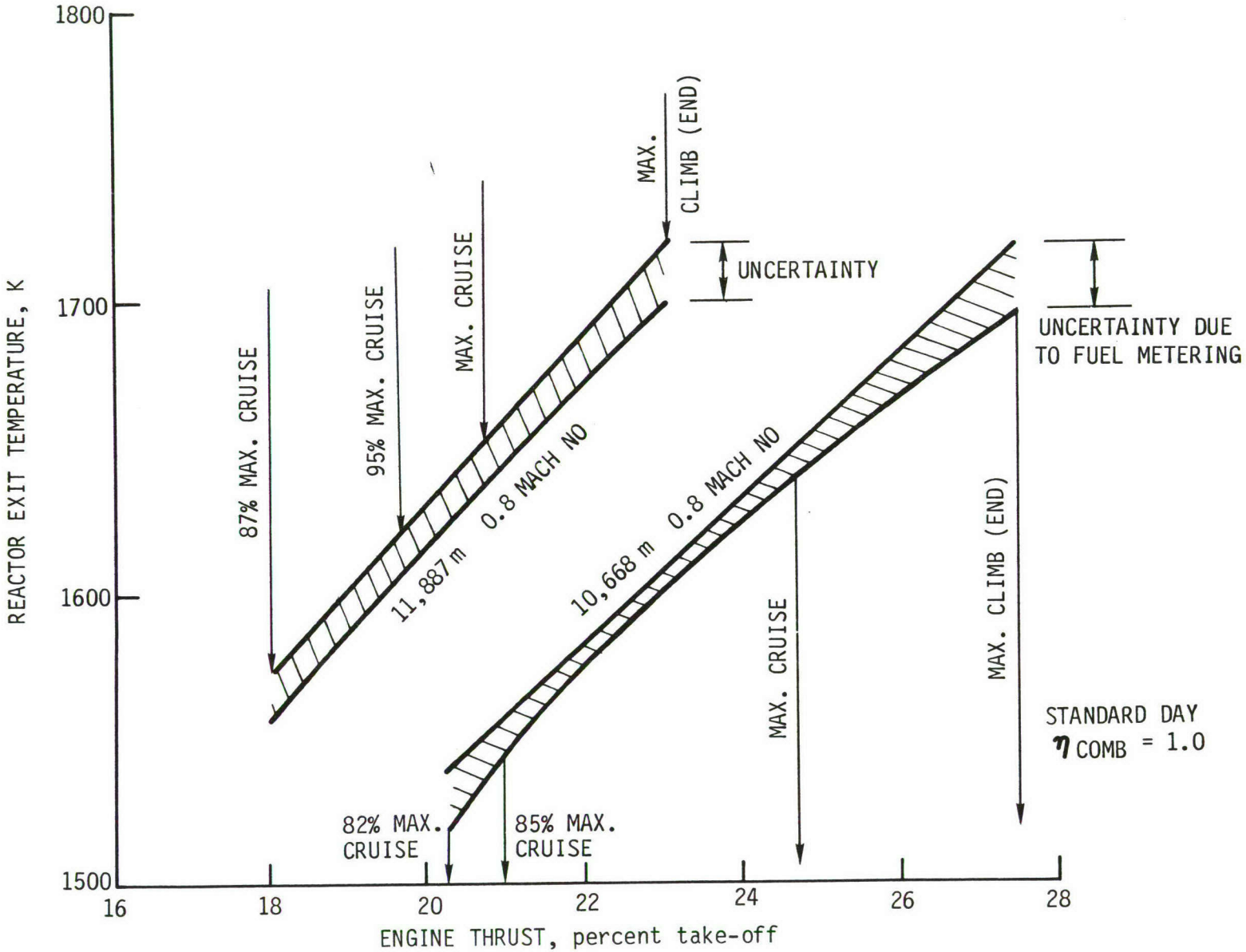


Figure 48 Concept 5: Catalytic Reactor Exit Temperatures at Cruise with Engine Speed-Control of Fuel Staging (Fixed Geometry)

Figure 49 shows the catalytic main-combustor exit temperatures during cruise. The temperature uncertainty due to fuel flow metering inaccuracy is 22 K which is much less in the main combustor than that in the pilot. This is advantageous for control of radial profile. Exit temperatures are such that NO_x emissions from the main combustor should be nonexistent. As cruise power and altitude are reduced, the main combustor exit temperatures are also reduced. Figure 50 gives exit temperatures during climb for the catalytic main combustor. The main combustor is not quite a constant exit temperature reactor, even with the uncertainty associated with fuel metering. The exit temperatures from the reactor at all flight conditions are such that reactor durability should not be a problem.

For safety in operation, it is extremely desirable that the main combustor be alight during the approach mode. Figure 51 shows operation of the main combustor during a typical descent from cruise and entry of the approach mode. From the minimum cruise condition, the throttle is retarded to flight idle for descent, thereby shutting-off fuel to the main, shuttling fuel to the pilot, and operating the variable geometry. The catalytic reactor goes out and begins to cool down. At the end of descent, the throttle is opened to select approach power. The catalytic reactor, which it is conservatively assumed has cooled down completely to the compressor delivery air temperature, begins to heat up with the increasing air temperature. In this case, the optimistic assumption is made that the reactor responds instantly to the compressor delivery temperature. The reactor is not fueled until an air temperature of 600 K is reached. This temperature is about equal to the aged-reactor light-off temperature; therefore light-off should be achieved satisfactorily. At the approach condition, the reactor is operating at a maximum temperature of 1256 K and should be in a suitable condition to give low exhaust emissions of CO and UHC. It would also be in a condition to accept an aircraft "go-round" demand in the event of an emergency.

Arrangement of the Main Combustor

It was decided to place the pilot combustor inboard of the main combustor. It was also decided to apply a variable-geometry system to this pilot combustor. Implicit in these two decisions is a tremendous problem which arises because the pilot-combustor fuel injectors, ignitor plug and variable-geometry actuation all have to pass in some fashion through the annular main combustor in order to reach the pilot.

The logical solution was to relax the goal of an annular main combustor in order to provide access to the pilot. The can-form was therefore selected for the catalytic main combustor. The number of cans chosen was 20.

Catalytic-Reactor Sizing

The total mass of fuel and air mixture to be processed by the catalytic reactor in the main combustor at take-off power in this concept is the same as that in Concept 3. Therefore, the residence time for the present reactor is the same as that used in Concept 3.

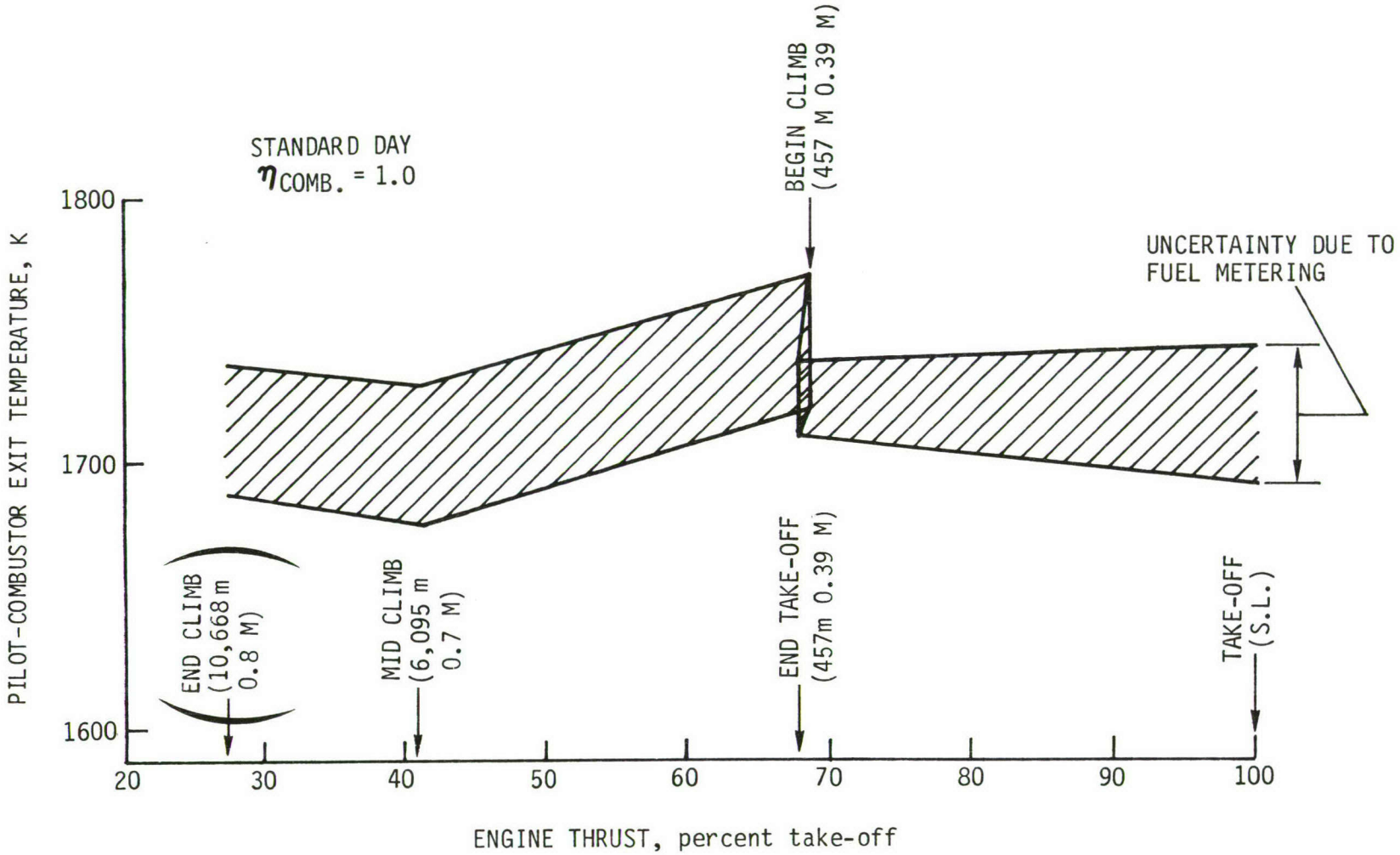


Figure 49 Concept 5: Pilot-Combustor Exit Temperatures During Typical Climb with Engine Speed Control of Fuel Staging & Variable Geometry

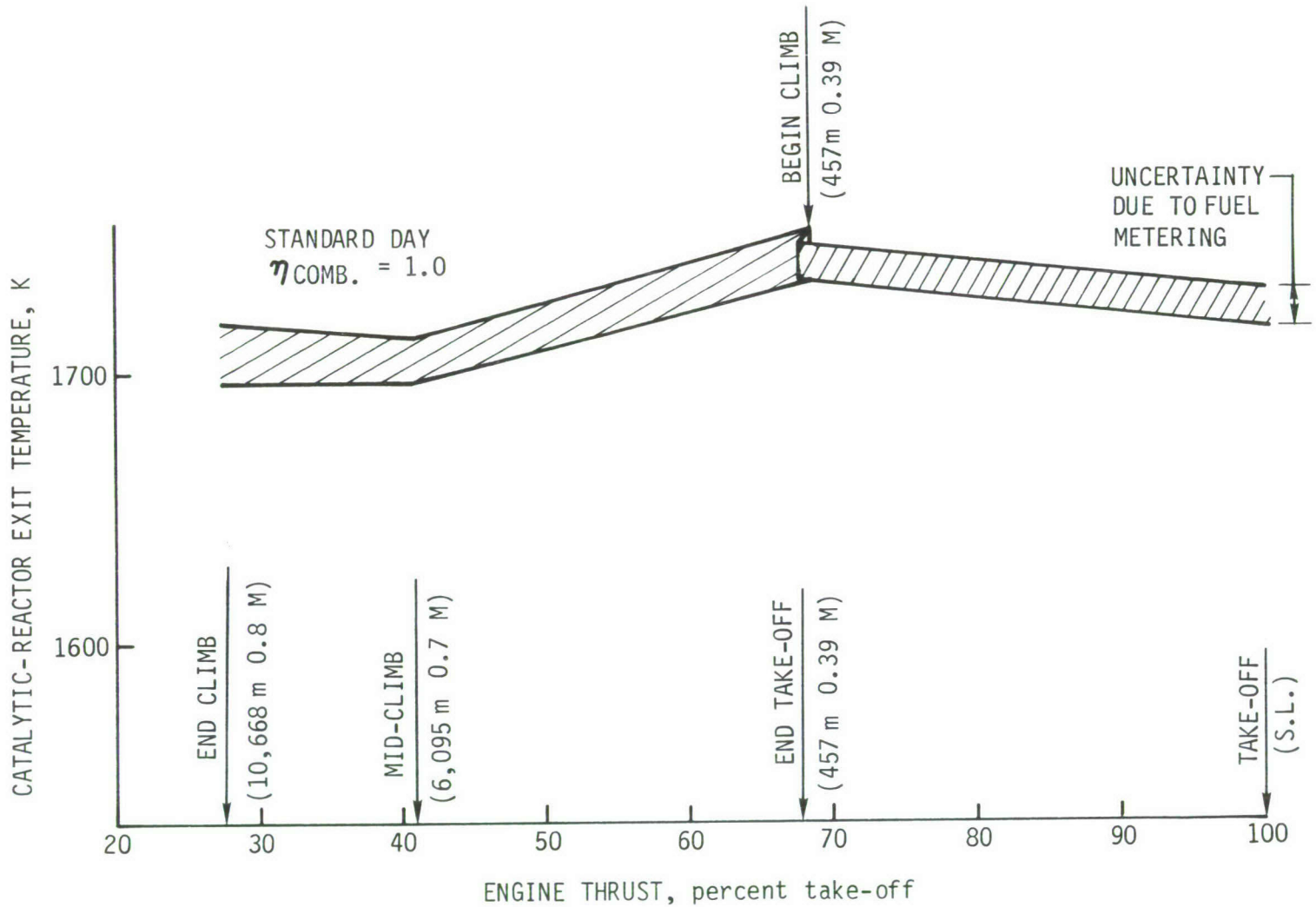


Figure 50 Concept 5: Catalytic Reactor Exit Temperatures During Typical Climb with Engine Speed Control of Fuel Staging (Fixed Geometry)

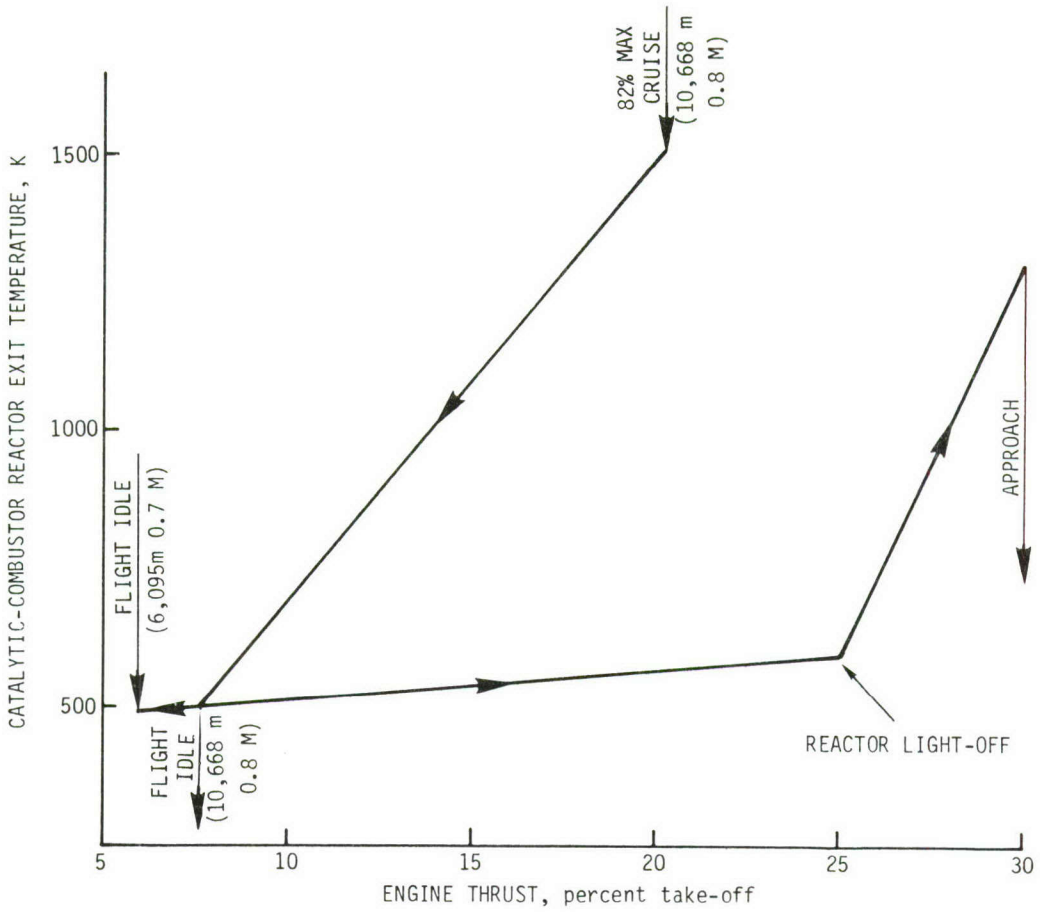


Figure 51 Concept 5: Catalytic-Combustor Reactor Exit Temperatures During Typical Descent and Approach with Speed-Control of Fuel Staging (Fixed Geometry)

The required length for each 6.985 cm diameter reactor is 20.86 cm. At the radial position of the cans, a can internal diameter of 6.985 cm was chosen. The total available face area of the catalytic reactor was 766.4 cm^2.

Catalytic-Reactor Pressure Losses

The total-pressure losses through the 20.86 cm long reactors is given in Table XI.

TABLE XI

CONCEPT 5: REACTOR PRESSURE LOSSES

Reactor	1	2	3	4
Porosity, percent	65.5	69.0	79.0	78.0
Cell hydraulic dia., cm	0.09754	0.127	0.213	0.310
Cell density, cells/cm^2	40	45	16	10
Total-pressure loss, percent	6.62	4.57	1.81	0.79

With the pressure loss goal of 1.6 percent, it can be seen that only reactor No. 4 is satisfactory. This is in marked contrast to Concept 3 where Table IX shows that reactor numbers 2, 3 and 4 are suitable. The difference arises from the increase in reference velocity in the present concept due to the reduced reactor face area offered by the twenty cans.

Fuel Preparation Length

The residence time in the main-combustor fuel preparation zone, which is limited by autoignition, is 1.2 milliseconds. At the velocity pertaining in the cans, this translates to an allowable length of 3.66 cm.

Fuel Injector Selection

The number of fuel injectors will be one per main-combustor can. However, consideration of the section entitled "Fuel Preparation", under heading 5.1, reveals the need for a large number of injectors to achieve suitable atomization, mixing and evaporation. Each can has one support carrying fuel, but the head of the support carries multiple injectors of the prefilming airblast type. This type of system is successfully used in several Pratt & Whitney Aircraft can-annular engines.

The number of fuel injectors for the pilot combustor follows the guidelines of Concept 3 and is equal to 30.

Concept 5 Design Summary

The resulting design parameters for Concept 5 are therefore:

Pilot combustor:

Dome height, cm	5.84
Primary zone volume, m^3	0.010
Primary zone mean radius, cm	32.56
Primary zone length, cm	10.16
Idle ϕ	1.0
Take-off ϕ (Primary zone)	0.693
Take-off ϕ (Overall)	0.4085
No. fuel injectors	30
$\dot{m}_f$, max, kg/s	0.374
Fixed inlet area, cm^2	47.1
Total inlet area, cm^2	80.00
Variable-geometry initiation	81% max. core speed

Main combustor:

Dome height, cm	6.985
No. cans	20
Fuel prep. length, cm	3.66
Can pitch radius, cm	42.55
Reactor length, cm	20.86
Idle ϕ	0
Takeoff ϕ	0.4085
$\dot{m}_f$,max, kg/s	1.098
Cut-in speed	81% max. core speed
Cut-in ϕ	0.25
Reactor face area, cm^2	766.4
Reference velocity, m/s	30.5

Total-pressure-loss at take-off, percent

Diffuser	1.66
Turning	0.60
"Liner"	2.00
Bed	0.79
Mixing	0.10
	5.15

Total combustion air for exit-temperature profile trim, percent	15

Concept 6: Separate catalytic combustor for cruise operation (Figure 52)

One of the major objectives of the program is to achieve low exhaust NO_x during high-altitude cruise operation. Therefore, adoption of a catalytic combustor has been considered for use only at cruise. Concept 6 which includes a separate, small catalytic combustor is used in conjunction with a small pilot combustor at altitude cruise. By having a separate cruise combustor, the catalytic reactor can be optimized for essentially single point operation. Fuel preparation in the reactor can be improved since the autoignition delay time is increased due to the lower temperatures and pressures experienced during cruise operation. At all other engine operating points the catalytic combustor is nonfunctioning. A continuously-operating small pilot combustor is necessary for reasons of flight safety.

Concept 6 addressed take-off and landing emissions separately from cruise, by means of a version of the National Aeronautics and Space Administration/Pratt & Whitney Aircraft Experimental Clean Combustor Program Vorbix I combustor (Reference 18).

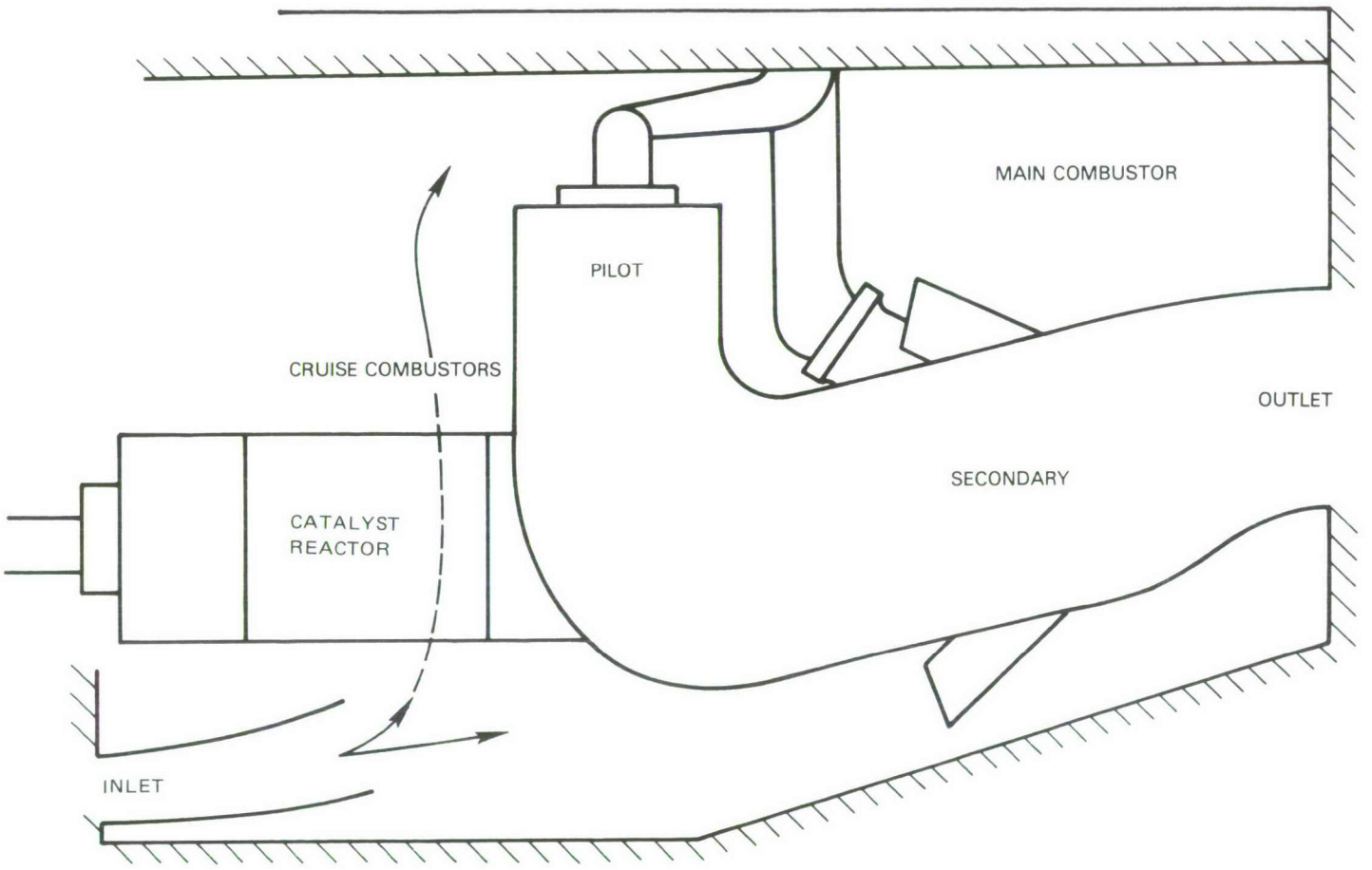


Figure 52 Concept 6 Showing Folded Vorbix Main Combustor with Radial Inflow Pilot, and Individual Catalytic Cruise Combustor

However, the severe penalties for the above improvements in the catalytic reactor operation are as follows:

1. When the cruise catalytic combustor is shut down, a nitrogen purge will be required for the fuel injectors. This prevents the formation of coke in them during the high temperatures experienced at take-off.

2. A separate means has to be found to satisfy the Environmental Protection Agency 1979 emissions regulations governing take-off NO_x.

3. Accommodation of the combustor within the envelope of Figure 7 will require folding of the Vorbix combustor.

4. For proper secondary stage operation, variable geometry has to be applied to the cruise catalytic combustor to close off its air supply when it is not in operation.

5. The pilot stage of the Vorbix would be required to operate continuously in the interests of safety. Take-off would be on pilot and secondary of the Vorbix, and cruise would be on Vorbix pilot and cruise catalytic combustor. As a result, total NO_x emissions would be higher than they need be.

Total-Pressure Loss Breakdown

The percent total-pressure loss breakdown modified to account for increased losses associated with the folded arrangement is as follows:

Diffuser	1.66
Turning	1.20
Liner	2.00
Mixing	0.10
Reactor	0.79
	5.75

Diffuser Design

The diffuser design devised for Concept 1 was adopted. However, the walls were curved rather than linear.

Folded Vorbix-Combustor Design

The design of the Vorbix combustor was based on that of the Energy Efficient Engine study, which itself was based on the ECCP Phase III Run 4, combustor, (Reference 18).

The pilot is designed for a 0.7 equivalence ratio excluding cooling. The secondary is designed for a 1867 K flame temperature calculated on all airflow except secondary cooling and dilution. The percent of total airflow is as follows:

Pilot combustion air (includes 3 percent dome cooling)	23.4
Pilot-liner cooling air	10.0
Secondary Vorbix air	39.0
Secondary dilution air	5.6
Secondary liner cooling air	22

The secondary fuel injection is single sided with outer diameter fuel injection only. An asymmetric vorbix tube air split is used, with 31.2 percent of total air being injected in association with the secondary fuel flow, and 7.8 percent on the inner diameter. The dilution is single sided also, with 5.6 percent being added on the outer diameter.

The folded arrangement should have a beneficial effect on stability of the pilot. It should also improve pattern factor due to the pilot fuel injectors not looking directly at the turbine section. The right angled turn should also improve mixing, but at the probable expense of liner durability.

It proved necessary to reduce the secondary length by 5.08 cm due to overall length constraints, although the volume was maintained at the Energy Efficient Engine value. A throatless design was used. The impact of these changes from the Vorbix test demonstration on the emission performance cannot be assessed at this time.

The pilot is designed to react 45.6 percent of the total fuel flow at takeoff, at an equivalence ratio of 0.4821 (including all pilot airflow). At idle, the pilot equivalence ratio is 0.793. This is a relatively low value, but the air loading parameter is low also due to the more than adequate volume.

The secondary is designed to cut-in with a step-function fuel schedule to avoid a CO problem at low secondary equivalence ratios. This results in a step-down in pilot fuel flow. The secondary cut-in is at a speed of 79 percent of maximum core speed, N_2. The sea-level fuel schedule is shown in Figure 53.

Cruise Catalytic Combustor Design

The design point for the catalytic combustor is the maximum cruise point at 0.8 flight Mach number at 10,668 m altitude. This combination gives the most severe conditions with respect to autoignition. Autoignition has proved to be the controlling factor limiting fuel preparation.

