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ADVANCED CATALYTIC COMBUSTORS FOR LOW POLLUTANT EMISSIONS

PHASE I FINAL REPORT

By

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FOREWORD

The work described herein was conducted by the General Electric Aircraft Engine Group under Contract NAS3-20820. The work was performed under the direction of the NASA Project Manager, Mr. A. J. Szaniszlo, Airbreathing Engine Division, NASA-Lewis Research Center. Additional support was provided by the United States Air Force Project Officer, Capt. J. A. Martone, HQ AFESC/ROVC, Tyndall AFB, Florida.

Key General Electric contributors to this program were: A.L. Meyer, Program Manager, D.W. Bahr, Technical Program Manager; C.C. Gleason, Principal Investigator; W.J. Dodds, Combustor Aerothermal Design; and J.S. Kelm, Combustor Mechanical Design.

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF TABLES (Concluded)

1.0 SUMMARY

The multiphase Clean Catalytic-Combustor Program is being undertaken by NASA and the Air Force to evaluate the feasibility of employing catalytic combustion technology in the aircraft gas turbine engine field to achieve control of the emissions of oxides of nitrogen (NO_x) for subsonic, stratospheric cruise aircraft operation.

The Phase I Design Study effort described in this report involved the conceptual design of several full-annular combustors using catalytic techniques, followed by an evaluation of these designs and subsequent selection and detailed preliminary design of the two most promising concepts. The objective of this design study program was to identify catalytic combustor designs that have the greatest potential to meet several specific emissions and performance goals. One of these goals is the attainment of very low NO_x emission levels (≤ 1 g/kg) at subsonic cruise conditions in addition to meeting the 1979 EPA landing/takeoff emissions standards for Class T2 aircraft engines, while also meeting normal commercial engine operational and durability requirements. These designs incorporate advanced catalytic reactor technology together with advanced combustor aerothermodynamic and mechanical design features for fuel and airflow scheduling.

In this Phase I Program, six catalytic combustor design concepts were defined and analyzed. These designs were sized specifically for the NASA/GE Energy Efficiency Engine (E^3) design, but the technology is applicable to other advanced high-pressure-ratio aircraft turbofan engines. The General Electric design effort was supported by a subcontract with Engelhard Industries Division of Engelhard Minerals and Chemicals Corporation, specialists in the catalytic combustion field. Based on an evaluation of predicted emissions, performance, and operational characteristics of the six design concepts, two fixed geometry, parallel staged concepts were selected for further design efforts.

Results of the Phase I design effort indicate that catalytic combustion is a promising means for obtaining ultralow NO_x emissions at aircraft cruise operating conditions. Levels below 2 g/kg appear to be obtainable without the use of variable geometry; however, the application of catalytic combustion to practical aircraft combustion systems presents several major development challenges.

2.0 INTRODUCTION

Catalytic-combustors systems have shown the needed potential for producing ultralow NO_x pollutant-emission levels along with stable combustion of fuel-air mixtures that have flame temperatures less than 1800K. 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, Ref. 1) and the National Academy of Science (Ref. 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 (Ref. 3). In response to these findings, the U.S. Environmental Protection Agency (EPA) has promulgated standards for aircraft smoke and gaseous emissions in the vicinity of airports (Ref. 4). Although no specific cruise standards have been proposed, it was recommended that new engine 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 new combustion technology requirements, the Clean Catalytic-Combustor Program is being undertaken to evolve and demonstrate catalytic-combustor system designs which can provide ultralow NO_x pollutant-emissions levels at stratospheric cruise operating conditions as well as providing full-range operation while meeting applicable 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_2 per kilogram of fuel. The normal-cruise operating conditions are representative of advanced technology engines with pressure ratios of approximately 30 to 1 and with turbine-inlet temperatures of about 1700K at sea-level takeoff conditions. This goal represents more than an order-of-magnitude decrease from levels obtained with current technology engines (16 - 22 g NO_2/kg fuel).

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

3.0 PROGRAM DESCRIPTION

The Clean Catalytic Combustor program was initiated to evolve and demonstrate combustor designs that provide extremely low exhaust emissions through the use of catalytic combustion techniques while maintaining a performance equal or superior to that of near-term advanced aricraft gas-turbine engines. This effort is planned in three phases which consist of a design study, screening tests, and combustor refinement. The Phase I design study, which is described in this report, consisted of three tasks: (I) Conceptual Design, in which six catalytic-combustor concepts were defined; (II) Analysis and Evaluation, wherein each of the six conceptual designs was analyzed and evaluated for the potential to meet combustor performance goals and for the feasibility of development into a practical engine system; and (III) Preliminary Design, where a more detailed preliminary design was performed on the two most promising concepts identified during analysis and evaluation of the conceptual designs.

3.1 PROGRAM GOALS

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

1. $NO_x \leq 1$ g/kg at subsonic cruise
2. Combustion efficiency

   99.9% at sea-level takeoff
   99.5% at engine idle
   99.9% at all other operating conditions

3. Capable of meeting the U.S. Environmental Protection Agency (EPA) 1979 emissions standards for T_2 aircraft over the landing-takeoff cycle for altitudes less than 915 meters. (Reference 3.)
4. Combustor total pressure loss, $\Delta P/P$, $\leq$ 5 percent over all operating conditions.
5. Capable of meeting engine performance requirements, to include 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 was an advanced Energy Efficient Engine (E^3) that is typical of the high pressure ratio, high bypass ratio engines that will be developed for commercial aviation service within the next ten to twenty years. This reference engine (CFX18) is a direct-drive-fan, mixed-exhaust-flow version of a series of turbofan engines evaluated as a part of the current NASA/GE Energy Efficient Engine Preliminary Design and Integration Study Program conducted under Contract NAS3-20627.

A major objective of the E^3 program is to obtain a 12 percent reduction in specific fuel consumption (sfc) at cruise conditions. This objective is referenced to the CF6 family of engines which represents the most efficient engines currently in commercial service. Low sfc values at cruise conditions are achieved with the E^3 by efficiency improvements in its various components and by an increase in cycle pressure ratio at cruise conditions. The E^3 cycle pressure ratio at maximum cruise conditions is 35.8 to 1 versus 31.0 to 1 for the CF6-50 engine which gives considerably higher inlet pressures and temperatures for the E^3 combustion system. At sea-level static conditions, the engines have equal overall pressure ratios (30 to 1).

The E^3 cycle is especially appropriate as a reference engine cycle because of the combustor inlet-air pressures and temperatures of this cycle at cruise conditions, which are indicative of the trend of future commercial engine development. As a consequence of the high pressures and high temperatures, the achievement of low NO_x at cruise conditions becomes more difficult to accomplish. Cycle parameters for the E^3 reference engine at nine cycle operating conditions are presented in Table I. These cycle conditions were based on current values available at the outset of the Phase I Program, and were "frozen" throughout this program. Key engine-cycle and combustor operating parameters are presented for the idle, climbout, takeoff and approach power settings, which are the operating conditions specified in the Environmental Protection Agency (EPA) takeoff/landing cycle. Also shown are hot-day takeoff operating conditions, where conditions are most severe in terms of autoignition and durability; and a range of cruise conditions, where ultralow NO_x emission levels are being sought.

The preliminary design of the E^3 combustor is illustrated in Figure 1. This combustor consists of a short-length, low emissions, double-annular combustor design which is based on the results of the NASA/GE Experimental Clean Combustor Program (ECCP) which is described in Reference 5. As with the cycle data, envelope dimensions for this combustion system were established based on current values available at the outset of this program and frozen for the duration of the program. Early in the conceptual design of the low emissions catalytic combustors, it was recognized that several of the combustion systems under consideration would require additional volume not available within the E^3 preliminary design combustor

Table I. Advanced Low-Emissions Catalytic Combustor Program Reference Engine Cycle Parameters.

Cycle Point	6 Percent Idle	30 Percent Approach	85 Percent Climb	100 Percent Takeoff	Hot Day Takeoff	Very Hot Day Takeoff	Max. Cruise	Normal Cruise	Min. Cruise
Ambient Conditions	Std Day	Std Day	Std Day	Std Day	+15K	+35K	+10K	+10K	+10K
h_o, Flight Altitude, km	0	0	0	0	0	0	10.7	10.7	10.7
M_o, Flight Mach No.	0	0	0	0	0	0	0.80	0.80	0.80
F_N, Installed Net Thrust, kN	9.74	48.70	138.04	162.36	162.39	137.29	37.47	29.98	14.99
W_3, Compressor Exit Airflow, kg/s	10.70	28.76	55.20	61.69	60.05	51.71	26.99	23.95	17.74
W_{36}, Combustor Airflow, kg/s	9.53	25.58	49.12	54.93	53.48	46.04	24.04	21.32	15.79
P_{T3}, Compressor Exit Total Pressure, MPa	0.401	1.183	2.626	3.020	3.007	2.589	1.306	1.121	0.774
T_{T3}, Compressor Exit Total Temperature, K	485.0	632.6	781.6	813.8	851.3	864.3	782.1	745.1	676.9
T_{T4}, Combustor Exit Total Temperature, K	940.3	1135.3	1528.7	1617.7	1693.1	1691.8	1595.1	1488.4	1289.4
W_f, Fuel Flow, kg/s	0.1136	0.3546	1.0948	1.3399	1.3867	1.1752	0.5887	0.4680	0.2743
f_{36}, Combustor Fuel-Air Ratio, g/kg	11.9	13.9	22.3	24.3	25.9	25.5	24.5	22.0	17.4
M_3, Compressor Exit Mach No. (1)	0.281	0.296	0.286	0.283	0.282	0.285	0.281	0.282	0.289

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

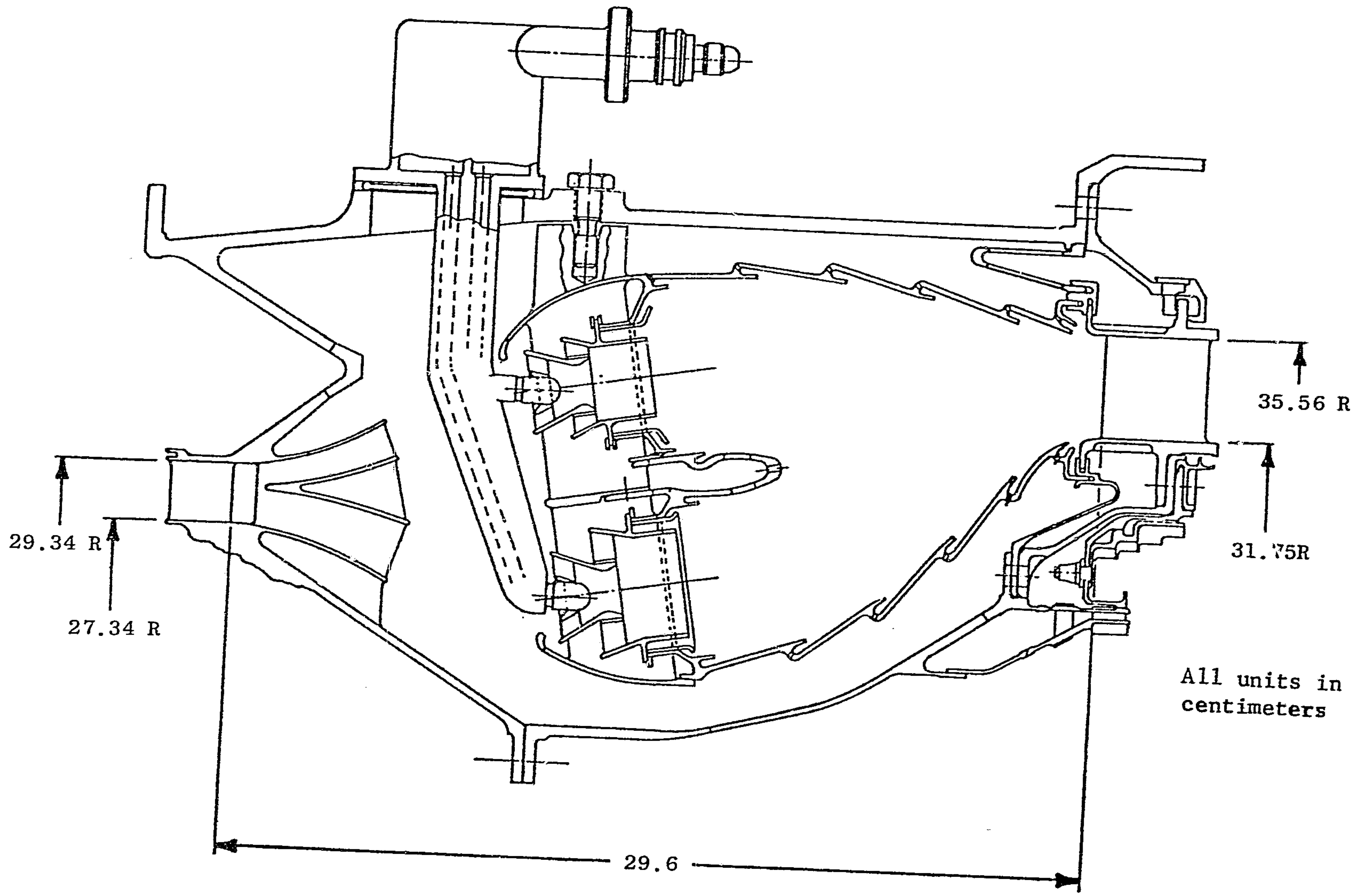


Figure 1. Reference Engine Combustion System.

envelope. Therefore, in the design of these catalytic combustion systems, it was assumed that the combustor envelope could be lengthened to accommodate these systems. The impact of this increased length was considered in the evaluation of each combustor design. All conceptual and preliminary designs were sized to match the compressor exit and turbine inlet dimensions shown in Figure 1. Combustor inner and outer casing dimensions were allowed to vary according to the requirements of each of the combustor designs, but in all cases combustor casings were contoured to avoid interference with fixed components. This consideration limited the outer casing diameter to 112 cm, which corresponds to the expected inner diameter of the fan shroud.

4.0 GENERAL CATALYTIC COMBUSTOR DESIGN CONSIDERATIONS

4.1 CATALYTIC-REACTOR OPERATING CHARACTERISTICS

Over the past five years, a growing body of technical literature has developed describing low emissions combustion tests carried out using catalytic reactors (References 6 through 23). These tests have confirmed the potential for obtaining ultralow levels of NO_x with high combustion efficiency through the use of catalytically supported lean combustion. Combustor tests utilizing propane, diesel oil, and aviation fuels at conditions which simulate steady-state gas turbine operating conditions are all reported. The proven performance range of catalytic reactors for combustion is summarized in Table II.

Table II. Catalytic Reactor Experimental Performance Range for Combustion.

<u>Temperatures</u>

Inlet: 593 - 813 K
Operating: 1363 - 1703 K

<u>Pressure</u>

0.1 - 1.0 MPa

<u>Heat Release Rate</u>

0.25 to 50 Mcal/sec-atm-m^3 catalyst

<u>Fuels</u>

Gaseous
Distillate

<u>Typical Performance</u>

Combustion Efficiency: 99.9 percent

Emissions:	NO_x	< 2	ppm*
	CO	< 30	ppm
	HC	< 4	ppm

* For fuels containing negligible amounts of bound nitrogen.

A catalytic reactor for combustion or alternately a combustion catalyst is comprised of three components. These are the substrate, the wash coat, and the catalytically active components. The principal function of the substrate is to serve as a stable nonreactive support for the catalyst and wash coat. Two general types of substrates are available: the pelletized, which consists of a large number of small pellets contained within a casing; and the honeycomb, which consists of a single monolith containing a multiplicity of small, parallel channels. The use of the honeycomb monolith substrate is strongly favored for combustion catalysts which require minimum volume and the lowest possible pressure drop. With the advent of the automotive catalytic muffler, a wide range of honeycomb substrate material has been made available. These include cordierite, mullite, alumina, silicon carbide, silicon nitride, and zircon-type composites. Wash coats are used as a means for dispersing the metal catalysts on the relatively low surface area monolithic supports. Typically these materials are predominantly alumina, with a range of proprietary stabilizers added to improve the sinter resistance of the catalyst at high temperatures. Catalytically active components may consist either of precious metals such as platinum or palladium, or base metal oxides. Generally, better low temperature activity is obtained with the precious metals, but the base metal oxides allow higher use temperatures.

The performance range for present-generation catalysts is outlined in general terms in Table II. However, the operating range and performance characteristics of a specific catalyst are quite interactive, depending on fuel type, inlet air temperature, and catalyst space velocity. Although combustion catalysts are typically active for a wide variety of fuels, catalyst activity can vary widely from fuel to fuel. Table III, for instance, lists the measured catalytic ignition temperature for six clean fuels using CATCOM* catalyst DXA-111. In this first-generation catalyst, the lightoff temperatures range from 300 K for hydrogen to 743 K for methane. A change of catalyst material and concentrations can shift the relative activity for combustion of parafinic, aromatic, and olefinic fuels, where catalyst composition can affect the catalyst lightoff temperature by as much as 150 K.

Table III. Catalytic Ignition Temperature for Commercial and Synthetic Fuels with CATCOM* Catalyst DXA-111.

Fuel	Ignition Temperature, K
Hydrogen	< 298
Methane	743
Propane	608
No. 2 Diesel Oil	553
JP-4	516
150-Btu Gas	443

* Registered Trademark, Engelhard Industries.

The low emissions operating range will, of course, vary depending on the fuel and catalyst used. Table IV describes a test series (summarized in Appendix B) carried out by Engelhard Industries as part of this Phase I effort. In a series of tests, Jet A fuel was burned in 10.2 and 12.7-cm lengths of a CATCOM catalyst designated as DXE-441, which is described in Table V. Operating parameters were selected to closely approximate the catalyst approach velocity and inlet temperature ranges of the catalytic-combustor designs. The approximate ranges of inlet conditions were as follows:

Catalyst Inlet Temperature, K	600 to 800
Catalyst Inlet Pressure, MPa	0.304
Catalyst Approach Velocity, m/s	20 to 35
Fuel-Air Ratio, g/kg	16 to 26

As indicated in Table IV, very high combustion efficiencies can be obtained with negligible NO_x emissions over a fairly wide range of operating conditions. However, in order to obtain efficiency above 99 percent fuel-air ratio must be as high as 26.0 g/kg at the low inlet temperature conditions.

High fuel-air ratios are required to provide temperatures high enough for appreciable homogeneous thermal reaction within the catalyst channels. This effect is shown in Figure 2, which is a plot of efficiency as a function of fuel-air ratio at constant inlet pressure and temperature based on data obtained in the Engelhard test series. At fuel-air ratios below about 20 g/kg, combustion efficiency is constant at approximately 60 percent. This represents the total conversion due to heterogenous catalytic reaction. As the fuel-air ratio is increased above 20 g/kg, combustion efficiency rises very rapidly to levels above 99 percent. This efficiency increase is due to the catalytically supported homogeneous (gas phase) reaction within the catalyst channels (References 17 and 19).

Recent catalyst life studies reported in Reference 20 have demonstrated that precious metal combustion catalysts are capable of operating under low emissions conditions for a minimum of 1000 hours life. The primary test objective of that program was to prove the feasibility of operating selected catalyst cores under combustion conditions for extended periods. A 1000-hour life test using No. 2 diesel fuel at simulated automotive gas-turbine steady-state operating conditions was selected as the criterion for endurance testing. The first 1000-hour life test was completed on Engelhard catalyst DXB-222 in February 1976. This life test was conducted in a one-inch-diameter laboratory test rig at the operating conditions listed in Table VI. Table VI also lists, for comparison, the initial and final measurements recorded during the life test. Differences reflected by the data recorded in Table VI are well within anticipated experimental error. As seen in Table VI, NO_x emissions levels were very low, and combustion efficiency was essentially 100 percent. The life test demonstrated excellent high performance durability over 1000 hours with no deterioration in

Table IV. Laboratory Test Data for 12.7 cm Length of Catalyst DXE-441*

Temperature Inlet K	Approach Velocity M/S	Fuel-Air Ratios g/kg	Exit Temperature K	$\Delta P/P$ Percent	Emission, vppm			Combustion Efficiency, Percent
					CO	HC	NO_x	
618	22.6	26.0	1343	3.11	135	-	-	99.8
623	22.7	21.0	1160	2.83	1960	1300	-	88
623	22.7	22.0	1265	2.83	1000	85	-	97.4
623	22.1	23.0	1315	2.94	390	15	-	99.2
623	22.1	24.0	1352	2.96	165	*5	-	99.7
623	22.7	26.0	1400	3.05	45	2	<1	99.9
642	27.4	26.0	1367	3.16	125	-	<1	99.8
731	19.6	18.8	1283	1.89	260	<1	1	99.6
731	19.6	21.0	1428	2.28	70	<1	1	99.9
753	24.8	21.0	1320	2.61	3220	175	<1	92.5
760	34.1	19.0	1251	4.00	3890	200	1	90.2
765	34.1	21.0	1304	4.27	1610	25	1	96.6
768	34.1	23.0	1437	4.44	760	4	2	98.6
772	21.7	19.0	1278	2.28	455	30	2	98.7
773	25.4	17.0	1240	2.83	1860	42	<1	95
773	25.4	19.0	1336	2.83	660	9	-	98.4
803	33.4	16.0	1180	3.05	2960	630	<1	86
803	33.4	18.0	1313	3.14	1240	76	<1	96.4
803	33.4	20.0	1359	3.28	380	3	<1	99.1

Table V. Description of Combustor Catalyst Tested

Catalyst Designation	-	DXE-441*
Nominal Cell Density	-	15 Holes/cm^2
Cell shape	-	Sine Wave
Length	-	12.7 cm
Channel Hydraulic Diameter	-	1.72 mm
Porosity	-	54.2 percent
Support Material	-	Zircon Composite
Catalyst Components	-	Proprietary Preparation of Palladium on Stabilized Alumina

* Engelhard Industries

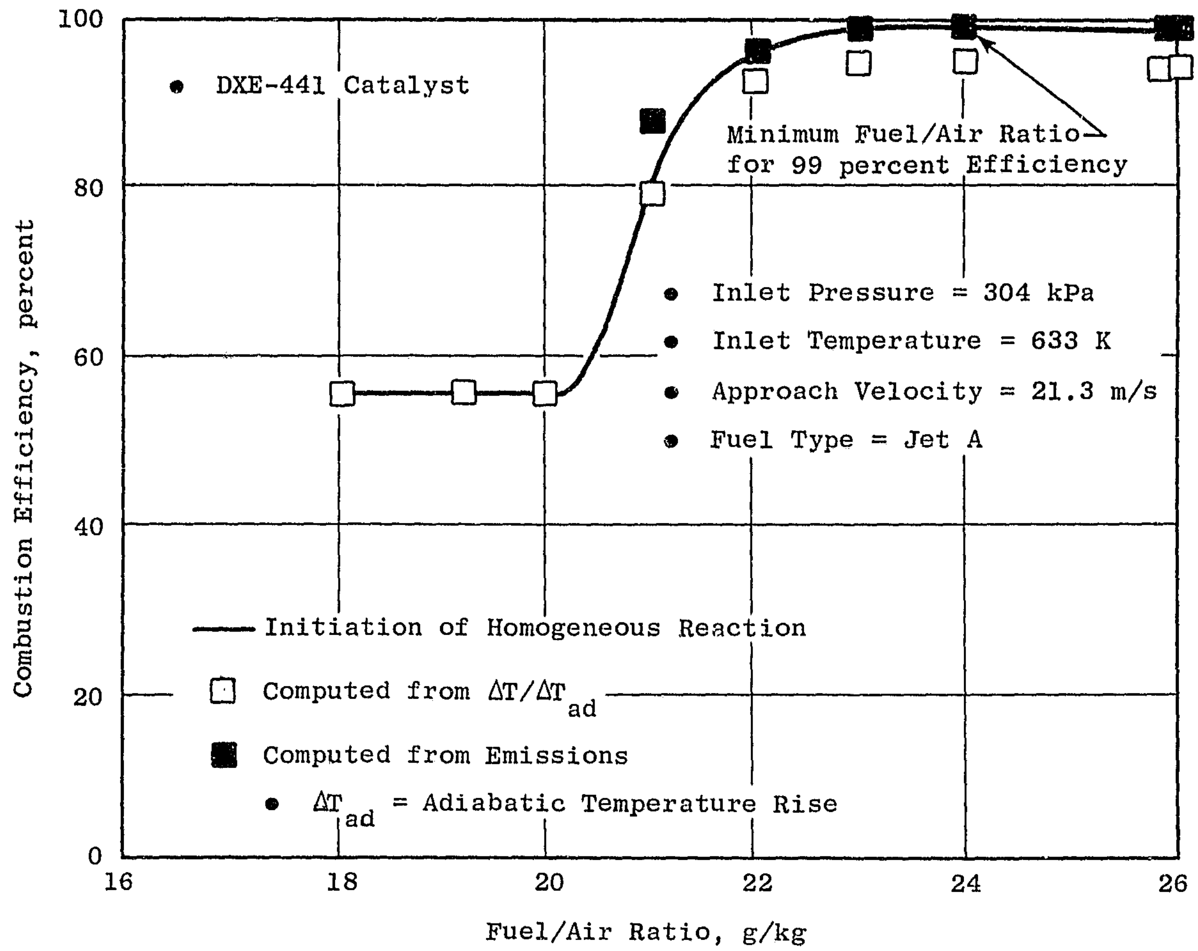


Figure 2. Effect of Inlet Fuel-Air Ratio on Catalytic Reactor Combustion Efficiency.

Table VI. Comparison of Operating Conditions and Performance Data at Start and End of Life Test for Engelhard Catalyst Core DXB-222 and Diesel No. 2 Fuel.

	Start 11/19/75	End 2/27/76
Operating Hours on No. 2 Diesel Fuel	33.00	993.60
Airflow, kg/hr	11.58	11.58
Fuel-Air Ratio	0.0263	0.0268
Inlet Air Temperature, K	633	628
Outlet Temperature, K	1398	1453
Adiabatic Temperature, K	1576	1595
Inlet Pressure, kPa	110	110
Pressure Drop, kPa	9.79	9.44
Pressure Drop, percent	8.8	8.5
Reference Velocity, m/s	13.0	12.9
Combustion Efficiency, percent	99.85	99.89
Heat Release Rate, Mcal/sec-m^3-atm	10.2	10.2
Emissions[1], vppm		
CO	65	60
HC	6	1
NO	3.8	4.2
Catalyst Core Dimension	2.5 cm dia x 15.2 cm L	2.5 cm dia x 15.2 cm L

[1]All emissions measured with water cooled sampling probe located 10.2 cm downstream of catalyst core.

performance after an initial break-in period of 24 hours at the indicated conditions.

The above discussion describes the present state of the art in low emissions combustion catalysts. Continuing test programs conducted by catalyst manufacturers will be concerned with both the development of a broader data base for catalytically supported combustion and with improvements in combustor and catalyst design. Catalyst life tests at higher temperatures and pressures will determine the ultimate performance range of the present-generation catalysts. Further improvements in catalyst technology are likely, however, and aircraft combustor designs should not be restricted solely to the present state of the art.

Improvements in catalyst performance will occur primarily in:

- Catalyst pressure drop
- Low temperature activity
- Maximum use temperature

Advances in support configuration will help reduce catalyst pressure drop. Current first-generation catalysts such as those described in Table IV are typically 55 percent open area honeycombs with 0.45 mm walls. Further development of improved substrate manufacturing procedures should make 0.15 to 0.20 mm walls and 75 to 80 percent open area obtainable. This would decrease the pressure drop for the given catalyst by about 20 percent in value.

Another support configuration change which may improve catalyst performance is the use of the "graded cell" approach, reported in Reference 21, which uses large cells at the front of the catalyst bed and small cells at the back of the bed. Analytical studies have indicated that the large cells will allow increased mass throughout without blowing out the heterogeneous reactions at the front of the bed, while the smaller channels prevent "break-through" (loss of thermal reactions within the channels) at the back of the bed.

Improved and new catalyst materials will tend to lower the catalytic-reactor lightoff and minimum-use temperatures. However, these improvements will probably not be sufficient to allow the use of a catalytic reactor at idle conditions without the use of a preburner. Additionally, it would be expected that some tradeoff between maximum-use temperature and low temperature activity would exist because the catalytic materials which are most active at low temperatures (precious metals) are generally less stable at high temperatures.

Catalyst maximum-use temperatures depend on limits imposed by both the support and catalytically active components. Zirconia-spinel substrates are currently available (Reference 22) which provide the capability to operate at temperatures up to 1973 K. However, the durability of this type of substrate has not been proven. Evaluations of substrate durability, mechanical strength, and thermal shock resistance as a function of material, wall thickness, and cell geometry (hexagonal, rectangular, sine wave, and flexible rectangular cell shapes) have not documented the capability to meet aircraft gas-turbine operating requirements. Current first-generation precious metal catalysts are limited to maximum-use temperatures of approximately 1587 K for extended time periods because of thermal stability of the catalytically active components. Potential for operation at temperatures up to 1973 K has been predicted for base metal oxide catalysts (Reference 23), but the low temperature activity of this type of catalyst would probably not be sufficient for operation at the minimum cruise condition without preburning. Segmented-bed designs in which the catalyst composition is varied from a precious metal at the front of the bed to a base metal oxide at the back of the bed may be a practical means to provide a good low temperature activity with increased maximum-use temperature capability. However, the extent to which this technique will actually increase the catalyst continuous-use temperature is unknown.

For the purposes of this Phase I Program, catalyst design criteria were based on projected catalyst development over a five to ten year period, which roughly corresponds to the development time required for a new aircraft engine. A general assumption in these projections was that low temperature activity would be comparable to that of current state-of-the-art precious metal catalysts, and that primary emphasis would be placed on increasing maximum-use temperature and reducing pressure drop. Specific design guidelines used were as follows:

<u>Ingition Temperature</u> - Comparable to CATCOM catalyst DXA-111 (Table III).

<u>Conversion and Emissions</u> - Comparable to CATCOM catalyst DXA-441 (Table IV and Appendix B).

<u>Maximum-Use Temperature</u> - Maximum continuous temperature of 1811 K consistent with 5-10 year projection provided in Table VII.

<u>Pressure Drop</u> - Based on uniform cell size with catalyst open area of 70 percent.

The performance requirements for the reference engine combustor are compared with the projected catalyst capabilities in Table VIII. It is apparent that the catalyst cannot cover the entire range of operation. Specifically, idle operation does not appear to be obtainable without the use of a conventional pilot burner or a catalyst preburner to increase the catalyst inlet temperatures, and both idle and approach operation require some type of fuel staging or airflow modulation to provide catalyst exit temperatures within the advanced catalyst operating range. At the

Table VII. Catalytic Reactor Maximum Use Temperature Projections.*

Availability Period	Projection Basis	Use Temperature Limit
Current	Demonstrated, 1000 hr test	1587 K with excursions to 1644 K
Near Term (2-3 Years)	Modest catalyst development effort required	1644 K with excursions to 1700 K
Far Term (5-10 Years)	Major catalyst development effort required	1811 K

* Engelhard Industries

Table VIII. Comparison of Advanced Catalytic Reactor Performance With Reference Engine Requirements.

Performance Parameter	Advanced Catalyst Operating Range	Reference Engine Operating Conditions			
		6 Percent, Idle	30 Percent, Approach	Cruise Range	100 Percent, Takeoff
Pressure, MPa	-	0.4	1.2	0.8 - 1.3	3.0
Combustor Inlet Temperature, K	600 - 1100	485	633	677 - 782	864
Combustor Exit Temperature, K	1350 - 1811	940	1135	1289 - 1488	1693
Total Pressure Loss, Percent	2 - 3	-	5.0	5.0	5.0
Combustor Efficiency, Percent	99.9	99.5	99	99	99.9

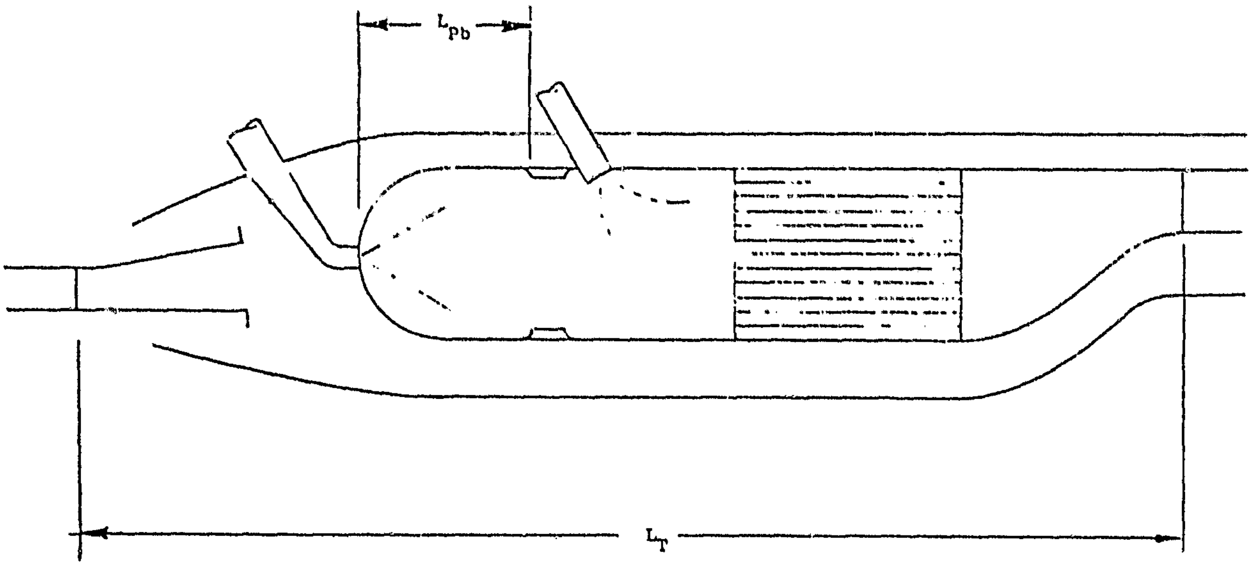
same time, although advanced catalytic-reactors are expected to be able to handle the high exit temperature at takeoff conditions, a uniform fuel-air mixture must be provided at the catalyst inlet to maintain temperatures within the allowable catalyst operating range. This task is complicated by autoignition, which severely limits the allowable mixing residence time between the fuel injection point and the catalytic-reactor inlet face. These design considerations are discussed in the following paragraphs.

4.2 CATALYTIC-COMBUSTOR DESIGN FEATURES

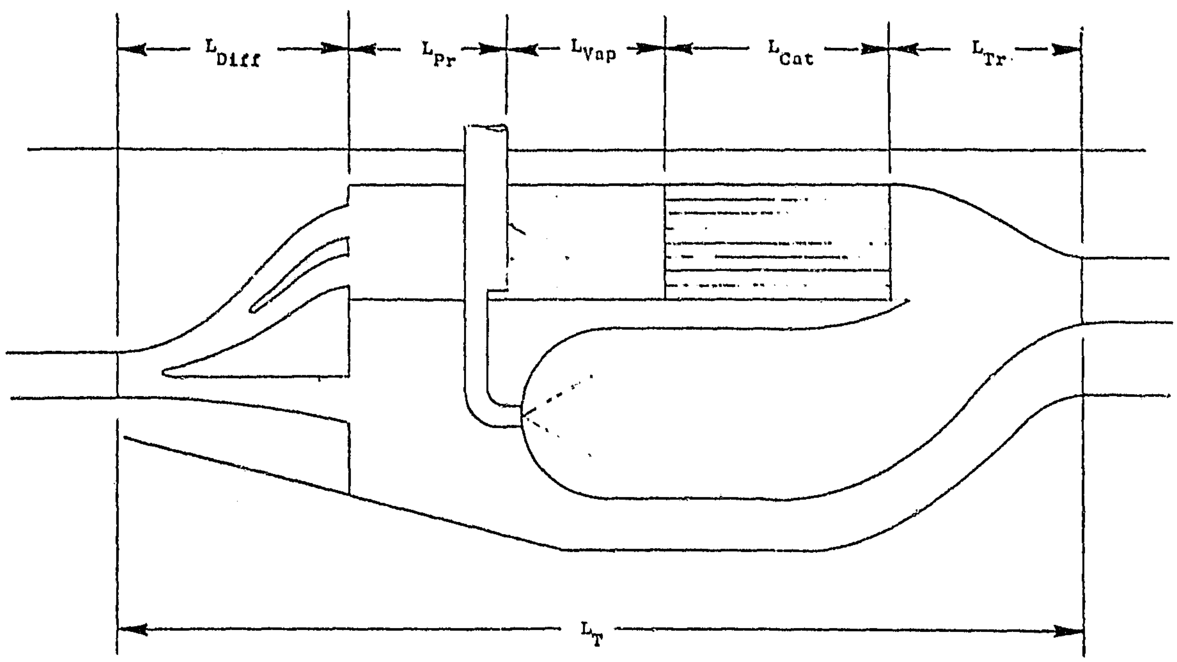
Practical designs for aircraft gas turbine main combustion systems which employ catalytic combustion technology to decrease NO_x emissions levels require consideration of several design features. Two simplified combustion system design concepts that illustrate these features are presented in Figure 3. For the series design arrangements of Figure 3(a), the catalytic reactor is positioned downstream of a conventional pilot combustor primary zone and secondary fuel injection system. At engine lightoff and low power operating conditions, the pilot combustor is operated normally and the catalyst bed serves as a "cleanup" device to reduce CO and HC emissions levels at these low power operating conditions. At high-power operating conditions and at cruise conditions, a major proportion of the total fuel flow is introduced through the secondary fuel injection system within or just downstream of a band of secondary air dilution holes. The resulting lean fuel-air mixture is reacted in the catalytic reactor, and, consequently, NO_x emission levels are very low at these conditions. The parallel design arrangement of Figure 3(b) results in a reduced system length. In this design, the combustor inlet flow is divided into two streams. The inner stream flows into a pilot combustor that is fueled for engine lightoff and low power operating conditions, and the outer stream flows into a flow mixing region and then through a catalyst bed. At high-power engine conditions and at cruise conditions, a major portion of the fuel is injected into the outer flowpath upstream of and leading to the catalytic reactor.

As shown in Figure 3(b), the overall length of the catalytic combustion system can be divided into five major-length segments. These five segments are the diffuser length, L_{Diff}; the velocity profile mixing length, L_{Pr}; the fuel-air mixing/vaporization length, L_{Vap}; the catalytic bed length, L_{Cat}; and the turbine flow transition length, L_{Tr}. For the series design of Figure 3(a), an additional primary combustion zone length, L_{PB}, is necessary for the pilot burner. Each of these burner length segments represents a different set of design considerations. These design considerations are presented in the following discussion beginning with the catalytic-reactor design configuration and the length required for the catalyst bed.

Catalytic-reactor design involves the specification of catalyst composition and substrate configuration. Honeycomb substrates are



(a) Series — Staged Catalytic Combustor



(b) Parallel — Staged Catalytic Combustor

Figure 3. Simplified Catalytic-Combustor Design.Concepts.

characterized in terms of channel shape, channel density (holes/cm^2), length, and segmentation.

In the selection of a catalytic-reactor design, the principal tradeoffs are combustion efficiency and pressure drop. Ideally, one would wish to provide just sufficient catalyst length to achieve complete combustion for an "aged" catalyst, so as to minimize pressure drop. In practice, a safety factor is utilized. In addition to this efficiency/pressure drop tradeoff, a catalyst design for a practical aircraft gas-turbine combustor should require minimum length and volume in order to approach the size and weight of conventional combustors. In the initial phase of this program, overall catalytic-reactor size and pressure drop were selected by using proven heat release rates and existing pressure drop data. Initial nominal sizing parameters were:

Catalyst Approach Velocity	30.5 m/s
Catalyst Length	12.7 cm
Catalyst Pressure Drop	4 percent

Catalytic-reactor isothermal pressure-loss characteristics used for combustor sizing are shown in Figure 4. This figure is for a nonsegmented catalytic-reactor having a nominal cell density of 15 channels/cm^2 and 70 percent open area. Catalytic-reactor pressure-loss coefficient consists of two components. One component is related to the sudden expansion losses or blockage of the support and is independent of Reynolds number. The second component, which comprises 60 to 70 percent of the total-pressure loss, is related to the viscous drag in the channels. This component varies significantly with Reynolds number and the ratio of length to hydraulic diameter of the channel. The variation in pressure-loss coefficient with Reynolds number as shown in Figure 4 did not affect the designs because in all cases Reynolds numbers were above 5000. Under these conditions, flow is fully turbulent (due to the irregular channel shape) and pressure loss does not vary significantly with increasing Reynolds number. Thus, for combustor analyses under isothermal conditions, the catalytic-reactor can be treated essentially as an orifice.

Catalytic-reactor pressure loss increases under nonisothermal (combustion) conditions due to heat addition and increased channel velocity. Above a Reynolds number of approximately 5000, this nonisothermal pressure loss is found to follow the following relation:

$$\frac{\left.\left[\frac{\Delta P}{P}\right|_{Comb}}{\left.\left[\frac{\Delta P}{P}\right|_{iso}} = \frac{2}{3}\,\frac{T_{exit}}{T_{inlet}}$$

where $|\Delta P/P|_{comb}$ is the pressure loss with combustion, $|\Delta P/P|_{iso}$ is the isothermal pressure loss, T_{exit} the reactor exit temperature, and T_{inlet} is the reactor inlet temperature.

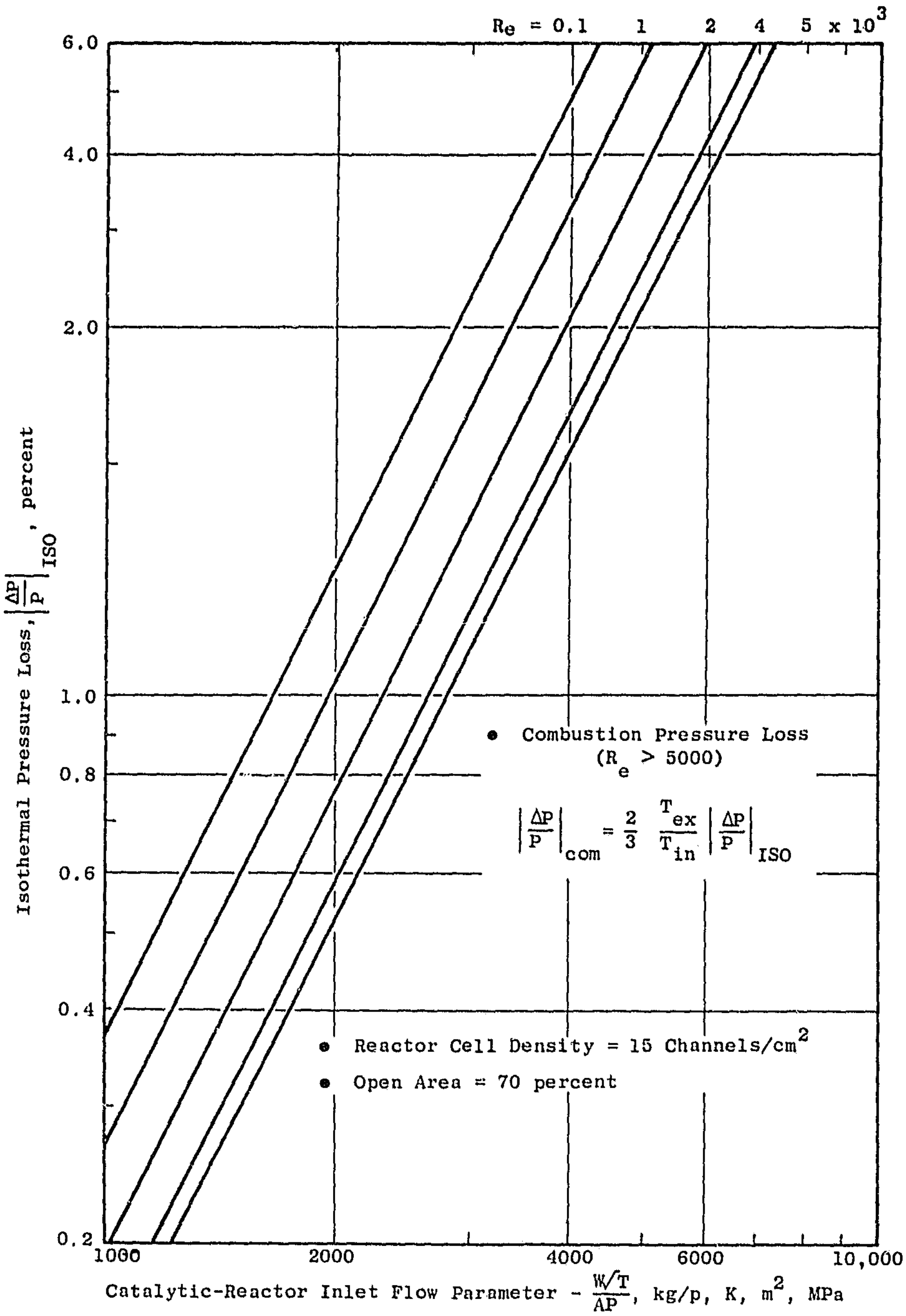


Figure 4. Catalytic Reactor Isothermal Pressure Loss Characteristics (12.7 cm Length).

