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Small Engine Technology (SET)—Task 4, Regional Turboprop/Turbofan Engine Advanced Combustor Study

Robert Reynolds, Ram Srinivasan, Geoffrey Myers, and Manuel Cardenas
AlliedSignal Engines, Phoenix, Arizona

October 2003

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Note that at the time of research, the NASA Lewis Research Center was undergoing a name change to the NASA John H. Glenn Research Center at Lewis Field. Both names may appear in this report.

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LIST OF ACRONYMS AND ABBREVIATIONS

Abbreviation	**Definition**
AE	AlliedSignal Engines, Phoenix, AZ
AST	Advanced Subsonic Technology
AZ	Arizona
C	Degrees Celsius
CAEP	ICAO Committee on Aviation Environmental Protection
CCD	Charge Coupled Device Camera
CFD	Computational Fluid Dynamics
CO	Carbon Monoxide
COEI	Carbon Monoxide Emissions Index
COM3D	AlliedSignal 3-D CFD Computer Code
CO_2	Carbon Dioxide
deg	Degrees
DoD	(U.S.) Dept. of Defense
DoE	(U.S.) Dept. of Energy
D.O.E.	Design of Experiment
D_p	Mass of constituent in ICAO LTO cycle
dP/P	Differential Pressure Ratio
EC	European Council
EI	Emissions Index
F	Degrees Fahrenheit
F/A	Fuel-to-Air Ratio
FAA	(U.S.) Federal Aviation Administration
Fab.	Fabrication
FARs	Federal Aviation Administration Regulations
F_n	Output thrust
F_{00}	Rated output
ft	Feet
ft/sec	Feet per second
Gr	Grams
HCEI	Unburned hydrocarbons emissions index
H_2O	Water
hp	Horsepower
hr	Hour
ICAO	International Civil Aviation Organization
ID	Inner diameter
IGN	Ignition
in	Inches
ISA	International Standard Atmosphere
kN	KiloNewtons
kW	KiloWatts
LAS	Lithium Alumino Silicate
lb	Pound
lb/hr	Pounds per hour
LBO	Lean blowout

LIST OF ACRONYMS AND ABBREVIATIONS (Contd.)

Abbreviation	**Definition**
lbs	Pounds
lb/sec	Pounds per second
LDI	Lean Direct Ignition
LeRC	NASA Lewis Research Center, Cleveland, OH
LPP	Lean, Pre-Mix Pre-Vaporized
LTO	Landing and takeoff
msec	Milliseconds
N/A	Not Applicable, not available
NASA	(U.S.) National Aeronautical and Space Administration
NO	Nitrous Oxide
NOEI	Oxides of Nitrogen Emission Index
NO_x	Oxides of Nitrogen
N_2	Nitrogen gas
OD	Outer diameter
OTL	Outer transition liner
OPR	Overall pressure ratio
O_2	Oxygen gas
PDPA	Phase Doppler Particle Analyzer
PF	Pattern factor
pph	Pounds per hour
ppm	Parts per million
PR	Pressure ratio
psia	Pounds per square inch absolute pressure
Pt	Total pressure
PZ Phi	Primary zone equivalence ratio
P3	Pressure
rpm	Revolutions per minute
RQL	Rich-Quench-Lean
sec	Seconds
SET	Small Engine Technology
SLTO	Sea level takeoff
SMD	Sauter Mean Diameter
SN	Smoke Number
™	Trade Mark
Tt	Total temperature
T3	Temperature
UHC	Unburned Hydrocarbons
U.S.	United States
VOC	Volatile organic compounds
Wa	Air flow (Weight)
Wa,tot	Total air flow
Wf	Fuel flow (Weight)
Wf, comb	Combustor fuel flow
2-D	Two-Dimensional
3-D	Three-Dimensional

FINAL REPORT
NASA SMALL ENGINE TECHNOLOGY (SET) PROGRAM
TASK 4
REGIONAL TURBOPROP/TURBOFAN ENGINE ADVANCED COMBUSTOR STUDY
(CONTRACT NO. NAS 3-27483)

1.0 INTRODUCTION AND SUMMARY

1.1 Introduction

Emissions regulatory limits for the small size class of turboprop and turbofan engines are expected to become more stringent in the near future, particularly with respect to oxides of nitrogen (NOx). This concern is based on the importance of NOx emissions in the generation of photochemical smog in and around the airspace of airports. Engine manufacturers that wish to be competitive in the 21st century will have to include low-emissions combustion systems in their product lines, which will require the use of new technologies in gas turbine combustor design.

The NASA Small Engine Technology (SET) Task 4, Advanced Combustor Study, provided the means by which a number of different low-NOx emissions technologies could be analytically screened to determine concepts that have a high potential of achieving low emissions in small, advanced-cycle gas turbine engines. The results of this analytical screening were used to select a number of different concepts for future hardware development and possible inclusion into the AlliedSignal Engines (AE) product lines.

1.2 Summary

Three proposed AE products, designated the Model TFE731-80A, AS807, and AS918 engines, respectively, were identified as analytical test beds for the evaluation of low-NOx emissions technologies. These designs represent the business turbofan, regional turboprop, and regional turbofan engine classes, respectively. For each of these engine designs, three different levels of NOx reduction technology were assumed, designated as Baseline, Near-Term, and Advanced Technology. The Baseline level represented current combustor design practices that could be applied to a new engine design; Near-Term represented design practices using new technologies that are currently available; and the Advanced Technology level employs technologies not currently available but that are to be developed by the year 2005 time frame.

For each of the three engine designs, a preliminary combustor design was performed using each of the three different NOx-reduction technology levels; each level used the same basic NOx-reduction philosophy of Lean Direct Injection (LDI). Each of the configurations was analyzed using a three-dimensional (3-D) Computational Fluid Dynamics (CFD) computer code, to predict a number of combustor performance parameters including the emission indices for NOx, carbon monoxide (CO), and unburned hydrocarbons (UHC). The analyses involved modeling each configuration at four different power settings, corresponding to the International Civil Aviation Organization (ICAO) Landing and Takeoff (LTO) cycle operating points [i.e., approach, idle, sea-level takeoff (SLTO), and climb]. A predicted LTO cycle value was then computed for each configuration and the values were compared. One additional configuration was also designed and analyzed, comprising a combination of the most promising features of the Near-Term technology configurations.

Based on the concepts developed for NOx control, a list of Barrier Technologies that could hinder or prevent the implementation of low-NOx combustion designs were identified and are discussed briefly. These technologies include: Fuel/air Mixing, Fuel Injection and Coking, Advanced Wall Cooling and Materials, Fuel Control, and Altitude Ignition and Relight. An assessment of these Barrier Technologies identified Advanced Wall Cooling and Fuel/air Mixing as the most important, and the ones on which development efforts should be concentrated.

The analytical screening of the various concepts showed that the NOx LTO values of the Baseline combustors could be reduced on average by 34 to 70 percent through the application of various techniques, all within the general framework of LDI. When the concepts were rated, not just on emissions, but for a broad spectrum of factors, the ten configurations could be separated into two basic groups; with the top six configurations essentially indistinguishable within the range of uncertainty of this trade study. These six configurations were then used to identify three basic techniques that could be applied to any future engine program aimed at demonstrating low-NOx combustor hardware.

These common NOx-reduction concepts include:

1) Increased swirler and primary-orifice flow rates to reduce the primary zone (PZ) equivalence ratio to approximately 0.7;
2) Small fuel-preparation chambers surrounding each injector, to allow the fuel to partially evaporate and mix with the air before being introduced into the main reaction chamber; and
3) A double-dome swirler arrangement to stratify the PZ fuel/air distribution.

2.0 BACKGROUND

2.1 Program Objective

The objective of the NASA Small Engine Technology (SET) Task 4, Advanced Combustor Study Program, was to identify design configurations and technology having high potential to achieve low emissions in small, advanced cycle [up to overall pressure ratio (OPR) = 35] gas turbine engines. The small size class includes turboprop and turboshaft engines up to 5000 hp, and turbofan engines up to 20,000 lb. thrust. The program was divided into the tasks listed below:

- Review of current and future international emissions regulations
- Identification of state-of-the-art emissions control technology used in current propulsion engines
- Definition of three Baseline Engine Cycles with the corresponding International Civil Aviation Organization (ICAO) LTO cycle operating points [Approach, Idle, Sea-Level Takeoff (SLTO), and Climb]
- Calibration of the current emissions submodels of the in-house AlliedSignal Engines 3-D CFD reacting flow code with existing engine and combustor rig test data
- Informal "brainstorming" to develop low-emissions concepts for each Baseline cycle
- Preliminary designs for each low-emissions candidate
- Prediction of combustor performance and emissions for the concepts, using the calibrated 3-D CFD code
- Identification of emissions reduction Barrier Technologies
- A trade study comparing each candidate concept, on the bases of initial fabrication cost, operability, weight, and other parameters, in addition to emissions performance
- Creation of a Technology Development Plan for introducing low-emissions combustors into the AlliedSignal Engines product line.

2.2 Current Emissions Standards

The current gas turbine propulsion engines emissions regulatory environment is defined by U.S. Federal Aviation Administration Regulations (FARs)(1)* and International Civil Aviation Organization (ICAO) publications.(2)

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* References given in parentheses are listed in section 5.0.

The combination of current FAA and ICAO regulations divides aircraft engines into two Sea Level Takoff (SLTO) thrust categories:

1) SLTO Thrust (Fn) less than 6000 lbs., and
2) SLTO Thrust (Fn) equal to or greater than 6000 lbs.

2.3 Current and Proposed Emissions Regulations

The smaller engines (SLTO Thrust Category 1) are only regulated for smoke emissions, as defined by the Limit Smoke Number (SN), not to exceed SN = 50. SN is defined as:

$$\mathbf{SN = 83.6 * (F_{oo})^{-0.274}} \qquad [1]$$

Where: $\mathbf{F_{oo}}$ is the rated output in kiloNewtons.

Larger engines (SLTO Thrust Category 2) with SLTO thrust of 6000 lb. or greater are subject to limits on UHC, CO, NOx, and smoke emissions. The gaseous emissions limits are calculated based on a standard LTO cycle, with the specific objective of improving airport air quality in the control zone from ground level to 3000 ft. elevation. Emissions indices (emissions mass rate per 1000 units of fuel mass rate) are measured at each of four throttle settings. The total mass of each gas produced in the cycle (D_p) is based on a fixed time in each operating mode given by:

$$Dp = \sum_{i}^{4} t_i m_i EI_i$$

where t_i **- time at operating point** i**, min**
m_i **- flowrate of fuel at operating point** i**, kg/min**
EI_i **- emission index at oeprating point** i**, g/kg of fuel**

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The power settings and time-in-mode defining the landing and takeoff (LTO) cycle operating points are summarized in Table 1.

TABLE 1. DEFINITION OF LTO CYCLE OPERATING POINTS.

Operating Condition	Power Setting, Percent	Time In Mode, Minutes
Idle/Taxi	7	26.0
Approach	30	4.0
Climb	85	2.2
SLTO (Sea Level TakeOff)	100	0.7

The ICAO gaseous emissions limits are then defined in terms of the rated engine output at International Standard Atmosphere (ISA) Standard Day, Sea Level conditions (**F_{oo}**), and the pressure ratio (**PR**) according to the following formulas:

Oxides of Nitrogen (NOx): $\mathbf{D_p/F_{oo} = 40 + 2*PR}$ [2]

Carbon Monoxide (CO): $\mathbf{D_p/F_{oo} = 118}$ [3]

Hydrocarbons (UHC): $\mathbf{D_p/F_{oo} = 19.6}$ [4]

ICAO regulations for NOx are expected to be more stringent, beginning in the near future. At the 1991 meeting of the ICAO Committee on Aviation Environmental Protection (CAEP), a recommendation for a 20-percent reduction in NOx emissions by 1996 was adopted and made part of the regulations. In support of increased stringency, ICAO is evaluating additional reductions in permissible NOx emissions, with a proposed reduction of an additional 20 percent by the year 2000 under consideration. The European Council (EC) has proposed a reduction in NOx emissions of 33 percent with respect to the 1996 regulations, and the Environmental Ministers from Germany, Holland, and Sweden are recommending a 40-percent reduction in NOx by the year 2000, followed by a 60-percent reduction by 2005. The Environmental Ministers of these EC countries are also recommending a 20-percent reduction in NOx for engines of less than 6000 pounds rated thrust. This is an extension of the current regulations that now apply only to larger engines, rated at 6000 lbs thrust or more. A summary of the existing and proposed regulations for gaseous emissions is provided in Tables 2 and 3.

Carbon monoxide (CO) and unburned hydrocarbons (UHC) emissions have not been subjected to the same level of attention as NOx output in recent international debates. The very stringent air quality standards of the state of California, for example, place the emphasis on NOx and volatile organic compounds (VOCs) as the prime culprits in smog production. The percentage reductions currently proposed by the ICAO do not apply to UHC and CO emissions. However, UHC and CO emissions represent cycle inefficiency, and should be minimized from that standpoint.

FAA Regulations(1) specify that turboprop and turboshaft engines must be certified for smoke emissions, according to the following formula:

$$\mathbf{SN = 187*(F_{oo})^{-0.168}} \quad [5]$$

In **Eq. [5]**, the rated output is in kiloWatts, and applies to engines with rated thrust above 1000 kW (1340 hp). More stringent emissions requirements for regional turboprop aircraft have not yet been proposed.

TABLE 2. EMISSIONS REGULATIONS FOR TURBOFAN ENGINES GREATER THAN 6000 POUNDS THRUST.

Regulatory Agency	Effective Year For Regulation	LTO Regulatory Limits		
		NOx	CO	HC
ICAO	1995	40.0 + 2.00 * PR	118	19.6
ICAO	1996	32.0 + 1.60 * PR	118	19.6
EC*	1999-2000	21.5 + 1.07 * PR	118	19.6
3 EC Ministers**	2000	0.6 * {32 + (1.6 * PR)} at PR = 30	118	19.6
3 EC Ministers**	2005	0.4 * {32 + (1.6 * PR)} at PR = 30	118	19.6

* EC = European Council
** Environmental Ministers from Germany, Holland, and Sweden.

TABLE 3. REGULATIONS FOR TURBOFAN ENGINES LESS THAN 6000 POUNDS THRUST.

Regulatory Agency	Effective Year for Regulation	LTO Regulatory Limits		
		NOx	CO	HC
ICAO	1995	None	None	None
ICAO	1996	None	None	None
3 EC Ministers*	2000	0.8 * {32 + (1.6 * PR)} at PR = 30	118	19.6

* Environmental Ministers from Germany, Holland, and Sweden.

2.4 Study Goals

Although the primary concern of this study was NOx emissions reduction, it was realized that gains in this area would be useless if they were made at the expense of other combustor operational parameters. For this reason, the list of goals included a number of parameters, which are identified in Table 4.

TABLE 4. GOALS OF THE NASA SET TASK 4 ADVANCED COMBUSTOR STUDY.

Item	Goal
NOx LTO Value	50 Percent Reduction
UHC LTO Value	20 Percent Reduction
CO LTO Value	20 Percent Reduction
Smoke Number (SN)	SN Less Than 20
Cost	Same Or Lower
Weight	Same Or Lower
Operability [Lean Blowout (LBO), Ignition]	Same Or Better

A comparison of the performance data for several current AlliedSignal engines with the existing emissions standards is given in Table 5, quoting both the emission indices and the $\mathbf{D_p/F_{oo}}$ values. Note that of these, only the Model LF507 engine, at 7000 lb. takeoff thrust, is subject to the current gaseous emissions regulations.

All of these AlliedSignal production engines would meet the current 1996 ICAO emissions standards. Considering the strong possibility of more stringent emission limits by the year 2005, the goals for this study were set more aggressively. Also, the goals were set to account for the potential variation in emissions from engine-to-engine, such that the average measured emissions plus several worst-case standard deviations would still not exceed the limit. Figure 1 shows a plot of the allowable LTO NOx emission level versus engine pressure ratio (PR) for several different current and proposed regulations. Values for a number of gas turbine engines from other manufacturers (purposely not specifically identified), representing a typical selection across the aerospace industry, are included for comparison.

The goals for UHC and CO emissions in this study were set to ensure that the NOx reductions were not met at the expense of an increase in other pollutants. The goals also reflect a slight increase in engine efficiency. The goals are intended to be met without operability or reliability penalties, and without significant penalties in fabrication cost, weight, or repairability.

2.5 Program Scope

During this study, a number of different configurations were analyzed in a relatively short period; therefore, it was not possible to perform more than a preliminary design for each of the selected geometries. The study was an effort to identity potential concepts and to perform the analysis necessary to determine if the concepts were capable of meeting the goals of the study. It should be remembered that each of the designs identified in this report would need to be developed considerably before it would be prudent to order actual hardware for testing. Since the reported designs are preliminary, a complete description is not always provided. Rather, only those details pertaining to particular NOx reduction techniques are included, and other incidental details of the design have purposely been omitted.

TABLE 5. ALLIEDSIGNAL ENGINES PRODUCT LINE EMISSIONS SUMMARY.

Value	Engine Model No.				
	TFE731-3	**TPE331-14**	**ALF502L-2**	**LF507-1F**	**CFE738**
Pressure Ratio (PR)	14.3	11.35	13.15	13	23.12
Rated Output Thrust	3213 lb	1400 shp	7505 lb	6966 lb	5900 lb
Nitrogen Oxides (NO) Emissions					
Takeoff NOEI	19.15	11.5	13.43	14.52	27.2
Climb NOEI	16.02	11.2	12.03	12.02	26.4
Approach NOEI	6.92	8.8	6.47	6.39	16.31
Idle NOEI	3.72	5	3.38	3.28	5.63
Dp/Foo	51.4	N/A	35.2	34.9	69.25
Dp/Foo Limit	68.6	N/A	66.3	66	86.24
Percent of Limit	74.93	N/A	53.09	52.88	80.30
Carbon Monoxide (CO) Emissions					
Takeoff COEI	1.13	1.5	0.4	0.2	0.668
Climb COEI	1.62	1.8	0.3	0.3	0.709
Approach COEI	15.56	4.8	3.97	4.43	3.056
Idle COEI	47.7	24.5	45.63	37.83	45.97
Dp/Foo	137.7	N/A	107.3	90.1	107.2
Dp/Foo Limit	118	N/A	118	118	118
Percent of Limit	116.69	N/A	90.93	76.36	90.85
Hydrocarbons (HC) Emissions					
Takeoff HCEI	0.062	0.07	0.02	0.01	0.521
Climb HCEI	0.072	0.08	0.023	0.01	0.534
Approach HCEI	1.41	0.22	0.183	0.12	0.959
Idle HCEI	9.04	2.94	6.65	4.72	10.21
Dp/Foo	24	N/A	15.3	10.8	24.69
Dp/Foo Limit	19.6	N/A	19.6	19.6	19.6
Percent of Limit	122.45	N/A	78.06	55.10	125.97

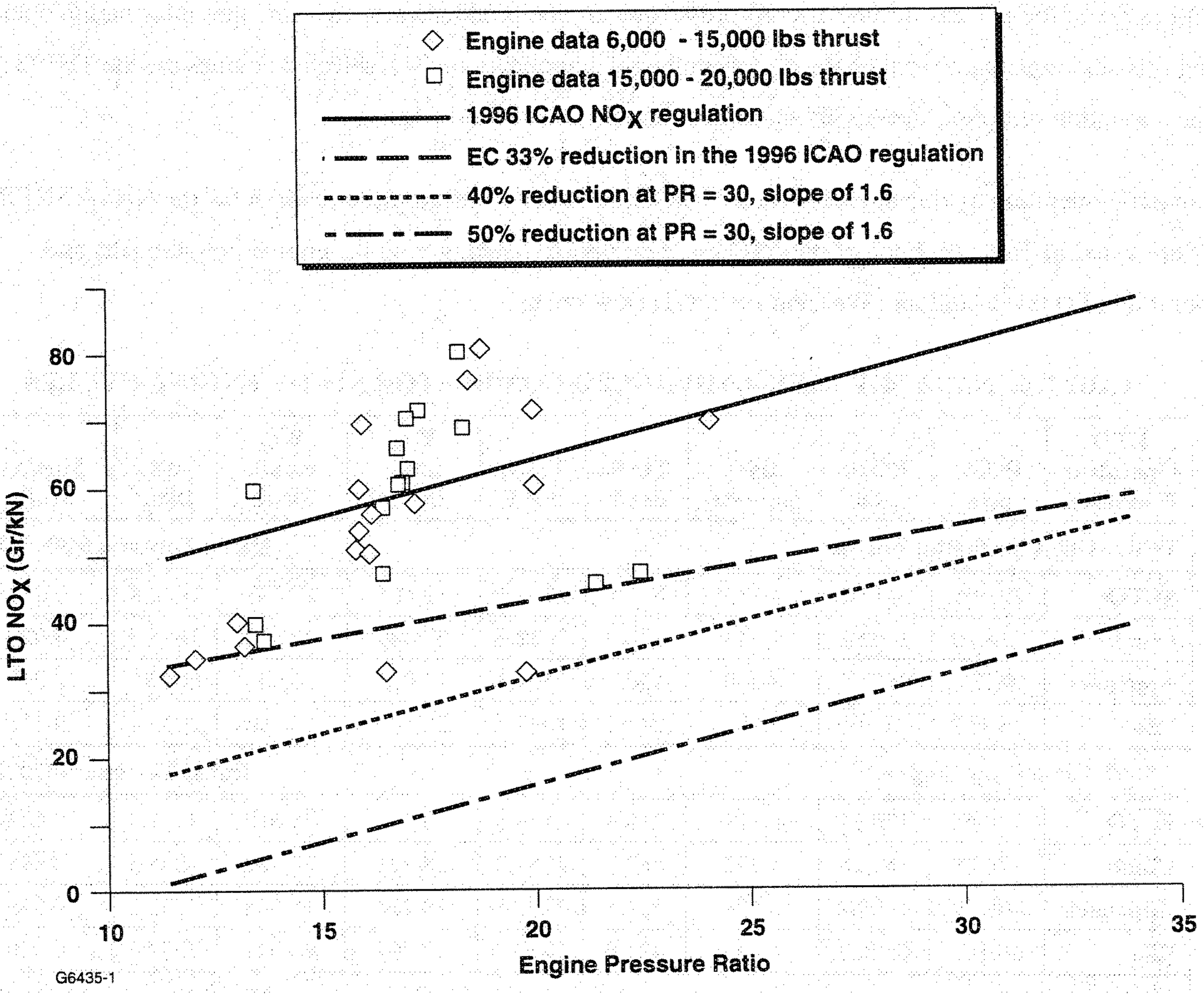


Figure 1. Emissions Limit Requirements For Turbofan Engines (Fn > 6000 lbs.)

3.0 TECHNICAL DISCUSSION

3.1 Engine Configurations

For the purposes of this NASA Small Engine Technology (SET) study, three engine configurations were selected on which different techniques for NOx reduction could be analytically tested. These engine configurations reflect the full range of the AE gas turbine aircraft propulsion engine product lines, ensuring that information obtained during this study program would have direct commercial application. The selected engines are the TFE731-80A business aviation turbofan, the AS807 turboprop, and the AS918 turbofan.

The specific operating cycle values for each of the three engine configurations chosen for the NASA SET Task 4 study are listed in Table 6. Each of the LTO cycle points are listed, giving the engine pressure (**Pt**) and temperature (**Tt**) levels and air (**Wa**) and fuel (**Wf**) flow rates.

TABLE 6. NASA SET TASK 4 ADVANCED COMBUSTOR STUDY ENGINE CYCLES.

LTO Operating Condition	Pt3.0, psia	Pt3.9, psia	dP/P, percent	Tt3.0, deg F	Tt3.9, deg F	Wa, total, lb/sec	Wa, comb, lb/sec	Wf, lb/hr	Fuel/Air Ratio
TFE731-80A Turbofan Engine									**Rated Thrust = 5499.5 lbs.**
SLTO	253.05	241.08	4.730	826.1	2104.0	31.455	27.093	2002.8	0.021
Climb	216.70	206.92	4.513	770.0	2002.6	27.489	23.670	1675.8	0.020
Approach	89.76	85.775	4.440	490.7	1504.4	12.823	11.041	604.81	0.015
Idle	35.157	33.757	3.982	247.4	1047.5	5.5382	4.7186	203.94	0.012
AS807 Turboprop Engine									**Rated Thrust = 4470 lbs.**
SLTO	185.66	176.17	5.111	715.9	2154.5	30.722	25.610	2091.0	0.023
Climb	170.08	161.25	5.192	687.9	2054.7	28.721	23.889	1836.8	0.021
Approach	106.27	100.82	5.128	554.5	1795.3	19.204	15.648	1062.2	0.019
Idle	68.102	65.068	4.455	421.0	1773.7	12.707	9.9041	725.03	0.020
Model AS918 Turbofan Engine									**Rated Thrust = 18,416 lbs.**
SLTO	343.24	323.40	5.780	937.1	2568.4	73.030	56.749	5668.2	0.028
Climb	297.19	279.87	5.828	881.8	2428.6	64.808	50.360	4670.4	0.026
Approach	125.80	118.47	5.827	584.6	1777.5	31.644	24.167	1611.1	0.019
Idle	53.374	50.253	5.847	350.6	1262.6	15.442	11.655	564.65	0.013

3.1.1 TFE731-80A Turbofan Engine

The combustion system design for the Model TFE731-80A engine, shown in Figure 2, is a growth version of the combustor used on the existing Model TFE731 business aviation turbofan engine line. Although the TFE731-80A design thrust level is below the 6000 pounds thrust limit for required gaseous emissions regulation, emission levels are a definite discriminator in the business aviation market, and proposed growth versions of this engine will exceed 6000 lbs. takeoff thrust. The TFE731-80A market is aimed at "stretched" versions of existing medium-size business aircraft. The baseline -80A combustor design employs 20 single-circuit airblast fuel injectors. The combustor OD liner, ID liner, and outer transition liner (OTL) are effusion cooled. The primary zone equivalence ratio is 0.78, and the residence time is approximately 8 milliseconds. The TFE731-80A combustion system pattern factor (PF) design goal is 0.18, and the design maximum allowable wall temperature is 1500F (816C). Current models in the TFE731 engine family have demonstrated successful altitude relight capability above 35,000 feet, and lean blowout (LBO) fuel/air ratios below 0.009 at altitude.

