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ANALYTICAL EVALUATION OF THE IMPACT OF BROAD SPECIFICATION FUELS ON HIGH BYPASS TURBOFAN ENGINE COMBUSTORS

FINAL REPORT

by

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16 Abstract

An analytical study was conducted to assess the impact of the use of broad specification fuels on the design, performance, durability, emissions and operational characteristics of combustors for commercial aircraft gas turbine engines. Single stage, vorbix and lean premixed prevaporized combustors, in the JT9D and an advanced Energy Efficient Engine cycle were evaluated when operating on Jet A and ERBS (Experimental Referee Broad Specification) fuels. Design modifications, based on criteria evolved from a literature survey, were introduced and their effectiveness at offsetting projected deficiencies resulting from the use of ERBS was estimated.

The results of the study indicate that the use of a broad specification fuel such as ERBS, will necessitate significant technology improvements and redesign if deteriorated performance, durability and emissions are to be avoided. Higher radiant heat loads are projected to seriously compromise liner life while the reduced thermal stability of ERBS will require revisions to the engine-airframe fuel system to reduce the thermal stress on the fuel. Smoke and emissions output appear to be inherent to fuel chemistry and are projected to increase with the use of broad specification fuels. While the basic geometry of the single stage and vorbix combustors are compatible with the use of ERBS, extensive redesign of the front end of the lean premixed prevaporized burner will be required to achieve satisfactory operation and optimum emissions

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FOREWORD

This report presents the results of an analytical study conducted by the Commercial Products Division, Pratt & Whitney Aircraft Group of United Technologies Corporation to assess the impact of the use of broad specification fuels in combustors for commercial aircraft gas turbine engines. This effort was conducted for the National Aeronautics and Space Administration Lewis Research Center under Contract NAS3-20802.

The NASA Project Manager for this study was Arthur L. Smith of the Fuels Branch, Lewis Research Center, Cleveland, Ohio and the P&WA Program Manager was Dr. Robert P. Lohmann. Portions of the technical effort were conducted at the United Technologies Research Center by Eugene J. Szetela and Dr. Alexander Vranos.

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1.0 SUMMARY

This report presents the results of an analytical study conducted to assess the impact of the use of broad specification fuels on the design, performance, durability, emissions and operational characteristics of combustors for commercial aircraft gas turbine engines. The study was directed at defining the necessary design revisions and projected impacts when combustors intended initially for operation on the current Jet A specification fuel were operated on a fuel of higher aromatic content. The particular high aromatic content fuel selected for this study was ERBS (Experimental Referee Broad Specification Fuel), the tentative specification for which was established at a NASA directed workshop on alternate hydrocarbon fuels in June 1977.

The study was initiated with an extensive literature survey to accumulate the available data on the use of fuels of various composition in combustion devices. This data was correlated to generalize the impact of fuel properties on combustor performance and operation. From this information, revised design criteria consistent with the use of ERBS fuel were developed and influence coefficients, defining the incremental changes in combustor performance and emissions when ERBS was substituted for Jet A fuel, were established. The areas of combustor operation investigated included emissions and smoke, liner heat load, combustion stability and ignition, fuel atomization, vaporization and autoignition and thermal stability.

The second phase of the program consisted of a design study in which the effect of the use of ERBS fuel was assessed for three different types of combustors operating in both the JT9D and the advanced technology, higher pressure ratio Energy Efficient Engine cycles. The combustor types included conventional single stage, vorbix and lean premixed prevaporized concepts and were selected because, in combination with these engines cycles, they would be representative of the entire spectrum of combustor technology that could be in commercial aircraft service in the 1990 time period and beyond. The design study phase was initiated with the definition of reference combustors of each type, designed for operation on Jet A fuel. After assessing the impact of the use of ERBS fuel in these combustors, without modification, the study progressed to address various design modifications that could be incorporated to offset projected deficiencies.

The results of the study indicated that the use of a broad specification fuel, such as ERBS, has a significant impact on the design, operation and projected performance and emissions of all of the combustors. The deficiencies requiring the greatest technology evolution and component redesign are in the area of combustor liner and turbine airfoil durability and the reduced thermal stability of the fuel. Operation of combustors designed for Jet A fuel on ERBS is projected to lead to a 25 to 40 percent reduction in liner fatigue

life. Since attempting to restore the liner life by increasing the cooling flow adversely affects emissions; and in some configurations the ability to control combustor exit temperature pattern factor, improved liner materials and more effective cooling concepts will be required.