The correlations presented above and shown in Figure 4 were used in all combustor evaluation and preliminary design analyses.

With the selected catalyst approach velocity and length, a heat release rate of approximately 25 Mcal/sec-atm-m^3 is obtained assuming that all fuel and air is reacted within the catalyst at standard day takeoff conditions. This value is in the upper range of proven catalyst performance (Table II) but leaves some safety margin. The catalyst approach velocity of 30.5 m/s is close to the maximum proven value. This high approach velocity was selected by considering fuel-air mixing and autoignition times which are discussed in the following sections.

4.3 AUTOIGNITION AND FLASHBACK

A major problem area in the design of premixing-prevaporizing fuel systems for catalytic combustors is the inherent possibility of autoignition of the fuel-air mixture upstream of the catalytic-reactor especially at the takeoff conditions. Autoignition occurs if the residence time of the fuel-air mixture is longer than the autoignition time for the fuel used at compressor exit temperatures and pressures. Another major problem area is the possibility of flashback of flame from the flame stabilization region into the upstream fuel-air mixture. Flashback can occur if the velocity in any region in the upstream combustible mixture is below the turbulent flame speed and if this upstream low-velocity region extends downstream to the inlet of the catalytic-reactor. Flames from autoignition or flashback could propagate upstream and stabilize at some point on a wall surface or from the fuel injector tubes. Consequently, the fuel-air mixing section must be carefully designed to eliminate the possibility of flashback, and the residence times for the fuel-air mixture must be small enough to prevent autoignition.

At the outset of the design effort, a literature review was conducted to obtain realistic estimates of autoignition delay times applicable to the reference engine cycle. The scope of four investigations (References 24 through 27) which were particularly applicable to the catalytic combustor design concepts and reference engine cycle are summarized in Table IX.

Predicted autoignition delay times based on results of these studies are presented for several key operating conditions in Table X. All of the correlations predict that hot-day takeoff is the most severe condition. Excluding the correlations of Reference 27, predicted times vary from 2.2 to 3.9 ms. The much lower autoignition delay times predicted by Reference 27 are thought to be due to peculiarities of the experimental apparatus used, so this result was discounted. Therefore, a maximum allowable residence time of 2.0 ms was established as a criterion for fuel-air carburetion systems which were required to operate at the takeoff condition. For systems which did not operate above the cruise range, the autoignition delay time was allowed to be up to 10 ms.

In applying the above autoignition delay time requirements to the design and evaluation of the catalytic combustor concepts, the total residence time, including components due to bulk velocity, nonuniform velocity profiles, wakes,

Table IX. Comparison of Autoignition Experiments and Results.

Reference	Fuel Injector/Duct Description	Fuel Types	Range of Test Conditions (Approx.)				
			Air Velocity (m/s)	Air Temp. (K)	Air Press. (MPa)	Equiv. Ratio	Delay Time (ms)
Marek, et al (24)	Upstream centered simplex atomizer in 10.2-cm-dia. x 66 cm duct	Jet A. Ambient T	10 to 40	590 to 833	0.5 to 2.5	$\leq$0.7	5 to 100
Stringer, et al (25)	Wall flush-mounted diesel injector in 4x4x36 cm duct	Avtur(Jet A). Avtag(JP-4). Diesel (45-50 Cet.) 18 other pure commercial & mixed fuels. Ambient T.	$\leq$21	770 to 980	3.0 to 6.0	0.2 to 7.0	0.6 to 5.0
Spadaccini (26)	Downstream centered simplex & air assist atomizers in 11.4-cm-dia. diverging duct	JP-4, #2 & #6. Heating oils. 305 to 450 K	10 to 34	670 to 870	0.7 to 1.6	$\leq$0.15	6 to 50
Duesurneau (27)	Cross-stream injection in 4.2-cm-dia. duct, 26 to 83 cm long	Kerosene. 285 to 305 K	70	720 to 1070	0.6 to 1.2	0.5 to 8.0	4 to 12

Table X. Comparison of Autoignition Delay Time Predictions at Design Conditions.

Engine Operating Condition	Inlet Temperature, K	Inlet Pressure, MPa	Fuel-Air Ratio, g/kg	Autoignition Delay Time, Milliseconds			
				Mareck[24] Jet A	Stringer[25] Jet A	Spadaccini[26] JP-4	Ducourneau[27] Kerosene (a) Egn 4 - Egn 3
Hot Day, Max Cruise	782	1.31	24.5	11.3	16.1 - 9.6	12.7	6.0 - 5.1
Std. Day Climbout	782	2.63	22.3	5.6	8.1 - 5.4	3.7	1.3 - 1.0
Very Hot Day Takeoff	864	2.59	25.5	4.4	3.2 - 2.5	2.8	0.9 - 0.5
Std Day Takeoff	814	3.02	24.3	4.4	4.7 - 3.3	2.4	0.8 - 0.5
Hot Day Takeoff	851	3.01	25.9	3.9	3.1 - 2.4	2.2	0.7 - 0.4

(a) Assumes a mixture containing 50 percent of the combustor airflow and 80 percent of the combustor fuel flow and recirculation were considered. These factors are further discussed in Section 6.1.3.

One factor which was not considered explicitly in the design and evaluation of the concepts was the possibility of preignition due to preheating of the fuel-air mixture due to radiation from the inlet face of the catalyst. This would present a significant problem in any of the combustor designs and would require that a radiation shield be placed between the catalyst and the mixing section. The use of a radiation shield would be equally applicable to any of the catalytic-combustor concepts studied.

4.4 FUEL-AIR MIXING AND VAPORIZATION

In order to obtain good emissions and performance in a catalytic combustion system, a uniform fuel-air mixture must be provided at the catalytic-reactor inlet face. A spatial variation in equivalence ratio can result in excessively high temperatures (above the catalyst maximum-use temperature) due to rich mixtures in one region of the catalyst, and low combustion efficiency due to lean mixtures in another region. For example, at the conditions indicated in Figure 2, combustion efficiency in a region having a fuel-air ratio below about 24 g/kg will be less than 99 percent, and maximum-use temperature will be exceeded in regions having fuel-air ratios above about 35 g/kg.

In a catalytic combustion system for aircraft gas-turbine applications, the maximum length of the fuel-air mixing and vaporization system is limited by the allowable autoignition delay time and mixture velocity. Within this length, the fuel is injected into the mixing region, evaporated, and mixed with the airstream. Based on the autoignition delay time of 2 ms and catalyst face velocity of 30.5 m/s discussed in the previous sections, the maximum length allowed for a premixing duct having a constant cross-sectional area is 6.1 cm if the velocity profile is uniform and wakes and boundary layer effects are negligible.

In a practical liquid fuel injection system, the number of fuel injection points is limited by minimum orifice size required to prevent plugging, and minimum orifice pressure drop required to provide uniform fuel flow to each of the orifices. Based on afterburner experience, the minimum recommended orifice size is 0.51 mm, and minimum recommended pressure drop is about 0.1 MPa. Although these are not absolute limits, the use of smaller orifices or lower pressure drop would entail increased developmental risk. Another factor which must be considered in the design of liquid fuel injection systems is injector insulation. Experience has shown that a majority of the injector structure should be of double wall construction, with a small air gap providing insulation to prevent fuel decomposition and fouling within the fuel tubes.

Early in the program, preliminary studies were conducted to estimate fuel evaporation and fuel-air mixing requirements. Evaporation studies using the computer program described in Reference 28 indicated that with the airstream velocity, residence time and orifice diameter specified above, less than 50 percent fuel evaporation would be obtained at the normal cruise operating condition. Further, assuming a single cylindrical catalytic-reactor is used to react all of the combustor fuel and airflow at normal cruise operating conditions, a catalyst diameter (D) of 41.2 cm would be required to obtain an approach velocity of 30.5 m/s. With the specified mixing length (L) of 6.1 cm, and the number of fuel injection points (N) limited to 180 by orifice size and pressure drop constraints, the effective mixing length (L_{mix}) is only about two equivalent diameters ($L_{mix} = L\sqrt{N/D}$). Recent efforts to develop fuel-air carburetion concepts for use in gas turbine catalytic combustion systems, which are summarized in Reference 29 through 31, indicate that about 6 equivalent diameters are required to obtain mixture uniformity within ± 10 percent. One method which can be used to improve both fuel evaporation and fuel-air mixing is to decrease the cross-sectional area of the premixing tube at the fuel injection plane. This increases airstream velocity, which improves fuel atomization and increases mixing length for constant residence time, as well as reducing the equivalent duct diameter at the fuel injection plane. By increasing airstream velocity to 61 m/s, mixing length is increased to 12.2 cm, or about 5.6 equivalent diameters. Under these conditions, estimated fuel evaporation is increased to approximately 98 percent, and fuel-air mixture uniformity is improved. Therefore, in the catalytic combustor conceptual designs in which catalyst stage operation at takeoff conditions was anticipated, reduced-area, increased-length mixing ducts were utilized to provide a nominal airstream velocity of 61 m/s at the fuel injection plane. In these designs, flow is rapidly decelerated to the required catalytic-reactor approach velocity just upstream of the reactor. This feature was incorporated into five of the six designs presented in Section 5.0. Analysis of fuel-air mixing in these systems is presented in Section 6.3.

4.5 INLET DIFFUSER

As discussed above, a fuel injection passage velocity of 61 m/s was selected for several of the catalytic combustion system conceptual designs, while the compressor exit velocity is approximately 155 m/s. Hence, the flow must be diffused through an area ratio of 2.54 before entering the fuel injection section. This diffusion must be accomplished within a very short length, with relatively low pressure losses, and the velocity profile must be very flat and uniform at the fuel injection plane downstream of the diffuser. A simple, straight diffuser, designed according to the criteria expressed by the Stanford diffuser flow regimes for nonseparating diffusers (Reference 32) would have a length of more than 250 cm. However, good diffuser performance can be achieved within a much shorter length through the use of multiple-passage step diffusers.

This type of diffuser is shown in Figure 3. After leaving the compressor exit, the flow is diffused through a short, straight prediffuser. This flow is then reaccelerated as it is divided into several separate, parallel streams by annular splitter vanes. Each splitter vane passage is treated as a simple diffuser, and the length of the diffusing section in this passage is selected to fall within the nonseparating regime of the Stanford correlations. Flow separation in the diffuser would cause a large increase in pressure losses and would result in severe profile distortions at the exit plane of the diffuser. The splitter vane passages have short constant-area sections at the inlet and exit ends of each passage to permit profile mixing before entering the next stage of diffuser. In the last stage of the diffuser, the flow is dumped into a constant-area passage ahead of the fuel-air mixing region of the catalytic reactor.

The length of this profile mixing passage, L_{Pr} (Figure 3), is selected to permit the flow leaving the splitter vane passages to mix across the wakes generated behind the splitter vanes and the buff regions at the walls of the passages. The splitter vanes serve a dual purpose. They reduce the lengths of the diffuser passages, and they divide the wake regions into a larger number of smaller wakes, and, consequently, reduce the length required for the profile mixing region.

These diffuser design techniques apply primarily to the "straight-through" combustor conceptual designs (Concepts 3 and 6) presented in Section 5.0. However, multiple passages were also used to decrease diffuser length requirements in the reverse flow and series-staged design concepts. In these concepts, the desired flat velocity profile within the fuel-air mixing region is generated by first dumping the airflow into a low velocity region (either the combustor plenum or pilot dome) and then accelerating the flow into the mixing region.

5.0 CATALYTIC COMBUSTOR CONCEPTUAL DESIGNS

During the initial phase of combustor conceptual design, a total of approximately twenty concepts were identified. All of these concepts incorporated (1) a conventional pilot stage specificially sized for relight and low idle emissions requirements, and (2) a lean premixed catalytic stage sized specifically for ultralow NO_x emissions at cruise. The concepts differed in physical arrangement and in operating and staging arrangements at high power levels. The primary differences in physical and operating arrangements were as follows:

1) The pilot and catalytic stages could be in series or parallel.

2) In the parallel staged designs, the pilot could be either inside or outside of the catalyst stage. In the concepts where the catalyst stage was located on the ouside, the catalyst stage configuration could be either straight-through as in a conventional annular aircraft combustor, or located above the inlet diffuser with a plenum feed as in conventional land-based turbine designs. Similarly, in the case of series staging, the pilot stage could be located as in a conventional straight-through combustor or folded so as to provide a more direct inlet flowpath to the catalyst.

3) Variable geometry could be used on the pilot stage, main stage, or both to change the airflow split with engine operating conditions.

4) The catalytic stage could be used at all high power operating conditions, or a third noncatalytic stage could be provided to supplement or replace the catalytic stage at takeoff conditions.

Each of the above features was included at least once in the six combustor configurations selected for conceptual design and evaluation. These six design concepts are described in the following paragraphs.

5.1 BASIC SERIES-STAGED CONFIGURATION

The Basic Series-Staged catalytic combustor design concept shown in Figure 5 (Concept 1) consists of a straight-through pilot stage mounted upstream of the catalyst stage. This concept does not employ variable geometry or a takeoff stage. About 30 percent of combustor airflow enters the pilot dome, and the remainder of the flow, except for liner cooling, enters the combustor through an array of 90 mixing chutes which are located immediately downstream of the pilot burner zone. This flow is approximately 40 percent of total combustor airflow.

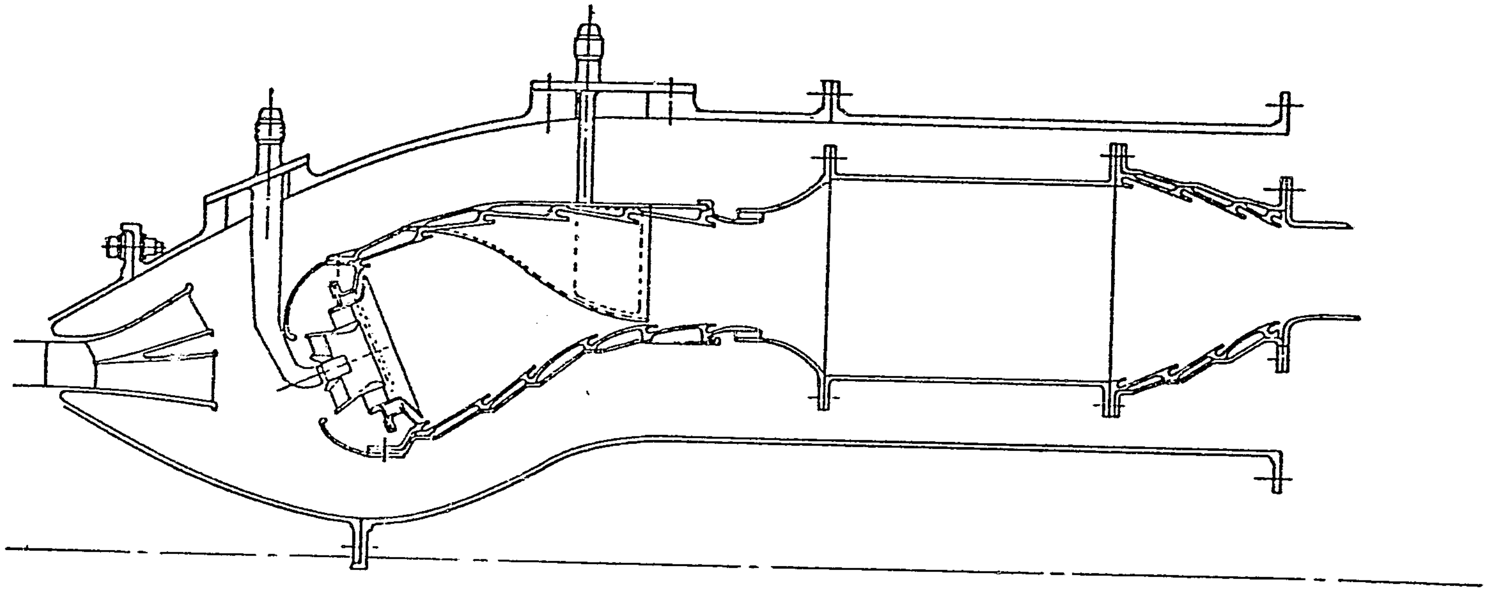


Figure 5. Catalytic Combustor Concept 1, Basic Series-Staged Configuration.

At engine lightoff and power levels up to approximately 25 percent of rated thrust (just below the 30 percent approach power level), only the pilot burner is operated, and the catalyst is used as a cleanup device. As power is increased beyond the 25 percent level, the pilot stage is cut back and fuel is injected through aerodynamic multiple-point cross-stream injectors located in each of the mixing chutes.

The cross-sectional area of the combustor is reduced at the exit plane of the mixing chutes in order to accelerate the airflow from the pilot zone. This improves the velocity profile leaving the pilot burner and also improves mixing between the pilot stream and the air exiting the mixing chutes by increasing the mixing length (limited by autoignition considerations). The air velocity through the mixing chutes is designed to be very high in order to promote good fuel atomization within the chutes and ensure rapid mixing and dispersion of the fuel droplets across the entire flow field upstream of the catalytic-reactor. Immediately upstream of the reactor, the flow is rapidly diffused to the catalyst approach velocity required to obtain a satisfactory catalytic-reactor efficiency and pressure drop. Downstream of the reactor, the flow is accelerated to the required combustor exit velocity through a short converging section.

5.2 SERIES-STAGED CONFIGURATION WITH VARIABLE GEOMETRY

The Series-Staged catalytic combustor configuration with variable geometry (Concept 2) is shown in Figure 6. This concept is similar to the Basic Series-Staged configuration with the following additions and modifications:

1. Variable geometry has been added to the fuel injection chutes.
2. A folded pilot burner configuration is used.
3. External fuel-air mixing chutes are used.
4. A third stage has been added downstream of the catalyst.

At lightoff and lower power operating conditions, the variable geometry vanes are closed and only the pilot stage is fueled. Under these conditions, the combustor airflow distribution is very similar to that of Concept 1; however, total combustion-system pressure drop is increased to approximately 10 percent of compressor discharge total pressure (P_3) because of the increased blockage of the vanes. Slightly below the approach power level the vanes are opened. With the vanes open, system pressure drop is reduced to about 5 percent of P_3 and fuel injection chute airflow is increased to approximately 70 percent of combustor airflow. As a result of this increase in chute airflow, mixtures exiting the fuel injection slots are leaner, and less mixing between the chute and pilot flows is required to obtain uniform mixtures at the catalytic-reactor inlet.

At high-power conditions of 85 to 100 percent of rated thrust (climbout and takeoff), the pilot burner is operated very lean to reduce its NO_x emissions levels, and a majority of the fuel is routed to the high-power stage. This high-power stage consists of an array of 60 radial vee-gutters which are located on the downstream face of the catalytic-reactor. The hot

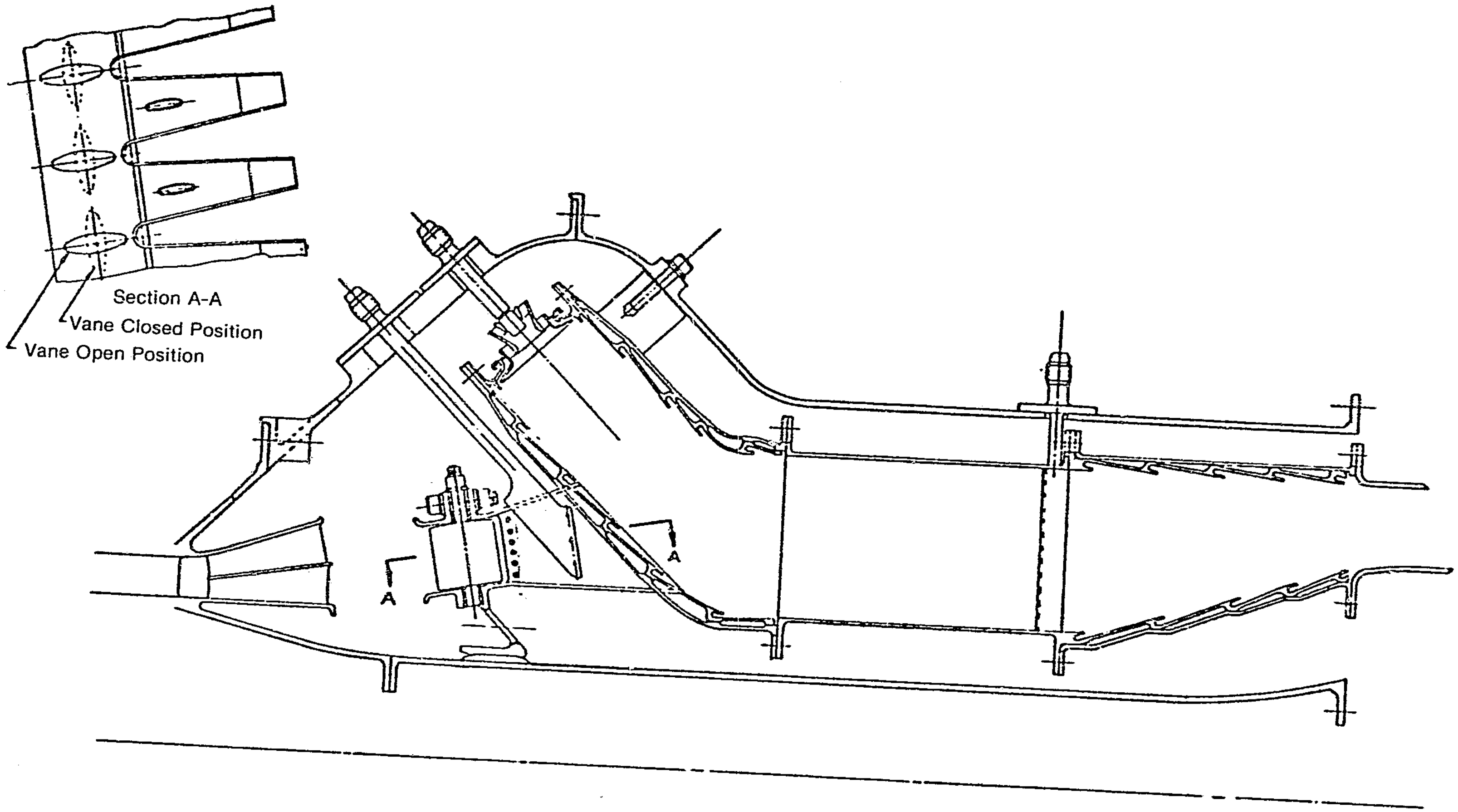


Figure 6. Catalytic Combustor Concept 2, Series-Staged Configuration with Variable Geometry.

pilot burner gases flowing through the catalytic-reactor at these conditions help to stabilize the combustion process. An extended aft combustor section is added to provide high combustion efficiency and uniform temperature distributions during takeoff-stage operation.

The use of variable geometry and a takeoff stage in this combustor concept simplifies the fuel-air mixing problem. Less mixing between the free stream and fuel injection chute flows is required because of the leaner chute mixtures obtained with variable geometry, and allowable mixing section residence times are increased because the system incorporates a separate takeoff stage, and therefore does not have to meet autoignition criteria at takeoff. The decreased severity of these criteria allows the use of external mixing chutes on this concept and eliminates the requirement for the reduced-area mixing section used upstream of the catalyst in Concept 1. In the conceptual design shown in Figure 6, 60 external mixing chutes and 60 multiple-jet, cross-stream fuel injectors are used. Upstream of the fuel injectors, the chutes merge into an annular section containing 60 variable geometry vanes which are actuated by external actuators via an internal unison ring (not shown). When opened, these vanes are aligned with the centerbodies which divide the ducts in order to minimize the effects of vane wakes on fuel injection. An array of cylinders located upstream of the fuel injectors has been provided to improve the velocity profile at the fuel injection plane.

5.3 BASIC PARALLEL-STAGED CONFIGURATION

The Basic Parallel-Staged combustor conceptual design (Concept 3) is shown in Figure 7. A double-annular design approach is used in this concept in which the inner annulus is comprised of a catalytic combustor stage and the outer annulus is a conventional pilot burner. No variable geometry is used.

In this concept, approximately 60 percent of the combustor airflow is routed through the catalyst stage. The remaining airflow is used for the pilot dome and liner cooling. At lightoff and up to about 25 percent power, only the pilot stage is fueled. Above 25 percent power, most of the fuel is burned in the catalyst. Fuel which cannot be accommodated by the catalyst stage because of maximum-use temperature limitations is burned in the pilot stage.

A novel feature of this combustor design is the configuration of the main-stage fuel injectors, which are integrated with the combustor inlet diffuser assembly. Air entering this diffuser flows into four passages. Pilot dome and liner cooling air is conducted through the outer prediffuser passage, and catalyst stage airflow enters the two center passages. The use of this multiple passage design enables flow to be diffused through a relatively high area ratio ($R_A = 2.0$) in a short distance. Catalyst stage fuel flow is routed through passages in the diffuser struts to the splitter vane located at the entrance to the catalyst stage fuel-air mixing duct and is injected radially into the airstream through orifices near the trailing edge of this vane. The fuel injector/diffuser is divided circumferentially into six segments which can be removed individually for

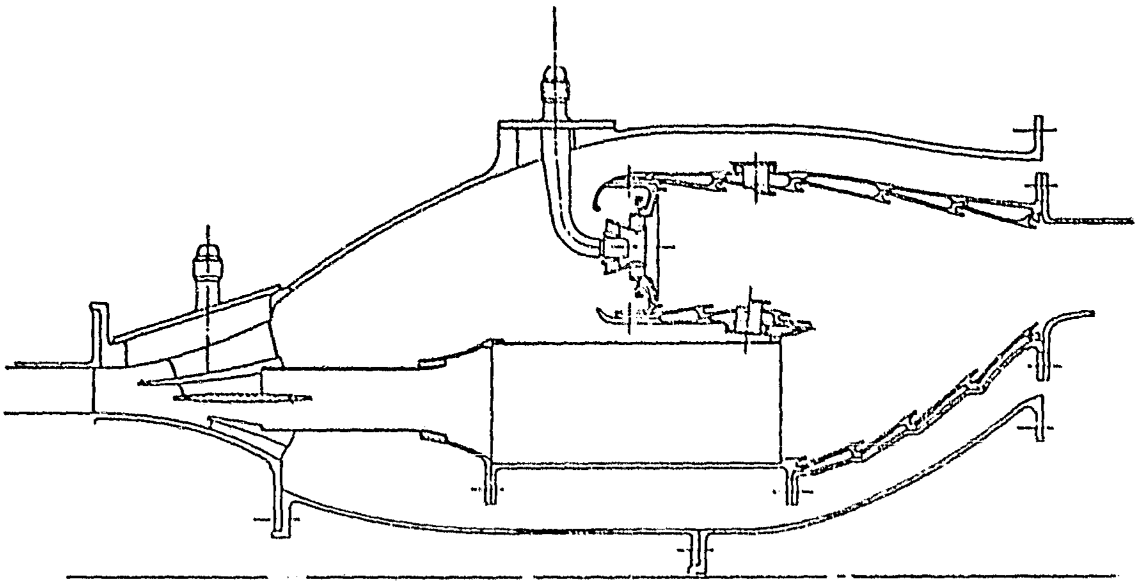


Figure 7. Catalytic Combustor Concept 3, Basic Parallel-Staged Configuration.

cleaning and maintenance.

The mixing-duct length downstream of the fuel injector is sized for a nominal flow velocity of 61 m/s at the cruise conditions in order to provide adequate length for vaporization and mixing without exceeding autoignition delay time limits at the takeoff power level. Flow is rapidly diffused to the appropriate catalytic-reactor approach velocity just upstream of the catalyst inlet face. In this design, boundary layer blowing is used to prevent flow separation in this diffusing region.

5.4 CANNULAR REVERSE-FLOW PARALLEL-STAGED CONFIGURATION

The Cannular Reverse-Flow Parallel-Staged catalytic combustor conceptual design (Concept 4) is shown in Figure 8. Flow distributions and operation of this design are nearly identical to the Basic Parallel-Staged design. Principle differences are the positioning of the pilot stage in the inner annulus, and the use of a cannular reverse-flow catalyst stage.

The catalyst stage in this design consists of 30 cylindrical premixing tubes and catalytic-reactors. Fuel injection is through 30 pressure atomizing nozzles inserted axially into the center of the premixing duct through the catalyst stage casing. Flow from the inlet prediffuser is dumped into the combustor plenum, then fed into the premixing ducts through annular turning passages. Uniform velocity profiles at the fuel injection plane are obtained through the use of turning vanes and by accelerating the flow through the turning passages. As in the Basic Parallel-Staged concept, a nominal airstream velocity of 61 m/s is used in the mixing duct to provide increased length for fuel-air mixing.

5.5 REVERSE-FLOW PARALLEL-STAGED CONFIGURATION WITH VARIABLE GEOMETRY

A cross-sectional view of the Reverse-Flow Parallel-Staged combustor with variable geometry (Concept 5) is shown in Figure 9. This concept is similar in appearance to Concept 4 except that an annular catalyst stage is used. Other additional design features include the use of variable vanes in the catalyst stage flowpath and a takeoff stage similar to that used in Concept 2.

The addition of variable geometry to this parallel-staged design concept enables the catalytic-reactor airflow to be increased at the cruise condition. The pilot stage is sized to obtain good performance at low-power conditions with the variable vanes closed. With the vanes open at intermediate and high-power conditions, pilot flow is reduced and an increased proportion of combustor airflow passes through the catalytic-reactor. This feature improves combustor NO_x reduction potential by increasing the proportion of fuel flow which can be burned in the catalyst at high power. With the variable vanes closed at lightoff and low-power

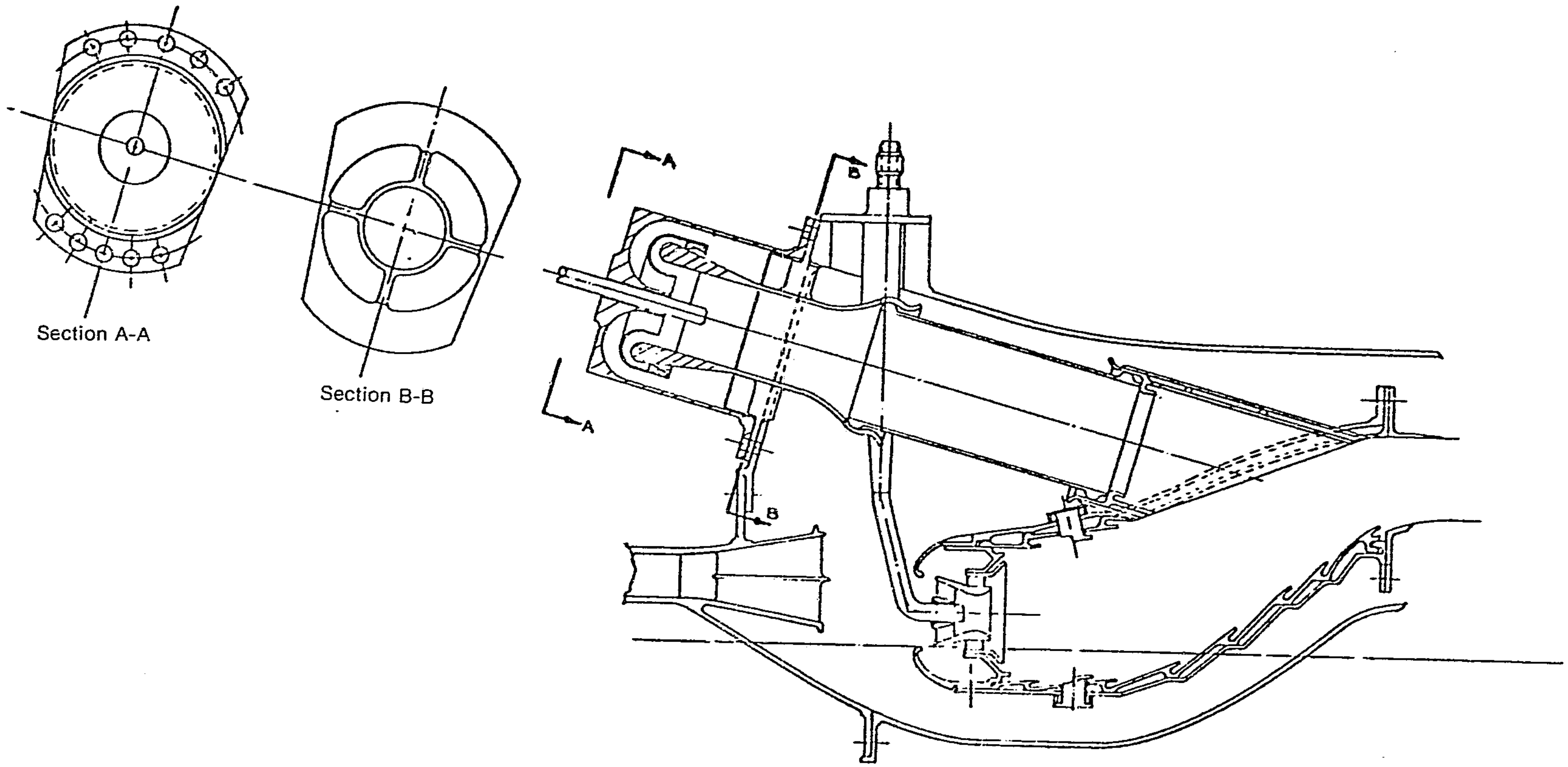


Figure 8. Catalytic Combustor Concept 4, Cannular Reverse-Flow Parallel-Staged Configuration.

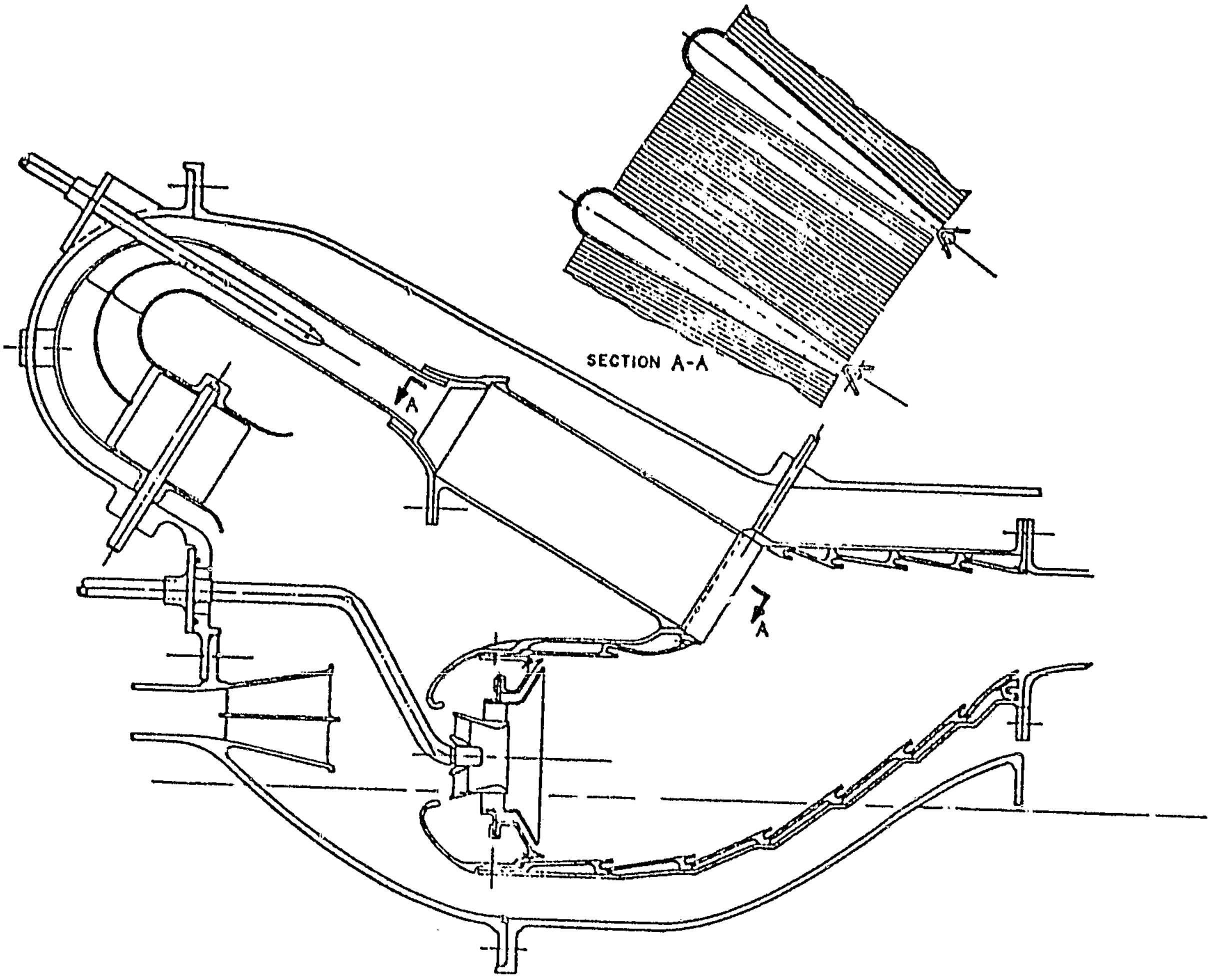


Figure 9. Catalytic Combustor Concept 5, Reverse-Flow Parallel-Staged Configuration with Variable Geometry.

operating conditions, about 40 percent of the combustor airflow goes through the catalytic-reactor. Because of the vane blockage, pressure drop in this operating mode is increased to approximately 14 percent of the compressor discharge pressure. Since pilot stage dome and liner cooling flows must be sufficient to allow both pilot- and main-stage operation with the variable vanes open, these cooling flows are increased by a factor of two due to the increased pressure drop with the vanes closed.

During idle-mode operation, only the pilot stage is fueled. At power levels above about 25 percent of rated thrust, the variable vanes are open and most of the combustor fuel flow is admitted to the catalytic-reactor. In this operating mode, catalytic-reactor airflow is increased to approximately 70 percent of total combustor airflow, and combustion system pressure drop is reduced to the design value of 5 percent. At high-power conditions, permissible fuel flow to the pilot and catalyst stages may be limited by maximum temperatures and/or auto-ignition considerations. At these conditions, the remaining fuel flow would be admitted to the takeoff-stage vee-gutters located at the catalyst exit.

The converging annular catalyst used in this combustor design has a decreasing cross-sectional area from the inlet to the exit plane of the bed. To simplify catalytic reactor fabrication, annular catalyst sectors are used with wedge-shaped spacers as shown in Figure 9 (Section A-A). These spacers are purged with a small amount of cooling flow which is also used to cool the takeoff-stage vee-gutters.

5.6 RADIAL/AXIAL PARALLEL-STAGED CONFIGURATION WITH VARIABLE GEOMETRY

The Radial/Axial Parallel-Staged combustor shown in Figure 10 (Concept 6) is essentially two separate combustion systems in parallel. In this design concept, the outer annulus combustor is piloted premixing-prevaporizing design based on the Radial/Axial combustor investigated in the NASA/GE Experimental Clean Combustor Program (Reference 5). This outer annulus combustor is used at all operating conditions except cruise. At cruise conditions, the variable geometry vanes are rotated to divert the flow to the catalytic combustion system located in the inner annulus. These vanes are shaped to pass only about 10 percent leakage flow when closed and to present very low blockage when the vanes are open. The inner and outer vane sets for this system are actuated individually with concentric shafts which pass through the combustor casing.

This design approach takes maximum advantage of conventional combustor design technology since the combustor used for all steady-state

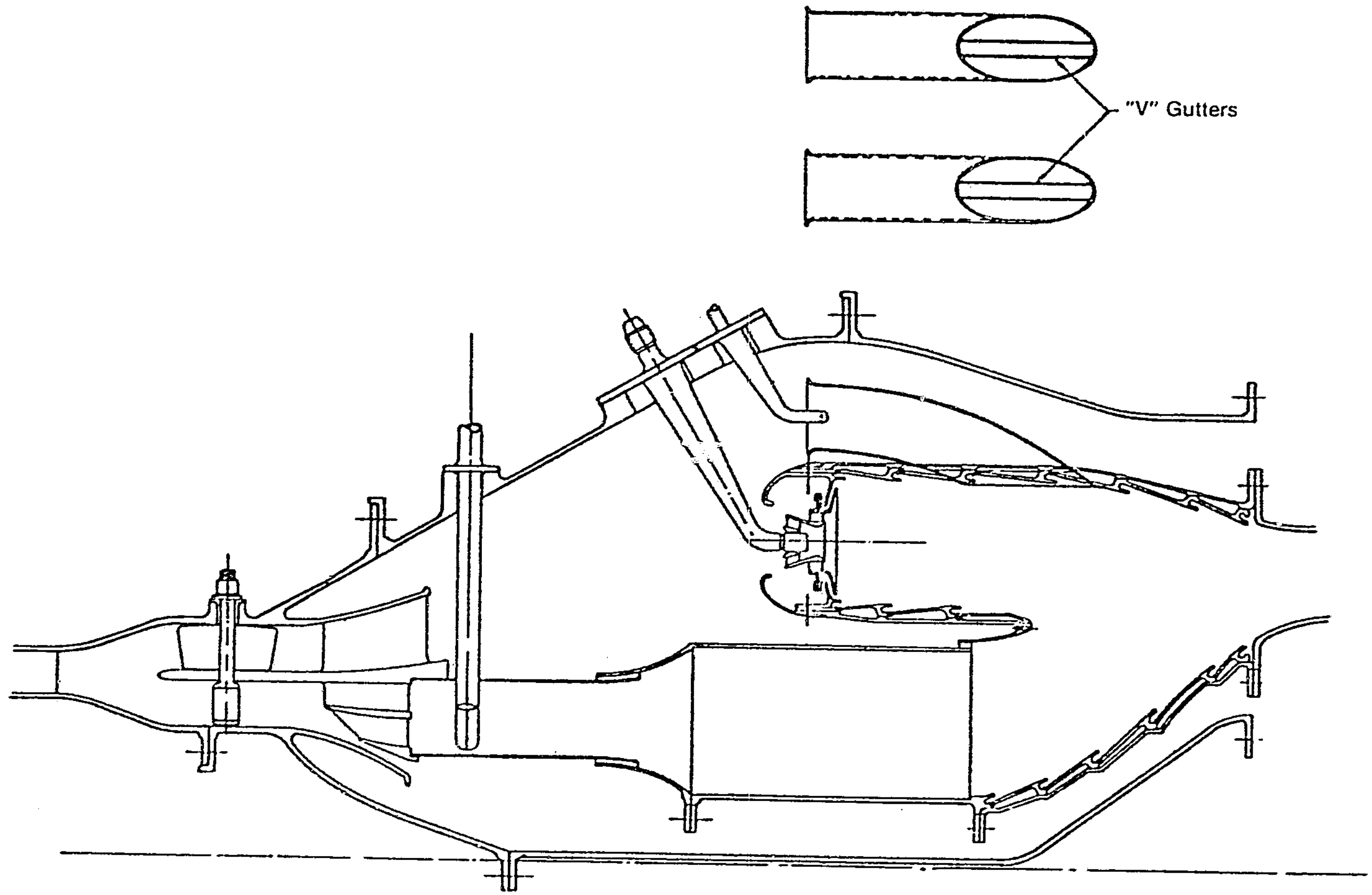


Figure 10. Catalytic Combustor Concept 6, Radial/Axial Parallel-Staged Configuration with Variable Geometry.

and transient operation during landing and takeoff maneuvers can be essentially a conventional design. The range of operation required of the catalytic combustor is thus limited to cruise conditions, which results in less severe operating constraints on this system. On the other hand, this system does not take advantage of the catalytic combustor emissions reduction potential during landing and takeoff maneuvers.