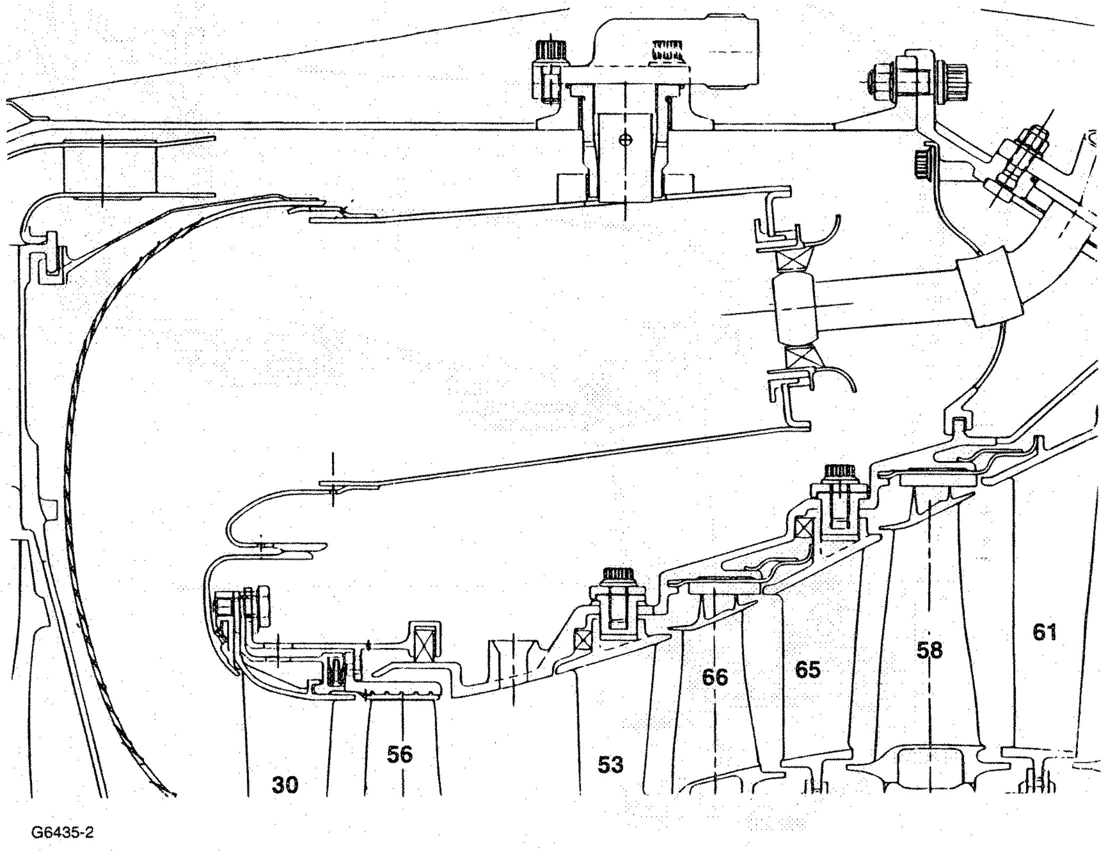


Figure 2. TFE731-80A Turbofan Engine Combustion System Configuration.

3.1.2 AS807 Turboprop Engine

The Baseline combustion system design for the 5000 shaft horsepower (shp) Model AS807 turboprop engine is shown in Figure 3. The AS807 engine design employs an effusion cooled, reverse-flow combustor, with an impingement/effusion-cooled transition liner and 23 single-circuit, prefilming airblast fuel atomizers. The engine application is aimed at regional turboprop aircraft. The Baseline AS807 combustor design primary zone equivalence ratio is 1.6, and the residence time is 9.5 milliseconds. The pattern factor (PF) design goal is 0.23; however, PF = 0.16 has been demonstrated during rig testing. Operability requirements are similar to those for the TFE731-80A engine, discussed previously.

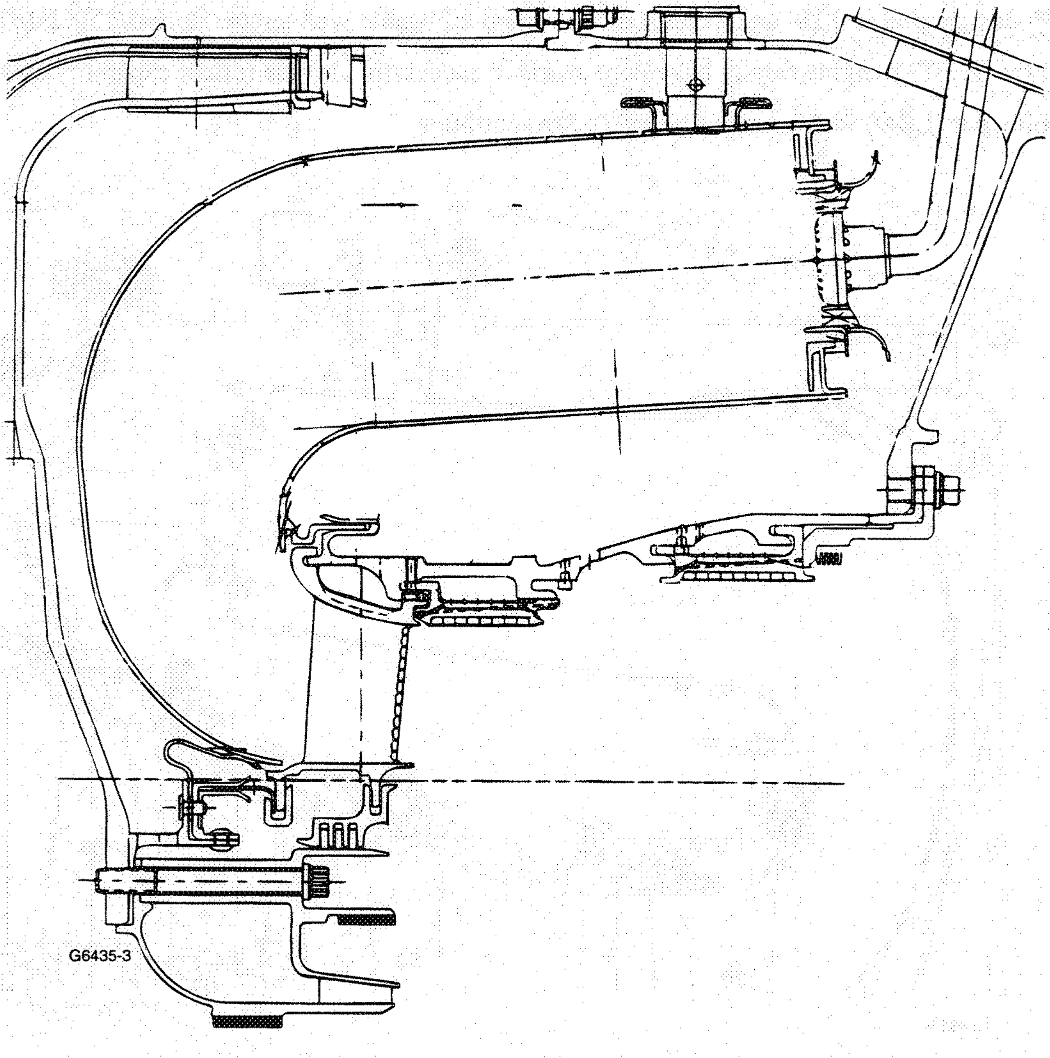


Figure 3. AS807 Turboprop Engine Combustion System Configuration.

3.1.3 AS918 Turbofan Engine

The Baseline combustion system configuration for the Model AS918 turbofan engine is shown in Figure 4. This thru-flow combustor is based on the current production TFE1042 engine and uses a machined-ring, film-cooled design. The AS918 combustor design uses 12 dual-orifice pressure atomizers, with a primary zone equivalence ratio of 0.95 and a residence time of 8.2 milliseconds. Although this is only a proposed engine design, it is rated at 18,000 lbs. thrust and would therefore be subject to limits on gaseous emissions as well as smoke regulation. The proposed application would be a 50- to 70-passenger class commuter airliner.

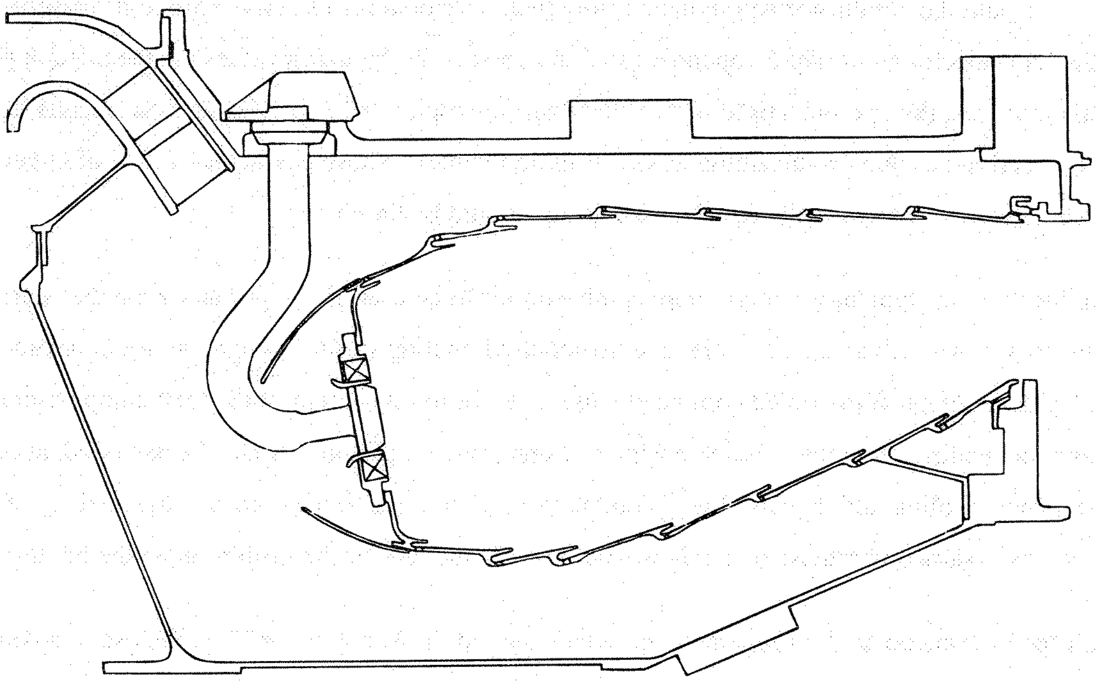


Figure 4. AS918 Turbofan Engine Combustion System Configuration.

3.2 Approach

An initial task of the SET study was to establish several working assumptions on which the concept evaluations were to be based. It was first decided that the primary NOx control method would be Lean Direct Injection (LDI), as this technique results in configurations more closely resembling existing designs and, therefore, lower associated risk. It was also felt that LDI, as a method, was capable of producing the NOx reduction levels desired. Other techniques, such as Lean Premix Pre-vaporized (LPP) and Rich-Quench-Lean (RQL) have inherent problems that make them less attractive. LPP systems have a tendency to flash back into the premixer from the combustor, while RQL configurations have potential carbon formation problems in the rich zone and durability problems in the quench area.

In conjunction with LDI, a design philosophy was adopted whereby the fuel injectors were an integral, rather than a separate, part of the overall combustion system, since proper interaction between the injector spray characteristics and the combustor aerodynamic flow field is critical for effective emissions control. Rather than design the fuel-injector assembly independently of the combustor, by using values for the injector parameters from historical databases, the approach used in this study was to employ the 3-D CFD analysis results to define the injector characteristics that produced the lowest emission values. These characteristics would then be used to create a specification on which the fuel-injector design would be based.

Since LDI techniques typically require more combustor air to be used in the primary zone than current state-of-the-art combustors, it was advantageous to reduce the required cooling flows through the use of advanced cooling schemes. Conventional film-cooled combustors use up to 30 to 40 percent of the total compressor discharge flow for cooling, depending upon the selected design and operating conditions. Since the use of advanced techniques such as effusion cooling and the Lycolite™ combustor wall construction can reduce the cooling air required by 50 percent, it was assumed that these techniques would be considered for the designs generated in this study.

Although such advanced cooling schemes can reduce the required cooling air flow, the use of advanced combustor materials can potentially eliminate the need for cooling completely. In particular, ceramic liners have been successfully demonstrated in research combustors,(3) and offer an alternative to metallic wall construction. Although not currently used in production gas turbine engines, it is quite likely that ceramic combustor materials will have sufficiently matured by the year 2005 and are, therefore, considered in this study.

The screening of different low-NOx concepts requires a detailed understanding of the primary-zone, fuel-and-air distribution and mixing. Current research has shown that this knowledge can be efficiently obtained through the use of 3-D CFD computer codes. It was therefore decided that the primary method for evaluating the concepts would be examination of the output of 3-D CFD analyses. Since any program which models complex processes, such as the thermodynamics inside a gas turbine combustor, will necessarily entail certain approximations, the results from the 3-D CFD code contain a degree of uncertainty. Since this is unavoidable for any current CFD code, the primary function of the models was to provide a relative assessment of the different combustor geometries, allowing a selection to be made based on the lowest predicted level of emissions.

3.3 Model Description And Calibration

The AlliedSignal in-house 3-D CFD code (COM3D) employed for this study uses a structured orthogonal grid; a pressure-based, sequential-solution algorithm for momentum and continuity;(4) a k-e two-equation turbulence model; and a global, three-step kinetic mechanism. The first reaction in the kinetic mechanism was the fuel decomposition into carbon monoxide and water (CO and H_2O) and the second was oxidation of the CO into carbon dioxide (CO_2). In both reactions, the Arrhenius rate constants were based on comparisons with measured test data from a research combustor,(5) while the turbulence-chemistry interaction was handled by the Eddy Breakup Model, using coefficients derived from the same measured data. The third reaction was the global oxidation of gaseous nitrogen (N_2) into nitrous oxide (NO), using rate expressions that were also generated by comparison with engine test data. It was assumed that the oxides of nitrogen (NOx) in the LTO cycle were comprised entirely of NO.

Before the screening process for combustor design was started, 3-D CFD model runs were performed for several combustor geometries for which measured emissions test data were available. These configurations included a turbofan engine (Model TFE1042), a test rig for a typical reverse-flow combustor (LP512_Rig), and a test rig for a research combustor that operated at near-stochiometric fuel/air ratio conditions (PRIZM_Rig). Table 7 summarizes the predicted and measured emission levels for each of the comparison applications. It is clear that the predicted emissions levels at many points differ considerable from the measured values. However, examination of the data shows that the predicted values follow the trends of the measured data reasonably well. For this reason, it was felt that the kinetics model in the 3-D CFD code would be adequate for the task of screening the various combustor design concepts, since the different configurations would always be compared on a common basis. In addition, the largest discrepancies seen in the comparisons between the measured data and the model predictions were for UHC and CO emissions. For NOx, which was the primary emission considered in this study, the absolute emission level was predicted reasonably well. This gives confidence to the LTO NOx Emission Index (NOEI) values shown later in this report. The UHC and CO LTO Emissions Index (HCEI and COEI) values are also quoted, but, the confidence factor for those values is not as high.

TABLE 7. COM3D 3-D CFD EMISSIONS PREDICTION SUMMARY.

Conditions	TFE1042			LP512_Rig			PRIZM_Rig		
Fuel/Air Ratio	0.0285	0.024	0.012	0.0213	0.013	0.0105	0.0657	0.0458	0.0257
T3, deg F	876	755	366	697	614	268	400	556	556
P3, psia	243	88.8	53	130.1	88.6	38.9	41.36	41.82	41.57
Measured Test Data									
NOEI	18.5	14.1	4.9	13.93	8.67	2.98	---	---	---
HCEI	0.5	0.4	8.2	0.034	0.054	0.295	10.07	0.22	29.33
COEI	0.8	0.6	48.5	0.28	1	13.4	290.22	10.99	12.34
Smoke No. (SN)	32.6	19	3.9	---	---	---	---	---	---
COM3D Predicted Values									
NOEI	20.11	12.5	3.98	9.7	5.978	0.48	---	---	---
HCEI	0.726	0.29	0.45	0.007	0.021	50.12	166	12.96	115.4
COEI	4.02	1.64	20.2	0.09	0.222	112.7	537	132.8	153.5
Smoke No. (SN)	39	37.6	18.2	---	---	---	---	---	---

3.4 Combustion System Designs

For the purposes of this study, a concept matrix was defined that included three different configurations for each of the three different engines, giving a total of nine possible geometries. This matrix is shown in Table 8. The three different configurations were designated Baseline, Near-Term, and Advanced Technology, respectively, representing three different levels of NOx control technology. The Baseline configurations represent the current NOx emissions technology and design philosophy; Near-Term configurations employed a low-NOx design philosophy, but were limited to currently-existing material, manufacturing, and fuel injector technologies. Thus, these six configurations for each engine design could be constructed and tested in the current timeframe. For the Advanced Technology configurations, any conceivable technology could be considered, even if it does not currently exist, providing it could be developed by the year 2005 timeframe.

One additional configuration, designated "AST Baseline" was also included in the comparison matrix. Analysis of this configuration was performed only for the AS918 engine cycle. It was intended to be a combination of all of the most-promising NOx reduction technology concepts, but was limited to injector and material technologies currently available. This geometry will be the initial configuration for any follow-on programs intended to produce low-NOx combustor hardware.

TABLE 8. NASA SET TASK 4 STUDY CONCEPT MATRIX.

Engine Cycle	SET Study Configurations			
	Baseline	Near-Term	Advanced Technology	AST Baseline
TFE731-81A	• Effusion-cooled, reverse-flow combustor/OTL • 20 Injectors • PZ Phi = 0.83	• Circumferential staging • Reduced inlet swirl • LDI • PZ Phi = 0.75	• Effusion-cooled, reverse-flow combustor • 20 Pre-mixer injectors located in individual ceramic cans	(N/A)
AS807	• Effusion-cooled, reverse-flow combustor/OTL • 23 Injectors • PZ Phi = 0.91	• Effusion-cooled, reverse flow combustor/OTL • 23 Injectors • PZ Phi = 0.73	• 2 Injectors per sector for radial staging • Overall PZ Phi is variable, per operability needs	(N/A)
AS918	• Film-cooled, machined-ring, through-flow combustor • 12 Injectors • PZ Phi = 1.18	• Effusion-cooled, reduced volume, sheet metal through-flow combustor • 12 injectors • PZ Phi = 0.75	• Annular CMC combustor • Active wall cooling eliminated • 56 Low-cost "pre-mixer" injectors • Lean PZ	• Effusion-cooled, reduced volume, through-flow combustor • 12 Injectors in individual effusion-cooled mixing cans • PZ Phi = 0.79

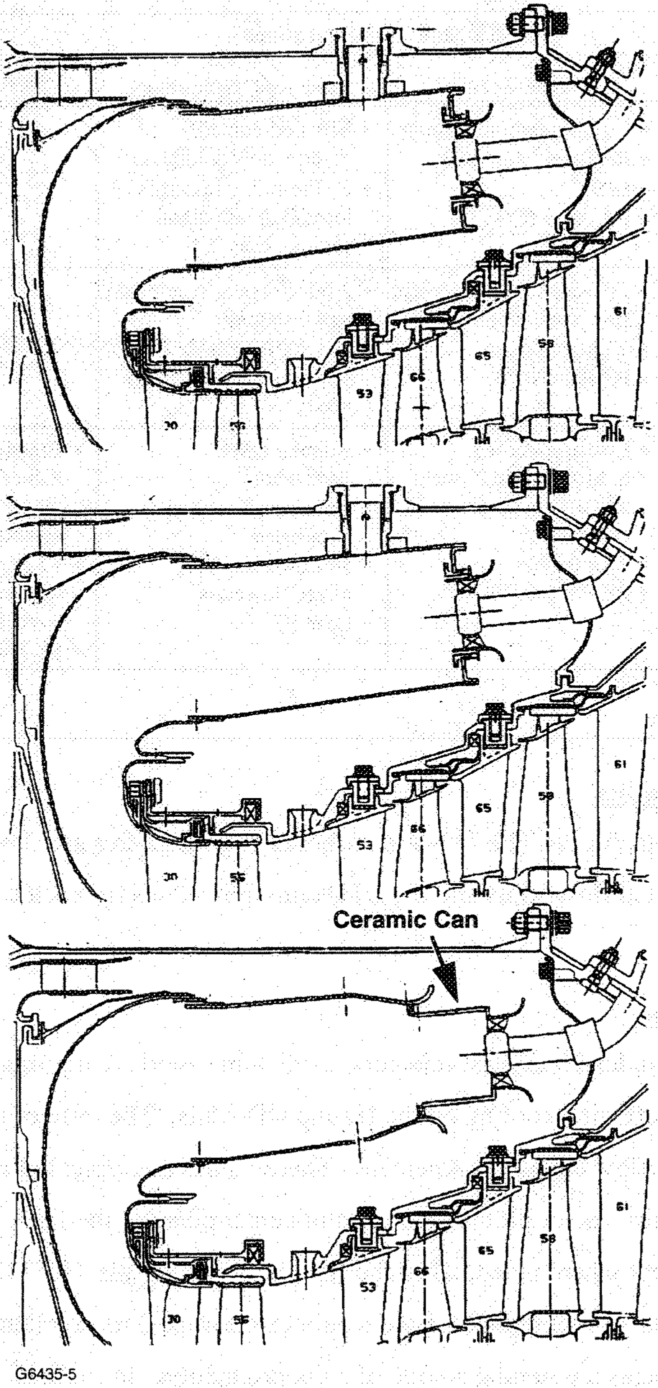
N/A = Not Applicable.
PZ Phi = Primary Zone Equivalence Ratio.

3.4.1 TFE731-80A Turbofan Engine Studies

The three selected combustor configurations for the TFE731-80A turbofan engine studies are shown schematically in Figure 5, and a summary of the calculated flow splits and the LTO emission values for each configuration are listed in Table 9.

3.4.1.1 TFE731-80A Baseline Combustor

The Baseline combustor configuration includes 20 airblast injectors, axial dome swirlers, a primary zone equivalence ratio (PZ Phi) of 0.78, and employs effusion cooling on the ID and OD walls. The ratio of primary-to-swirler airflow is 0.96, and the percent dilution airflow equals 24.4 percent. These values are typical of new engine designs. Figure 6 shows a predicted velocity vector plot for the injector center plane of the -80A Baseline combustor for the SLTO condition. (Except where noted, all of the figures shown for the TFE731-80A and the other configurations are for SLTO). The large recirculation zone would be conducive to excellent idle efficiency and lean stability. However, it also represents a potential source of NOx production. In Figure 7, the contour plot of predicted gas temperatures for the same injector center-plane shows large regions of 3500F+ levels. Figure 8 shows predicted NOx contours, also for the same combustor plane. As seen in Table 9, this configuration is predicted to produce an NOx LTO value of 61.8. While this engine design would be below the thrust limit for regulation, if compared to the Fn>6000 class regulation, the predicted NOx value is only 83 percent of the current limit.



Baseline
Effusion Cooled
20 Piloted Airblast Nozzles

LTO Values
NOx - 61.8
UHC - 94.0
CO - 230

Near Term
Effusion Cooled High-Flow Swirler
20 Simplex Airblast Nozzles
Nozzle Staging at Idle

LTO Values
NOx - 48.5
UHC - 1.41
CO - 12.2

Advanced Technology
Effusion Cooled
20 Simplex Airblast Nozzles
Nozzle Staging at Idle
20 Fuel "Preparation" Cans

LTO Values
NOx - 16.6
UHC - 0.17
CO - 4.58

Figure 5. TFE731-80A Turbofan Engine Combustor Configurations.

TABLE 9. TFE731-80A TURBOFAN COMBUSTOR CONFIGURATIONS SUMMARY.

Characteristic	Units	Baseline	Near-Term	Advanced Technology
Swirler Flow	%	11.46	21.22	25.50
Injector Flow	%	6.73	6.73	6.20
Dome Cooling Flow	%	7.34	7.26	0.00
OD Wall Cooling Flow	%	15.24	15.30	10.50
ID Wall Cooling Flow	%	9.83	9.81	5.80
Primary Flow	%	10.96	10.96	38.10
Intermediate Flow	%	0.00	0.00	0.00
Dilution Flow	%	24.41	14.66	0.00
Bypass Flow	%	13.89	13.89	13.89
PZ Equiv. Ratio (PZ Phi)	–	0.78	0.60	0.48
Residence Time	msec	7.73	7.73	6.73
Pressure Drop	dP/P	4.68	4.71	4.70
NOx LTO	g/kN	61.8	48.5	16.6
NOx Compliance. Ratio*	–	0.83	0.65	0.22
CO LTO	g/kN	94.0	1.4	0.2
CO Compliance. Ratio*	–	1.95	0.10	0.04
UHC LTO	g/kN	230.0	12.2	4.6
UHC Compliance. Ratio*	—	4.79	0.07	0.01

* Compliance Ratios are the ratios of the predicted LTO value to the current regulatory limit.

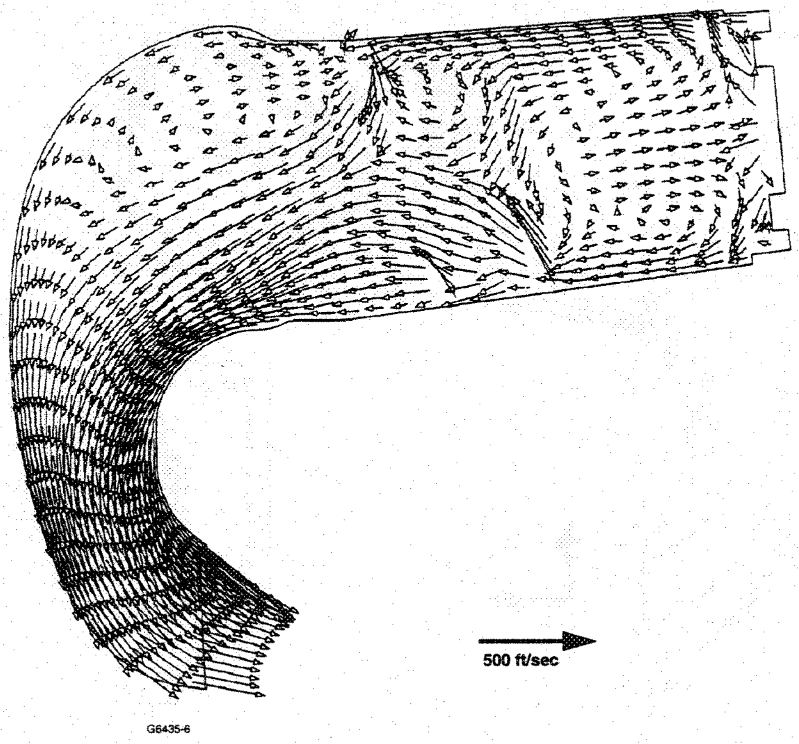


Figure 6. TFE731-80A Baseline Combustor Predicted Velocity Vectors.