The ignition delay time at cruise of 3.69 ms is increased over that at sea level. This allows the mixing to be improved and hence, permits the allowable equivalence ratio to be 0.496 before substrate temperature limits are reached. With this equivalence ratio the cruise combustor airflow is 37.27 percent of the total. To minimize cruise NO_x, the air is to react as much fuel as possible catalytically.

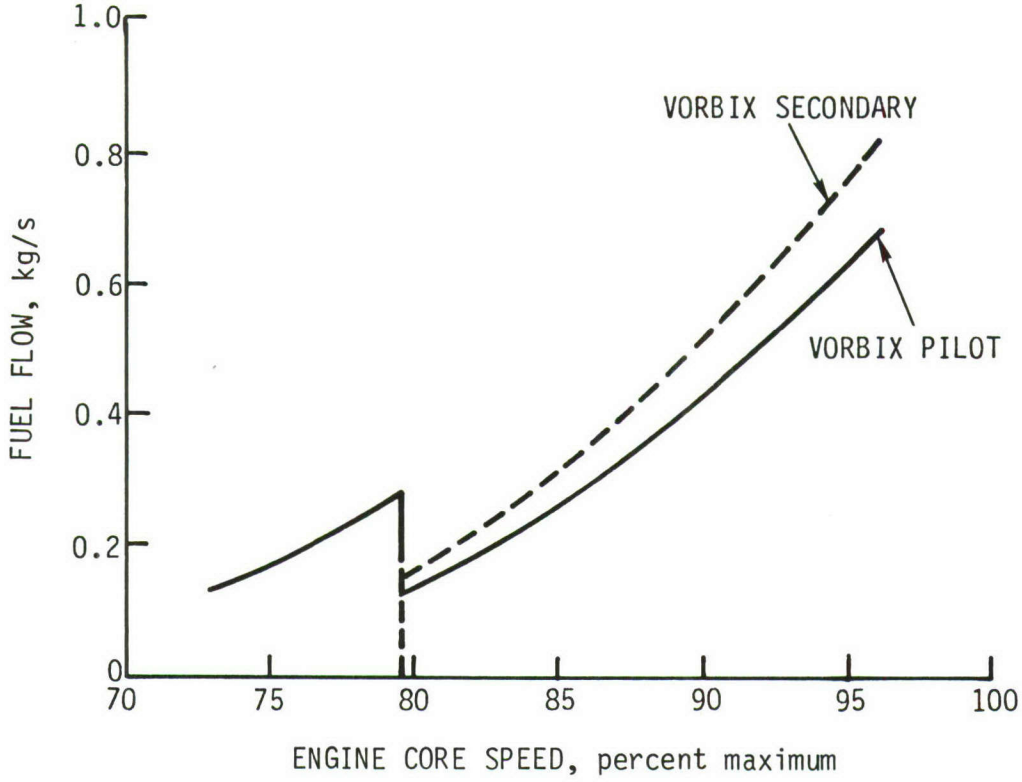


Figure 53 Concept 6: Fuel Flow Rate Dependence on Engine-Core Speed

It is not practical to handle the large flow shifts required with this concept. The amount of air required could result in even cooling air being taken from the main combustor vorbix secondary. Coupled with the extreme complexity of three separate fuel systems and variable geometry, these facts eliminate the concept from serious consideration.

5.2 Combustor Design Details and Operation

The aim of this section is to translate the preliminary sizings of the six concepts carried out in Section 5.1, "Identification of Concepts" into flowpaths.

To save later repetition, the flowpaths are presented for each concept in more detail than would normally be given in a flowpath.

Concept 1: Combustor layout. - Figure 54 shows a section of Concept 1. The design has been accommodated within the envelope given in Figure 7, without any deviations.

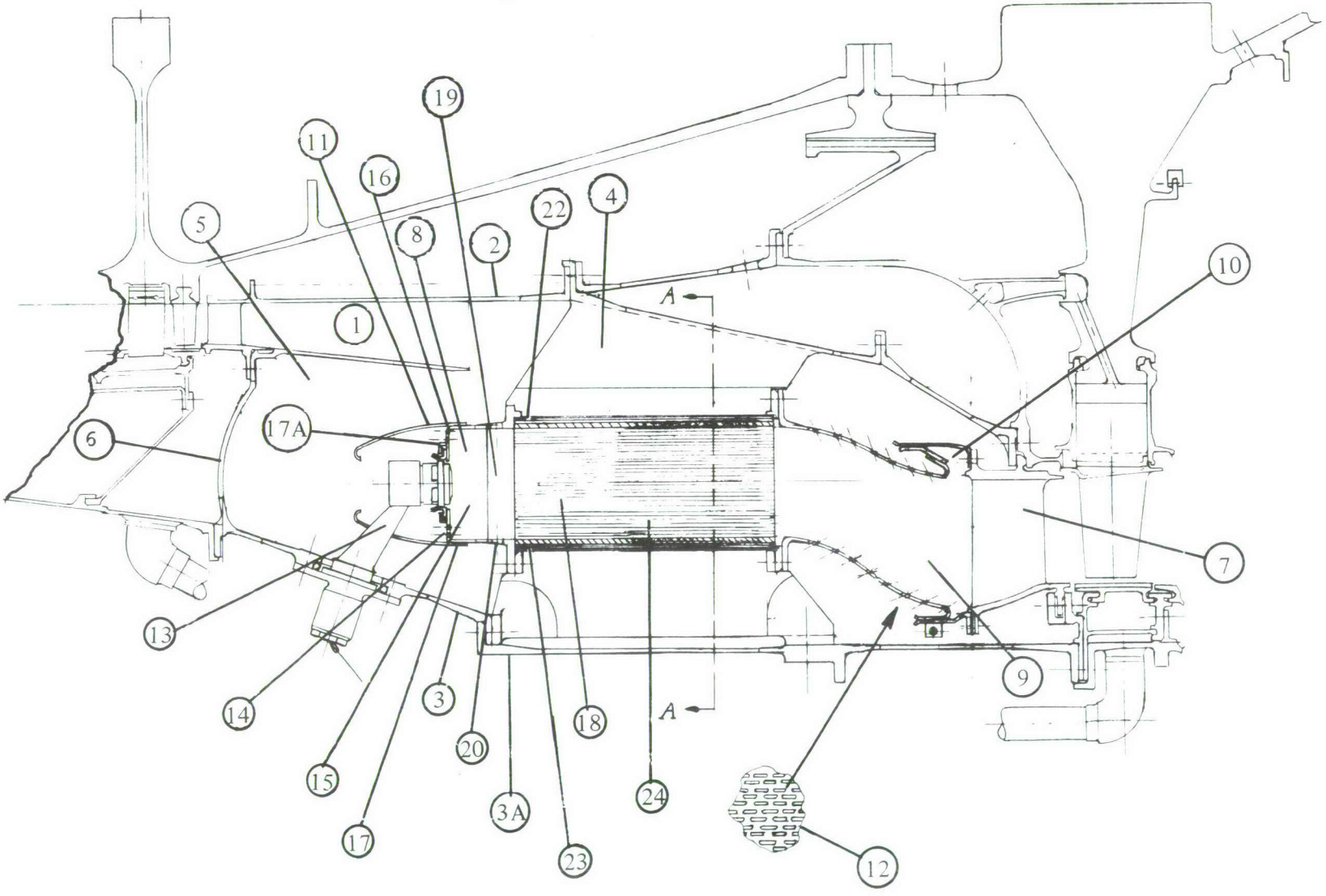


Figure 54 Concept 1: Longitudinal Section

Air flows from the compressor into the asymmetric annular prediffuser (1) described in the section entitled "Diffuser Design". The inner wall of the prediffuser is formed by the inner air casing (2). Loads are carried from the inner casing to the outer casing (3) by means of ten radial struts (4) downstream of the prediffuser. A plenum chamber (5) is formed by the inner and outer air casings, a forward diaphragm (6) and the turbine assembly (7). Compressed air from the prediffuser is dumped into the plenum chamber.

Contained in the plenum chamber is an annular combustor (8). The combustor is supported on the radial struts, and is connected to an annular turbine entry duct (9). The turbine entry duct is supported by a seal (10) on the turbine section. Air from the plenum chamber enters the combustor through an annular hood (11), and through an advanced cooling scheme (12) applied to the turbine entry duct.

Contained within the hood (11) are 30 prefilming airblast-atomizing fuel injectors (13). The fuel injectors are externally removable, and are mounted on the forward portion of the outer air casing. The injectors are carried in a 6.35 cm annular height dome (14), and discharge a partially-premixed, well-atomized fuel and air spray into a fuel preparation section (15) where further mixing and fuel evaporation takes place. The fuel preparation section is formed by annular inner (16) and outer (17) liners.

The dome is provided with a multitude of small holes (17A) surrounding the fuel injectors. These holes are fed with air from under the hood, and discharge individual small jets into the fuel preparation section. The purpose of these jets is to provide sufficient entrainment air for the fuel and air jets from the fuel injectors, so that they do not recirculate back onto the dome. If such recirculation were permitted, the safe residence time in the fuel preparation section would be exceeded and autoignition of the mixture might take place.

The prepared fuel and air mixture leaves the fuel preparation zone to enter an annular catalytic reactor (18). The reactor has a length of 13.6 cms and a form as described in the 5.0 section entitled "Catalytic Reactor Pressure Losses".

The mounting of the reactor is shown in Figure 55, which is a cross section of the catalytic reactor. It can be seen that the annular reactor is made up of ten self-contained segments contained between the radial struts. Access to these segments is provided by removing the fuel injectors, unfastening a sliding portion of the outer case (3A), and sliding it forward to expose the plenum chamber and the catalytic reactor. This is accomplished without removing the turbine module from the engine. By this means, the individual segments of reactor may be removed for inspection, repair and replacement by withdrawing radially outwards from between the struts.

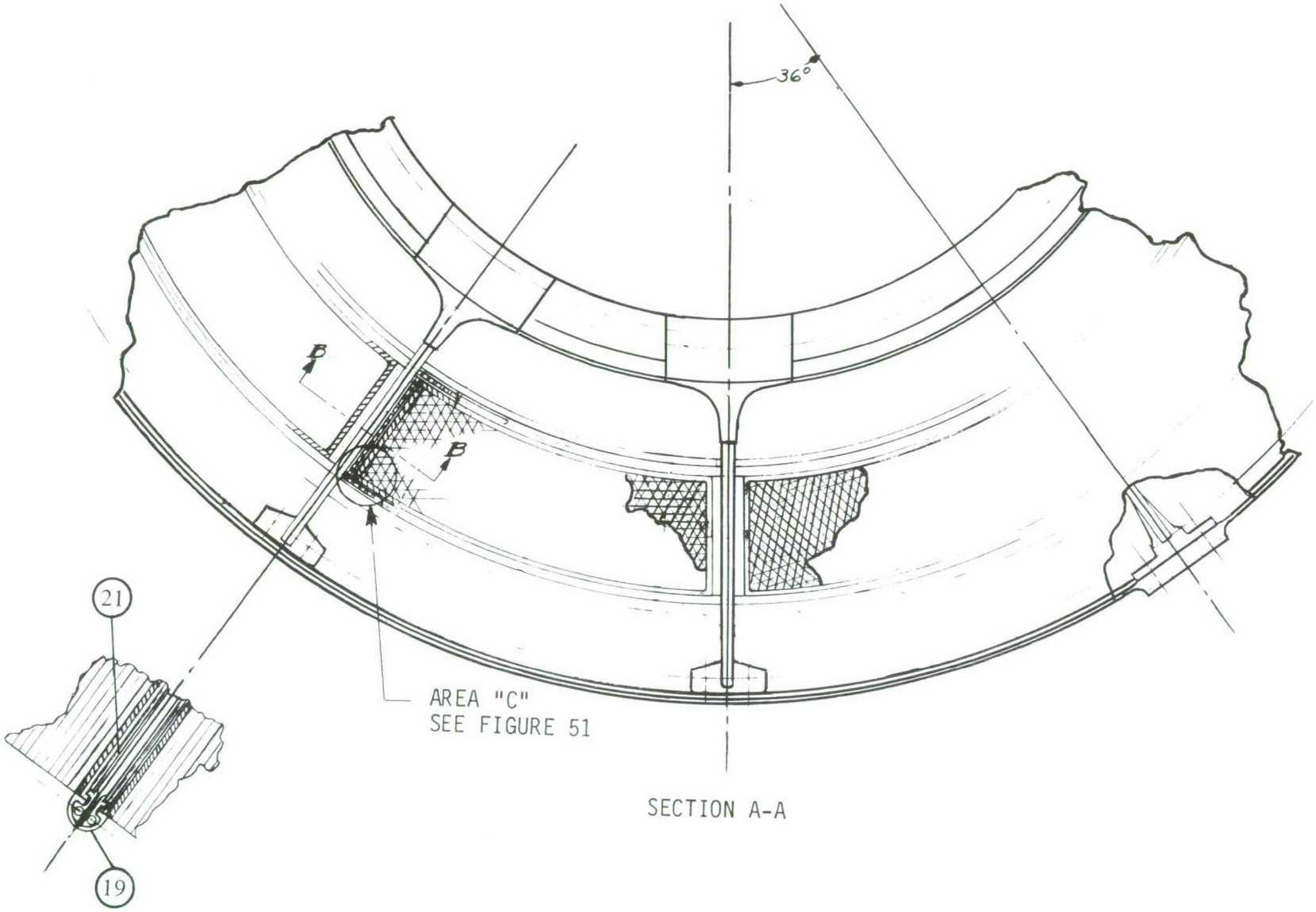


Figure 55 Concept 1: Section A-A

The leading edges of the struts (19) are protected by introducing a small amount of internal cooling air to the aerodynamic fairings by feed from openings (20) in the ends in the plenum chamber. This cooling air enters the cooling passages (21) mounted on the sides of each segment of the reactor, and is discharged to the lower pressure in the annular duct. This is illustrated in Figure 56. The inner and outer FINWALL panels of the reactor segment canning are fed with cooling air from the plenum through metering holes (22) and (23). The spent cooling air is discharged to the lower pressure in the annular duct.

Aerodynamic drag loads on the honeycomb making up the reactor (24) are transmitted to the casings first through the graded ceramic (25), Feltmetal (registered trademark of Huyck Corporation, Rensselaer, New York) pad (26) and backing sheet (27), then the FINWALL (28) and finally, the struts via the catalytic-reactor segment retainings.

Concept 1: Operation. - Compressed air is delivered by the engine compressor to the prediffuser where it is diffused to a low exit Mach number. The diffuser air is further diffused by dumping from the prediffuser exit into the plenum chamber.

Air from the plenum chamber feeds the turbine first vanes and blades. The annular turbine entry duct advanced cooling scheme is also provided with cooling air from the plenum chamber. The annular duct may also contain small trim air ports for adjusting the radial temperature profile leaving the catalytic reactor to a form suitable for the turbine blades; if so, these ports are fed with air from the plenum chamber. The airblast fuel injectors, the dome air, strut leading edges and catalytic reactor FINWALL are all fed with compressed air from the plenum chamber.

All the engine fuel flow at any operating condition is introduced by means of the airblast fuel injectors. External recirculation of the spray is prevented by the dome air, and internal recirculation is prevented by limiting the injector swirl number to a value less than the critical, (Reference 19). The spray angle is controlled by means of careful injector-swirler design and air deflector caps, so that fuel is not placed on the liner walls forming the fuel preparation section.

The equivalence ratio at catalytic reactor entry is 0.388. The fuel is reacted in the catalytic reactor and the products enter the annular duct, where any final temperature profile adjustment is made by means of dilution ports.

Concept 2: Combustor layout. - Figure 57 shows a section of Concept 2. The flowpath is very similar to that for Concept 1 as shown in Figure 54. The design has been accommodated within the envelope given in Figure 7 without any deviations. However, reference to Figure 54 reveals that the greater axial length of the present concept has impacted the compressor bleed for active clearance control in the turbine.

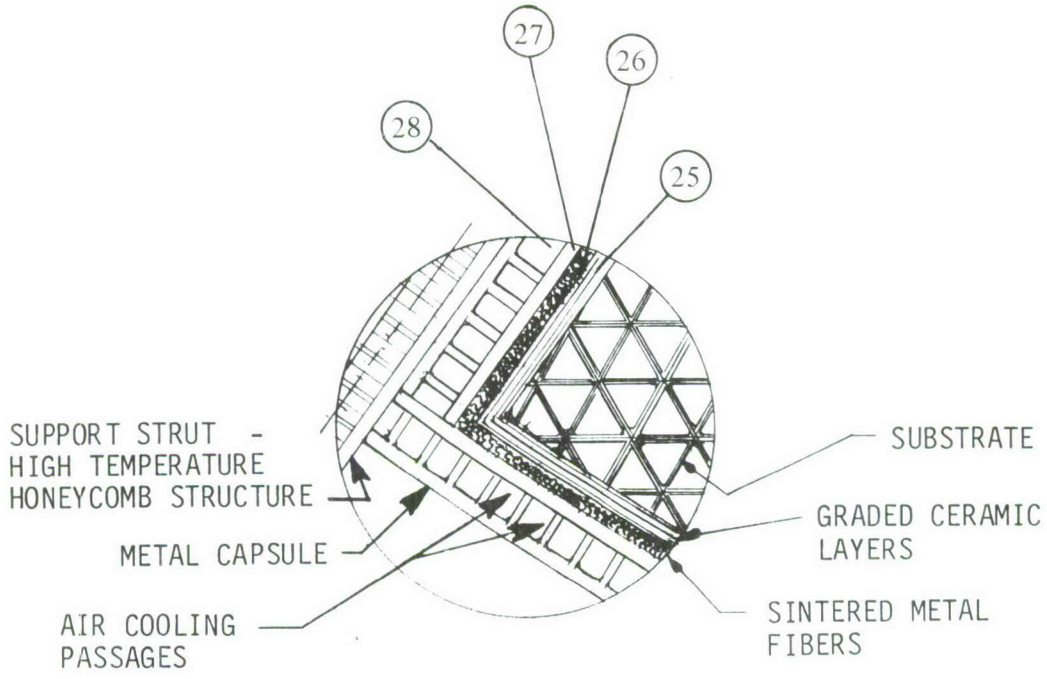


Figure 56 Concept 1: Enlarged View of Area "C"

Air flows from the compressor into the asymmetric annular prediffuser (1). The inner wall of the prediffuser is formed by the inner air casing (2). Loads are carried from the inner casing to the outer casing (3) by means of ten radial struts (4) downstream of the prediffuser. A plenum chamber (5) is formed by the inner and outer air casings, a forward diaphragm (6) and the turbine assembly (7). Compressed air from the prediffuser is dumped into the plenum chamber.

Contained in the plenum chamber is an annular hybrid combustor (8). The combustor is supported on the radial struts, and is connected to an annular turbine entry duct (9). The turbine entry duct is supported by a seal (10) on the turbine section. Air from the plenum chamber enters the initial burning zone (initial burning zone) (11) of the homogeneous reactor portion of the hybrid combustor through an annular hood (12) and through an advanced cooling scheme (13) applied to inner and outer liners, (14) and (15) respectively.

Contained within the hood are 30 prefilming airblast-atomizing fuel injectors (16). The fuel injectors are externally removable, and are mounted on the forward portion of the outer air casing. The injectors are carried in a 6.35 cm annular height dome (17), and discharge a partially-premixed, well-atomized fuel and air spray into the initial burning zone. Dome cooling is also provided (18), and is fed by air from under the dome. An ignitor plug (19) is provided for the initial burning zone; it is mounted off the outer air casing and penetrates the outer liner. The initial burning zone has a length of 7.95 cm.

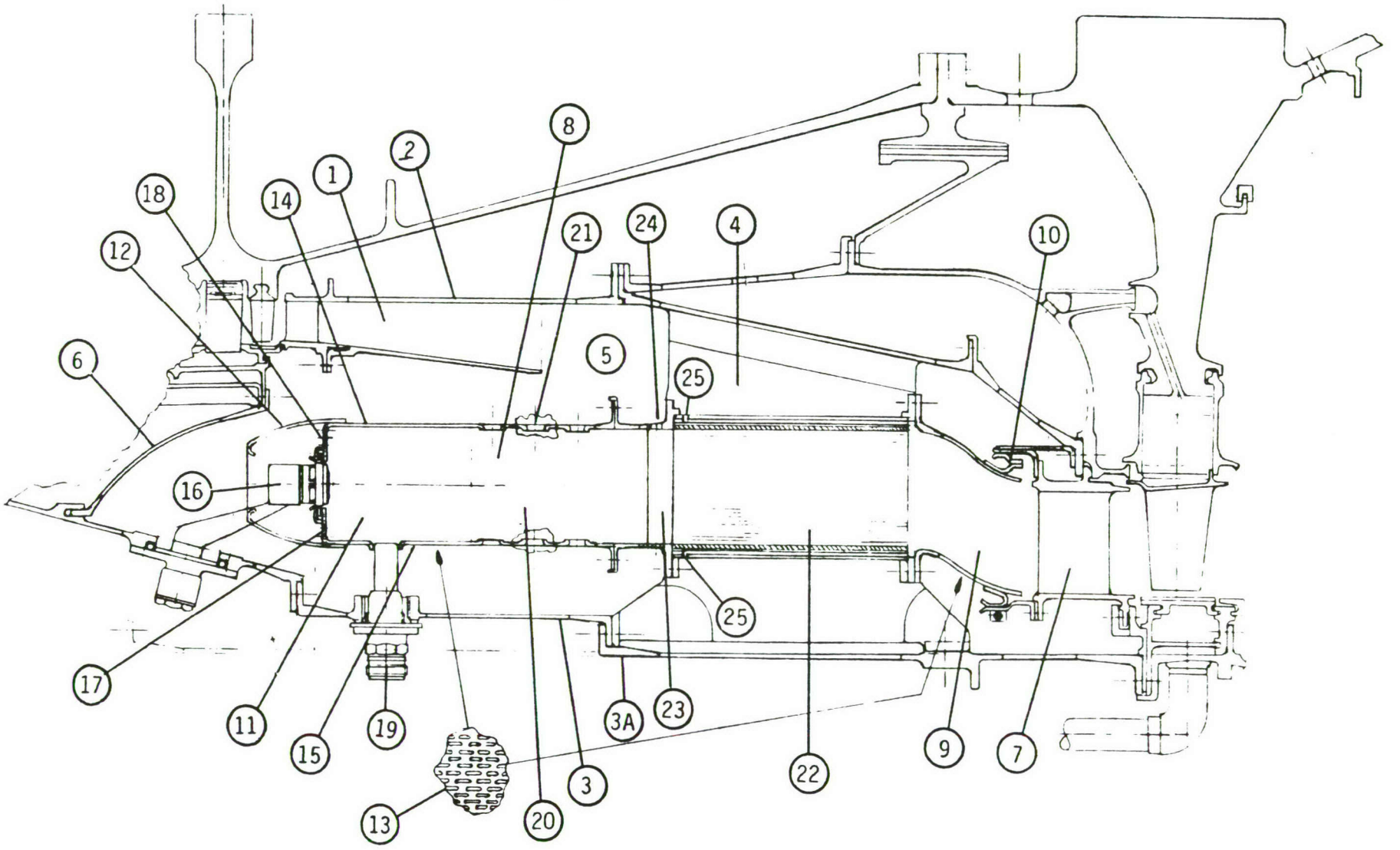


Figure 57 Concept 2: Longitudinal Section

Downstream of the initial burning zone is a quench zone (20) where large amounts of air are admitted through the inner and outer liners by arrays of holes (21) to mix uniformly and rapidly with the effluent from the initial burning zone without reaction. The quench zone has a length of 12.7 cm.

The mixture of fresh air and initial burning zone effluent leaves the quench zone to enter an annular catalytic reactor (22) for further reaction. The reactor has a length of 13.3 cm and a form as described in the section entitled "Catalytic-Reactor Pressure Losses". The reactor is canned in a manner illustrated in Figure 56.

The mounting of the catalytic reactor is identical with that for Concept 1 and illustrated in Figure 55. The annular reactor is made up of ten selfcontained segments contained between the radial struts. Access to these segments is provided by removing the fuel manifold and the ignitor, unfastening a sliding portion (3A) of the outer case, and sliding it forward to expose the plenum chamber and the catalytic reactor. By this means the individual segments of the reactor may be removed for inspection, repair and replacement by withdrawing radially outwards from between the struts. This is accomplished without removing the turbine module from the engine.

The leading edges of the radial struts (23) which are exposed to the hot gases of the quench zone, are protected in a similar fashion to Concept 1, except that the cooling airflow is increased and internal leading edge impingement cooling might be used. The arrangement is shown in Figure 55. The cooling air is supplied from the plenum chamber by openings (24) in a double-ended feed to minimize pressure losses. The cooling technique is very similar to that used in some types of turbine first vanes. The leading edge cooling air enters the FINWALL cooling passages mounted on the sides of each reactor segment, to cool the Feltmetal mounting of the honeycomb and to protect the struts. The spent air is then discharged to the lower pressure in the annular duct. The inner and outer FINWALL panels of the reactor segment canning are fed with cooling air from the plenum through metering ports (25). The spent cooling air is again discharged to the lower pressure in the annular duct.

Aerodynamic drag loads on the honeycomb of the reactor are transmitted to the casings through the reactor canning and the struts via the catalytic reactor segment retainings.

Concept 2: Operation. - Compressed air is delivered by the engine compressor to the prediffuser, where it is diffused to a low exit Mach number. The diffused air is further diffused by dumping from the prediffuser exit into the plenum chamber. The extremely low air velocities existing in the plenum chamber permit the air to flow around the annular combustor to the various feeds into the combustor, with acceptable losses in total pressure.

Air from the plenum chamber feeds the turbine first vanes and blades. The annular duct advanced cooling scheme is also provided with cooling air from the plenum chamber. If the annular duct contains ports to provide radial temperature profile trimming for the turbine, these are also fed with air from

the plenum chamber. The airblast fuel injectors, dome cooling, liner advanced cooling, the quench zone air ports, the strut leading edges in the combustor area, and the catalytic reactor FINWALL are all fed with compressed air from the plenum chamber.

All the engine fuel flow at any operating condition is introduced by means of the airblast fuel injectors into the initial burning zone. The spray of fuel and air is controlled by means of radial inflow air swirlers built into the injectors so that unreacted fuel does not reach the relatively cool liner walls where it might be chilled and result in considerable UHC being produced. Sufficient air is admitted through the dome so that the equivalence ratio in the initial burning zone at engine idle is close to the stoichiometric value. By this means, the loading of the initial burning zone at idle is such that combustion efficiencies in excess of 99.5 percent will be attained. The measures described will produce engine exhaust emissions which will satisfy the Environmental Protection Agency 1979 regulations for CO and UHC. Although NO_x is produced due to the high flame temperatures, the amount is not large since the fuel and airflows are not great at idle conditions.

At engine powers above idle the equivalence ratio in the initial burning zone rises above unity (Figure 58) and there is insufficient oxygen to react all the fuel; oxygen consumption efficiency is of course, 100 percent. Flame temperatures remain essentially constant at the idle values right up to take-off power, but NO_x production declines since there is insufficient oxygen available to oxidize atmospheric nitrogen, and in the reducing atmosphere, the nitrogen reacts preferentially with fuel fragments to form amines. All liquid fuel, however, is vaporized in the initial burning zone, and partial reaction occurs.

Any unreacted but vaporized fuel and partially reacted fuel, leaves the initial burning zone and enters the quench zone where additional air is added and mixed extremely rapidly to produce very fuel-lean mixtures. With careful design of the air addition ports for rapid mixing, the chemical reactions are quickly frozen in the quench zone as the bulk gas temperature plunges, and no further conversion of initial burning zone gases takes place. Autoignition of the hydrogen contained in the unburned fuel gases during their residence times in the quench zone is prohibited because the lean flammability limits of hydrogen/air/inerts mixtures at the mixed conditions are exceeded (see Figure 25). No NO_x is produced in the quench zone therefore, due to the low temperatures.

The well-mixed and relatively hot air and fuel gases leave the quench zone and enter the catalytic reactor. The temperature of the gases entering the catalytic reactor is such that the mixture is reacted as soon as it diffuses to the catalytically-active surfaces provided in the reactor. There is some danger that preferential diffusion of hydrogen to the active surfaces might result in local high temperatures being encountered in the reactor, and this aspect would require further exploration. The catalyst effectively extends the lean limit of flammability of the mixture so that reaction takes place outside its normal flammability limits for homogeneous reaction. The amines formed in the initial burning zone are also reacted. Because the reactions take place at

very low equivalence ratios, the reaction temperatures are low enough that NO_x is not produced. Provided sufficient residence time is available in the reactor all the fuel will be reacted and no exhaust of CO or UHC will occur. The reactor is sized to satisfy this condition.