5.7 CONCEPTUAL DESIGN SUMMARY

Combustor sizing parameters for each of the six conceptual designs are presented in Table XI. Combustor sizing was based on the following considerations:

- The combustors were sized to operate within the range of reference engine cycle conditions indicated in Table I.

- Pilot stage dome and dilution airflows were selected to provide approximately stoichiometric dome mixture for rapid HC consumption, diluted to approximately 0.6 equivalence ratio for rapid CO consumption, in accordance with chemical kinetic caluculations and NASA/GE Low Power Emissions Reduction program experience (Reference 32). Pilot stage swirler flows were reduced somewhat in the fixed-geometry, parallel-staged configurations (Concepts 3 and 4) to increase available catalytic-reactor airflow. This represents a tradeoff between idle CO and HC emissions, which would be increased by the decreased swirler flow, and high-power cruise emissions, which would be reduced with increased catalyst flow.

- Pilot-stage dome velocity was selected to be in the range 6.1 - 7.6 m/s for stability and relight in accordance with GE design practice.

- Dome and liner specific cooling airflows were set to approximately the reference engine combustor design levels.

- Catalysts are 10.2 cm long and pressure drop with combustion is assumed to be 4 percent at a face velocity of 30.5 m/s. Concepts 1 and 2 have reduced catalytic-reactor face velocities and proportionally reduced catalyst pressure drops.

- Except for Concept 2, fuel preparation zones were sized for 2 milliseconds residence time to preclude autoignition at takeoff conditions. Concept 2 was not designed for catalyst operation at takeoff, so the fuel preparation zone is sized for 4 milliseconds residence time.

Table XI. Catalytic Combustor Design Parameters.

Concept No.	1	2	3	4	5	6
Combustion System Length, cm	54.6	57.2	41.9	32.8	36.8	54.4
Maximum Envelope Diameter, cm	82.8	96.2	80.4	91.1	105.3	92.6
Combustor $\Delta P/P$ (Cruise/Idle), %	4/4	4/8	4/4	4/4	3/12	4/4
Overall $\Delta P/P$ (Cruise/Idle), %	5/5	5/10	5/5	5/5	5/14	5/5
Number of Fuel Stages	2	3	2	2	3	3
Variable Geometry Features	N/A	Combustor Vanes	N/A	N/A	Combustor Vanes	Diffuser Vanes
Catalyst Fuel Injector Type	Radial Spraybar	Radial Spraybar	Circum-ferential Spraybar	Pressure Atomizing Nozzles	Axial Spraybar	Radial Spraybar
Number of Catalyst Fuel Injectors	90	60	10	30	30	40
Number of Pilot Injectors	24	40	40	30	30	40
Takeoff Stage Type	N/A	Series Direct Injection	N/A	N/A	Series Direct Injection	Parallel, Premixed
Takeoff Stage Burning Length, cm	—	14.0	—	—	14.0	12.7
Number of Takeoff Stage Injectors	—	30	—	—	30	40
Flow Splits (Cruise/Idle), $\%W_c$:						
Pilot-Stage – Swirler	15/15	6/16	11/11	10/10	8/16	1.5/14
– Dome Cooling	7/7	3/7	5/5	7/7	4/8	1.0/9
– Dilution	6/6	2/6	6/6	6/6	0/0	0/0
– Liner Cooling	20/20	8/20	8/8	9/9	6/12	0.8/7
Aft Cooling	10/10	10/16	11/11	10/10	11/22	11.2/12
Profile Trim	0/0	0/0	2/2	0/0	2/4	0/0
Total Catalyst Flow	90/90	90/84	57/57	58/58	69/38	80/8
Takeoff Stage (3 Stage Only)	—	90/84	—	—	69/38	5.5/50
Pilot-Stage Dome Velocity*, m/s	7.0	7.0	6.1	7.0	6.9	7.6
Pilot-Stage Dome Height, cm	7.6	5.6	5.1	6.1	8.6	5.6
Catalyst Face Velocity (Cruise), m/s	21.3	24.1	30.5	30.5	30.5	30.5
Catalyst Height, cm	8.6	7.9	5.1	6.1**	4.6	6.9
Catalyst $\Delta P/P$ (Cruise/Idle), %	2/2	2.5/1.8	4/4	3/3	3/0.9	3.5/0.4

* Calculated for Idle Flow Splits at Takeoff Density (GE Design Practice)

** Diameter (30 Cylinders)

During the course of analysis and evaluation of the six conceptual designs, several of the initially selected design details and sizing parameters indicated in Table XI were varied to improve combustor performance. These variations are discussed in the following sections on conceptual design analysis and evaluation.

6.0 CONCEPTUAL DESIGN ANALYSIS AND EVALUATION

6.1 CONCEPT ANALYSES

Analysis of the conceptual designs presented in Section 5.0 was, by necessity, an iterative process. In several cases, initial analyses based on tentative fuel and airflow schedules indicated a requirement for modifications which, in turn, required a revision in flow scheduling. Prime examples of such modifications are the requirement for increased dome flows in Concepts 3 and 4 (parallel staged, nonvariable geometry) in order to meet low-power emission requirements, and the use of convective liner cooling techniques aft of the catalytic-reactor. In both of these cases, the change in airflow requirements affected the fuel and airflow schedules. Final iteration of design analyses is described in the following sections, which start with fuel and airflow scheduling.

6.1.1 Fuel and Airflow Scheduling

Fuel and airflow schedules were developed for each of the conceptual designs to satisfy all operating requirements of the pilot and catalyst stages over the reference engine combustor operating range. Specific flow-scheduling criteria were as follows:

- Pilot dome airflow must be sufficient to obtain acceptable emission and performance with fuel flow admitted through the pilot stage injectors from lightoff through the approach operating conditions. Pilot dome flow requirements at idle conditions were determined from emissions analysis (Section 6.1.4). Required flow levels are presented in Table XII.

- Liner cooling flows must be sufficient to provide acceptable liner temperatures at all operating conditions. Liner cooling flows presented in Table XII were obtained from liner cooling analyses discussed in Section 6.1.5.

- Sufficient pilot-stage fuel flow must be supplied to provide a stable pilot flame at all operating conditions in order to preclude the necessity to relight the pilot during engine deceleration. In order to minimize pilot-stage fuel flow requirements at high-power conditions, only a small fraction (10-17 percent) of the pilot injectors were fueled. It was assumed that four or five cups equally spaced around the pilot annulus would be sufficient to provide rapid flame propagation.

- Catalytic-reactor inlet-air temperature must be above 600 K prior to fueling the catalyst stage in order to assure rapid catalyst ignition.

- The catalyst stage must be in operation at and above the approach power level (30 percent of rated thrust) in concepts not incorporating a takeoff stage and in variable geometry designs having increased pressure drop at idle. This criterion was selected (1) to minimize the required

Table XII. Catalytic Combustor Airflow Requirements (Idle).

Location	Percent of Total Combustor Airflow					
	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6
Pilot Stage						
Swirler	15.2	15.2	15.5	15.7	15.5	15.0
Primary Dilution	6.0	6.0	6.0	6.0	6.0	6.0
Dome Cooling	4.4	4.4	3.8	3.3	4.7	4.0
Liner Cooling/Profile Trim	23.9	16.2	12.0	14.0	12.2	16.4
Catalytic-Reactor	100.0	100.0	62.7	61.0	61.6	10.0
Main Stage	-	-	-	-	-	48.6
Fuel Injection Chute	50.5	58.2	-	-	-	-

pilot stage operating range, thereby minimizing pilot stage combustion and liner cooling airflow requirements, and (2) to provide continuous catalyst operation during approach maneuvers to avoid a transition lag in the event that a rapid increase in power is required. Transition to catalytic operation below the approach power level is particularly important to variable geometry Concepts 2 and 5, which have increased pressure drop during idle mode operation.

- Local catalyst inlet fuel-air ratios must be sufficient to obtain combustion efficiency above 99 percent. Fuel-air ratio requirements for 99 percent efficiency as a function of reactor inlet temperature and approach velocity are shown in Figure 11.

- Local reactor fuel-air ratios must be below levels required to obtain the maximum catalyst use temperature of 1811 K.

Approximate limits due to the catalytic-reactor maximum-use temperature and minimum fuel-air ratio are shown for the landing/takeoff and cruise cycles in Figures 12 and 13. In order to remain between these limits with Concepts 1 through 5, fuel staging is required to maintain the effective catalyst fuel-air ratio between the upper limit restricted by maximum-use temperature and the lower limit required to obtain satisfactory combustion efficiency. A possible catalyst fuel staging schedule to stay within permissible fuel-air ratio limits is also shown on these figures.

The flow schedule shown in Figures 12 and 13 applies to Concept 1, in which all fuel and airflow pass through the catalytic reactor. At approach conditions in this example, the effective catalyst airflow is reduced to about 53 percent by a sector burning approach in which only 48 of the 90 catalyst stage injectors are fueled. As thrust is increased beyond 60 kN, the peak fuel-air ratio within the fueled sector approaches the upper limit imposed by maximum use temperature, (assuming a fuel-air mixture nonuniformity of approximately 10 percent). At this point, four additional injectors are fueled (for a total of 52 out of 90), which increases the effective catalyst airflow to 58 percent of combustor airflow. In this example, the number of injectors fueled is increased in four discrete increments in going from approach to takeoff power. In practice, the number of increments would depend on the fuel-air mixture uniformity which could be obtained and the uncertainty in local fuel-air ratio of the control system used.

In the above example, effective catalyst airflow was controlled by varying the size of the catalytic-reactor sector fueled. Additional control of this parameter could be obtained by varying the pilot stage fuel flow in any of the concepts, and, in Concept 6, by modulating the catalytic-reactor airflow. This would be accomplished by opening the main-stage variable geometry vanes to bypass a portion of the airflow.

A flow schedule showing the effect of the various pilot and catalytic-reactor operating constraints is shown in Figure 14. This figure, which depicts the Concept 3 flow schedules, is typical of Concepts 3 through 5. In these concepts, catalytic-reactor fuel flow is introduced just below the approach power level (30 percent of rated thrust), and pilot-stage fuel flow is simultaneously decreased to maintain overall combustor fuel flow requirements. At this point, catalytic-

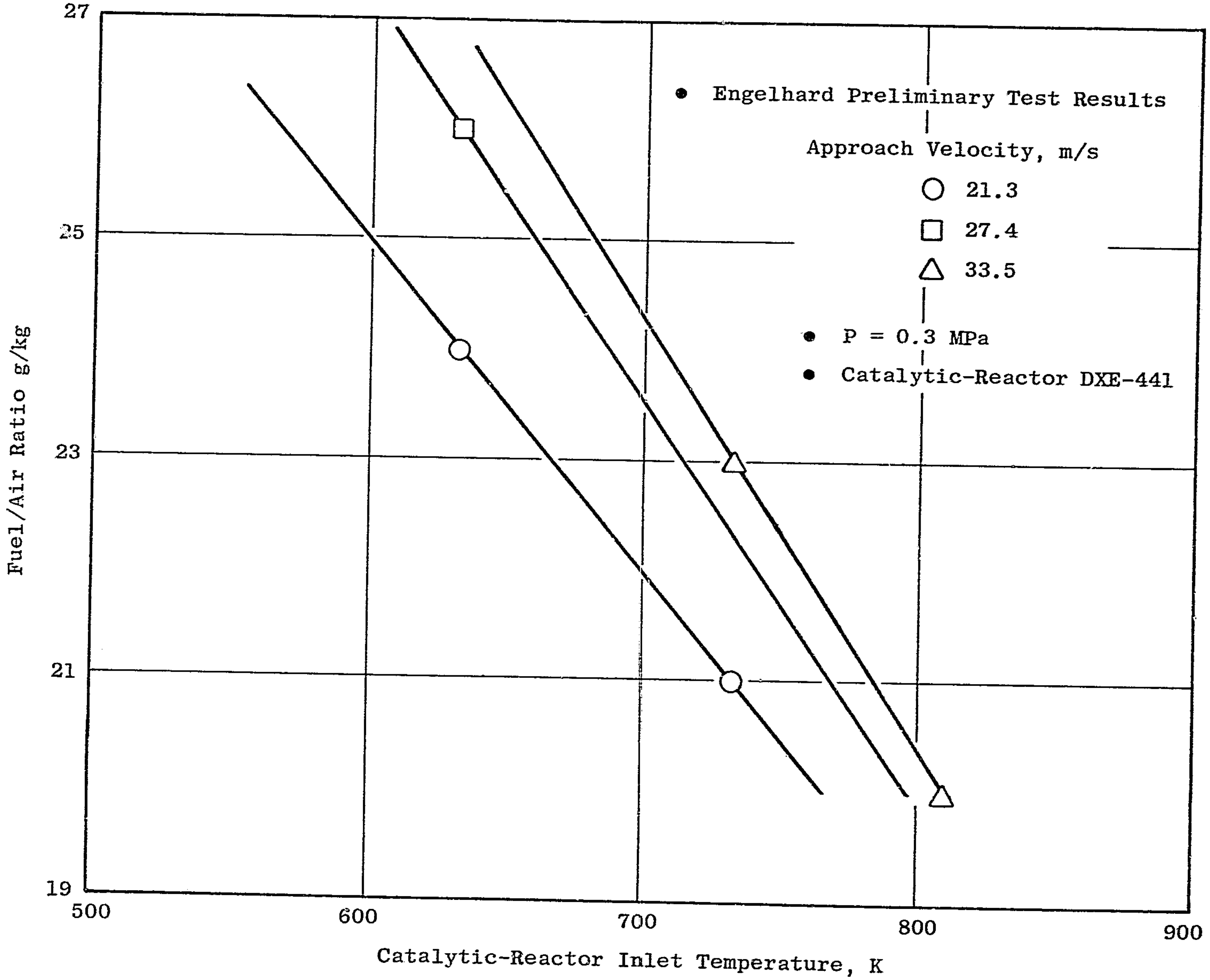
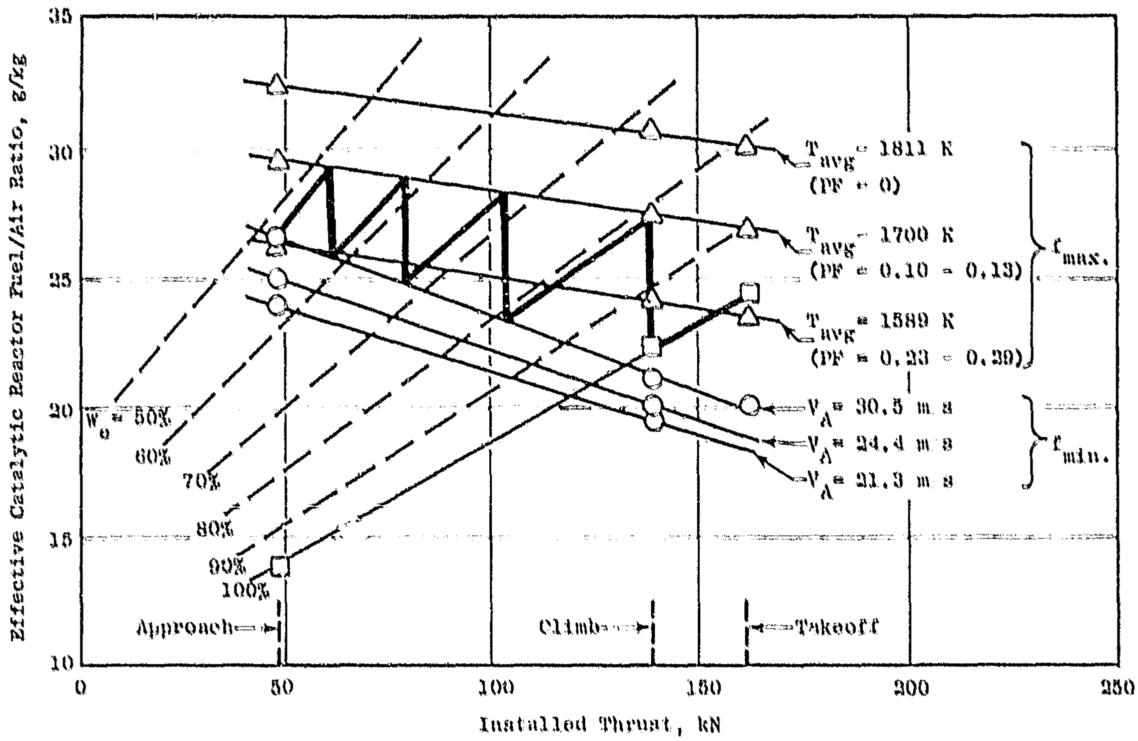


Figure 11. Minimum Fuel-Air Ratio Requirements for a 99 Percent Combustion Efficiency.



$f_{max.}$ = Maximum Fuel/Air Ratio, Limited by Average Reactor Inlet Temperature (T_{avg}) and Pattern Factor (PF)

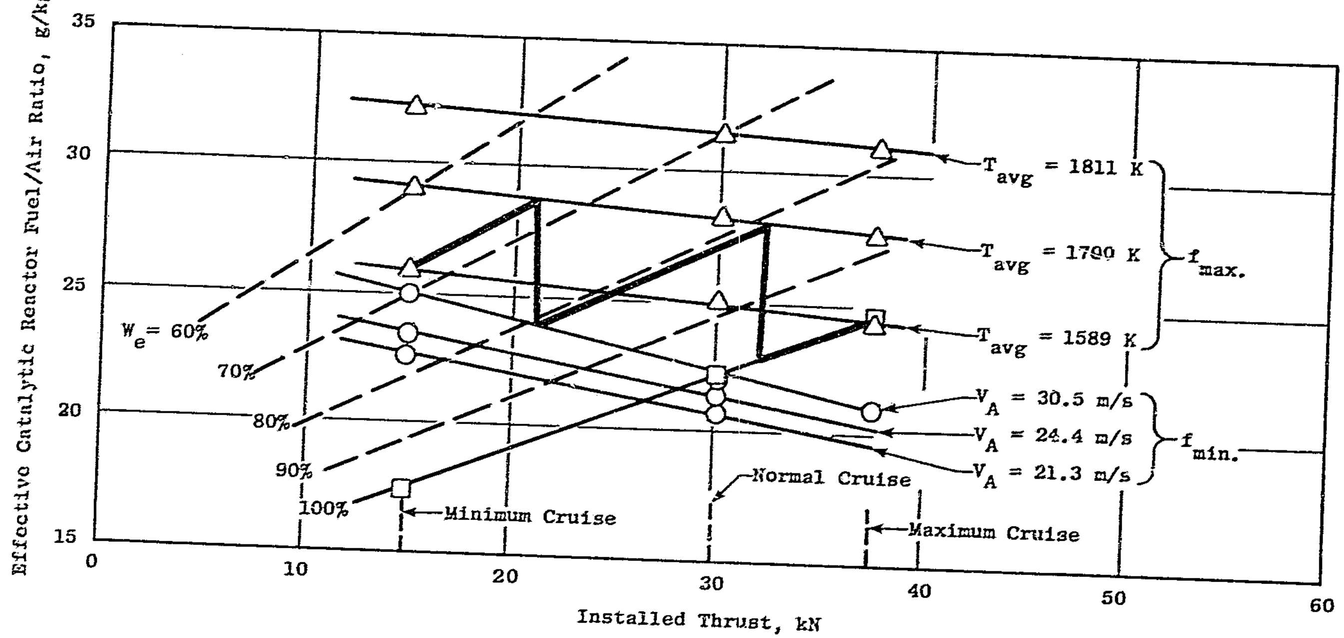
$f_{min.}$ = Minimum Fuel/Air Ratio for 99% Combustion Efficiency, as a Function of Reactor Approach Velocity (V_A)

W_e = Effective Reactor Airflow, percent

$$W_e = \frac{\%W_c \text{ to Reactor}}{\%W_f \text{ to Reactor}} \times \% \text{ Reactor Fuelled}$$

——— Reactor Fuel Staging Schedule

Figure 12. Catalytic Reactor Fuel-Air Ratio Limitations - Landing/Takeoff Cycle.



$f_{max.}$ = Maximum Fuel/Air Ratio, Limited By Average Reactor Inlet Temperature (T_{avg}) and Pattern Factor (PF)

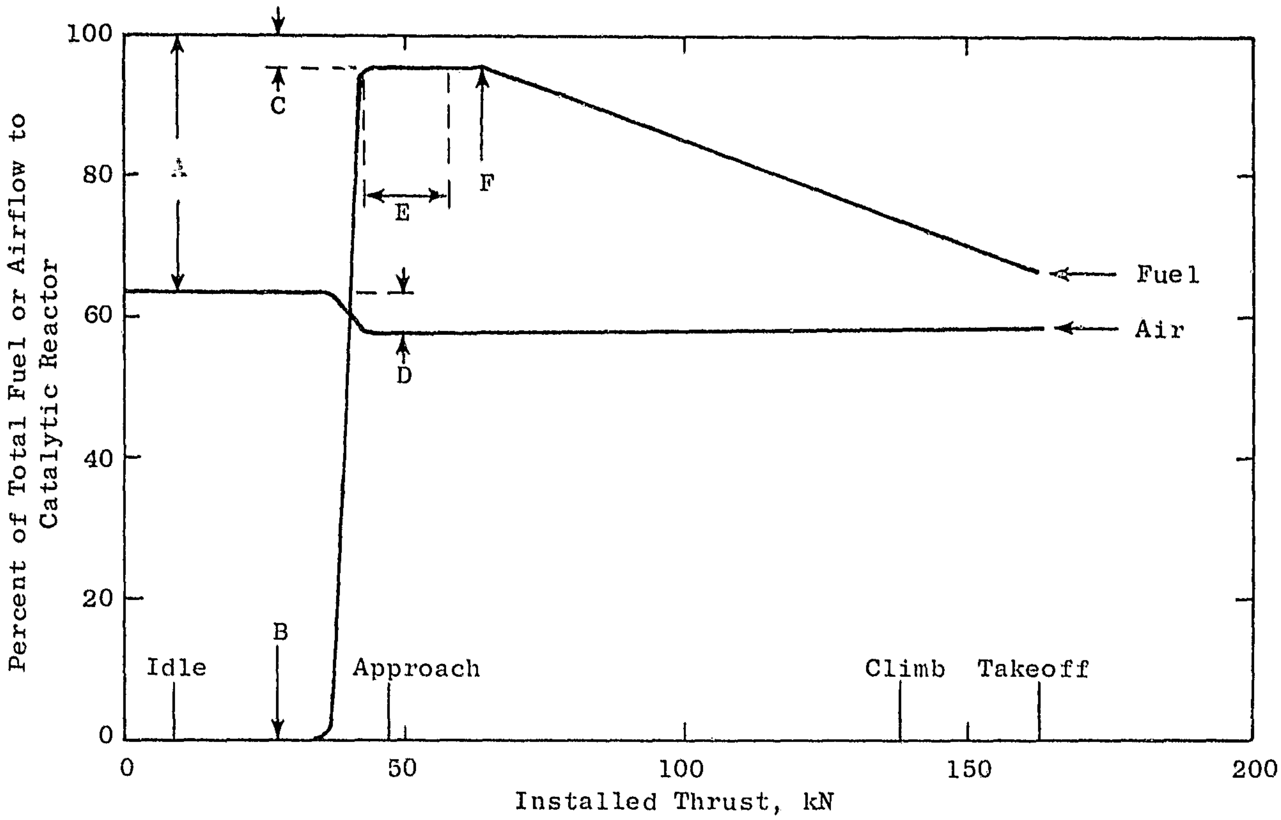
$f_{min.}$ = Minimum Fuel/Air Ratio for 99% Combustion Efficiency, as a Function of Reactor Approach Velocity (V_A)

W_e = Effective Reactor Airflow, percent

$$W_e = \frac{\%W_c \text{ to Reactor}}{\%W_f \text{ to Reactor}} \times \% \text{ Reactor Fuelled}$$

——— Reactor Fuel Staging Schedule

Figure 13. Catalytic Reactor Fuel-Air Ratio Limitations - Cruise Cycle.



A. Pilot Stage Airflow Required for Good Idle Performance.

B. Combustor Inlet Temperature Equals Catalytic-Reactor Ignition Temperature.

C. Minimum Fuel Flow Required to Maintain Stable Combustion Pilot Stage (4 to 40 Injectors Fueled).

D. Airflow Decrease Due to Reactor Temperature Rise.

E. Fuel Staging Required to Maintain Local Reactor Fuel-Air Ratio above Level Required for 99 percent Efficiency.

F. Catalytic-Reactor Fuel Flow Reduced to Stay below Reactor Maximum Use Temperature.

Figure 14. Fuel and Airflow Scheduling Limits (Concept 3).

reactor airflow is decreased due to increased catalytic-reactor flow resistance under combustor conditions. (In variable geometry Concept 5, the variable vanes are opened at this point to increase reactor airflow.) Between the subapproach transition and about 65 percent of rated thrust, pilot-stage fuel flow is held constant, and circumferential fuel staging is utilized to obtain acceptable local fuel-air ratio at the inlet to the catalytic reactor. Above the 65 percent thrust level, the catalytic reactor is uniformly fueled, and fuel which cannot be used because of maximum-use temperature limitations is injected into the pilot stage.

In final flow scheduling for the series-staged designs (Concepts 1 and 2), all combustor airflow enters the catalytic reactor at all operating conditions. This assumes the use of convection cooling of the combustor aft section as discussed in Section 6.1.5. Fuel flow in these combustors is scheduled such that only the pilot stage is fueled up to approximately 25 percent power. Above the 25 percent power level, approximately 95 percent of combustor fuel flow is routed to the catalytic-reactor injectors. It was assumed that the remaining flow would be used to maintain a small pilot flame in the pilot stage. In practice, it might be necessary to completely extinguish the pilot stage in order to avoid autoignition upstream of the catalyst at power levels above 50 percent of rated thrust. In Concept 2, the variable geometry vanes are opened above the 25 percent power level to decrease pressure drop and increase catalytic-reactor fuel-injector chute flow.

In Concept 6, all operations within the landing/takeoff cycle are conducted with the main stage operating. Transition to catalytic operation takes place at cruise conditions.

Pilot-stage fuel and airflow levels at key combustor operating conditions are shown in Table XIII. The flow levels presented in this table, which were used for subsequent emissions and performance analyses, assume the use of convection cooling techniques in the combustor aft section, as discussed in Section 6.1.5. Maximum catalytic-reactor fuel flows were selected to allow a ± 10 percent variation in fuel-air ratio within the fueled sector of the reactor. Under these conditions, the third fuel system and flameholders initially included in Concepts 2 and 5 were not required at steady-state operating conditions.

6.1.2 Combustor Pressure Loss

Models used to estimate combustor pressure loss and flow distribution for each of the six combustor concepts are shown in Figure 15. For the purpose of conceptual design studies, these models were somewhat simplified, and incompressible flow orifice relationships were used to estimate pressure drop across the pilot domes and liners. Variable geometry vanes in these analyses were modeled as variable area orifices. Because of the relatively low pressure losses involved, the incompressible-flow assumption results in relatively small error.

Diffuser pressure loss was estimated using the static pressure recovery curves of Figure 16. All of the concepts used step diffusers with identical passage design parameters which provide an estimated prediffuser loss of 0.7 to 1.0 percent. An additional dumping loss of about 1.3 percent due to flow separation (with no static pressure recovery) at the diffuser step was added for

Table XIII. Pilot-Stage Fuel and Airflow Schedules.

Concept	Percent of Total Combustor Airflow to Pilot Stage				
	Idle	Approach	Climb	Takeoff	Normal Cruise
1	49.5	49.5	49.5	49.5	49.5
2	41.8	11.1	11.1	11.1	11.1
3	37.3	42.4	41.9	41.4	42.5
4	39.0	44.1	43.6	43.1	44.0
5	38.4	20.4	21.0	20.8	21.3
6*	92	92	92	92	10

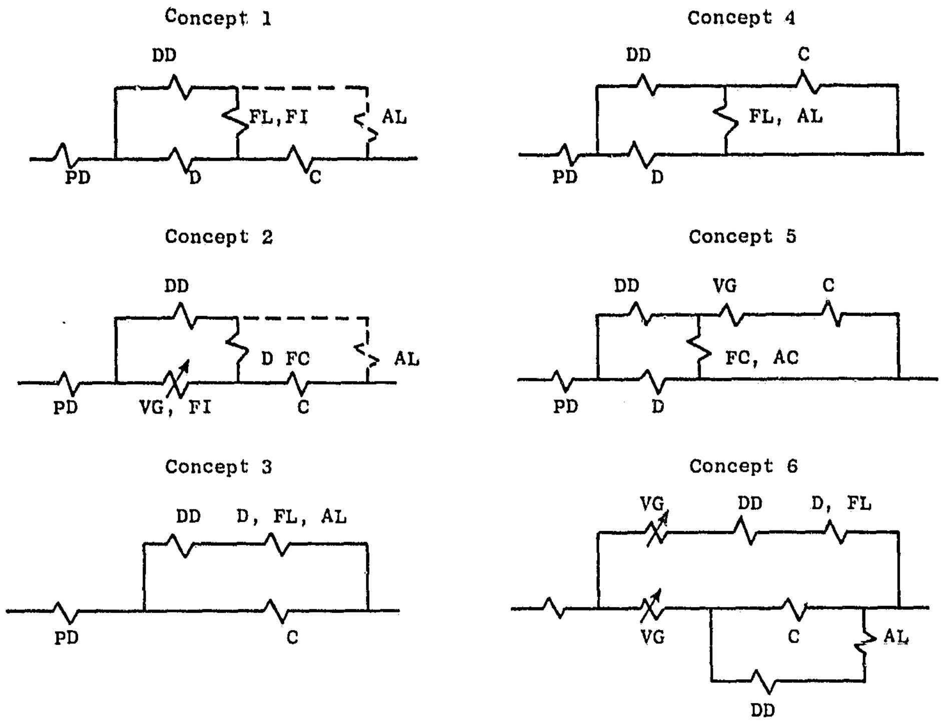
Concept	Percent of Total Combustor Fuel Flow to Pilot Stage				
	Idle	Approach	Climb	Takeoff	Normal Cruise
1	100	7.2[b]	3.8[b]	3.5[b]	3.9[b]
2	100	1.1[a]	0.6[a]	0.5[a]	0.5[a]
3	100	4.8[a]	27.3	34.2	24.8
4	100	8.1[a]	29.4	35.8	27.0
5	100	3.8[b]	2.1[b]	10.8[c]	2.1[b]
6*	100	100	100	100	0.2[a]

*Indicates main and pilot-stage fuel flow.

a - 10 percent sector fueled.

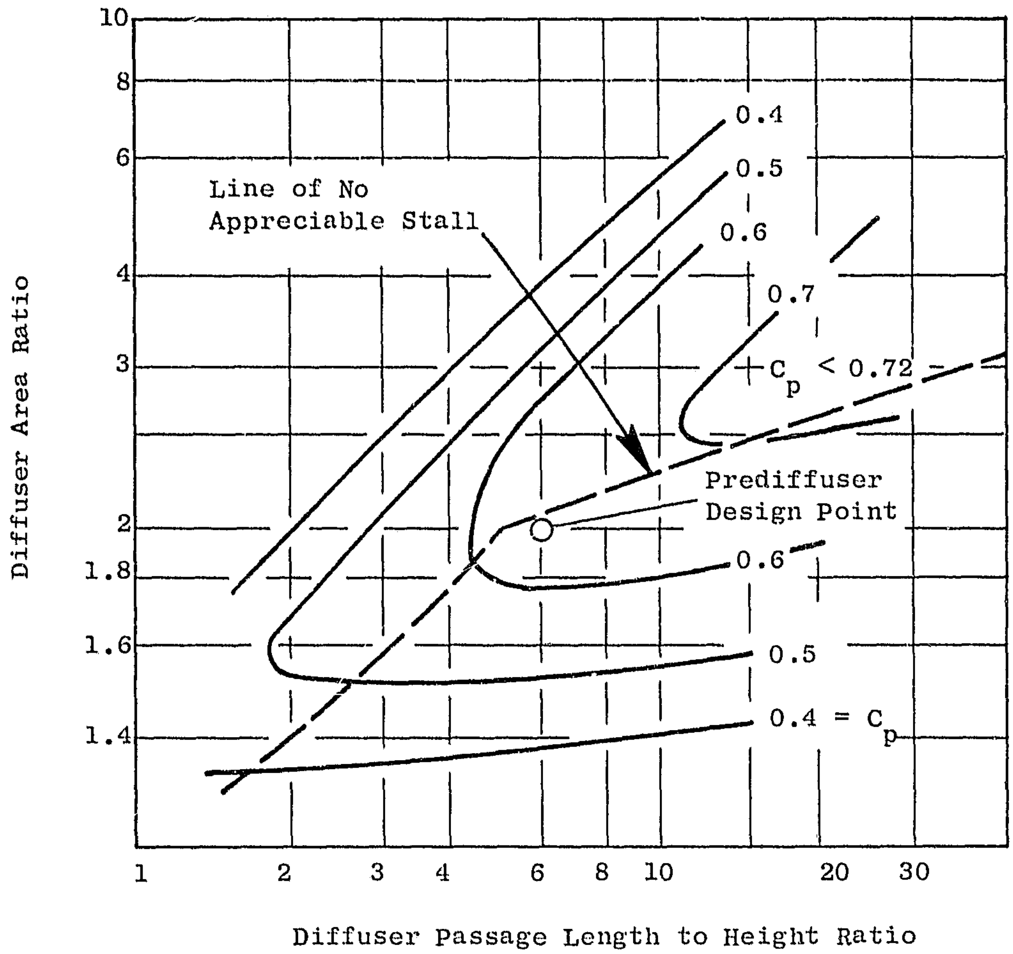
b - 17 percent sector fueled.

c - 50 percent sector fueled.



Symbol	Component	Flow/Pressure Loss Relationship
PD	Prediffuser	$\Delta P/P$ = 0.07 percent
DD	Dump Diffuser (without cowl)	$\Delta P/P$ = 1.3 percent
D	Pilot Dome	
FL	Forward Liners (pilot cooling and dilution)	$\Delta P/P = \dfrac{W^2 \, RT_3}{2A_e^2 \, P_3^2}$
AL	Aft Liners	
C	Catalytic-Reactor	See Figure 4.2-2
VG	Variable Geometry	$\Delta P/P = \dfrac{W^2 \, RT_3}{2A_e^2 \, P_3^2}$ (A_e Variable)
FI	Fuel Injection Slot or Chute	$\dfrac{\Delta P}{P} = \dfrac{W^2 \, RT_3}{2A_e \, P_3^2}$

Figure 15. Combustor Pressure Loss and Flow Distribution Models.



- Prediffuser Design Point - All Concepts

Diffuser Area Raio	-2
Passage Length to Height Ratio	-6
Static Pressure Rise Coefficient, C_p	-0.63
Prediffuser Pressure Loss	-0.7 Percent

- Maximum Dump Diffuser Loss -1.4 Percent

Figure 16. Two-Dimensional Diffuser Pressure Loss (Reference 32).

airflow which was not directed into a cowling. Diffuser pressure loss (as a percentage of compressor discharge pressure) was taken to be constant over the engine operating range since compressor exit Mach number is approximately constant.

Catalytic-reactor pressure loss was calculated with the relationships presented in Section 4.2. In the case of the series combustor designs, where catalytic-reactor inlet temperature is increased by preburning, catalytic-reactor pressure loss was calculated using the isothermal pressure loss relationship.

Combustor system pressure drops over the engine operating range for each of the catalytic combustor concepts are indicated in Table XIV. These values are consistent with the air and fuel flow splits given in Table XIII. Pressure loss for all concepts meets the program goal of 5 percent at the approach power level and above. At the idle conditions, pressure loss is increased with variable geometry Concepts 2 and 5.

Results of a cycle analysis performed to evaluate the effect of increased pressure loss at idle conditions are shown in Table XV. Increased idle pressure drop results in a very slight decrease in idle emissions (see Section 6.1) as a result of increased combustor inlet temperature and pressure. However, specific fuel consumption is increased by 3.8 percent for the 10 percent drop and by 8.1 percent for the 15 percent pressure drop. These increases correspond to increases of 0.2 and 0.4 percent in total fuel requirements for a 2-hour flight. Increased pressure drop also decreases compressor stall margin for the reference engine. Total idle stall margin is reduced by about one-fourth of the nominal design value when pressure drop is increased to 10 percent, and by up to one-half at 15 percent. Both of these factors detract from overall engine performance, but engine operating characteristics are expected to be acceptable.

6.1.3 Fuel-Air Carburetion

Criteria of interest in the analysis of the premixing-prevaporizing fuel-air carburetion systems used in the catalytic-combustor conceptual designs were as follows:

Autoignition

Based on the discussion presented in Section 4.3, a maximum bulk residence time of 2 ms is allowable for operation at hot-day takeoff conditions for Concepts 3 through 5. For Concept 6, which does not employ the catalyst stage above the maximum cruise condition, 10 ms residence time was allowed. These criteria provide a 55 to 60 percent safety margin for experimental, variation in stream velocity, and additional residence time in the fuel injector wake. Based on the relationship between blockage width and autoignition residence time reported in Reference 34, if the velocity is otherwise uniform, this safety margin limits the maximum physical blockage width within the fuel injection system to only 0.7 cm in order to avoid flashback at the hot-day takeoff condition.

Table XIV. Combustion System Pressure Loss Estimates.

Concept	Combustion System Pressure Drop, Percent				
	Idle	Approach	Climb	Takeoff	Normal Cruise
1	6.0	5.0	5.0	5.0	5.0
2	10.0	5.0	5.0	5.0	5.0
3	4.1	5.2	4.9	4.8	5.0
4	4.1	5.2	4.9	4.8	5.0
5	14.1	4.9	4.9	4.8	5.0
6	5.0	5.2	5.0	5.0	5.0

Table XV. Effect of Combustor Pressure Drop on Reference Engine Parameters At Idle.

	Standard-Day Sea Level Static Operating Conditions							
F_n, Installed Net Thrust, percent	4.0	4.0	4.0	4.0	6.0	6.0	6.0	6.0
$\Delta P_T/P_3$, Combustor Pressure Drop, percent	5.0	10.0	15.0	20.0	5.0	10.0	15.0	20.0
W_3, Compressor Exit Airflow, kg/s	8.79	8.58	8.28	7.80	10.88	10.65	10.41	9.72
W_{36}, Combustor Airflow, kg/s	7.70	7.52	7.25	6.83	9.52	9.33	9.13	8.52
P_{T3}, Compressor Exit Total Pressure, kPa	321.3	336.7	353.2	369.8	401.7	421.5	443.7	462.3
T_{T3}, Compressor Exit Total Temperature, K	448.3	454.7	463.8	480.3	485.1	491.6	499.0	522.7
T_{T4}, Combustor Exit Total Temperature, K	898.6	935.1	989.8	1091.1	940.9	971.4	1006.6	1120.6
W_f, Fuel Flow, 3/5	90.0	94.4	100.8	112.4	113.9	118.2	123.1	138.5
f_{36}, Combustor Fuel-Air Ratio, g/kg	11.7	12.6	13.9	16.5	12.0	12.7	13.5	16.3
M_3, Compressor Exit Mach No. (1)	0.280	0.262	0.242	0.218	2.290	0.270	0.252	0.228

The above criteria were met in parallel staged Concepts 3 through 6. However, in both of the series staged concepts, the effective fuel-air residence time will be strongly affected by details of mixing between the free stream and flow from the fuel injection slots. It is expected that autoignition could be avoided in Concept 1 because of the increased pilot stage flow velocity in the fuel-air mixing region. A similar reduced-area mixing section would probably be required to avoid autoignition in Concept 2.

Mixture Uniformity

As discussed in Section 6.1.1, the catalytic-reactor inlet mixture must fall within a specified range of fuel-air ratios in order to stay within maximum use temperature and efficiency limits. At the approach power level, for example, if the catalyst inlet velocity is 30 m/s, fuel-air ratio must be between about 26 and 33 g/kg based on the approximate limits shown in Figure 12. If the average fuel-air ratio is 29.5 g/kg, the inlet mixture must be uniform within $\pm$ 12 percent. The combustor could be operated within local fuel-air ratios as low as about 20 g/kg with increased CO and HC levels, but local deviation above about 33 g/kg would cause catalytic-reactor damage. In order to take full advantage of the catalytic-reactor 62 emissions reduction potential, a goal of $\pm$ 10 percent maximum spatial variation in inlet fuel-air ratio was established. This goal is consistent with the fuel and airflow schedules specified in Section 6.1.1

Fuel uniformity at the catalytic-reactor inlet face of the parallel staged catalytic combustor concepts with multiple point injectors is determined by the initial fuel distribution and drop size at the fuel injection plane and the spreading downstream of this plane due to turbulent diffusion. In the series staged designs, fuel-air mixture uniformity also depends on mixing between the fuel-air mixture exiting the fuel injection chute and the internal combustor flow. For the conceptual design analyses, the initial fuel distribution was modeled as an array of point sources. This model is conservative, for increased spreading due to initial fuel penetration is not included. At a distance downstream of the fuel injection plane, the fuel-air ratio profile due to a single point source has been correlated in References 35 through 37 by a function of the form

$$f \propto e^{-R^2/m},$$

where R is the radial distance from the point source axis and m is defined as the spreading index. The general relationship between spreading index, injector spacing, and fuel-air mixture uniformity for a square array of point source injectors is shown in Figure 17. As indicated, it is necessary that the ratio of the square of injector spacing to the spreading index be less than 2.6 to obtain the required fuel uniformity (10 percent variation).