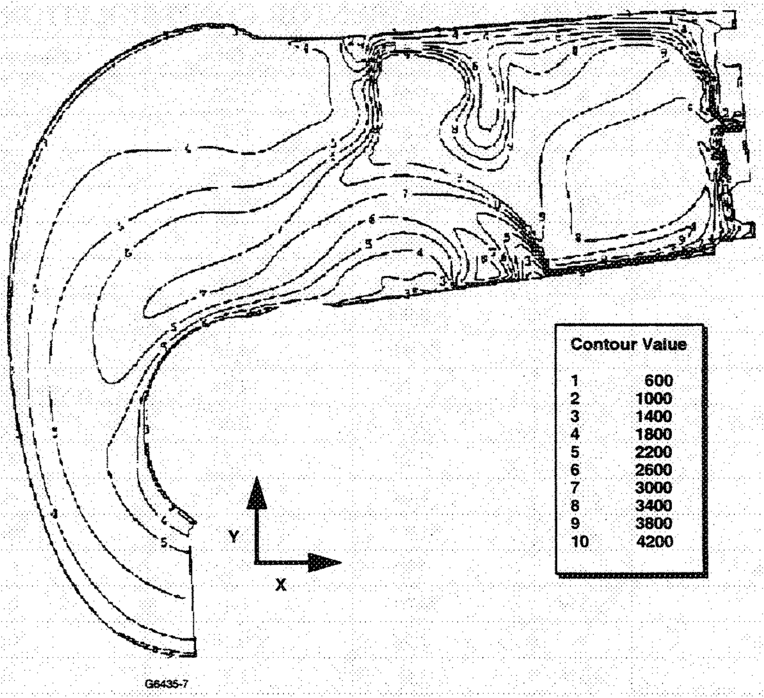


Figure 7. TFE731-80A Baseline Combustor Predicted Temperature Contours (deg. F).

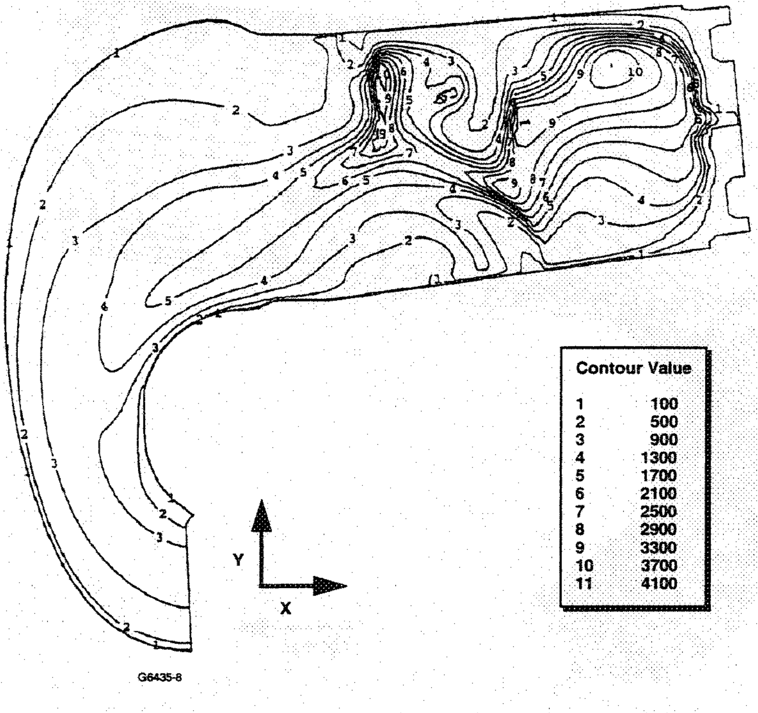


Figure 8. TFE731-80A Baseline Combustor Predicted NOx Contours (ppm).

3.4.1.2 TFE731-80A Near-Term Combustor

For the TFE731-80A Near-Term combustor geometry, the design approach was to reduce NOx with a minimum of changes to the Baseline configuration. This configuration is aimed at retrofitting an existing engine combustion system to met emission regulations, without making drasic changes to the engine. In this situation, NOx control could be accomplished by making the primary zone (PZ) more lean through increased swirler flow at the expense of dilution air, as shown by the flow splits in Table 9. This approach could be quickly implemented with no combustor tooling or fixture changes. Although NOx reduction would be expected, it is likely that the idle efficiency for this geometry could be excessively low, and that a staging arrangement for the fuel injectors would be required. Thus, the ease by which the combustor could be modified to reduce NOx might be offset by an increase in the complexity of the fuel delivery system required for proper operation at all operating conditions. After completing the 3-D CFD model analysis, the predicted velocity vector plots for the Near-Term configuration, shown in Figure 9, were created. The slightly-higher velocities and increased recirculation in the primary zone are evident by comparison with Figure 6. More significantly, the predicted overall PZ temperature levels are lower, with a reduction in the 3500F+ zones as shown in Figure 10. Also, the high-temperature areas would be fully contained within the primary zone, rather than spreading into the intermediate zone, as seen in Figure 7 for the Baseline configuration. This predicted temperature reduction is directly reflected in a reduction of the predicted LTO NOx levels, from 61.8 to 48.5.

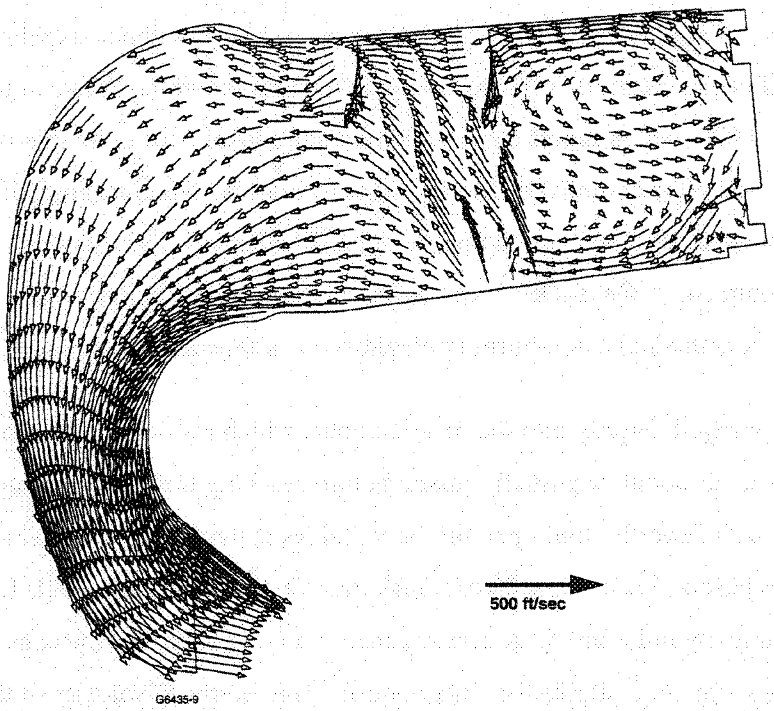


Figure 9. TFE731-80A Near-Term Combustor Predicted Velocity Vectors.

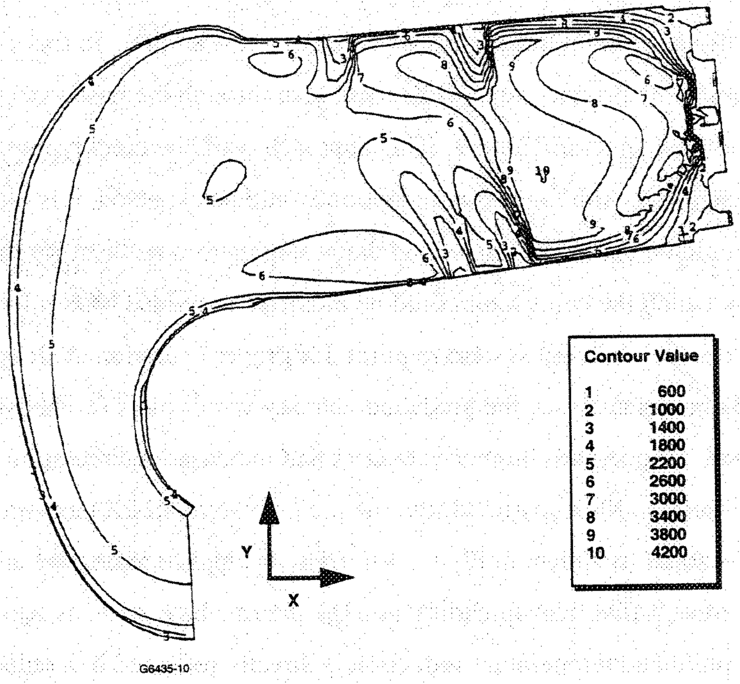


Figure 10. TFE731-80A Near-Term Combustor Predicted Temperature Contours (deg. F).

As expected, the idle efficiency of the Near-Term configuration was very low without staging, so an arrangement was devised wherein only half of the injectors were flowing at idle. This increased the local fuel/air ratio for the active injectors from 0.012 to 0.024, which raised the local temperature levels to a point that permitted the UHC and CO reactions to be completed. It is assumed that in the implementation of fuel staging, the functioning injectors would be arranged in clusters. Thus, for an engine using 20 injectors, with only half the injectors operating, the arrangement would be: 5-On, 5-Off, 5-On, 5-Off, or some other similar pattern. This arrangement minimizes the number of injectors that have non-burning neighbor(s) and the associated quenching.

In current combustors, fuel is sprayed directly into the reaction zone, which results in high-temperature, NOx production areas. If the fuel and air could be partially mixed before reaching the reaction zone, a more uniform fuel/air mixture would result, with fewer high-temperature areas. This is the approach on which the Advanced Technology configuration was based. Each of the 20 fuel injectors was mounted in a small, 1.5 inch diameter ceramic can, as shown schematically in Figure 5. A ceramic material was chosen for the cans because no cooling air would be required, making more air available for NOx control. The reference velocity of these cans, 37 ft/sec, was high enough to prevent the occurrence of any significant amount of reaction inside the cans.

Thus, the cans act as "fuel-preparation chambers", giving the fuel and air time to mix before being introduced into the main combustor. This configuration uses some of the elements of the Lean Premix Pre-vaporized (LPP) method of NOx control, but avoids any potential "flashback" problems, since no damage would occur during transient engine operation if the flame temporarily enters the ceramic cans. Once the engine returns to steady operation, the flame would move back into the main combustor.

3.4.1.3 TFE731-80A Advanced Technology Combustor

In the TFE731-80A Advanced Technology combustor configuration, one swirler was used to generate swirl in the can, while another was positioned at the interface between the cans and the main-annular, metal-walled combustor. One of the functions of this second swirler was to provide an air sweep of the burner-dome surface area between the preparation cans. To minimize the size of the reaction zone, the dilution and primary air were combined into a single orifice row, which was located relatively close to the exit of the preparation cans. In addition, the jets were made relatively large and the OD and ID rows were offset, such that the jets interweaved rather than impinging upon each other. The jets were set to penetrate nearly to the opposite wall, creating large-scale mixing to quickly remove any high-temperature areas in the primary zone.

Predicted velocity vector plots for this configuration are shown in Figure 11. The compact size of the primary zone and the intense velocities in the fuel preparation chambers are evident. The resulting predicted temperature contours, shown in Figure 12, clearly indicate a reduction in size (and therefore residence time) of the primary zone resulting from this configuration. Also evident is the quickness with which the primary orifice row reduces the temperature, thus limiting NOx production. Finally, the predicted NOx contours shown in Figure 13 and the values in Table 9 indicate that the NOx LTO level of this Advanced Technology configuration would be reduced by 73 percent, compared to the Baseline configuration.

As with the Near-Term configuration, the predicted high flows and mixing rates generated in the primary zone would make it difficult to maintain idle efficiency, so a staging arrangement similar to the Near-Term configuration, where only half of the injectors were active at idle, was used. The resulting predicted idle emission levels were extremely low, as reflected in the LTO values given in Table 9.

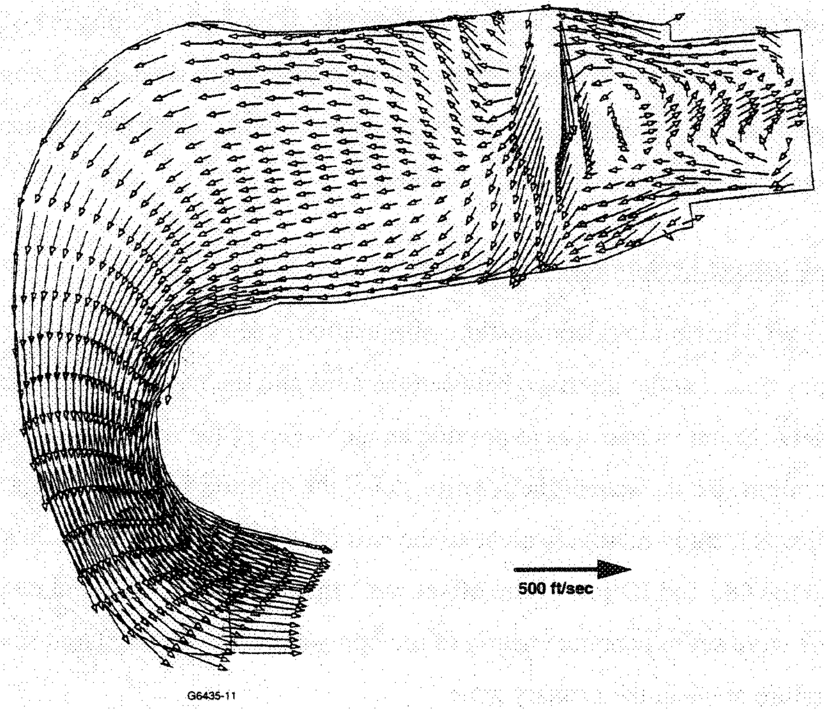


Figure 11. TFE731-80A Advanced Technology Combustor Predicted Velocity Vectors.

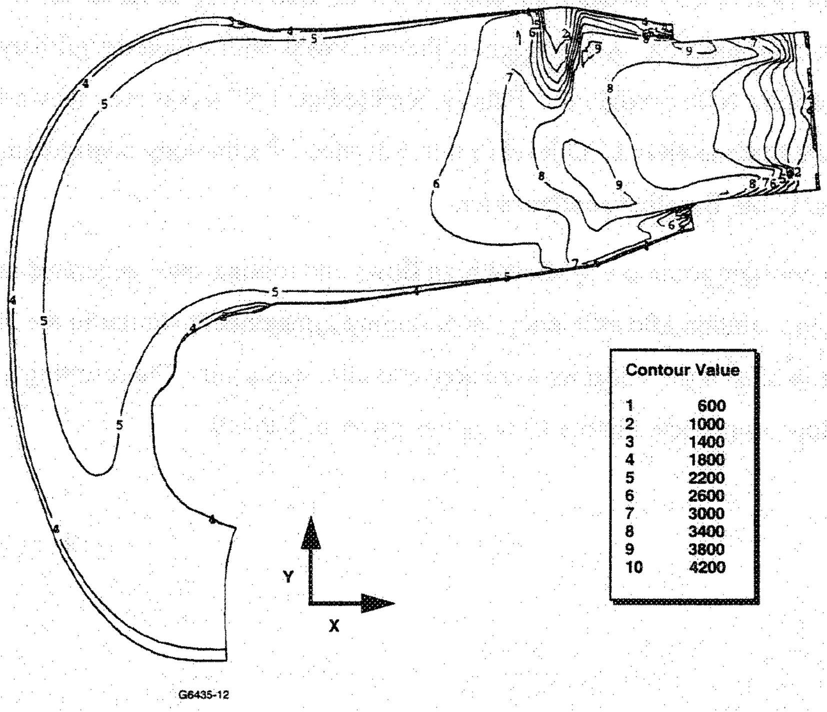


Figure 12. TFE731-80A Advanced Technology Combustor Predicted Temperature Contours (deg. F).

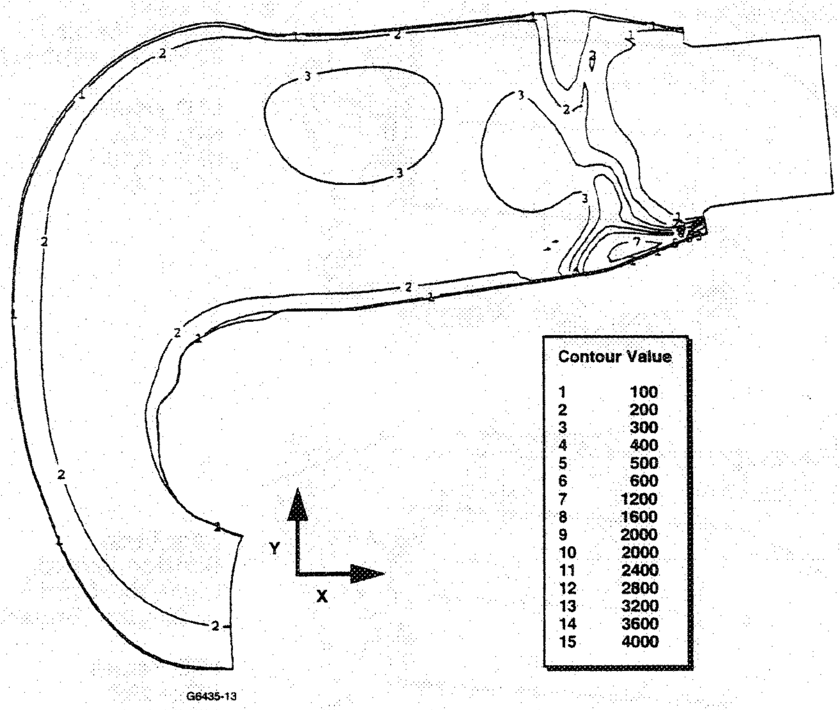


Figure 13. TFE731-80A Advanced Technology Combustor Predicted NOx Contours (ppm).

3.4.2 AS807 Turboprop Engine Studies

Currently, turboprop engines are regulated only for smoke. The LTO cycle calculations are based on engine thrust (**Fn**), rather than shaft horsepower (**shp**) . To properly evaluate the emissions from the AS807 turboprop and compare them with values for the TFE731-80A and AS918 turbofan engines, the AS807 cruise shaft horsepower was converted to a thrust value with the following equation:

Thrust (Fn) = 550*(prop efficiency)*shaft horsepower/Va **[6]**

Where:

Propeller efficiency is assumed to be 0.8

Va is the air velocity relative to the engine in ft/sec.

For this study, the AS807 cruise Mach number was taken to be 0.58, which resulted in a rated thrust (**Fn**) of 4470 lb. The three combustor configurations for the AS807 regional turboprop engine that were studied are shown schematically in Figure 14. The corresponding flow splits and LTO cycle values are listed in Table 10.

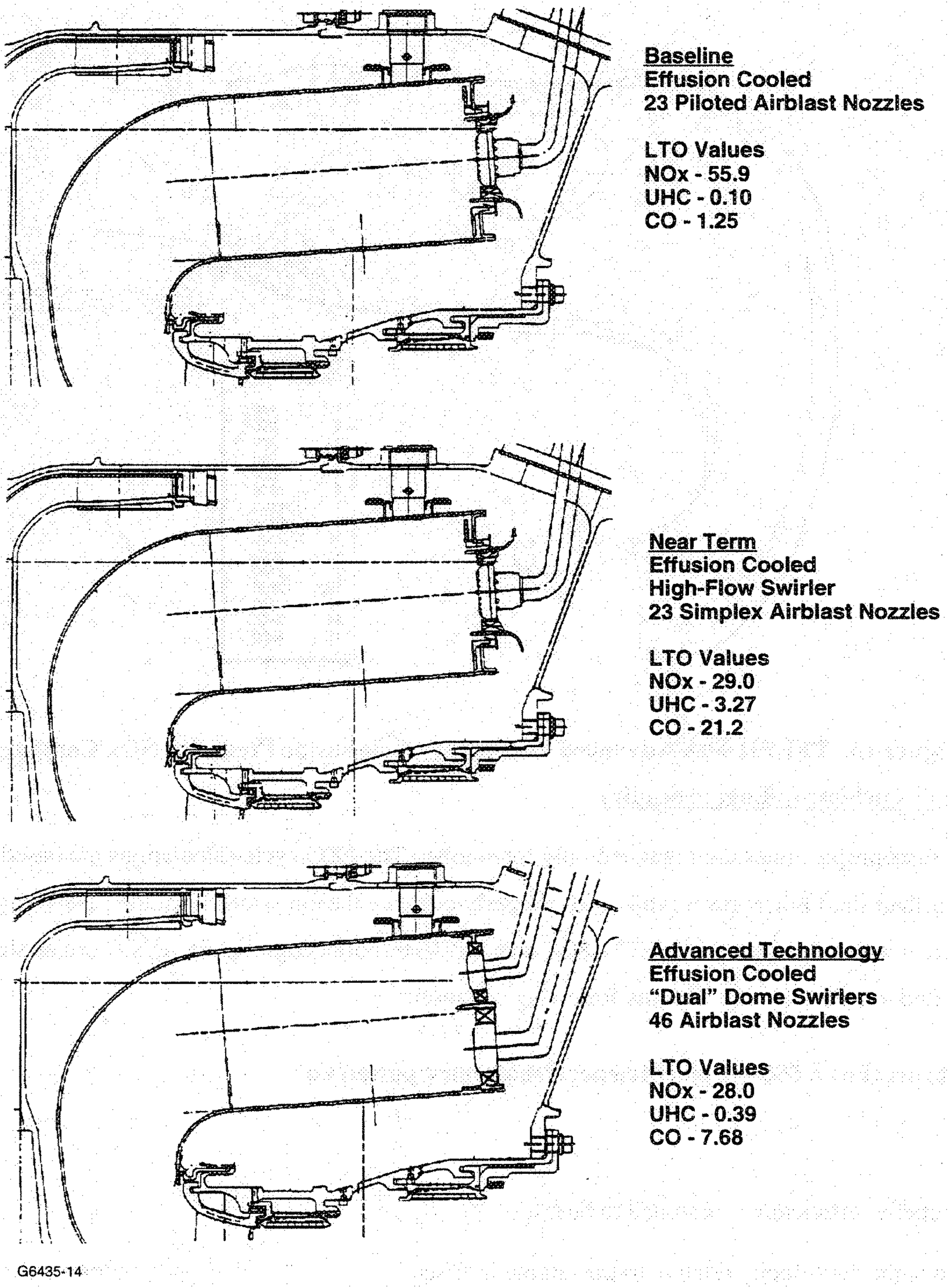


Figure 14. AS807 Turboprop Engine Combustor Configurations.

TABLE 10. AS807 TURBOPROP COMBUSTOR CONFIGURATIONS SUMMARY.

Characteristic	Units	Baseline	Near-Term	Advanced Technology
Swirler Flow	%	14.64	18.43	21.69
Injector Flow	%	2.40	10.00	6.97
Dome Cooling Flow	%	5.18	5.15	5.12
OD Wall Cooling Flow	%	9.11	9.14	9.10
ID Wall Cooling Flow	%	14.90	14.96	14.90
Primary Flow	%	15.74	8.49	8.44
Intermediate Flow	%	0.00	0.00	0.00
Dilution Flow	%	16.50	12.30	12.24
Bypass Flow	%	22.37	22.37	22.37
PZ Equiv. Ratio (PZ Phi)	---	0.83	0.68	0.67
Residence Time	msec	16.30	16.30	16.30
Pressure Drop Ratio, dP/P	---	0.05	0.05	0.05
NOx LTO	g/kN	55.9	29.0	28.0
NOx Compliance. Ratio*	---	0.65	0.44	0.43
CO LTO	g/kN	1.3	21.2	7.7
CO Compliance. Ratio*	---	0.01	0.18	0.07
UHC LTO	g/kN	0.1	3.3	0.4
UHC Compliance. Ratio*		0.01	0.17	0.02

* Compliance Ratio is the ratio of the predicted LTO value to the current regulatory limit.

3.4.2.1 AS807 Baseline Combustor

The Baseline configuration is similar to the TFE731-80A Baseline, and uses 23 injector/axial swirler sets, with conventional primary and dilution orifice rows and effusion cooling on the OD and ID combustor walls. In this case, the AS807 Baseline configuration represents an effusion-cooled variant of an existing turboprop combustor.

The AS807 Baseline combustor geometry was modeled and analyzed with the AlliedSignal 3-D CFD code, and the results are shown in Figures 15 through 17. Figure 15 is a velocity vector plot for the axial plane passing through the injector centerline, and shows a conventional recirculation zone terminated by the primary jets. The temperature field for the same combustor plane is shown in Figure 16. Of interest here are the high-temperature (>3000F) regions that extend into the intermediate zone and beyond, creating areas of high residence time where NOx would be produced. This flow-field characteristic is typical of conventional combustors having a primary zone equivalence ratio on the order of 1.0, as was the case here. The predicted NOx contour plot for the same plane is shown in Figure 17. Comparison with the temperature contours verifies the expected correspondence between high temperature and high-NOx concentration.