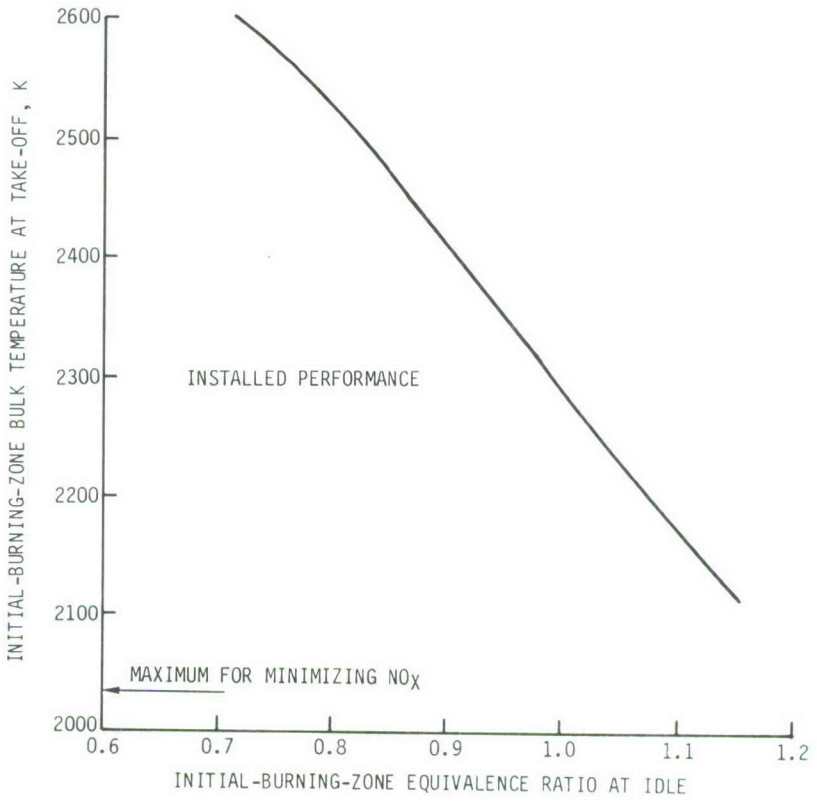


Figure 58 Concept 2: Dependency of Initial Burning Zone Bulk Temperature at Takeoff on Initial Burning Zone Idle Equivalence Ratio

Control of smoke generation in the fuel-rich initial burning zone is possible provided that the maximum bulk equivalence ratio is not above the range of 1.6-1.7, and provided that mixing within the initial burning zone is such that local pockets do not exist where the equivalence ratio is greater than 1.8-2.0. These conditions have been achieved by careful choice of the initial burning zone equivalence ratio at idle speed for the engine turn-down ratio, and by the use of airblast fuel injectors.

Concept 3: Combustor layout. - A section of Concept 3 is shown in Figure 59. The design has been accommodated within the envelope given in Figure 7 without any deviations. However, like Concept 2, Figure 57, the pilot fuel injectors have required adjustment of the compressor bleed for active clearance control in the turbine, as may be seen by comparing with Figure 60.

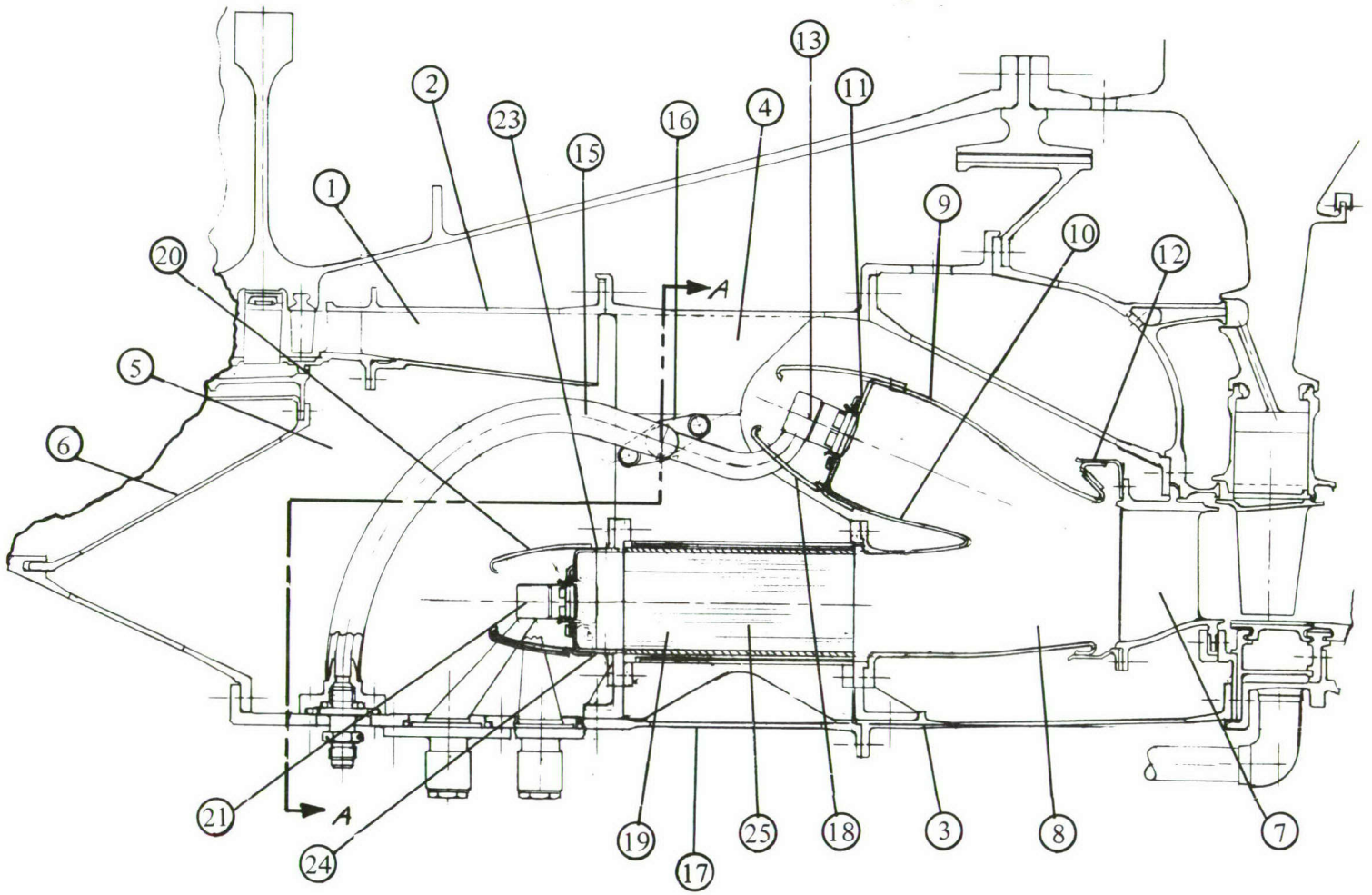


Figure 59 Concept 3: Longitudinal Section

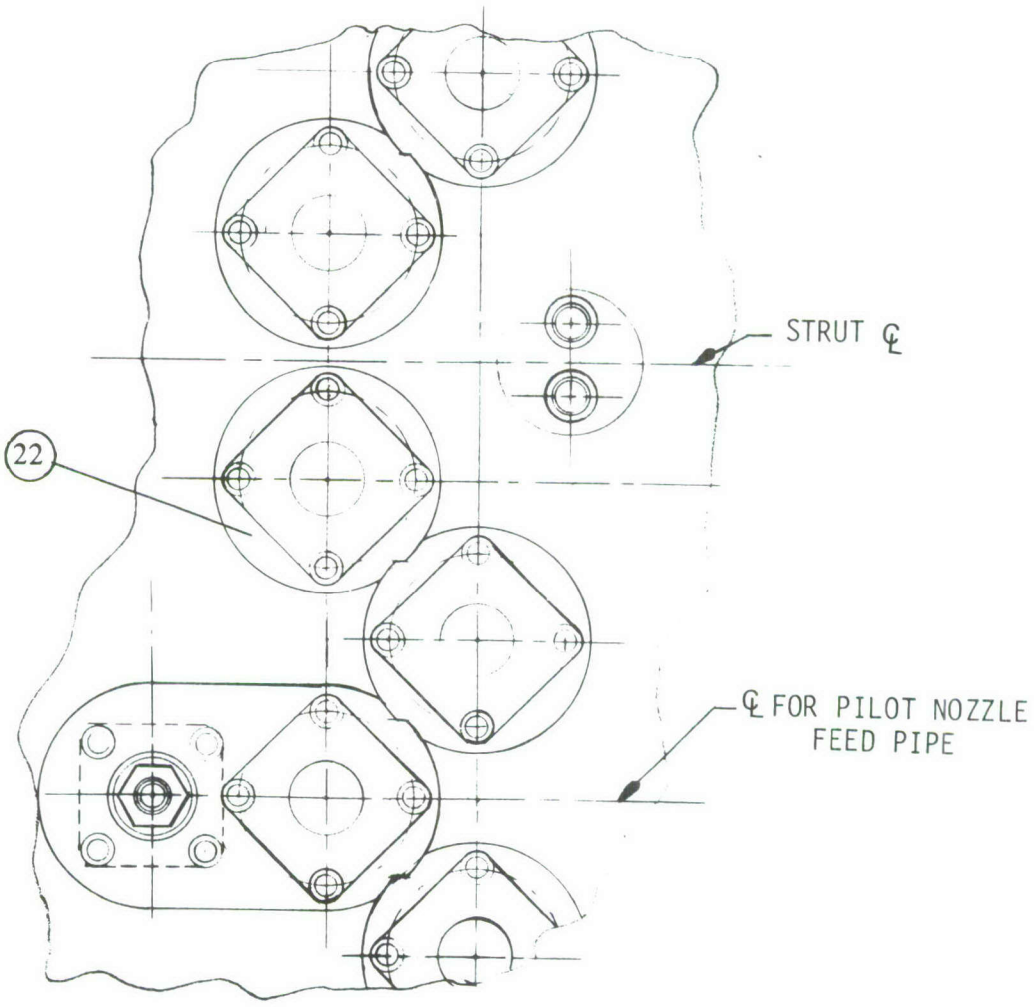


Figure 60 Concept 3: Developed View of Nozzle Support Pads

Air flows from the compressor into the asymmetric annular prediffuser (1). The inner wall of the prediffuser is formed by the inner annular air casing (2). Loads are carried from the inner casing to the outer casing (3) by means of 10 radial struts (4) downstream of the prediffuser. A plenum chamber (5) is formed by the inner and outer air casings, a forward diaphragm (6) and the turbine asesmbly (7). Compressor air from the prediffuser is dumped into the plenum chamber. This basic layout is a common feature of the three concepts so far discussed, and they differ only in the diaphragm and outer casing mechanical details; there are no functional differences.

Contained in the plenum chamber and supported by the radial struts, an annular turbine entry duct (8) and the outer casing, are the combustors. The combustors consist of an inboard annular pilot combustor, and an outboard annular main combustor. The arrangement can be seen in Figure 61, which displays a cross section. The radial struts are cut-out locally to accommodate the annular pilot combustor.

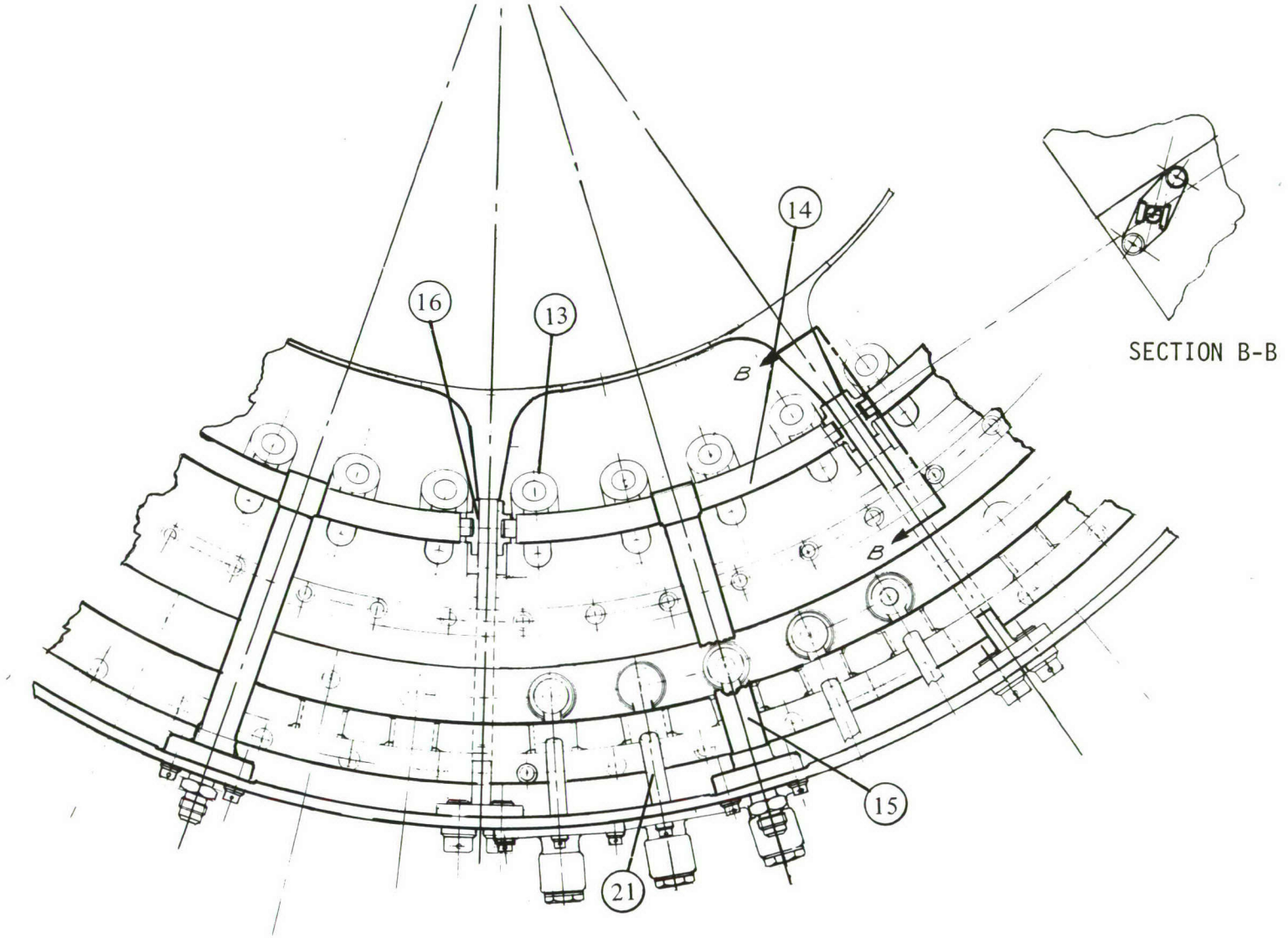


Figure 61 Concept 3: Cross Section A-A

The annular pilot combustor consists of a pair of inner and outer liners (9) and (10), connected and closed at the forward end by a dome (11) of annular height 5.84 cm. The rear of the annular pilot combustor is connected with the annular passage to form the common annular duct feeding the turbine. The rear of the pilot combustor is supported with a seal (12) at the turbine first vanes. The length of the primary zone of the pilot combustor is 10.16 cm.

Contained in the dome are 30 airblast fuel injectors (13). (Figure 61 shows 40; this number can be accommodated in the dome, but creates difficulties for the fuel injector support.) The injectors are internally manifolded (14) in clusters of 3 from a single goose-neck support (15) in a tee-form. The single support is carried on the air casing. To minimize vibration and to provide additional steadying for the long goose-neck support, the ends of the tee-manifold are carried in mounts (16) on the radial struts. The pilot injector-cluster is made to be internally removable so that the sliding outer air case (17) can be moved forward on the engine for access to the plenum chamber, as with the earlier concepts. The fuel injectors deliver fuel in conjunction with a supply of air taken from under an annular load (18). Part of the air passing through a fuel injector is arranged to flow through an integral radial-inflow air swirling device, as described for Concept 2.

Contained outboard of the annular pilot combustor is the main annular combustor (19). The main combustor is fed with air from under an annular hood (20). Contained within the hood are 50 prefilming airblast atomizing fuel injectors (21). This conflicts with the number given in the section entitled "Concept 3: Design Summary". The reduction in number was brought about by the close-packing of the bosses (22) (Figure 60) on the outer air casing. As it was, a staggered arrangement of injectors proved to be necessary. The injectors are externally removable, and are mounted on the forward portion of the outer air casing. The injectors are mounted in an annular dome of annular height 5.36 cm. The dome is provided with a multitude of small holes which provide air jets to inhibit mixture recirculation, as described in the section entitled "Concept 1: Operation".

The injectors discharge a partially-premixed, well-atomized fuel and air spray into a 2.68 cm long fuel preparation section where some slight further mixing and evaporation take place. The fuel preparation section is formed by liners (23) and (24).

The prepared fuel and air mixture leaves the fuel preparation zone to enter an annular catalytic reactor (25). The reactor has a length of 11.5 cm. and a form as described in the section entitled "Catalytic-Reactor Pressure Losses". The reactor is illustrated in Figure 55. The reactor is in 10 selfcontained segments, as described in the "Concept 1 and 2: Layout" sections. Cooling of the strut leading-edges and the reactor canning is as described in the section entitled "Concept 1: Layout." Drag loads on the reactor honeycomb are transferred to the casing as previously described.

The exhaust from the catalytic reactor enters the annular turbine entry duct, together with that from the pilot combustor, and then flows through the turbine section.

Concept 3: Operation. - Compressed air is delivered by the engine compressor to the prediffuser where it is diffused to a low exit Mach number. The diffuser air is further diffused by dumping from the prediffuser exit into the plenum chamber.

Air from the plenum chamber feeds the turbine first vanes and blades. The annular turbine entry duct advanced cooling scheme is also provided with cooling air from the plenum chamber. The annular duct may also contain small trim-air ports for adjusting the radial temperature profile leaving the catalytic reactor to a form suitable for the turbine blades; if so, these ports are fed with air from the plenum chamber. Air from the plenum chamber feeds the pilot combustor liner cooling, and provides all the combustion air for the pilot and main combustors.

The engine is started and accelerated to idle speed on the pilot combustor, which is a low emissions design. The idle equivalence ratio is unity. No fuel is supplied to the main combustor.

As the engine is accelerated from idle, the primary zone of the pilot combustor becomes initially somewhat richer. However, when the engine speed reaches a point where the compressor delivery air temperature is at or above the extinction temperature for the catalytic reactor in the main combustor, the rate of fuel increase is reduced as fuel is progressively fed to the main combustor, so that at take-off, the pilot combustor equivalence ratio is 0.4085, at which condition negligible NO_x will be formed.

Fuel is progressively fed to the main combustor as speed is increased, where it is reacted catalytically at low equivalence ratio. At takeoff conditions, the reactor equivalence ratio is 0.4085, equal to that of the pilot combustor. The reaction temperatures in the main combustor are always low enough that insignificant NO_x is formed.

Concept 4: Combustor layout. - Figure 62 provides a cross section of Concept 4. The design has been accomodated within the axial length defined by Figure 7, but the diameter has had to be increased slightly. Also, comparison with Figure 54 does show that there has been an impact on the compressor bleed for active clearance control in the turbine.

A plenum chamber into which a prediffuser dumps is established exactly as described for all the previous concepts. A sliding outer case is also provided for access to the plenum chamber and its contents.

Contained in the plenum chamber is an annular hybrid combustor that is very similar to that described in the section entitled "Concept 2: Layout". The major difference is at in the present concept, the separate quench zone has been eliminated. Support of the combustor on the radial struts and with the annular turbine entry duct, is as described in the section entitled "Concept 2: Layout". This includes the reactor canning and cooling, and the cooling of the strut leading-edges in the combustion region.

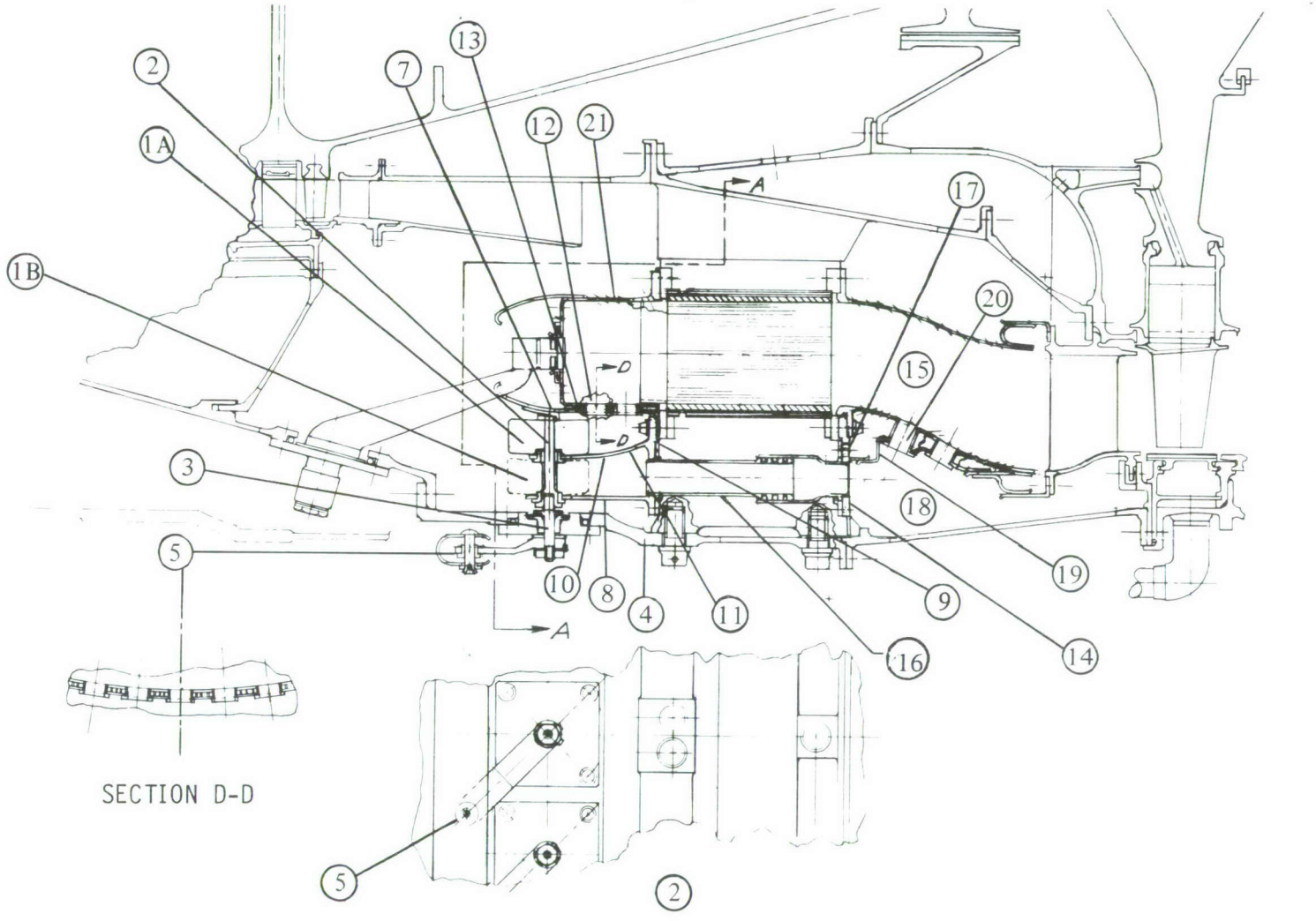


Figure 62 Concept 4: Longitudinal Section

The major difference between Concept 2 and the present concept is the addition of variable geometry to the initial burning zone.

The variable geometry system consists of a number of double butterfly valves (1A) and (1B), mounted on a common drive shaft (2). The shafts pass through glands (3) in the outer casing (4) and are connected to a unison ring (5). Actuation of the butterfly valves therefore follows established practice for variable geometry compressors. The valves are set on the shaft at an angle to each other such that when one is open the other is closed. A number of these valves are circumferentially disposed around the combustor. The valves are mounted in an annular bulkhead (6), shown in Figure 63, a cross sectional drawing. The bulkhead is supported on its inner diameter by the outer hood (7) mounted on the combustor. Figure 63 shows 40 pairs of valves, and is matched to the 40 fuel injectors. For the 30 injector design there are 30 pairs of valves; the maximum flow area remains constant.

The bulkhead extends radially outwards across 80 percent of the outer shroud and is closed at its outer diameter by a drum (8). An aftbulkhead (9) creates a closed annular volume that is divided internally by an axial baffle (10) into two annular compartments. The inner butterfly valve (1A) feeds the inner compartment, and the outer butterfly (1B) feeds the outer compartment. A circumferential row of small bleed ports (11) allows a fixed, metered bleed from the outer compartment to the inner compartment. The inner compartment allows flow into the combustor initial burning zone through a row of grommeted ports (12) contained in the initial burning zone outer liner (13), which is a double-wall construction. Air from under the hood is allowed to flow into the annular space between the outer liner double walls to feed the inner outer liner cooling scheme. A further, downstream, annular bulkhead (14) closes off the outer shroud completely at the entry plane of the annular turbine entry duct (15). Communication between the outer compartment and the shroud downstream of the aft bulkhead (14) is provided by 90, circumferentially disposed, tubes (16) mounted in both bulkheads. These tubes are in two separate parts that slide over each other to accommodate thermal growth; piston ring seals prevent leakage of air from the tubes. The tubes are sized so that metering is done by valve (1B). Shroud air can bypass the forward compartments through the unblocked 20 percent of outer shroud, and flow round the tubes to feed the catalytic reactor FINWALL cooling holes. A series of ports (17) allow some of this air to pass through the aft bulkhead to feed the cooling scheme on the outer wall of the turbine entry duct. This cooling scheme is isolated from the aft outer shroud (18) by a double wall construction (19). Air from the aft outer shroud is dumped into the turbine entry duct by a series of grommeted ports (20).

A total of 30 prefilming airblast fuel injectors are provided in the dome, and are externally mounted on the forward portion of the outer air casing. Figure 63 shows 40 fuel injectors can be accommodated in the dome. However, the outer casing becomes so overcrowded that the number was reduced.

A row of fixed small metering ports (21) are provided in the initial burning zone inner liner. These ports help to achieve a better balanced initial burning zone flow than that provided by just the ports (12) alone.