The spreading index has been correlated to experimental data as a function of orifice diameter, fuel and air velocity, air density, and axial distance downstream of the fuel injection plane in References 35 and 36. Analytical correlations for point source spreading index as a function of turbulence level (eddy diffusivity), stream velocity, droplet size, and axial distance from the point source have been derived in Reference 37. The effects of turbulence level and droplet size on spreading index are shown in Figure 18. Also shown on this

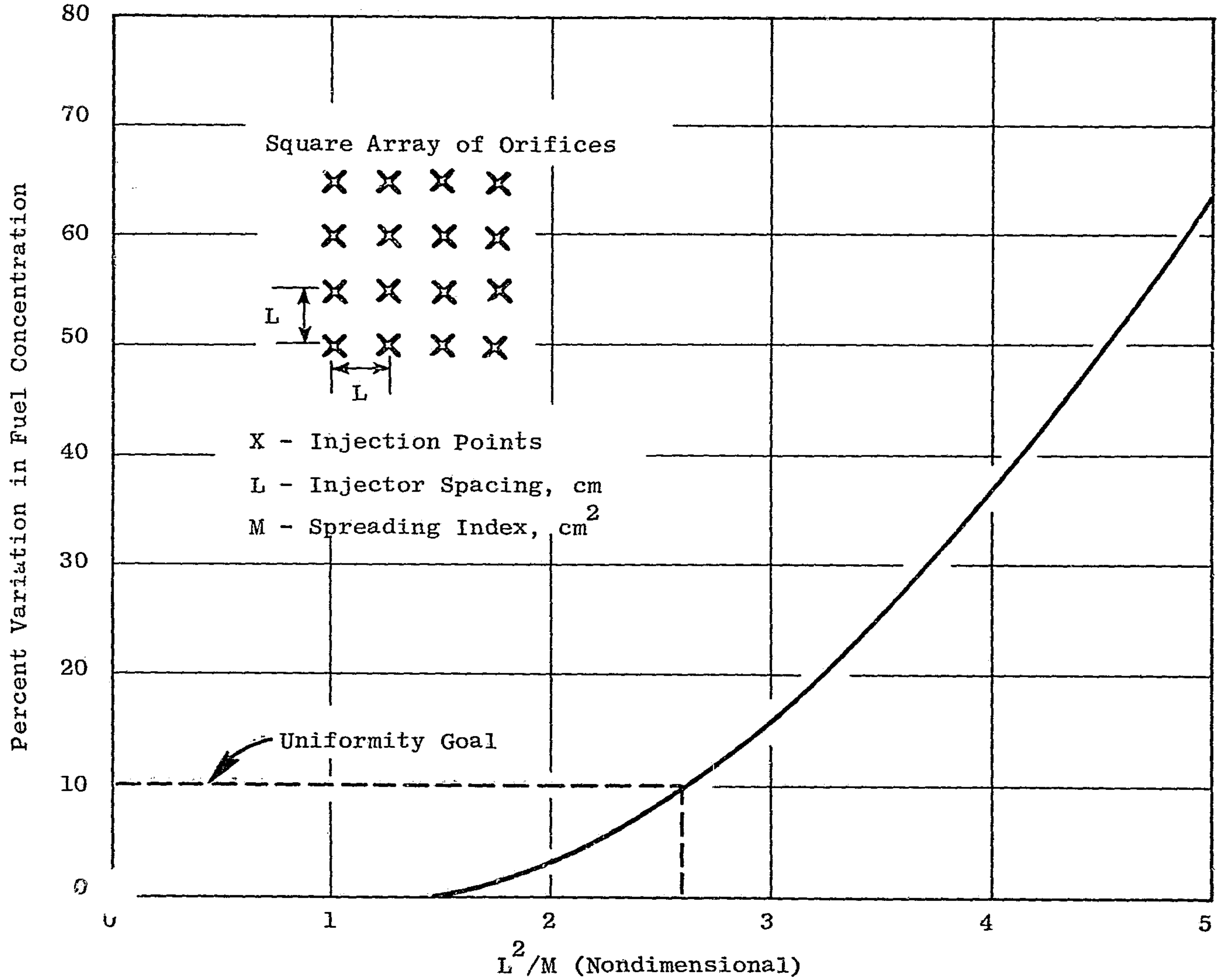


Figure 17. Effect of Spreading Index and Injection Point Separation on Fuel Concentration Uniformity.

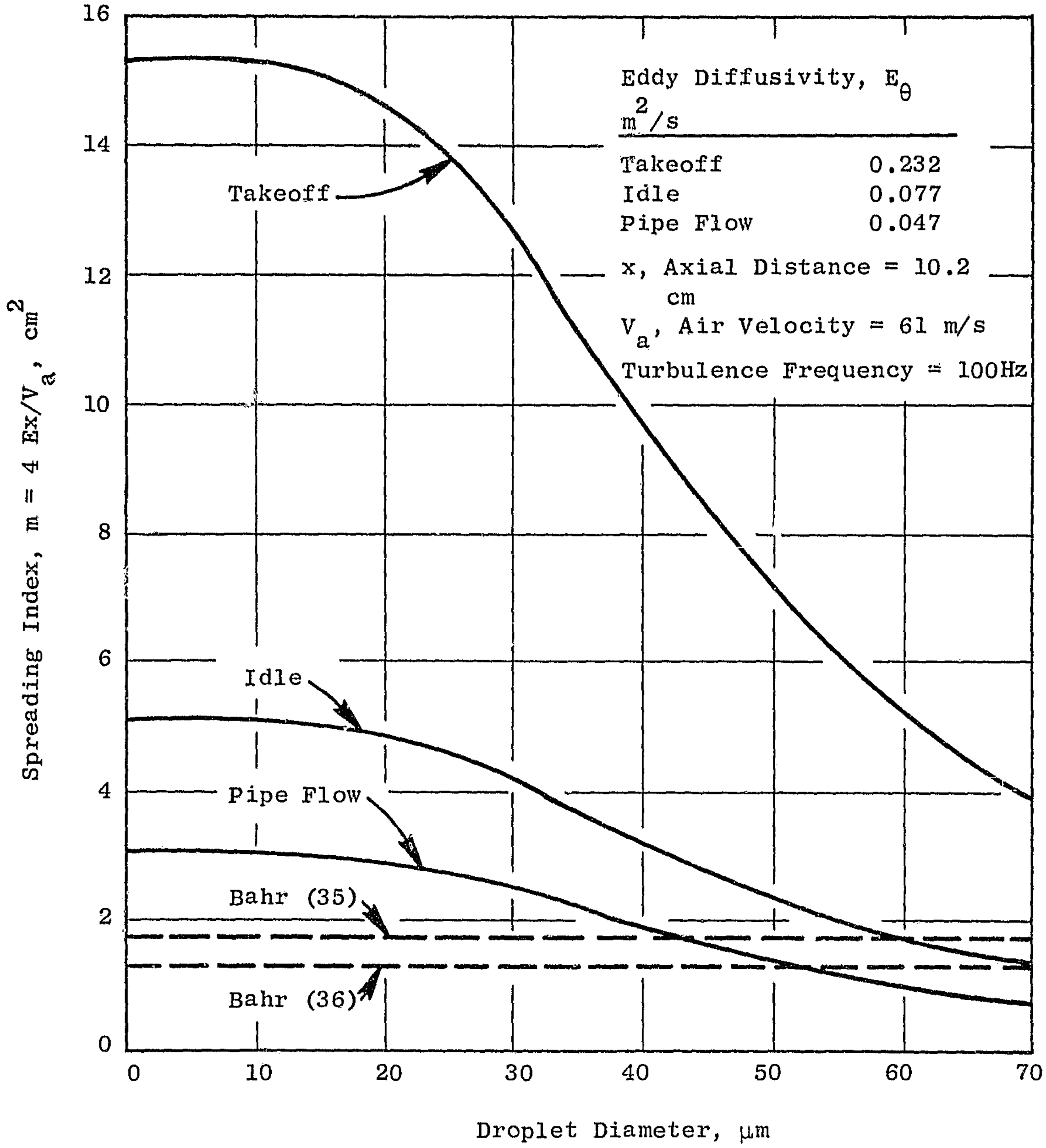


Figure 18. Effect of Eddy Diffusivity and Droplet Diameter on Fuel Spreading Index (Reference 37).

figure are levels calculated from the data correlations of References 35 and 36. Engine eddy diffusivity levels in this figure are conservative estimates based on ECCP Turbulence Measurements Addendum (Reference 38) data, which are representative of levels obtained within the combustor inlet diffuser.

In Figure 18, turbulence intensity was taken to be 5 percent at idle, increasing to 15 percent at takeoff, and turbulence scale was taken to be 2.54 cm (the approximate height of the fuel-air mixing ducts). Pipe flow diffusivity was based on measurements reported in Reference 37. As indicated in this figure, spreading index levels predicted by the analytical correlation agree quite well with the experimental correlations, assuming pipe-flow turbulence levels and a droplet size of approximately 50 μm.

As indicated in Figure 18, spreading index within the engine is expected to be considerably higher than predicted by rig tests, particularly if the flow is routed directly from the inlet diffuser to the fuel injector duct as in Concepts 2, 3, and 6. However, the diffuser turbulence can be expected to decay rapidly, particularly in configurations in which the flow is first dumped into the combustor housing, then reaccelerated into the mixing section as in Concepts 1, 4, and 5.

Based on the above considerations, fuel spreading depends strongly on fuel injector spacing and spreading index. The specific criterion for the conceptual combustor design was that the ratio of the square of maximum injector spacing to the spreading index be less than 2.6, where the spreading index is based on pipe flow levels for Concepts 1, 4, and 5, and on idle turbulence levels for Concepts 2, 3, and 6. In both cases, the assumed droplet diameter was 30 μm.

The above spreading analyses are idealized due to the fact that it is assumed that fuel flow will be distributed perfectly uniformly among the point sources. In order to approach this condition with actual hardware, it is necessary to ensure that some minimum pressure drop is available to meter the flow and that this pressure drop is large compared to internal flow losses. For preliminary design studies, a minimum fuel injection orifice pressure drop value of 0.1 MPa was set as a design criterion.

Fuel Evaporation

Based on consultation with Engelhard Industries personnel, catalyst operation is feasible with a relatively large proportion of the fuel flow unevaporated at the catalytic-reactor inlet. During the steady-state operation, fuel droplets approaching the hot catalyst surface evaporate very rapidly and are unlikely to damage the catalyst. Any fuel droplets entering the catalyst could be expected to result in locally fuel-rich regions passing through the catalyst channels, which could lead to increased NO_x production. Consequently, at cruise conditions, it is thought to be desirable to have complete evaporation in order to obtain the full emissions benefits of catalytic combustion.

Fuel evaporation over the catalytic-reactor operating range was predicted using several correlations from the literature. The fuel injector configuration to which these correlations apply, and evaporation predictions based on these correlations, are presented in Table XVI. As indicated in this table, all correlations indicated that fuel evaporation will be sufficient for catalytic-reactor operation at all inlet conditions. Of the methods shown, the most applicable to the catalytic combustor conceptual design is the "Heatup" computer program (Reference 28). This program was used to determine the effect of variation in airstream velocity, fuel temperature, orifice diameter, and airstream pressure at the nominal approach operating conditions (Figures 19 and 20). Based on these studies, fuel evaporation at the approach condition will be close to 70 percent in all concepts. If development tests indicated that higher evaporation levels were required, evaporation could be controlled by appropriate selection of orifice diameter or by preheating the fuel.

Pressure Drop

Total allowable fuel-injection system plus catalytic-reactor pressure drop varies from 3 to 4 percent in the six combustor concepts. Any fuel injection system drag pressure loss requires that catalyst approach velocity be reduced to reduce catalyst pressure loss. This, in turn, requires either a reduction in fuel injection system velocity or increased diffusion of the fuel-air mixture upstream of the catalyst inlet, both of which increase the difficulty of obtaining a uniform fuel distribution without autoignition. Therefore, the design goal was to obtain negligible fuel injection pressure loss unless significant improvements in fuel spreading were obtained.

Velocity Profiles

Nonuniform air velocity profiles within the fuel injection system and at the catalyst inlet can lead to (1) autoignition in low velocity regions and (2) reduction in efficiency due to increased velocity within a portion of the catalytic reactor channels. The second of these problems is self-correcting to some extent because the flow will tend to be redistributed by the resistance of the channels. For example, the average velocity head in the fuel injection section represents only about 20 percent of the total catalyst pressure loss. Thus, doubling the local velocity head (41.4 percent increase in velocity) would only result in an increase of about 10 percent in local channel velocity. On the other hand, the 55 to 60 percent safety margin in autoignition criteria is eliminated if local velocity is more than 35 percent below the average, even if no wakes or other flow disturbances are present. In order to retain some safety margin in autoignition, a design goal of ± 20 percent variation in stream velocity was selected.

Durability

In order to provide good durability and reliability with continuous use, it is necessary to minimize the effects of fuel decomposition within the fuel injection system. Therefore, in analyzing the fuel injection systems, studies were performed to determine insulation requirements to maintain fuel temperature below 420 K prior to injection. In all systems, a minimum allowable fuel injection orifice diameter of 0.4 mm was selected to prevent plugging. With the further requirement for at least 0.1 MPa fuel injection pressure drop at the minimum cruise

Table XVI. Comparison of Fuel Evaporation Predictions at Design Conditions.

Fuel Injection Conditions:

- Stream Velocity - 61 m/s
- Orifice Diameter - 0.635 mm
- Maximum Fuel Injection Pressure Drop - 4.5 MPa
- Evaporation Length - 10.2 cm

Reference		Predicted Fuel Evaporation, Percent: Approach	Climb	Takeoff	Min. Cruise	Normal Cruise	Max. Cruise
"Heatup" (28)	JP-5 Cross Stream Injection	67	100	100	86	98	100
Tacina [a] (41)	Jet-A, DF-2 Multiple Conical Tube Injector	85	100	100	84	99	100
Foster and Ingebo (42)	JP-5 Contra-Stream Injection	85	100	100	59	73	98
Bahr (36)	Isooctane - Contra-Stream Injection	40	51	55	51	53	58
	- without Pressure Factor[b]	93	96	99	92	95	97
Rao and Lefebvre (43)	Kerosene-Airblast Atomizer (Flow Number = .0456 ℓ hr.$^{-1}$ Pa$^{-1/2}$)	89	97	98	86	92	95

[a] Stream velocity corrected for tube blockage.

[b] Tests conducted near atmospheric pressure. Original Correlation: $\frac{N}{100 - N} \alpha P^{-1.2}$

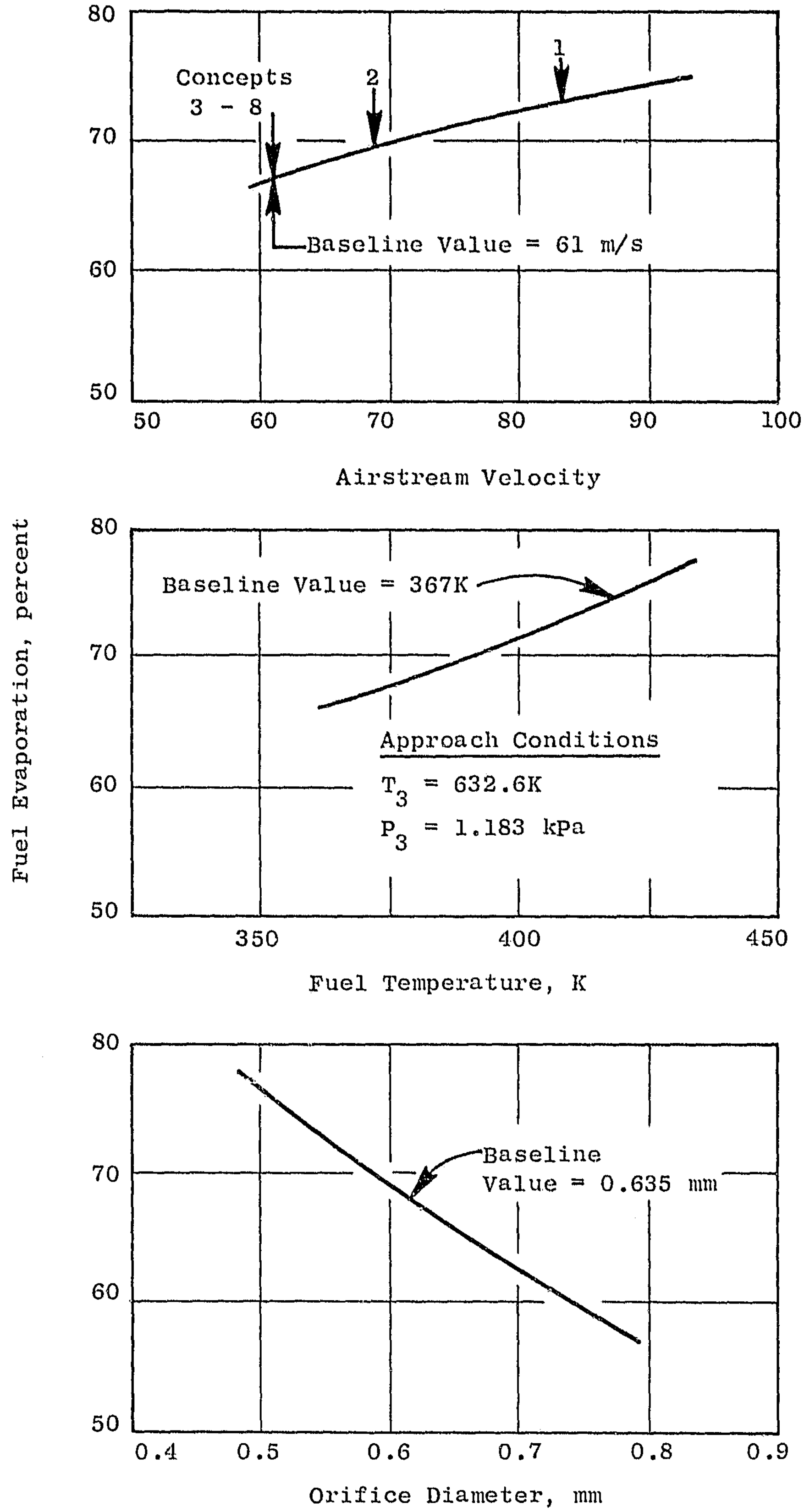


Figure 19. Effect of Variation in Operating Conditions on Fuel Evaporation (''HEATUP'' Computer Program, Reference 28).

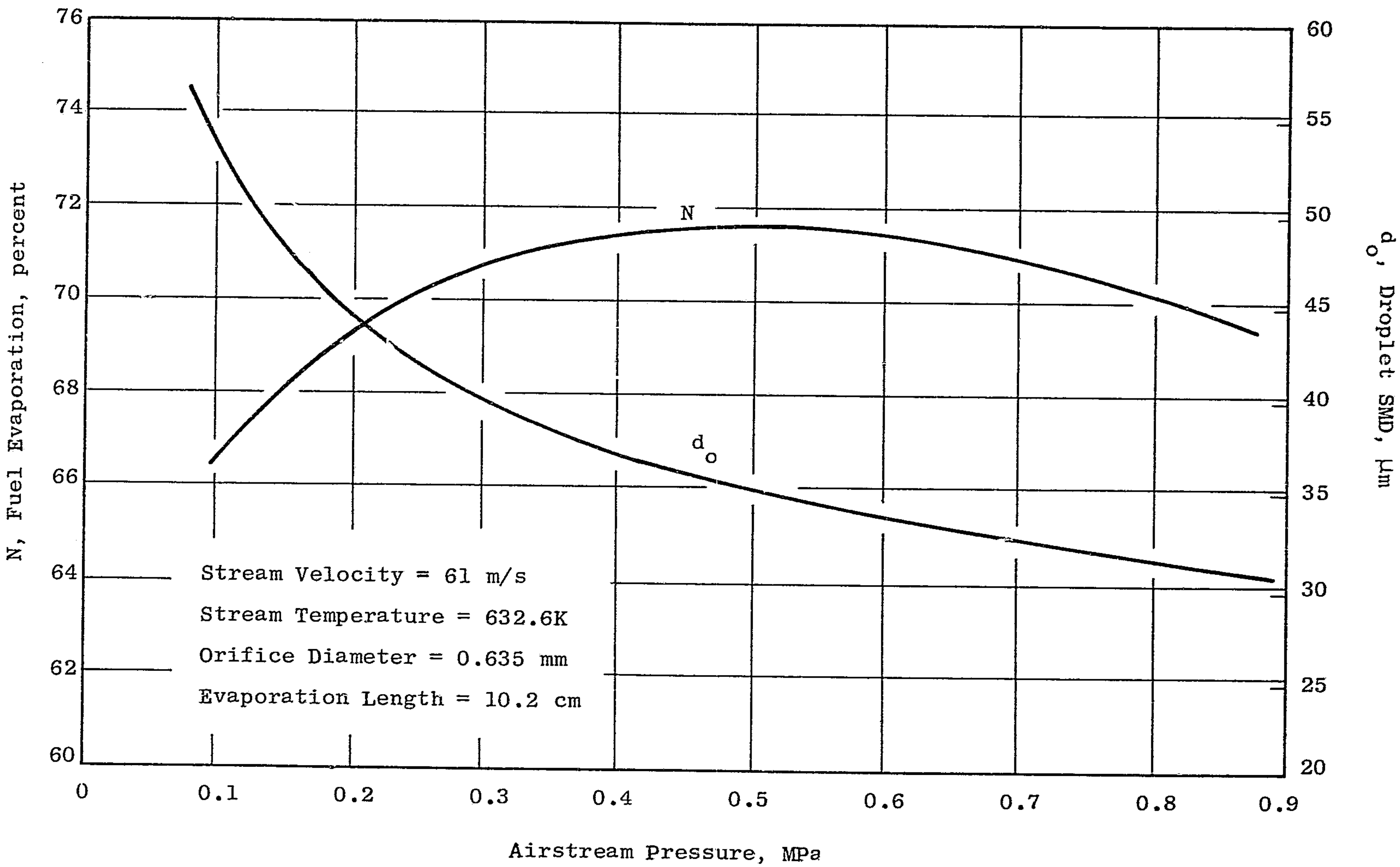


Figure 20. Effect of Pressure o... Evaporation.

operating condition, the total number of fuel injection orifices is limited to about 270 if all orifices are to be fueled at minimum cruise.

During conceptual design analyses, several fuel injection systems which had recently been developed in small-scale experimental programs (References 29 through 31, and 44) were considered for application to the ALECC designs. The injection systems considered were as follows:

1) Sonecore nozzle (with and without swirl).
2) Splash groove injector (with and without swirl).
3) Simplex injector (with and without swirl).
4) Multiple jet injector (cross-stream and contra-stream).
5) Pressure (wall) injection (with and without swirl).
6) Air-blash blade injector.
7) Multiple conical tube injector.

Several of these injection systems, including the Sonecore nozzle, splash groove, pressure (wall) injectors, and simplex nozzle required swirlers to obtain good mixture uniformity. The use of swirlers in the designs was not considered practical because of the increased risk of autoignition, the difficulty of adapting swirlers to the annular fuel injection systems, and the increased pressure drop across the swirlers. The conical tube injector was also considered to have a high risk of autoignition because of the diffusion immediately downstream of the fuel injection tubes (which would tend to extend the tube wakes), and because of the step expansion at the tube exit. This system also has a relatively high pressure loss. Little data were available on the air-blast blade, but autoignition was observed with this system, apparently as a result of increased residence time in the separated flow region at the base of the blades.

Of the carburetion systems considered, the multiple-jet cross-stream injector appeared to have the highest probability of meeting all design criteria.

The fuel-air carburetion systems used in the initial designs of Concepts 1, 2, 3, 5, and 6 are, in principle, multiple-jet cross-stream injectors with the following modifications:

- The fuel injectors are streamlined to minimize wakes.
- The fuel injectors are supported upstream of the fuel injection point. Direct contact between the wall and injector is eliminated at the fuel injection point to avoid autoignition in the separated flow region (as in the air-blast blade design). An exception was made in the case of Concept 6, which is supported at the fuel injection point. This was done to simplify injector installation and is allowable because of the increased autoignition delay times with this concept, which is not operated in the catalytic mode at the takeoff power level.
- As in the multiple conical tube injector, airstream velocity is increased above the catalytic-reactor inlet level at the fuel injection point.

However, rather than diffusing in the wake of the fuel injectors, a constant area duct is maintained for an appreciable distance downstream of the injectors. In the series designs (Concepts 1 and 2), freestream diffusion takes place between the fuel injection slot exit and the catalyst. In the parallel designs, the walls of the duct upstream of the catalyst are contoured to simulate the streamlines which would be observed in unconfined flow approaching the catalytic-reactor.

Based on the results of conceptual design analyses, fuel-air carburetion presents a major development challenge in the design of a practical catalytic combustor. Of the six concepts studied, only Concept 3 met all design criteria, and even in this concept the safety margin was very narrow. As drawn, none of the other concepts met the fuel spreading criterion. However, modifications were identified to meet this criterion in Concepts 4-6. Required modifications were as follows:

Concept 4 - Replace pressure atomizing fuel injection system with multiple source injector.

Concept 5 - Increase number of injectors from 30 to 120.

Concept 6 - Increase number of injectors from 40 to 80.

In the series designs, fuel-air mixing and autoignition analyses are complicated by the requirement for mixing between the pilot stage and fuel injection chute flows. It is anticipated that very extensive development effort would be required to obtain acceptable performance with these systems.

In development of any of the systems studies, it may be necessary to use techniques such as axial staging (long mixing length for low power operation, short mixing length for high power operation) or fuel prevaporization to obtain adequate carburetion. However, the use of either of these techniques would result in length, weight, and complexity penalties. Therefore, in the Phase I studies, it was assumed that in initial development efforts a single-stage, liquid-fuel injection system would be investigated.

6.1.4 Emissions

Overall combustor gaseous emissions for each of the combustor concepts were predicted by individually estimating emissions indices for the conventional pilot stage and the catalytic-reactor, then fuel-flow weighting these levels to obtain an overall emissions estimate.

The form and constants used to predict pilot stage gaseous emissions are shown in Table XVII and Figure 21. These correlations were obtained from ECCP Phase I results (Reference 45) and proprietary General Electric MS 10,000 component test data. The correlation form has been used to correlate emissions data for several different combustors. The pilot stage correlations for CO, HC and NO_x include corrections for inlet total temperature (T_3), pressure (P_3), and pilot dome flow (W_d), which is indicative of pilot burner residence time. The effect of variation in residence time due to changes in reference velocity with changing operating conditions is implicitly included in the temperature and pressure

Table XVII. Pilot-Stage Emissions Estimates.

Basis	Experimental Clean Combustor Pilot-Stage Emissions Data			
Form	$EI = EI_B \left(\frac{P_3}{P_{3_B}}\right)^{\alpha} Exp\left(\frac{T_3 - T_{3_B}}{\tau}\right)\left(\frac{\omega_d}{\omega_{dB}}\right)^{\beta} K_f$			
Constants		CO	HC	NO_x
Pressure Exponent	α	-1.0	-2.0	0.37
Temperature Constant	τ, K	-140	-55	190
Dome Flow Exponent	β	1.0	1.0	-1.0
Fuel-Air Ratio Correction Factor	K_f	1.0	1.0	See Figure 21
Reference Emission Index	EI_B, g/kg	25	1	20
Reference Inlet Temperature	T_{3_B}, K	429	429	733
Reference Inlet Pressure	P_{3_B}, MPa	0.296	0.296	1.16
Reference Fuel-Air Ratio	f_{P_B}, g/kg	11.9	11.9	11.9
Reference Pilot-Stage Dome Flow	ω_{d_B}, % W_{36}	17.4	17.4	17.4
Total Emission Index	$EI_{comb} = \frac{W_{f_{pilot}}}{W_{f_{comb}}} \times EI_{pilot} + \frac{W_{f_{catalyst}}}{W_{f_{comb}}} \times EI_{catalyst}$ Combustor Emissions = Pilot-Stage Contribution + Catalyst Stage Contribution			

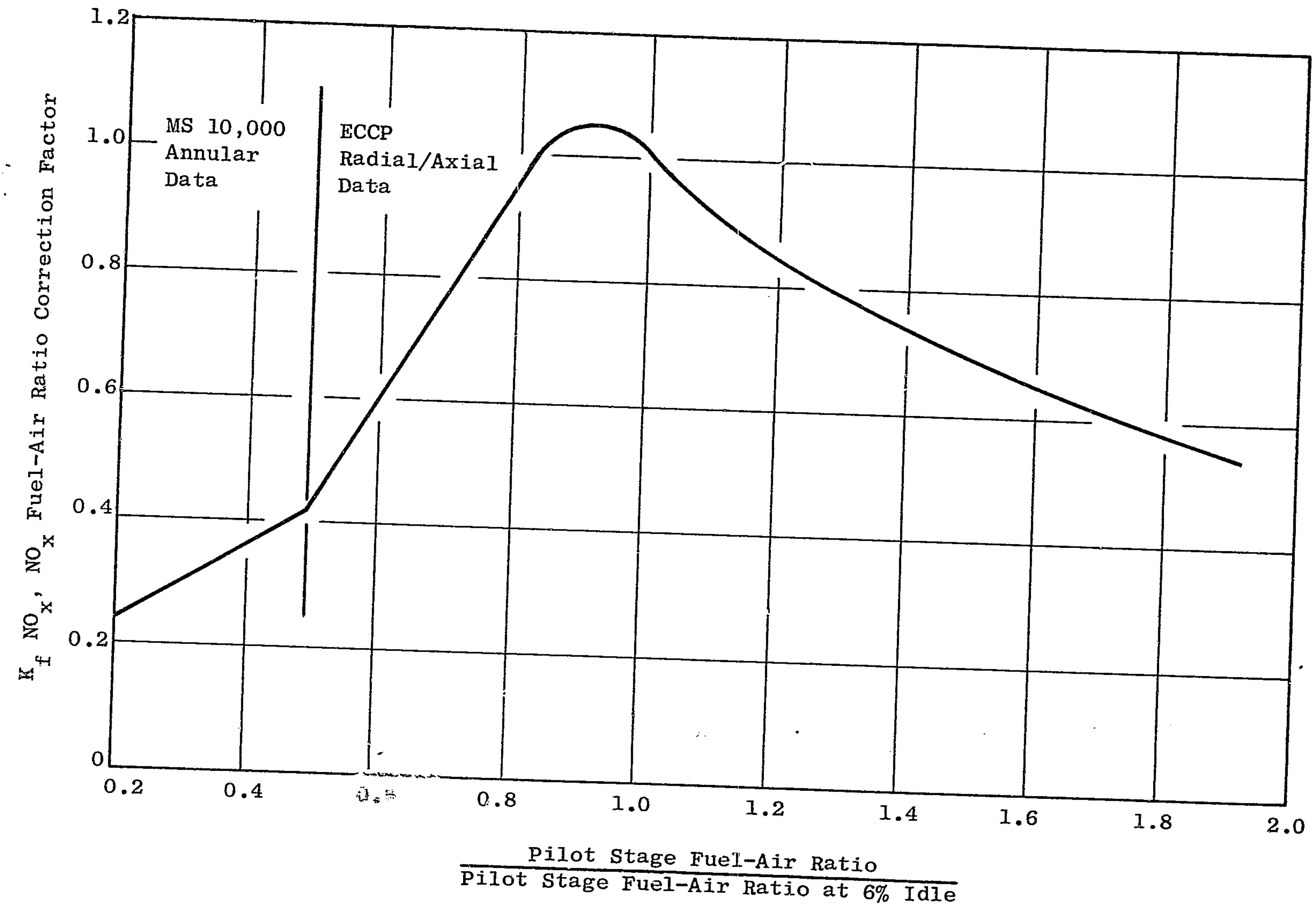


Figure 21. Fuel-Air Ratio Correlation Factor for Pilot Stage NO_x.

constants. A pilot dome fuel-air ratio correction is also included for NO_x, emissions (Figur 21). Concept 6 main stage emissions at the climb and takeoff power levels were taken from predictions developed for the E^3 radial/axial configuration studied in the NASA/GE Analysis of Conceptual High Bypass Turbofan Engine Combustion (ANCON) Program (Reference 46).

In order to ensure that idle emissions predictions would be representative, pilot-stage airflow distributions for the six catalytic-combustor concepts were revised so that minimum emissions would be obtained using a conventional pilot dome. Flow levels for all concepts (Table XII) were set such that a stoichometric dome mixture (swirler air plus 50 percent of splash plate cooling air) would be obtained at the 6 percent idle operating condition to provide for rapid HC consumption. This mixture is then diluted to an equivalent ratio of 0.6 to 0.7 (including all dome flow plus primary dilution) for rapid CO consumption.

Catalytic-reactor gaseous emissions estimates (Table XVIII) were based on preliminary results of the Engelhard catalytic-reactor test series (Appendix B), and typical performance levels are given in Reference 17. Constant emissions were used because no data were available for catalytic-reactor operation at use temperatures up to 1811 K.

Overall gaseous emissions levels for the six combustor concepts are presented in Table XIX. Predicted emissions levels for all concepts meet or closely approach program goals. Predicted levels not meeting program goals include NO_x at normal cruise for Concepts 3 and 4 and at maximum cruise for Concepts 3, 4, and 5. Concept 6 NO_x EPAP is also slightly above the reference engine goal of 3.0 lb/1000 lb-thrust-hour/cycle. In all cases, failure to meet the goals is due to excess pilot or noncatalytic main stage NO_x emissions.

Based on ECCP Phase III engine test results (Reference 47), pilot-stage smoke emissions are primarily dependent on pilot stage fuel-air ratio. With the fuel and airflow schedules indicated in Table XIII, those engine test results indicate that pilot stage smoke emissions levels will be below a smoke number of 5 at all steady-state operating conditions. Since the fuel-air mixtures reacted in the catalyst are extremely lean, no appreciable smoke formation is expected in the catalyst stage. Therefore, overall smoke emissions from all concepts are predicted to be less than SN=5, which is well below the applicable standard of SN=20 (Reference 4).

6.1.5 Heat Transfer

Heat transfer analyses were conducted to refine cooling flow estimates for the six combustor concepts. Resulting pilot-stage cooling levels are included in flow scheduling considerations (Table XII). Cooling flow levels were set to provide liner peak temperatures below 1150 K for pilot-only operation up to the approach condition, and operation with up to 35 percent of total combustor fuel flow supplied to the pilot stage at the hot-day takeoff condition.

Table XVIII. Catalytic Reactor Emissions Estimates

Basis	–	Preliminary Results of Engelhard Task II Test Program (Appendix B)
	–	Reference 17
Typical Performance (JP-5 Fuel)	–	NO_x < 5 ppm
	–	Combustion Efficiency 99.9 Percent
	–	Fuel-Air Ratio 20 g/kg
Catalytic Reactor Emissions Predictions (All Power Levels)	–	NO_x EI < 0.4 g/kg
	–	COEI < 3.0 g/kg
	–	HCEI < 0.3 g/kg
	–	Combustion Efficiency 99.9 Percent

Table XIX. Concept Emissions Estimates.

Power	Emission, g/kg, Efficiency, Percent	Emission Level for Concept 1	2	3	4	5	6
Idle (6 Percent)	CO	12.4	11.2	12.4	12.4	10.1	12.4
	HC	0.2	0.2	0.2	0.2	0.1	0.2
	NO_x	3.5	3.7	3.5	3.5	3.9	3.5
	ηb	99.7	99.7	99.7	99.7	99.8	99.7
Approach (30 Percent)	CO	2.9	3.0	3.0	2.9	2.9	1.5
	HC	0.3	0.3	0.3	0.3	0.3	0 0
	NO_x	0.7	0.6	0.6	0.7	0.7	9.9
	ηb	99.9	99.9	99.9	99.9	99.9	99.9
Climb (85 Percent)	CO	2.9	3.0	2.3	2.2	3.0	6.1
	HC	0.3	0.3	0.2	0.2	0.3	0.1
	NO_x	0.9	0.7	3.3	3.5	0.9	14.0
	ηb	99.9	99.9	99.9	99.9	99.9	99.8
Takeoff (100 Percent)	CO	2.9	3.0	2.0	2.0	2.7	3.7
	HC	0.3	0.3	0.2	0.2	0.3	0.1
	NO_x	0.9	0.7	10.2	11.5	2.0	17.5
	ηb	99.9	99.9	99.9	99.9	99.9	99.9
EPAP*	CO	2.1	2.0	2.0	2.0	2.0	2.3
	HC	0.1	0.1	0.1	0.1	0.1	0,0
	NO_x	0.6	0.6	1.2	1.3	0.7	3.0
Normal Cruise	CO	2.9	3.0	2.5	2.4	3.0	3.0
	HC	0.3	0.3	0.3	0.3	0.3	0.3
	NO_x	0.7	0.6	1.9	2.1	0.7	0.5
	ηb	99.9	99.9	99.9	99.9	99.9	99.9
Maximum Cruise	CO	2.9	3.0	2.4	2.4	3.0	3.0
	HC	0.3	0.3	0.2	0.2	0.3	0.3
	NO_x	0.7	0.6	2.2	2.6	1.5	0.5
	ηb	99.9	99.9	99.9	99.9	99.9	99.9

* Lb/1000 lb-thrust-hours/cycle.

The only significant deviation from the baseline E^3 combustor pilot-stage metal temperatures was an increase of approximately 80 K in liner peak temperature for Concepts 1 and 2 at the approach condition. This increase, which was due to reduced backside impingement cooling effectiveness resulting from decreased liner pressure drop in these concepts, is not expected to have a strong effect on liner life.

As indicated previously (Section 6.1.1), catalytic-reactor fuel flow at high power is restricted by limitations on maximum temperature, which is in turn determined by catalytic-reactor airflow level and inlet fuel concentration uniformity. Heat transfer analyses were performed to determine whether catalyst airflow could be increased by reducing or eliminating cooling flow to the combustor aft section. These analyses indicated that because of the uniform catalyst exit temperature profiles required to meet catalyst use temperature restrictions, the combustor liners immediately downstream of the catalyst can be cooled by backside convection if a 0.5-mm thick thermal barrier coating is used. Turbine cooling air is used for aft section cooling in this method, and aft film cooling is eliminated. This cooling method was utilized in all concepts and is reflected in the fuel and airflow schedules of Section 6.1.1.

The only major problem area identified in heat transfer studies was cooling of the fuel injection chutes employed in Concept 1. One-dimensional analysis indicates that average chute metal temperatures can be maintained below 1150 K if chute velocities are above 68 m/s and a 0.5 mm thermal barrier coating is employed. However, it is anticipated that much higher temperatures would occur locally in the upstream portion of the chute due to increased heat transfer in regions where flow exiting the pilot dome swirlers impinges on the chutes. The use of film cooling in these regions would be prohibitive because of the large chute surface area, the difficulty of stabilizing a film on the irregular chute surface, and the limited amount of cooling airflow available.

6.1.6 Operational Characteristics

Operational characteristics considered in evaluating the catalytic combustor concepts included ground start and altitude relight, transition to catalyst stage operation, and transient behavior during accelerations and decelerations.

Altitude relight and ground start characteristics are influenced by dome geometry and velocity, ignitor location, and dome and combustion system pressure drops. The pilot dome of each concept was designed in accordance with GE design practice to provide good ignition characteristics under normal operating cond[illegible]s. Therefore, any ignition problems with the catalytic combustors are expected be a result of nontypical pressure drop characteristics.

Increased idle-mode combustor pressure drop with Concepts 2 and 5 would expected to cause ignition difficulties; however, pressure drop can be adjust[illegible] by adjusting the variable geometry vanes to provide optimum lightoff conditions. With Concept 1, overall pressure drop is typical of conventional combustors, but pilot dome pressure drop is reduced. This reduced pressure drop would be expected to result in poor fuel atomization and mixing which would be detrimental to ignition characteristics, particularly at altitude relight conditions.

Conditions required for transition to catalyst stage operation have been discussed in Section 6.1.1. Fuel and airflow schedules for each concept were selected to ensure that catalyst inlet temperature and fuel-air ratios will be sufficiently high to ensure rapid catalyst ignition. Transition to catalyst operation is expected to be straightforward in the nonvariable geometry/designs (Concepts 1, 3, and 4). In these concepts, transition will involve a redistribution of fuel from pilot to main stage injectors. In the parallel concepts, catalyst fuel flow will have to "lead" pilot stage fuel flow cutback to allow for a short delay in catalyst ignition. Transition in variable geometry Concepts 2 and 5 will be complicated slightly because of the variable geometry features. In these concepts, the variable geometry vanes must be opened completely before the catalytic-reactor injectors are fueled. This will result in some transition delay, and some additional pilot-stage cooling flow may be required because of the richening of the pilot dome fuel-air mixture which occurs as the vanes are opened. Alternatively, the variable geometry could be redesigned to allow catalytic-reactor fueling with the vanes partially open.

Transition to catalytic-reactor burning will be most difficult with Concept 6. This design is essentially two different combustors, one for landing/takeoff operations and one for cruise. Transition consists of switching from one combustor to the other during steady-state operation. A tentative method for transitioning from the main stage to the catalyst stage is given in Table XX. For this method, both the main and catalyst stages are partitioned into 180° sectors in order to maintain acceptable pressure drops and uniform flow patterns into the two stages during the transition. This transition sequence requires an involved control system to actuate four sets of variable geometry vanes and six fuel systems (two main stage plus one catalyst stage in each sector). Combustor exit temperature and velocity profiles would also be of some concern because of circumferential variations in fuel and airflows during the transition. If pressure drop or exit temperature or velocity profiles were unacceptable with this method, additional partitioning would be required.

Transient operation requirements include the ability to accelerate from ground idle to 95 percent of rated thrust in five seconds, and to decelerate from 100 to 20 percent thrust in six seconds. The primary concern in this area is with vane actuation and catalyst ignition delays during transition in variable geometry Concepts 2 and 5. It is anticipated that extensive analysis and development would be required to achieve vane actuation rates and fuel scheduling to prevent transition stalls in these concepts. Catalyst transient response is also of some concern in Concepts 3 and 4 because of possible catalytic-reactor ignition lag during acceleration from idle to takeoff.

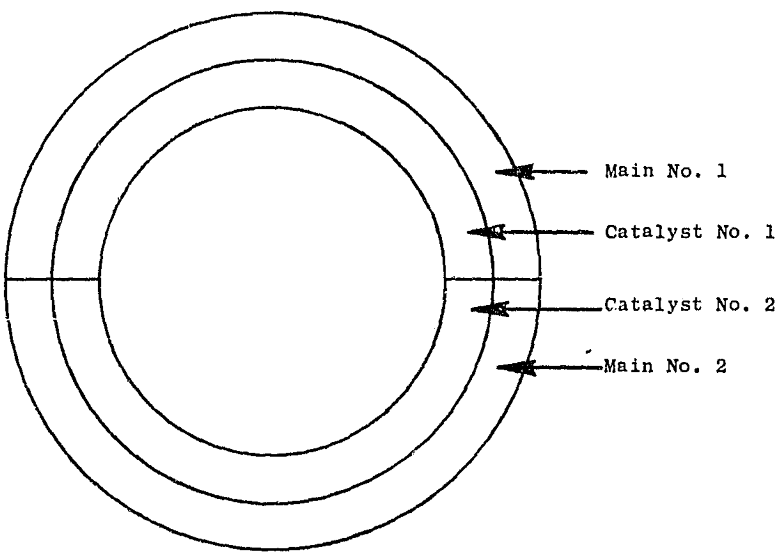
6.1.7 Mechanical Design

Each of the six conceptual designs was evaluated mechanically by comparison with the current E^3 double-annular combustor design. The catagories chosen for comparison were as follows:

- Cost
- Weight
- Length

Table XX. Tentative Procedure for Transition to Catalytic Reactor Operation.

Action	Combustor Pressure Drop, Percent	Percent of Total Combustor Fuel or Airflow to Catalytic-Reactor	
		Fuel	Air
0. Normal Cruise, Main Stage Only	5.0	0	10
1. Open Catalytic Reactor Sector #1	2.8	0	33
2. Transition 40 Percent Fuel Flow to Catalytic Reactor Sector #1	2.8	40	33
3. Simultaneously Close 50 Percent Main Sector # 1 and Open Catalytic Reactor Sector #2 (all main stage fuel transferred to main Sector #1)	2.8	40	67
4. Transfer 40 Percent Fuel to Catalytic Reactor Sector #2	2.8	80	67
5. Close Main Sector #2, Simultaneously Increasing Catalytic Reactor Fuel Flow (1 and 2) to 100 Percent	5.0	100	90



- Load Frame Requirements
- Variable Geometry Actuation
- Number of Fuel Systems
- Liner Complexity
- Catalyst Accessibility

Table XXI compares concept design values in several of these categories. Criteria used to evaluate these categories are described below:

- Cost - Cost ratings were provided by Value Engineering. This organization within General Electric commonly provides estimated costs for advanced prototype designs and projected 250th-unit production costs. Although the cost rankings were relative, similarities to existing designs were included in the cost evaluation whenever possible. The rankings were on a production cost basis.

- Weight - Weight was estimated for the outer casing, diffuser system, combustor fuel nozzles, and fuel manifolding systems. The following assumptions were made:

  - All component densities = 8.3 g/cm^3 except catalyst
  - Catalyst density = 2.5 g/cm^3
  - Film and impingement liners 1.0 mm thick
  - Outer casing 2.0 mm thick
  - Fuel nozzle casing boss weight 113 g each

  Each actuation system was assumed to add 10 percent to the total system weight. If the combustor casing configuration was such that a load frame would be required to transmit thrust loads through the engine, an additional weight increase of 30 percent to the total system weight was included. It should be noted that weight increases for the inner casing and shafts due to length increases of the combustor were not included.

- Length - Increased length would penalize the engine design through increased weight, system vibration difficulties, and increased bearing loads. Studies have shown that an increase of 15 cm overall engine length will have a relatively small effect on E^3 bearing loads, but a 25 cm increase would have a very severe effect. For this reason, the longer concepts (1, 2, and 6) would probably require a three-bearing engine design and would not be compatible with the current two-bearing engine unless combustor length were significantly reduced.