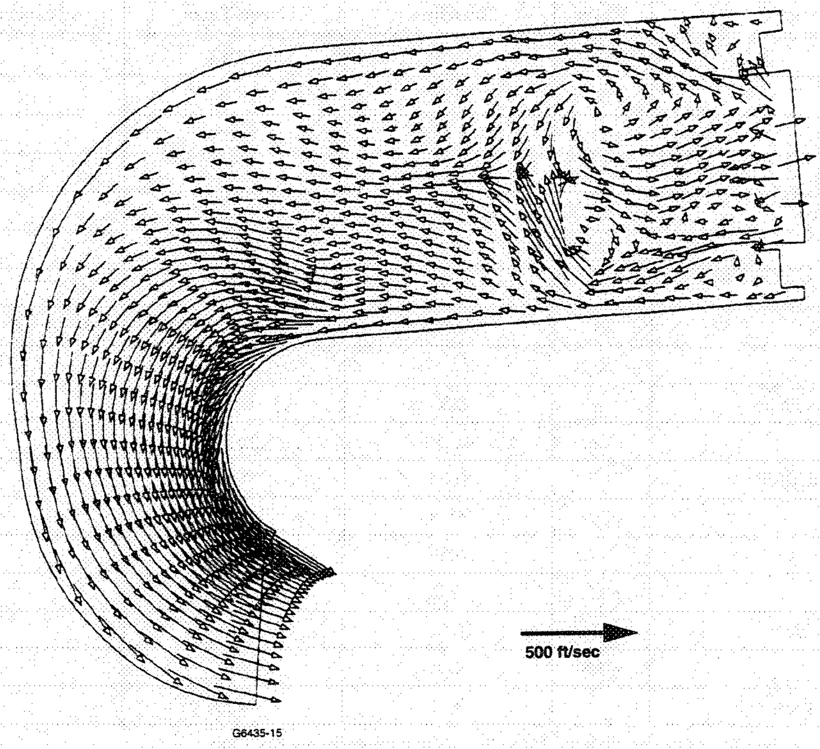


Figure 15. AS807 Baseline Combustor Predicted Velocity Vectors.

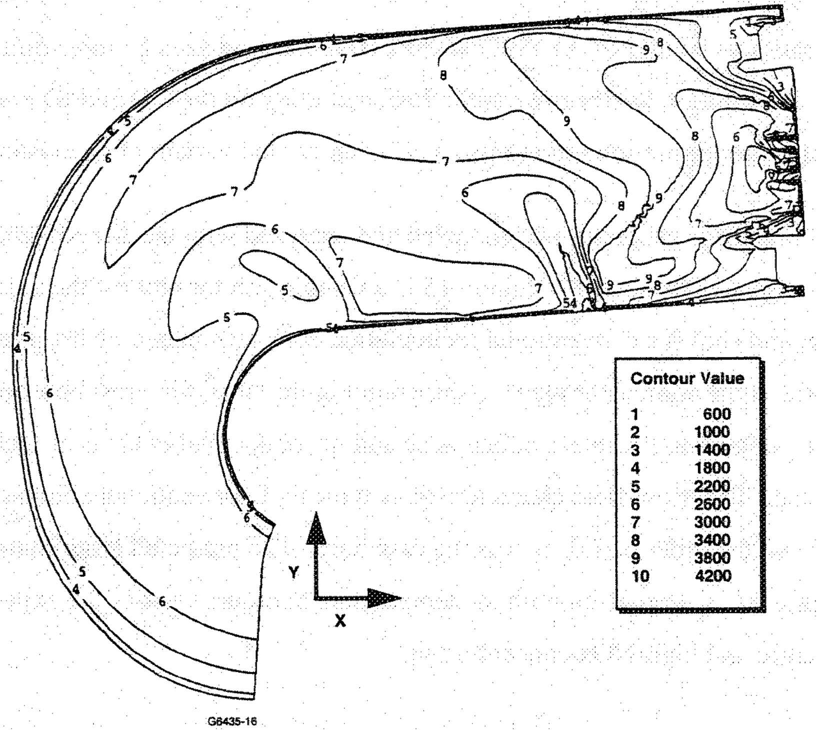


Figure 16. AS807 Baseline Combustor Predicted Temperature Contours (deg. F).

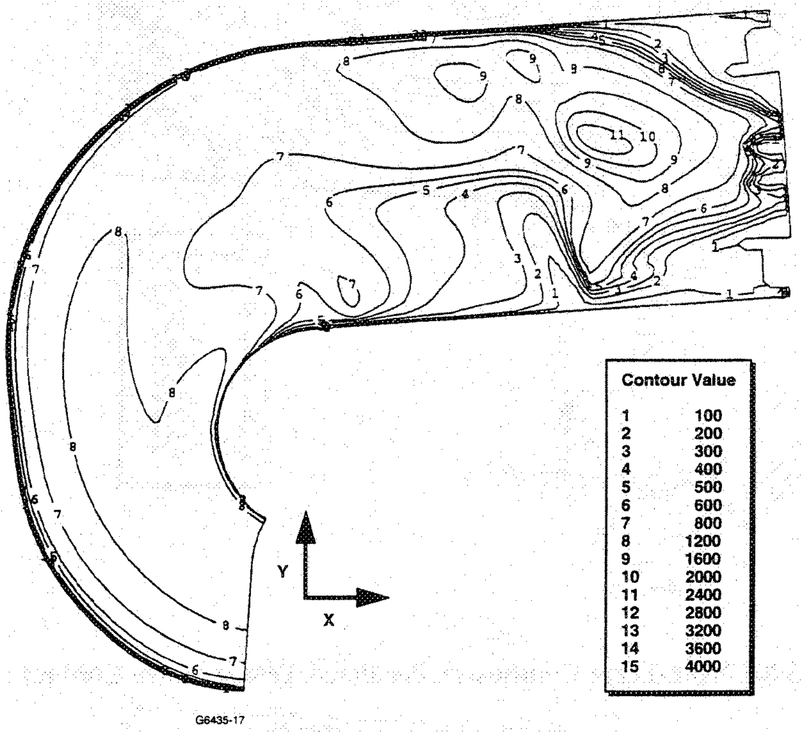


Figure 17. AS807 Baseline Combustor Predicted NOx Contours (ppm).

3.4.2.2 AS807 Near-Term Combustor

For the AS807 Near-Term combustor configuration, a design philosophy similar to that applied to the TFE731 was employed. The modifications to the Baseline geometry were minor, consisting of increasing the swirler and injector airflow by decreasing the primary and dilution air. The impact of the increased swirler flow on the predicted Near-Term temperature fields can be seen by comparing Figure 18 with Figure 16 (Baseline configuration). The 3000F+ zones are reduced in size and are better contained within the primary zone in the Near-Term combustor design. As expected, the lower temperatures result in lower predicted NOx concentrations, as seen in Figure 19, and a lower calculated LTO NOx value of 29, a 48-percent reduction compared to the Baseline value of 55.9. In this situation, it was not necessary to use injector staging to obtain idle efficiencies that will meet the regulations, although the levels of CO and UHC are higher than the Baseline values (see Table 10).

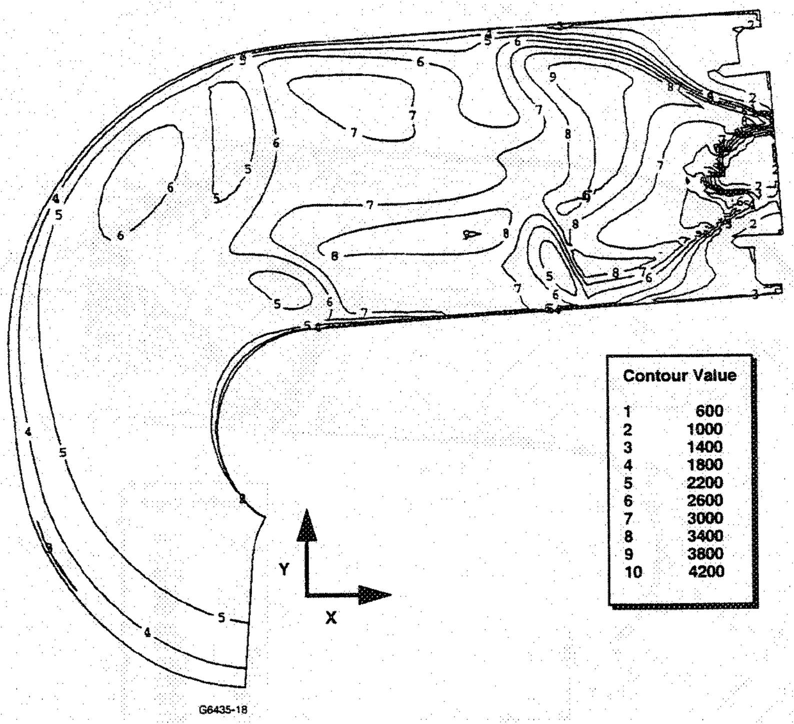


Figure 18. AS807 Near-Term Combustor Predicted Temperature Contours (deg. F).

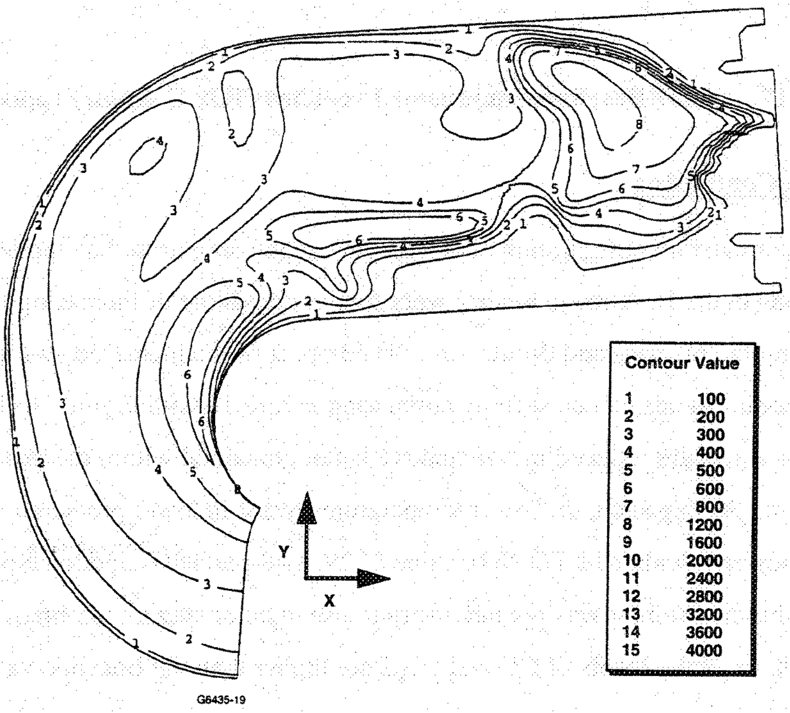


Figure 19. AS807 Near-Term Combustor Predicted NOx Contours (ppm).

3.4.2.3 AS807 Advanced Technology Combustor

The goal for the AS807 Advanced Technology combustor configuration was to satisfy the conflicting requirements of a lean, relatively low-temperature zone needed to limit NOx, with a rich, high-temperature zone needed to reduce the idle emissions. An approach, used successfully on larger engines, divides the normal combustor primary zone into two annular regions, by adding short, intermediate walls between the OD and ID panels. The smaller of the two regions has an equivalence ratio close to stochiometric, serving as a pilot and as the main primary zone for idle operation. The secondary annular zone (that is usually larger) has a lean equivalence ratio that limits NOx. At high power, most of the fuel flows through this secondary dome. At idle, these fuel injectors are turned off. This concept works well for large engine combustors because there is sufficient room to include the rather bulky, double-dome arrangement. However, for engines in the size class of the AS807, it is physically impossible to use the conventional double-dome and still maintain a reasonable channel height.

For the AS807 Advanced Technology configuration, the double-dome design was modified to use a double swirler/injector design, mounted in a conventional dome. The smaller of the two was made the pilot / idle swirler, and was sized to give an equivalence ratio of 1.0. The larger of the injector/swirler sets was configured so that the injector was completely turned off at idle but flowed 70 percent of the fuel at Sea Level Takeoff (SLTO) conditions. Velocity vector plots for axial planes through the primary and secondary injector centerplanes are shown in Figures 20 and 21, respectively. As can be seen, the recirculation zone created by each of the swirlers tends to create isolated regions immediately downstream of the swirlers which mimic the physical separation of a conventional double-dome arrangement. The corresponding temperature contours for the same planes are shown in Figures 22 and 23, respectively. Although the NOx levels for this Advanced Technology configuration were approximately the same as the Near-Term geometry, both were lower than the assumed regulatory limit (for Fn<6000 lbs. engines). However, a significant improvement in the UHC and CO idle emissions was achieved, without the use of injector staging.

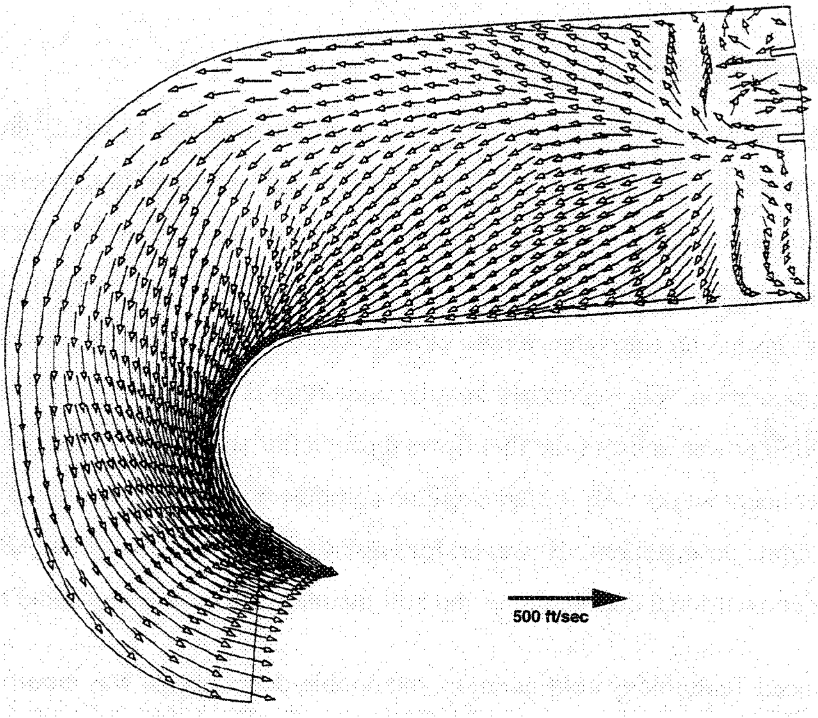


Figure 20. AS807 Advanced Technology Combustor Predicted Velocity Vectors - Primary Swirler Centerline.

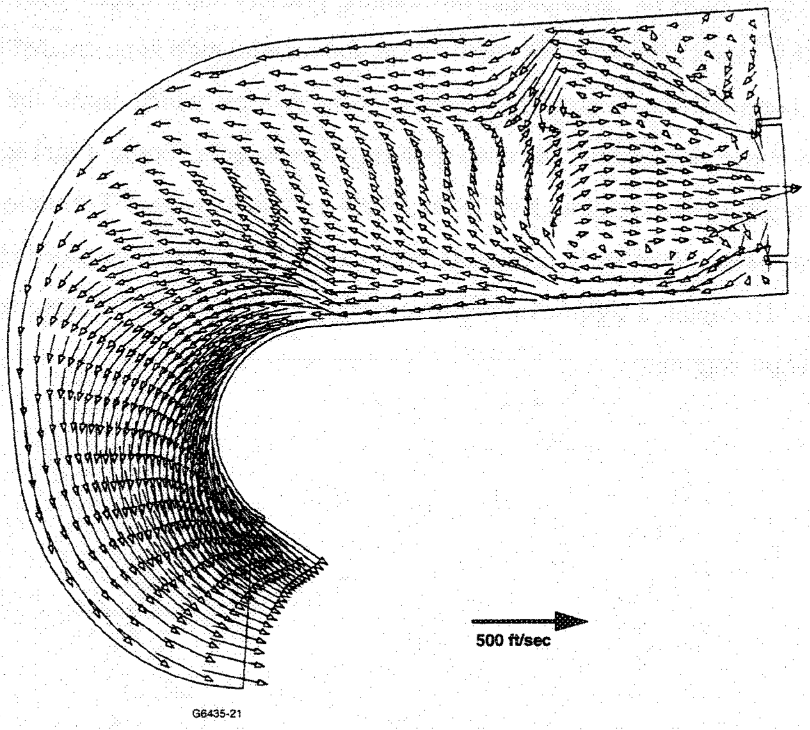


Figure 21. AS807 Advanced Technology Combustor Predicted Velocity Vectors - Secondary Swirler Centerline.

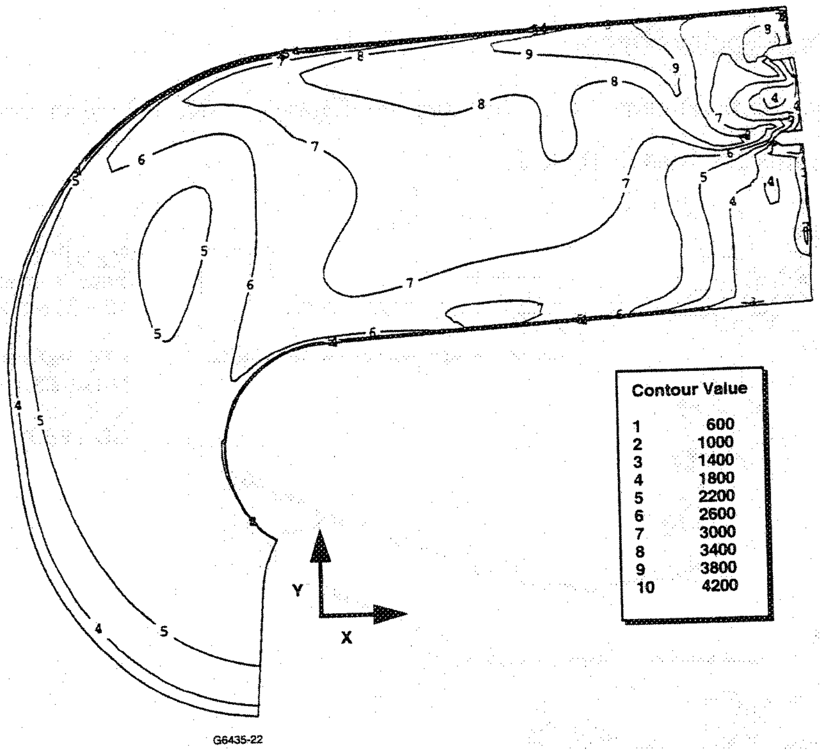


Figure 22. AS807 Advanced Technology Combustor Predicted Temperature Contours - Primary Swirler Centerline (deg. F).

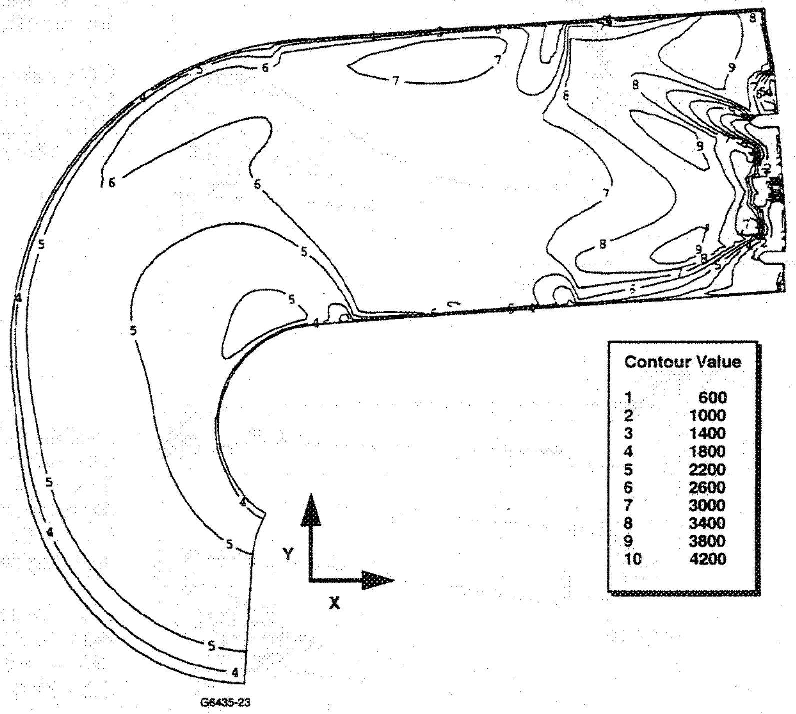


Figure 23. AS807 Advanced Technology Combustor Predicted Temperature Contours - Secondary Swirler Centerline (deg. F).

3.4.3 AS918 Turbofan Engine Studies

For the AS918 regional turbofan engine cycle, the three configurations selected are shown in Figure 24, and the corresponding flow splits are listed in Table 11.

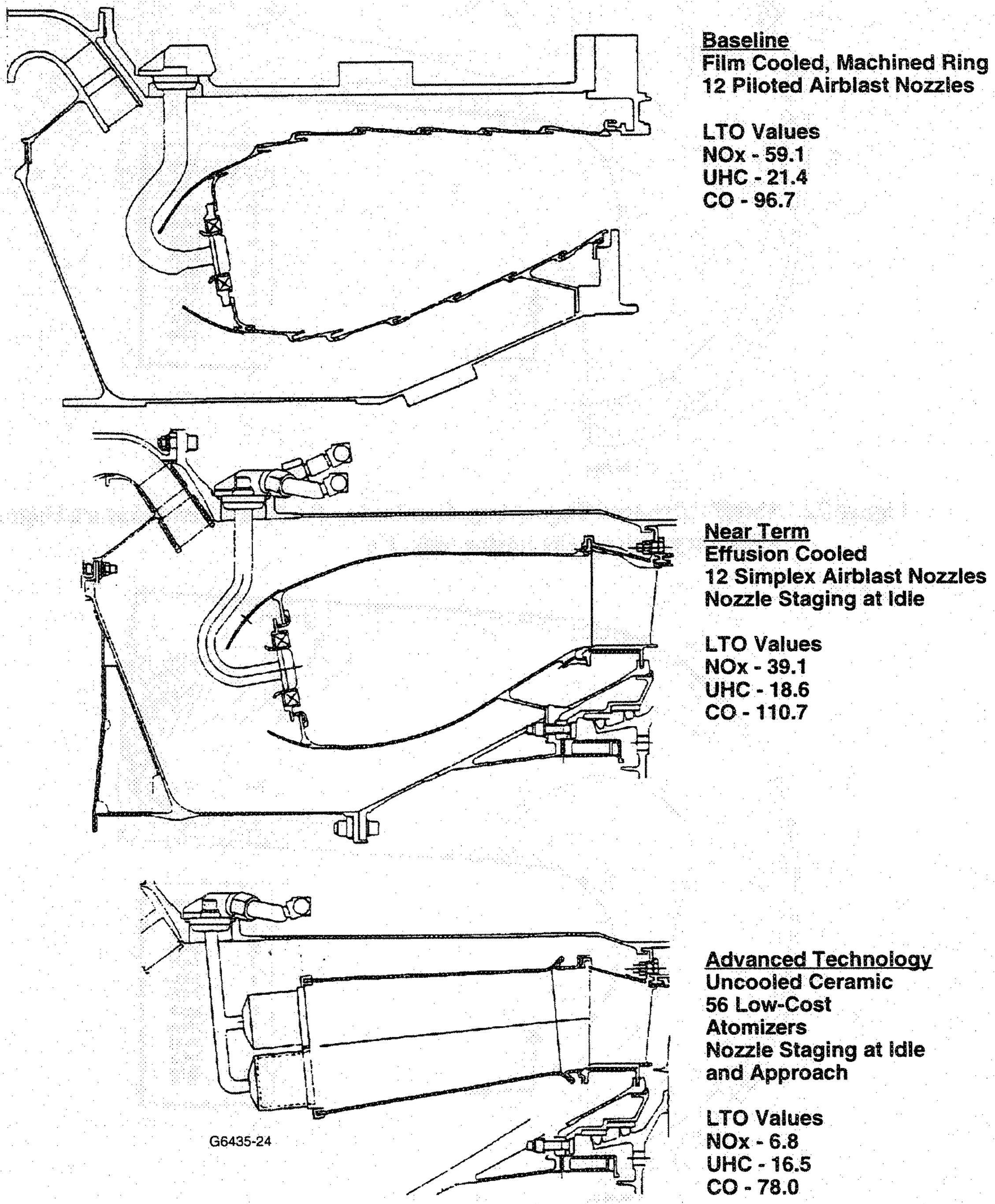


Figure 24. AS918 Turbofan Engine Combustor Configurations.

TABLE 11. AS918 AND AST918 TURBOFAN COMBUSTOR CONFIGURATIONS SUMMARY.

Characteristic	Units	AS918 Configurations Baseline	 Near-Term	 Advanced Technology	AST918
Chamber Swirler Flow	%	0.00	0.00	0.00	10.00
Main Injector Flow	%	15.07	21.00	0.00	12.00
Injector Flow	%	2.72	6.00	30.00	5.30
Dome Cooling Flow	%	2.89	4.00	8.00	0.00
OD Wall Cooling Flow	%	19.21	9.14	0.00	6.00
ID Wall Cooling Flow	%	11.06	4.83	0.00	6.00
Primary Flow	%	11.53	22.74	21.71	10.00
Intermediate Flow	%	9.43	0.00	0.00	0.00
Dilution Flow	%	5.82	10.00	18.00	24.40
Bypass Flow	%	22.29	22.29	22.29	22.29
PZ Equiv. Ratio (PZ Phi)	---	0.96	0.70	0.62	0.83
Residence Time	msec	8.20	6.06	5.29	4.72
Pressure Drop Ratio, dP/P	---	5.91	5.80	5.80	5.8
NOx LTO	g/kN	59.1	39.1	6.8	14.4
NOx Compliance. Ratio*	---	0.68	0.45	0.08	0.17
CO LTO	g/kN	96.7	110.7	78.0	81.1
CO Compliance Ratio*	---	0.82	0.94	0.66	0.69
UHC LTO	g/kN	21.3	18.6	16.5	1.9
UHC Compliance. Ratio*	---	1.09	0.95	0.84	0.10
* Compliance Ratio is the ratio of the predicted LTO value to the current regulatory limit.					

3.4.3.1 AS918 Baseline Combustor

The AS918 Baseline combustor design is a close derivative of the production AlliedSignal Model TFE1042 design, which uses 12 airblast injectors with machined-ring, film-cooled walls. Since the operating conditions of the A918 were significantly different from those of the TFE1042, the primary-zone orifice pattern was altered to achieve a primary zone fuel/air ratio of 0.96. The resulting predicted velocity vectors for an axial plane through the injector at the SLTO condition are shown in Figure 25. As is typical of current designs, the primary zone is large and contains high-temperature zones, as can be seen in the predicted temperature contours for the same injector centerplane, shown in Figure 26. This is also reflected in the predicted NOx contours shown in Figure 27 and in the calculated NOx LTO value of 59.1.