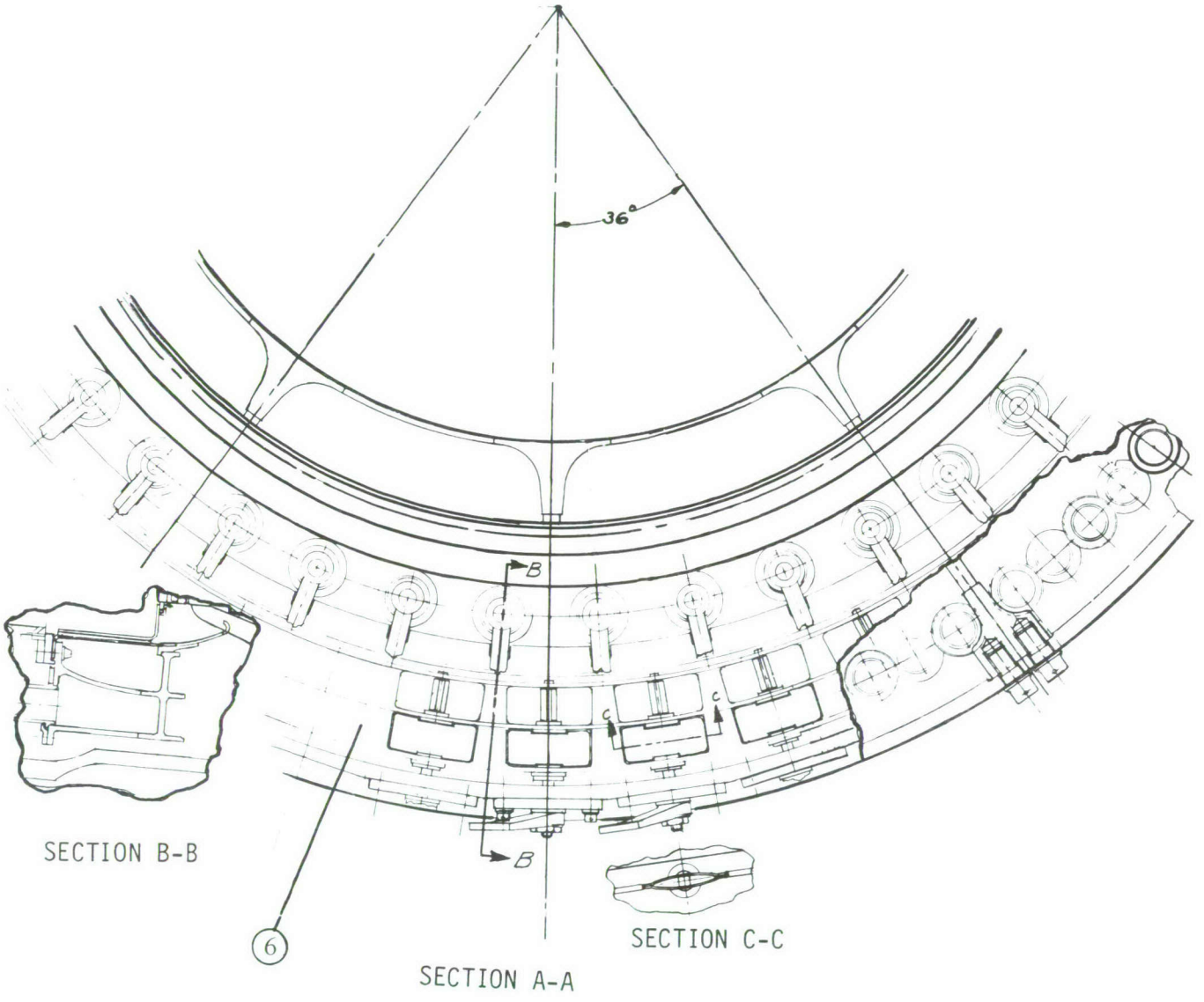


Figure 63 Concept 4: Cross Section A-A

Concept 4: Operation. - For engine starting and idling, the inner butterfly valve (1A) is closed and the outer valve (1B) is open. At idle speed, the initial burning zone equivalence ratio is 0.684. In this condition, all the initial burning zone air is supplied through the fuel injectors, dome, liner cooling, and the initial burning zone inner liner ports (21). Air enters valve (1B) and is dumped eventually into the turbine entry duct through the ports (20). Some air from the outer compartment passes through the bleed ports in the axial baffle to pressurize the inner compartment. This prevents aspiration of flame from the initial burning zone into the inner compartment.

As the engine throttle is advanced, the inner butterfly valve is progressively opened and the outer butterfly is progressively closed. This differential movement maintains a constant inlet area to the combustor, thereby preserving a constant pressure loss flow function relationship.

Opening of valve (1A) and closing of valve (1B) allows the initial burning zone equivalence ratio to be reduced as more air enters from the inner compartment. This air is obtained by the reduction in air being dumped into the turbine entry duct. At the take-off condition, the initial burning zone equivalence ratio is 0.4085, which avoids NO_x production.

The catalytic reactor receives the effluent from the initial burning zone and reacts the CO and UHC produced at idle and at high power due to disturbance of the recirculation in the initial burning zone. This disturbance is likely to occur at some operating points because of the fixed dilution jets of the inner liner and the variable jets of the outer.

High power smoke is not a problem with this design since operation is always lean enough on a bulk basis to avoid the fuel-rich mixture pockets which give rise to free carbon.

Concept 5: Combustor layout. - The design (Figure 64) has been accommodated within the axial length defined by Figure 7, but similarly to Concepts 3 and 5, the outer diameter has been increased very slightly, and there has been an impact on the location of the compressor bleed for active clearance control in the turbine.

The concept is very similar to Concept 3, described in the "Concept 3" section, except that variable geometry has been added to the pilot combustor, and the catalytic main combustor has been separated into a number of individual cans.

Compressor delivery air enters the combustion section by means of a single-sided prediffuser (1) and is dumped into an annular plenum chamber formed by inner and outer air casings (3) and (4). The plenum chamber is closed at its forward end by the diaphragm (5). The air casings and are connected by a number of radial struts (6) that transmit loads from the inner casing to the outer casing The outer casing is made in sections so that the center section (4A) when unfastened can slide forward to provide access to the plenum chamber and its contents, and to the turbine first vanes (7) through the annular duct (8).

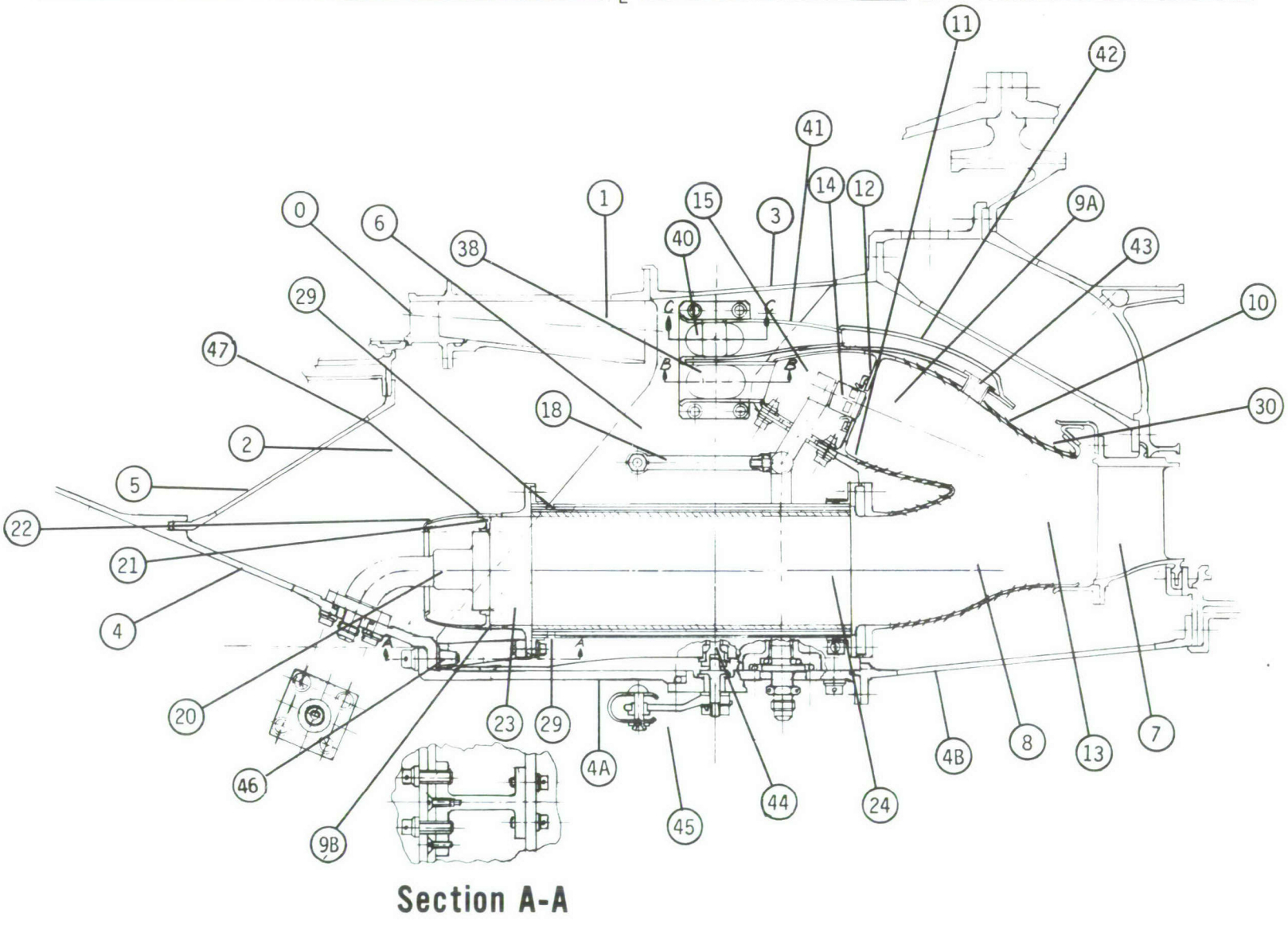


Figure 64 Concept 5: Longitudinal Section

Contained within the plenum chamber supported by the radial struts (6), the annular duct (8) and the outer casing are the combustors. The combustors consist of an inboard annular pilot combustor (9A), and 20 outboard can-type main combustors (9B). The arrangement can be seen in Figure 65 which displays a cross section. The struts are cut out locally to accommodate the annular combustor while the cans (9B) are placed in pairs between the struts (6).

The annular pilot combustor consists of a pair of inner and outer liners (10) and (11) connected and closed at the forward end by a dome (12). The rear of the annular pilot combustor is connected with the annular passage to form a common annular duct (13) feeding the turbine first vanes. The rear of the pilot combustor inner liner is supported with a seal at the turbine first vane. Contained in the dome are 30 fuel injectors of the aerating type. The fuel injectors deliver fuel in conjunction with a supply of air taken from a hood (15). The forward end of the pilot combustor is supported through the hood at the radial struts. The pilot combustor fuel injectors are internally manifolded (16) in clusters of three from a single support (17) which is carried on the outer air casing. The main support (17) passes radially between a pair of can main combustors between struts. Torsional movement of the arrangement is prevented by a drag-link (18) secured to a radial strut. The injected fuel is atomized and distributed in the combustor by the air taken from the hood. Part of the air passing through the fuel injector is arranged to flow through a radial-inflow air swirling device. This device is designed to take advantage of the high shear stresses developed to obtain ultra-fine atomization of the liquid fuel and mixing with the injector air. A plurality of small holes are dispersed in the dome to admit air from under the hood. The purpose of these holes is to cool the dome.

Contained outboard of the annular pilot combustor are the main combustors. Two are contained between each pair of struts and the pilot combustor fuel injector main supports pass between these cans, and midway between each pair of support struts. The cans are supported at their forward ends off the outer air casing and at their rear by a diaphragm (19) mounted at the forward end of the annular duct. Each can is supplied with a single fuel injector (20) mounted in a circular dome (21) closing the forward end of each can. These fuel injectors are of the aerating type and are designed to significantly increase the surface area of the liquid fuel prior to it being exposed to the atomizing air which is supplied from under the individual hoods (22). Contained in the domes are a plurality of holes fed with air from under the hoods. The purpose of these holes is to provide a multiplicity of airjets to prevent the establishment of external recirculation zones on the dome interior surface.

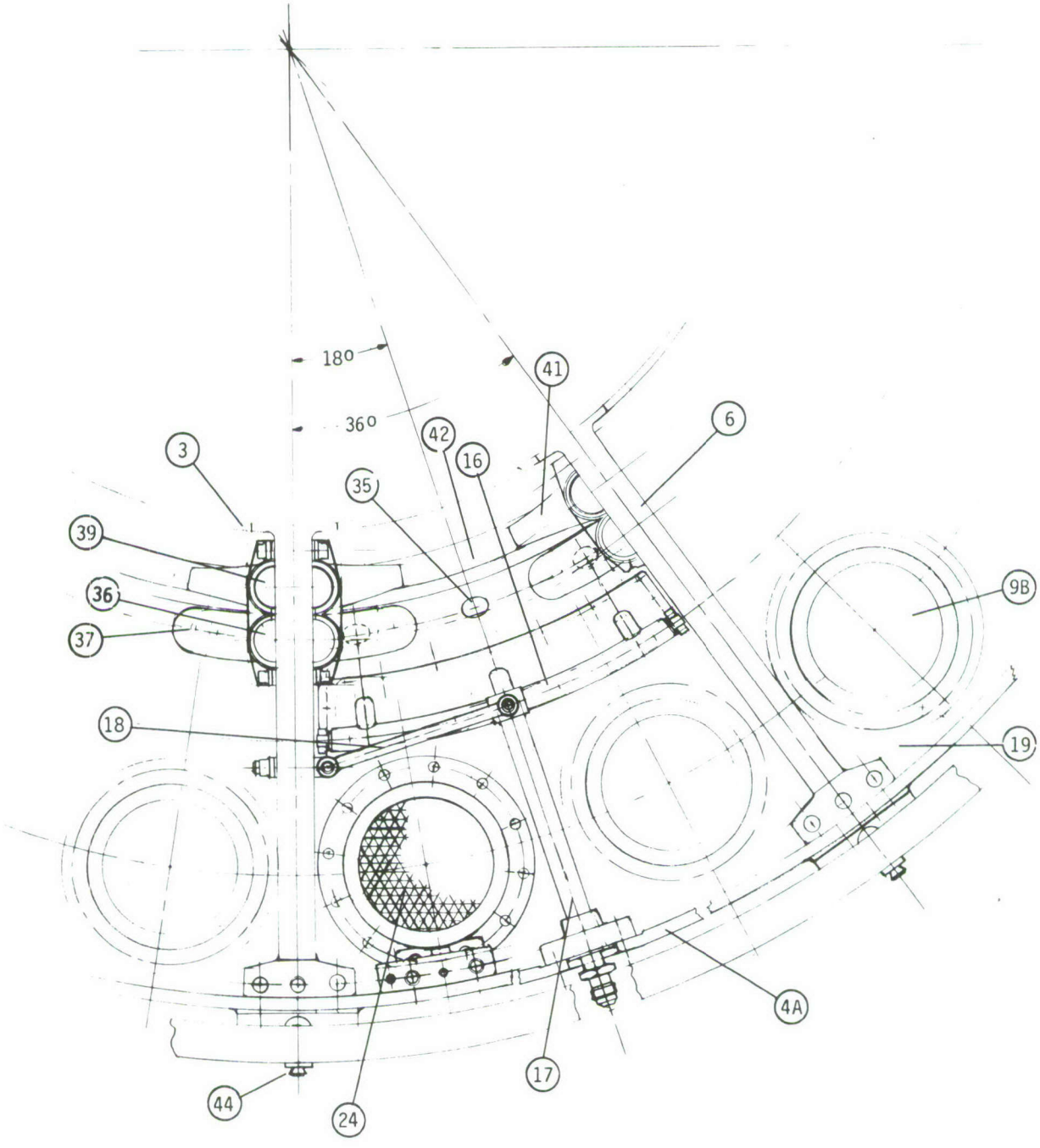


Figure 65 Concept 5: Cross Section

Contained in the main combustors downstream of a small fuel preparation zone (23) is a catalytic reactor (24). An individual cross section of catalytic reactor is shown in detail in Figure 66. It consists of a core of ceramic (Zirconia, ZrO_2) honeycomb (24A) which can have passages of several shapes and sizes. The honeycomb is coated with a calcinated refractory wash coat which is impregnated with a catalyst material of mixed metal oxides. The edges of the honeycomb are sealed with a sprayed intermediate layer of graded ceramic (25). This intermediate layer is laid up in five or more layers with a layer composition which changes successively from pure ZrO_2 adjacent to the honeycomb to a suitable metal alloy on the outside. The treated honeycomb and intermediate layer are attached at the edge to a compliant mounting pad of Feltmetal (26). The Feltmetal pad is made up from a mat of short, 0.0203 millimeter diameter chopped metal wires, compressed to desired density and sintered together. The pad is not less than 2.54 millimeter thick and has a density in the range of 35 to 50 percent of the base alloy. The resilient mounting so formed overcomes the poor mechanical strength, low mechanical shock resistance and thermal growth incompatibilities of the honeycomb with the engine. The graded intermediate layer with its varying composition, matches up the different coefficients of thermal expansion of the Feltmetal and the zirconia so that the attachment does not fail under temperature transients. To protect the Feltmetal from damage it is brazed on its exposed surface to a 1.3 millimeter thick sheet Hastelloy X carrier with a nickel-chrome braze.

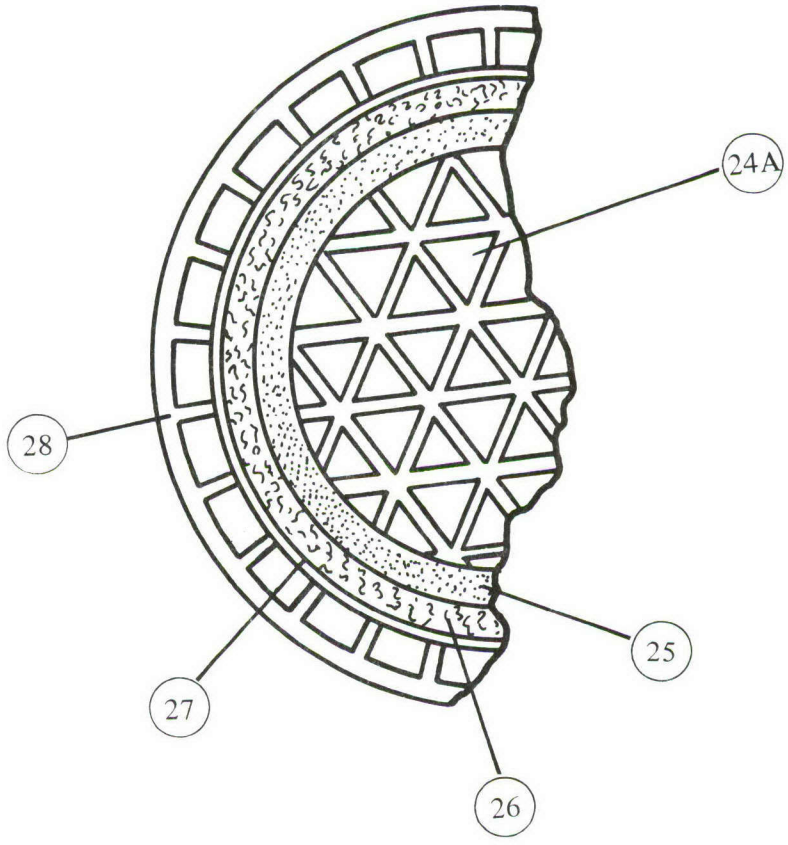


Figure 66 Concept 5: Cross Section of Catalytic Reactor

It is required that the interface temperature of the Feltmetal and the graded ceramic should be low enough to avoid oxidation of the Feltmetal alloy. To avoid putting the ceramic into tension, it is necessary that the interface temperature be as low as possible, with the ceramic temperature as high as possible. These requirements are satisfied by providing external cooling.

Panels of FINWALL (28) are formed and bonded to the carrier sheet to provide cooling passages for the outer surfaces of the reactor. These panels are fed with air from the plenum chamber by means of holes (29). The spent cooling air is discharged to the lower pressure in the annular duct.

Aerodynamic drag loads on the honeycomb are transmitted to the outer air casing first through the graded ceramic, then the Feltmetal pad and backing sheet, then the FINWALL, to the mounting piece (46).

The pilot combustor inner and outer liners and the annular duct, are provided with an advanced air cooling scheme (30).

The pilot combustor is provided with a means of ignition for engine starting as shown in Figures 67 and 68. A spark plug (31) is carried on the aft outer air casing section and penetrates the annular duct between cans, contained in a heat-shield (32) and an air-cooled fairing (33) mounted off the diaphragm. The plug enters the pilot combustor outer liner at an appropriate position by means of a ferrule (34).

The pilot combustor is provided with a means of combustion air modulation through a variable geometry arrangement.

The hood of the pilot combustor is fed with air from the plenum chamber and the prediffuser by two means: a fixed metering area provided as open ports (35) in the hood itself, and by a variable metering area provided as intakes (36) on each radial strut, as shown in Figure 68. Air from the intakes is fed to the enclosed hood volume by bifurcated ducts (37). The bifurcated ducts help to distribute the air in the hood so that the fuel injectors are fed evenly. The air modulation is performed in the intakes by means of butterfly valves (38).

When air modulation of the pilot combustor is performed, it is essential that the pilot combustor pressure loss characteristic remain fixed. This is achieved by providing a differential inlet area change, e.g. opening a compensating area as the butterfly is closed and viceversa, so that the total open area remains constant and air is just shuttled from entering one part of the combustor to another part.

A differential inlet area change is achieved by means of a second intake (39) also controlled by a butterfly valve (40), and mounted on the radial struts. Air from this intake is carried by means of bifurcated ducting (41), again for distribution, to a manifold (42) which feeds grommeted air addition ports (43) in the pilot-combustor inner liner.

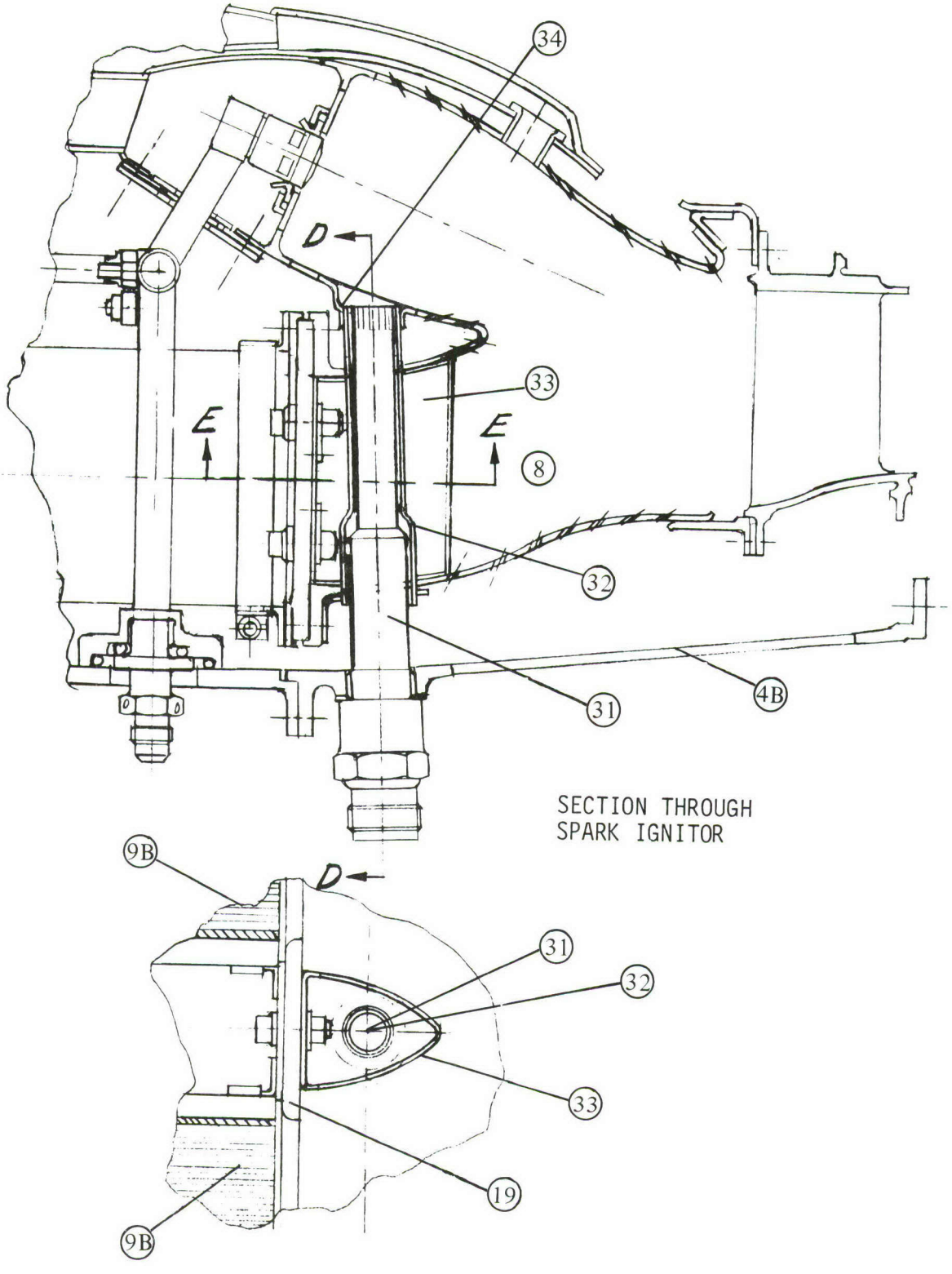


Figure 67 **Concept 5: Ignition System**

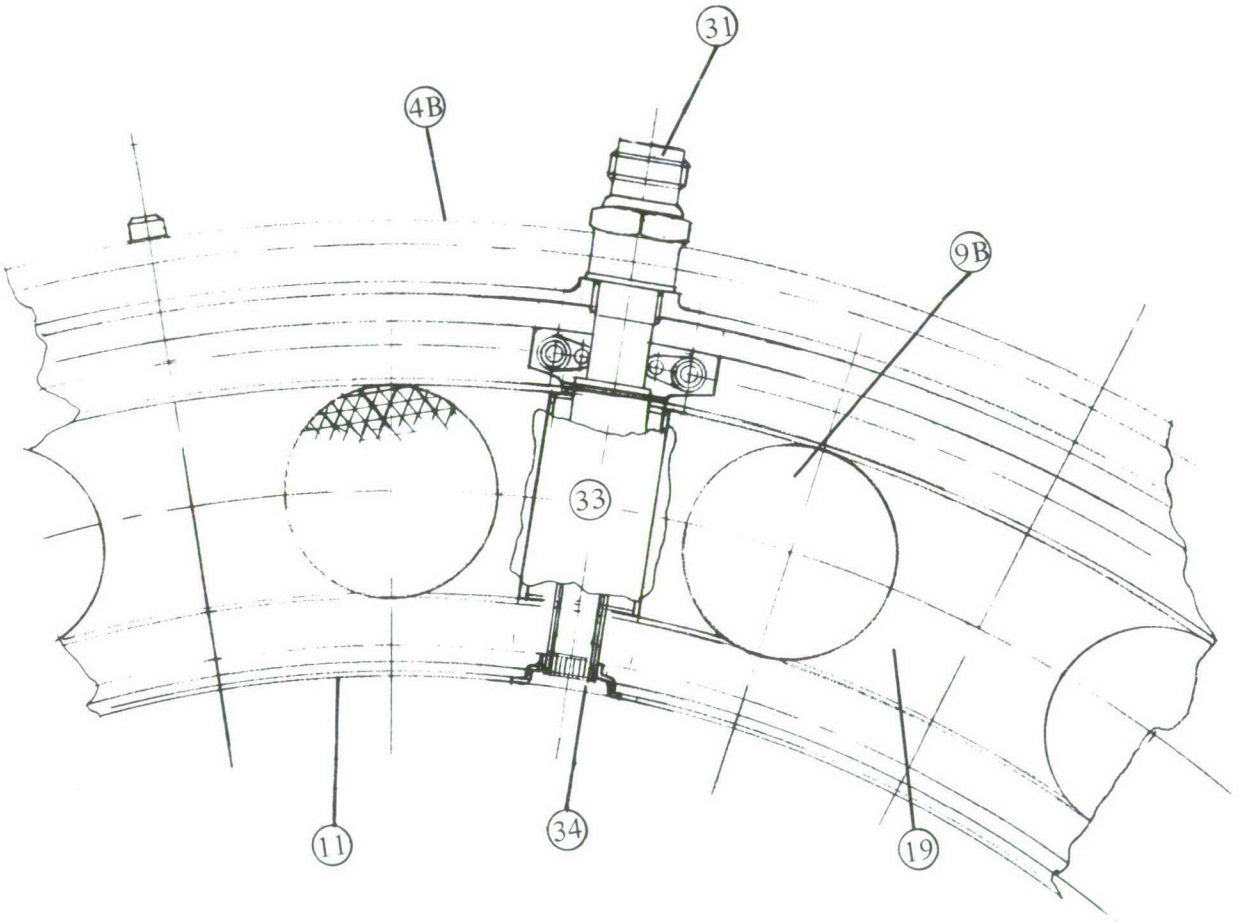


Figure 68 Concept 5: Cross Section of Ignition System

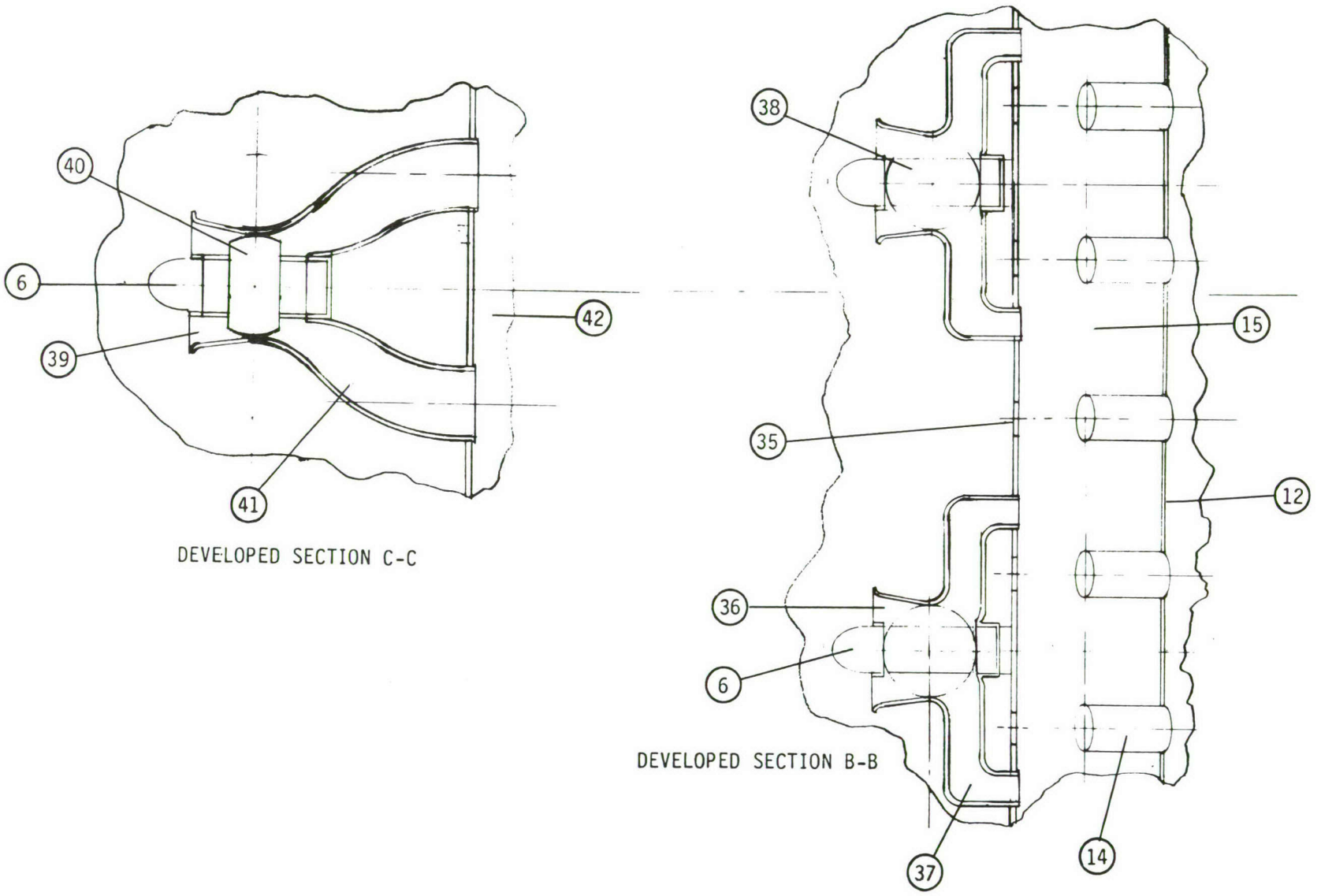


Figure 69 **Concept 5: Pilot-Combustor Variable Air-Supply Ducting**

The air addition ports are downstream of the primary zone of the pilot combustor. Thus, the variable geometry modulates the airflow to the pilot combustor primary zone by changing the airflow through the fuel injectors and dome. Sufficient fixed open area is provided to ensure the airblast atomization is not affected by operation of the variable geometry. The total open area of the combustor always remains constant whatever the positions of the variable geometry values and, thereby ensuring operation on a constant pressure loss characteristic.