Table XXI. Concept Mechanical Design Comparison.

Parameter	Baseline E^3	Concept Design Value 1	2	3	4	5	6
Cost Factor	1.0	2.0	3.0	1.7	2.0	2.3	2.3
Weight Increase, kg	0	58	98	25	24	70	62
Length, cm	29.7	54.6	57.2	42.2	32.8	37.1	53.9
Number of Fuel Systems	2	2	3	2	2	3	3
Number of Actuation Systems	0	0	1	0	0	1	2
Load Frame Required	No	No	Yes	No	Yes	Yes	No

- Load Frame Requirements - Concepts 2, 4, and 5 have outer case geometries that are not favorable for axial load transmission through the engine. A load frame would be required to transmit thrust and maneuver loads. Concept 4 was penalized less severely for this requirement because the cannular design would allow a simpler frame with load struts passing between the cans.

- Variable Geometry Actuation - In evaluating designs with actuation, several considerations were included. The controlling mechanism must penetrate the casing and be sealed against leakage. Each actuation system includes added maintenance and a potential reliability problem. Thus, in addition to the weight penalty assigned for the addition of each actuation system, a penalty for variable geometry actuation systems was included in the evaluation.

- Fuel Systems - Similarly, multiple fuel systems were penalized. Each additional fuel system increases the difficulty of reliability and maintainability. Further problems with the vibrational stability of the fuel nozzles can be experienced when the length becomes excessive. These considerations were included in the fuel systems ranking.

- Liner Complexity - The catalytic-reactor accessibility category reflected the relative difficulty encountered in changing the catalyst material. Current catalyst projected lives of 1000 to 2000 hours make it desirable to provide direct access to the catalyst without requiring a total teardown of the engine. Designs requiring considerable disassembly for access to the catalytic-reactor were penalized more than designs with direct access.

6.2 CONCEPT EVALUATION AND RATING

Each of the six combustor concepts was rated on its potential to meet the goals for emissions, aerothermal performance, fuel-air carburetion system performance, operating characteristics, and for the degree of mechanical complexity. Each of these areas was first broken down into specific criteria. The development risk of each concept with respect to these criteria was then described with the following numerical scale:

3 - Expected to meet the design goal with normal development.

2 - Additional development required to meet goal.

1 - Major development effort required to meet goal. High developmental risk.

These ratings were then weighted according to their relative importance to combustor operation and were combined to provide overall ratings.

Concept emissions are rated in Table XXII. These ratings were based on emissions predictions given in Table XIX, and reflect the increased NO_x levels predicted for cruise range operation with Concepts 3, 4, and 5, and the relatively high NO_x EPAP predicted with Concept 6. The best overall emissions ratings were obtained by series Concepts 1 and 2.

Combustor aerothermal performance is rated in Table XXIII. Increased design risk was determined in the following areas:

- Combustion Efficiency - At off-design conditions during catalyst stage operation, the use of circumferential fuel staging would be expected to result in decreased efficiency in Concepts 1, 2, 3, and 5 due to the presence of lean "fringe" areas between fueled and unfueled sectors. This does not apply to the cannular design (Concept 4) or to Concept 6 which uses airflow modulation instead of fuel staging.

- Pressure Drop - Concepts 2 and 5 were downgraded because of increased idle pressure drop.

- Profile Factor - Parallel staged Concepts 3, 5, and 6 are expected to require some additional development to trim radial temperature profiles. The cannular configuration of Concept 4 is expected to provide a better radial temperature profile because of improved mixing between the catalyst and pilot stage flows.

to require some additional development to trim radial temperature profiles. The cannular configuration of Concept 4 is expected to provide a better radial temperature profile because of improved mixing between the catalyst and pilot stage flows.

- Combustion Stability - Concept 6 was downgraded for possible instability during the transition between main and catalyst stage operation.

- Maximum Liner Temperatures - Concept 1 was rated a high design risk because of potential problems with cooling of the fuel injection chutes. Some additional development is also expected to be required to cool the transition area at the junction of the cannular catalytic-reactor stage and annular pilot stage in Concept 4 and the junction of premixing tubes and pilot stage liners in Concept 6.

Concept fuel-air carburetion performance is rated in Table XXIV. Concept 6 rated highest in all aspects of carburetion performance, primarily due to the fact that catalyst stage operation is not required at the takeoff power level. Performance of series Concepts 1 and 2 was generally rated lower than that of the parallel concepts because of the requirement that fuel must first be mixed with the air stream passing through the fuel injection slots, and then this

Table XXII. Emissions Evaluation Scoreboard.

Design Parameter	Goal	Weighting Factor	Concept Rating/Weight Rating 1	2	3	4	5	6
NO_x Emissions, g/kg								
Normal Cruise	1	1.0	3/3	3/3	1/1	1/1	3/3	3/3
Maximum Cruise	1	0.5	3/1.5	3/1.5	1/.5	1/.5	2/.1	3/1.5
EPA Parameter, $\frac{\text{lb.}}{\text{1000 lb.-Thrust Hr./Cycle}}$								
CO	4.3	1.0	3/3	3/3	3/3	3/3	3/3	3/3
HC	0.8	1.0	3/3	3/3	3/3	3/3	3/3	3/3
NO_x	3.0	1.0	3/3	3/3	3/3	3/3	3/3	2/2
Overall Weighted Rating			3.0	3.0	2.3	2.3	2.9	2.8
Ranking			1.5	1.5	5.5	5.5	3.0	4.0

Table XXIII. Combustor Aerothermal Performance Evaluation Scorecard.

Design Parameter	Goal	Weighting Factor	Concept Rating/Weighted Rating 1	2	3	4	5	6
Combustion Efficiency, Percent								
Takeoff	>99.9	1.0	3/3	3/3	3/3	3/3	3/3	3/3
Idle	>99.5	1.0	3/3	3/3	3/3	3/3	3/3	3/3
All Other	>99	0.5	2/1	2/1	2/1	3/1.5	2/1	3/1.5
Pressure Drop, Percent								
Idle	< 5	0.5	3/1.5	1/0.5	3/1.5	3/1.5	1/0.5	3/1.5
All Other	< 5	1.0	3/3	3/3	3/3	3/3	3/3	3/3
Exit Radial Temperature								
Profile Factor	<0.125	1.0	3/3	3/3	2/2	3/3	2/2	2/2
Pattern Factor	<0.25	1.0	3/3	3/3	3/3	3/3	3/3	2/2
Combustion Stability	Stable combustion at all conditions	1.0	3/3	3/3	3/3	3/3	3/3	2/2
Maximum Liner Temperature, K	<1150	1.0	1/1	3/3	3/3	2/2	3/3	2/2
Overall Weighted Rating			2.7	2.8	2.8	2.9	2.7	2.5
Ranking			4.5	2.5	2.5	1	4.5	6

Table XXIV. Fuel-Air Carburetion System Performance Evaluation Scorecard.

Vaporization, Percent	>90	1.0	3/3	3/3	3/3	3/3	3/3	3/3
Bulk Residence Time, msec	<2(10*)	1.0	2/2	1/1	3/3	3/3	3/3	3/3
Flow Blockage, cm	<0.7(3.5*)	1.0	1/1	1/1	2/2	2/2	2/2	3/3
Fuel Uniformity, Percent	±10	1.0	2/2	2/2	3/3	3/3	3/3	3/3
Orifice Size, mm	>0.4	1.0	3/3	3/3	3/3	3/3	3/3	3/3
Maximum Fuel Temperature, K	>422	0.4	3/1.5	3/1.5	3/1.5	3/1.5	3/1.5	3/1.5
Sensitivity to Inlet Distortion	-	1.0	3/3	3/3	2/2	3/3	3/3	3/3
Weighted Average			2.2	2.2	2.6	2.7	2.7	3.0
Ranking			5.5	5.5	4	2.5	2.5	1

* Concept 6

air stream must be mixed with the pilot dome airflow prior to entering the catalyst. Mixing of these air streams without obtaining autoignition will require careful chute design and extensive development. However, one advantage of the series designs is that some burning upstream of the catalyst is allowable. Thus, it might be preferable to intentionally preburn at takeoff by using the pilot stage to stabilize the flame upstream of the catalyst.

Concept operational characteristics are rated in Table XXV. Altitude relight with Concept 1 was rated as an increased development risk because of decreased pilot dome pressure drop, which would be expected to result in poor fuel atomization and mixing at relight conditions. Variable geometry Concepts 2 and 5 were assigned increased risk with respect to transition to catalyst stage operation because of the requirement that the variable vanes be completely open before the catalyst stage is fueled. As the vanes open during transition, pilot stage airflow is decreased and the pilot will operate very rich until catalyst stage fuel is applied. These concepts were also assigned high risk with respect transient operation because of the vane actuation delay. Transition to catalytic-reactor operation was rated as a very high development risk because of the complexity of the transition procedure. Overall operating characteristic ratings were generally highest for the fixed geometry concepts.

The relative mechanical design merit of each concept was rated with respect to the criteria discussed in Section 2.7. A numerical rating between 0 and 10 (which roughly correspond to a development risk range of 2 to 3) was assigned based on the relative merit of the design compared to the baseline E^3 combustor. A weighting factor was applied to each category to correct for its relative impact on overall mechanical design. Each combustor concept was then assigned an overall merit rating based on a compilation of the individual scores and the weighting factors. For comparison with other aspects of combustor design, this overall mechanical rating was also converted into a development risk rating. Concepts 3 and 4 were the most promising from a mechanical design standpoint. The most serious mechanical design problem is the extended length of Concepts 1, 2, and 6. These concepts would require modifications to reduce combustor length in order to avoid the requirement for a three-bearing engine design. The ratings are presented in Table XXVI.

Concept Selections

Overall emissions and performance ratings for the six concepts are compared in Table XXVII. Emissions ratings were generally higher for the series staged designs (Concepts 1 and 2), and performance ratings were higher for the fixed geometry parallel staged designs (Concepts 3 and 4). Thus, the selection of a preferred design was strongly dependent on the relative importance attached to emissions and performance. If emissions were weighted equal to overall performance (Table XXVII, 3.0), Concepts 1 and 5 would be preferred. However, if each of the performance areas evaluated was considered separately and weighted equal to emissions (Table XXVII, 4.0), Concepts 3 and 4 would be preferred.

Although Concept 3 and 4 emissions ratings were decreased due to predicted NO_x levels which were above the program goal of 1 g/kg, the predicted levels still represent an order of magnitude reduction from NO_x emissions obtained with

Table XXV. Operational Characteristics Evaluation Scorecard.

Design Parameter	Goal	Weighting Factor	Concept Rating/Weighted Rating 1	2	3	4	5	6
Altitude Relight, m	5000	1.0	2/2	3/3	3/3	3/3	3/3	3/3
Transition to Catalyst Stage Operation	Smooth Continuous	1.0	3/3	2/2	3/3	3/3	2/2	1/1
Ground Start-Time to Full Propagation, sec.	10	1.0	3/3	3/3	3/3	3/3	3/3	3/3
Transient Behavior, sec.								
Accel (Ground Idle to 95 Percent)*	5	1.0	3/3	2/2	3/3	3/3	2/2	3/3
Decel (100 to 10-20 percent)	6	1.0	3/3	3/3	3/3	3/3	3/3	3/3
Weighted Rating			2.8	2.6	3.0	3.0	2.6	2.6
Ranking			3	5	1.5	1.5	5	5

* Percent of sea-level takeoff thrust.

Table XXVI. Mechanical Design Evaluation Scorecard.

Design Aspect	Weighting Factor	Concept Rating/Weighted Rating Baseline E^3	1	2	3	4	5	6
Cost	3	7/21	6/18	1/3	5/15	4/12	3/9	3/9
Weight Increase	3	10/30	4.1/12.3	0/0	7.4/22.2	7.0/21	2.9/8.7	3.7/11.1
Length Increase	3	10/30	0.9/2.7	0/0	5.5/16.5	8.9/26.7	7.3/21.9	1.2/3.6
Prime Requirement	2	10/20	10/20	0/0	10/20	3/6	0/0	10/20
Actuation Requirement	2	10/20	10/20	5/10	10/20	10/20	5/10	0/0
Fuel Systems	1.5	3/4.5	3/4.5	0/0	3/4.5	3/4.5	0/0	0/0
Liner Complexity	1.0	9/9	5/5	2/2	9/9	5/5	9/9	6/6
Catalyst Accesibility	0.5	10/5	5/2.5	2/1	2/1	9/4.5	5/2.5	2/1
Weighted Rating	16	8.7	5.3	1.0	6.8	6.2	3.8	3.2
Developmental Risk Rating		2.9	2.5	2.1	2.7	2.6	2.4	2.3
Ranking		-	3	6	1	2	4	5

Table XXVII. Overall Evaluation.

Design Aspect	Concept Rating/Ranking					
	1	2	3	4	5	6
1.0 Emissions	►3.0/1.5	►3.0/1.5	2.3/5.5	2.3/5.5	2.9/3.0	2.8/4.0
2.0 Performance						
2.1 Aerothermal	2.7/4.5	2.8/2.5	2.8/2.5	2.9/1.0	2.7/4.5	2.5/6.0
2.2 Operational	2.8/3.0	2.6/5.0	3.0/1.5	3.0/1.5	2.6/5.0	2.6/5.0
2.3 Fuel-Air Carburetion	2.2/5.5	2.2/5.5	2.6/4.0	2.7/2.5	2.7/2.5	3.0/1.0
2.4 Mechanical	2.5/3.0	2.1/6.0	2.7/1.0	2.6/2.0	2.4/4.0	2.3/5.0
2.5 Overall (Average)	2.55/4.00	2.43/4.75	2.78/2.25	2.80/1.75	2.60/4.0	2.60/4.25
3.0 Average (1.0 + 2.5)	►2.78/2.75	2.72/3.13	2.54/3.88	2.55/3.63	►2.75/3.50	2.70/4.13
4.0 Average (1.0 + 2.1 + 2.2 + 2.3 + 2.4)	2.64/3.5	2.54/3.83	►2.68/2.90	►2.70/2.50	2.66/3.80	2.64/4.20

current combustor technology. This emissions reduction is obtained without the increased idle pressure drop and variable geometry control requirements which characterize Concept 5.

Based on the above considerations, Concepts 3 and 4 were selected for preliminary design studies. The preliminary designs of these combustor concepts are described in the following section.

7.0 PRELIMINARY COMBUSTOR DESIGNS

Several basic similarities exist between the catalytic combustor concepts selected for preliminary design studies. Each of the selected concepts consists of a conventional pilot stage, specifically designed to meet light off and low power operating requirements, which is mounted parallel to a lean premixing catalyst stage designed specifically to provide low NO_x emissions at the cruise operating conditions. Neither of the designs incorporates variable geometry to control stage stoichiometry over the engine operating range, so stoichiometry must be controlled by variation of the fuel flow split between the pilot and catalytic-reactor stages. Primary differences between the selected concepts are the radial locations of the pilot and catalytic-reactor stages (pilot located in inner or outer annulus) and the configuration of the catalytic-reactor stage (straight-through annular or reverse-flow cannular). Because of the similarities between the selected concepts, it was possible to incorporate several common design features and to conduct several parallel analyses on the two combustor designs. Therefore, in the following sections, results of preliminary design studies on the selected concept have been presented in parallel to best demonstrate the similarities and relative strengths and weaknesses of the two designs.

7.1 COMBUSTOR DESCRIPTIONS

7.1.1 Basic Parallel-Staged Combustor (Concept 3)

A cross-sectional view of the Basic Parallel-Staged catalytic combustor showing airflow distribution at the idle operating conditions is presented in Figure 22. Details of combustor construction are shown in Figures 23 through 26. This combustor retains the overall features depicted in the conceptual design (Figure 7), including the outboard-mounted conventional annular pilot stage and the inboard-mounted annular catalyst stage. However, several design details were modified. Modifications incorporated into the preliminary design are as follows:

Inlet Diffuser

The combustor inlet diffuser was rearranged relative to the conceptual design by extending the central catalyst stage diffuser splitter vane upstream, and by reducing the length of the splitter between the pilot and catalyst stage. This diffuser reconfiguration was intended to provide a more uniform velocity profile at the catalytic-reactor stage fuel injection plane by providing symmetrical diffusion upstream of the injection point. Diffuser length was also decreased slightly by this reconfiguration. This diffuser has been sized such that flow is first diffused slightly upstream of each splitter vane, then reaccelerated to the inlet Mach number as it flows around the vane leading edge. Thus, there is no net diffusion up to Plane B shown in Figure 23. Flow to the catalyst stage is diffused through an area ratio of 2.0 between Planes B and C. This flow is then dumped through an area ratio of 1.27 at Plane C to obtain the selected catalytic-reactor stage fuel-injection velocity of 61 m/s (at cruise inlet conditions). Overall pressure loss within the catalytic-reactor stage

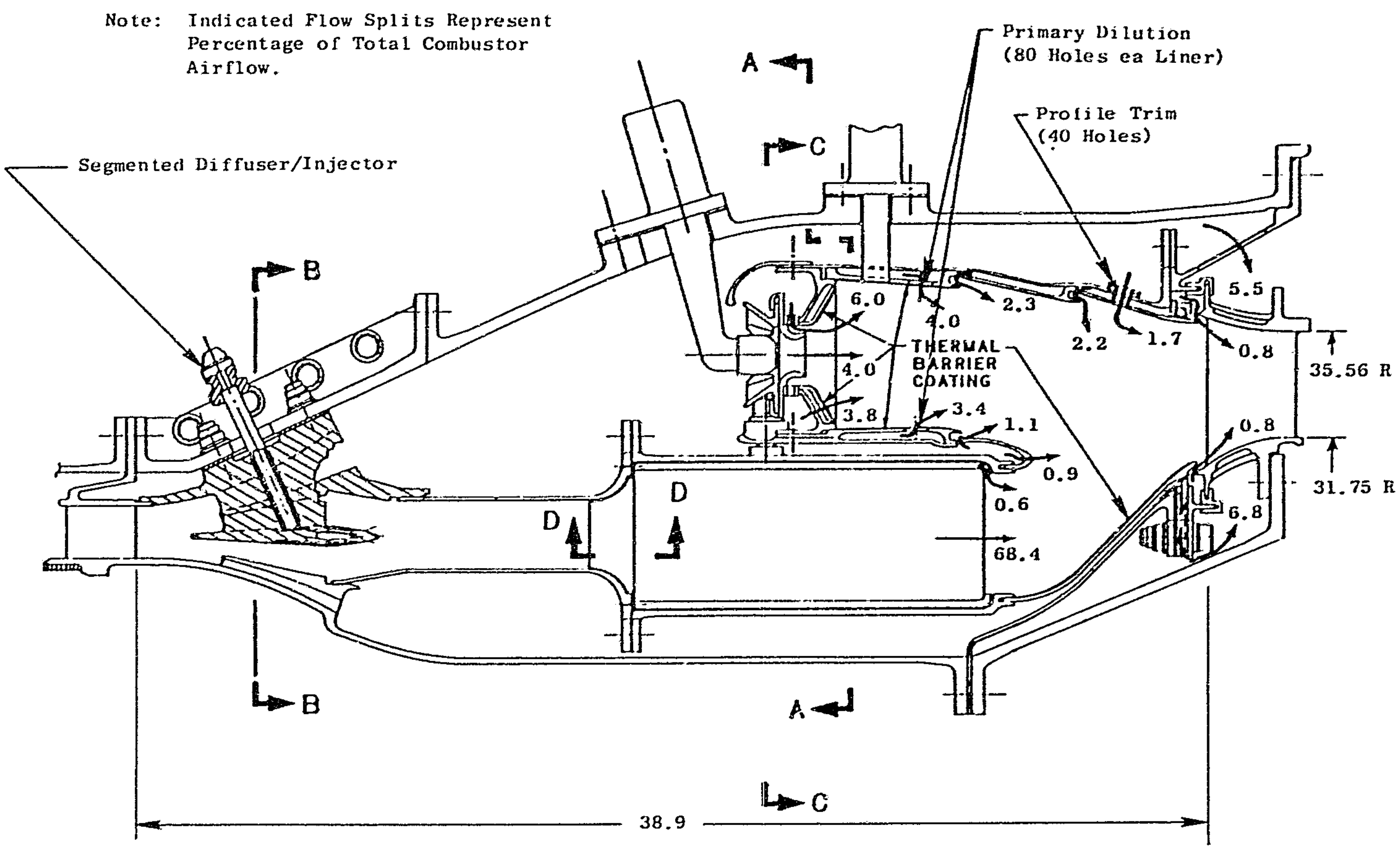


Figure 22. Basic Parallel-Staged Combustor Idle Airflow Distribution.

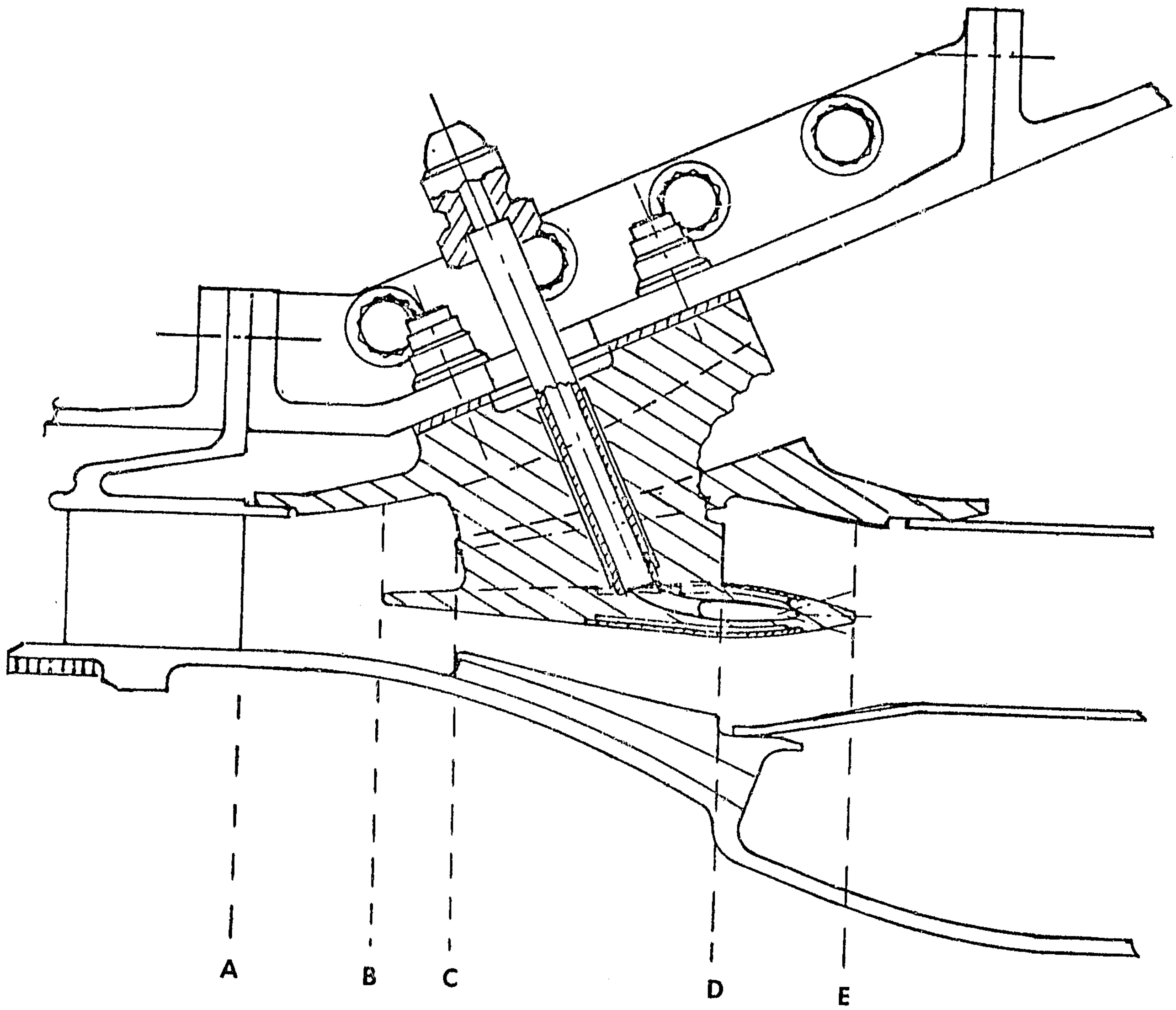


Figure 23. Basic Parallel-Staged Combustor Inlet Diffuser.

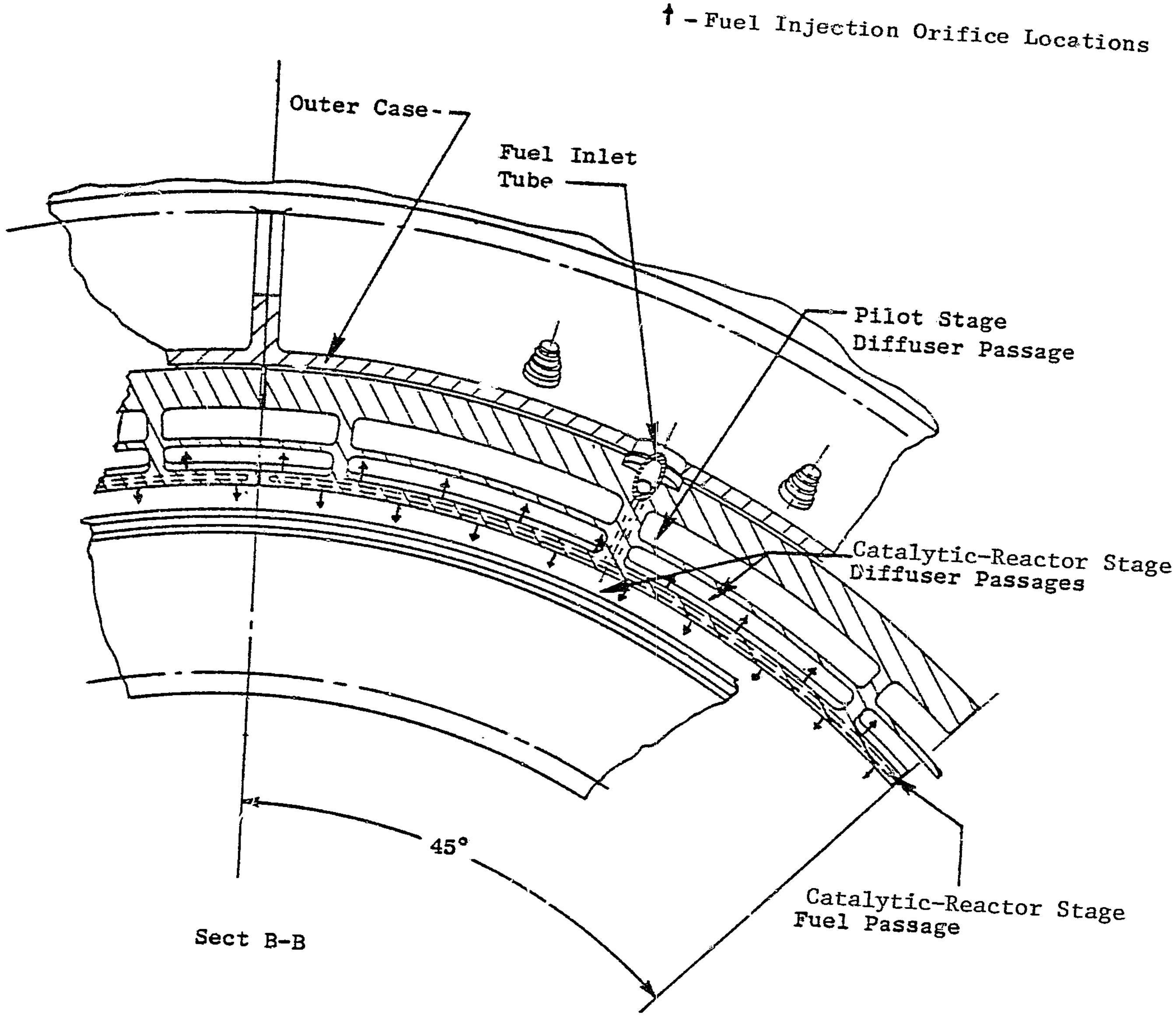
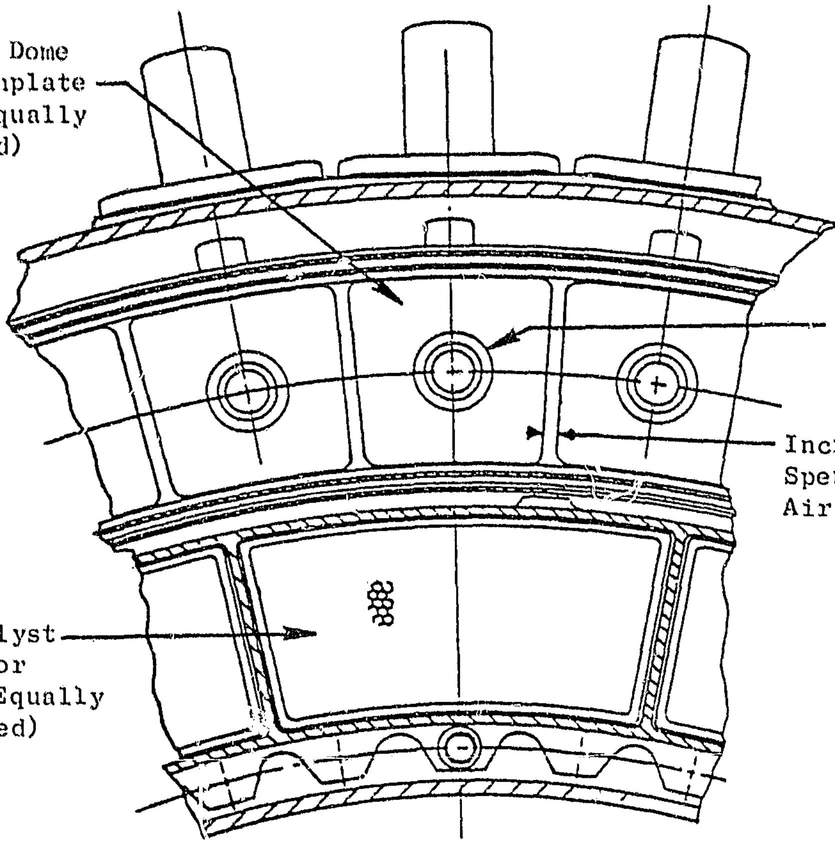
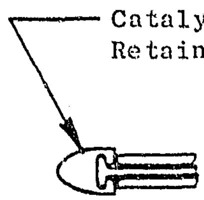


Figure 24. Basic Parallel-Staged Combustor Fuel-Injector/Diffuser.

C-2



Sect A-A



Sect D-D

Figure 25. Basic Parallel-Staged Combustor Catalytic Reactor and Dome.

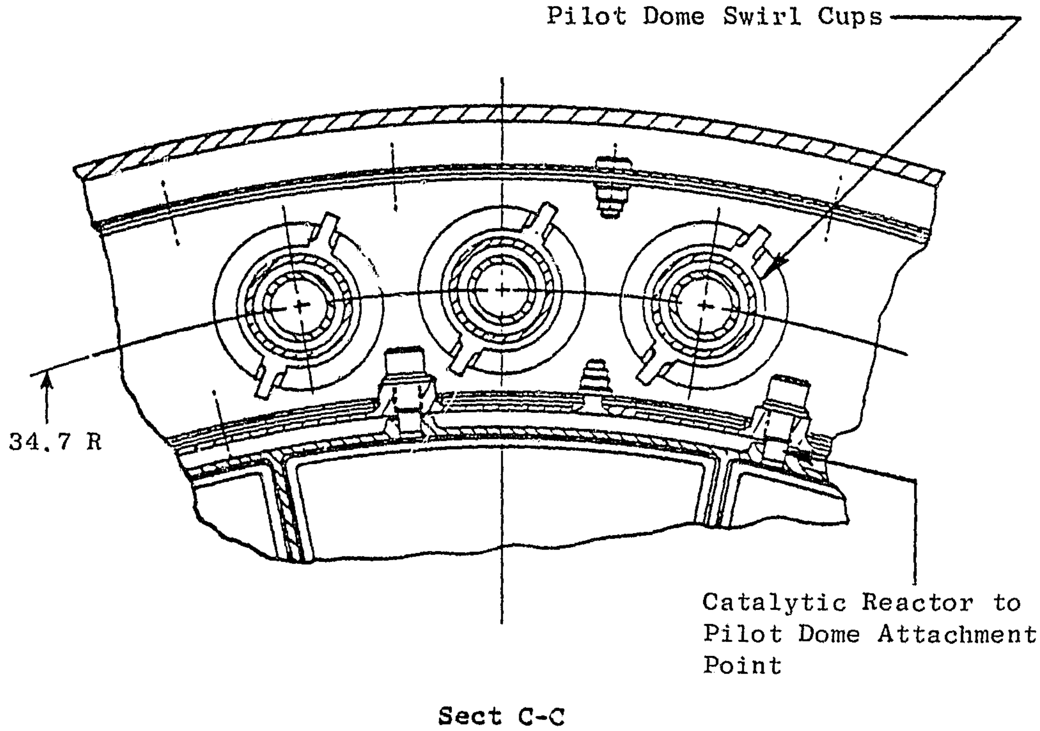


Figure 26. Basic Parallel-Staged Combustor Dome (Forward Looking Aft).

diffuser system is estimated to be between 0.7 and 1.0 percent of compressor discharge pressure. A similar prediffuser loss is obtained in the inner and outer diffuser passages and additional dumping loss of about 1.3 percent is taken through the inner and outer passage step diffusers.

Catalytic-Reactor Fuel Injectors

The thickness of the circumferential fuel injector/splitter design shown in the conceptual design was increased to 7.6 mm to provide additional space for the double wall construction shown in Figure 23. This design was implemented to prevent heating of the fuel within the injector system to temperatures above 422 K, which can cause fuel decomposition and deposition within the fuel passages and orifices. To accommodate this increased thickness, the entrance to the fuel mixing duct was contoured to maintain a constant flow area between the step diffuser and the end of the fuel injector (Planes C and D in Figure 23). The fuel injector/splitter used in the preliminary design consists of eight circumferential segments, each having separate internal fuel distributions passages and fuel injection orifices. A circumferential cross-sectional view of this assembly is shown in Figure 24. These cast fuel injector/splitter assemblies are attached to eight matching segments of the outer case. Each injector segment contains 18 equally spaced 0.51-mm fuel injection orifices which are positioned alternately on the inner and outer surfaces of the injector. Internal fuel passages within the injector are sized for a nominal flow velocity of 10 m/s at the takeoff power level. This velocity was selected based on afterburner experience to provide acceptable internal pressure losses, minimize injector fill times, and prevent fuel heating and decomposition.

Catalytic-Reactor Construction

A circumferential view of the catalytic reactor and pilot dome is shown in Figure 25. This reactor consists of 16 catalyst segments which are aligned such that each fuel injector assembly fuels two segments. This segmented catalyst approach was used to decrease thermal and mechanical stresses which would exist in a full-annular catalyst bed, and to provide a support structure to transmit loads between the pilot dome and aft inner liner. Inlet flow to the catalytic-reactor segments is routed around aerodynamic centerbodies which extend upstream of the inlet as shown in Figure 25 (Section D-D). These centerbodies are removed to insert the catalytic-reactor segments into the support structure. Additional details of catalytic-reactor mounting are discussed in Section 7-3. With the inboard mounted catalyst system shown in Figure 22, replacement of the catalytic reactor requires a complete combustor disassembly. However, inspection of the catalytic-reactor inlet is facilitated by the segmented circumferential fuel injector design. Removal of a fuel injector segment provides good access to the catalytic-reactor inlet face.

Liner Cooling

Convection liner backside cooling techniques have been used in concert with thermal barrier coatings both in the pilot stage and in the aft sector of the combustor. As incidated previously, these techniques were employed to reduce film cooling air requirements, thereby increasing available catalytic-reactor airflow. Cooling of the aft section inner liner is accomplished by forcing turbine inner shroud and vane body cooling air between the liner and a false inner wall. This air is then routed to the turbine through "wiggle strips" in the inner aft combustor mounting flange. Spacing between the false wall and the combustor liner is set to provide a flow velocity of about 65 m/s along the liner. The hot side of the liner surface is protected by 0.51-mm thermal barrier coating. Because of the pressure drop associated with this cooling technique, not all of the turbine cooling air can be used. Higher pressure cooling air required for the vane leading edges and the outer shroud is supplied through the outer combustor passage. Cooling of the first panel of the pilot stage is accomplished by first using primary dilution air to impingement cool the liner backside. This air is then routed from the impingement cavity through the primary dilution holes. Liner cooling and pilot dome features are discussed further in Section 7.1.3.

Combustor Length

Total combustion system length was reduced from 41.9 cm to 38.9 cm by shortening the diffuser and combustor aft section. As indicated in Section 6.1, combustion system length reduction decreases weight, vibration, and bearing loads.

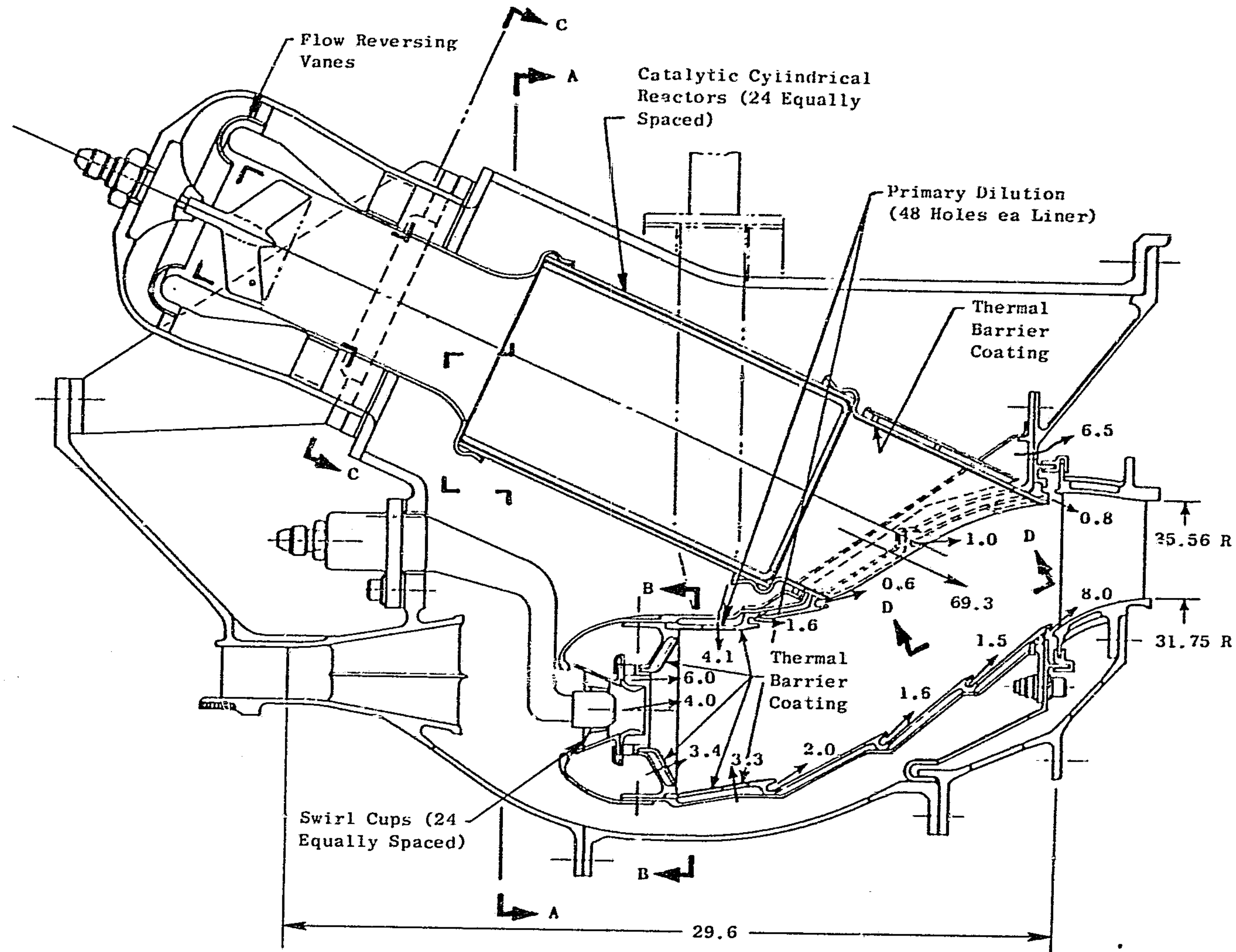
7.1.2 Cannular Reverse-Flow Parallel-Staged Combustor (Concept 4)

The preliminary design of the Cannular Reverse-Flow Parallel-Staged Combustor concept showing idle airflow distribution is presented in Figure 27. Auxiliary views of this combustor appear in Figures 28 through 30. As with the Basic Parallel Staged design, essential features of the conceptual design, including the inboard-mounted annular pilot stage and cannular catalyst stage, were retained. Design details which were refined or modified during the preliminary design process are as follows:

Catalyst Stage Configuration

The number of catalytic reactors was reduced from 30 to 24 to increase the spacing between the cans. An additional increase in spacing was obtained by increasing the angle of the cans relative to the combustor centerline. Additional spacing was required to enable the use of 360° flanges between the can assemblies and combustor casing as shown in Figure 28. A view showing the revised can spacing is shown in Figure 29.

Turning passages at the forward end of the fuel-air mixing ducts were sized to provide a radius of curvature to duct height ratio of about 2.2 for both the inner and outer passages, based on passage inlet height. Flow is accelerated from 46 to 55 m/s through each passage. Turning vanes were located such that 70 percent of the duct flow passes through the outer passage. Turning losses with this configuration are estimated to be between 0.2 and 0.3 percent of combustor inlet pressure.



Note: Indicated Flow Splits Represent Percentage of Total Combustor Airflow

Figure 27. Cannular Reverse-Flow Combustor Idle Airflow Distribution.

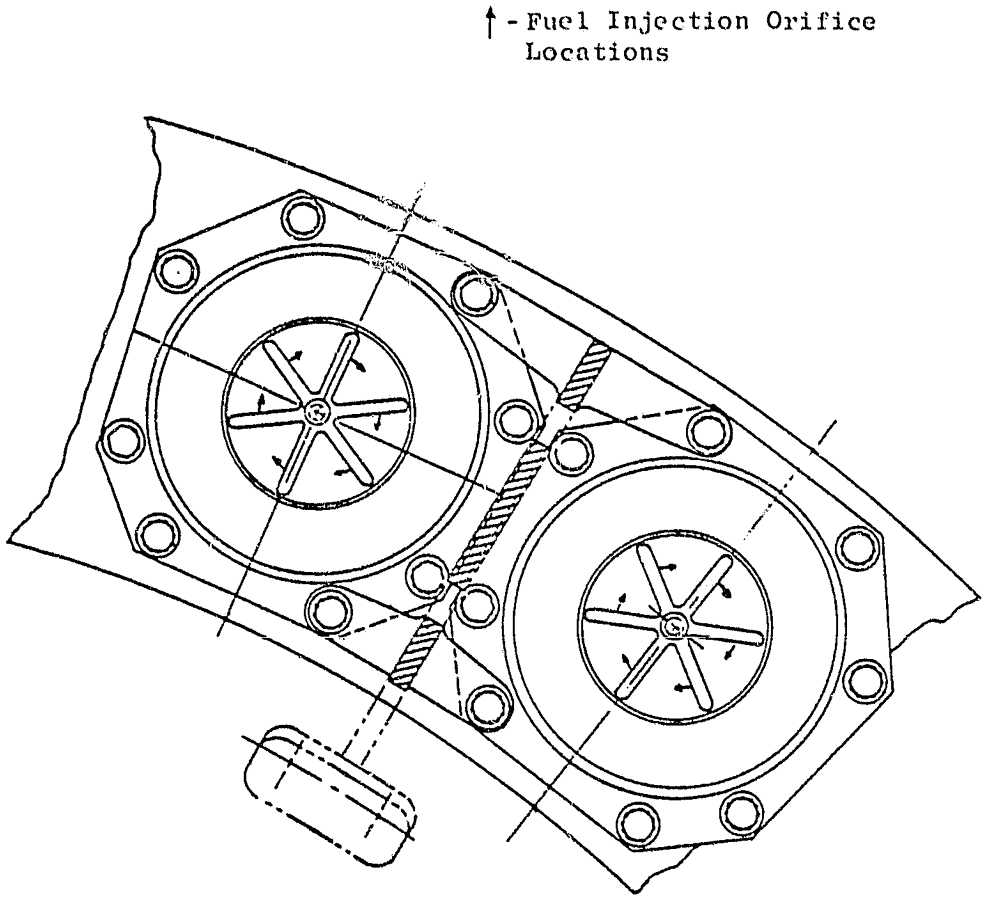


Figure 28. Catalytic Reactor Fuel Injectors for the Cannular Reverse-Flow Combustor.