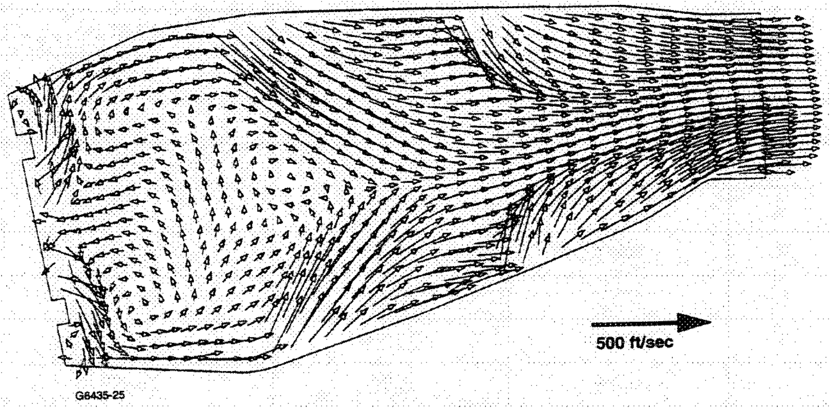


Figure 25. AS918 Baseline Combustor Predicted Velocity Vectors.

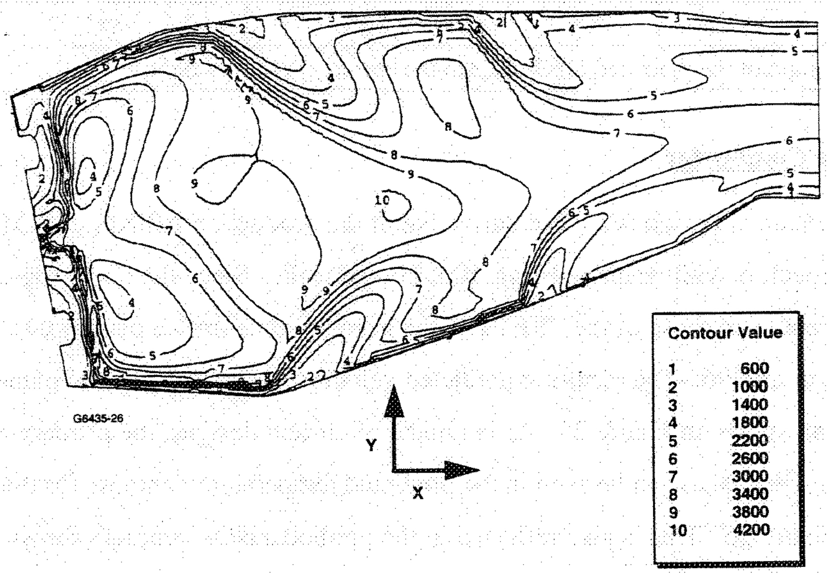


Figure 26. AS918 Baseline Combustor Predicted Temperature Contours (deg. F).

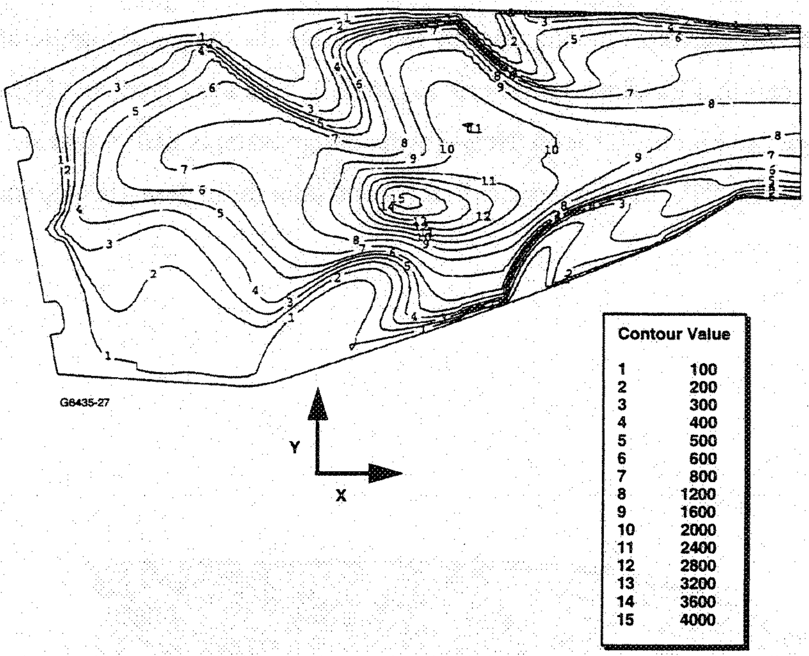


Figure 27. AS918 Baseline Combustor Predicted NOx Contours (ppm).

3.4.3.2 AS918 Near-Term Combustor

Modifications to the AS918 Near-Term combustor concept were more significant than for the other engines. To reduce the residence time, the entire burner was shortened 1.9 inches, and the film cooling was replaced with effusion cooling. This reduced the required cooling air from 30.3 percent to 14 percent of the total compressor discharge flow, with the difference gained being added to the swirler flow. The primary and intermediate rows were combined into a single row of 22.7 percent flow rate, divided equally between the OD and ID, followed by a dilution row of 10 percent, also equally divided. By increasing the primary flow, the high temperatures in the primary zone were quenched, thus limiting NOx formation. In addition, the OD and ID orifice rows were circumferentially arranged so that the jets were interweaved, rather than impinging. This arrangement generates large-scale mixing that produces a more-uniform temperature field.

The high swirler flow rates and high mixing rates used in the AS918 Near-Term combustor concept made it challenging to reduce the idle emission levels below the regulation limits. It was found that staging was necessary, done by halving the number of fuel injectors operating at idle, in order to meet the CO and UHC requirements.

The effects of these changes, compared to the AS918 Baseline geometry, can be seen in Figure 28, which shows the Near-Term combustor injector center plane velocity vector plot. A strong recirculation zone, terminated by primary jets that penetrate to the opposite wall, contributes to the high mixing rates. The corresponding predicted Near-Term temperature contours, shown in Figure 29, indicate a more-compact primary zone (compared to the Baseline), and also that the strong, interweaving primary jets prevent the escape of high-temperature gas that occurred in the more-conventional Baseline design (see Figure 26). The peak predicted NOx concentration indicated on the contour plot in Figure 30 for the Near-Term configuration is half of that shown for the similar Baseline plane (compare Figure 27) , a characteristic that is consistent throughout the AS918 combustor.

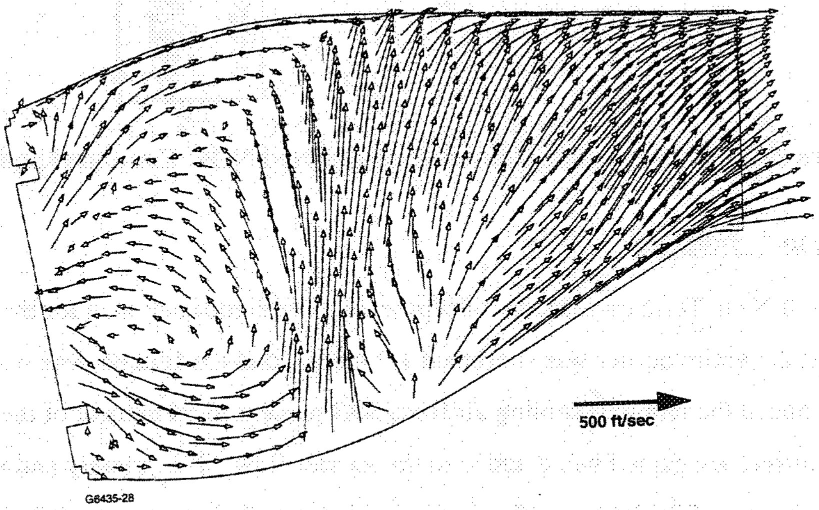


Figure 28. AS918 Near-Term Combustor Predicted Velocity Vectors.

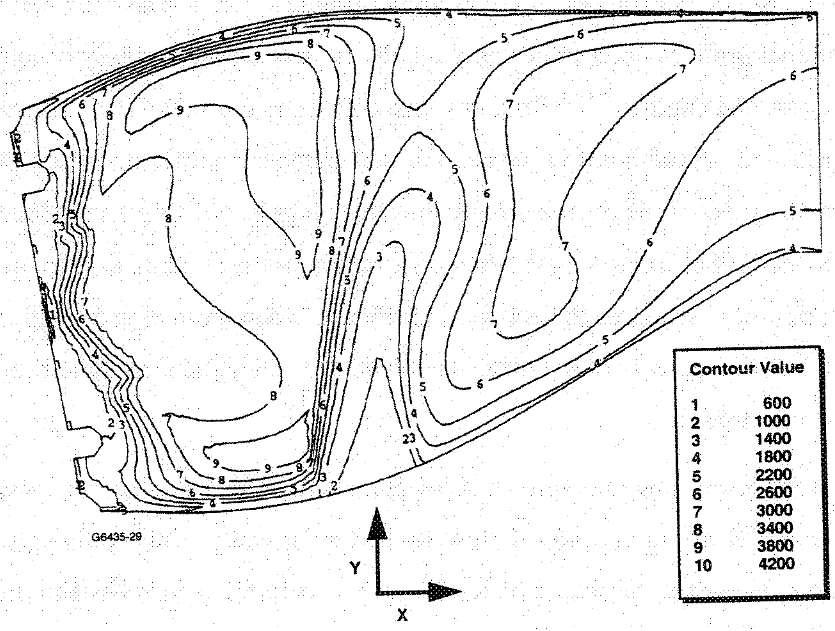


Figure 29. AS918 Near-Term Combustor Predicted Temperature Contours (deg. F).

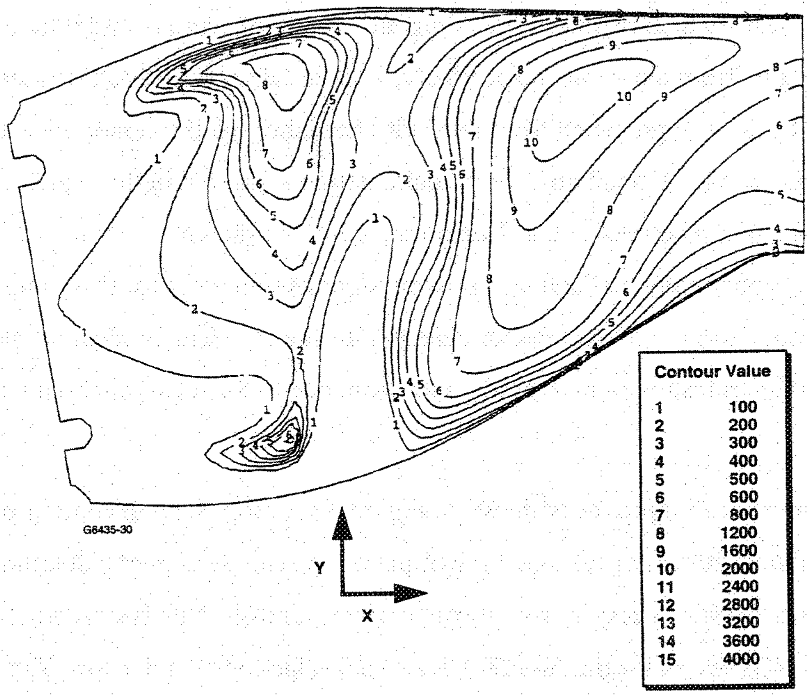


Figure 30. AS918 Near-Term Combustor Predicted NOx Contours (ppm).

3.4.3.3 AS918 Advanced Technology Combustor

The approach used for the AS918 Advanced Technology combustor concept was to take advantage of low-cost atomizer technology that has been developed at AlliedSignal Engines over the last 10 years. Injectors of an extremely simple design that produce acceptable spray quality have been successfully developed and tested on several research combustors and engines. (3) These low-cost atomizers consist of a simple chamber, into which low-velocity fuel is introduced. Axial holes in the head of the chamber impinge upon and break up the fuel jet, while tangential slots on the sides of the chamber body introduce highly-swirling air that completes the atomization process. One traditional method of improving the fuel distribution in the combustor is to use additional injectors. However, the increased cost of that approach becomes significant, when more than 50 fuel injectors are required in the design. Thus, low-cost injector technology offers an advantage, since the manufacturing expense is only a fraction of conventional injectors.

Another consideration when increasing the number of injectors is that, from packaging considerations, the likelihood is increased that fuel would be sprayed close to the burner walls. This could present a problem for metallic wall construction. However, advanced materials such as ceramics can withstand the considerably higher temperature levels found in such arrangements.

All of these considerations were included in the final AS918 Advanced Technology combustor design (see Figure 24). A total of 56 low-cost atomizers were arranged in two rows in the dome, discharging into an annular combustor with ceramic walls which requires no cooling air. A row of primary and dilution orifices are located at 0.63 and 1.2 channel heights from the dome, respectively, with an OD and an ID skirt located in the dome, used to eliminate the corner vortices. The predicted SLTO velocity field through the center plane of one pair of low-cost atomizers is shown in Figure 31. A small amount of recirculation is present in the center of the injector chamber along with some reaction, as can be seen in the temperature contours shown in Figure 32. The low-cost injectors serve as a pre-mixer to evaporate the fuel and also provide stabilization areas for the flame. While it is possible that the flame could recede farther into the injector chamber during transient combustor operation, the flame would be immediately expelled upon resumption of steady operation, due to the relatively high reference velocities in the injectors.

The effect of the large number of injectors is shown in Figure 33, a cross-section contour plot of the fuel/air ratio at a 0.15 channel height downstream of the injector exit plane. As can be seen, the distribution is very uniform, which is a desirable characteristic necessary for NOx emissions control. This is supported by Figure 34, which shows a contour plot of NOx levels for the AS918 Advanced Technology combustor. The absence of high fuel/air ratio zones, and the corresponding high temperatures, limits the overall NOx production to levels 88 percent below the Baseline design.

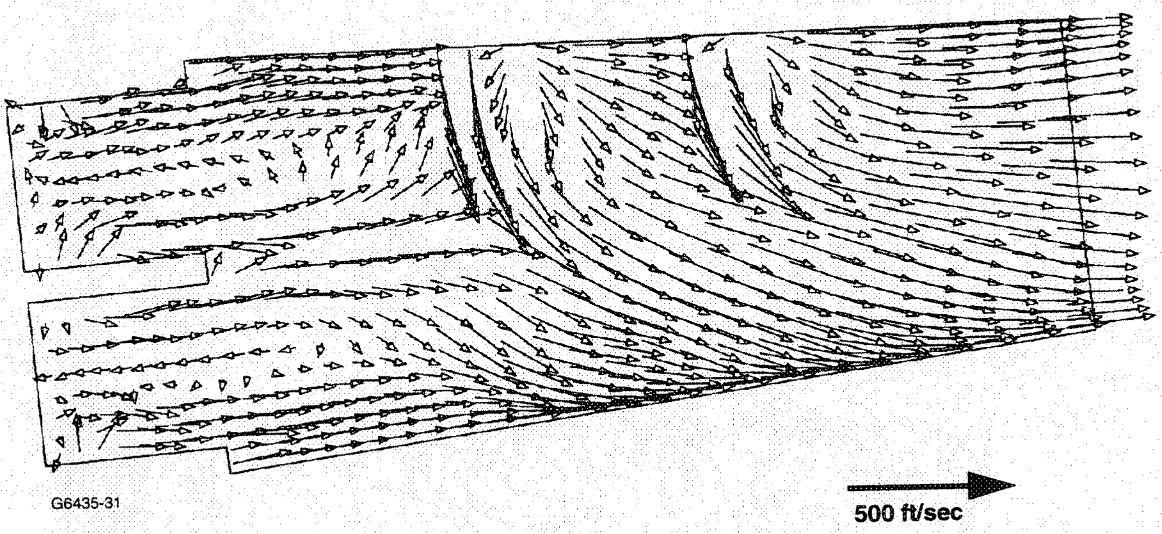


Figure 31. AS918 Advanced Technology Combustor Predicted Velocity Vectors.

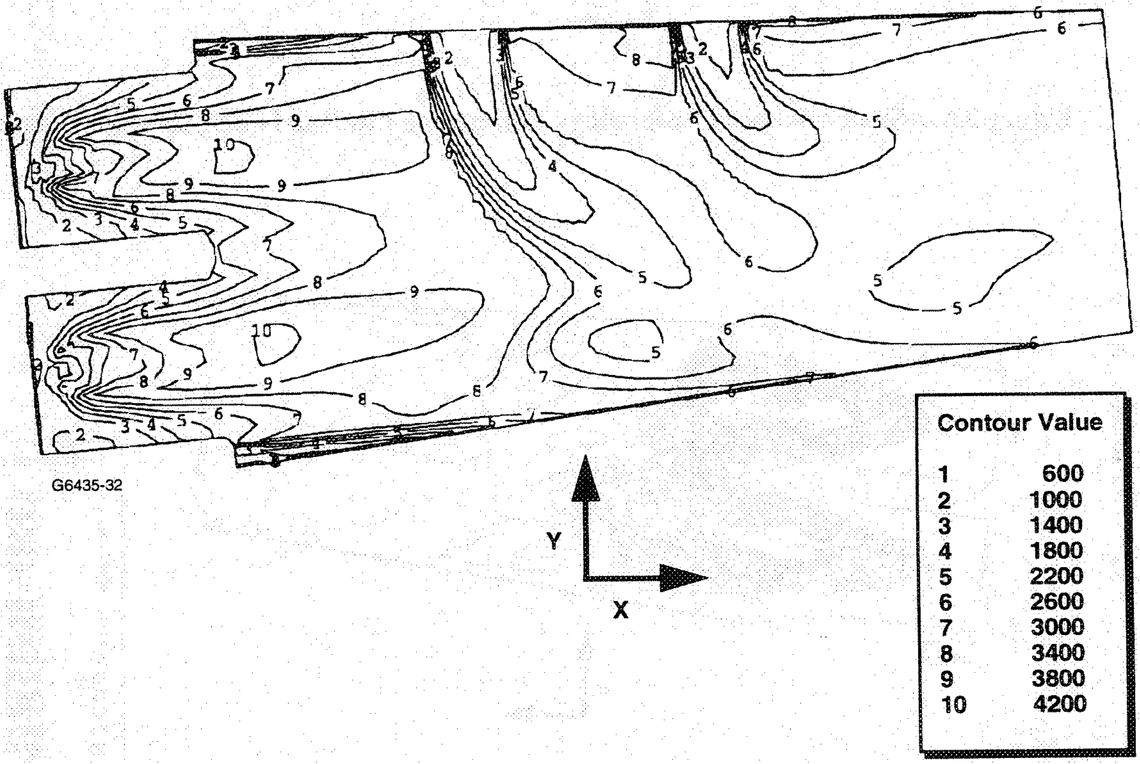


Figure 32. AS918 Advanced Technology Combustor Predicted Temperature Contours (deg. F).

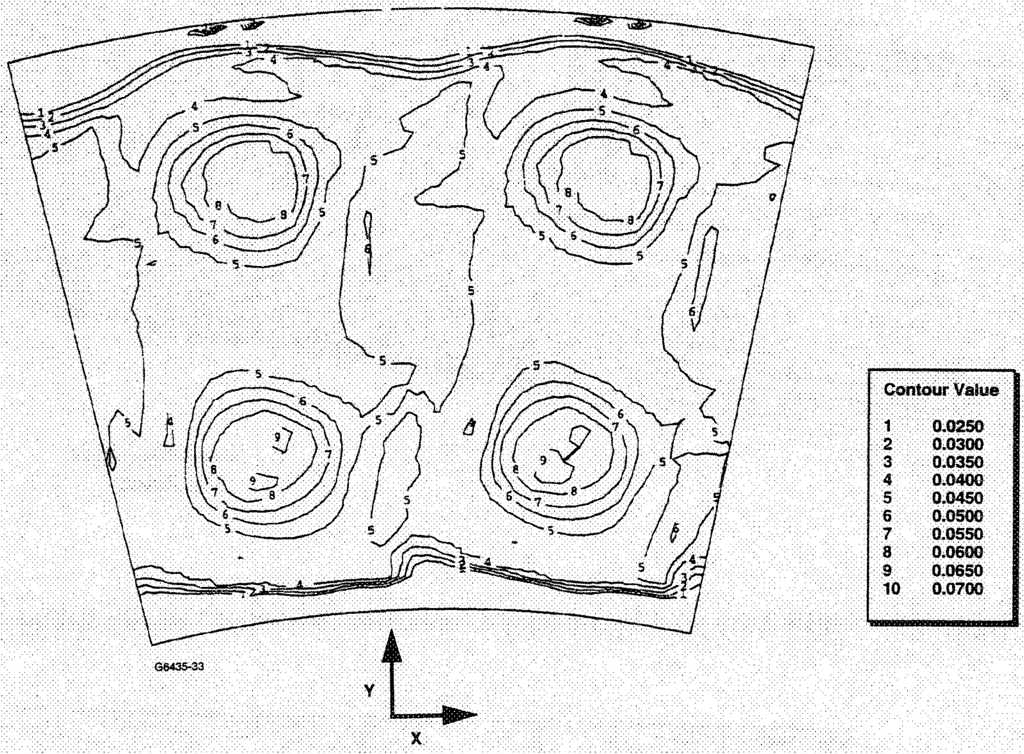


Figure 33. AS918 Advanced Technology Combustor Predicted Fuel/Air Ratio Contours.

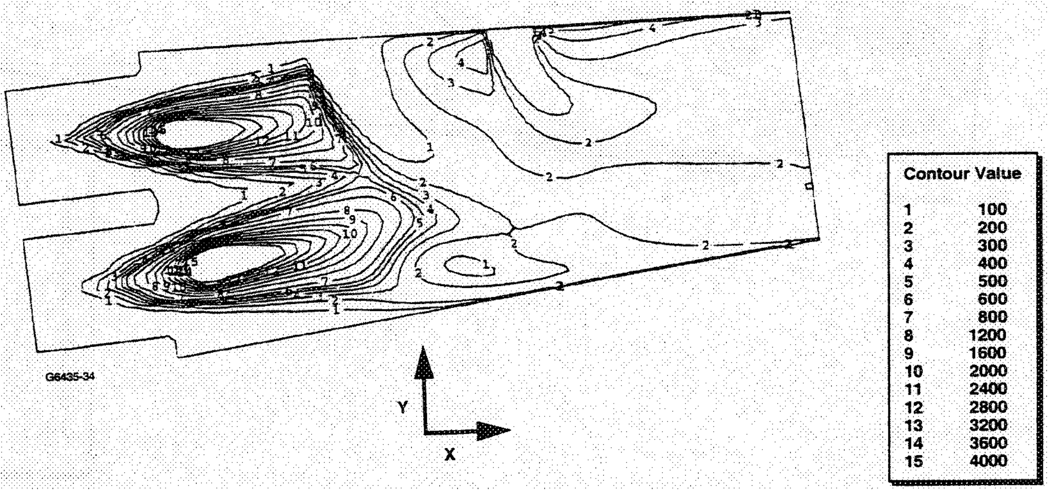


Figure 34. AS918 Advanced Technology Combustor Predicted NOx Contours (ppm).

3.4.4 AST918 Turbofan Engine Studies

3.4.4.1 AST918 LTO Cycle Combustor Configuration

An additional AST turbofan combustor configuration was analyzed during this study, to define the initial configuration to be used for future, follow-on programs intended to produce low-NOx combustor hardware. For this effort, the basic geometry of the AS918 turbofan engine and its corresponding cycle were used, as this engine is in a size class currently subject to emissions regulation. This effort combined the most-promising NOx control techniques that had been investigated during the other phases of the SET study into a single configuration, but limited the choices to currently-existing injector and combustor material technologies. Thus, some of the more-aggressive concepts were given a lower priority. An effort was also made to limit the number of injectors to a reasonable level and to avoid the use of fuel-injector staging. Although staging can significantly reduce idle emissions, this technique exhibits inherent problems of fuel-injector control, engine operability, coking of the inactive injectors, and turbine durability.

The combustor design selected for the AST study configuration is shown in Figure 35. The AST918 combustor incorporates many features from the TFE731-80A Advanced Technology combustor concept. Twelve, dual-circuit, airblast injectors are mounted in metal, fuel-preparation chambers discharging into a compact, annular combustor. One swirler surrounds each injector, and a second swirler is positioned at the interface between the chambers and the main combustor. Close-coupled primary and dilution rows are used, incorporating plunged orifices which create jet-injection angles perpendicular to the wall. Effusion cooling is used for both the preparation chambers and for the main combustor inner and outer annular walls.

An additional feature of the AST918 combustor is the conical, rather than cylindrical-shaped, fuel-preparation chambers. The increased area of the conical chambers assists in generating a low-pressure region in the center of the chamber, promoting recirculation. The increased recirculation provides better flame stabilization and higher combustion efficiencies at idle, eliminating the need for fuel-injector staging.

The flow splits for the AST918 combustor configuration are listed in Table 11. These values were partially determined by a numerical optimization experiment that examined the effect of several different parameters on various outputs using classical Design of Experiment (D.O.E.) techniques. It was also found that the effusion holes in the fuel-preparation cans needed to be angled 60 degrees off the axis, so that a high swirl rate was maintained inside the cans, to decrease the idle emissions. If the effusion holes were <u>not</u> angled, the swirl generated by the injector swirler would be <u>reduced</u> by the introduction of the cooling flow, and this would significantly <u>increase</u> the idle emissions output levels.