The butterfly valves (38) and (40) are mounted on a common driveshaft (44). This eliminates the need for complicated follower-linkages to ensure complete synchronization between the two variable areas. Use of butterfly valves and means air modulation is achieved by simple rotary motion, and sliding, hot surfaces are eliminated. The drive shafts (44) are carried within the struts. The drive for the variable geometry is provided by a unison-ring arrangement similar to that used in variable stator axial-flow compressors (45).

Concept 5: Operation. - The present concept achieves effective emissions control over all engine operating ranges by means of splitting combustion of the total engine fuel flow into two stages, arranged in parallel. The first of these stages is a homogeneous reactor, and the second is a heterogeneous reactor. Physical staging of the fuel flow between the reactors is used. To avoid lean blow out problems of the homogeneous reactor, a two-position variation of the combustion airflow is used through a variable geometry system. The variable geometry is applied only to the homogeneous reactor and is arranged to ensure operation on a fixed pressure loss versus flow-function characteristic.

Compressed air is delivered by the engine compressor to the prediffuser where it is diffused to a low exit Mach number. The diffused air is further diffused by dumping from the prediffuser exit into the plenum chamber.

Air from the plenum chamber feeds the turbine first stage vanes and blades. The annular duct and the common annular duct advanced cooling schemes are fed with cooling air provided from the plenum chamber. The pilot combustor liner cooling is fed also from the plenum chamber. The pilot combustor and main combustor are fed with combustion air from the plenum chamber. Cooling air for the catalytic reactor canning comes from this source. The annular duct and the common duct may contain small trim air ports for adjusting the radial temperature profile leaving the catalytic reactor and that entering the common annular duct from joint effluent from combustors and, to a form suitable for the turbine blades; if so, these ports are fed with air from the plenum chamber.

For engine starting and idle operation only the homogeneous reactor is fueled. This is because catalysis does not proceed at low temperatures and the catalytic reactor requires preheating. The variable geometry butterfly valves are set so that most of the airflow enters the hood and is delivered to the combustor through the dome and the fuel injectors. The flow areas are chosen so that the primary-zone equivalence ratio is close to stoichiometric at idle speed. By this means the loading of the primary zone at idle is such that com-

bustion efficiencies in excess of 99 percent will be attained. The spray of fuel and air is controlled by means of radial-inflow air swirlers built into the injectors so that unreacted fuel does not reach the relatively cool liner walls and where it might be chilled and result in considerable UHC being produced. The measures described will produce engine exhaust emissions which will satisfy the Environmental Protection Agency regulations for CO and UHC. Although some NO_x is produced due to the high flame temperatures, the amount is not large since the fuel flow is not great at idle conditions.

At engine powers just above idle the equivalence ratio in the primary zone of the homogeneous reactor can fall slightly. Good emissions characteristics are maintained by choosing the idle equivalence ratio such that the variation of equivalence ratio in the speed range just above idle does not significantly affect combustion efficiency.

When the air temperature rise due to compression gives a compressor delivery air temperature above the extinction temperature for the catalyst reactor, the heterogeneous reactor, or main combustor, is fueled. To ensure that the catalytic reactor operates with high conversion efficiency and does not introduce a UHC or CO emissions problem during its lightup and stabilization phase, the fuel-staging is done with a stepfunction change, as Figure 38 indicates. This results in reactor temperature high enough to give essentially 100 percent complete fuel conversion.

Fuel is introduced into the heterogeneous reactor through an aerating fuel injector which provides ultra-fine atomization of the liquid fuel and good partial premixing with the injector air. The majority of the combustion air for this reactor is introduced through the fuel injectors. The remaining air is introduced through the domes in a series of uniformly distributed holes around the fuel injectors. The purpose of these holes is to prevent recirculation of fuel and air mixture back to the dome from the spray introduced by the injectors. Prevention of recirculation in the fuel preparation zone is essential to avoid autoignition of the fuel and air mixture due to excessive residence time. Also contained in the domes at the interface with the liner are annular wall-jets (47). The purpose of these jets is to inhibit flashback from the hot catalytic reactor to the fuel and air mixture being prepared. This is achieved in three ways: first by cooling the liner which is heated by conduction from the reactor; secondly by energizing the boundary layer on the liner so that the local velocity adjacent to the wall is generally always greater than the flame speed in the mixture, and thirdly by placing a layer of pure air at the wall where, on the wall itself, the velocity must be zero (no-slip condition).

In the fuel preparation region the fuel is atomized, mixed with air and vaporized prior to entering the catalytic reactor. No chemical reaction takes place in the fuel preparation region since ignition is prevented by the means described above.

The prepared mixture of fuel vapor and air enters the catalytic reactor where, as a very lean mixture normally outside the limits of flammability, it is reacted catalytically at relatively low temperatures. The reaction products

leave the heterogeneous reactor by flowing from the catalytic reactor and passing through the diaphragm to enter the annular duct. From the annular duct the effluent enters the common annular duct where it mixes with the effluent from the annular pilot combustor to enter the turbine.

Since a smooth fuel flow versus thrust characteristic is required for the engine as a whole, the step-fueling of the heterogeneous reactor introduces a step-drop in the homogeneous reactor fuel flow. This would drop the equivalence ratio in the homogeneous reactor below that for stable combustion, and a lean blow-out would result when the main combustors are turned on. The homogeneous reactor serves as a pilot combustor for the heterogeneous reactors and the engine, and it is required to operate continuously at all times in the interests of flight safety. A lean blow-out, therefore, is not permitted. A lean blowout of the pilot combustor is prevented by operating the variable geometry simultaneously with the fueling of the main combustor such that the equivalence ratio in the primary zone of the pilot does not fall below a threshold value. No further operation of the variable geometry beyond the simple two positions shown in Figure 45 is necessary.

Figure 44 shows the stoichiometry variation in the two combustors which results from the fuel staging and the variable geometry operation. The equivalence ratio in the main combustor is very low so that the temperature level that results in significant NO_x production is not exceeded. By means of the catalytic reactor extending the lean limit of flammability, the bulk of the fuel can be reacted at these low temperatures. The remainder of the fuel is reacted at slightly higher temperatures in the pilot combustor, but the amount of NO_x produced is not excessive since only about 25 percent of the total fuel flow is involved.

The control of fuel/air ratio in both combustors, that results from fuel staging and air management through variable geometry, gives equal exit temperatures from both combustors at all conditions when both are fueled. Therefore, control of the turbine-inlet radial temperature profile in the common annular duct is conventional and relatively simple. This avoids the turbine blade durability problems which can be encountered by parallel combustors.

High-power smoke is not a problem with this design since operation is always lean enough on a bulk basis to avoid the fuel-rich mixture pockets which give rise to free carbon.

By the above means the Environmental Protection Agency emissions regulations for takeoff are satisfied. At cruise also, the reaction temperatures through the two combustors are so low that negligible NO_x is produced.

Concept 6: Combustor layout. - Figure 70 shows a cross section of Concept 6. This concept could not be accommodated with in the envelope defined by Figure 7. The outer diameter is increased a small amount, and the axial length is such that gross overhang of the compressor rear stages is required. This affects the compressor bleed for turbine active clearance control, and also active clearance control of the compressor.

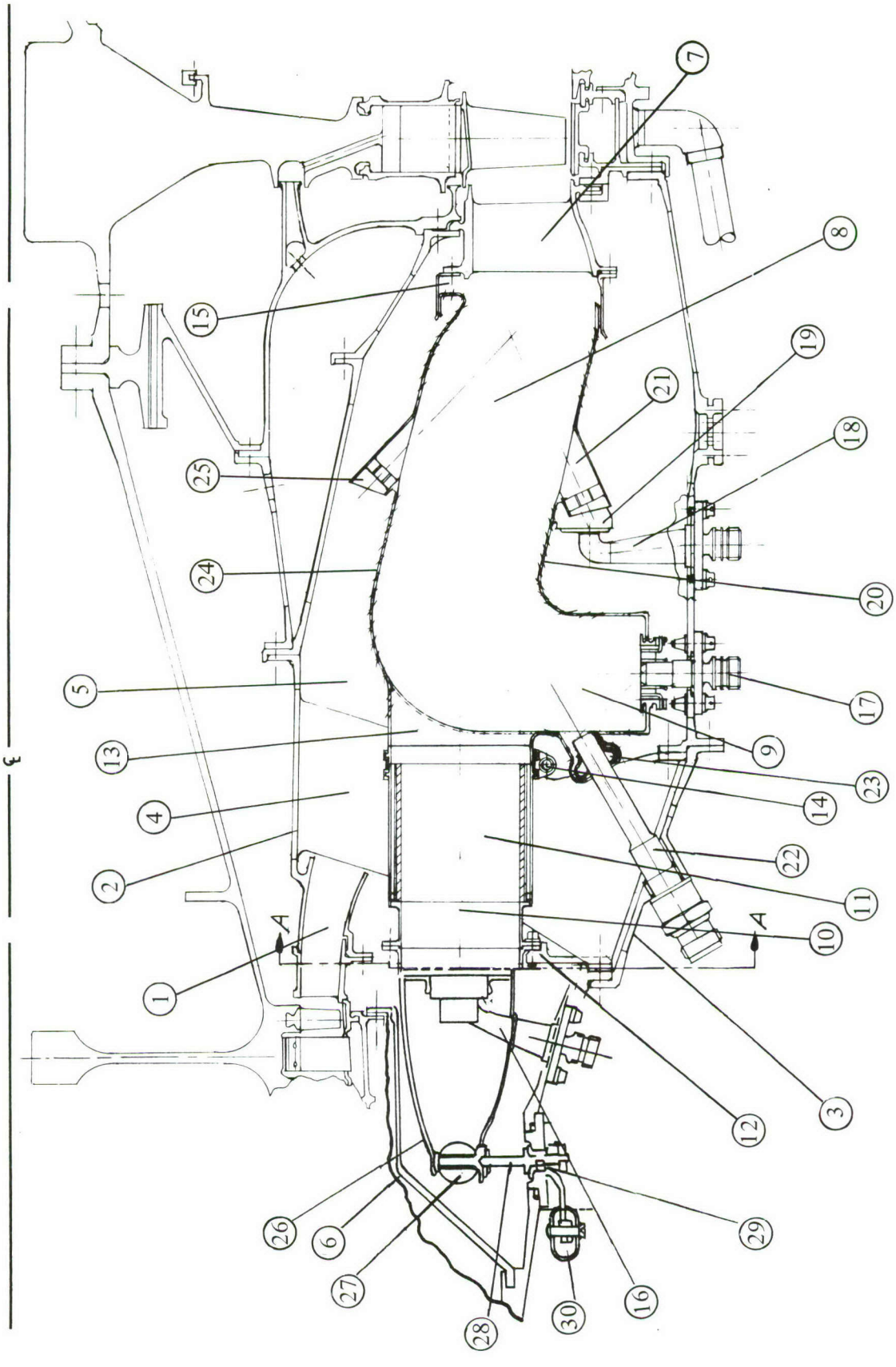


Figure 70 Concept 6: Longitudinal Section

Comparison of Figure 70 with Figure 54 reveals that considerable rearrangement of the inner casing has proved necessary to accommodate the design. The selected diffuser has had to be abandoned because of forward movement of the radial struts due to the arrangement of the Vorbix main combustor. An Energy Efficient Engine-type strutless, curved diffuser of limited area ratio has had to be introduced. The increased dump Mach number given by this, results in increased pressure losses.

Air flows from the compressor into the curved prediffuser (1). The inner wall of the prediffuser is formed from the inner air casing (2), with a small inner dump step. Loads are carried from the inner casing to the outer casing (3) by means of 20 radial struts (4) immediately downstream of the prediffuser. A plenum chamber (5) is formed by the inner and outer air casings, a forward diaphragm (6), and the turbine assembly (7). Compressed air from the prediffuser is dumped into the plenum chamber.

Contained in the plenum chamber are the combustors. The combustors consist of the Vorbix main combustor (8) with its folded pilot (9), and the cruise combustor (10) containing the catalytic reactors (11). The Vorbix is annular in form, and the cruise combustor consists of 20 individual cans, each with a catalytic reactor. The catalytic reactors are canned, mounted and cooled as previously described. The cruise combustors are between the struts and discharge into the vorbix main combustor. Figure 71 illustrates this.

The cruise combustors are mounted individually from the outer casing by support brackets (12), and are secured to a transition piece (13) on the main combustor by clamp-rings (14). Access to the catalyst sections is provided by a sliding portion of the outer case. The main combustor is supported at its rear on the turbine first vane by means of a seal (15).

Each can of the cruise combustor is provided with a single fuel support (16) that is externally removable and is carried on the outer casing. The head of the fuel support contains multiple prefilming airblast injectors for good atomizing, mixing and distribution of the fuel discharged in the fuel preparation zone.

The Vorbix pilot combustor has its fuel injectors (17) directly mounted on the outer air casing, and externally removable. The secondary stage fuel injectors (18) are also mounted on the outer casing, and feed short carburetor tubes (19) on the outer liner (20) and positioned between the outer row of vorbix-swirler tubes (21). An ignitor plug (22) is mounted on the outer casing and enters the Vorbix pilot by means of a tube with a sealed swivel (23). On the inner liner (24) are mounted the inner row of Vorbix swirler tubes (25). An advanced cooling scheme is provided for the Vorbix liners.

Mounted on the domes of the cruise combustor are individual hoods (26). The hoods are closed at their forward ends by single butterfly valves (27) with driveshafts (28) passing through glands (29) in the outer casing. The shafts are connected to a unison ring (30). Actuation of the butterfly valves, therefore, follows established practice for variable geometry compressors.

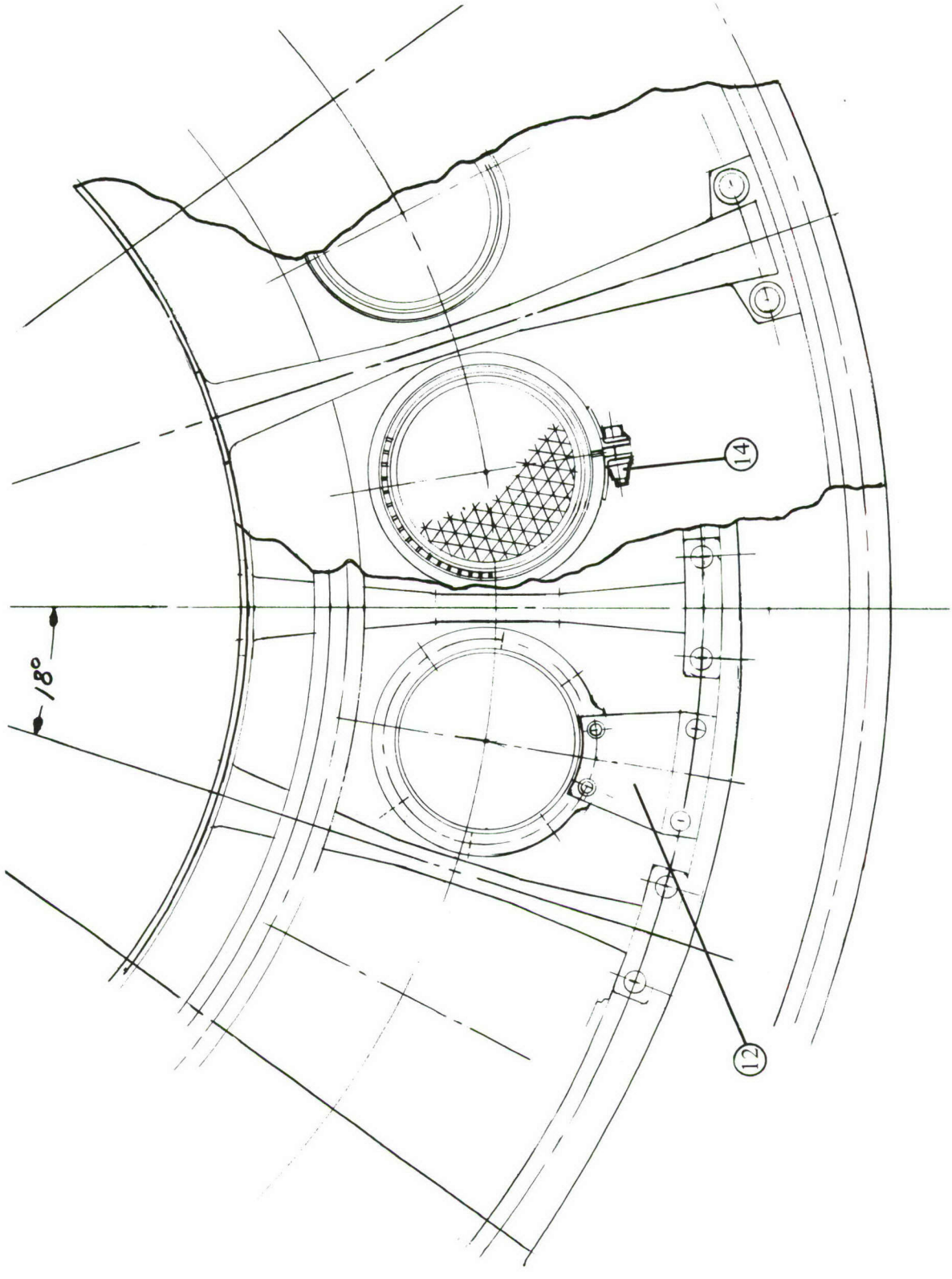


Figure 71 Concept 6: Cross Section A-A

Concept 6: Operation. - The engine is started and idled on the pilot of the Vorbix main combustor. No fuel is supplied to the Vorbix secondary or the cruise combustors. The butterfly valve on the cruise combustor is closed.

For takeoff, the pilot and secondary stages of the Vorbix combustor are fueled. No fuel is supplied to the cruise combustors, and the variable geometry remains closed. Reliance is placed on the Vorbix combustor for satisfying the existing 1979 Environmental Protection Agency regulations for emissions on the landing-takeoff cycle.

At cruise, the pilot continues to be fueled, while the secondary stage of the vorbix main combustor is not fueled. The butterfly valve is opened and fuel is supplied to the cruise combustor. Note that the system as described does not preserve a constant pressure drop versus flow function relationship.

SECTION 6.0 CONCEPT EVALUATION

6.1 Estimated-Performance Comparison

The concepts were chosen for their potential to satisfy the exhaust pollutant goals. The aerothermodynamic design of the concepts was carried out to satisfy the emissions requirements. Due consideration was given to satisfaction of the operational requirements for a gas turbine engine applied to commercial transport aircraft. Special note had to be taken of the peculiar requirements of the catalytic reactor, which formed the core of all the concepts.

Emissions. - At the completion of this preliminary design procedure emissions estimates were made for the concepts as they had been translated into preliminary designs. A comparison of the emissions performances estimated is given in Table XII. This table shows that Concepts 1 and 6 could not satisfy the goals; the former because it is non-self-starting, and the latter because a suitable system could not be worked out in the envelope available. Concept 3, although exhibiting very creditable emissions reductions compared to a conventional engine was not able to meet the goals of the program. Concepts 2, 4, and 5 appear promising.

TABLE XII

SUMMARY OF ESTIMATED EMISSIONS

Concept No.	1	2	3	4	5	6*	Regulations
Environmental Protection Agency 1979 regulation landing and takeoff cycle, EPAP							
NO_x	0	1.97-3.81[x]	3.09-3.78	0.280	1.52-3.04	-	3.0
CO	0.23+	3.54	3.704	3.38	3.62	-	4.3
UHC	0	0	0.44	0	0.41	-	0.8
Cruise $EINO_x$	0	0-0.13	1.19-12.26	0.32	1.11	-	1.0

\+ Not self-starting
x All values with margins included
* Concept found to be impractical

Concepts 2 and 4 appear able to meet all of the goals, even with the usual production engine margins applied. Concept 5 is only just over the goal for altitude cruise.

Other criteria have to be considered in addition to those of a performance nature. Specifically, these are weight, complexity (reliability) and cost.

Weight. - A relative weight ranking of the concepts is shown in Table XIII.

TABLE XIII

RELATIVE WEIGHT RANKING OF THE CONCEPTS

Concept No.	Order (Lightest = 1)
Energy Efficient Engine	3
1	1
2	2
3	4
4	5
5	6
6	7

Note that Concepts 1 and 2 are actually lighter than the baseline. This is because of the simpler fuel system which Concepts 1 and 2 have compared to that for the Energy Efficient Engine combustor. The heaviest one is Concept 5, because of the can-configuration of the catalytic secondary combustors and the variable geometry. It should also be noted that the actual difference in kilograms between some of the concepts is quite small, e.g., between Concepts 3 and 6 less than 3 kg.

Complexity and cost. - Cost and complexity are closely related. Crude cost estimates have been made to give a cost ranking based on the components making up the complete combustion chamber. The main components are indicated in Table XIV. The ranking in order of increasing cost follows in Table XIV. This ranking is for the concepts only.

TABLE XIV

COMPONENTS CONTAINED IN THE CONCEPTS

Concept	Bed		Fuel System			Combustors			Variable Geometry	
No.	Annular	Can	1	2	3	Pilot	Secondary	Main	Yes	No
1	X		X					X		X
2	X		X					X		X
3	X			X		X	X			X
4	X		X					X	X	
5		X		X		X	X		X	
6		X			X	X	X	X		X

Table XV contains no surprises: the most complex design is the most expensive on a first cost basis.

TABLE XV

RELATIVE FIRST-COST RANKING OF THE CONCEPTS

Concept No.	Order (Least expensive = 1)
1	1
2	1
3	3
4	2
5	4
6	5

Reliability may be expected to be the inverse of a complexity ranking, with reduced reliability associated with movable components.

6.2 Basis for Evaluation

Evaluation criteria. - The six conceptual designs developed under Task II are evaluated and compared with each other under the following main areas:

Emissions

Gaseous emissions of carbon monoxide, unburned hydrocarbons and oxides of nitrogen around the Environmental Protection Agency 1979 regulation landing and takeoff cycle, EPAP; emissions of oxides of nitrogen during high-altitude cruise; particulate emissions (smoke) at sea level take-off conditions.

Performance

The performance criteria will consist of total-pressure losses, pattern factor, radial temperature profile, combustion efficiency, stability and light off.

Durability

Durability will be assessed in respect of catalytic-reactor substrate and catalyst material, catalytic-reactor mounting, reactor exposure to high face temperatures, canning cooling designs, and fuel preparation as it affects reactor temperatures.

Installation

The catalytic combustor concept must be compatible with advanced engine design trends, and the various installations will be so assessed. In this, size and weight play important parts.

Operations

Operations involves two aspects: dynamic response of the system and control of the engine, and, fabricability, first cost, reliability, accessibility and repairability. In addition and encompassing both of these aspects, complexity and safety are interrelated and are of prime importance.

Development

The catalytic combustor represents a significant step forward from the conventional gas-turbine combustor. For commercial airline application and operations in the changing fuel and economic climates at the threshold of the twenty-first century, the potential for any future developments must be present. However, the risks associated with the concept must be acceptable. The term "acceptable" has to be interpreted in tne context of undeveloped nature of the aircraft gas-turbine catalytic combustor.

Scoring. - Each individual criterion will be rated as follows:

Unacceptable	0
Acceptable	1
Good	2
Excellent	3

Weighting factors. - A weighting factor appropriate for each main area will be applied to the total score for the area.

The purpose of the catalytic combustor study is to reduce emissions. The emissions main area will, therefore, rank high. However, reduced emissions cannot be achieved at the expense of performance. For this reason, the performance main area will be ranked equal with the emissions main area. Durability, installation and operations main areas will be ranked equal with other each, but lower than emissions and performance. Development will be ranked somewhat less than durability, installation and operations.

Table XVI presents the scoring system which will determine the selection of the two concepts.

TABLE XVI

CONCEPT SCORING SYSTEM

Main Area	No. Sub-Divisions	Max. Raw Score	Weighting Factor	Max. Possible Final Score
Emissions	3	9	6	54
Performance	6	18	3	54
Durability	6	18	2	36
Installation	3	9	4	36
Operations	9	27	1.33	36
Development	2	6	4.5	27

A large-number score approach is deliberately used to minimize potential subconscious adjusting of scores to favor particular concepts. Consideration of the maximum final score column reveals that the importance of the various groups of main areas is as follows:

Emissions/Performance:	Durability/ Installations/Operations:	Development:
6	4	3

6.3 Results

Score Sheets. -Tables XVII through XXIII give the score sheets for the concepts in each main area. Each table gives the raw and weighted scores of all concepts in each main area. The raw scores are broken into sub-divisions.

Table XVII presents the emissions scoring.

Out of a maximum possible weighted score of 54, Concept 4 was top scorer with 54, Concept 1 was second with 42, and Concepts 2 and 5 were joint third with 36.

Table XVIII presents the performance scoring.