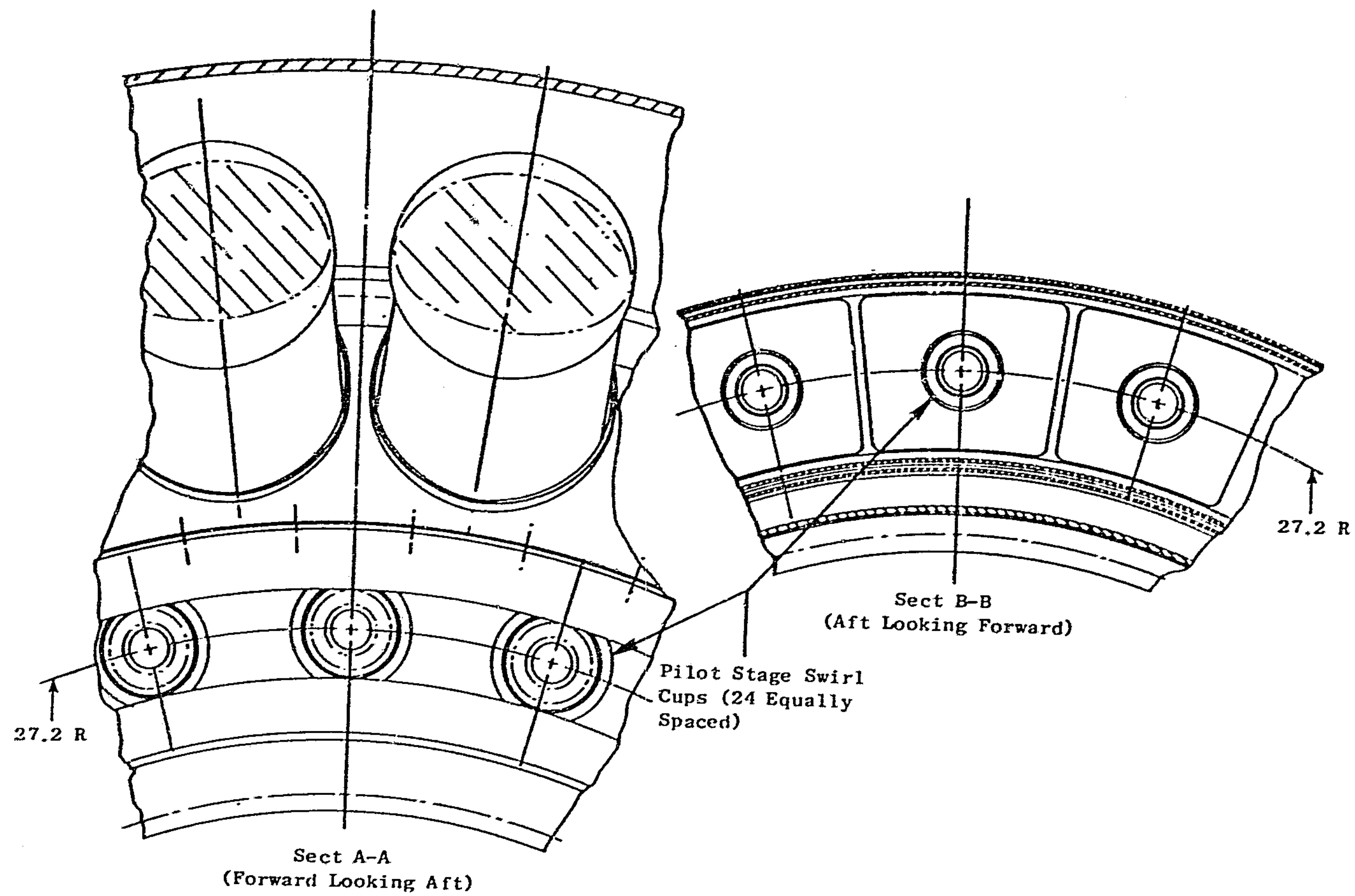


Figure 29. Cannular Reverse-Flow Combustor Circumferential Spacing.

Fuel Injectors

Pilot-stage fuel injector lead-in tubes, which were mounted on the outer casing and projected between the catalyst cans in the conceptual design, were repositioned to the forward casing. This change was intended primarily to increase the natural frequency of the injectors to acceptable levels. Catalytic-reactor stage fuel injectors, which were shown as single-point pressure atomizing nozzles in the conceptual design, were also reconfigured. In the preliminary design, as shown in Figure 28, each can contains an injector consisting of six radial blades, each of which contains a single, cross-stream 0.51-mm fuel injection orifice positioned to inject fuel in a clockwise direction. These orifices are located such that equal areas exist inside and outside of the fuel orifice radius. The fuel injection blades are located in a converging duct which is contoured to provide a net acceleration of the airflow from 55 to 61 m/s over the fuel injection section, in order to minimize the possibility of separation in this region. Single-wall construction has been utilized in the fuel injector blades to minimize blade thickness.

Liner Cooling

Details of the can-to-annulus transition are shown in Figure 30. Film cooling from the slot immediately upstream of the transition is sufficient to protect the liners up to the point of minimum can spacing (Plane E-E). However, downstream of this point, additional film cooling flow is required to protect the shaded region shown in View D-D of Figure 30. This additional cooling flow is admitted around the periphery of the cans as shown in Views E-E thru J-J. Toward the aft end of the liner (H-H and J-J), the liner surface is contoured to provide a smooth flowpath at the entrance to the turbine. At the aft end of the liner, cooling flow is metered through a row of "multijet" holes between the catalyst cans to provide a uniform cooling film at the turbine inlet.

As in the Basic Parallel Staged design, convective cooling techniques and thermal barrier coatings have been used to reduce liner cooling airflow requirements. Pilot stage cooling is identical in both designs. The cannular liners immediately downstream of the catalytic-reactor are cooled by backside convection using turbine and pilot stage outer liner cooling air. All cooling air for outer liner Panels 2 through 4, plus aft slot and turbine outer shroud and vane body cooling, first passes through an annulus formed by the catalytic-reactor can and a concentric can shroud. The annulus height is controlled by standoffs to maintain a uniform gap around the catalytic-reactor can. Flow exiting this annulus dumps into a cavity which, in turn, feeds the liners and turbine. This cooling arrangement requires the use of a triple-wall outer liner. Aft can cooling pressure drop with this configuration is estimated to be between 0.5 and 1.0 percent.

Combustor Length

Combustor system length was reduced to 29.6 cm, compared to 32.8 cm in the conceptual design, by decreasing the spacing between the diffuser and pilot dome cowls and shortening the aft transition section. This length is identical to that of the reference engine combustion system.

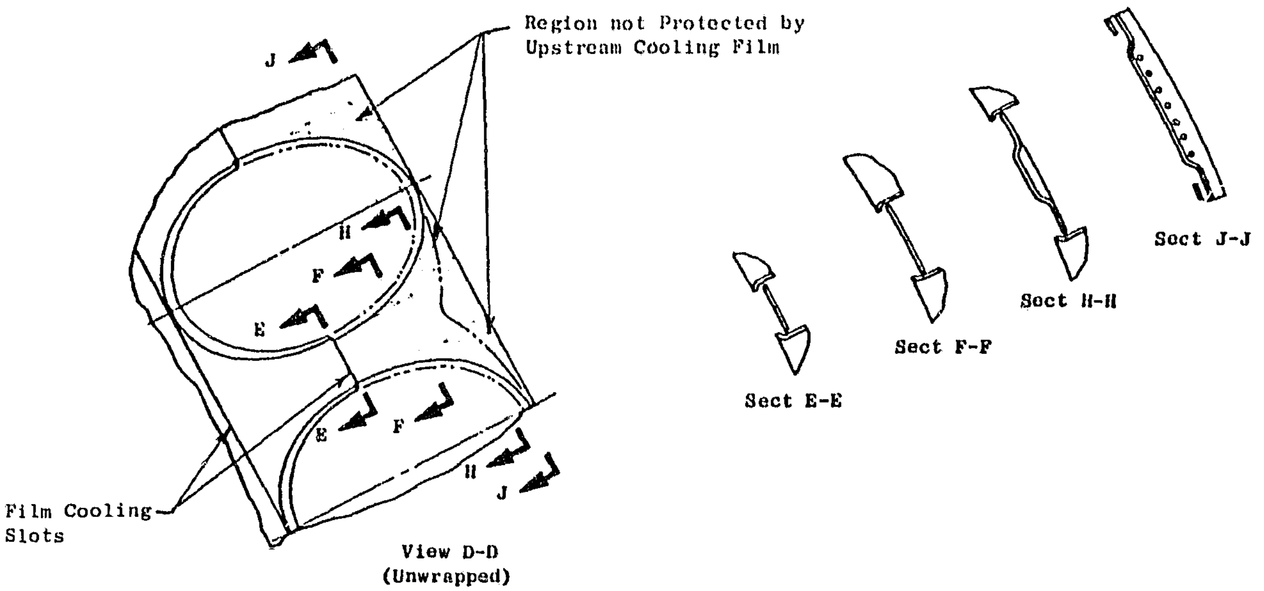


Figure 30. Cannular Reverse-Flow Combustor Transition Cooling.

7.1.3 Common Design Features

Design features common to the two catalytic combustors are described below:

Pilot Stage

Design features incorporated into each of the pilot stage designs are shown in Figure 31. Each of the pilot domes was sized to accept pilot-stage fuel injectors similar to those used in the reference engine pilot stage. Duplex (dual orifice) nozzles are used to provide good fuel atomization over the fuel flow range from combustor lightoff to approach power. These nozzles are comprised of two concentric swirl chambers and exit orifices which are separately supplied with fuel. From lightoff to about 10 percent thrust, only the primary orifice is fueled to provide good atomization during lightoff and at idle. Above 10 percent power, a flow divider opens to fuel the secondary orifice, thus decreasing the fuel injector pressure drop at intermediate power conditions. A nozzle outer diameter of 1.4 cm was selected to provide space for an air shroud to prevent carboning of the nozzle.

Each fuel nozzle is mounted at the center of a swirl cup consisting of two concentric counterrotating swirlers. The vortices formed by these swirlers produce a low pressure region along the swirler centerline, which provides a recirculating flow pattern for flame stabilization. The fuel and air exiting the cup are rapidly mixed in the shear region formed at the boundary of the counterrotating vortices. A venturi downstream of the primary swirler exit is used to prevent recirculation of hot products of combustion into the vicinity of the fuel nozzle. Allowance for differential thermal growth between the hot combustor and the cooler fuel nozzle and combustor casing is provided through the use of a floating primary swirler which is allowed to move relative to the secondary swirler.

Impingement backside cooling is used throughout the pilot stage dome and liners. This allows the use of the "hot-wall" emissions reduction concept demonstrated in the NASA/GE Low Power Emissions Reduction Program (Reference 33). In this concept, low power CO and HC emissions are reduced by reducing or eliminating film cooling in the forward portion of the pilot stage, and increasing liner hot side temperature through the use of thermal barrier coatings. In the designs of this program, both the splash plate and first panel of the cooling liner are coated with a 0.5-mm thickness of ceramic material consisting of a NiCrAlY bond coat followed by a coat of yttria-stabilized zirconia. To reduce film cooling on the first panel, spent splash plate cooling air is routed between the swirl cups by leaving only a small gap ($\approx$ 0.4 mm) between the splash plate and forward liner and providing a larger gap ($\approx$ 4 mm) between the splash plates, as shown in Figures 25 and 28. The first panel is cooled using forward dilution air which is routed first through small impingement orifices to cool the liner backside and then from the impingement cavity to the combustor through the primary dilution holes. One concern in the use of this method was with the degree of jet penetration obtainable with the reduced pressure drop available. Calculations using jet penetration correlations presented in Reference 48 indicate that the available pressure drop will be sufficient to provide penetration beyond the combustor pitch line.

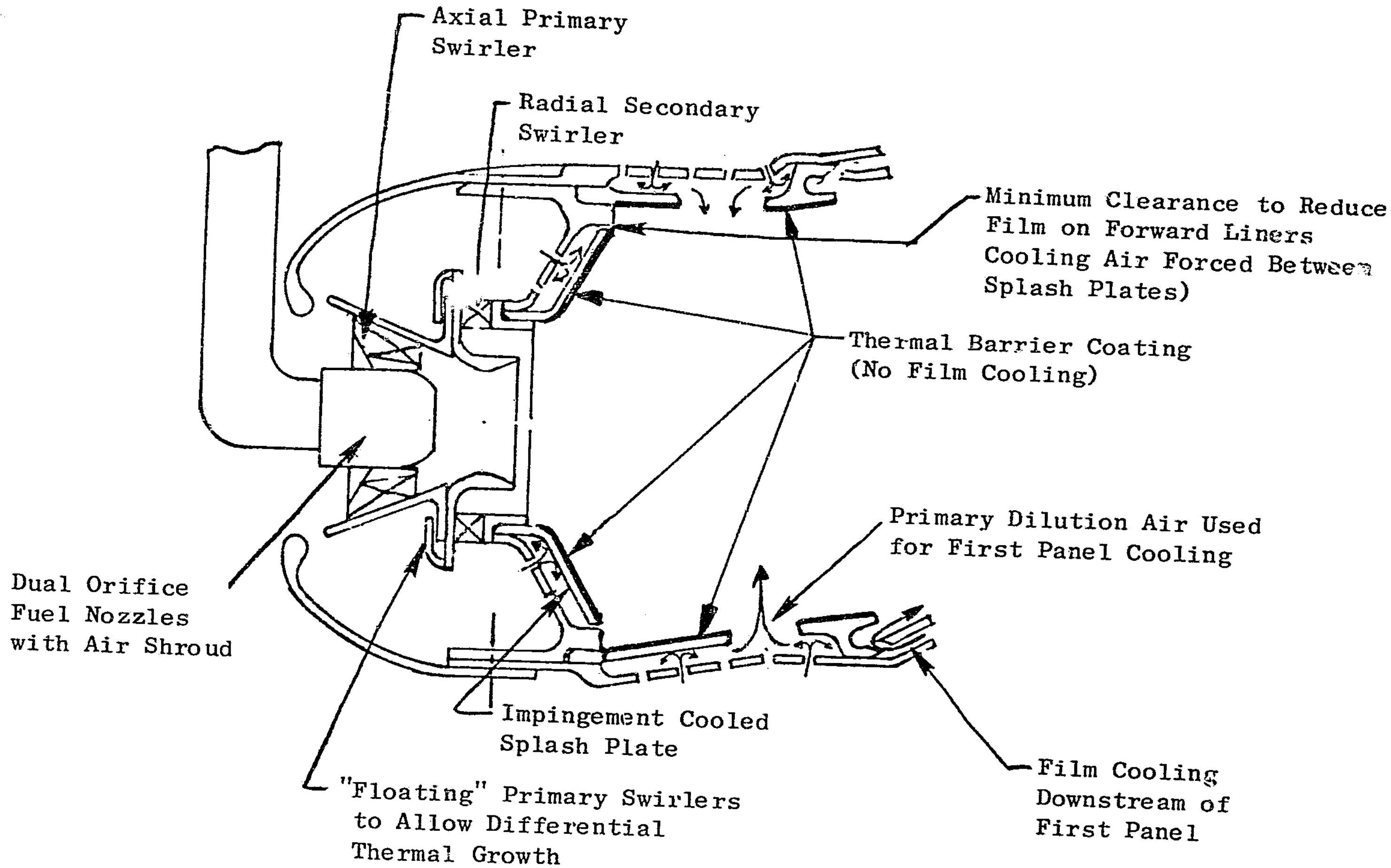


Figure 31. Pilot Dome Design Features.

The primary objective in the use of the hot-wall combustor technology was not to reduce idle emissions per se, but rather to reduce pilot-stage airflow requirements by running richer in the pilot dome. The tradeoff between emissions reduction and pilot dome flow requirements is illustrated in Figure 32, where CO emissions obtained with the LOPER hot-wall combustor are compared to conventional pilot stage emissions obtained in the NASA/GE Experimental Clean Combustor Program (ECCP, Reference 5). As shown in this figure, potential CO reductions of up to 85 percent can be obtained with the LOPER technology if pilot dome stoichiometry is unchanged. Alternatively, equivalent CO emissions can be obtained by decreasing the dome flow by approximately 35 percent (Φ_{dome} = 1.54). The LOPER combustor was an ideal case, with a long well-sheltered combustion zone, and emissions from the shorter catalytic-combustor pilot-stages would be expected to be higher. Therefore, for catalytic-combustor application, pilot-dome airflow reduction from the ideal value was limited to 23 percent Φ_{dome} = 1.3). Pilot dilution was also reduced (by 36 percent) to provide dilution to Φ = 0.83 at the 6 percent idle condition. A comparison of ECCP configuration D11 and catalytic-combustor pilot-stage flows is shown in Table XXVIII. As indicated in this table, pilot dome operation in the ECCP double-annular development combustor was slightly on the rich side of the ideal stoichiometry. Although the catalytic-combustor stoichiometry is somewhat higher than the double annular, the use of the LOPER hot-wall design features would be expected to result in a net idle CO and HC emissions reduction in the catalytic-combustor designs.

Liner Cooling

The basic liner cooling concept selected for the Phase I preliminary designs is impingement-plus-film cooling. In this concept, a double-wall liner construction is used as shown in Figure 33. Cooling air is first conducted through an array of small holes in the outer wall and forced to impinge on the "cool" surface of the inner wall to provide high, backside heat-transfer coefficients. This air then passes from the liner impingement cavity through slot metering holes to impingement cool the liner overhang. Finally, the cooling air exits through the film cooling slot to form a continuous cooling film which protects the hot side of the inner liner. Typically, 50 percent of the available pressure drop is taken across each of the liner walls. This cooling method was considered particularly applicable to the Phase I designs for several reasons. First, the use of impingement cooling is required to apply the LOPER "hot-wall" emissions reduction concept. Second, this liner cooling method lends itself to the use of an advanced, extended-life segmented liner construction such as that being used in the reference engine combustor. Finally, the use of this liner cooling method allows cooling flows to be reduced relative to conventional film cooling, which allows catalytic section airflow to be maximized.

Impingement-cooled splash plates used to protect the pilot domes are similar to those used in conventional combustor designs, except that a 0.51-mm thermal barrier coating is applied to reduce cooling flow requirements.

Catalytic-Reactor Mounting

Standard catalyst mounting methods applicable to gas-turbine catalytic-combustor applications have not yet been established, and further design and develop-

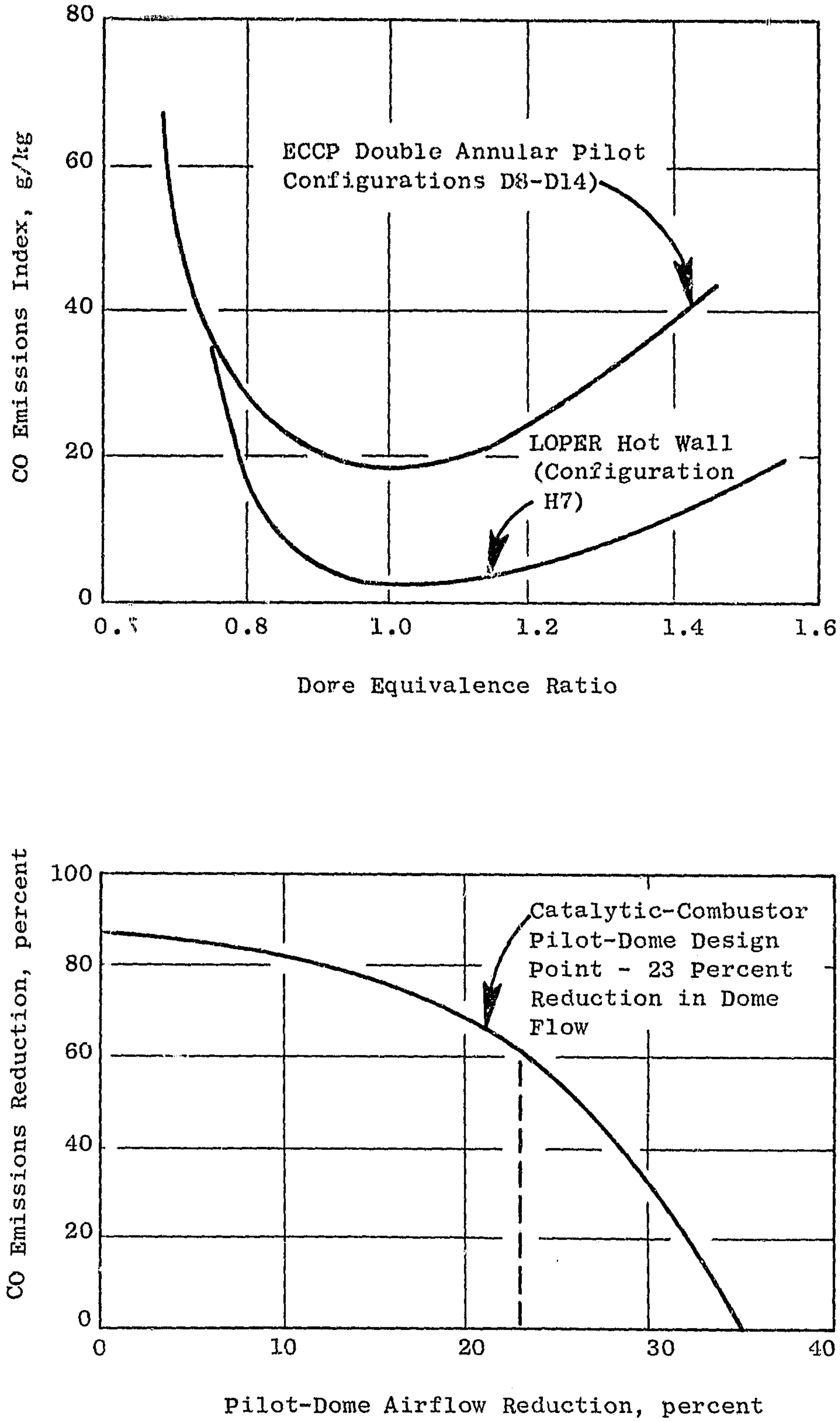


Figure 32. Emissions Airflow Reduction Tradeoff.

Table XXVIII. Comparison of Catalytic-Combustor and ECCP Pilot-Stage Stoichiometry.

	ECCP D11	Basic Parallel-Staged	Cannular Reverse Flow
Design Fuel/Air Ratio, g/kg	11.0	11.9	11.9
Swirler Flow, Percent W_c	12.5	10.0	10.0
Dome Cooling, Percent W_c	4.5	3.8	3.4
Pilot Primary Dilution, Percent W_c	4.7	7.4	7.4
Dome Combustion Air[a], Percent W_c	14.8	13.8	13.4
Dome Equivalence Ratio	1.09	1.26	1.30
Primary Zone Combustion Air[b], Percent W_c	21.7	21.2	20.8
Primary Zone Equivalence Ratio	0.74	0.82	0.84

a – Swirler flow + 1/2 dome cooling for ECCP; swirler flow + all dome cooling for catalytic combustors.

b – Swirler flow + dome cooling + primary dilution.

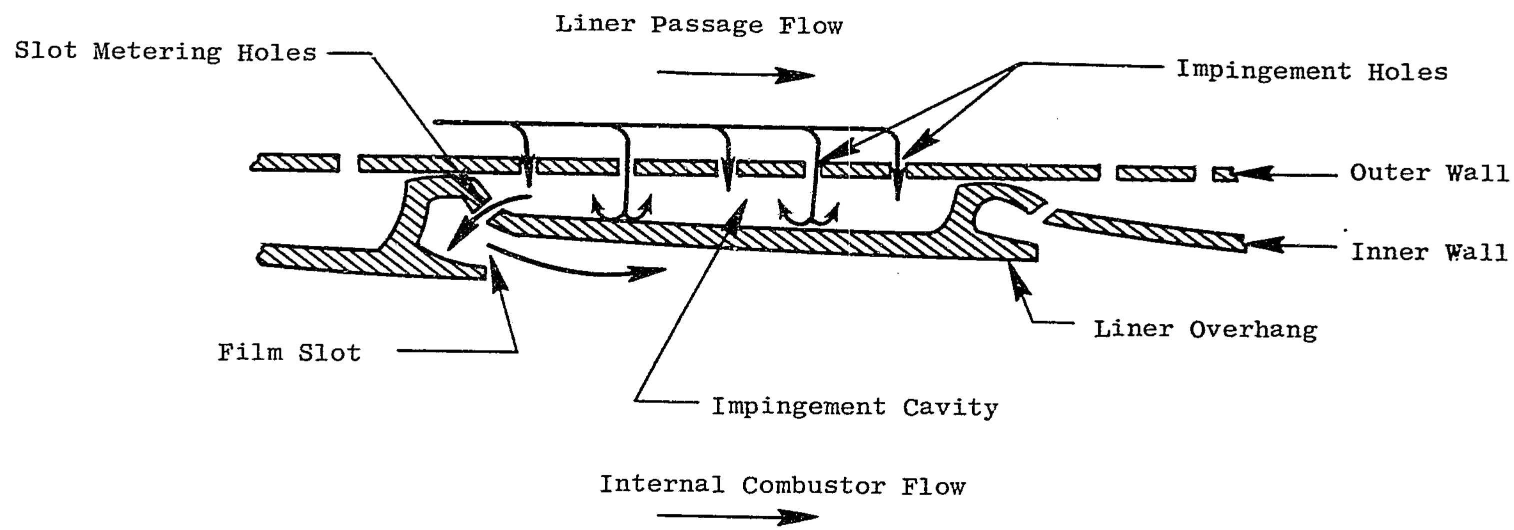


Figure 33. Double-Wall Liner Cooling Scheme.

ment efforts will be required to identify mounting techniques which will provide good performance for long-term cyclic operation. Design aspects which must be considered in catalytic-reactor mounting are (1) allowance for differential thermal growth between the catalyst substrate and the catalytic-reactor holder, (2) catalytic-reactor holder cooling and heat loss, (3) catalyst substrate thermal stress and pressure loading, and (4) leakage around the catalyst. In previous 60-degree sector test experience with the LOPER catalytic-combustor concept (Reference 33), two types of catalytic-reactor mounting methods were investigated. In initial tests, the catalytic-reactor was supported around its circumference by a ceramic fiber material, and axial loads were carried by direct contact between the ceramic substrate and the metallic holder. With this mounting method, substrate cracking occurred due to distortion of the metallic support rings which carried the axial loads. In subsequent tests, an uncooled compliant layer of metallic gauze was used both around the circumference of the catalytic-reactor and to carry the axial loads. This mounting system performed well under the conditions tested ($T_3 < 500$ K, $P_3 < 0.4$ MPa); however, it is expected that cooling flow would be required to protect the metallic gauze during operation at higher pressures and temperatures. In order to avoid plugging of the metallic gauze by impurities in the cooling air, a compliant layer of larger-scale coiled wire could be used as described in Reference 49.

In order to eliminate the cooling requirement, the catalytic-combustor designs utilize the support system shown in Figure 34. In this system, both circumferential and axial loads are carried by a ceramic fiber material. It is expected that this material will be sufficiently compliant to allow for differential thermal growth because the catalytic-reactor is divided into small segments. No cooling flow is used in this mounting system, but a small amount of purge air is admitted at the forward end of the mount to prevent leakage of the fuel-air mixture into the compliant layer. The outer channels of the catalytic-reactor are plugged in order to provide a thermal barrier to minimize heat loss and reduce heat loads to the metallic support.

7.1.4 Catalytic-Combustor Operation and Control Requirements

With both of the selected combustor concepts, operations between lightoff and 25 percent of rated thrust are conducted with uniform fueling of the pilot-stage. Above about 65 percent thrust, all injectors of both the pilot and catalyst stages are fueled. However, in the intermediate power range (25 to 65 percent of rated thrust), the combustor fuel-air ratio is not sufficiently high to allow uniform fueling of both stages, so it becomes necessary to fuel partial sectors of the pilot stage, catalyst stage, or both. In the conceptual design studies, pilot-stage fuel flow was minimized by sector burning (10 to 17 percent sector) of the pilot-stage, and increasingly large sectors of the catalyst stage were fueled as power was increased. With this method of staging, the catalytic-reactor stage was used to modulate engine speed, and at least three discrete increases in the size of the catalytic-reactor sector fueled are required.

In the preliminary design studies it was determined that control complexity could be reduced, and increased safety margin in catalytic-reactor stage fuel-air ratio could be obtained, by setting a constant fuel-air ratio (for the catalytic-reactor) and by using the pilot stage to modulate engine speed. Fuel-flow schedules for steady state operation are as shown in Figure 35. Between 25 and

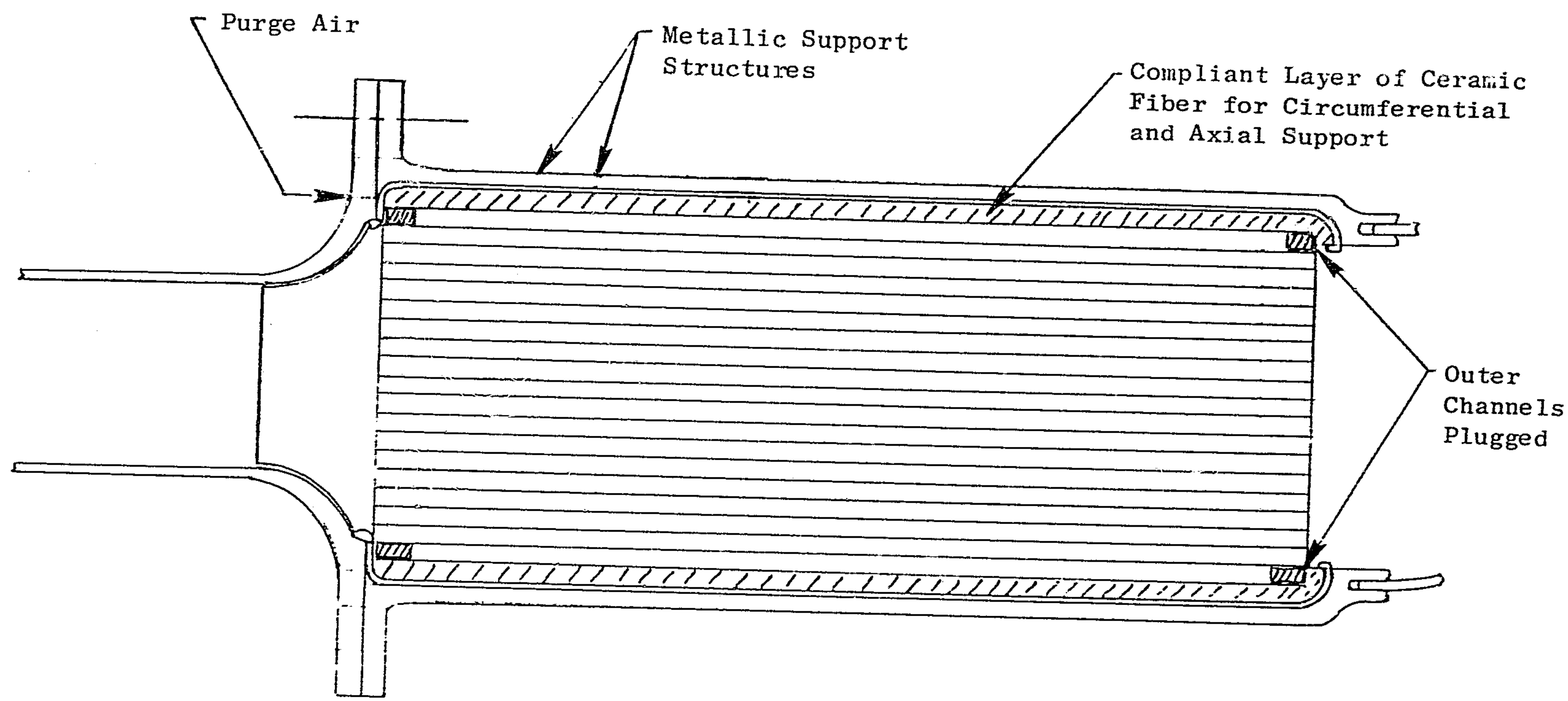


Figure 34. Catalytic Reactor Mounting Details.

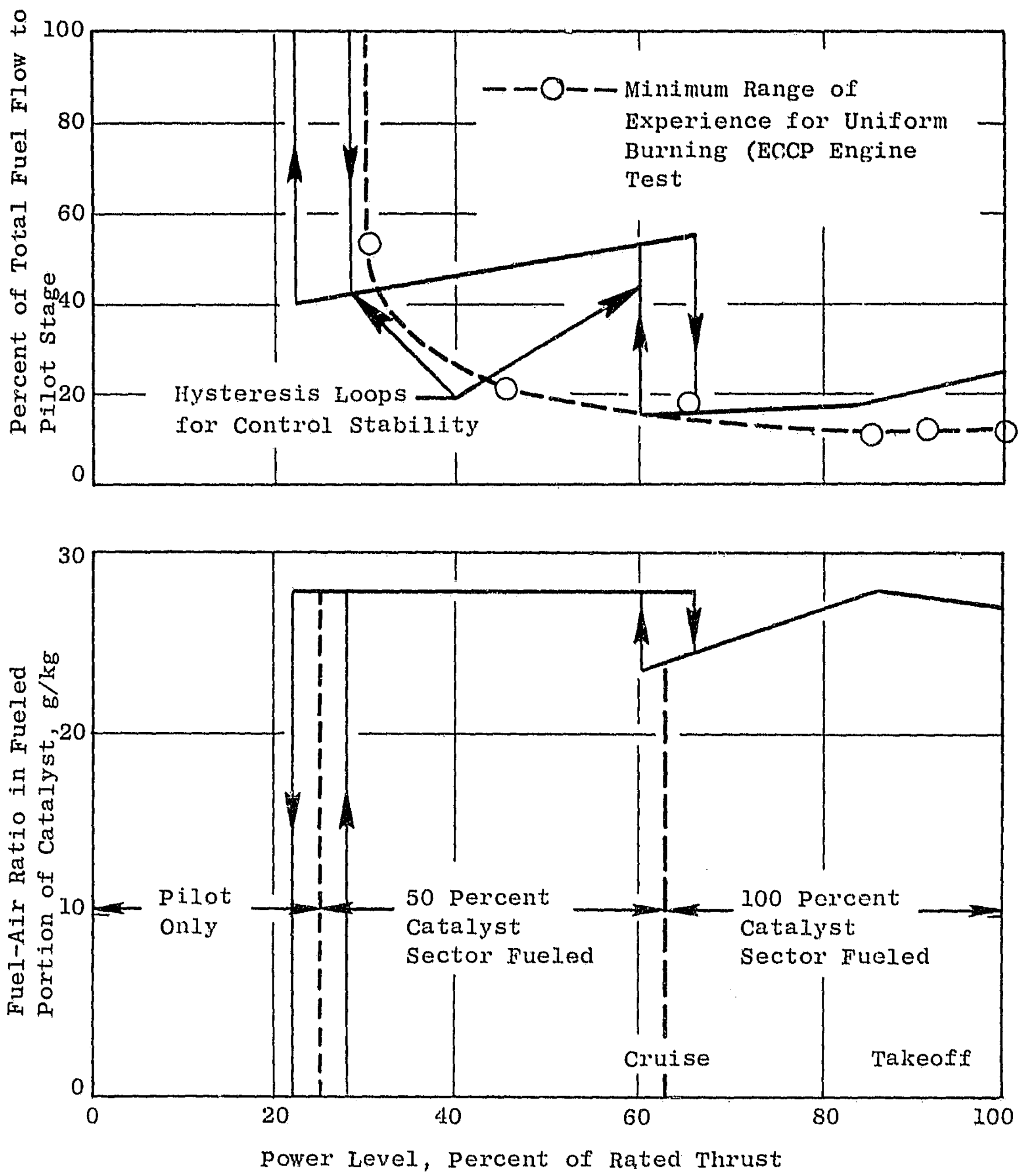


Figure 35. Cannular Reverse-Flow Combustor (Concept 4) Fuel-Flow Schedules.

63 percent power, a 50 percent sector (12 of 24 cans) is fueled. Fuel-air ratio in this sector is maintained at 28 g/kg, and pilot-stage fuel flow is increased with increasing thrust. As indicated in Figure 35, the percentage of total fuel flow to the pilot stage for 25 and 31 percent thrust-level range is below the minimum value for uniform pilot-stage burning based on ECCP engine tests. However, because the catalytic-combustor pilot stages were designed to run richer than the ECCP designs, it is expected that these low flow levels can be run without sector burning in the pilot stage. Tentative combustor operating parameters with this fuel scheduling approach are presented for each of the preliminary designs in Tables XXIX and XXX.

The reference engine will incorporate a Full Authority Digital Electronic Control (FADEC) system such as that shown in Figure 36. This type of system provides the capability to economically accommodate the additional control functions required for precise staging of fuel to the pilot and catalytic combustion stages through the use of time-sharing features.

Actuation components which will be required for operation of both of the preliminary catalytic-combustor designs include three fuel manifolds to provide fuel to the pilot-stage and the two sectors of the catalyst stage. Two electronically controlled fuel-flow splitter valves will be required to distribute the flow among these manifolds. One of these splitters will be used to control the proportion of total fuel flow supplied to the pilot stage. The second splitter will be used to distribute flow between the catalyst stage sectors. If pilot stage sector burning is used, one additional splitter and fuel manifold will be required. The reference engine with the baseline double-annular combustor will use one splitter and two fuel manifolds.

Additional control logic required for operation of the catalytic combustion system will include: (1) logic to ensure that the combustor inlet temperature is above the minimum catalytic-reactor ignition temperature prior to initiating fuel flow to the catalytic-reactor stage; (2) logic to protect against lean blowout of the pilot stage; (3) logic to protect against catalytic-reactor over-temperature and breakthrough; and (4) logic to detect and correct for auto-ignition and flashback as well as mechanical failure of the catalytic substrate.

Any of the above control functions could be achieved using either indirect or direct closed loop control techniques. However, it is anticipated that closed loop control (with direct feedback) will be required to adequately control the catalyst fuel-air ratio and to initiate corrective measures for auto-ignition and catalyst failure. For closed loop control of catalyst fuel flow, additional sensors will be needed to feed back catalyst bed temperature information. It is anticipated that optical pyrometers would fulfill this need. Additional temperature sensors located in the premixing duct would be required to detect autoignition.

7.1.5 Combustor Materials

Materials tentatively selected for the catalytic-combustor preliminary designs are shown in Figure 37. The pilot and catalytic-reactor stage liner materials in both designs are sheet or forged HS188. This alloy was designed for stability of the microstructure and properties during heat treatment and

Table XXIX. Tentative Operating Parameters: Basic Parallel-Staged Combustor.

Operating Condition	Idle	Approach		Transition #2		Climb	Takeoff	Cruise
		Pre-Transition	Post-Transition	Pre-Transition	Post-Transition			
Power, Percent Thrust	6	30	30	63	63	85	100	-
T_3, K	485	633	633	722	722	782	814	745
P_3, MPa	0.401	1.183	1.183	2.076	2.076	2.626	3.020	1.121
Catalyst Stage								
Sector Fueled, Percent	0	0	50	50	100	100	100	100
Airflow, Percent W_c	68.4	68.4	65.9	66.8	63.0	62.8	63.4	62.2
Fuel Flow, Percent W_f	0	0	66.6	49.5	80.0	78.9	70.2	80.5
Fuel-Air Ratio, g/kg	0	0	14.0	14.0	24.0	28.0	27.0	28.4
Catalyst Approach Velocity, m/s	33.5	39.8	38.4	40.5	38.2	39.1	40.8	37.5
Fuel-Air Residence Time, ms	2.1	1.8	1.8[a]	1.7[a]	1.8	1.8	1.7	1.9
Autoignition Delay Time[b], ms	-	-	188	23.3	23.3	8.1	4.8	30.7
Catalyst Exit Temperature, K	485	633	1147	1236	1559	1717	1720	1714
Allowable Pattern Factor	-	-	0.23[c]	0.14[c]	0.30	0.10	0.10	0.10
Pressure Drop, Percent P_3	3.5	3.7	4.2	3.8	4.3	4.3	4.1	4.3
Pilot Stage								
Sector Fueled, Percent	100	100	100	100	100	100	100	100
Airflow, Percent W_{36}	31.6	31.6	34.1	33.2	37.0	37.2	36.6	37.8
Fuel Flow, Percent W_f	100	100	33.4	50.5	20.0	21.1	29.8	19.5
Fuel-Air Ratio, g/kg	37.7	43.9	13.6	28.8	10.2	12.7	19.9	11.3
Exit Temperature, K	1760	2030	1140	1680	1105	1190	1510	1170
Dome Velocity, m/s	4.0	4.8	5.2	5.3	5.9	6.0	6.2	6.0
Dome Equivalence Ratio	1.26	1.47	0.45	0.96	0.34	0.42	0.66	0.38
System ΔP, Percent P_3	4.2	4.5	4.9	4.6	5.1	5.0	4.8	5.0

a - Bulk residence time does not account for flow redistribution during sector burning.

b - Autoignition time based on Stringer's Arrhonius equation.

c - Allowable pattern factor within fueled sector.

Table XXX. Tentative Operating Parameters: Cannular Reverse Flow, Parallel-Staged Combustor.

Operating Condition	Idle	Approach		Transition #2		Climb	Takeoff	Cruise
		Pre-Transition	Post-Transition	Pre-Transition	Post-Transition			
Power, Percent Thrust	6	30	30	63	63	85	100	-
T_3, K	485	633	633	722	722	782	814	745
P_3, MPa	0.401	1.183	1.183	2.076	2.076	2.626	3.020	1.121
Catalyst Stage								
Catalysts Fueled (24 total)	0	0	12	12	24	24	24	24
Airflow, Percent W_{36}	69.3	69.3	67.0(29.1[a])	67.5(30.1[a])	65.9	65.6	66.1	65.2
Fuel Flow, Percent W_c	0	0	58.8	44.6	83.7	82.3	73.2	84.4
Fuel-Air Ratio, g/kg	0	0	28.0	28.0	24.0	28.0	27.0	28.9
Catalyst Approach Velocity, m/s	27.0	32.0	26.9	29.0	31.7	32.3	33.8	31.2
Fuel-Air Residence Time, ms	2.2	1.8	2.2	2.0	1.8	1.8	1.7	1.9
Autoignition Delay Time[b], ms	-	-	188	23.3	23.3	8.1	4.8	30.7
Catalyst Exit Temperature, K	485	633	1590	1679	1559	1717	1720	1714
Allowable Pattern Factor	-	-	0.23	0.14	0.30	0.10	0.10	0.10
Pressure Drop, Percent P_3	2.1	2.3	2.7	2.5	2.8	2.7	2.6	2.8
Pilot Stage								
Sector Fueled, Percent	100	100	100	100	100	100	100	100
Airflow[c], Percent W_{36}	30.7	30.7	33.0	32.5	34.1	34.5	33.9	34.8
Fuel Flow, Percent W_f	100	100	41.2	55.4	16.3	17.7	26.8	15.6
Fuel-Air Ratio, g/kg	38.9	45.2	17.4	32.2	9.1	11.4	19.3	9.9
Exit Temperature, K	1780	2060	1255	1860	1060	1150	1490	1120
Dome Velocity, m/s	4.5	5.4	5.8	5.9	6.2	6.5	6.6	6.3
Dome Equivalence Ratio	1.30	1.51	0.58	1.08	0.30	0.38	0.65	0.33
System ΔP, Percent P_3	4.3	4.6	5.1	4.8	5.1	5.0	4.8	5.0

a - Figures in parentheses indicate flow,through fueled portion of catalyst.

b - Autoignition time based on Stringer's Arrhonius equation.

c - Includes all film cooling.