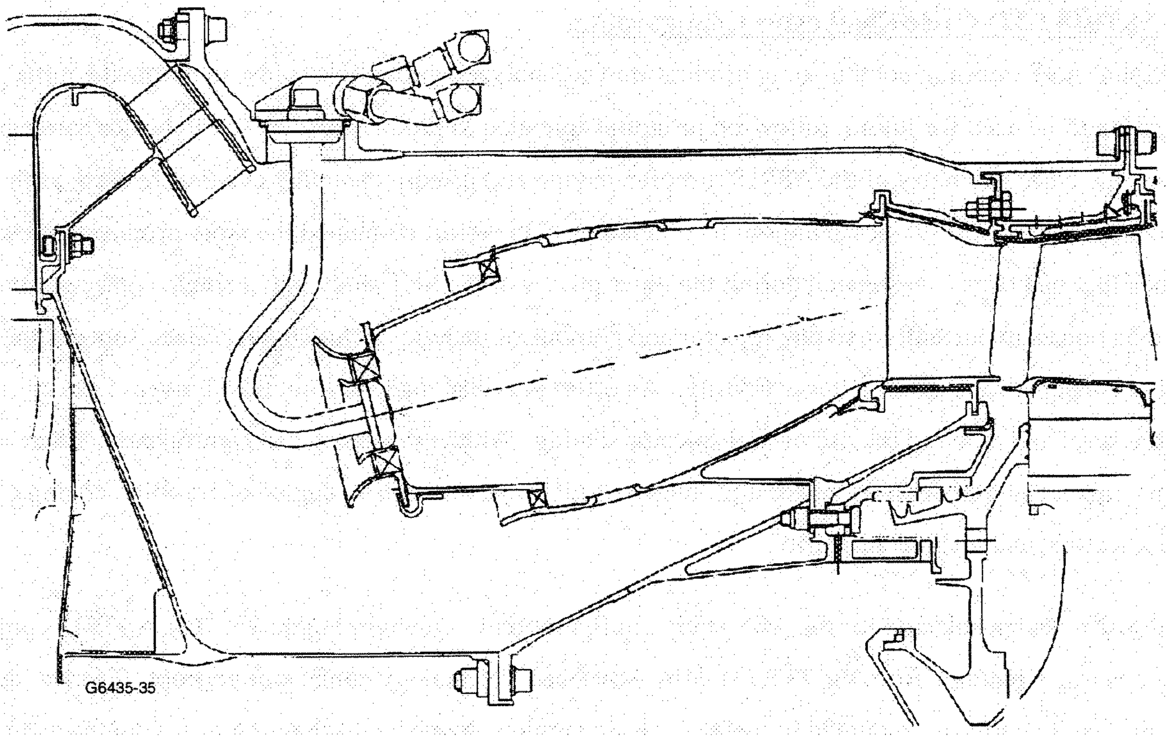


Figure 35. AST918 Turbofan Engine Combustor Configuration.

Figure 36 shows the predicted AST918 velocity vector plot for the SLTO condition at an axial plane through the center of the injector and fuel-preparation chamber. The results of 3-D CFD analyses showed that positioning the 12-OD and 12-ID primary jets so that they impinge upon each other provided the best method to terminate the rich central core produced by the fuel-preparation chambers. However, the 24-OD and 24-ID dilution orifices are arranged circumferentially, such that the jets are interweaved. This is evident in the center plane plot shown in Figure 36. In this figure, an OD jet is shown but the ID jets are located on a different circumferential plane and are not visible. The strong recirculation generated in the fuel-preparation chambers (assisted by the conical shape of the chambers) is also evident in the figure. This recirculation provides a strong flame-stabilization point for low-power operation.

The corresponding calculated temperature contours for the same AST918 combustor plane are shown in Figure 37. The high temperatures predicted near the fuel-preparation chamber walls are an area of concern, and this effect must be investigated further in a future program. Adjustments in the secondary spray-cone angle (currently 60 degrees), chamber effusion-cooling rates, injector swirler flow rates, and/or the chamber length may be required to improve this situation. Figure 37 also shows the small, compact primary zone and large primary flow that were necessary to achieve low-NOx emissions levels. The NOx concentration contours are shown in Figure 38 and may be compared to Figure 27 (for the AS918 Baseline combustor configuration) to appreciate the reduction in NOx levels achieved with the AST918 combustor design.

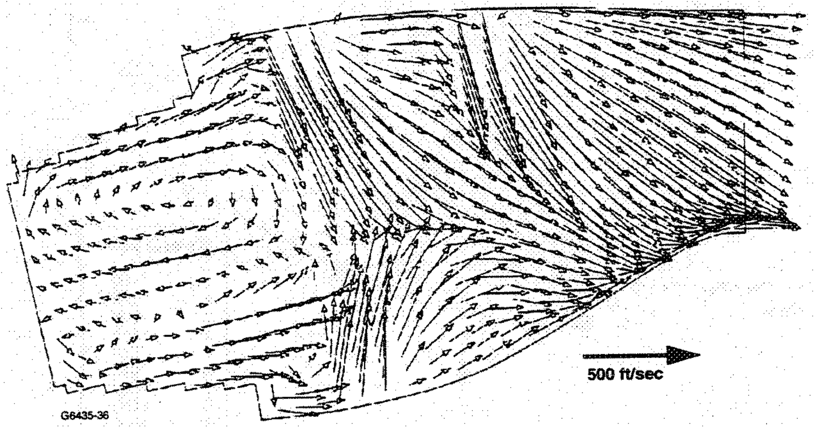


Figure 36. AST918 Combustor Predicted Velocity Vectors.

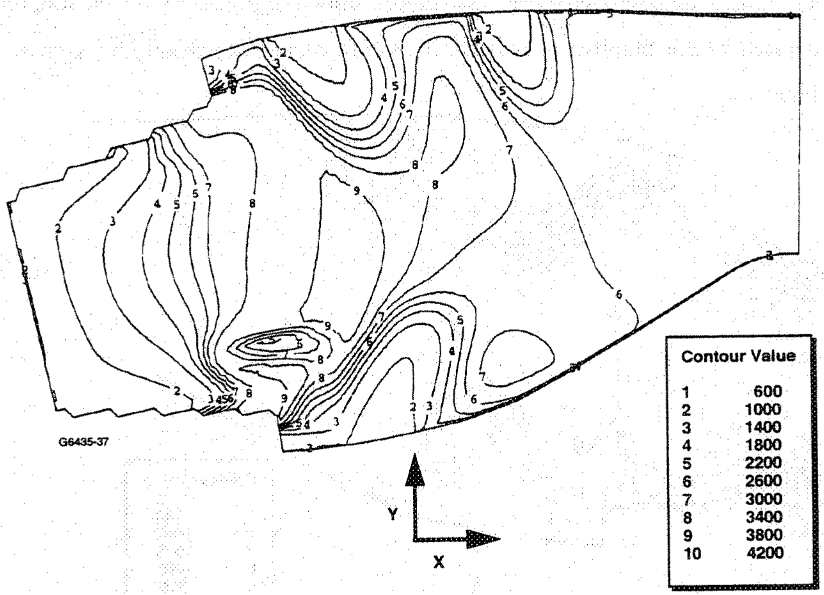


Figure 37. AST918 Combustor Predicted Temperature Contours (deg. F).

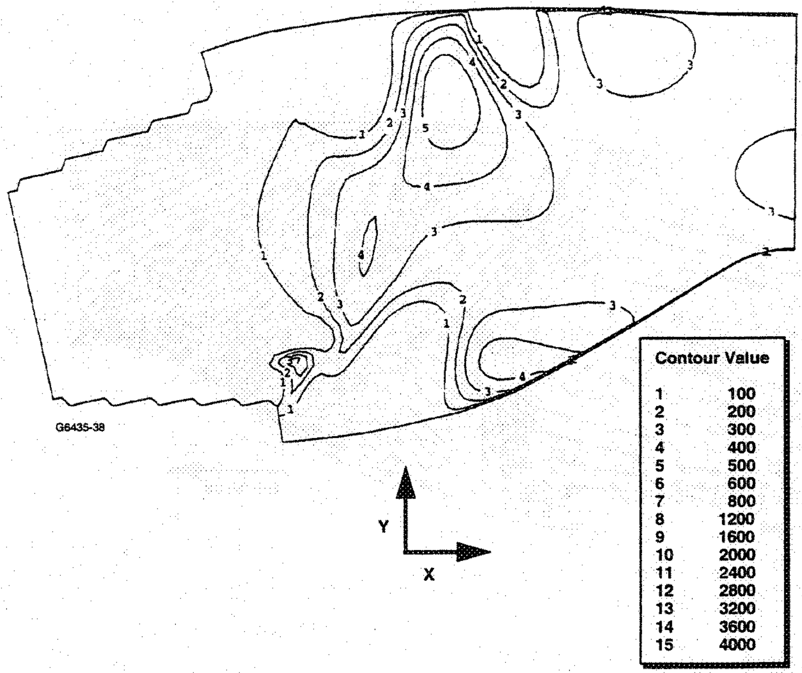


Figure 38. AST918 Combustor Predicted NOx Contours (ppm).

At idle, the AST918 fuel-preparation chambers act as pilots, allowing the flame to stabilize and produce reasonable efficiencies. This can be seen by inspecting the calculated temperature contours shown in Figure 39 for the idle operation point, where the high-temperature core generated by the chamber is evident. This core is created partially by the narrow (30 degree) cone angle of the primary tip of the injectors.

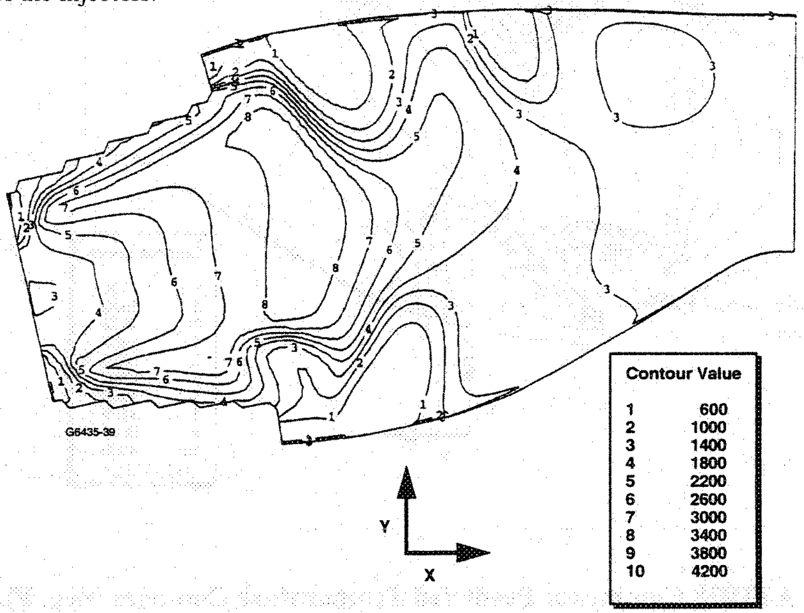


Figure 39. AST918 Combustor Predicted Temperature Contours At Idle (deg. F).

3.4.4.2 AST918 Lean Blowout(LBO) Investigation

A brief investigation of the lean-blow-out (LBO) characteristics was conducted for the AST918 combustor configuration. Although LBO is a time-dependent phenomenon, a technique was developed to analytically assess the LBO characteristics using 3-D steady-state calculations made with the existing AlliedSignal steady-state 3-D CFD code. AE had established through in-house efforts that a combustion efficiency of approximately 80 percent for a particular combustor computed with the steady-state model corresponded to, or was slightly above the LBO level measured in the test cell. Thus, for a particular design, the idle operation point was measured several times, using a different fuel flow value for each run. From these tests, the combustion efficiency versus fuel/air ratio was plotted, and the 80-percent point was used to establish the LBO fuel/air ratio. This process was accomplished for the AST918 combustor configuration, and the results are shown in Figure 40. Inspection of this plot shows that the expected LBO point occurs at a fuel/air ratio of approximately 0.004, which is typical of other existing engines. Obviously, this result does not comprise a complete assessment of the LBO characteristics of the AST918 combustor, but the conclusion does give confidence that the performance of the AST918 design would be reasonable.

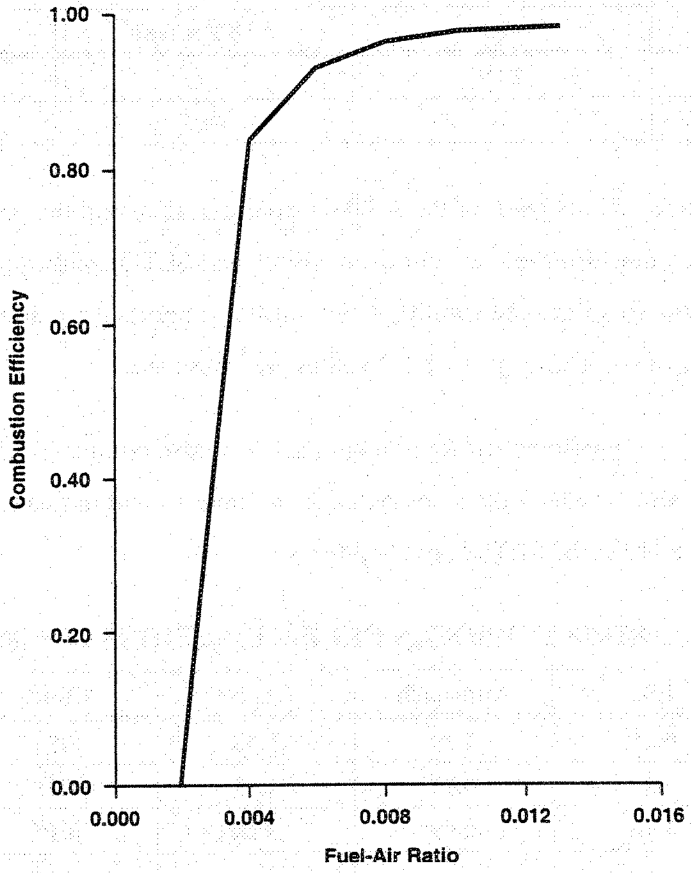


Figure 40. AST918 Predicted Combustion Efficiency Characteristic.

3.4.4.3 AS918 and AST918 Cruise Operation Emissions Levels

Throughout the course of this study, the emphasis has been placed on the analysis of the engine emissions for the LTO cycle points, the operating points are used to calculate an emission level. The points themselves are not regulated. The LTO cycle was formulated to examine the engine emissions occurring in and around the controlled airspace of airports from zero to 3000 feet altitude. However, there is also concern about NOx emissions during the cruise phase of operation. It has been assumed in the aircraft engine industry that if an engine is redesigned or modified to reduce LTO emissions, then there would also be a corresponding reduction seen in the Cruise NOx levels. This assumption has been supported by the calculations performed during this study. As shown in Table 12, the percentage reduction of the NOx LTO cycle was matched by a reduction in the predicted cruise NOx Emissions Index (NOEI).

TABLE 12. AS918 CRUISE NOx REDUCTION COMPARED WITH LTO NOx REDUCTION.

	Baseline	Near-Term	Advanced Technology
NOx LTO	**59.1**	**39.1**	**6.8**
Percent Reduction	**---**	**33.8 Percent**	**88.5**
Cruise NOx EI	**25.9**	**11.3**	**2.28**
Percent Reduction	**---**	**40.5**	**91.2**

The Cruise operating point was also analyzed for the AST918 configuration, and the predicted emissions indices are listed in Table 13. The EI values for the idle, approach, climb, and SLTO conditions are also shown. As can be seen, the general levels of the EI values are similar, which further supports the assumption that cruise NOx emissions would be addressed automatically if the LTO values are improved.

For the AST918 configuration, the predicted smoke number (SN) was also computed using the 3-D CFD code for all of the power settings analyzed. Theses values are included in Table 13 and indicate that the goal of SN values less than 20 were analytically met for the SET study conditions.

TABLE 13. AST918 TURBOFAN CRUISE EMISSIONS COMPARISON.

	Idle	Approach	Cruise	Climb	SLTO
NOx EI	**0.23**	**1.29**	**7.98**	**8.54**	**14.4**
CO EI	**58.3**	**0.72**	**1.57**	**1.17**	**1.53**
UHC EI	**1.16**	**0.09**	**0.26**	**0.19**	**0.25**
Smoke Number (SN)	**<0.1**	**<0.1**	**13.6**	**1.55**	**6.58**

3.5 Barrier Technologies Studies

The successful design of low-emissions combustion systems requires changes in the standard combustor design paradigms. The challenges of meeting stringent NOx limits at high power while maintaining or improving the idle emissions of CO and UHC may require the use of technologies not currently employed in production combustors. These areas of technology, which represent barriers to the implementation of the low-NOx designs, were identified, and can be roughly divided into five categories:

1. Fuel/Air Mixing
2. Fuel Injection and Coking
3. Advanced Wall Cooling and Materials
4. Fuel Control
5. Altitude Ignition and Relight.

These topics are individually addressed in the following sections.

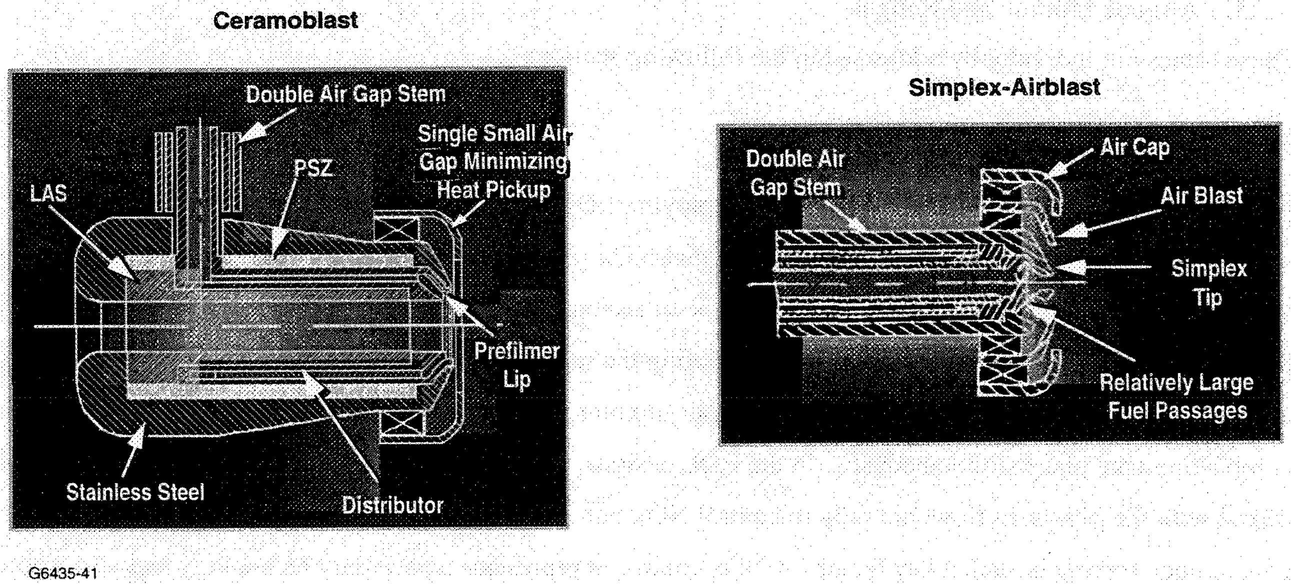
3.5.1 Fuel/Air Mixing

In any low-NOx combustor concept, whether employing LDI, RQL, or LPP techniques, the common key to a successful design is proper fuel/air mixing. Thermal-NOx formation is an exponential function of the local gas temperature, and to achieve proper control of NOx emissions, any local, high-temperature pockets must be avoided by thoroughly mixing the fuel and air before or during the reaction process. In the LPP methods, this mixing is accomplished before the introduction of the fuel/air mixture into the reaction chamber. For LDI, the mixing and combustion take place simultaneously. In the RQL designs, the quenching air must be quickly and thoroughly mixed with the rich-burn flow, not only to control NOx but also to prevent liner thermal distress in the quench zone. Since mixing is such a key factor for NOx control, it represents a necessary technology and also a potential barrier.

3.5.2 Fuel Injection and Coking

A key to limiting NOx formation is improved distribution of the fuel, eliminating local zones of high fuel/air ratio. An obvious method to better distribute the fuel is the use of additional injectors. Therefore, it is quite likely that low-NOx combustor designs could have a larger number of fuel injectors than the present conventional designs. However, increasing the number of fuel injectors adds complexity, resulting in higher costs and maintainability barriers.

For low-power operation, the arrangement with more fuel injectors can result in extremely lean operation, potentially resulting in either combustor blowout or the production of higher CO and UHC emissions. Both conditions are unacceptable. To remedy this, a common practice is to stage the fuel injectors such that at idle, only a few injectors are flowing fuel, while the others are turned off completely. However, the potential for coking of the inactive injectors is high. Thus, a coking-resistant fuel injector represents a barrier technology for low-NOx combustor designs. Two potential methods for controlling fuel-injector coking are shown in Figure 41. In the first concept, using a simplex airblast injector, most of the atomization is accomplished by the injector airflow. Thus the fuel passages can be made relatively large. The amount of coking that does occur should not significantly affect the injector-to-injector fuel distribution. The second concept illustrated in Figure 41 is an insulated fuel injector, that limits the heat transfer to the fuel passages, which reduces the coking tendency.


Ceramoblast

Simplex-Airblast

Figure 41. Fuel Injector Anti-Coking Concepts.

3.5.3 Advanced Combustor Wall Cooling and Materials

A promising NOx-control technique involves the combination of burning at lean equivalence ratios (LDI) and generating large-scale mixing to minimize local rich zones. Use of these techniques requires an additional quantity of combustor air, which, with current combustor liner designs, might not be available, as a large fraction of the airflow is already devoted to wall cooling. Thus, advanced wall-cooling techniques that reduce the required amount of cooling air and make available additional air for combustion, represent necessary technologies to achieve proper NOx control. Some promising methods for reducing cooling air requirements are shown in Figure 42 and are described in the following sections.

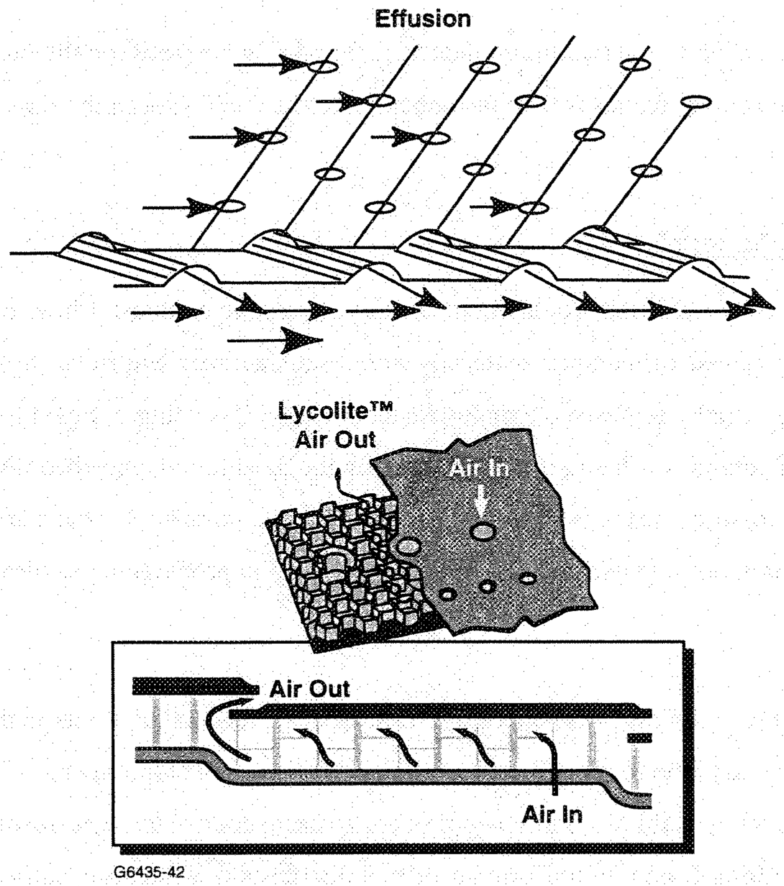


Figure 42. Advanced Combustor Wall Cooling Concepts Can Reduce Required Cooling Airflow, Providing Additional Combustion Air.

3.5.3.1 Effusion Cooling

To produce effusion cooling, several thousand small (approximately 0.020 inch) diameter holes are drilled at a shallow angle through the burner walls during manufacture. These holes increase the liner external-surface heat transfer coefficient by removing the boundary-air layer. Heat is then absorbed directly from the liner as the air passes though the wall, and full-coverage cooling is provided on the burner hot side. The use of effusion cooling has demonstrated a 30 to 40 percent reduction in required cooling air, compared to conventional film-cooling methods.

3.5.3.2 Lycolite™ Cooling

The AlliedSignal proprietary Lycolite™ cooling technique, also shown in Figure 42, is a dual-wall, counterflow design that can reduce the required cooling air up to 60 percent, compared to conventional film-cooling methods. A thin, honeycomb structure is sandwiched between, and brazed to, the dual walls. Gaps in the honeycomb structure through which the cooling air passes are arranged such that the air is forced to alternate between the inner and outer walls. This circulatory air motion generates a high level of turbulence, which results in high values of heat transfer coefficient, ensuring the maximum heat transfer takes place between the inner and outer walls. After passing through the honeycomb, the air is then introduced into the combustor in the same manner as a conventional cooling film.

3.5.3.3 Ceramic Liner Materials

The ultimate in cooling flow reduction would entail the use of ceramic combustor liner materials, as no cooling air would then be required because the ceramic materials would satisfactorily withstand the highest temperatures. Although this technique actually represents a materials technology, it is being grouped here, under the wall-cooling section, since the use of ceramics is being driven directly by the need for advanced cooling methods as engine cycle temperature and pressure levels are increased. Although ceramic materials can survive at temperature levels well above the melting point of metals, they are not currently used in production gas turbine propulsion engines.

3.5.4 Fuel Control

For proper control of NOx emissions, lean operation must be achievable at all points in the flight envelope. Thus, precise control of the fuel/air ratio at all engine operating conditions is a requirement. The typical gas turbine fuel control operates using average values of burner-temperature rise to control the fuel flow to the injectors. Injector-to-injector variation resulting from non-uniform air or fuel distribution, which is usually not considered in the control logic, poses a barrier to reducing the local NOx production.

One promising method to maintain more precise control over local injector fuel/air ratio is shown in Figure 43. This technique employs individual temperature sensors mounted on the turbine stator located downstream of each fuel injector, providing feedback signals for the fuel control logic to actuate electronic trimming valves on the corresponding injector. In this way, the injector-to-injector fuel/air ratio may be automatically adjusted for any variations in air and/or fuel flow.