TABLE XVII

EMISSIONS SCORING

Sub-Division	Concept					
	1	2	3	4	5	6
Sea-Level Emissions	3	2	2	3	3	1
Cruise Emissions	3	3	1	3	1	2.5
Sea-Level Smoke	1	1	2	3	2	1
Raw Score	7	6	5	9	6	4.5
Weighted Score	42	36	30	54	36	27
Max. Possible Score = 54						

TABLE XVIII

PERFORMANCE SCORING

Sub-Division	Concept					
	1	2	3	4	5	6
Pressure Losses	2	2	0	2	0	1
Pattern Factor	2	3	2	3	2	1
Radial Profile	2	2	1	2	3	1
Combustion Eff.	0	2	1	2	2	2
Stability	0	3	1	1	1	1
Light-Off	0	3	1	1	3	2
Raw Score	6	16	6	11	12	8
Weighted Score	18	45	18	33	36	24
Max. Possible Score = 54						

With respect to pressure losses, none of the concepts had maximum raw scores. This was because the choice of catalytic-reactor substrate was limited to high porosities in all cases. Concepts 1, 2 and 4 had about the same total pressure

losses, with a same freedom on choice of substrate. Concept 5 had a lower total pressure loss, but a choice of only one reactor substrate of those studied; Concept 3 was in the same position. Concept 6 should have had acceptable pressure losses because the catalytic reactor was only flowing during cruise operation. However, a constant pressure has loss versus flow function relationship was not preserved for the concept.

Pattern factor potential was considered excellent for Concepts 2 and 4, and not so good for the other concepts since fuel preparation in all these remaining concepts was constrained by considerations of autoignition. The incomplete airflow control, and reduced length after the Vorbix secondary fuel injections, were counted against Concept 6. Concept 3 was scored low because the contribution of radial profile to pattern factor was felt to be a possible problem. Concept 3 was scored low for radial profile since the pilot combustor is hotter than the secondary combustor at all conditions except takeoff. This is likely to result in higher temperatures at the hub of the turbine blades, which is undesirable. Concept 6 is again scored low because of the turning of the pilot, and incomplete air control. Concept 5, with equal equivalence ratios in the pilot and secondary combinations at all conditions where the secondary is operating, scored high for this reason.

Concept 1 was scored low on combustion efficiency, because it is not self-starting. Concept 3 is scored low because of the very low equivalence ratios at which the catalytic reactor is first fueled.

The stability score of Concept 6 is low because of the incomplete air control, reduced length of vorbix secondary.

Concept 3 is scored low with respect to light-off ability because of the way the secondary is fueled initially. Concept 4 scored low because of concerns that operation of the variable geometry might result in disturbance of the initial burning zone recirculation zone.

Out of a possible weighted score of 54, Concept 2 was top with 45 and Concept 5 scored high with 36.

Table XVIV presents the durability scoring.

In respects of both catalyst and substrate durabilities, those concepts involving series combustion, i.e., Concepts 2 and 4, are scored low; Concept 4 particularly so because of the high reactor inlet temperatures at idle.

Liner cooling and canning cooling requirements were ranked on a surface area basis, with special consideration for Concept 4 due to the adverse effects the variable geometry arrangement has on that concept.

Reactor face temperatures were not considered a problem, with the single exception of Concept 4 at idle, as discussed above.

TABLE XVIV

DURABILITY SCORING

Sub-Division	Concept					
	1	2	3	4	5	6
Catalyst Substrate	2	1	1	0.5	2	2
Catalyst	2	1	1	0	2	2
Liner Cooling	3	1	2	1	1	0
Reactor Face Temp.	3	3	3	0.5	3	3
Canning Cooling	2	1	0	3	0	1
Fuel Prep.	0.5	3	1	3	1	1
Raw Score	12.5	10	8	8	9	9
Weighted Score	25	20	16	16	18	18
Max. Possible Score = 36						

Fuel preparation was limited due to autoignition constraints for all concepts except those employing series combustion, i.e , Concepts 2 and 4. Concept 6 was somewhat better off since it is only fueled during cruise when increased ignition delay times permit better fuel preparation.

Concept 1 with a weighted score of 25 out of a possible maximum of 36, came out as superior in respect of durability, with Concept 2 at 20 following.

The scoring of the concepts for their installations in contained in Table XX.

Table XXI contains the scoring of operations. Concept 2 is scored well on engine control since it is essentially a conventional system. Safety is based on failure of a component, and flight operational safety. For example, Concept 3 is scored low on safety because of the dangers associated with potential blow-out of the pilot combustor when the secondary is fueled, and difficulty in lighting the secondary combustor after a descend due to low equivalence ratio.

Concept 2 scored highest with 30.59 out of a possible 36 weighted score.

Table XXII describes the scoring for development potential. Assessment of the risks associated with development of a concept has to be subjective. Obvious guidelines exist: the simpler a concept the better its chance of success; similarly, the closer a concept is to existing conventional practice the less the risk associated with it.

TABLE XX

INSTALLATION SCORING

Sub-Division	Concept					
	1	2	3	4	5	6
Compatibility	2	2	1	2	1	0
Size	2	2	1	2	1	0
Weight	3	3	1	1	0	0
Raw Score	7	7	3	5	2	0
Weighted Score	28	28	12	20	8	0
Max. Possible Score = 36						

TABLE XXI

OPERATION SCORING

Sub-Division	Concept					
	1	2	3	4	5	6
Dynamic Resp.	1	2	1	1.5	1.5	1
Engine Contl.	0	3	1	1	1	0
Fabricability	2	2	3	1	2	1
First Cost	3	3	2	2	1	0
Reliability	3	2	1	1	2	-1
Accessibility	3	3	1	1	0.5	-1
Repairability	2	2	2	1.5	1.5	0
Complexity	3	3	2	1.5	1	0
Safety	0	3	1	2	3	2
Raw Score	17	23	14	12.5	13.5	1
Weighted Score	22.61	30.59	18.62	16.63	17.96	1.33
Max. Possible Score = 36						

TABLE XXII

DEVELOPMENT SCORING

Sub-Division	Concept					
	1	2	3	4	5	6
Potential	0	2	1	1	2	2
Risk	0	3	1	1	1	-1
Raw Score	0	5	2	2	3	1
Weighted Score	0	22.5	9	9	13.5	4.5
Max. Possible Score = 27						

With these guidelines, Concept 1 scores poorly since it is not a selfstarting system, and Concept 2 scores highly since it is simple and closest to conventional practice. Concept 5 scores above the simpler Concept 4, because it appears the risks associated with achievement of the performance are lower for Concept 5, while development of the asymmetric initial burning zone recirculation zone which is inherent in the continuously modulating variable geometry of Concept 4 appears likely to present problems.

Ranking. - Ranking is based on the accumulated scores from Tables XVII through XXII. Table XXIII tabulates the individual scores and gives their summation with and without the emissions score. The two final scores are presented so that it is clear how the final ranking was influenced by the emissions goals.

Consideration of Table XXIII gives Concept 2 with a clear top score, and this is so with or without emissions. Second highest score, again both with and without emissions, is Concept 4. Concept 1 is in third place on an emissions basis but is virtually tied with Concept 5 without emissions. Concept 6 emerges in last place.

Two most promising concept selection. - It can be seen from Table XXIII that Concept 2 emerges as a clear winner and Concept 6 as a clear loser. Concept 4 is in second position and Concept 5 in third position. Although Concept 1 has scored high, it really cannot be considered a practical design due to the inability to start cold without prohibitive auxiliary systems. It is difficult to accept Concept 4 as the second place design since the catalytic reactor is a redundant feature in this configuration. Emissions control can be achieved through the variable geometry alone. The catalytic reactor is only required because the initial burning zone cannot be optimized for maximum combustion efficiency at idle because of temperature restrictions due to the downstream catalytic reactor!

TABLE XXIII

CONCEPT SUMMARY SCORES

Main Criteria	Concept					
	1	2	3	4	5	6
Performance	18	45	18	33	36	24
Durability	25	20	16	16	18	18
Installations	28	28	12	20	8	0
Operations	22.61	30.59	18.62	16.63	17.96	1.33
Development	0	22.5	9	9	13.5	4.5
Emissions	42	36	30	54	36	27
Score without Emissions	93.61	146.09	73.62	94.63	93.46	47.83
Score with Emissions	135.61	182.09	103.62	148.63	129.46	74.83
Max. Possible Score = 243						

On the basis of Table XXIII and the discussion above, the following concepts are recommended for work under Phase II of this program:

First choice: Concept 2
Second choice: Concept 5

There is little to quarrel with on the choice of Concept 2. Concept 5 is selected over Concept 4 for the reasons given earlier.

7.0 PRELIMINARY DESIGN OF SELECTED CONCEPTS

7.1 Concept 2: Combustor Design

Structural configuration. - The basic layout for Concept 2 is given in Section 5.3.3 and is illustrated in Figure 58. This section describes any differences in detail from the preliminary layout.

Front-end Assembly

Small changes have been made in the dome design to improve control of the fuel/air spray from the airblast fuel injectors, and a revised dome cooling. Figure 72 provides a sketch of these changes (flow from right to left in this figure).

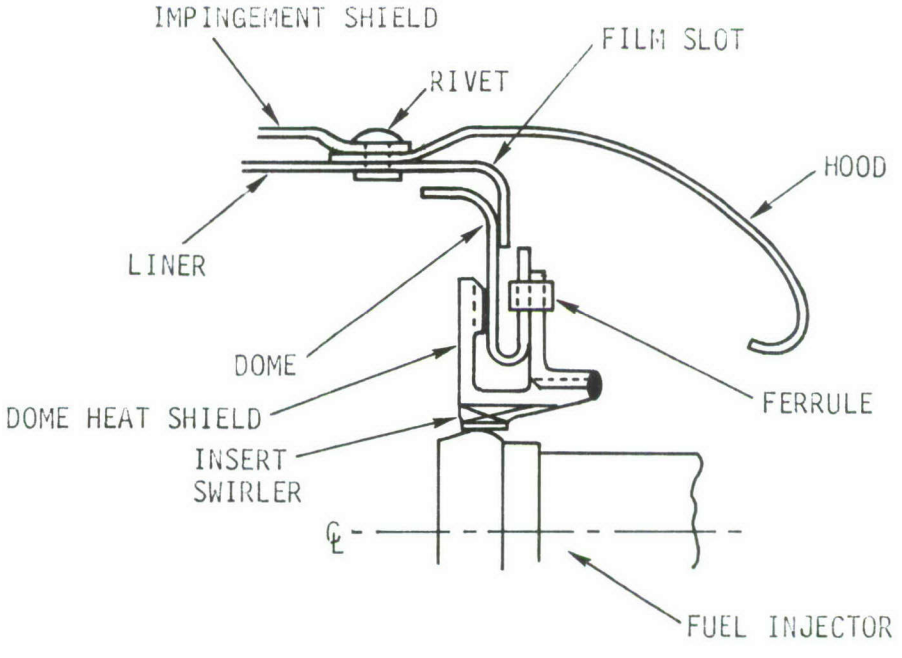


Figure 72 Dome Modification

The fuel injector enters a circular dome heat-shield that is mounted in a ferrule arrangement on the initial burning zone dome. The ferrule permits radial tolerance and thermal growth to be accommodated. The heat shield protects the majority of the dome from radiation heat loads. The heat shield is equipped with radial standoffs from the dome so that a fixed gap height between the shield and dome is maintained. The gap is fed with air through impingement holes. After impinging on the dome-side of the heat shield, the cooling air flows radially outwards through the gap to film cool the remainder of the dome. On the inner diameter of the heat shield is an integral insert swirler,

the inner shroud of which bears on the fuel injector. The purpose of the insert swirler is smoke control. The dome and the liner are welded together to form a small, conventional film cooling slot, that is fed with cooling air from under the hood. The sole purpose of this film cooling slot is to cool the rivets used to attach the hood and impingement shield to the liner.

Combustor Liner

The liner cooling scheme was modified slightly from that shown in Figure 57 by the addition of an impingement shield and the additional modifications entailed by this.

Figure 73 shows a sketch of the initial burning zone and quench zone, with the revised dome and impingement shields applied to the liners. The impingement shield is secured to the liner by rivets at the hood attachment, and aft by bolts at the flange connecting the homogeneous and heterogeneous reactors. The shield is cool and relatively light gage compared to the liners. Thermal growth differentials can be taken up by movement of the shield itself. These are not anticipated to be large because of the relatively low temperatures of the combustion and quench processes. The shield is supported off the liners by a series of local formed sheetmetal hat-sections spot-welded to the interior surface of the impingement shield. To minimize interruption of coolant discharge through the liner, an alternative support section would be a W-section.

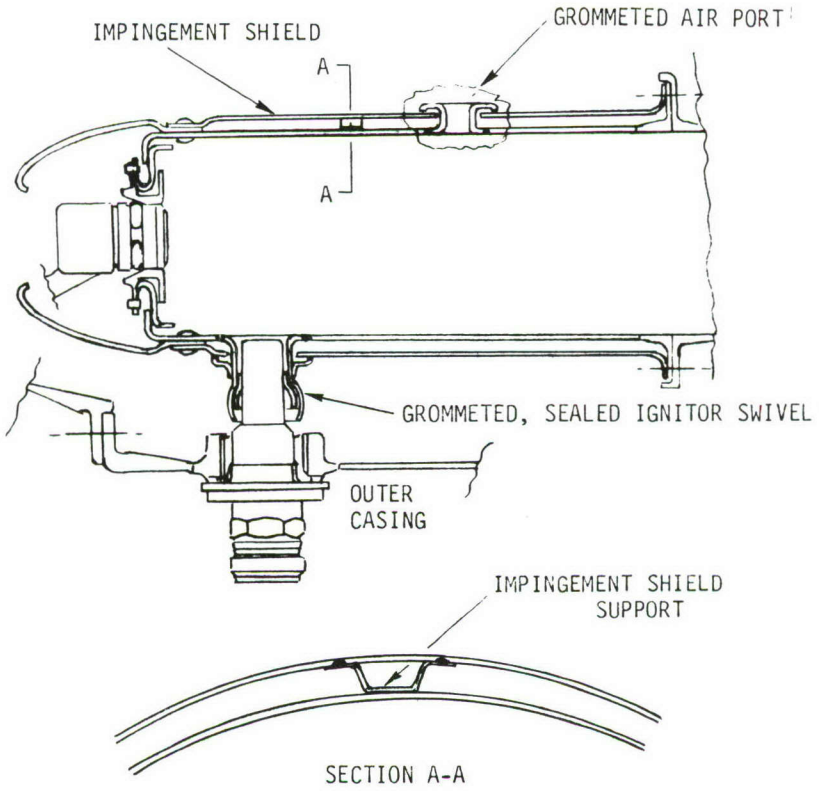


Figure 73 Liner Modification

Leakage of impingement air at the ignitor plug and the quench-air ports is prevented by the use of grommeted air ports and a grommeted, sealed ignitor swivel.

Figure 74 shows application of the impingement shield to the annular turbine entry duct. The shield is secured at the forward end to the flange attaching the entry duct to the radial struts. At the rear, the shield is free to slip in a fishmouth seal which is part of the combustor seal. This is necessary because the temperatures are higher at turbine inlet than in the quench zone.

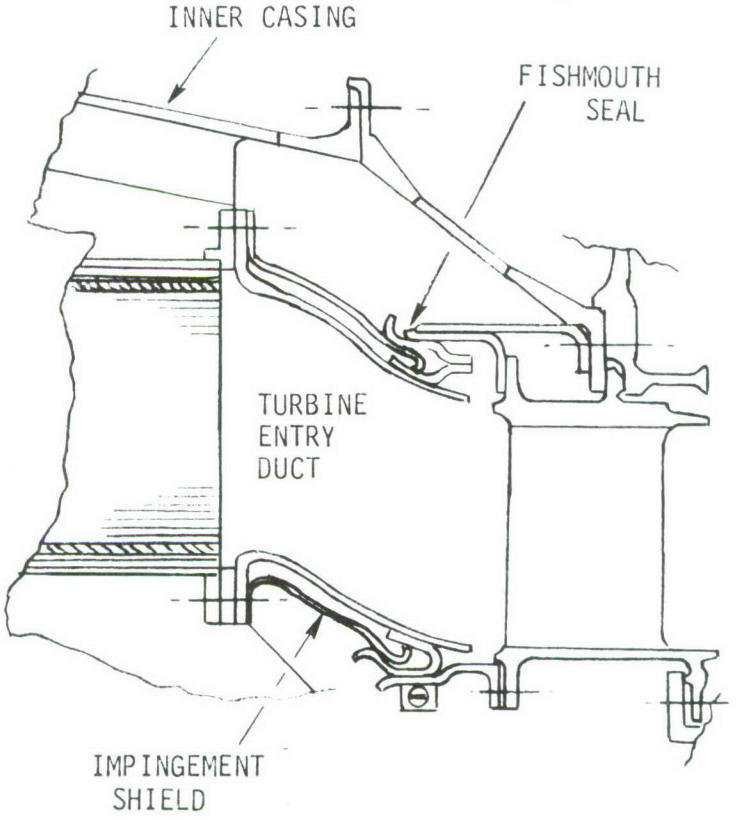


Figure 74 Turbine Entry Duct Modification

Catalytic Reactor

Alternative forms of reactors were considered. These, however, were also applicable to Concept 5, and will be described in the section entitled "Catalytic Reactor" for that concept.

Support System

No changes were made to the support system.

Aerothermal design. - Figure 75 shows a diagrammatic representation of Concept 2 with the flow conditions through the combustor at sea-level static take-off power on a standard day displayed on it.

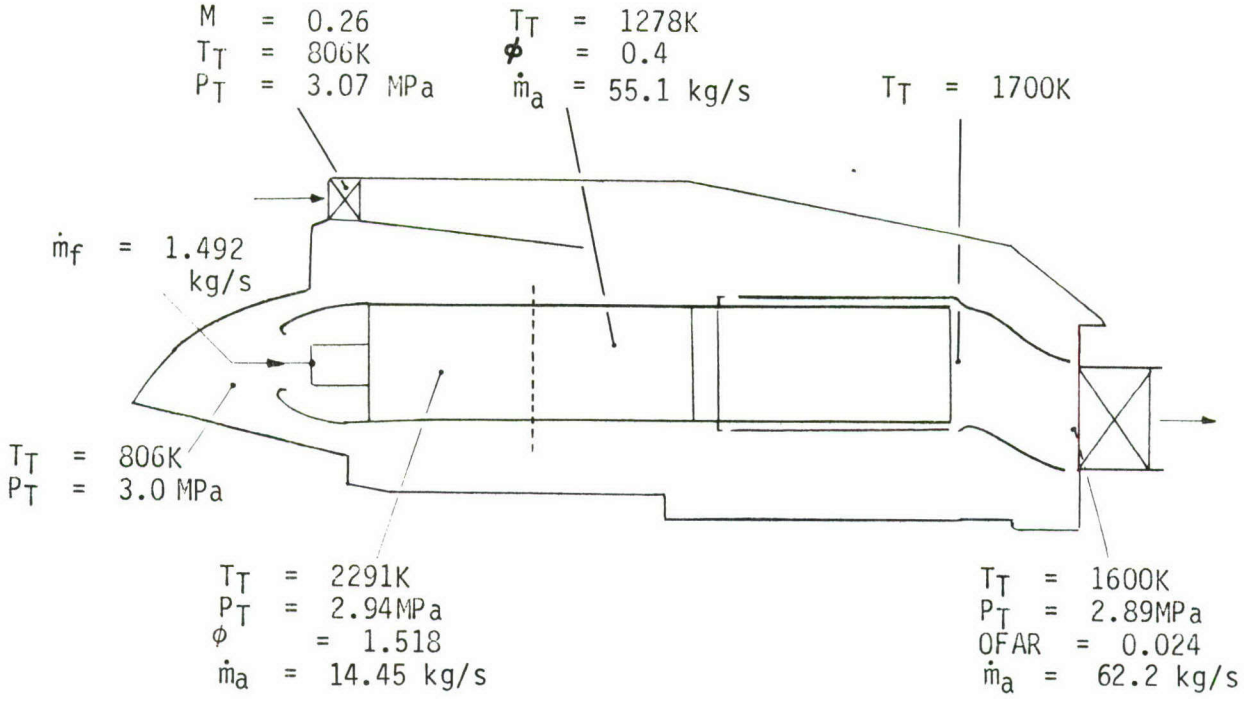


Figure 75 Concept 2: Flow Condition At Sea-Level-Static Takeoff

Cooling Systems

Analysis of performance data on a typical mission established the liner thermal design point as the 0.457 kilometer altitude, 0.39 flight Mach number at beginning climb conditions on a hot day. At these conditions the following applied:

Fuel flow rate, $\dot{m}_f$, kg/s	1.526
Compressor delivery total pressure $P_{T3.0}$, MPa	3.285
Compressor delivery total temperature $T_{T3.0}$, K	838.3
Combustor airflow, $\dot{m}_{a,4.0}$ kg/s	62.46
Initial burning zone airflow, kg/s	13.67
Quench airflow, kg/s	41.41
Initial burning zone temperature, K	2194
Reactor exit temperature, K	1739
Combustor exit total temperature	1644
Quench-zone temperature, K	1245

The areas (m^2) to be cooled (excluding the dome) are as below:

Initial burning zone	0.3763
Quench zone	0.5369
Turbine entry duct	0.2803
Catalytic reactor	0.7852

A preliminary analysis was made for the two materials and maximum average design metal temperatures using conventional film cooling. The estimates were made using the experience curve given in Reference 12, and provided a benchmark. For Hastelloy X material, 40.3 percent of the total combustor airflow would have been required and for IN 617 material, 31.6 percent. These amounts do not include the catalytic reactor cooling and are obviously unacceptably excessive. Therefore, an advanced cooling scheme was necessary.

For the various zones to be cooled, the required convective heat transfer coefficients to meet the material $T_{s,max}$ were calculated. Improved cooling schemes were then examined for their potential to satisfy the required convective heat transfer coefficients. Two promising candidates considered were a multi-hole "transpiration" scheme, and a combined impingement/multi-hole "transpiration" scheme, like that in Section 4.2.

A minimum hole diameter of 0.0635 cm was selected so that blockage in service would not be a problem. This was held constant for all cooling configurations. The "transpiration" wall thickness was taken as 0.1524 cm. The "transpiration" holes were assumed to be laser-drilled at an angle of 0.5236 radians to the surface. Where an impingement scheme was used the impingement shield was 0.762 cm from the transpiration surface.

For the catalytic reactor zone, the reactor container was cooled using a standard FINWALL analysis. The rectangular passages were 0.0762 cm wide and 0.1016 cm high.

Table XXIV provides a summary of the cooling airflow results of the analyses for the liners, and Table XXV gives the impingement/transpiration hole pitch to diameter ratios required to pass the cooling airflow.

It can be seen from Table XXIV that the transpiration cooling scheme actually takes more airflow than a conventional film cooling scheme. This is because of the minimum hole size stipulated, the need to fully cover the surface to be protected, and the wall pressure drop.

The combined impingement/transpiration scheme shows as the most attractive cooling arrangement since it takes only half the air of conventional film cooling. This scheme is so effective because of the combined heat transfer effects of the impingement air jets on the back side of the hot liner wall, and the convective cooling in the multiple holes in the liner wall itself. The calculations take no account of any film effect on the hot side of the liner wall. The impingement shield takes most of the overall liner pressure drop, which is converted to coolant jet-velocity. The low pressure drop across the

"transpiration" wall means full coverage can be achieved without excessive flow rates through the wall. A further advantage of the combined impingement/transpiration arrangement is that the impingement flow is bled away through the transpiration wall. This eliminates cross-flow between the impingement shield and the transpiration wall. Crossflow usually reduces the effectiveness of impingement cooling rather severely.

TABLE XXIV

LINER COOLING AIR SUMMARY

	Cooling Air, % W_{comb}			
	Transpiration		Impingement/ Transpiration	
Zone	HAST X	IN 617	HAST X	IN 617
Initial burning zone	23.2	21.0	9.7	8.0
Quench zone	20.2	17.7	5.6	4.4
Dilution zone	10.8	9.4	2.2	1.7
Reactor*	4.11	4.11	4.11	4.11
Totals:	58.31	52.21	21.61	18.21

*The FINWALL requires a constant 4.11 percent W_{comb} cooling for 1124 K temperature, which is appropriate for both materials, and a desirable maximum for the feltmetal resilient mounting material.

TABLE XXV

COOLING HOLE SPACINGS

	Hole p/d+			
	Transpiration		Impingement/ Transpiration	
Zone	HAST X	IN 617	HAST X	IN 617
Initial burning zone	5.6	5.6x	5.81/5.54	6.39/6.08
Quench zone	6.69	7.11	9.16/8.61	10.34/9.68
Dilution zone	7.64	8.67	17.65/13.33	14.91/11.36

+ Holes arranged in rows pitched p apart in either square or diamond array.

x pitch/diameter (p/d) came out less than the range covered in the calculations.

The impingement/transpiration cooling scheme is selected for Concept 2. Furthermore, it is clear that the conventional and familiar Hastelloy X material is a perfectly adequate choice for the transpiration wall. The impingement shield can be a lighter gage, less expensive material since it is not subject to temperatures much above compressor delivery values.

Of the FINWALL cooling air, 0.9 percent of combustor air is supplied through the radial strut leading-edges; the remainder is fed from the plenum directly through the supply ports in the canning.

The selection of the combined impingement/transpiration cooling scheme resulted in the liner modifications previously described in the Combustor Liner section. A sketch of the initial burning zone liner wall is shown in Figure 76, as an example.

7.2 Concept 5: Combustor Design

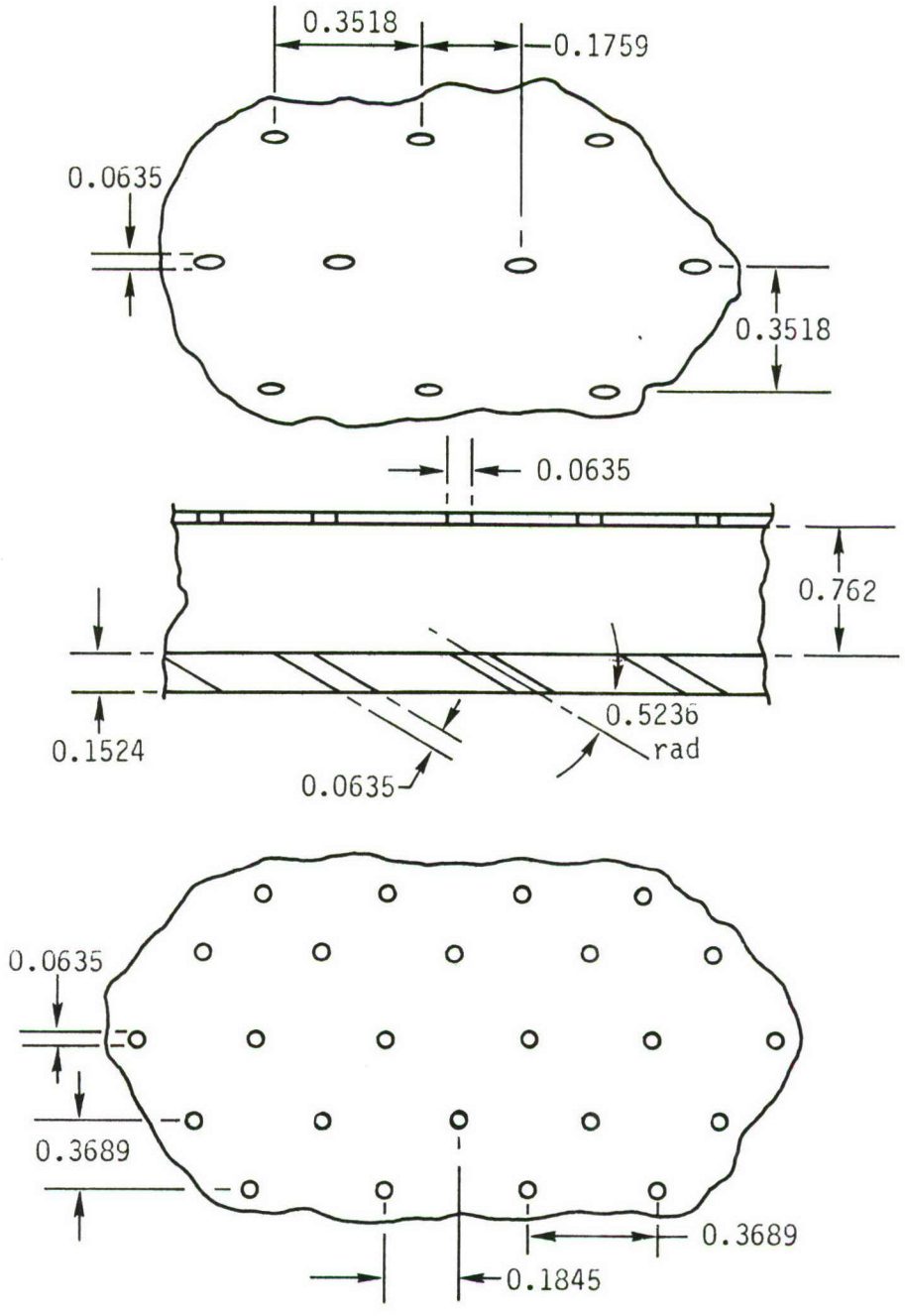
Structural configuration. - The basic layout for Concept 5 is given in Section 5.2, and is illustrated in Figures 64, 66, 67, 68 and 69. The present section describes any differences in detail from the preliminary layout.