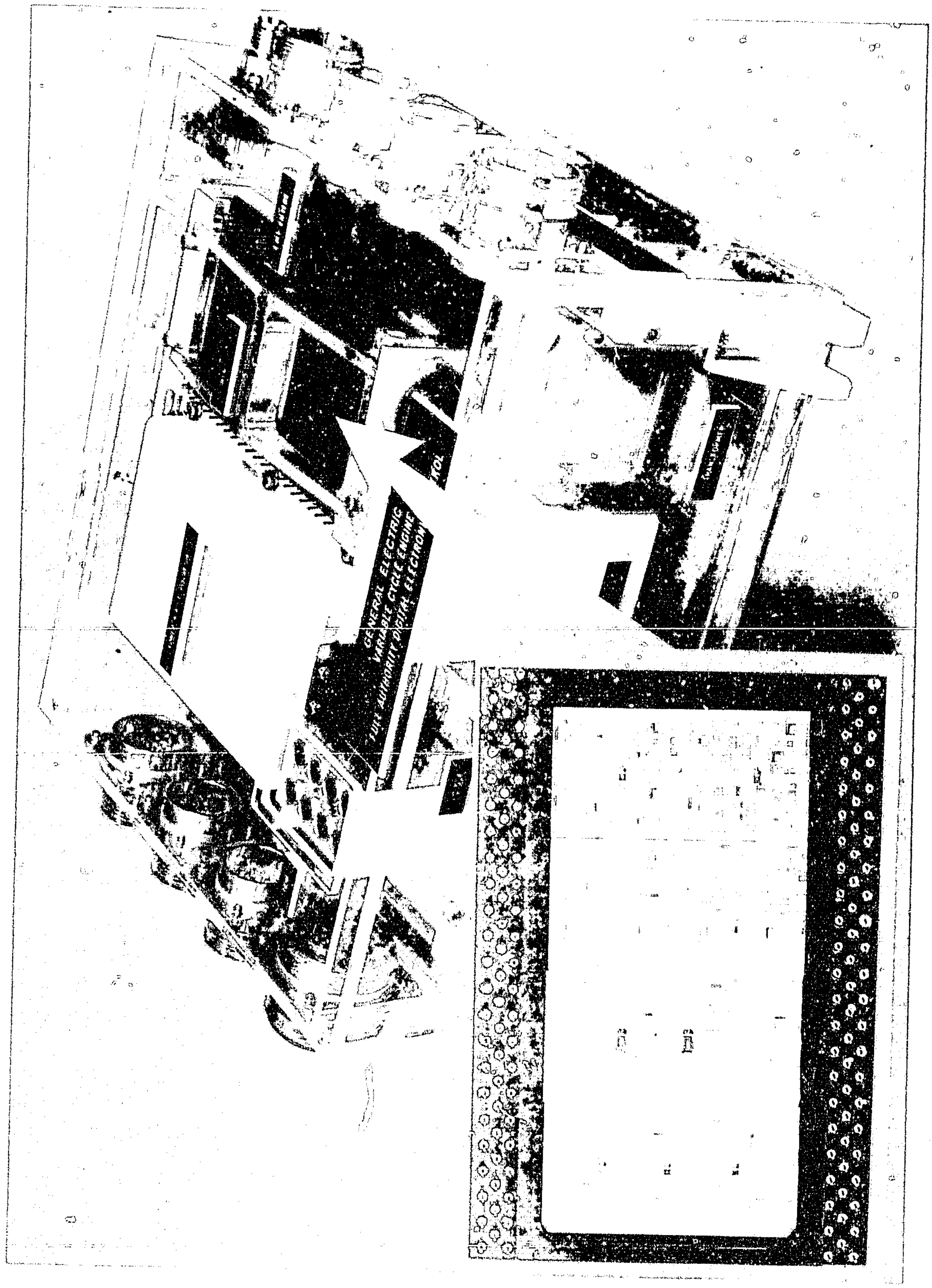


Figure 36. Full Authority Digital Engine Control (FADEC) Model and Typical Hybrid Substrate.

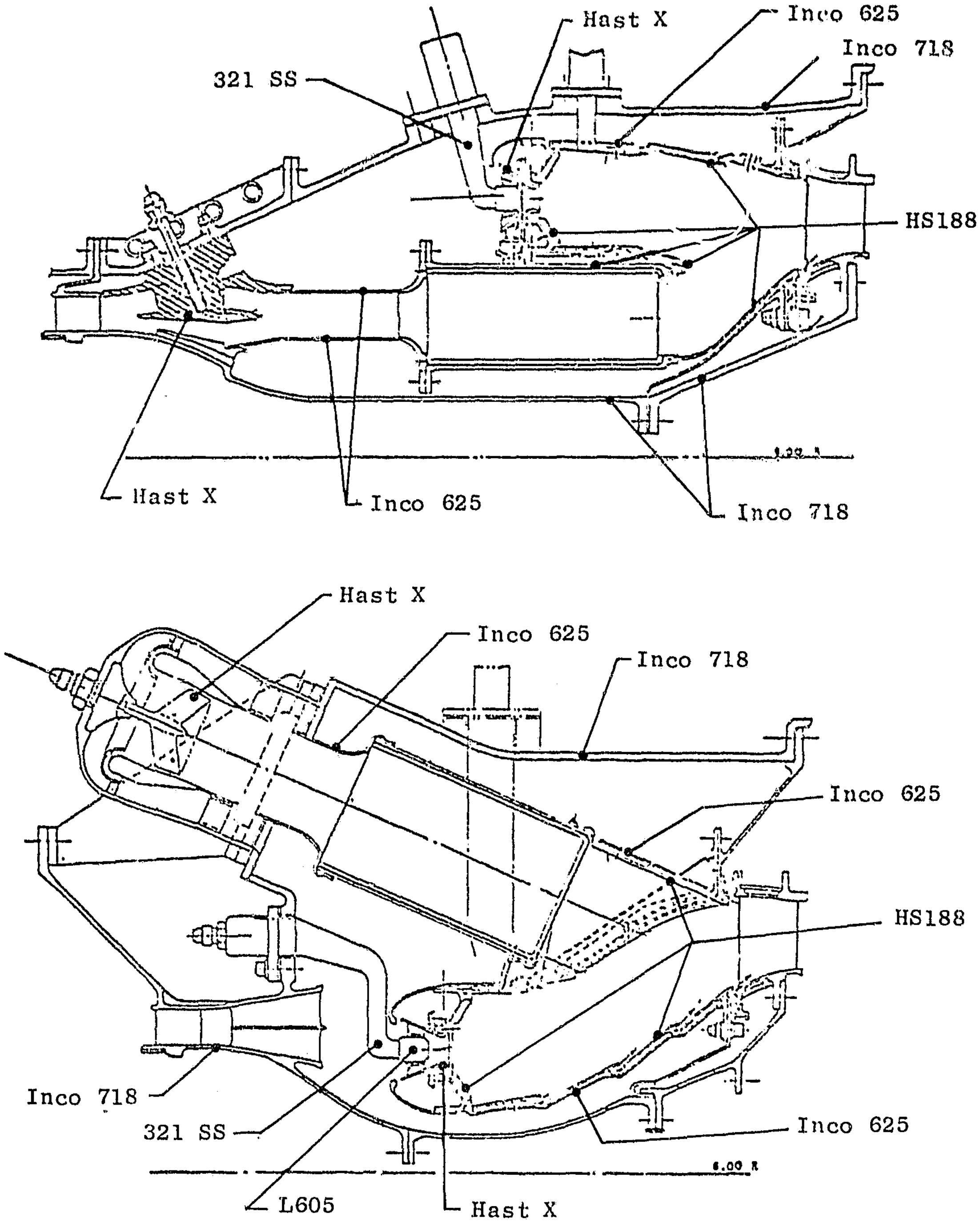


Figure 37. Catalytic Combustor Materials.

service. The hot corrosion resistance of HS188 is similar to L605 and somewhat better than Hastelloy X, another common liner material. HS188 exhibits good low cycle fatigue resistance up to operating temperatures in the 1150 K range. The dome structure, splash plates, and catalyst support structure are all fabricated from HS188 sheet material. A stabilized zirconia thermal barrier coating is applied to the dome splash plate and liner surfaces to reduce temperature levels in these components to the 1150 K temperature limit. The dome swirlers are cast Hastelloy X for low cost and uniformity of parts.

The structures not exposed to the hot combustion gases are machined or fabricated from Inco 625. This nickel-base alloy exhibits high strength capabilities up to 925 K and is thermally compatible with HS188. The Inco 625 structures include the outer impingement liner, outer cowl, and the diffuser extension shells mounted upstream of the catalyst support structure.

The combustor outer casing are subjected to high pressure loadings and must transmit compressor loads to the aft frame. Hence, Inco 718 is shown as the preferred material. These casings operate in a range up to 815 K, well within the limits of Inco 718.

The pilot-stage fuel systems of the Basic Parallel Staged Combustor are double-walled designs of 321 Stainless Steel. L605 nozzles are used to provide good wear resistance at the swirler-to-nozzle slip joint. The main stage fuel nozzles are cast Hastelloy X. This selection was made to maintain the thermal compatibility of the fuel nozzle assembly with the compressor OGV's and the Inco 625 main stage diffuser extension shell in the Basic Parallel Staged design, and with the Inco 625 mixing ducts in the Cannular Reverse-Flow design.

The diffuser/OGV structures are cast Inco 718. This provides adequate strength and stability for transmission of the high pressure nozzle loads. The inner nozzle support cone is machined from an Inco 718 forging.

7.2 PRELIMINARY DESIGN ANALYSES

Design Analyses were conducted based on the preliminary design drawings and tentative operating parameters described in Section 7.1 in order to refine design details and predict the performance of each of the catalytic combustor concepts. Results of these analyses are summarized in the following paragraphs.

7.2.1 Flow Analyses

Pilot-stage flow levels were selected primarily to obtain good performance at the idle thrust level. Therefore, flow analyses to size pilot-stage swirlers and dilution and cooling holes were conducted for idle operating conditions. Pressure data used for hole sizing were obtained using the CODET and CAP combustor design computer programs, which solve the general one-dimensional flow equations at increments along the combustor and annular passage centerlines. Passage and combustor internal pressures obtained are shown in Figures 38 and 39. In both combustor designs, liner orifices were sized such that there would be no axial variation in liner impingement cavity pressure in order to minimize leakage between liner panels. In the Cannular Reverse-Flow design (Figure 39),

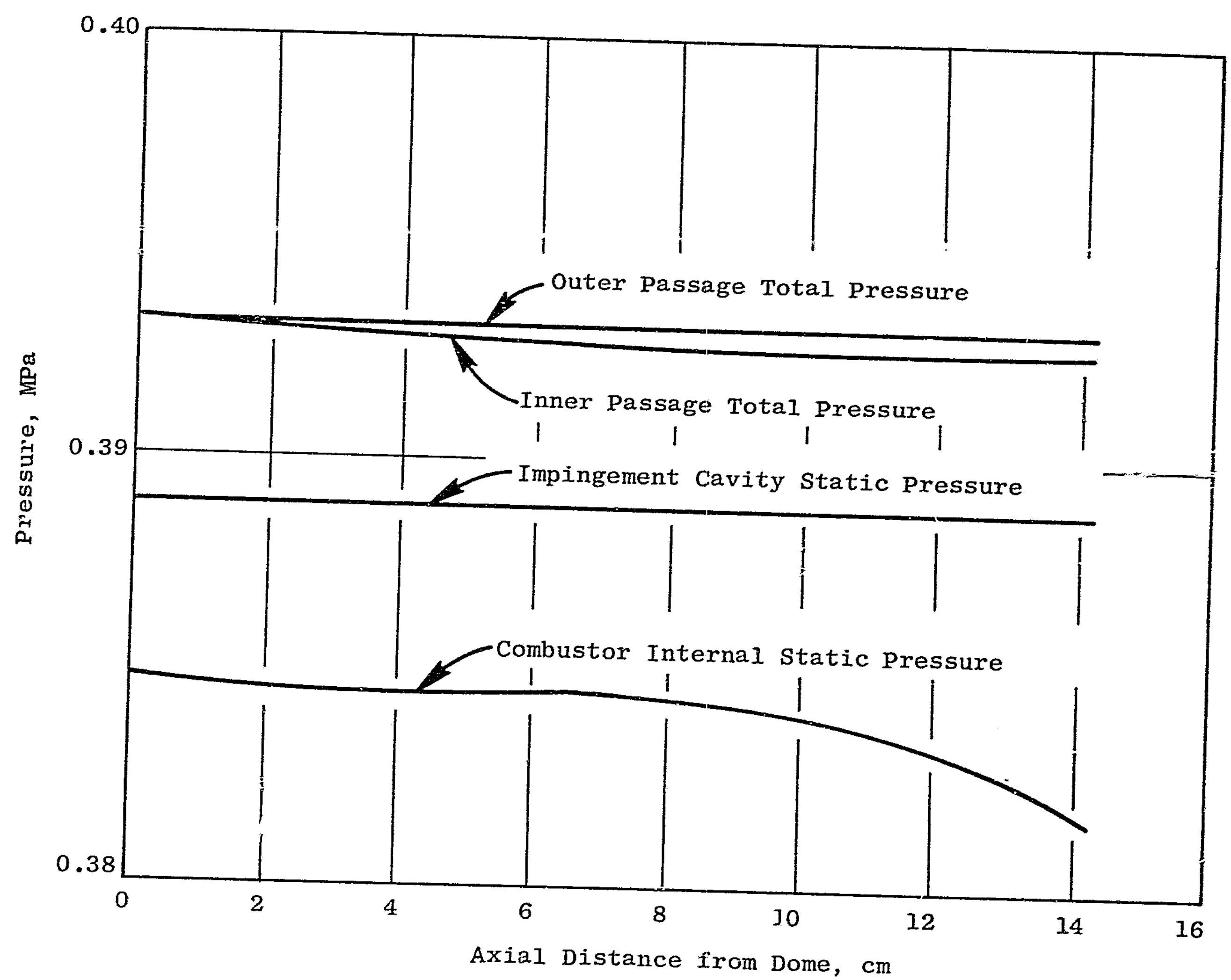


Figure 38. Combustor Pressure Distributions for the Basic Parallel-Staged Catalytic Combustor (Idle Power).

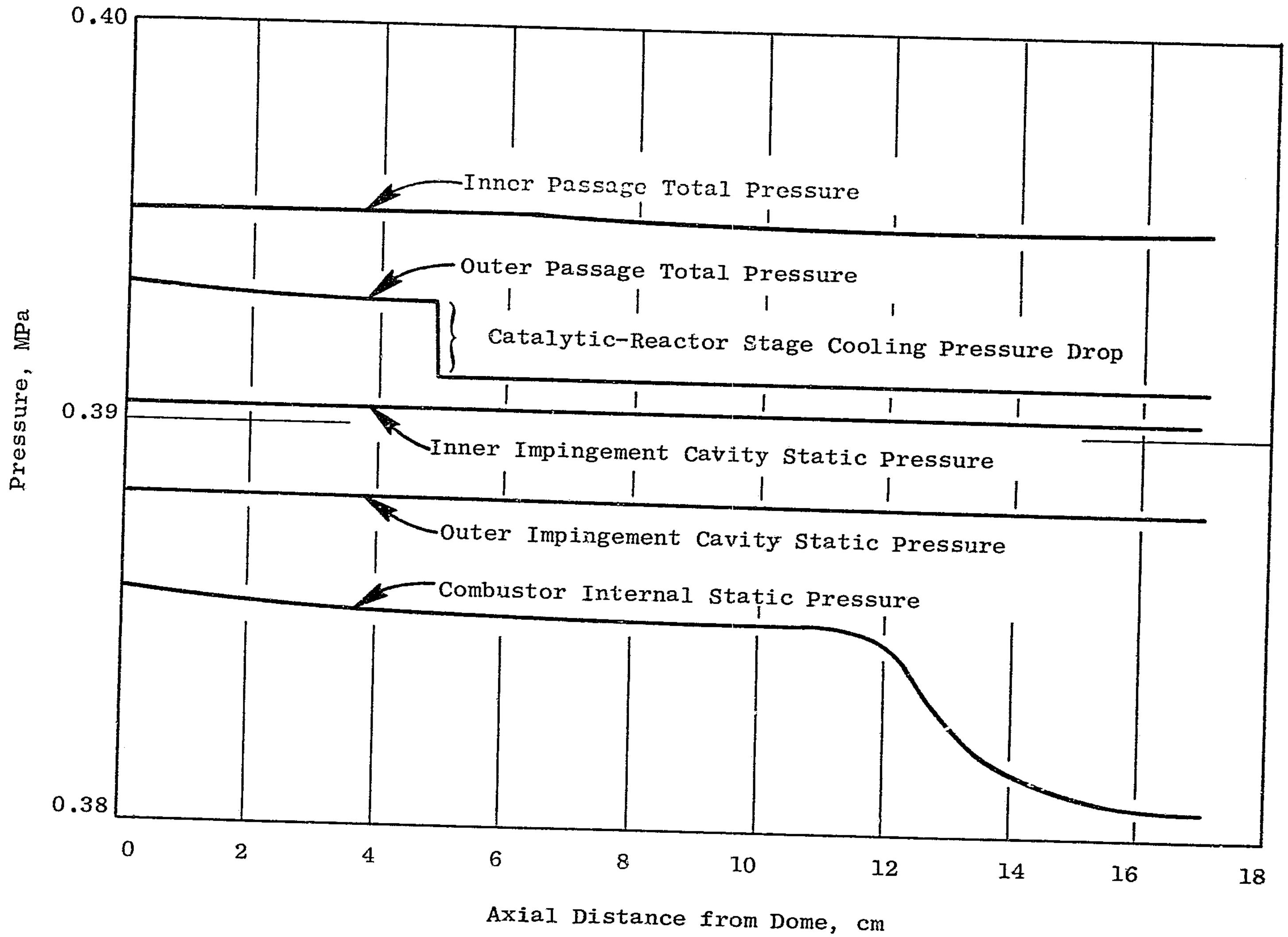


Figure 39. Combustor Pressure Distributions for the Cannular, Reverse-Flow Parallel-Staged Catalytic Combustor (Idle Power).

the outer impingement cavity pressure is lower than that within the inner cavity. This pressure was reduced because overall liner pressure drop is decreased by the use of series catalyst stage cooling which was estimated at 0.5 percent. In all cases, approximately 50 percent of available pressure drop at the center of the liner was used for backside impingement cooling, with remaining pressure drop used for film cooling. Detailed hole sizes for the two preliminary designs are presented in Tables XXXI and XXXII. Swirler sizing parameters are compared in Table XXXIII.

Additional flow analyses were conducted to determine the effects of variation in catalytic-reactor stage temperature rise on catalytic-reactor airflow levels and overall combustion system pressure drop at constant inlet flow function. As indicated in Figures 40 and 41, the Cannular Reverse-Flow combustor is less sensitive to changes in catalyst temperature rise than the Basic Parallel Staged design. This is because of the step diffuser dumping loss in series with the reverse-flow catalyst stages, which tends to decrease the effect of changes in catalytic-reactor flow resistance. The pressure drop and catalytic reactor flow values in Figures 40 and 41 were corrected for inlet flow function to obtain the values listed in Tables XXIX and XXX.

7.2.2 Heat Transfer Analyses

One- and two-dimensional heat transfer analyses were conducted (1) to ensure that selected cooling levels (initially based on reference engine cooling rates) would be sufficient to protect the combustion liner, (2) to predict the performance of the advanced cooling features incorporated into the pilot dome and catalyst stage aft sectors, and (3) to provide metal temperature data for prediction of combustor life. Analyses were conducted with standard heat transfer correlations which have been verified in previous combustor development programs.

A summary of heat transfer analysis results is presented in Table XXXIV. These analyses were based on the Cannular Reverse-Flow combustor design; however, because of the similarity in design and operation of the two combustor concepts, the results are equally applicable to the Basic Parallel Staged design. Additional analyses conducted based on the Basic Parallel Staged combustor indicated that metal temperatures would be within ± 20 K of the values indicated in Table XXXIV. Two-dimensional analyses were conducted to determine average and "hot-streak" liner temperature for a representative pilot-stage liner panel (Figure 42) where the hot-streak temperature is the expected peak panel temperature at any axial location. Additional one-dimensional analyses were conducted to determine the range of metal temperatures which would be expected in regions of the combustor where advanced liner cooling features are used, or where unusually high liner temperatures are expected. These regions include the first panel of the pilot stage and the region aft of the catalyst in both combustor designs, where the cooling film has been eliminated and backside convective cooling and thermal barrier coatings are utilized, and the aft panel of the pilot stage in the Cannular Reverse-Flow design, which is exposed to higher velocity air exiting the catalyst stage cans. In the latter case, it is expected that cooling film effectiveness may be significantly degraded. Predicted temperature levels in all regions studied are generally below 1150 K, which is comparable to levels

Table XXXI. Basic Parallel-Staged Combustor Preliminary Design Hole Sizes.

Location	Flow[a] % W_{36}	Effective Area, cm^2	Discharge Coefficient	Physical Area cm^2	Number of Holes	Hole Diameter, D, cm	Number of Hole Rows	Nominal Hole Spacing, S, cm	Spacing-to-Diameter Ratio, S/D	Web Thickness, cm
Impingement Cooling										
Outer Liner - Panel 1	4.0	24.2	0.81	29.9	1160	0.181	5	1.05	5.80	0.87
- Panel 2	2.3	13.9	0.83	16.8	860	0.158	4	1.13	7.17	0.97
- Panel 3	3.0	18.3	0.83	22.0	860	0.181	4	1.11	6.14	0.93
Inner Liner - Panel 1	3.4	21.0	0.65	32.3	940	0.209	5	1.05	5.02	0.84
- Panel 2	1.1	7.0	0.79	8.8	720	0.125	3	0.83	6.65	0.70
Film Cooling										
Outer Liner - Panel 1				No Film						
- Panel 2	(2.3)	14.5	0.80	18.1	800	0.170	1	0.305	1.80	0.135
- Panel 3	(2.2)	13.4	0.80	16.7	800	0.163	1	0.305	1.87	0.142
- Aft Slot	(0.8)	4.2	0.80	5.2	400	0.129	1	0.567	4.39	0.436
Inner Liner - Panel 1				No Film						
- Panel 2	(1.1)	6.9	0.80	8.6	500	0.117	1	0.246	2.11	0.129
- Centerbody	0.9	4.0	0.80	5.0	400	0.127	1	0.490	3.86	0.363
- Aft Slot	0.8	3.2	0.80	4.0	400	0.113	1	0.475	4.20	0.362
Primary Dilution (Panel 1)										
Outer	(4.0)	25.7	0.60	42.8	80	0.825	1	2.913	3.53	2.088
Inner	(3.4)	21.8	0.60	36.4	80	0.761	1	2.515	3.30	1.754
Splashplate Cooling	3.8	16.5	0.83	19.9	1695	0.122	7	0.775	6.35	0.653
Profile Trim Holes (Outer Liner)	1.7	7.4	0.95	7.7	40	0.495	1	5.705	11.53	5.210

a - Flow fed from impingement cavities shown in parentheses.

Table XXXII. Cannular, Reverse-Flow Parallel-Staged Combustor Preliminary Design Hole Sizes.

Location	Flow[a] % W_{36}	Effective Area, cm^2	Discharge Coefficient	Physical Area cm^2	Number of Holes	Hole Diameter, D, cm	Number of Hole Rows	Nominal Hole Spacing, S, cm	Spacing-to-Diameter Ratio, S/D	Web Thickness, cm
Impingement Cooling										
Outer Liner - Panel 1	1.1	23.6	0.83	28.4	1050	0.186	5	0.599	4.83	0.713
- Panel 2	1.6	11.8	[illegible]	[illegible]	825	0.159	4	0.839	5.88	0.739
- Panel 3	0.6	4.5	0.80	5.6	300	0.155	4	0.826	5.37	0.671
- Panel 4	1.8	13.4	0.80	16.7	740	0.169	4	0.699	4.13	0.530
Inner Liner - Panel 1	3.3	19.3	0.75	25.7	850	0.196	5	0.947	4.83	0.751
- Panel 2	2.0	11.7	0.83	14.1	900	0.142	4	0.752	5.28	0.610
- Panel 3	1.6	9.4	0.83	11.4	900	0.127	4	0.777	6.12	0.650
- Panel 4	2.3	13.6	0.83	16.3	900	0.152	4	0.805	5.30	0.653
Film Cooling										
Outer Liner - Panel 1		No Film								
- Panel 2	(1.6)	11.9	0.80	14.9	600	0.178	1	0.323	1.81	0.145
- Panel 3	(0.6)	4.4	0.80	5.5	Preferential Transition Joint Cooling					
- Panel 4	(1.0)	4.7	0.80	5.9						
- Aft Slot	(0.8)	3.8	0.80	4.7						
Inner Liner - Panel 1		No Film								
- Panel 2	(2.0)	11.2	0.80	14.1	480	0.193	1	0.325	1.68	0.132
- Panel 3	(1.6)	9.0	0.80	11.2	549	0.163	1	0.315	1.93	0.152
- Panel 4	(1.5)	6.3	0.80	7.8	750	0.114	1	0.246	2.16	0.132
- Aft Slot	(0.8)	3.3	0.80	4.2	400	0.115	1	0.475	4.12	0.360
Primary Dilution										
Outer	(4.1)	32.2	0.60	53.6	48	1.192	1	3.962	3.32	2.770
Inner	(5.3)	19.1	0.60	31.8	48	0.919	1	3.251	3.54	2.332
Splashplate Cooling	3.4	16.1	0.80	20.1	1267	0.142	7	0.798	5.62	0.656

a - Flow fed from impingement cavities shown in parentheses.

Table XXXIII. Swirler Sizing Parameters (Idle Conditions).

Parameter	Design Value: Basic Parallel Staged	Design Value: Cannular Reverse-Flow
Number of Swirlers	40	24
Idle Pressure Drop Percent P_3	2.15	3.11
Primary Swirler		
Flow Per Swirler, Percent W_{36}	0.100	0.167
Effective Metering Area, cm cm^2	0.436	0.592
Number of Vanes	8	10
Vane Thickness, mm	0.76	0.76
Vane Exit Root Diameter, cm	1.40	1.52
Vane Exit Tip Diameter, cm	2.01	2.17
Metering Gap, mm	1.96	2.03
Vane Length, cm	1.11	0.93
Venturi Throat Diameter, cm	1.11	1.42
Swirl Angle, ^{o}CW-ALF	60.5	54.2
Discharge Coefficient	0.7	0.7
Secondary Swirler		
Flow Per Swirler, Percent P_3	0.150	0.250
Effective Metering Area, cm^2	0.654	0.887
Number of Vanes	16	12
Vane Thickness, mm	0.76	1.27
Vane Inner Radius, cm	1.09	1.32
Vane Outer Radius, cm	1.83	1.79
Vane Angle, ^{o}	54.2	68.3
Flow Exit Angle, ^{o}CW-ALF	67.7	70.8
Vane Chord Length, cm	0.97	0.84
Discharge Coefficient	0.69	0.69

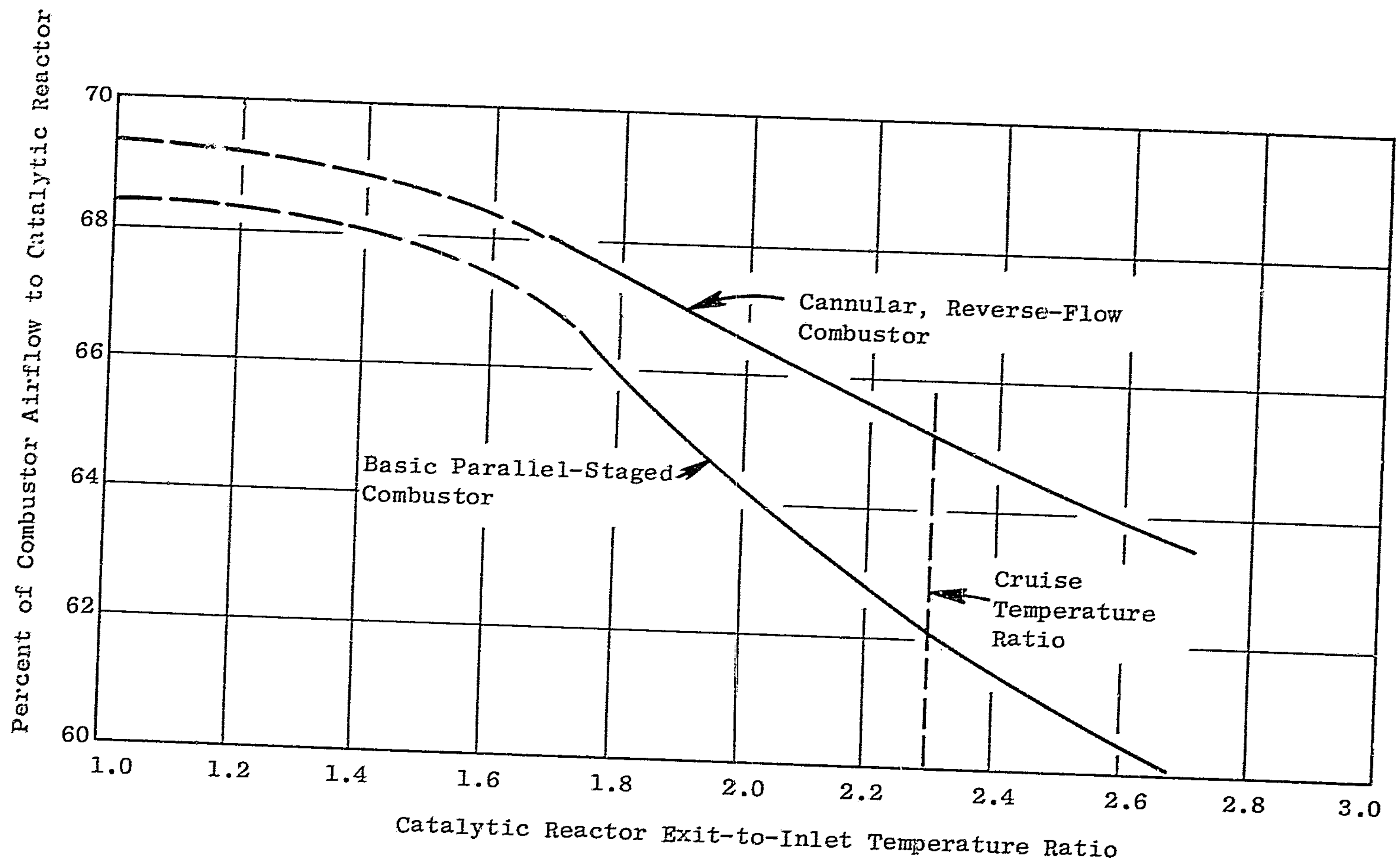


Figure 40. Effect of Catalytic Reactor Temperature Rise on Reactor Airflow (Cruise Inlet Conditions).

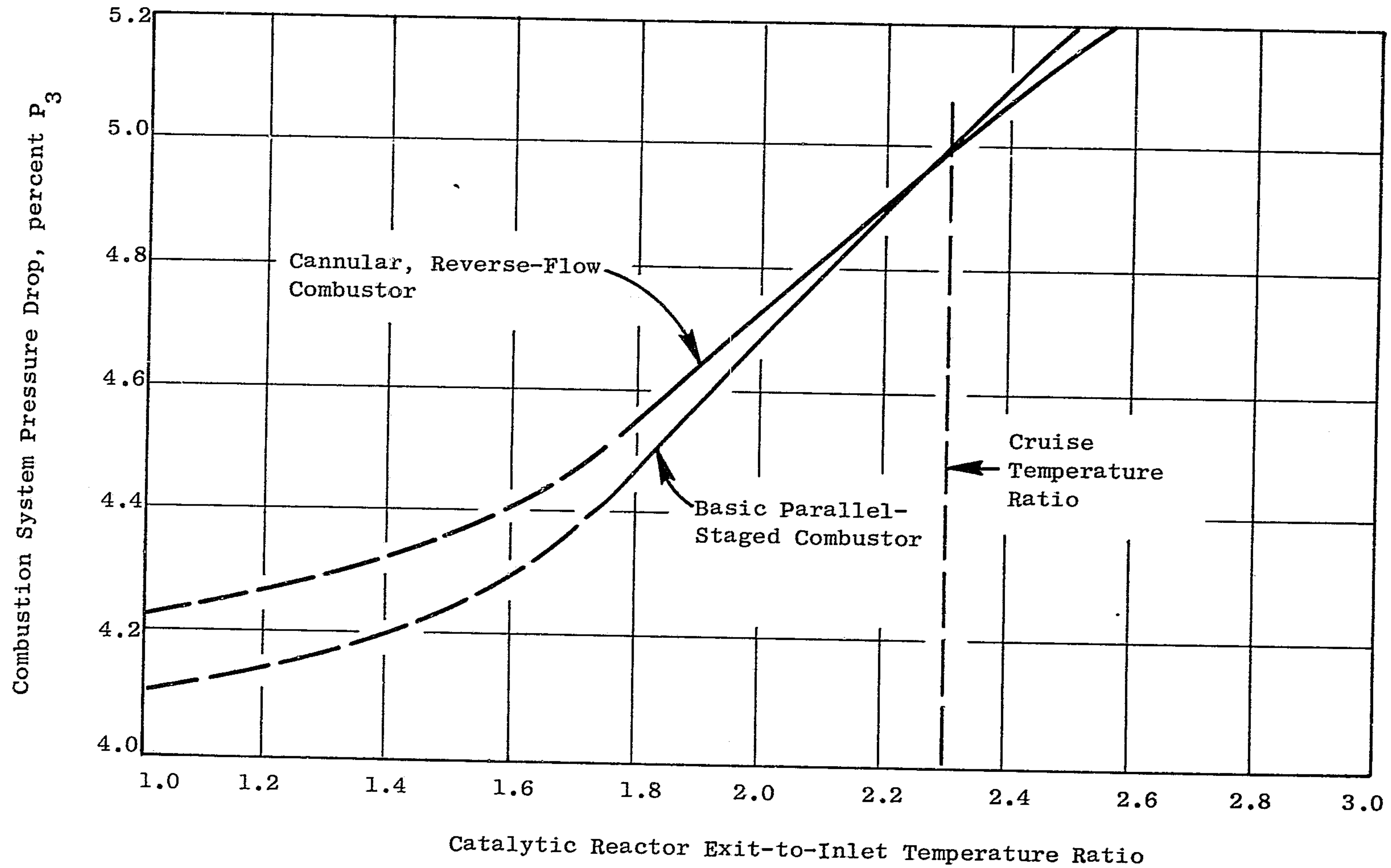


Figure 41. Effect of Catalytic Reactor Temperature Rise on Combustion System Pressure Drop (Cruise Inlet Conditions).

Table XXXIV. Heat Transfer Analysis Summary.

Stage	Location	Configuration	Analysis Type	Power Level	Predicted Average Temperature, K*	Predicted Hot-Streak Temperature, K*
Pilot Stage	Panel 1	- Impingement Backside Cooling - No Film Cooling - 0.5 mm Thermal Barrier	One Dimensional	Approach (100% W_f to Pilot)	-	1050 (1350) 1135 (1488)**
				Takeoff		1089 (1478)
	Center Panel	- Impingement Backside Cooling - Film Cooling	Two Dimensional	Approach (100% W_f to Pilot)	See Figure 42	See Figure 42
	Aft Panel	- Impingement Backside Cooling - Film Cooling	One Dimensional	Takeoff	1094	1172 1311 - No Film
Catalyst Stage	Aft Section	- Convection Backside Cooling - No Film Cooling - 0.5 mm Thermal Barrier	One Dimensional	Takeoff	1100 (1339)	1156 - (1433)

* Numbers in parentheses indicate thermal barrier coating surface temperature.
** Stoichiometric Hot Streat

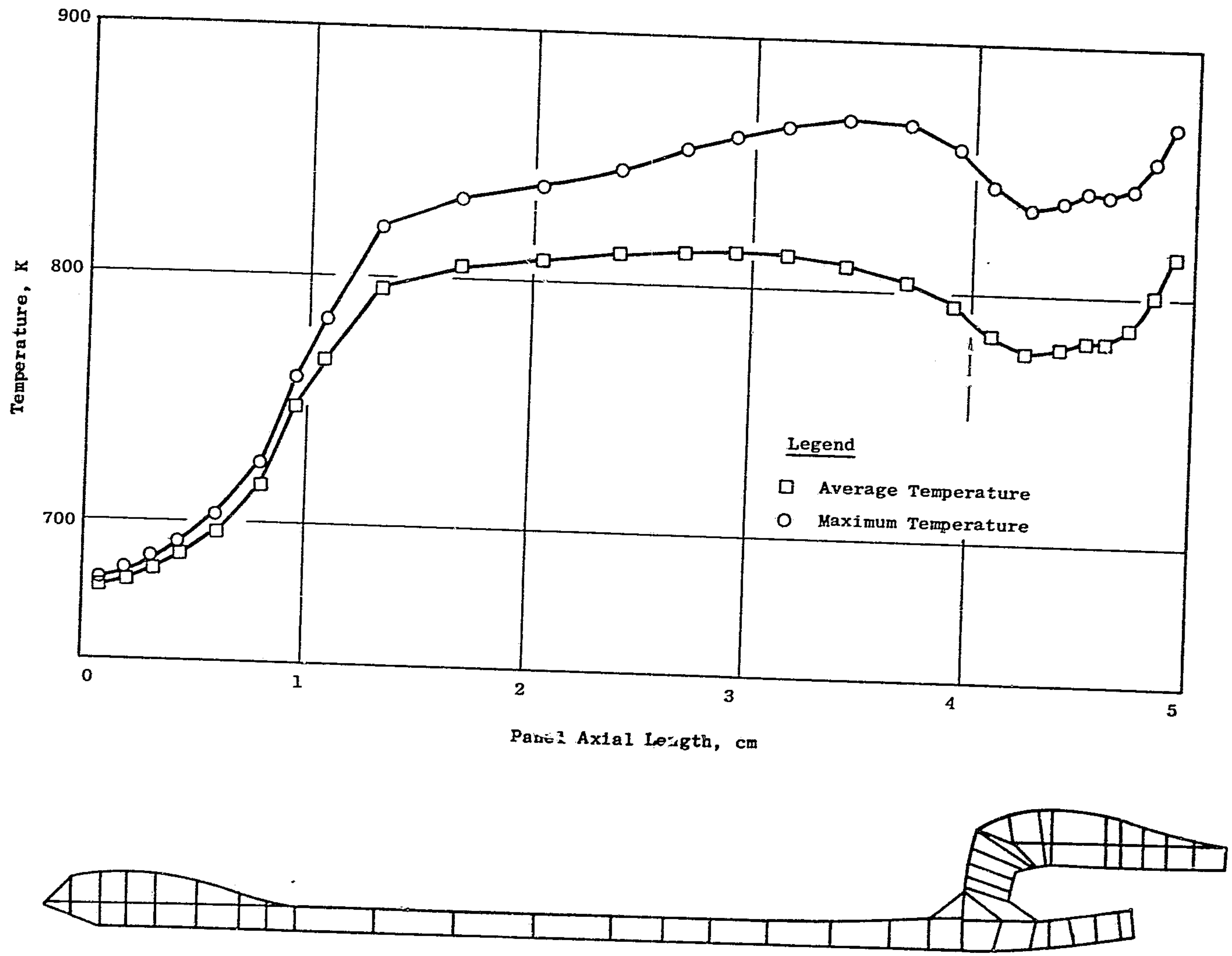


Figure 42. Pilot Stage Liner Temperatures, Approach Power Level (Panel 3) Inner Cannular.

obtained in the reference engine combustor. Based on the aft panel analyses, metal temperatures in this region of the cannular design could run as high as 1311 K if the film cooling is totally ineffective because of the scrubbing action of the catalytic-reactor exit airflow. Thus, during combustor development, it may be necessary to add preferential cooling to this panel or to contour the catalytic-reactor exit ducts to reduce scrubbing. Another development concern will be the long-term durability of the thermal barrier coatings used in both of the combustor designs, which are predicted to operate at peak surface temperature approaching 1500 K.

7.2.3 Fuel-Air Preparation System Performance

Fuel-air carburetion systems for both of the combustor preliminary designs utilize multiple-point cross-stream injectors. In selecting fuel injection patterns for these systems, conservative values for minimum orifice size (0.5 mm) and minimum injection pressure (0.1 MPa) were utilized. This limited the maximum number of fuel injection points to approximately 150. As described in Section 7.1, each of the preliminary designs used injection systems having a total of 144 orifices.

Results of fuel-air preparation system analyses are as follows:

Fuel Evaporation

Predicted fuel evaporation for each of the conceptual designs is indicated in Table XXXV. Evaporation levels above 85 percent are expected at the approach conditions, and virtually complete evaporation is expected at the approach, climb, takeoff, and normal cruise power levels.

Mixture Uniformity

Fuel-air mixture uniformity within ± 10 percent is predicted with the Basic Parallel-Staged design due to the position of the fuel mixing duct, which is expected to see high turbulence levels characteristics of compressor exit flow (Figure 18). Mixture uniformity in the Cannular Reverse-Flow design will depend strongly on the turbulence levels associated with the flow reversing passages at the forward end of the catalyst cam. Variation between +20 and -50 percent of the average fuel-air ratio is predicted based on rig test correlations (low turbulence), if the fuel injector is modeled as a ring source (Reference 31). Significant development effort is expected to be required in order to obtain uniformity within ± 10 percent with this design.

Fuel droplet penetration calculated for both combustor designs (Table XXXV) appears to be sufficient to prevent wetting of the fuel injector surfaces at all conditions. Some additional development effort may be required with the Basic Parallel-Staged design to determine a fuel injection angle which will prevent wetting of the surface of the fuel-air mixing duct.

Table XXXV. Fuel Evaporation and Penetration - Dependence on Engine Operating Mode.

Concept	Condition	Airstream Velocity m/s	Initial Drop Diameter [a] m	Length For 99% Evaporation cm	Predicted Evaporation Percent [b]	Droplet Penetration [c] cm
BASIC PARALLEL-STAGED	Approach	62.4	21.5	15.9	89.4	1.08
	Climb	63.6	18.3	4.7	100.0	-
	Takeoff	66.3	17.3	3.8	100.0	1.18
	Normal Cruise	61.0	23.1	6.3	100.0	1.04 (0.90[d])
CANNULAR REVERSE-FLOW	Approach	52.5	24.5	17.4	87.0	1.13
	Climb	63.1	18.4	4.7	100.0	-
	Takeoff	66.1	17.4	3.8	100.0	1.23
	Normal Cruise	61.0	23.1	6.3	100.0	1.09 (0.90[d])

a. "Heatup" computer program (based on correlation of Reference 40.)

b. "Heatup" computer program. L = 10.2 cm.

c. Based on correlation presented in Reference 50, assuming normal injection.

d. Penetration at minimum cruise conditions.