If a large number of staged fuel injectors are used to achieve control of emissions, requiring some injectors to be turned on and off with each change in engine power setting, there exists a potential barrier in terms of the required injector operation and control technology. The required valving must be integrated into the engine fuel control to provide satisfactory engine operation over all power settings, not just those associated with the LTO cycle. Use of a large number of fuel injectors also presents other problems associated with the required fuel manifolding and mechanical access through the combustor plenum.

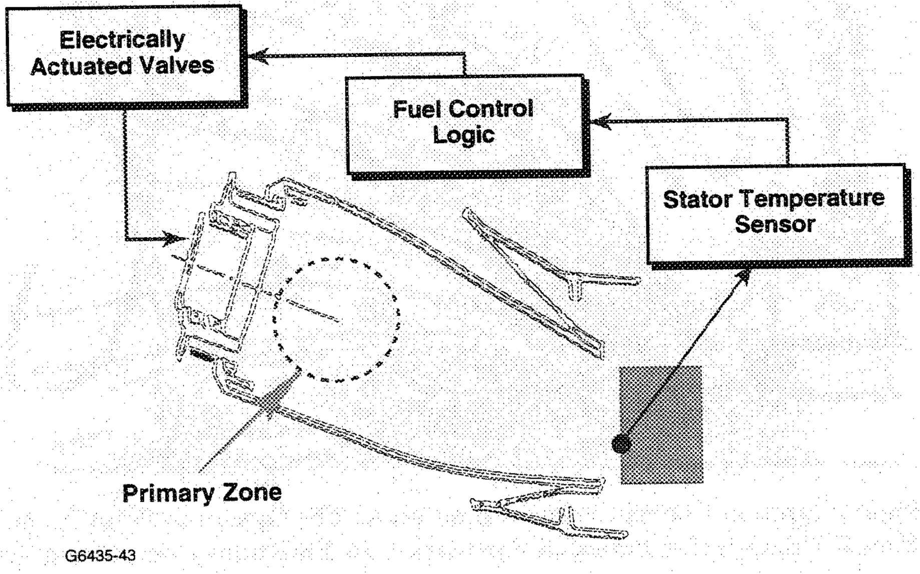


Figure 43. Individual Fuel Injector Control Concept Minimizes Injector-To-Injector Fuel/Air Ratio Variations.

3.5.5 Altitude Ignition and Relight

Low-NOx combustors using the LDI philosophy are characterized by lean operation, uniform fuel/air ratio distributions, and high mixing rates. These characteristics can be detrimental, however, to other desirable burner characteristics, an example of which is ignition. Good altitude ignition and relight requires relatively low-velocity air flow, high local fuel/air ratios, and low mixing rates. One technology under development that addresses these conflicting requirements is photon ignition, as illustrated in Figure 44. Instead of igniting the combustor near the liner wall as is done with conventional spark ignitors, a laser beam is focused at the optimum point in the combustor flow field. This ideal point can be near the burner centerline just downstream of the fuel injector, where recirculating flow and high fuel concentrations exist. This is an area that is inaccessible to conventional spark ignitors, because of durability problems. Photon ignition thus avoids conventional igniter design problems and offers opportunities for ultra-low emissions combustion systems.

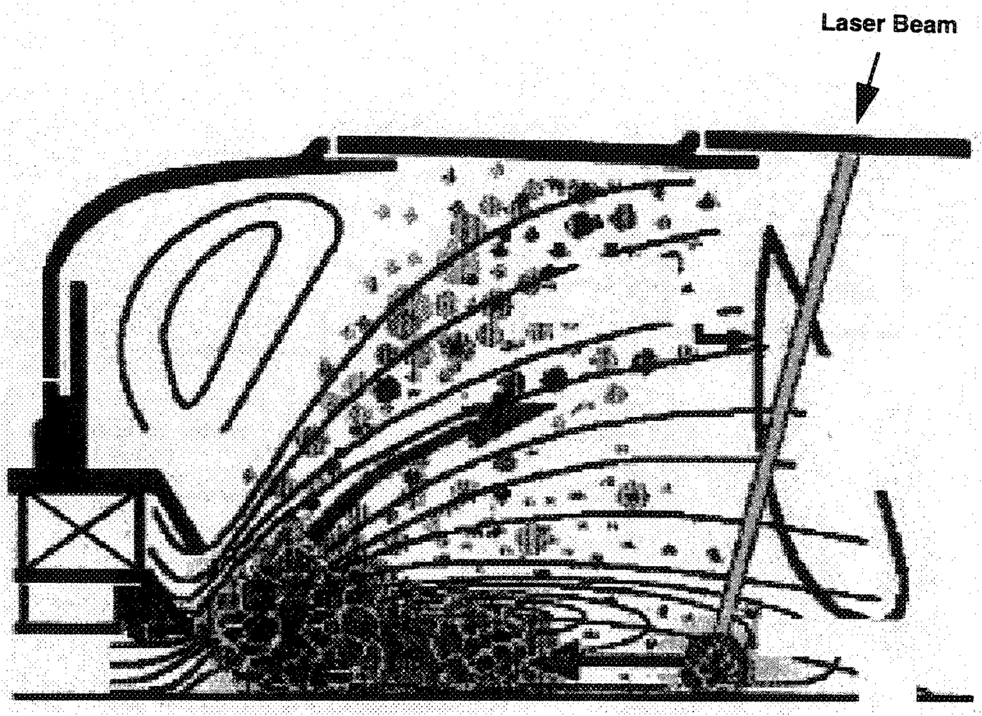


Figure 44. Photon Ignition Concept Permits Ignition At The Optimum Point In the Combustor Flow Field, Offering Potential For Ultra-Low Emissions Combustion Systems.

3.5.6 Barrier Technology Assessment

The preceding paragraphs have identified a number of potential barriers to the implementation of low-NOx technologies into combustor design. To determine a priority for implementation of improvements, these barrier technologies need to be assessed within the framework provided by the ten combustor configurations that were generated during this study. To accomplish this assessment, we have identified which of the barrier technologies were used for each of the different combustor configurations, as listed in Table 14. For the purposes of this assessment, it was decided to separate the Advanced Wall Cooling and Advanced Materials technologies into different categories.

The "Totals" values listed at the bottom of Table 14 are the frequency with which each barrier technology appeared among the various configurations. When these "Total" values are used to rank the technologies, the result is shown in Table 15. It can be seen that nearly all of the combustor configurations studied made use of the Advanced Wall Cooling and Fuel/Air Mixing technologies. This result is not unexpected, as LDI was the primary NOx control technique employed, and both of these technologies are paramount to the LDI philosophy. The Fuel Injection/Coking, Fuel Control, and Altitude Ignition/Relight technologies are used on the configurations that require fuel injector staging to achieve proper idle emissions control. From the results of this study, it can be concluded that NOx reduction may be achieved without the use of fuel-injector staging. However, as the NOx emissions regulations become more stringent, use of this technology will probably become necessary.

TABLE 14. BARRIER TECHNOLOGY ASSESSMENT.

Configuration	Fuel-Air Mixing	Fuel Injection/ Coking	Advanced Wall Cooling	Advanced Materials	Fuel Control	Altitude Ignition/ Relight
TFE731-80A Baseline	---	---	X	---	---	---
TFE731-80A Near-Term	X	X	X	---	X	X
TFE731-80A Adv. Tech.	X	X	X	X	X	X
AS807 Baseline	---	---	X	---	---	---
AS807 Near-Term	X	---	X	---	---	---
AS807 Adv. Tech.	X	X	X	---	X	---
AS918 Baseline	---	---	---	---		---
AS918 Near-Term	X	X	X	---	X	X
AS918 Adv. Tech.	X	X	X	X	X	X
AST918	X	---	X	---	---	---
Totals	**7**	**5**	**9**	**2**	**5**	**4**

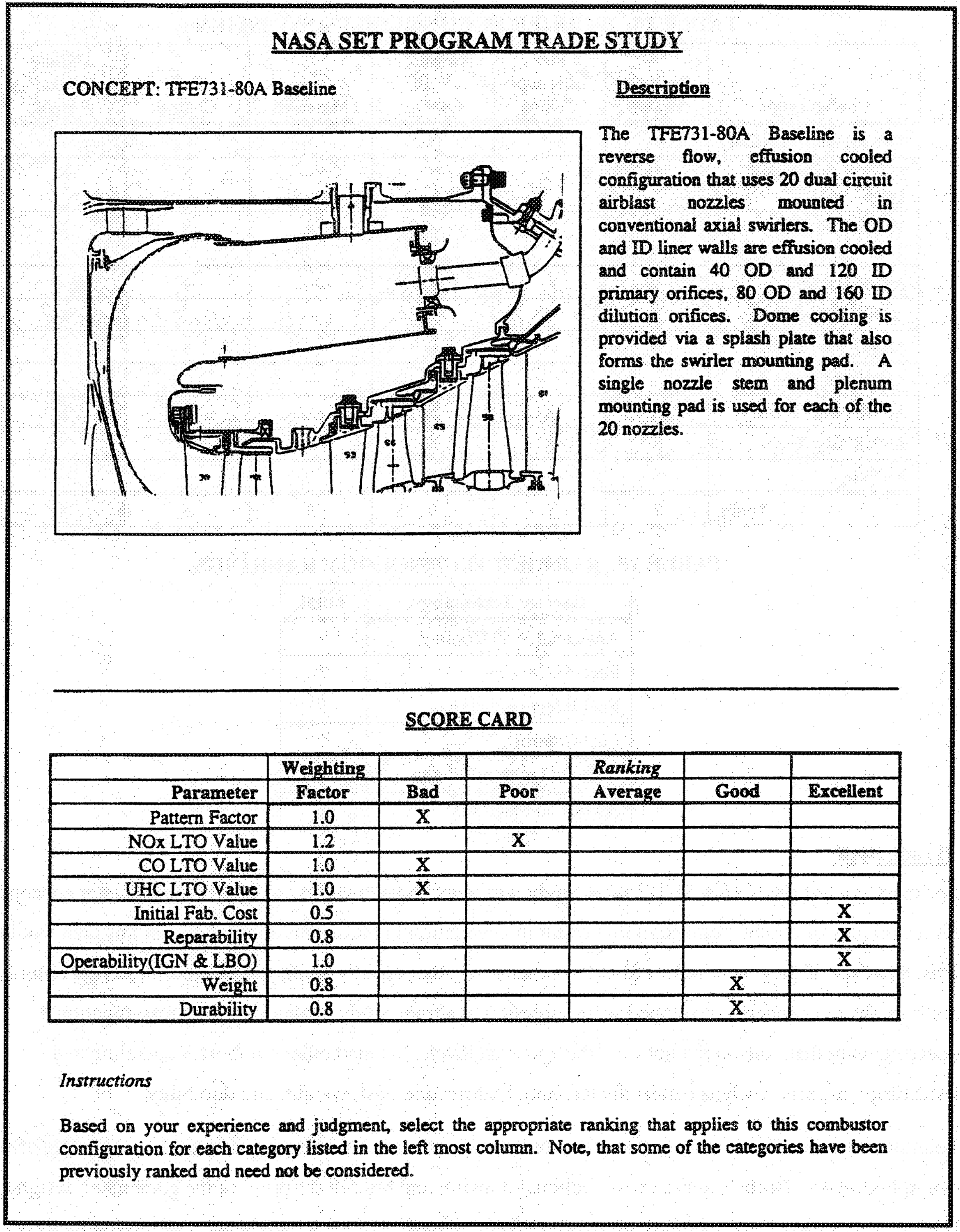
TABLE 15. BARRIER TECHNOLOGY RANKINGS.

Barrier Technology	Total
Advanced Wall Cooling	9
Fuel-Air Mixing	7
Fuel Injection/Coking	5
Fuel Control	5
Altitude Ignition/Relight	4
Advanced Materials	2

3.6 Trade Study

The primary goal of the NASA SET Task 4 Study was to evaluate a variety of different combustor concepts and to select techniques of combustor design that result in a reduction in NOx emissions. Gains in this area would be useless, however, if they were achieved at the expense of other equally-important combustor design criteria. For this reason, the ten concepts developed were subjected to a trade study evaluation by a cross-functional engineering team that considered not only the emission levels, but also other combustor operating and manufacturing aspects, such as pattern factor, initial fabrication cost, weight, and durability.

To help the cross-functional team perform the trade study, an evaluation form was created, an example of which is shown in Figure 45. At the top is a cross-sectional drawing and brief description of the combustor design concept, and below is a rating form containing nine different parameters. For each parameter, a weighting factor was assigned based on the relative importance.



NASA SET PROGRAM TRADE STUDY

CONCEPT: TFE731-80A Baseline

Description

The TFE731-80A Baseline is a reverse flow, effusion cooled configuration that uses 20 dual circuit airblast nozzles mounted in conventional axial swirlers. The OD and ID liner walls are effusion cooled and contain 40 OD and 120 ID primary orifices, 80 OD and 160 ID dilution orifices. Dome cooling is provided via a splash plate that also forms the swirler mounting pad. A single nozzle stem and plenum mounting pad is used for each of the 20 nozzles.

SCORE CARD

	Weighting			Ranking		
Parameter	Factor	Bad	Poor	Average	Good	Excellent
Pattern Factor	1.0	X				
NOx LTO Value	1.2		X			
CO LTO Value	1.0	X				
UHC LTO Value	1.0	X				
Initial Fab. Cost	0.5					X
Reparability	0.8					X
Operability(IGN & LBO)	1.0					X
Weight	0.8				X	
Durability	0.8				X	

Instructions

Based on your experience and judgment, select the appropriate ranking that applies to this combustor configuration for each category listed in the left most column. Note, that some of the categories have been previously ranked and need not be considered.

G6435-45

Figure 45. Example Trade Study Evaluation Sheet.

For example, the NOx LTO value was assigned the highest weighting, since this factor was the primary goal of the study. The other LTO values also were given high weights, since NOx control should not be achieved at the expense of idle efficiency. Pattern Factor and Operability were also weighted high, since a low-NOx combustor design that potentially could damage the turbine or suffer from lean blowout (LBO) would be of little value. Other factors such as combustor weight, durability, etc. were given lower weighting. While these were also important factors, compensation may be incorporated into an engine design to make up for any potential combustor deficiencies in those areas.

Ten of the evaluation sheets were created, one for each combustor concept, and the sets of sheets were given to a cross-functional team for evaluation. A consensus was reached on the ranking for each of the parameters, in which terms such as **Average (A)** represented middle-level or average performance, with **Excellent (E)** and **Bad (B)** representing the highest and lowest range of performance, respectively, for the ten configurations. Thus, the ranking was a relative comparison among the ten configurations, rather that an assessment against some industry standard of combustor design.

Some of the parameters could be evaluated directly from the results of the CFD analyses performed during the study. For example, pattern factor and the LTO emissions values had been computed for each design. Therefore, it was an easy task to compare the values and select the appropriate ranking. Some parameters such as Operability were not addressed directly, and inferences had to be made from the CFD results. Other parameters such as Initial Fabrication Cost were not addressed at all during the study. For these, the knowledge and experience of the cross-functional team was used to assign appropriate ranking values.

Once all of the forms were completed, the data were combined into Table 16. In this table, the ten configurations are listed down the left-hand column and the nine parameters are listed accross the top. An equivalent numerical value was assigned to each of the rankings, as defined at the bottom of the Table. The numerical equivalent of each ranking was then multiplied by the associated weighting factor and summed for all parameters. This resulted in the "Total Score" row in Table 16, representing a combined, weighted ranking for each configuration.

The final ranking is shown in Table 17. It can be seen that the ten configurations are separated into two distinct groups, with six configurations rated at about 32 points and the remaining four configurations rated at about 20 points. As there were some uncertainties in the rankings, there is no justification to attempt to differentiate between the configurations within each of the groups, because the difference in the numerical values were certainly within the range of uncertainty of the evaluations.

TABLE 16. NASA SET TASK 4 TRADE STUDY RANKINGS SUMMARY.

	Pattern Factor	NOx LTO	CO LTO	UHC LTO	Initial Fabr. Cost	Repairability	Operability (Ignition, LBO)	Weight	Durability	Total Score *
Weighting Factor	1.0	1.2	1.0	1.0	0.5	0.8	1.0	0.8	0.8	
TFE731-80A Turbofan										
Baseline	B	P	B	B	E	E	E	G	G	23.3
Near-Term	E	P	E	E	E	E	A	G	G	33.3
Adv. Tech	E	E	E	E	P	B	G	G	A	32.4
AS807 Turboprop										
Baseline	G	P	E	E	E	E	E	A	G	33.5
Near-Term	A	G	E	E	E	E	A	A	A	32.1
Adv. Tech	E	G	E	E	P	G	E	B	A	32.2
AS918 Turbofan										
Baseline	B	P	P	B	B	P	E	G	G	19.9
Near-Term	P	G	B	P	A	G	P	G	G	22.9
Adv. Tech	B	E	A	P	B	B	A	B	P	18.7
AST918	G	E	A	E	B	A	G	G	G	31.3
* Numeric Equivalents: Bad (B) = 1, Poor (P) = 2, Average (A) = 3, Good (G) = 4, Excellent (E) =5.										

TABLE 17. NASA SET TASK 4 TRADE STUDY FINAL RANKINGS.

Rank	Configuration	Score
1	AS807 Baseline	33.5
2	TFE731-80A Near-Term	33.3
3	TFE731-80A Adv. Tech.	32.4
4	AS807 Adv. Tech.	32.2
5	AS807 Near-Term	32.1
6	AS918 AST	31.3
7	TFE731-80A Baseline	23.3
8	AS918 Near-Term	22.9
9	AS918 Baseline	19.9
10	AS918 Adv. Tech.	18.7

By examining the trade study summary results in Table 17, it is easy to see why four of the configurations were rated significantly lower. With the exception of the AS918 Advanced Technology geometry, each of the configurations rated in the lowest group had rankings for LTO values in the Poor (P) and Bad (B) range. As these parameters received the highest weighting, it is understandable that those four configurations would be rated lowest. The AS918 Advanced Technology configuration, however, had reasonably low emissions values, but the required use of 56 injectors resulted in high weight, and the use of ceramic materials made the initial fabrication cost high and the anticipated durability low. These factors, though weighted lower, more than offset the low emissions values, giving an overall low ranking.

From this analysis, each of the top six configurations were rated essentially the same, and any of them could be selected as a candidate for further development. It may seem curious at first that the AST918 configuration, which was a combination of the best techniques investigated in the other nine designs, was rated essentially the same as several others, rather than significantly higher. It should be remembered that this configuration was limited to near-term technologies, using only 12 fuel injectors, and does not require the use of fuel-injector staging. Thus, some potential additional NOx reduction was traded for overall combustion system life-cycle cost, while meeting the proposed emissions standards. The AST918 combustor liner has high initial fabrication costs, which can be corrected through a minor redesign effort.

3.7 Low-Emissions Combustor Technology Development Plan

The Trade Study described in section 3.5 identified several promising low-emissions combustor concepts. A Technology Development Plan was established that includes analyzing up to five of these, or other, promising concepts from the SET Task 4 study, followed by test evaluations, then down-selection of the best concept and demonstration in engine tests. Figure 46 shows a roadmap for the proposed Low-Emissions Combustor Technology Demonstration Program. The Technology Development Plan includes the following tasks:

Task No.	Title
1	Combustion system preliminary design
2	Subcomponent study tests
3	Combustion system detail design and fabrication
4	Full-annular combustor tests at scaled operating conditions
5	Full-scale tests (To be performed at NASA-LeRC).

During the preliminary design phase of the program (Task 1) the combustor configuration will be defined for the specified engine operating conditions. During Task 2, the most-promising concepts selected from the SET studies will be evaluated in subcomponent studies to screen the best concept. Detail drawings of a full-annular combustor employing the best of the concepts will be generated and fabricated in Task 3. This concept will be evaluated in rig tests and optimized at scaled conditions during Task 4. The finalized configuration will be tested at full-scale conditions at the NASA LeRC facilities during Task 5. Figure 47 shows a preliminary schedule for the proposed Low-Emissions Combustion System Development Program.

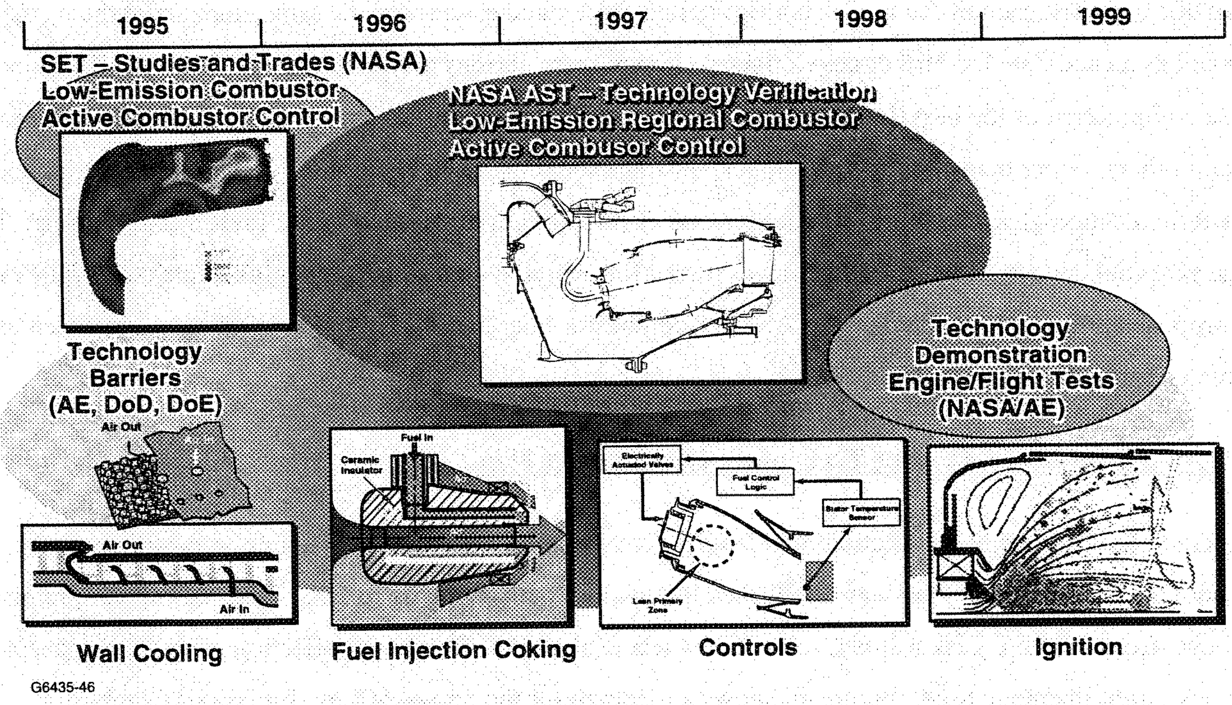


Figure 46. Proposed Low-Emissions Combustor Technology Development Program Roadmap.

The proposed Technology Development Program will include subcomponent tests to obtain simulated, primary-zone, emissions data to calibrate the emissions model of the CFD code. The needed test data will be obtained using an existing combustor test rig. The improved CFD model will then be used to analyze and refine the final combustor configuration. This effort will be performed concurrently with detailed thermal and stress analyses. Layout and detail drawings for three of the best configurations from this analysis will be generated, and hardware fabricated to perform partial combustor (sector) tests.

The fuel injectors will be developed in concert with the combustor aerodynamic design. The desired fuel-spray characteristics will be defined from the CFD analysis results. Concurrent engineering effort will be used to work with selected fuel-injector vendors to achieve the desired spray characteristics. This effort will include testing and refining prototype fuel injectors. The tests to be performed will include spray angle, patternation, and Phase Doppler Particle Analyzer (PDPA) tests at ambient conditions using an airbox, in addition to ambient ignition and Lean Blow Out (LBO) studies performed in a combustor simulator. The refined fuel-injector prototype will be further evaluated using laser sheeting and high-pressure spray-chamber tests (Figure 48).