Front-end Assemblies

There are no changes to the dome design of the catalytic main combustors. The analytical tools required to design the anti-recirculation air-jets in the dome remain in the process of development. Therefore, a detailed design study could not be carried out at this time. However, an illustration of the principle of recirculation-suppression and the design procedure being developed is given below.

Figure 77 is a representation of the base-case where no efforts are made to suppress external recirculation of the fuel/air mixture to the dome. The flashback-suppression slots are shown; the fuel injector is represented in this case with a single non-swirling jet. The figure shows streamlines calculated by numerical solution of the time-averaged Navier-Stokes equations with a two-equation $K-\epsilon$ modeling of the Reynolds stresses for closure. The calculation is symmetrical about the combustor centerline.

For the case shown in Figure 77, the fuel is introduced as a premixed vapor, and the fuel and air central jet has considerably more momentum tnan does the annular wall-jet for flashback suppression. For this arrangement, the wall-jet is drawn to the dome recirculation zone and entrained by the central jet. This defeats the flashback-prevention intention of the wall-jet. Diffusion of the central jet is very limited. Figure 78 shows the axial velocity profile at a distance 0.259 dome heights from injection. It is typical and shows the region of negative (flow reversal) velocities between the two jets. The wall-jet velocity divided by the initial fuel/air jet velocity at this station is 1.45 compared to its initial value of 0.62. The actual value of fuel/air jet velocity is 97.2 m/s. The reduction in wall-jet velocity impaired its usefulness at a flashback suppressor. Fuel might get into the recirculation and autoignite due to increased residence time.



Not To Scale

All Dimensions in cm

Figure 76 **Impingement/Transpiration Cooling Scheme for Initial Burning Zone Liner in Hastelloy X Material**

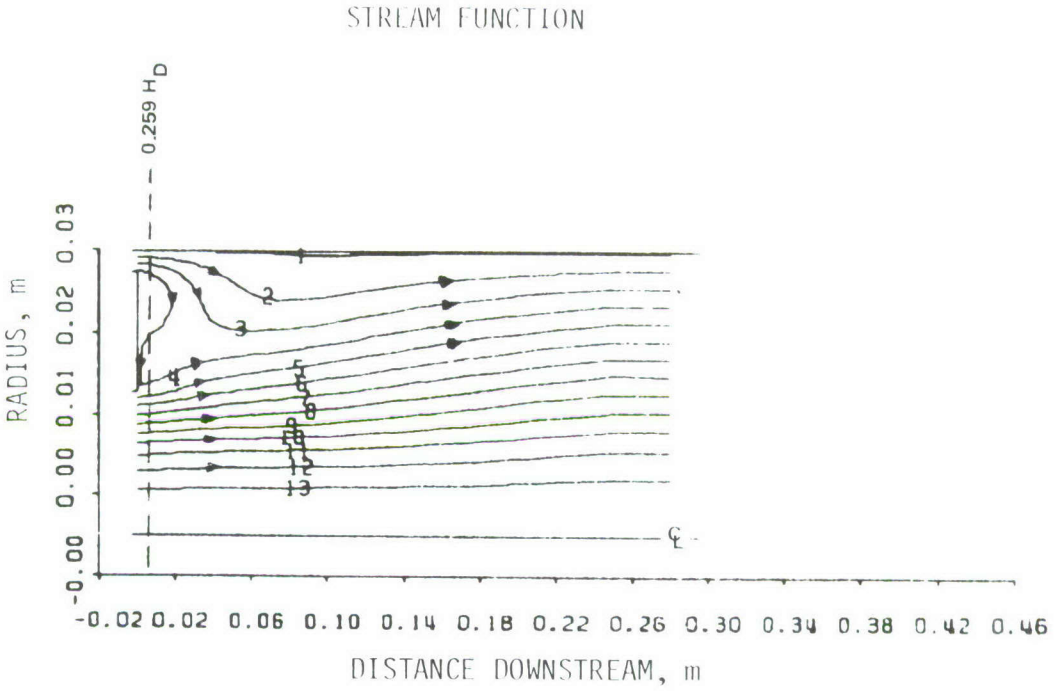


Figure 77 Concept 5: Catalytic Combustor Fuel Preparation Baseline Case with Wall Flashback Suppression Showing Streamlines

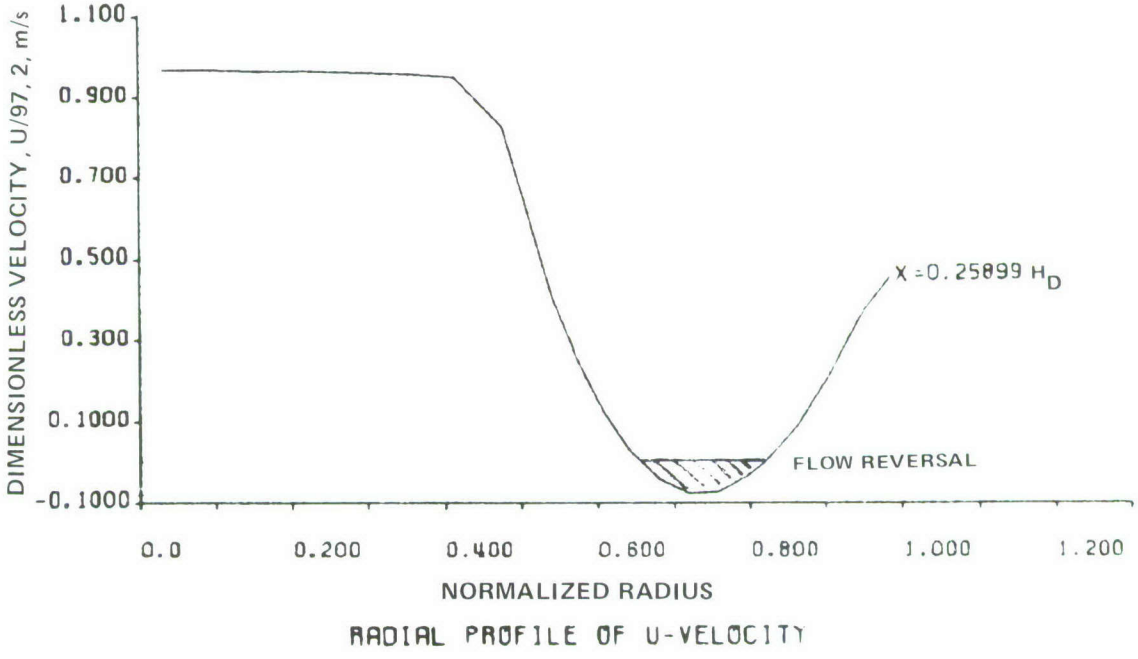


Figure 78 Radial Profile of Axial Velocity Close to Dome Showing Excessive Residence Time of Fuel-Air Mixture Due to Recirculation

Figure 79 shows the streamlines when anti-recirculation jets are added between the central and wall-jets. The anti-recirculation jets are represented as being completely annular because the three-dimensional flow version of the computer code is not yet completed. In this example, the velocity of the anti-recirculation jets is equal to that of the central jet, and the total mass flow of the center and anti-recirculation jets is equal to that of the central jet of Figure 77.

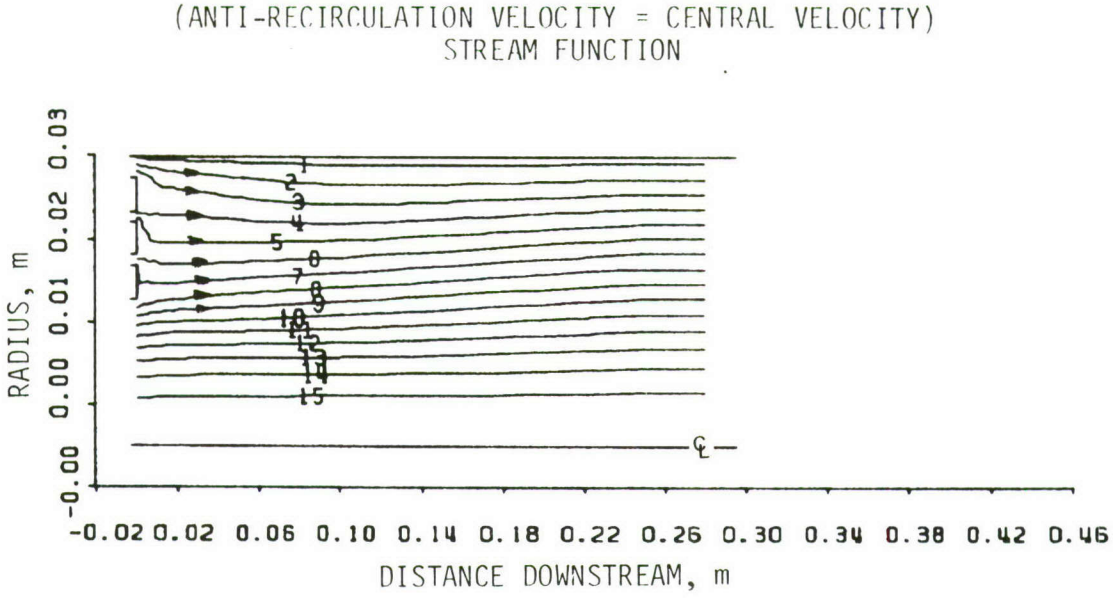


Figure 79 Elimination of Both Wall Flashback and Recirculation-Induced Autoignition

The streamline plot shows that the dome recirculation is eliminated completely. However, entrainment of the wall-jet into the central flow field still takes place as is indicated by the diffusion shown. Figure 80 shows the axial velocity profile at 0.259 dome heights from injection. The region of negative velocities has been eliminated. However, the ratio of wall-jet velocity to central jet initial velocity is reduced to 0.43 which, since the central jet initial velocity is itself reduced to 88.7 m/s compared to the base-case, represents a greater reduction than existed in the base-case. Therefore, although one problem has been solved and another has potentially been introduced.

Figure 81 shows the same geometric arrangement as Figure 79, but in this case the anti-recirculation jets have been introduced with a velocity equal to that of the wall-jet.

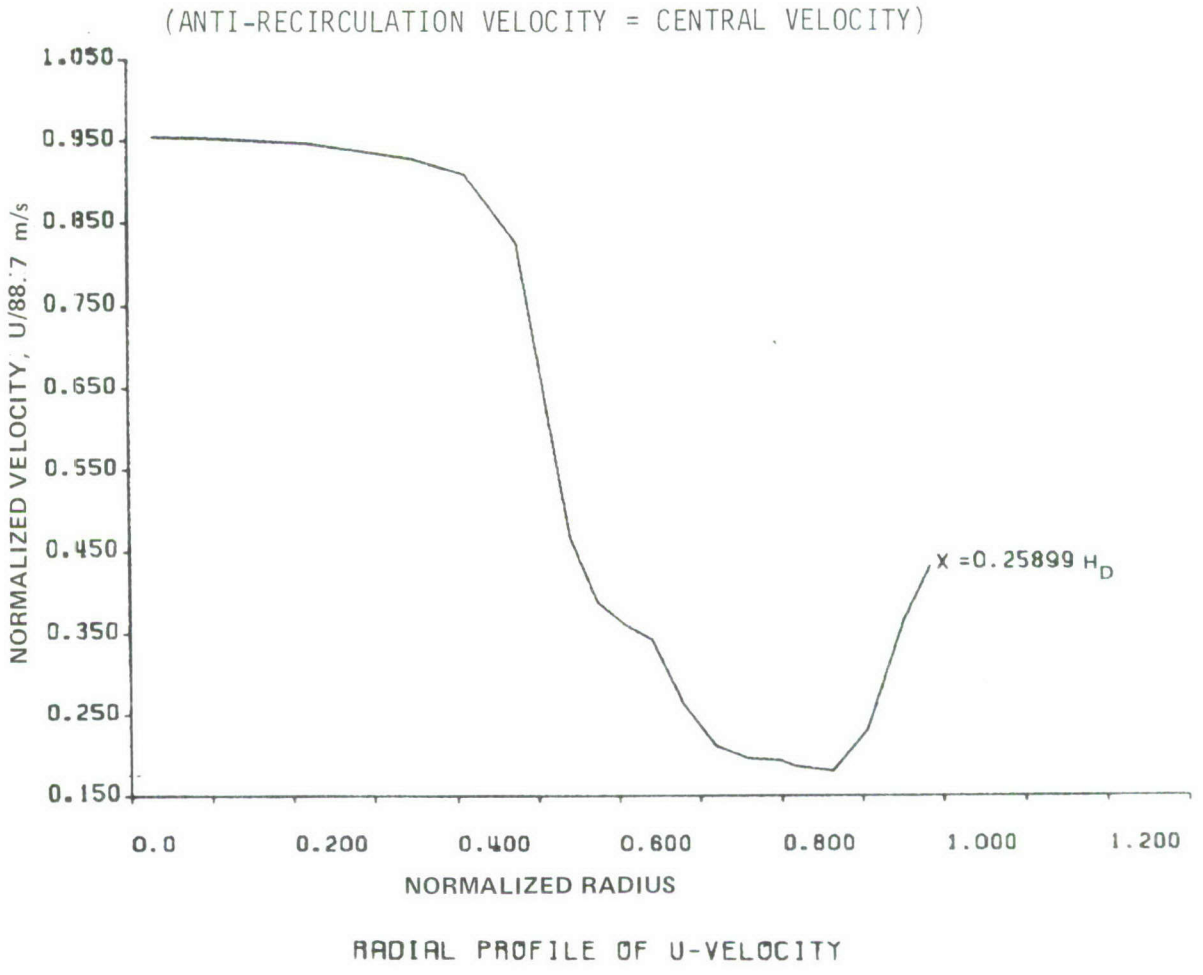


Figure 80 Radial Profile of Axial Velocity Close to Dome Showing Elimination of Recirculation

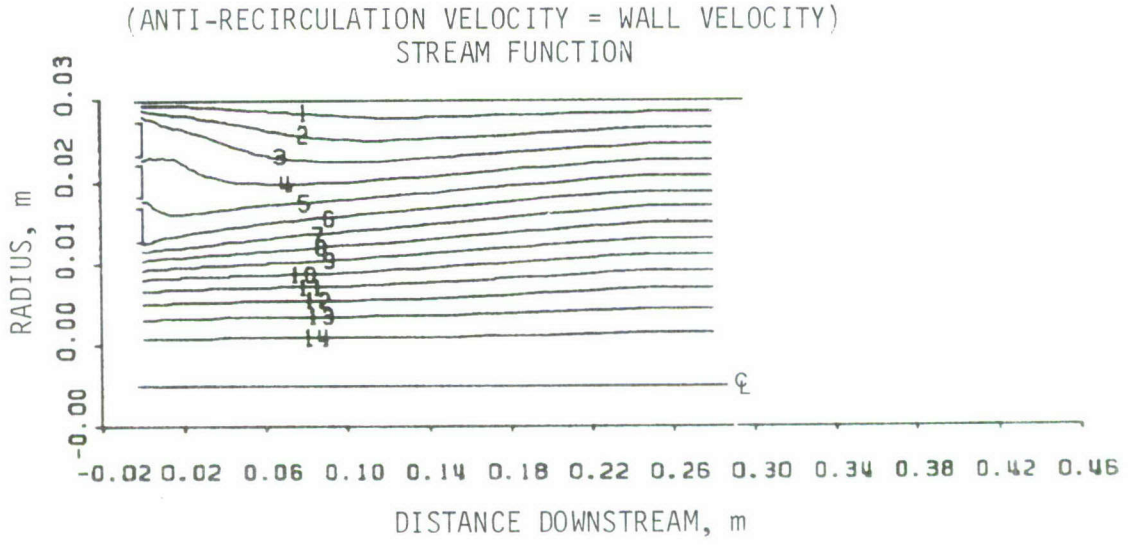


Figure 81 Streamlines for Revised Scheme of Flashback and Autoignition Suppression

The streamline plot shows that the recirculation to the dome is eliminated. Figure 82 gives the axial velocity distribution at 0.259 dome heights from injection. This confirms that recirculation is eliminated; however the minimum velocity is 5.7 m/s compared to 15.3 m/s for Figure 80, and -8.7 m/s for the base-case. This is because much less mass flow is introduced in this case than in the first anti-recirculation design. The velocity in the wall-jet is 46 m/s compared to 38 m/s in the first anti-recirculation design, and 43.7 m/s in the base-case.

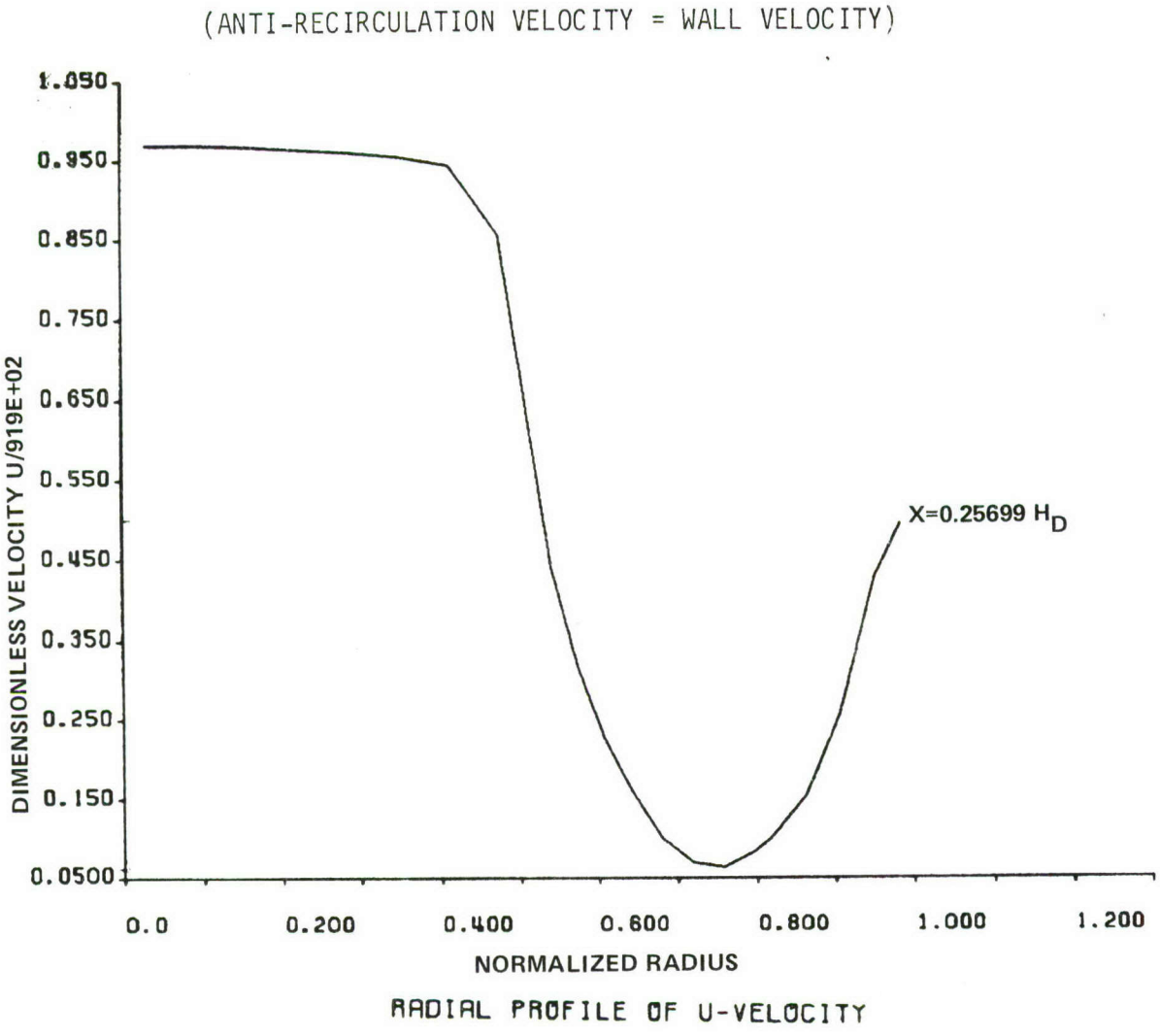


Figure 82 Radial Profile of Axial Velocity Close to Dome for Revised Scheme of Concept 5

The studies indicate that provided sufficient anti-recirculation air is used and if it is injected with a velocity less than that of the flashback-suppression air, dome recirculation can be successfully eliminated without impairing flashback suppression.

The fuel-injector unit of the catalytic secondary combustor (Item 20, see Figure 63 and Section 5.2), has to accommodate the inner row of anti-recirculation air jets. The foregoing remarks indicate a doublewall approach must be used so that full dome pressure drop does not result in the situation described in Figures 79 and 80. Figure 83 shows a sketch of a possible multi-source fuel injector incorporating anti-recirculation air-jets

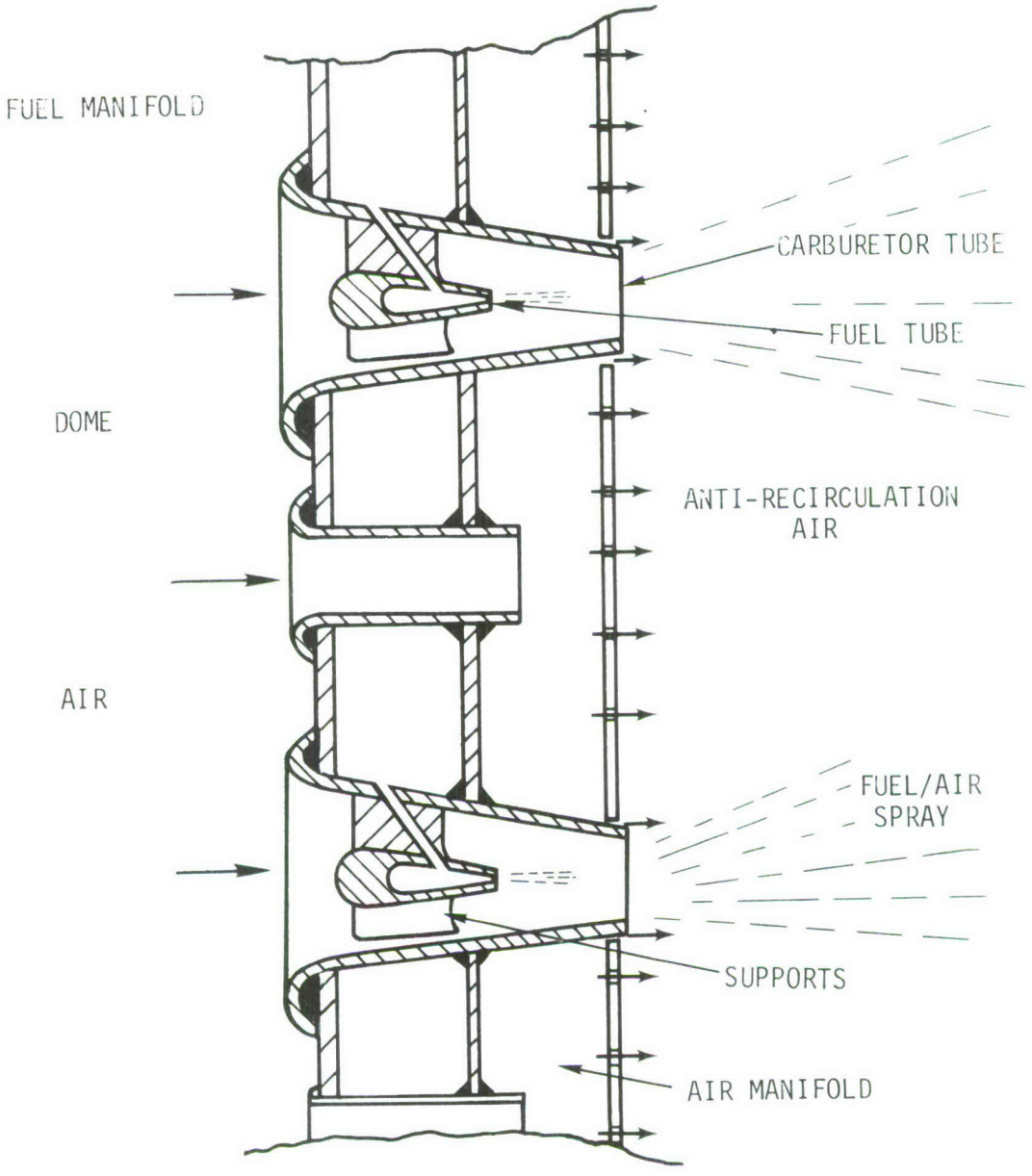


Figure 83 Possible Multi-Tube Fuel Injector/Dome for Concept 5 with Integral Air Manifold and Anti-Recirculation Air Jets

Detailed design of this dome is not complete.

The pilot combustor dome was modified to the more practical design used also in Concept 2 and illustrated in Figure 70.

Combustor Liners and Turbine-Entry Duct

As will be discussed, the liner cooling scheme was modified slightly from that shown in Figure 63, by the addition of an impingement shield and the small additional modifications entailed by this.

Figure 84 shows a sketch of the rear of the combustion section with the revised pilot dome and the impingement shield applied to the turbine entry duct outer wall.

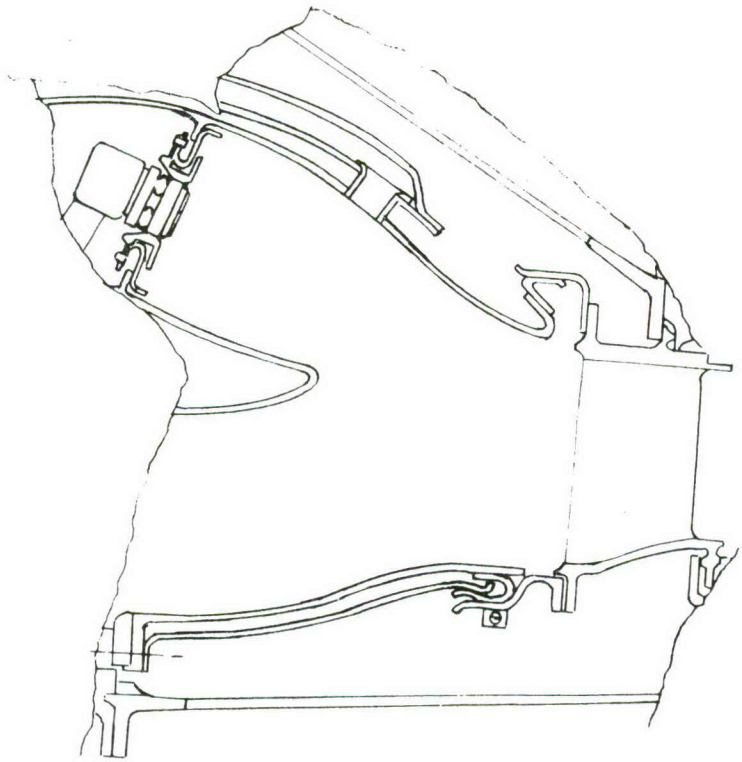


Figure 84 Liner Dome, Seal and Liner Modification

The impingement shield is secured at its forward and to the flange supporting the turbine entry duct off the radial skirts. At its aft end, it is carried in a fishmouth seal. This seal also forms the turbine entry duct rear support and seal. The shield is correctly gapped from the turbine entry duct by local supports, as illustrated in Figure 73.

Some alternative forms of arrangement were considered to improve performance.

The conflicting requirements of reducing the passage convective heat transfer coefficient at the front of the reactor to control blowout and simultaneously initiating gas phase reactions by increasing the mixture preheat to control extinction, have been essentially solved through the Acurex graded-cell reactor (Reference 20).