Sensitivity to Inlet Distortion and Swirl

The Basic Parallel-Staged combustor fuel-air carburetion system is expected to be very sensitive to compressor-exit distortion and swirl because of the location of the fuel injection section, which is immediately downstream of the diffuser exit. Measurements of temperature and velocity profiles at the compressor exit of a current technology combustor indicate that acceptable profiles can be obtained. Temperature measurements show a radial variation of about ± 1.5 percent across the annulus height. Typical radial and circumferential profiles obtained near takeoff power level are shown in Figure 43. A velocity variation between +25 percent and -50 percent of the average is indicated on the radial profiles, with an additional 30 percent decrement in the wakes of the outlet guide vanes (OGV). However, in the region corresponding to the catalyst inlet flow, the total variation is between about +25 percent and -5 percent of the average velocity. The flow decrement in the OGV wakes was measured at approximately one-third of the OGV chord length downstream of the OGV trailing edge. Minimal swirl was observed. This wake would be less apparent at the fuel injection plane, which is more than 2.5 chord lengths downstream. Based on these measurements, it is expected that acceptable velocity profiles can be obtained with careful diffuser design and development. The Cannular Reverse-Flow combustor should be insensitive to inlet distortion because the catalytic-reactor stage airflow is first dumped into the combustor plenum, then reaccelerated into the fuel-air mixing section. The primary development concern with this design will be obtaining a uniform velocity profile at the exit of the flow reversing vanes located upstream of the fuel injectors.

Fuel Injector Insulation

Minimal fuel-injector insulation has been used in both combustor preliminary designs in order to minimize fuel injector thickness and to provide aerodynamically clean fuel injection sections. Double-wall insulation used in the Basic Parallel-Staged combustor is expected to be sufficient to prevent fuel decomposition within the fuel injectors. However, additional injector development may be required to prevent decomposition in the Cannular Reverse-Flow design, where single-wall construction is used. With this construction, bulk fuel temperature rise through the injector is predicted to be below 20 K at all operating conditions, but internal fuel passage wall temperatures could be up to 570 K. This is somewhat higher than wall temperatures used in current fuel injector designs, which are maintained below about 480 K.

7.2.4 Combustor Emissions

Preliminary design emissions predictions are presented in Table XXXVI. Normal cruise NO_x emissions were reduced from about 2 g/kg to 1.2 - 1.5 g/kg by the use of the hot-wall dome to reduce pilot-stage airflow requirements. NO_x emissions at the approach conditions were increased relative to the conceptual designs because of the revised approach power fueling schedules. Both designs are expected to meet applicable EPA emissions standards. (Reference 3).

As with the conceptual designs, smoke emissions were predicted to be well below the applicable standards at all steady-state operating conditions.

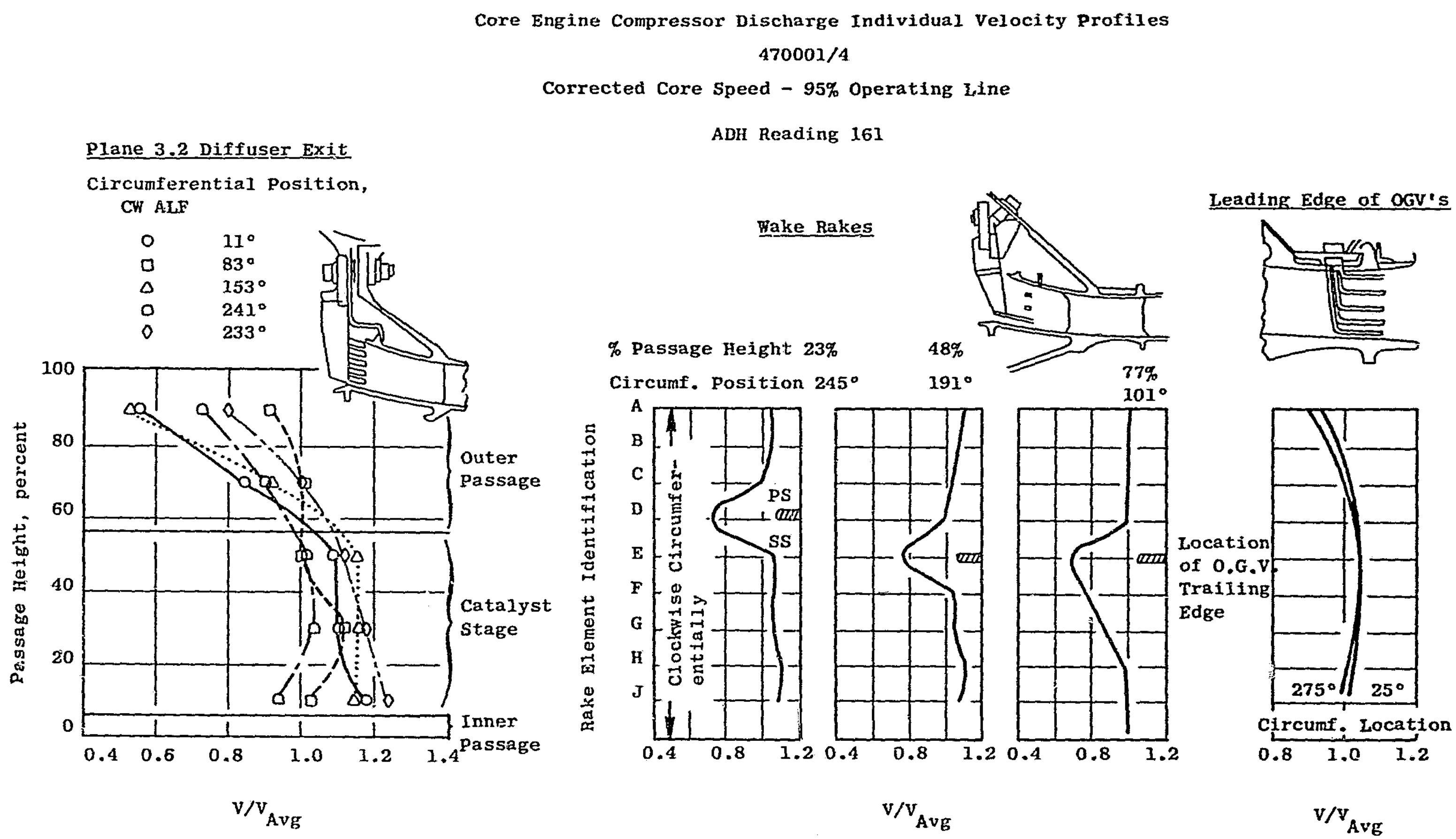


Figure 43. Typical Combustor Inlet-Diffuser Exit Velocity Profiles for Current Technology Engine (High Power Operation).

Table XXXVI. Predicted Pollutant Emissions[a] for the two Most Promising Concepts.

PARAMETER	Basic Parallel-Staged			Cannular Reverse Flow		
	CO	HC	NO_x	CO	HC	NO_x
Idle	12.4	0.2	3.0	12.4	0.2	2.9
Approach	2.5	0.2	1.7	2.4	0.2	2.0
Climb	2.4	0.3	2.5	2.5	0.3	2.2
Takeoff	2.2	0.2	7.8	2.3	0.2	7.3
Cruise	2.5	0.3	1.5	2.6	0.3	1.2
EPAP, Values[b]	1.96	0.07	1.00	1.97	0.07	0.96

a. Emission Index. (g/kg fuel)

b. EPA parameter. (pounds-mass/1000 pounds-thrust hours/cycles)

7.2.5 Combustor Exit-Temperature and Velocity Profiles

Predicted takeoff profile and pattern factors for the Basic Parallel-Staged combustor are shown in Figure 44. The average radial temperature profile is strongly inboard peaked, but peak temperatures (pattern factor) are more uniform because of the low catalyst stage pattern factor. Pattern factor is safely below the goal of 0.35 temperature profiles with this design. If necessary, the profile shape obtained with this combustor could be modified by burning an increased proportion of total fuel flow in the pilot stage; however, NO_x emissions would be increased.

A flat radial temperature profile is expected to be obtained with the Cannular Reverse-Flow design because of improved mixing between the pilot and cannular catalyst stage flows. The peak pattern factor is expected to be approximately the same as that of the Basic Parallel-Staged design (P.F. $\approx$ 0.24).

Although takeoff temperature profiles are expected to be favorable with both combustor designs, nonuniform radial and circumferential profiles at off-design conditions may present a problem. As indicated in Tables XXIX and XXX, during operation near the approach power level with only the pilot stage fueled, pilot-stage exit temperatures are predicted to be in excess of 2000 K. This is comparable to the conditions encountered in the reference engine double-annular combustor. During operations between 25 and 65 percent power, sector burning will be utilized in both combustor designs. Under these conditions, fueling requirements will be determined by a tradeoff between emissions and pattern factor considerations, particularly in the Basic Parallel-Staged Design (Figure 45) For minimum emissions with this design, it would be advantageous to fuel a single 180° sector of the catalytic-reactor and to uniformly fuel the pilot stage. With this fueling mode, there are only two "fringe" regions where fueled and unfueled sectors interface, resulting in locally lean fuel-air mixtures and decreased efficiency. However, in order to avoid asymmetrical growth in the turbine nozzle due to nonuniform circumferential temperature profiles, it will probably be necessary to fuel at least two opposed 90° sectors of the catalytic-reactor (for example, sectors A and C in Figure 45) and to fuel the pilot stage in the other two sectors (B and D). This results in four interface regions between fueled and unfueled sectors. This tradeoff does not apply to the Cannular design, since alternating catalyst stage cans can be fueled with no loss in combustor efficiency.

The relatively flat radial exit-temperature profiles provided by the catalytic combustor systems will probably require some adjustment in turbine cooling flow distribution, but no change in overall turbine cooling flow requirements is expected. Combustor exit velocity profiles are expected to be similar to those obtained with the baseline double-annular reference engine combustor. Variations in temperature and velocity profiles are not expected to have any significant effect on turbine performance because of the large acceleration (from Mach $\approx$ 0.1 to Mach $\approx$ 1.0) through the first stage turbine vanes.

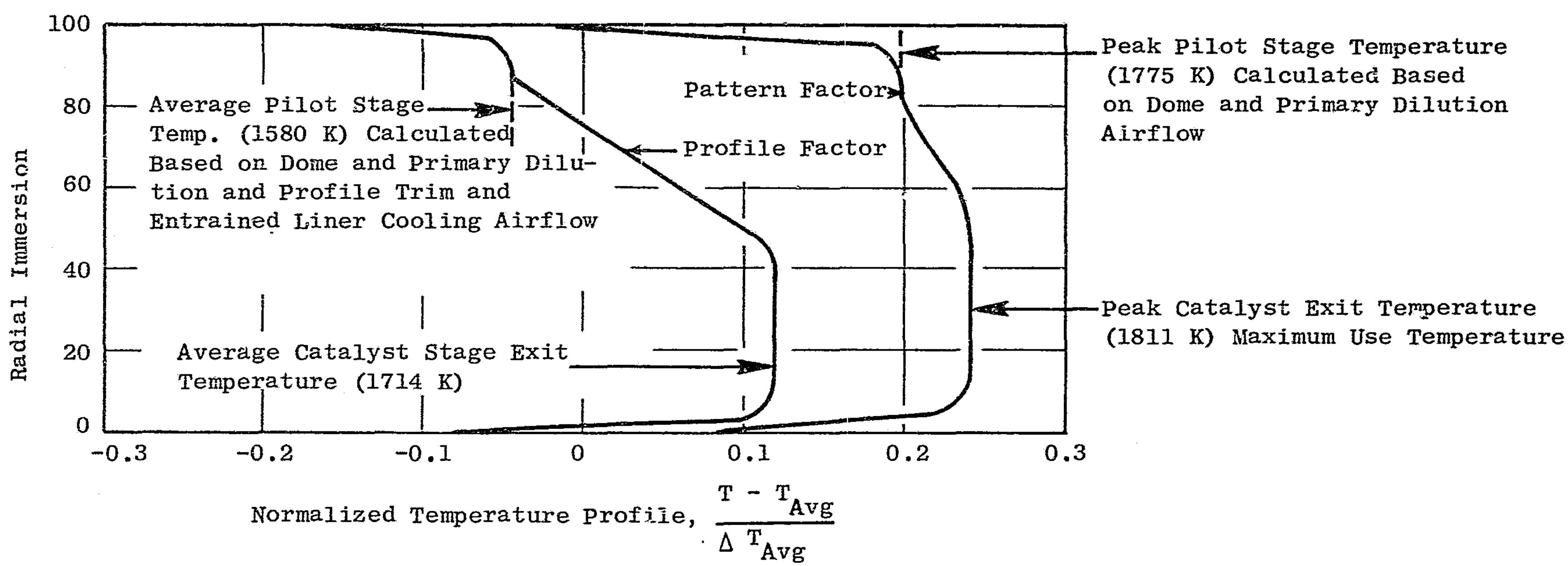


Figure 44. Predicted Exit Temperature Profiles for Basic Parallel-Staged Combustor Design.

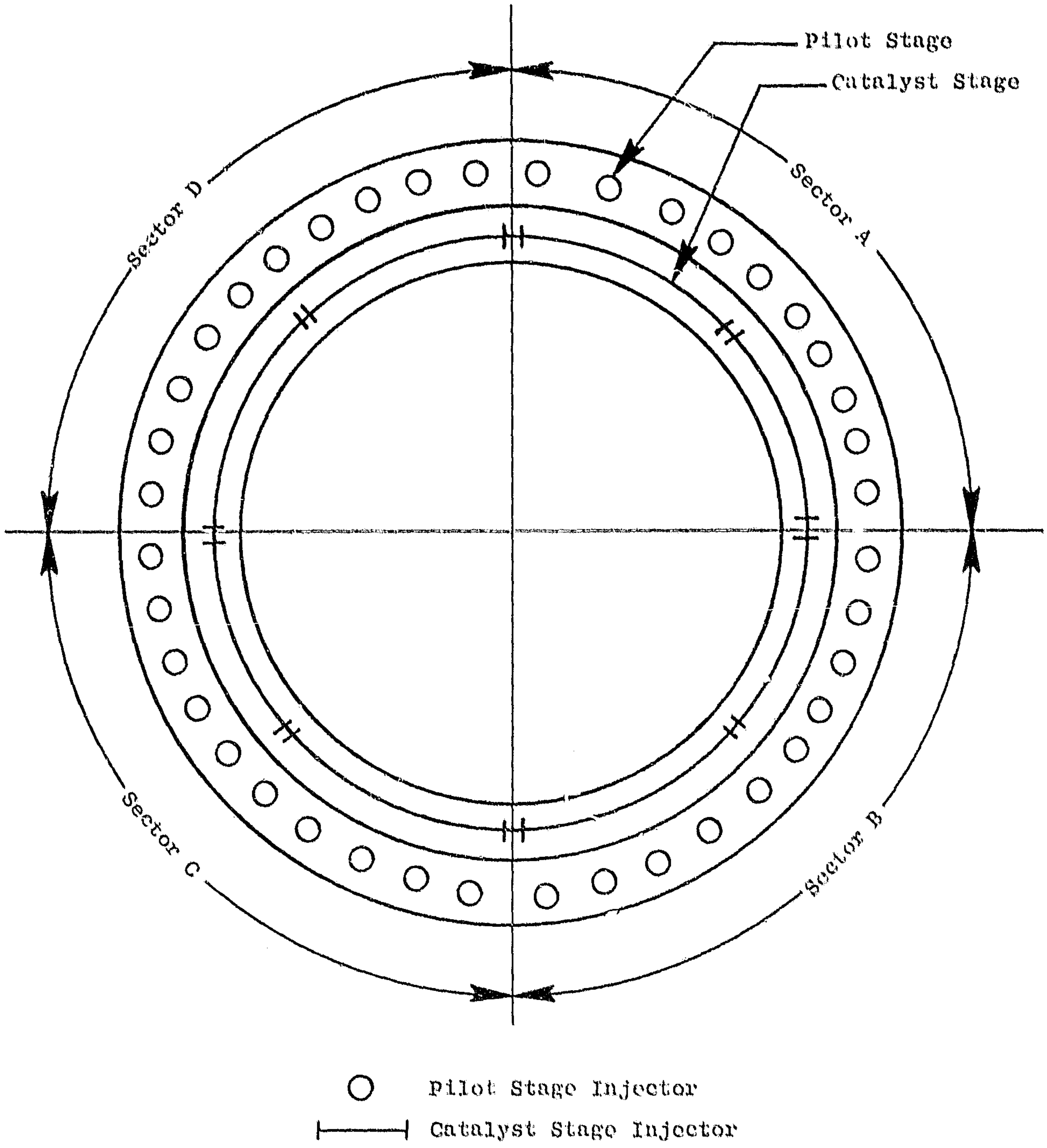


Figure 45. Basic Parallel-Staged Combustor Sector Burning.

7.2.6 Combustor Life

The liner construction approaches for both catalytic combustor concepts are basically the same. In addition, metal temperature predictions are very similar for both designs. Hence, the general life analyses of both concepts are the same.

The primary source of high stresses and failures in machined ring liners is the cooling ring configuration. High thermal gradients generally exist between the hot liner panel and the cooler ring nugget. The induced stresses are generally high enough to induce plastic deformation. Failures generally occur when low cycle fatigue (LCF) cracking progresses beyond a serviceable limit, or creep deformation affects the aerodynamic performance or interrupts the cooling system. To minimize the liner susceptibility to creep deformation and to maintain a high level of LCF strength, the liner cooling system was designed to limit the peak temperature to about 1150 K.

A preliminary analysis of the thermal gradients in the film liner was conducted for the purpose of estimating liner life. It was found, based on field experience data from liners of similar construction and materials, that an LCF life of 2000 to 2500 flight cycles could be expected for a typical commercial application. Repair or replacement of the liners at this point would then be required. Obviously this was a general analysis and did not include local discontinuity and deviation effects that occur, for example, at the junction of the cans with the annular chamber in the cannular design. Careful attention must be given to the heat transfers and mechanical design in regions such as this to avoid more severe life limiting conditions. An alternative combustor liner approach, the "shingle" liner, which employs a segmented low-stressed film liner and a 360° support structure, is used in the reference engine combustor.

This approach could also be incorporated into the Phase 1 designs. It is estimated that the shingle liner approach would extend the liner life to 18,000 or more cycles.

In order to achieve a long-life combustor dome design, care was taken to adequately shield the dome structure from the hot combustion gases using the splash plates. Hence, the limiting portion of the dome design becomes the oxidation life of the splash plate material. The application of long-life thermal barrier coating should provide adequate oxidation protection.

A preliminary analysis of the load carrying capability of the combustor outer casing was conducted for the Cannular Reverse-Flow design. The requirements of the Cannular system coupled with the pilot stage fuel nozzle requirements necessitated the design of a load transmitting frame. This frame produced a redundant structure in the region of the diffuser. The frame struts were designed with slotted bolt holes at the interface with the Cannular plate to allow for adjustments at assembly and thereby minimize part preloading. The forward support cone of the diffuser was designed with enough flexibility to keep thermal and mechanically locked-in stresses below 50 ksi. That is well within the design limits of Inco 718 and should present no life limiting problems.

8.0 CONCLUDING REMARKS

Some uncertainty remains in the prediction of catalytic-combustor system performance. Very uniform catalytic-reactor exit temperature profiles are expected, but catalytic-reactor present-day maximum-temperature constraints increase pattern-factor values during circumferential fuel staging at off-design conditions. Acceptable fuel-air mixture uniformity to the catalytic-reactor without autoignition will most likely require significant development. This is especially true for the broadened specification fuels that might replace Jet-A fuel. Single-stage liquid-fuel injectior is viewed as a marginally acceptable premixing-prevaporizing technique. Other methods such as axial fuel staging or external fuel vaporization add weight, length or complexity to the system. At the present time, the modified multiple-jet cross-stream injector appears to have the highest probability of meeting all carburetion system design criteria. Another uncertainty is catalytic-reactor durability. Long-term durability at steady-state operating conditions has been demonstrated; however, cyclic high-temperature performance has not been proven. It is expected that significant development effort will be required to establish catalyst, substrated, and mounting systems with sufficient durability and thermal shock performance. Additionally, advanced sensing techniques will have to be developed to provide precise and direct control of the catalytic-reactor fuel-air ratio. The digital control systems currently under development provide the necessary control functions for successful catalytic-combustor system operation. As a consequence of the previously mentioned considerations, additional effort is needed to determine component nonsteady operating characteristics and to experimentally define combustion-system components having sufficient flexibility for use over the range of operation required for aircraft gas-turbine combustors. Future experimental studies should address these component development requirements within the context of aircraft gas-turbine catalytic-combustor systems having full-range operating capability.

9.0 SUMMARY OF RESULTS

An analytical design and performance study was performed on six different catalytic-combustor systems for aircraft gas-turbine engine applications. The two most promising concepts from the six new concepts defined and studied were selected and further evaluated. Selection was based upon the best estimate potential for the meeting of the criteria for program emission goals, aerothermal performance, fuel-air carburetion system performance, operating characteristics and mechanical design features. Results of this Phase I study are as follows:

1. All catalytic-combustor systems studied are predicted to achieve ultralow aircraft gas-turbine engine emissions.

2. Fixed-geometry combustor configurations (Concepts 1, 3, and 4) are predicted to achieve normal-cruise NO_x pollutant-emission levels less than 2 g/kg-fuel which is on order of magnitude less than values for present-day conventional combustors.

3. Variable-geometry combustor configurations (Concepts 2 and 5) are predicted to achieve normal-cruise NO_x pollutant-emission levels less than 1 g/kg-fuel.

4. All catalytic-combustion systems evaluated are predicted to meet the program goal of the 1979 EPA emission standards for the landing-takeoff cycle of T-2 aircraft engines for altitudes less than 915 meters.

5. Overall smoke-emission levels from all concepts at all steady-state operating conditions are predicted to be much less than a smoke number of five. This value is well below the smoke standard value of 20.

6. Combustion efficiency goals of the program are met by all the concepts at all specified operating conditions.

7. Total-pressure loss for all concepts meet the program goal of five percent at the approach power level and above.

8. Two most promising catalytic-combustor systems chosen by using the previously mentioned criteria are the basic, parallel-staged configuration (Concept 3) and the annular, reverse-flow parallel-staged configuration (Concept 4).

9. Total-pressure loss for the two most promising concepts is predicted to be less than or equal to the program goal of 5 percent at all engine operating conditions.

10. Combustor-system combustion stability will be augmented by the thermal inertia provided by the catalytic reactor.

11. Advanced liner-cooling techniques utilizing thermal barrier coatings will permit additional significant reductions in NO_x pollutant-emission levels by the increasing amounts of fuel and of air that can be passed through the catalytic-reactor.

12. Fuel evaporation will be sufficient for catalytic-reactor operation at all inlet conditions.

APPENDIX A - NOMENCLATURE

Symbol		Units
A_e	Effective Flow Area	cm^2
CO, COEI	Carbon Monoxide Emission Index	g/kg
Cp	Diffuser Static Pressure Rise Coefficient	-
E	Eddy Diffusivity	m^2/s
d_o	Droplet Diameter	cm
f	Fuel-Air Ratio	g/kg
F*	Catalyst Apparent Friction Factor	-
F_N	Installed Net Thrust	kN
h_o	Flight Altitude	km
HCEI, HC	Hydrocarbon Emission Index	g/kg
K_f	Fuel-Air Ratio Emissions Correction Factor	-
L	Length or Spacing	cm
m	Spreading Index	-
M_o	Flight Mach Number	-
M	Mach Number	-
NO_xEI, NO_x	Oxides of Nitrogen Emission Index	g/kg
N	Fuel Evaporation	%
P	Pressure	MPa
PF	Pattern Factor	-
$\Delta P/P$	Pressure Drop	%
R	Radial Distance from Centerline	cm
R_A	Diffuser Area Ratio	-
Re/N_{Re}	Reynolds Number	-

Symbol		Units
sfc	Specific Fuel Consumption	g/Nt-s
T	Temperature	K
ΔT	Temperature Rise	K
Va	Air Velocity	m/s
V_A, U_{ref}	Approach Velocity	m/s
V_d	Dome Velocity	m/s
W	Airflow	kg/s
W_e	Effective Catalytic-Reactor Airflow	% W_{36}
W_d	Pilot Dome Flow	% W_{36}
W_f	Fuel Flow	kg/s
α	Pressure Exponent in Emission Corrections	-
β	Dome Flow Exponent in Emission Corrections	-
τ	Temperature Constant in Emission Corrections	K

Subscripts

ad	Adiabatic
B	Baseline or Reference Value
c	Combustor
Cat	Catalyst
comb	Combustion, Combustor
Diff	Diffuser
in	Inlet
iso	Isothermal
Pr	Profile
Tr	Transition
Vap	Vaporization
ex	Exit
3	Compressor Discharge
36	Combustor Exit
4	Turbine Inlet

APPENDIX B

CATALYTIC-REACTOR TEST PROGRAM

Autoignition delay considerations dictated that catalytic-reactor approach velocity in the combustor designs be in the upper range of catalyst test experience, where very limited data were available to predict catalyst performance. In order to verify the effects of increased approach velocity, a short test program was conducted by Engelhard Industries. The nominal run conditions for this program are presented in Table B-I. Except for inlet pressure, the test conditions closely simulate the range of catalyst operation required for aircraft gas-turbine designs.

The catalyst selected for this test program (DXE-441) has been described in Table V. This catalyst represents the current state of the art in terms of precious metal catalyst thermal stability and activity, based on accelerated thermal aging and atmospheric life tests. The honeycomb support configuration was selected from available stock to provide pressure drop comparable to the program goals.

Tests were conducted in the Engelhard Industries high temperature reactor system shown in Figure B-I. This system, which is described in detail in Reference 17, accommodates a 2.54-cm-diameter test catalyst. CO, HC, and NO_x emissions were measured 10.2 cm downstream of the catalyst inlet. The catalysts tested were 10.2 and 12.7 cm lengths of DXE-441.

Detailed test results are presented in Tables B-II and B-III. A comparison of results obtained with the two test catalysts showing the effect of approach velocity is presented in Figure B-2. Efficiency of both catalysts was high above fuel-air ratios of about 26 g/kg, but improved performance was obtained with the 12.7 cm catalyst at lower fuel-air ratios. Based on these results the longer catalyst was incorporated into the combustor designs. In using the catalyst test results for preliminary design fuel and airflow scheduling analyses, the catalyst approach velocity effect was scaled proportionally to catalyst open area. Under these circumstances, conversion performance at 30 m/s with the 70-percent-open-area catalyst used in design studies was assumed to be equivalent to performance at 22.4 m/s (30 x 52.5/70.00) with the test catalytic-reactor.

Maximum-use temperature limitations with the current technology test catalysts precluded operation at the fuel-air ratios used in the combustor designs. Therefore, preliminary design emissions estimates were based on projected performance as described in Table XVIII.

Table B-I. Catalytic-Reactor (DXE-441) Test Conditions

INLET TEMPERATURE, °K	633,722,811
INLET PRESSURE, kPa	304
FACE VELOCITY, m/s	21.3, 27.4, 33.5
FUEL-AIR RATIO, g/kg	18.0 to 26.3
FUEL	JET A

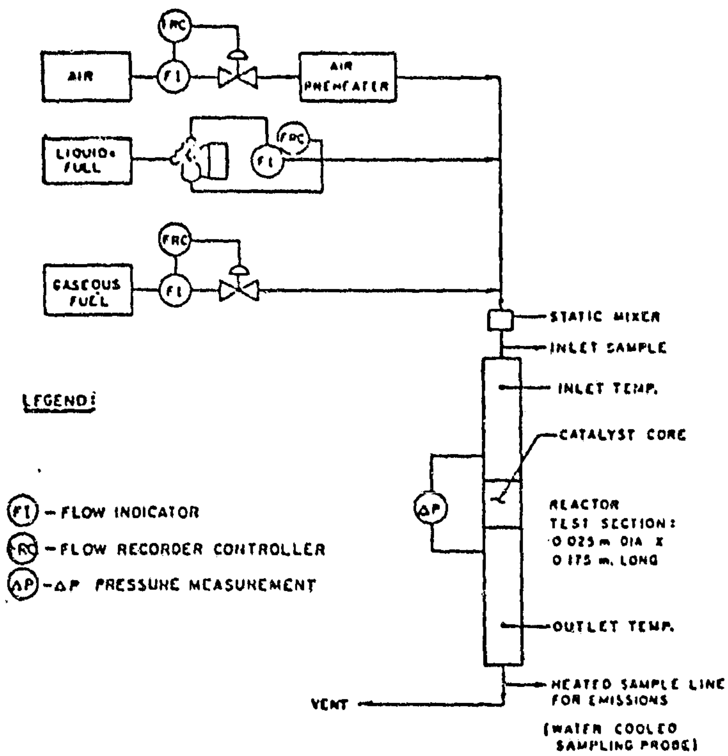


Figure B-1. Schematic of Engelhard Laboratory Test Rig for CATCOMB Catalysts.

Table B2. 10.2 cm Catalytic Reactor Test Results.

Run Number	Inlet Pressure MPa	Inlet Temperature K	Approach Velocity M/S	Reynolds Number	Fuel-Air Ratio	Reactor Exit Temperature,K 1	Reactor Exit Temperature,K 2	Pressure Drop Percent	CO_2 Percent	O_2 Percent	CO PPM	HC PPM	NO_x PPM	Combustion Efficiency Percent	Apparent Friction Factor
	.101	297	7.0	1437	.000	297		.47							.02029
	.102	297	11.6	2396	.000	297		1.06							.01686
	.104	297	22.6	4791	.000	297		3.14							.01299
	.108	297	32.7	7188	.000	297		6.41							.01272
	.116	297	40.9	9583	.000	297		10.58							.01342
	.122	297	48.6	11979	.000	297		15.12							.01359
	.205	297	34.6	14375	.000	297		7.27							.01287
	.308	297	23.0	14375	.000	297		3.13							.01254
	.411	297	17.2	14375	.000	297		1.69							.01209
	.135	633	47.4	3654	.000	628		9.29							.01871
	.170	633	37.8	3654	.000	628		4.27							.01352
	.205	633	31.4	3654	.000	628		3.06							.01402
	.308	633	20.9	3654	.000	628		1.26							.01308
	.411	633	15.6	3654	.000	628		0.78							.01443
126-1	.111	633	57.7	3654	.000	627		10.3							.01398
	.301	623	21.1	3654	.018	887	888	1.97							
	.301	623	21.1	3654	.019	893	898	1.97							
	.301	623	21.1	3654	.020	911	913	1.99							
	.301	623	21.1	3654	.021	923	932	2.06							
	.301	620	21.0	3654	.022	943	948	2.06							
	.301	618	20.9	3654	.023	964	966	2.08							
126-1	.266	628	24.1	3654	.000	628		2.09							.01481
	.301	608	20.7	3654	.024	978	975	2.13							
	.301	616	21.0	3654	.000	616		1.29							.01241
	.305	603	20.3	3654	.025	1343	1423	2.16	5.9	11.8	1040	350	5	.966	
	.305	603	20.3	3654	.026	1410	1453	2.16	6.2	11.4	2100	270	8	.955	

Reference Area $\simeq 3.403 \times 10^{-4}\ m^2$

Table B2. 10.2 cm Catalytic Reactor Test Results (Concluded).

Run Number	Inlet Pressure MPa	Inlet Temperature K	Approach Velocity M/S	Reynolds Number	Fuel-Air Ratio	Reactor Exit Temperature,K 1	2	Pressure Drop Percent	CO_2 Percent	O_2 Percent	CO PPM	HC PPM	NO_x PPM	Combustion Efficiency Percent	Apparent Friction Factor
127-1	.122	633	68.3	4698	.000	626	628	11.93							.01155
	.305	633	27.2		.000	626	628	2.11							.01285
	.305	623	26.8		.018	868	870	2.91							
	.305	623	26.8		.019	881	881	3.00							
	.305	623	26.8		.020	895	897	3.02							
	.305	623	26.8		.021	911	912	3.11							
	.305	623	26.8		.022	925	927	3.11							
	.305	623	26.8		.023	945	943	3.18							
	.305	623	26.8		.024	962	958	3.22							
	.305	623	26.8		.026	984	981	3.28							
	.305	623	26.8		.026	995	989	3.28							
	.305	623	26.3		.0268	1328	1495	3.44	5.6	12.8	1300	88	<1.0	.973	
128	.133	642	77.8	39	.000	639	640	17.13							.913
	.305	642	33.9		.000	639	640	3.16							.01264
	.305	628	33.1		.021	923	911	4.50							
	.305	628	33.1		.022	935	923	4.55							
	.305	628	33.1		.023	943	933	4.61							
128	.305	623	33.1		.024	955	944	4.61							
	.305	623	33.1		.025	973	963	4.72							
	.305	623	33.1		.026	983	973	4.78							
	.305		33.1		.026	1228	1451	4.88	5.4	12.8	1750	-	<1.0	.969	
129	.129	732	80.1	4513	.000	725	725	17.72							
	.305	732	33.8		.000	725	725	2.72							
	.305	761	33.8		.018	1113	1228	4.05							
	.305	728	33.8		.000	728	726	2.72							
	.305	756	33.8		.015	983	992	3.72							
	.305	762	33.8		.020	1285	1363	4.33	4.3	14.6	>5000	-		<.90	
	.305	773	33.8		.0217	1383	1418	4.55	4.2	14.1	>5000	-		<.90	
	.119	728	70.8	3707	.000	721	718	12.13							
	.305	728	27.5		.000	721	718	1.671							
	.305	758	27.5		.0148	973	973	2.39							
	.305	763	27.5		.0186	1183	1296	2.39	3.7	15.2	4000	800		.85	
	.305	763	27.5		.0216	1333	1383	2.73	4.25	13.9	>5000	1000	2.0	<.84	
130-1	.111	733	58.9	2883	.000	723	723	8.62							
	.305	733	21.5		.000	723	723	1.11							
	.305	761	21.5		.0144	993	995	1.55							
	.305	763	21.5		.0164	1115	1188	1.64	2.0	17.1	>5000	-			
	.305	770	21.5		.0189	1228	1333	1.72	4.0	14.6	2850	250	<1.0	.92	

Reference Area ≈ $3.403 \times 10^{-4}\ m^2$

Table B3. 12.7 cm Catalytic Reactor Test Results.

Number	Inlet Pressure MPa	Inlet Temperature K	Approach Velocity M/S	Reynolds Number	Fuel-Air Ratio	Reactor Exit Temperature, K 1	Reactor Exit Temperature, K 2	Pressure Drop Percent	CO_2 Percent	O_2 Percent	CO PPM	HC PPM	NO_x PPM	Combustion Efficiency Percent	Apparent Friction Factor
	.105	297	20.6	4381	.000	297	297	3.02							.01204
	.107	297	30.4	6572	.000	297	297	6.20							.01142
	.111	297	38.9	8761	.000	297	297	10.52							.01179
	.119	297	45.1	10952	.000	297	297	14.62							.01211
	.205	297	31.7	13143	.000	297	297	6.78							.01147
	.308	297	21.0	13143	.000	297	297	2.86							.01098
	.411	297	15.7	13143	.000	297	297	1.64							.01126
	.136	630	51.6	3957	.000	623	623	9.47							.01281
	.170	630	41.2		.000	623	623	5.86							.01245
	.205	630	34.2		.000	623	623	3.88							.01193
	.308	630	22.7		.000	623	623	1.76							.01226
	.411	630	17.0		.000	623	623	0.99							.01228
125	.119	531	59.2	3947	.000	623	623	12.98	-						.01333
	.305	618	22.6	3947	.026	1328	1458	3.11	5.65		135		-	.998	
125R	.117	635	60.3	3947	.000	631	631	13.14	-						.01311
	.305	623	22.7	3947	.026	1328	1473	3.05	5.6	12.6	45	2	<1.0	.999	
	.305	633	23.1	3947	.000	633	633	1.83	-						.01241
	.305	625	22.8	3947	.018	975	965	2.67							
	.305	623	22.7	3947	.019	993	983	2.72							
	.305	623	22.7	3947	.020	1003	1005	2.78							
	.305	623	22.7	3947	.021	1122	1198	2.83	4.3	14.8	1960	1300		.88	
	.305	623	22.7	3947	.022	1203	1328	2.83	4.7	13.8	1000	85		.974	
	.305	623	22.1	3836	.023	1246	1383	2.94	5.1	13.3	390	15		.992	
	.305	623	22.1	3836	.024	1282	1443	2.96	5.3	13.2	165	5		.997	
	.101	297	7.1	1453	.000	297	297	.56							.01904
	.101	297	11.8	2422	.000	297	297	1.35							.01647
	.101	297	23.6	3633	.000	297	297	4.15							.01269
	.108	297	33.0	4843	.000	297	297	8.35							.01299
	.116	297	41.3	6054	.000	297	297	13.23							.01317
	.126	297	47.5	7265	.000	297	297	18.23							.01375
	.205	297	35.0	7265	.000	297	297	9.09							.01263
	.308	297	23.2	7265	.000	297	297	3.76							.01183
	.411	297	17.4	7265	.000	297	297	2.07							.0116
131-1	.113	733	58.4	2900	.000	726	725	11.16							.01375
	.305	733	21.7	2900	.000	726	725	1.45							.01292
	.305	758	21.7	2900	.014	1030	1045	2.06							
	.305	766	21.7	2900	.0164	1148	1207	2.16							
	.305	772	21.7	2900	.019	1237	1318	2.28	4.1	13.8	455	30	2	.987	

Reference Area $\simeq 3.368 \times 10^{-4}$ m^2

Table B3. 12.7 cm Catalytic Reactor Test Results (Concluded).

Number	Inlet Pressure MPa	Inlet Temperature K	Approach Velocity M/S	Reynolds Number	Fuel-Air Ratio	Reactor Exit Temperature, K 1	Reactor Exit Temperature, K 2	Pressure Drop Percent	CO_2 Percent	O_2 Percent	CO PPM	HC PPM	NO_x PPM	Combustion Efficiency Percent	Apparent Friction Factor
131-1R	.305	731	19.6	2613	.000	724	724	1.23							.01342
	.305	731	19.6	2613	.0188	1243	1323	1.89	6.7	9.2	260	<1	1	.996	
	.305	731	19.6	2613	.0154	1130	1143	1.83							
	.305	731	19.6	2613	.021	1423	1433	2.28	8.1	13.1	70	<1	1	.999	
132-1	.120	738	64.7	3339	.000	723	716	14.34							
	.305	738	25.4	3339	.000	723	716	2.03							
	.305	765	25.4	3339	.015	1076	1113	2.72							
	.305	768	25.4	3339	.017	1163	1246	2.87							
	.305	773	25.4	3339	.017	1203	1276	2.83	3.75	-	1860	42	<1	.95	
	.305	808	25.4	3339	.021	1358	1393	2.94	4.2	-	2640	30/130	-	.939/.93	
	.116	723	65.6	3339	.000	713	710	12.49	-	-	-	-	-		
	.305	723	24.8	3339	.000	713	710	1.72	-	-	-	-	-		
	.305	753	24.8	3339	.021	1288	1353	2.61	4.6	-	3220	175	<1	.925	
133-1	.129	734	80.7	4488	.000	728	723	18.51							
	.305	734	34.1	4488	.000	728	723	2.90							
	.305	758	34.1	4488	.0136	978	980	3.83							
	.305	763	34.1	4488	.0151	1040	1073	3.83							
	.305	763	34.1	4488	.017	1129	1215	3.94							
	.305	760	34.1	4488	.019	1193	1309	4.0	4.1	17.9	3840	200	1	.902	
	.305	765	34.1	4488	.021	1305	1403	4.27	4.8	17.5	1510	25	1	.966	
	.305	768	34.1	4488	.023	1410	1463	4.44	5.5	15.7	760	4	2	.986	
134-1	.121	635	68.9	4687	.000	630	630	15.42							
	.305	635	27.4	4687	.000	630	630	2.03							
	.305	623	27.4		.018	884	884	2.83							
	.305	623	27.4		.020	913	911	3.05							
	.305	623	27.4		.022	933	933	3.05							
	.305	621	27.4		.024	962	959	3.05							
	.305	622	27.4		.025	978	978	3.08							
	.305	642	27.4		.026	1265	1470	3.16	5.9	12.0	125	-	<1	.998	
135-1	.123	812	82.7	3743	.000	803	800	16.05							
	.305	812	33.4	3743	.000	803	800	2.44							
	.305	803	33.4		.012	987	978	2.88							
	.305	803	33.4		.014	1028	1018	3.0							
	.305	803	33.4		.016	1144	1216	3.05	3.0	15.4	2960	630	<1	.86	
	.305	803	33.4		.018	1243	1383	3.14	3.95	15.0	1240	76	<1	.964	
	.305	803	33.4		.020	1283	1435	3.28	4.4	14.1	380	3	<1	.991	
	.305	803	25.4	3339	.019	1309	1363	2.83	4.2	-	660	9		.984	

Reference Area = 3.368×10^{-4} m^{-2}

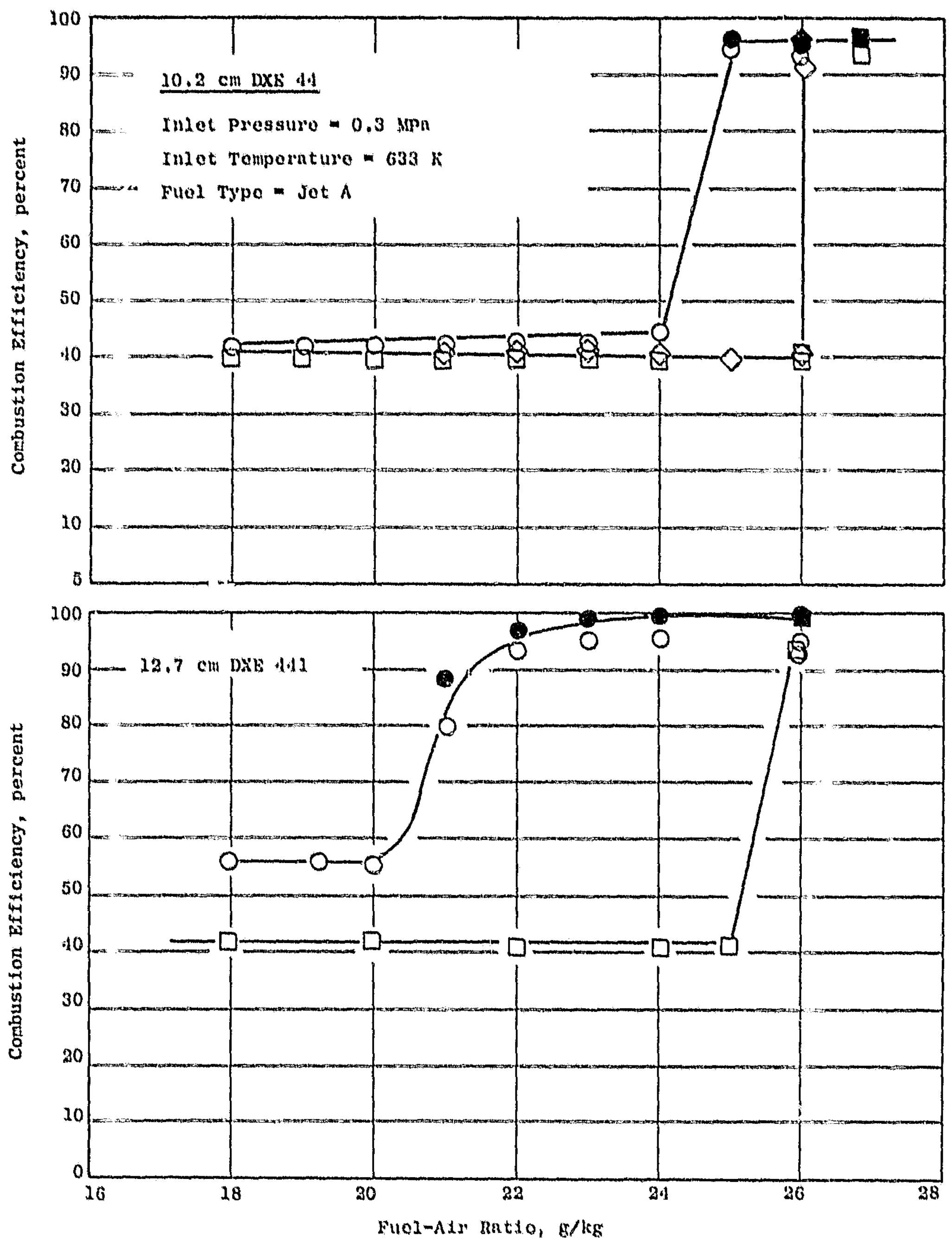


Figure B-2. Effect of Catalytic-Reactor Full-Air Ratio, Length and Approach Velocity on Combustion Efficiency.

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