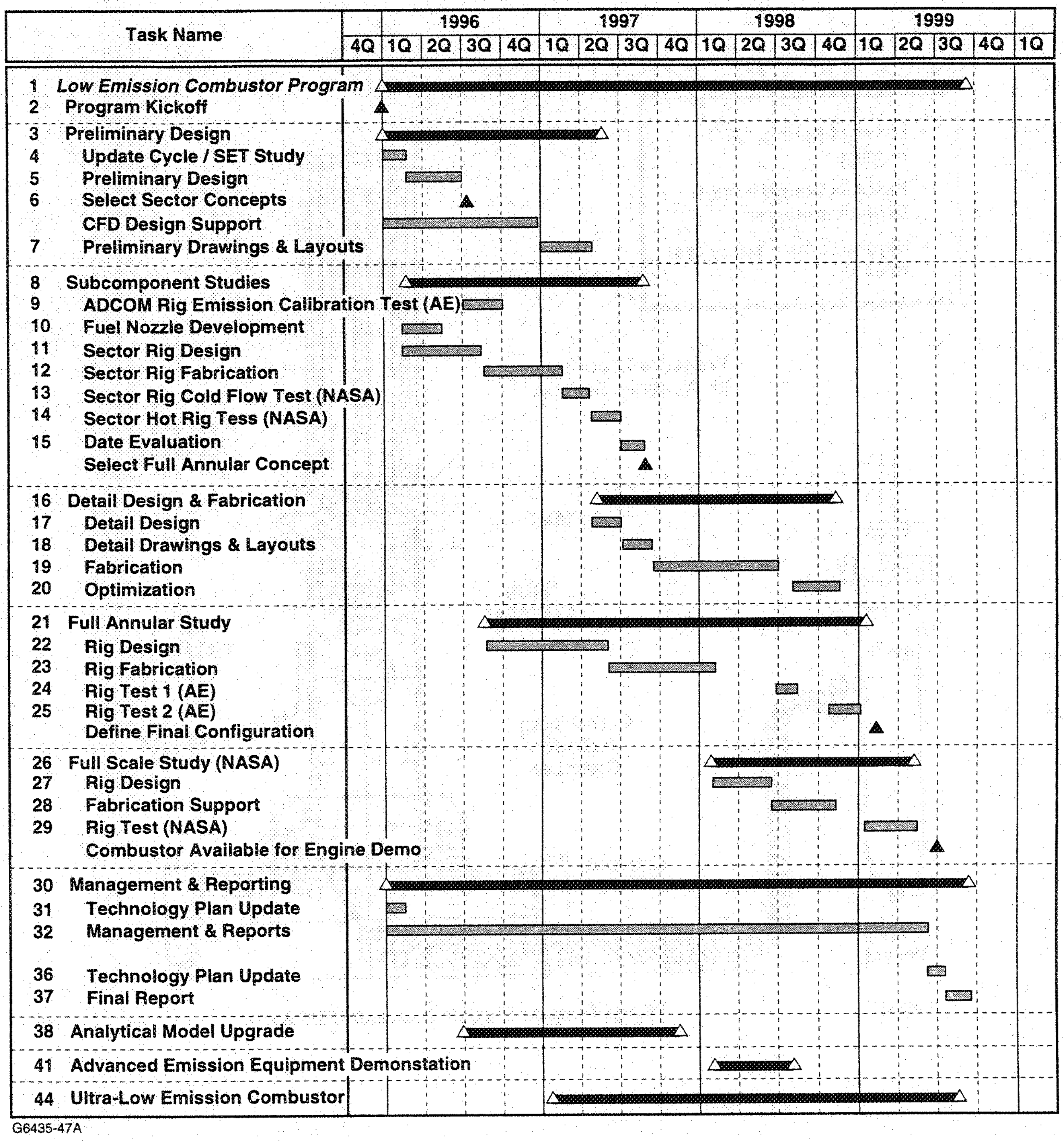
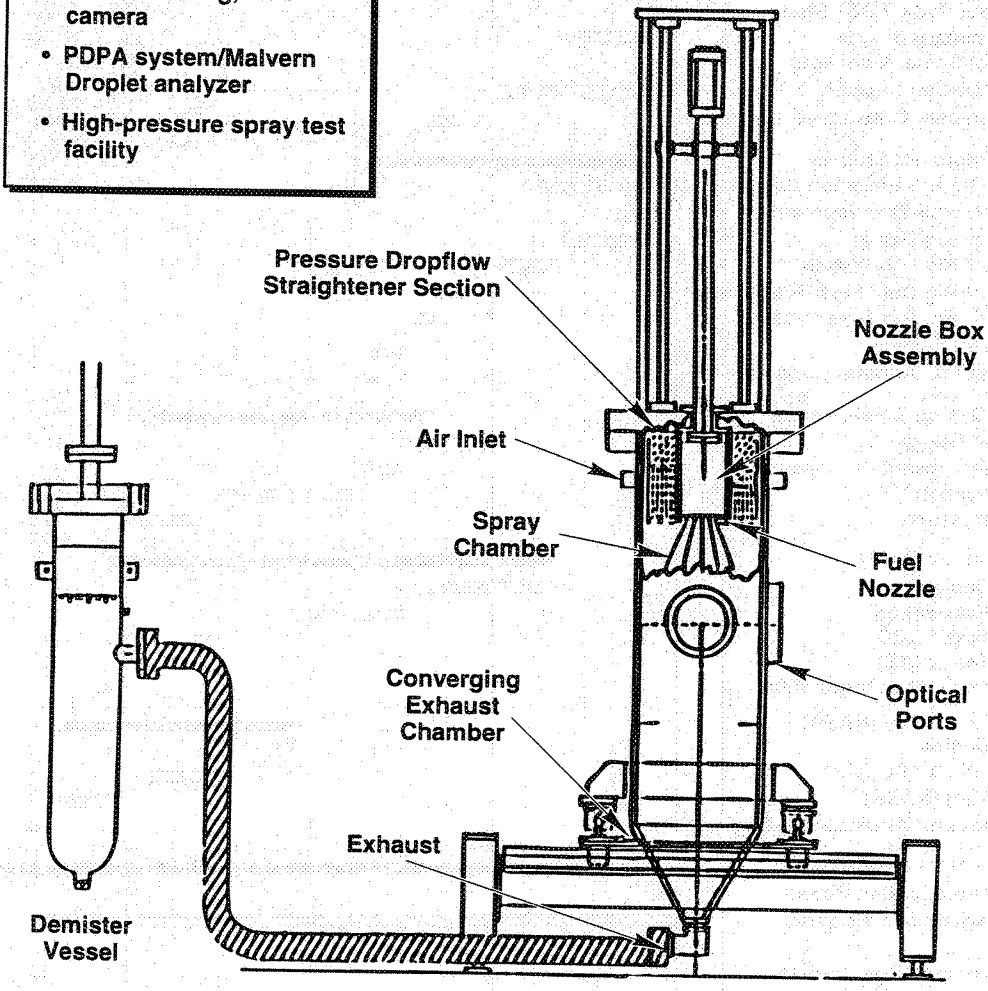


Figure 47. Preliminary Low-Emissions Combustor Technology Development Program Schedule.

- Laser sheeting, CCD camera
- PDPA system/Malvern Droplet analyzer
- High-pressure spray test facility

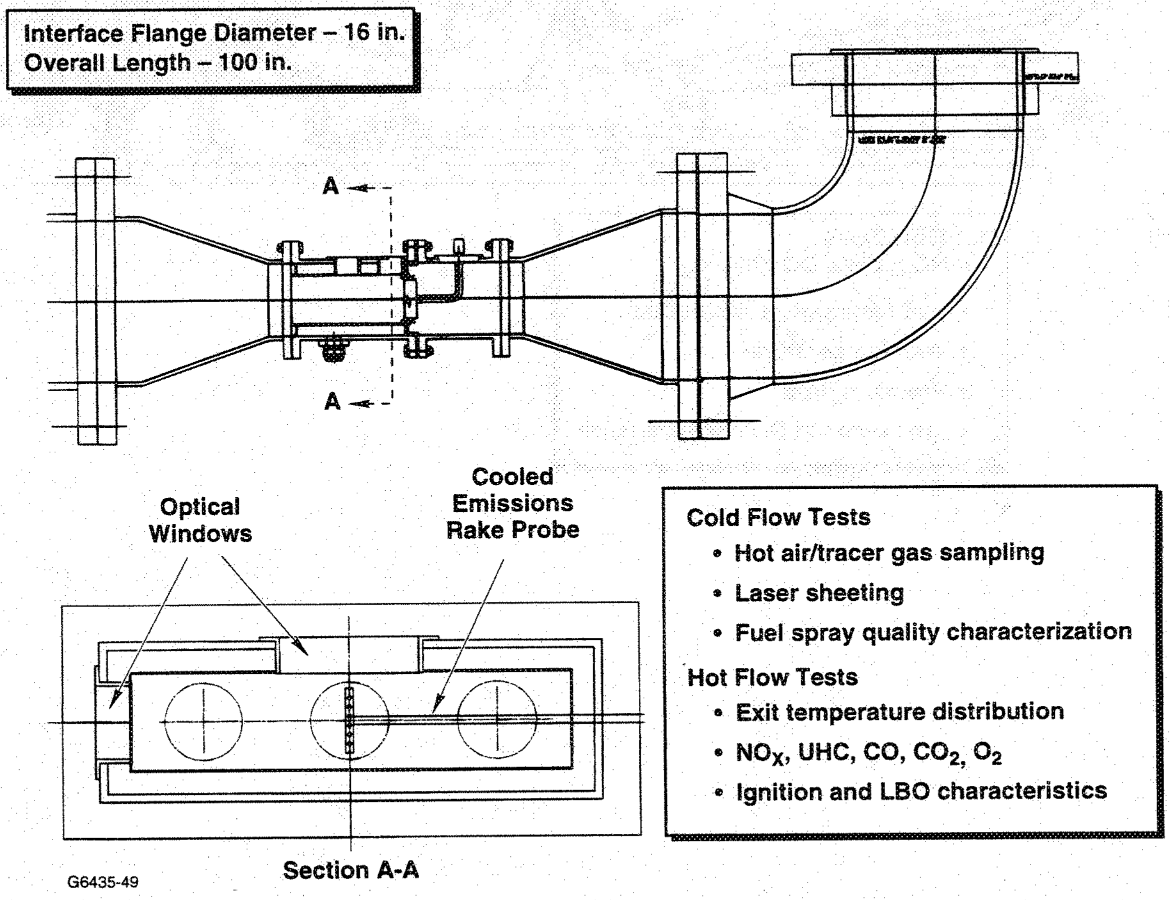


Phase Doppler Particle Analyzer (PDPA)

Figure 48. Fuel Injector Specialized Test Equipment.

A limited number of these fuel injectors will be fabricated and evaluated in a sector test rig (shown schematically in Figure 49). The sector test evaluations will include cold-flow gas sampling, laser sheeting to evaluate fuel/air mixing, and in-situ fuel spray quality characterization. In addition to the cold-flow tests, the sector rig tests will also include combustion tests to measure the exit temperature distribution, gaseous emissions, and ignition and LBO performance.

A full-annular combustor will be fabricated with a full set of fuel injectors of the best design concept screened from the sector tests. This combustor and the fuel injectors will be evaluated in a test rig (Figure 50) at scaled operating conditions. The full-annular combustor test evaluations will include ignition performance characterization, LBO, Pattern Factor, wall temperatures, gaseous emissions, and pressure drop. Any modification(s) needed to the combustion system will be made during this phase, followed by complete performance characterization. The combustion system and the test rig will then be installed in the NASA Lewis Research Center test facilities (in Cleveland, OH) and evaluated at full-scale operating conditions. A Test Evaluation Plan for engine tests of this combustion system will be defined at the conclusion of the rig tests.

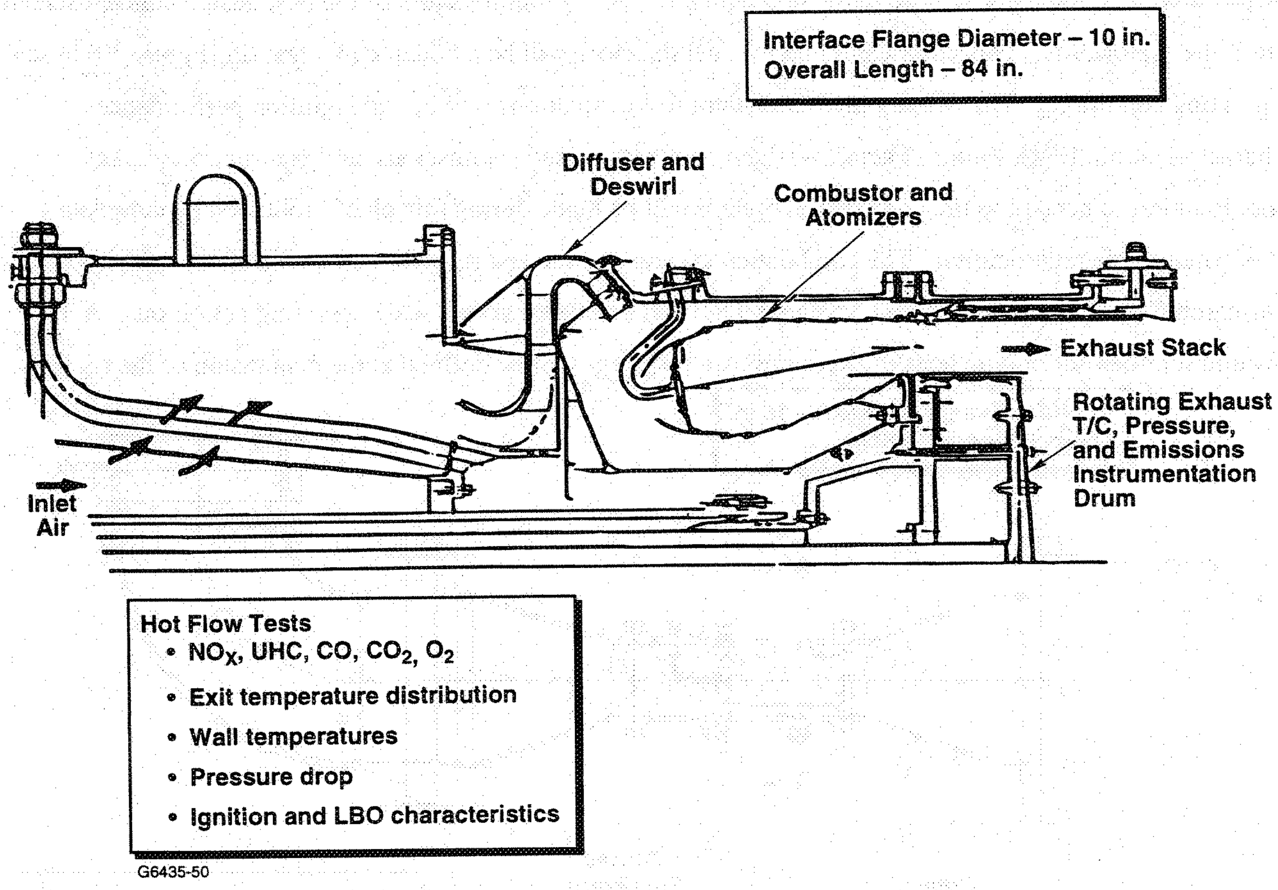


Interface Flange Diameter – 16 in.
Overall Length – 100 in.

Cold Flow Tests
- **Hot air/tracer gas sampling**
- **Laser sheeting**
- **Fuel spray quality characterization**

Hot Flow Tests
- **Exit temperature distribution**
- **NO_X, UHC, CO, CO_2, O_2**
- **Ignition and LBO characteristics**

Figure 49. Schematic of Combustor Sector Test Rig.



Interface Flange Diameter – 10 in.
Overall Length – 84 in.

Hot Flow Tests

- NO_X, UHC, CO, CO_2, O_2
- Exit temperature distribution
- Wall temperatures
- Pressure drop
- Ignition and LBO characteristics

Figure 50. Schematic of Full-Annular Combustor Test Rig.

3.8 Combustion Test Rig Structural Analysis

As part of the SET Task 4 study, a subcontract was initiated to perform a structural analysis of an existing turbofan combustion test rig. The ultimate goal of this effort was to determine the maximum pressure and temperature levels at which the exisitng test rig could be safely operated. It was expected that this test rig could be used during the planned follow-on NASA Advanced Subsonic Transport (AST) program to perform full-scale annular combustor tests at the NASA-LeRC (Cleveland, OH) test facilities. The NASA-LeRC facilities can achieve much higher inlet pressure and temperature levels than the AlliedSignal Engines (AE) Engineering Laboratory facilities (in Phoenix, AZ); therefore, it was necessary to know the upper limits of the test rig capability.

The subcontract was structured as several different tasks, the first of which involved creating a structural computer model of the pertinent test-rig components from the existing drawings and electronic CAD files. The subcontractor completed a program plan for the thermal/mechanical stress analysis, and supplied AE with an electronic, two-dimensional (2-D) model of the combustion test rig.

Meanwhile, AE began a test-rig design effort to support combustion system development for a new centerline engine. This new combustion test-rig will provide a possible alternative test vehicle for the planned NASA AST program. Therefore, the planned test-rig thermal/structural analysis subcontract effort has been suspended, until a final combustion test rig selection is made. Completion of the combustion test-rig structural analysis will be performed as part of the planned NASA AST program.

4.0 CONCLUSIONS AND RECOMMENDATIONS

The NASA Small Engine Technology (SET) Task 4, Advanced Combustor Study Program, has provided the means by which a number of different low- emissions combustor technologies could be analytically screened to determine concepts that have a high potential of achieving low emissions in small, advanced-cycle gas turbine engines. The results of this analytical screening were used to select a number of different concepts for future hardware development and possible inclusion into the AlliedSignal Engines (AE) product lines.

During this NASA SET study, combustor configurations employing various control techniques for oxides of nitrogen (NOx) emissions were analyzed for several different gas turbine aircraft propulsion engine geometries and operating cycles. Three proposed AE products, designated the Model TFE731-80A, AS807, and AS918 engines, respectively, were identified as analytical test beds for the evaluation of low-NOx emissions technologies. These designs represent the business turbofan, regional turboprop, and regional turbofan engine classes, respectively. For each of these engine designs, three different levels of NOx-reduction technology were assumed, designated as Baseline, Near-Term, and Advanced Technology. The Baseline level represents current combustor design practices that could be applied to a new engine design, Near-Term represents design practices using new technologies that are currently available, and the Advanced Technology level employs technologies not currently available but that are expected to be developed by the year 2005 time frame.

The combustor configurations analyzed ranged from very simple modifications that could be accomplished on an existing combustor design, to a complete redesign using the latest materials and fuel-injector technology, some of which is not yet fully matured. A tabulation of the techniques that have been found in this study to assist in NOx reduction is given in the paragraphs that follow. Note that not all of the methods may be applied simultaneously.

The predicted emissions output for each of the combustor configurations studied, compared to the applicable regulatory limits are summarized in Figures 51 through 53. In each case, a significant reduction in NOx emissions was achieved. This was accompanied, in most cases, by a reduction in unburned hydrocarbons (UHC) and carbon monoxide (CO) emissions as well. In those situations where a reduction in UHC and CO emissions was not achieved, the levels were still below the current regulatory limits. Considering all three engine configurations, the average NOx reduction achieved by the Near-Term methods compared to the Baseline was 34 percent, and the average reduction for the Advanced Technology methods was 70 percent, again compared to the Baseline results.

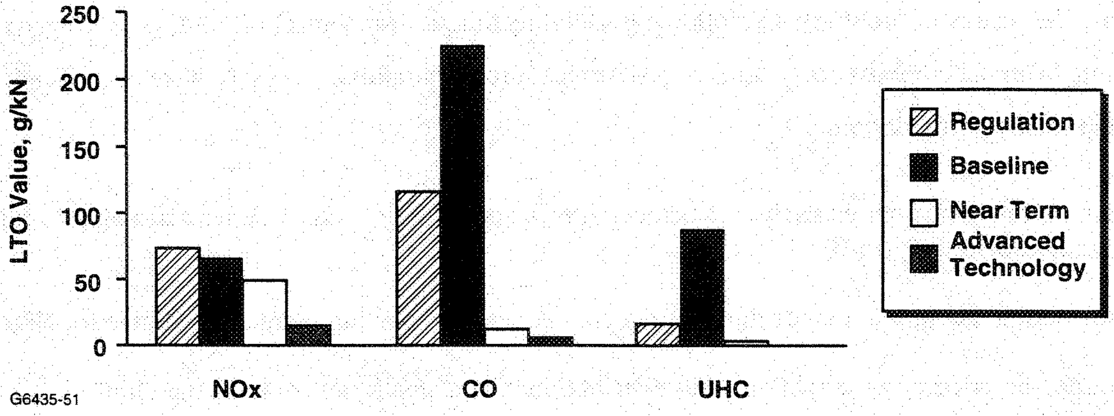


Figure 51. TFE731-80A Turbofan Engine Predicted Emissions.

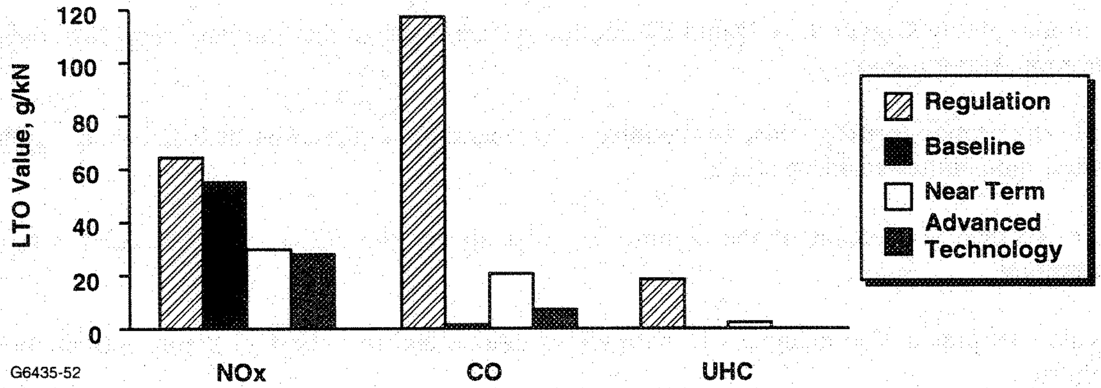


Figure 52. AS807 Turboprop Engine Predicted Emissions.

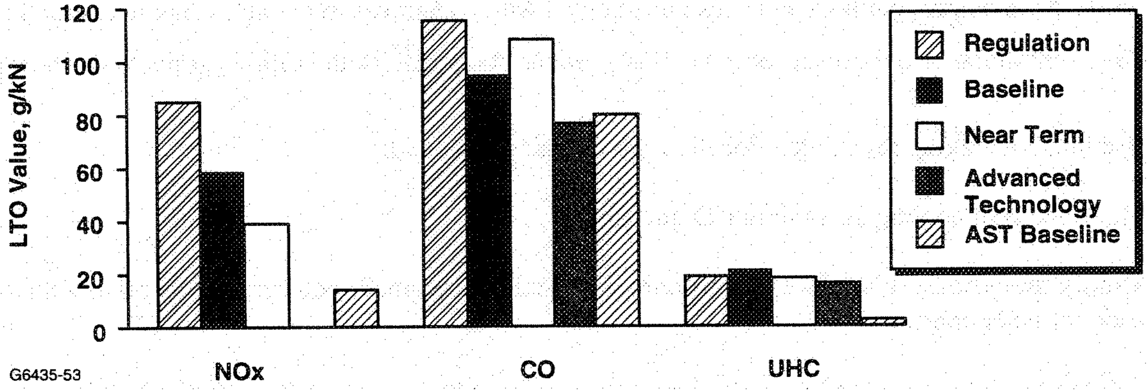


Figure 53. AS918 Turbofan Engine Predicted Emissions.

4.1 NOx Emissions Control Concepts

Based on the results of the study, the following useful techniques for control of oxides of nitrogen (NOx) emissions from the combustion systems of gas turbine aircraft propulsion engines have been identified. (They are not listed in any particular order.)

- Increase the main swirler airflow to achieve a primary zone (PZ) equivalence ratio of 0.7 (compared with the typical value of 0.9 to 1.0)
- Use effusion cooling to reduce the required cooling airflow, making more air available for NOx control
- Stratify the primary zone fuel/air ratio distribution; use a small, rich zone as the pilot, with a large, lean zone for NOx control
- Use a small number of large-diameter primary jets to induce large-scale mixing
- Circumferentially stagger the OD and ID dilution orifice rows, so that the jets interweave rather than impinge to promote better mixing
- Locate the primary orifices close to the injectors (separation on the order of 0.5 channel heights) to minimize the high-temperature residence time
- Use more than 20 percent of the compressor inlet air for the primary jets, to quickly lower the reaction temperature
- Provide fuel-preparation chambers to partially evaporate and mix the fuel before introduction into the main combustor
- Increase the number of injectors to distribute the fuel.

4.2 Idle Efficiency Concepts

The above NOx control methods must also be coupled with techniques to maintain engine operability and minimize emissions at low-power settings. Based on the study results, the following methods show promise:

- Use injector staging to maintain locally high fuel/air ratios at idle
- Minimize wall cooling air to limit CO quenching
- Stratify the primary zone (PZ) fuel/air ratio distribution; use small, rich zone as the pilot, with a large, lean zone for NOx control
- The pilot or idle injector cone angle should be narrow (<40 degrees) to keep the local fuel/air ratio high
- Maintain the fuel droplet Sauter Mean Diameter (SMD) as low as possible (<20 microns) to enhance fuel evaporation.

4.3 Selection of Fundamental Low-NOx Concepts

Based on the results of the Trade Study, six of the ten different configurations analyzed were rated as essentially equal. However, the ratings were very different in terms of the engine geometry and cycle values. For the purposes of future low-NOx combustor designs, it would be advantageous to identify the successful NOx-reduction techniques in more fundamental terms, that could be applied to any new combustor design regardless of the specified engine geometry. Examination of the top six configurations revealed the following three fundamental techniques for NOx control:

- Use increased swirler and primary flow to reduce the primary zone (PZ) equivalence ratio to approximately 0.7
- Use "fuel-preparation" cans to partially premix the fuel and air before introduction into the main combustor
- Use a "double-dome" swirler arrangement to stratify the PZ fuel-air distribution.

These three fundamental methods should be considered prime candidates for evaluation during any follow-on programs aimed at demonstrating reduced-NOx combustion system hardware. The selection of which technique to use would depend on the latitude permitted in the combustion system design (or redesign) and the NOx-reduction level desired. Current aircraft engine emissions regulatory limits could be met using increased swirler and primary orifice flows, with only minimum impact on the combustor configuration. If higher levels of NOx reduction are required, the fuel-preparation cans and double-dome swirler methods may have to be used, even though this would increase the complexity of the combustion system.

4.4 New Technology

Under the NASA SET Task 4, Advanced Combustor Study, AlliedSignal Engines has evaluated several low-emissions combustion system concepts for gas turbine aircraft propulsion engines. These concepts will satisfy the projected future emissions regulatory requirements of the selected regional turboprop and turbofan engine cycles. These concepts are highly configuration-dependent and are adaptations of current gas turbine engine combustion system technologies. No new patentable inventions, discoveries, improvements, innovations, or computer codes have resulted from this study to date.

This study identified several areas of new technologies that will be mandatory for future, ultra-low emissions combustors. Areas in which new combustor technologies should be developed to fulfill projected future aircraft propulsion engine needs include:

- Ceramic Matrix Composite (CMC) Material Systems, to eliminate combustor liner cooling
- Photon Ignition, to ensure acceptable altitude ignition and relight capability
- Advanced Fuel Control Systems, to address combustor operability characteristics
- Fuel Injector Anti-Coking, to address fuel system reliability issues.

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13. ABSTRACT ***(Maximum 200 words)***

Under the SET Program Task 4—Regional Turboprop/Turbofan Engine Advanced Combustor Study, a total of ten low-emissions combustion system concepts were evaluated analytically for three different gas turbine engine geometries and three different levels of oxides of nitrogen (NOx) reduction technology, using an existing AlliedSignal three-dimensional (3-D) Computational Fluid Dynamics (CFD) code to predict Landing and Takeoff (LTO) engine cycle emission values. A list of potential Barrier Technologies to the successful implementation of these low-NOx combustor designs was created and assessed. A trade study was performed that ranked each of the ten study configurations on the basis of a number of manufacturing and durability factors, in addition to emissions levels. The results of the trade study identified three basic NOx-emissions reduction concepts that could be incorporated in proposed follow-on combustor technology development programs aimed at demonstrating low-NOx combustor hardware. These concepts are: high-flow swirlers and primary orifices, fuel-preparation cans, and double-dome swirlers.

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