Reactors similar to those used by Acurex have been designed and considered. Figure 85 shows a cross section to illustrate the variation in cell size which results.

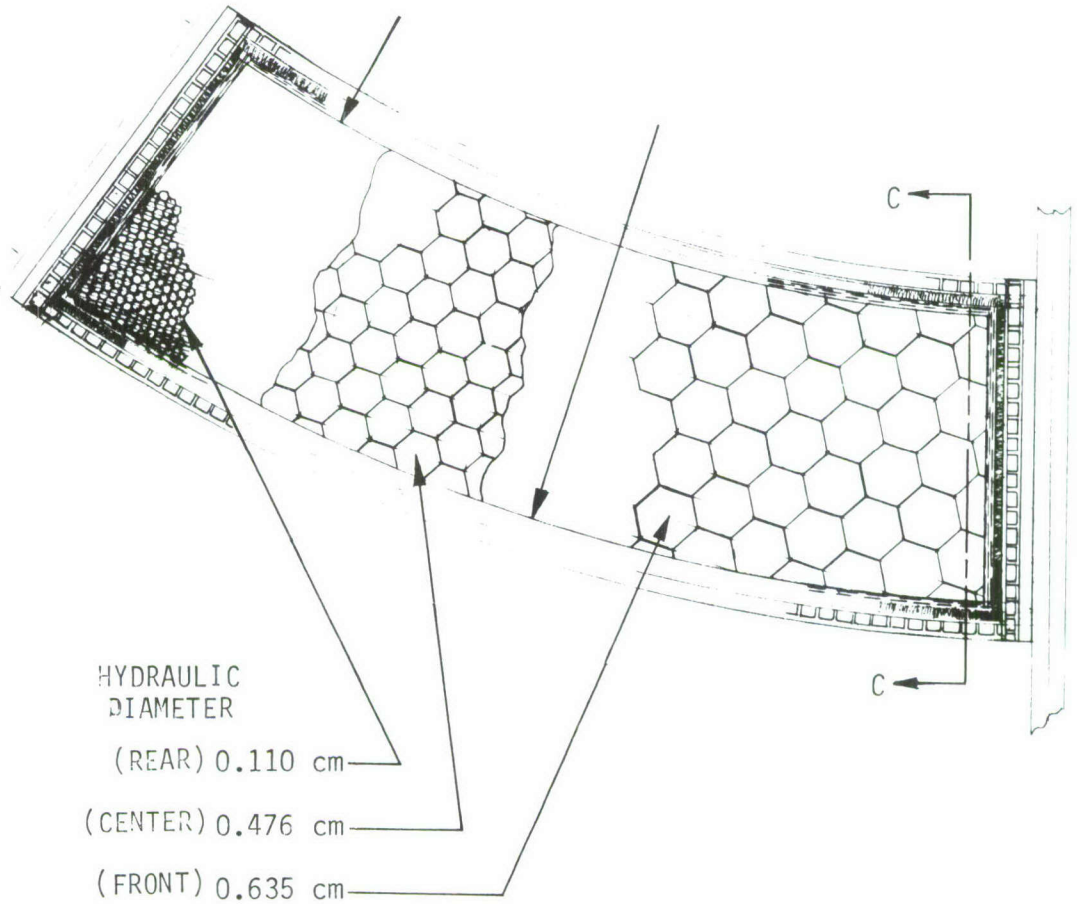


Figure 85 End View of the Three Element Catalytic Reactor

One important consideration has been evidenced in these calculations: light-off in the large-cell first element of the graded-reactor is very slow. A practical design therefore has to balance the breakthrough and blow-out demands very carefully. It would be desirable to hold the surface to volume ratio in the first element in the range of 1000 to 1500 m^{-1}. For ceramic substrates this can result in unacceptably thin walls. The change shown in

Figure 85 from the square cells of the original Acurex reactors (Reference 20) to a honeycomb form can certainly help this. Metal substrates with the required surface to volume ratio do not have the necessary durability.

Pressure losses in such a reactor have to be carefully considered also. For such reasons, the axial length of the section of smaller cells has to be limited, as Figure 86 shows. Figure 86 shows the elements separated by small distances. The reasons for this are twofold: first, to avoid pressure loss variation due to random arrangement of reactor elements in contact, and secondly to vent the canning cooling air to the interior of the reactor, as can be seen in Figure 86.

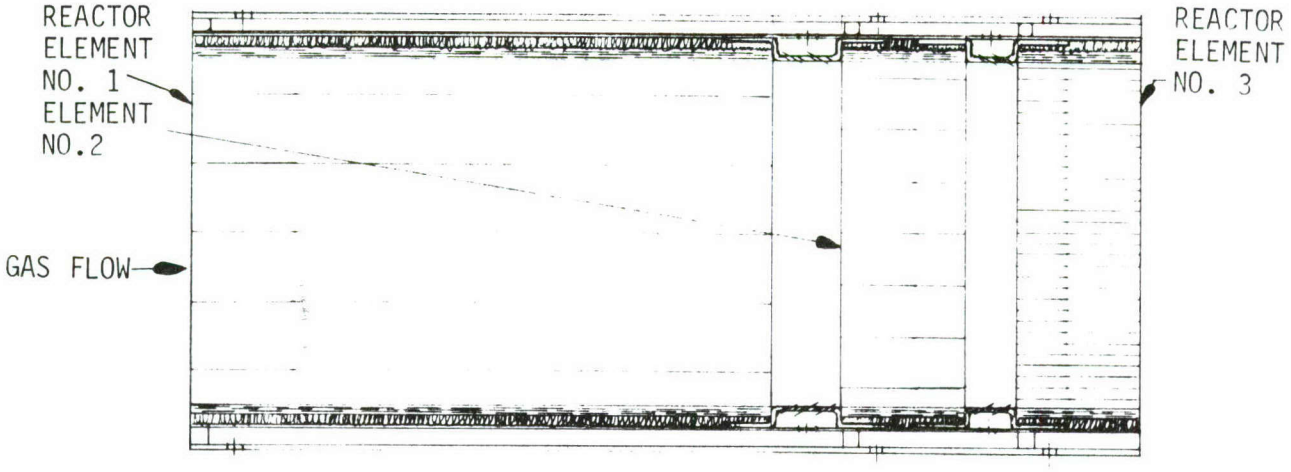
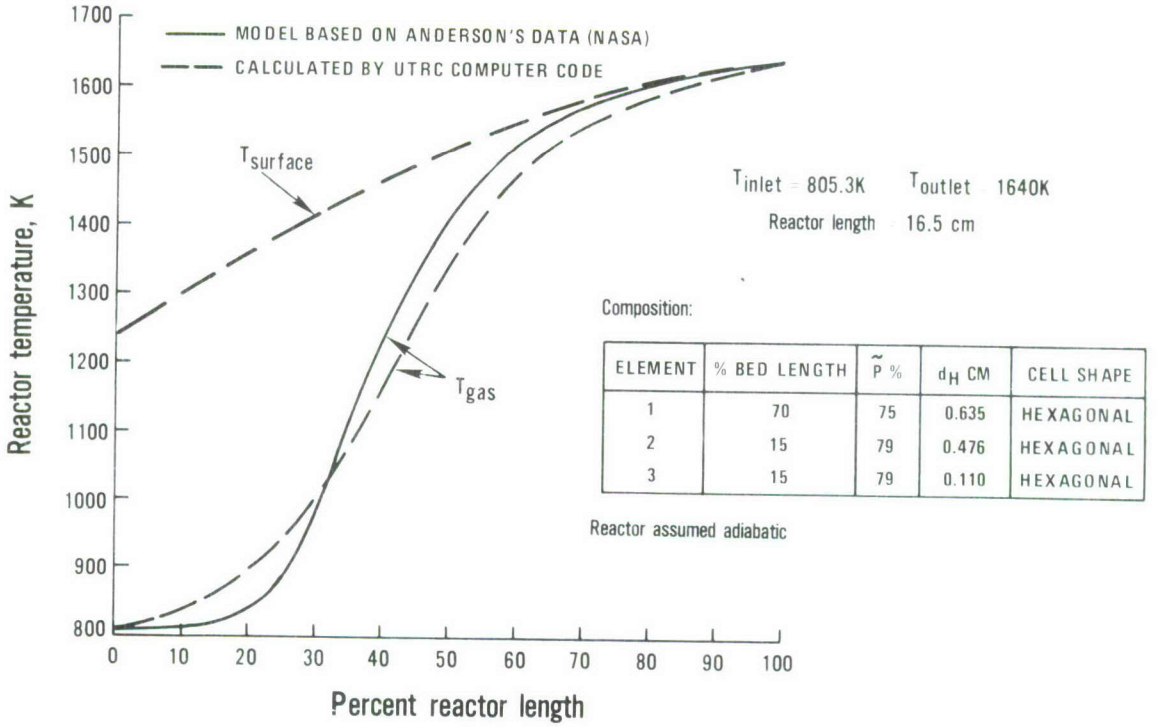


Figure 86 Three Element Catalytic Reactor

Venting canning cooling air and subsequent renewal with fresh air from the plenum chamber, is important in Concept 5 because of the large surface area to be cooled. Less air is used with several axial systems of FINWALL than with a single axial system.

Figure 87 shows calculations of gas and wall temperatures at take-off conditions through a graded-cell catalytic reactor of the type shown in Figure 85. The calculations were made by two methods which agree extremely well for gas temperatures, although the scaling method is for a specific reactivity.

Consideration of Figure 87 reveals that apparently not much happens in the first 30 percent of reactor length. However, the reactor surface temperature in the first 30 percent of length is considerably above the gas temperature due to conduction of heat forward from the hotter downstream portion of the reactor. Heat transfer from the hot surface to the gas is important in initiating the gas-phase reactions which result in the rapid temperature rise. The last 30 percent of the reactor contributes little to overall temperature rise but it is where 100 percent combustion efficiency is achieved. It is rather apparent that separating the elements, as shown in Figure 86 would interrupt the wall conduction process and hence adversely change initiation of gas-phase reactions. The effect of this would be the same as shortening the reactor, and emissions of CO would increase as a result.



ELEMENT	% BED LENGTH	$\tilde{P}$ %	d_H CM	CELL SHAPE
1	70	75	0.635	HEXAGONAL
2	15	79	0.476	HEXAGONAL
3	15	79	0.110	HEXAGONAL

Figure 87 Estimated Temperature Distribution for Graded-Cell Reactor At Takeoff

The separated element, graded-cell reactor approach was therefore dropped.

Concept 5 does not have much room for maneuverability with respect to reactor arrangement and pressure losses. This was the reason for considering the separated element, graded-cell reactor, as shown in Figure 86. Elimination of separated elements for the reasons discussed in connection with Figure 87 raised the problems of pressure loss calculations for graded-cell reactors with elements in contact. The analysis shows that it is not immediately clear exactly how to reliably calculate graded-cell reactor pressure losses, and comparative experimental data are lacking in the published literature. Therefore, for the present purposes, the graded-cell catalytic reactor has been adopted, but with the elements in contact with each other.

Support System

With the exception of the small changes to the turbine entry duct outer wall shown in Figure 84, no changes were made to the combustor support system.

For the graded-cell catalytic reactor, the individual elements would be joined together by the graded ceramic intermediate layer in the canning process.

Aerothermal design. - Figure 88 shows a diagrammatic representation of Concept 5 with the flow conditions through the combustors at sea-level static take-off power on a standard day displayed on it.

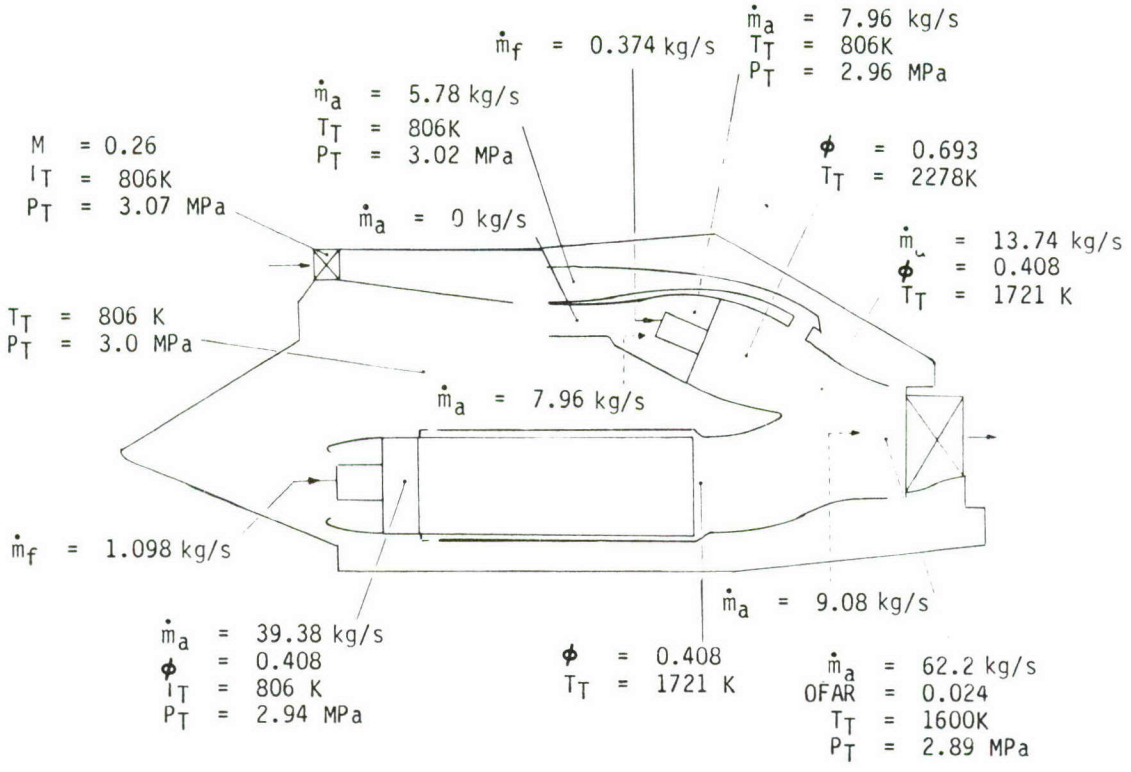


Figure 88 Concept 5: Flow Condition at Sea-Level-Static Takeoff

Note that for the hood of the pilot combustor, the overall pressure loss across the pilot has been split between the dome and the fixed metering feeding the dome. Two percent is taken across the dome, and the remainder across the fixed metering.

Cooling Systems

The liner design point was again established as the 0.457 kilometer altitude, 0.39 flight Mach number at beginning climb conditions on a hot day. At these conditions the following apply:

Fuel flow-rate pilot, kg/s	0.474
Fuel flow rate secondary, kg/s	1.144
Secondary airflow, kg/s	40.383
Total temperature at compressor delivery, K	838
Total pressure at compressor delivery, MPa	3.285
Pilot primary-zone airflow, kg/s	8.165
Pilot dilution airflow, kg/s	5.928
Pilot exit temperature, k	1772
Secondary exit temperature, k	1752
Turbine entry duct exit temperature, k	1641

The areas (m^2) to be cooled are as below:

Catalytic reactor reactor (20 cans)	0.9107
Pilot combustor inner wall (to aft seal)	0.2543
Pilot combustor outer wall (to junction with turbine entry duct)	0.1534
Turbine entry duct inner wall (to junction with pilot)	0.1024
Turbine entry duct outer wall (full annulus)	0.2960

No cooling is applied to the fuel preparation section of the catalytic secondary main combustions. It is not necessary since there is no direct combustion in this section.

Two cooling schemes were considered: multi-hole transpiration and impingement/transpiration. Two inner wall materials, conventional Hast-X and IN617, were used.

The designs of the cooling schemes were the same as that for Concept 2:

A minimum hole diameter of 0.0635 cm was selected so that blockage in service would not be a problem. This was held constant for all cooling configurations. The "transpiration" wall thickness was taken as 0.1524 cm. The "transpiration" holes were assumed to be laser-drilled at an angle of 0.5236 radians to the surface. Where an impingement scheme was used the impingement shield was 0.762 cm from the transpiration surface.

For the catalytic reactor zone, the reactor container was cooled using a standard FINWALL analysis. The rectangular passages were 0.1524 cm wide and 0.1905 cm high.

Table XXVI presents the cooling air requirements.

TABLE XXVI

CONCEPT 5: LINER COOLING-AIR SUMMARY

	Cooling Air, % W_{comb}			
	Transpiration		Impingement/Transpiration	
Zone	HAST X	IN 617	HAST X	IN 617
Pilot	8.30	7.30	1.20	1.00
Catalytic Reactor+	8.63	8.63	8.63	8.63
Turbine Entry Ducts	16.10	14.10	2.70	2.20
Totals	33.03	30.03	12.53	11.83

+The FINWALL requires a constant 8.63% W_{comb} for a 1153K temperature

Table XXVI indicates that use of IN 617 material reduces the required coolant flow by a small amount. The combined impingement/transpiration scheme is superior to the multi-hole transpiration scheme alone. The FINWALL cooling of the catalytic reactors requires a large amount of air and this is because of the poor surface area to volume ratio for cans. Even with the 8.63 percent W_{comb} cooling flow the felt metal temperature reaches 1158 K which is considered too high for commonly used felt metal materials. However, no optimization of the FINWALL^R passage geometry was attempted in these calculations. Such optimization can appreciably lower temperatures without much change in coolant flow.

Consideration of Figure 64 reveals the virtual impossibility of applying the impingement/transpiration cooling universally to the Concept 5 liners. Figure 84 shows a scheme where impingement/transpiration cooling is only applied to the outer liners of the turbine entry duct. Table XXVII gives the cooling-air requirement summary for this hybrid scheme.

TABLE XXVII

CONCEPT 5: ALTERNATIVE LINER COOLING AIR SUMMARY

		Cooling Air % W_{comb}	
Zone	Cooling Method	HAST X	IN617
Pilot	transpiration	8.30	7.30
Catalytic reactor	FINWALL	8.63	8.63
Turbine entry duct outer	impingement/ transpiration	1.55	1.26
Turbine entry duct inner	transpiration	6.38	5.97
Totals		24.86	23.16

Table XXVII compared to Table XXVI shows that the alternate hybrid cooling scheme uses about twice the cooling air of the best possible scheme. The use of IN617 material in place of Hastelloy X does not offer much saving.

The hybrid cooling scheme does not present a significant problem for the turbine entry duct since even for the Hastelloy X case, 7 percent of total combustor air remains available for profile trim from the assigned amount of air to be added in the turbine entry ducts. However, serious problems arise for the pilot combustor: the fixed pilot airflow amounts to 13.07 percent of the overall total. Therefore, with a cooling air requirement of 8.3 percent only 4.77 percent is available for the 30 air blast fuel injectors and for dome cooling. This is inadequate. Change to IN617 material brings a small relief, but does not solve the problem. Changing the number of fuel injectors does not help since fuel flow is increased proportionally with airflow.

Due to the ducting associated with the pilot's variable geometry it is desirable to change the pilot combustor outer wall only. This wall is not extensive in axial length, and proved amenable to conventional film cooling. Two film slots, designed with a 0.216 cm nominal height and a blowing ratio of 2, were added to this wall in place of the transpiration cooling. When applied for short distances film cooling can be competitive with transpiration cooling because of the build-up length required for the latter. Table XXVIII summarizes the cooling air requirements of this second alternative hybrid cooling scheme, while a diagrammatic representation is given in Figure 89.

TABLE XXVIII

CONCEPT 5: SECOND ALTERNATIVE LINER COOLING-AIR SUMMARY

Zone	Cooling Method	Cooling Air % W_{comb} HAST X	IN617
Pilot inner wall	Transpiration	4.0	3.1
Pilot outer wall	film	2.3	1.84
Pilot total		6.3	4.94
Catalytic reactor	FINWALL	8.63	8.63
Turbine Entry duct outer	Impingement/ transpiration	1.55	1.26
Turbine entry duct inner	transpiration	6.38	5.27
Totals		22.86	20.8

With this second alternative cooling scheme and IN617 material, 7.47 percent of total combustor air is available for the fuel injectors and dome cooling in the pilot. This is barely acceptable, but will do. Obviously, a redesign of the interface between the pilot and secondary combustors would be desirable.

Table XXVIV gives the hole designs for the impingement/transpiration and the transpiration cooling schemes.

Figure 90 shows a diagrammatic sketch of the catalytic reactor FINWALL.

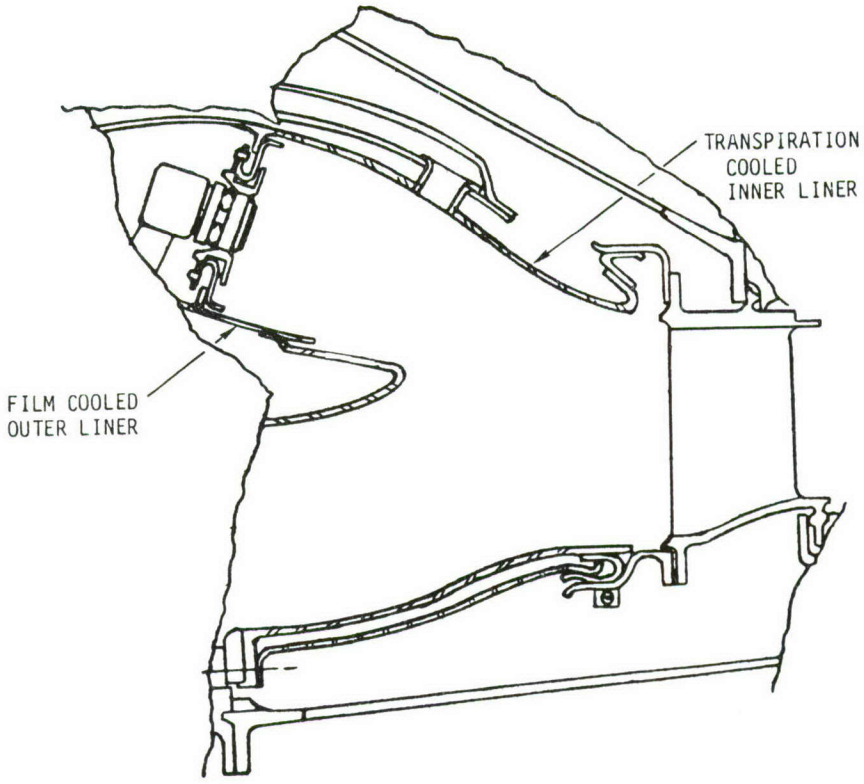


Figure 89 Second Alternative Liner Cooling Scheme for Concept 5

TABLE XXVIV

CONCEPT 5: COOLING HOLE SPACING

Zone	Hole pitch/diameter Transpiration HAST X	IN617	Impingement/Transpiration HAST X	IN617
Pilot inner wall	8.97	9.57		
Turbine entry duct outer			11.9/9.1	13.1/10.1
Turbine entry duct inner	6.46	6.9		

NOT TO SCALE

ALL DIMENSIONS IN CM

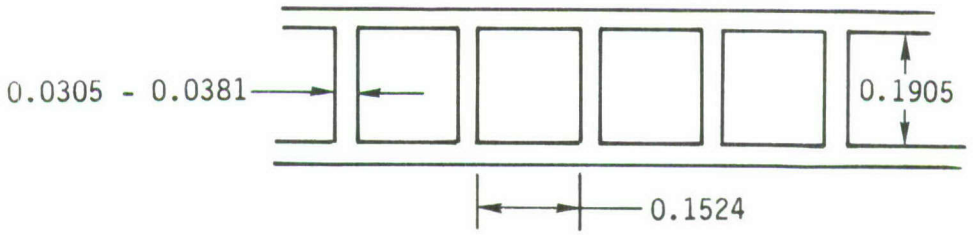


Figure 90 Concept 5: FINWALL

8.0 CONCLUDING REMARKS

Phase I has proved useful in that it has shown gaps and weaknesses in the support technology, revealed the need for improved design tools, and provided substantial insight for how an aircraft catalytic combustion system might be designed. Having highlighted design problems, the selected concepts should be redesigned with considerably more refinement than was used in the present preliminary studies.

The studies revealed a number of concerns. Foremost was the lack of suitable and satisfactory design tools. Of almost equal urgency was the poor state of the supporting technology required for the designs. Much needs to be done still before acceptable designs can be produced.

Six concepts for a low-emissions aircraft gas-turbine combustor employing catalytic reaction of some or all of the total fuel were conceived and explored. Two of these, the pure catalytic reactor and the Vorbix/catalytic cruise combustor system were early shown not to be feasible. The third, Concept 4, was shown to be a redundent system. The totally annular approach to the layout was demonstrated to be very inconvenient. Two concepts were shown to be feasible. Concept 2, a rich front end hybrid combustor, while of great length, is simpler, but still represents potential risks. Concept 5 was exceedingly complex but (aside from mechanical considerations) of lower risk. It appeared that the emissions goals could be met by engines employing these concepts.

The catalytic reactor is best suited to single point operating conditions, and as such, it appears ideal for the industrial gas turbine. To accommodate this nature in the aircraft gas turbine which is required not only to operate over a wide range of conditions, but also to have fast response, necessitates in most cases complicated control of the fuel and air supplies.

9.0 SUMMARY OF RESULTS

A preliminary design study was carried out on six aircraft gas turbine engine combustions utilizing catalytic reaction of all or some of the total fuel flow. The two most promising concepts was selected for further refinement. The program goals of altitude cruise and landing-takeoff cycle emissions, total pressure loss, combustion efficiency, and capability of meeting practical operating requirements, determined the selection. A summary of the results is given below:

1. While two of the concepts proved to be impractical, three of the concepts appear to be capable of satisfying the Environmental Protection Agency 1979 landing-takeoff cycle regulations for T-2 class engine emissions, and also of achieving cruise NO_x emissions less than 1.5 g/kg-fuel. Although this exceeds the program goal for cruise of less than 1 g/kg-fuel, it does represent an order of magnitude reduction compared to existing combustors.

2. The first choice (Concept 2) was found to have the potential for satisfying all the emission goals. Variable geometry was not required for this concept.

3. The combustion efficiency goals of the program were achieved at all the specified operating conditions by all three of the practical concepts.

4. The loss in total pressure for the practical concepts was within the program goal of 5.75 percent. Where variable geometry was used (Concepts 4 and 5) it was implemented in such a manner that a constant pressure loss versus flow function relationship prevailed at all operating conditions.

5. The two most-promising concepts selected were an annular, rich front-end, axially-staged, hybrid combustor (Concept 2), and a modulated airflow, radially-staged combustor with an annular pilot and catalytic main reactor in can-form (Concept 5).

SYMBOLS

Higher Case

ALP air loading parameter = $\frac{3.72\ (\dot{m}_a + \dot{m}_f)}{P^{1.8}.V.10^{.000794T}}$
(English units used, P in atmospheres

D injector characteristic dimension
DZ Dilution zone
EI emission index, - g. pollutant per kg fuel burned
FAR fuel to air ratio by mass
FN engine thrust (take-off)
H_d dome height
IBZ initial burning zone
K kinetic energy of turbulence
L length
LBO lean blow out
M Mach number
N diffuser inlet annular height, number of fuel injectors
N_2 core engine rotational speed
OFAR overall fuel to air ratio by mass
$\widetilde{P}$ catalytic reactor porosity
P_T total pressure
PF pattern factor
PZ primary zone
QZ Quench zone
SL sea level
SLS sea level static
SMD Sauter mean diameter for fuel spray
T_T total temperature
TED turbine entry duct
TO takeoff
TSFC thrust specific fuel consumption
UHC unburned hydrocarbons
V volume
W diffuser axial length
W_{comb} combustor airflow

Lower Case

d diameter of mean droplet representing fuel spray, cooling hole diameter
d_H hydraulic diameter
$\dot{m}_a$ mass flow rate of air
$\dot{m}_f$ mass flow rate of fuel
op operating value
p pitch
u velocity

Greek

δ	catalytic reactor axial length
ΔT	temperature rise
ΔP	loss in total pressure
$\Delta P/P$	pressure drop
η_{comb}	combustion efficiency
ρ	density
ϕ	equivalence ratio
τ	ignition delay, residence time
ϵ	dissipation rate of turbulaence

Subscripts

a	air
max	maximum
tot	total
3.0	station 3.0 (compresor delivery)
3.9	station 3.9 (turbine inlet)
4.0	station 4.0 (turbine inlet)

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