The reduced thermal stability of ERBS fuel, relative to Jet A, will require reconfiguring of the engine-airframe fuel system to reduce thermal stress on the fuel. Approaches involving rejection of the engine lubricating system heat to the airframe fuel tanks and the use of non-recirculating fuel pumps appear attractive for this purpose but require additional analysis because of concerns over excessive tank temperatures at some conditions and possible compromising of ignition.

The use of broad specification fuels is, in general, projected to lead to an increase in emissions and smoke output. The propensity for increased emissions appears, in most cases, to be fuel chemistry dependent. However, at least in the case of unburned hydrocarbons, a sensitivity to fuel atomization was deduced from some of the data examined and would suggest that reductions in this constituent might be achieved with improved fuel injector concepts. Fuel atomization also appears to be critical to ignition, particularly at cold fuel conditions, which would create further incentive for improvement of this component.

The results of the design study indicate that it would not be necessary to revise the basic aerothermal definition; including liner and diffuser/burner case contours, fuel injector density or burner section pressure loss; of a single stage or vorbix combustor to operate with ERBS fuel. In the case of the lean premixed prevaporized burner, fuel composition affects combustion stability and substantial increases in flameholder area would be required to achieve adequate altitude stability margin with ERBS. Other mechanisms critical to the operation of the premixed prevaporized combustor concept, such as vaporization and autoignition, are also sensitive to fuel composition and would dictate a complete redefinition of the front end of this type of combustor for operation on ERBS fuel.

2.0 INTRODUCTION

2.1 BACKGROUND

The production and reserve supply of petroleum crudes poses a continuing problem of availability, increasing costs and limited choice of crude type. Competition for the middle distillate products currently used for jet fuel, diesel fuel, heating oil and kerosene is particularly acute and the possibility of revising the current ASTM D-1655 specification for Jet A fuel for use in commercial aircraft gas turbine engines to include wider distillation range must be considered. Furthermore, since the supply of straight distilled fuel will become limited, middle distillate fractions will have to be produced by cracking higher boiling point constituents. If current specifications are to be maintained, energy intensive hydrogenation processes will be required to reduce the aromatic contents of these cracked fuels to the specified levels.

This prospect has been considered by the aircraft industry and a number of studies and experiments; many of which are cited as references in this report; have been conducted to obtain data on the effect of changes in fuel composition on the performance, emissions and overall design and operational aspects of gas turbine combustors. These programs generally employed Jet A, JP-5 or JP-4 as the reference fuel and involved testing fixed combustor configurations on the reference fuel and other products available; the latter including commercially available fuels such as diesel fuel and home heating oil, mixtures blended to produce selected variations in composition and limited samples of fuels derived from shale sources. The results of these investigations indicated that relaxing the fuel specification to permit higher aromatic contents or lower hydrogen/carbon ratios in the fuel would have significant impacts on gas turbine combustion systems. Emissions, particularly those at low power, and smoke formation were generally found to increase and in most cases, the higher carbon content of the fuel led to higher radiant heat loads on the liners as manifested by higher liner metal temperatures. Evaluation of the thermal stability of higher aromatic contents fuels in JFTOT and similar apparatus also indicated increased propensity for deposit formation with increasing aromatic content. Other potential problems, such as ignition at low inlet temperatures and fuel freezing during long duration high altitude flights also became apparent.

At this time it appears most appropriate to consolidate the results of these experiments and concentrate on the implications of a single fixed specification fuel relative to combustor design and performance. The Jet Aircraft Hydrocarbon Fuels Technology Workshop, convened at NASA Lewis Research Center in June 1977 provided the basis for establishing this fuel specification (Reference 1). The attendees; including representatives of the petroleum industry, engine and airframe manufacturers, airlines, the military and NASA; reviewed the experience to date and arrived at a tentative specification for ERBS (Experimental Referee Broad Specification Fuel). This specification represents a compromise in that it permits an increase in the aromatic content relative to the current Jet A specification while maintaining a balance with the various aspects of aircraft operation such as engine performance, operational aspects, fuel storage and thermal stability.

2.2 SPECIFICATION AND PROPERTIES OF ERBS FUEL

Table 2-I shows a comparison of the tentative specification for ERBS fuel and that for Jet A - the fuel currently used for the majority of commercial jet aircraft operations. Specifications of this type stipulate only the allowable limits on the composition of the fuel. The method of defining these limits differs, most notably in the means of limiting the fractions of aromatics and complex aromatics. The Jet A specification stipulates specific limits on the concentrations of these constituents while that for ERBS uses the hydrogen content of the fuel as the controlling parameter. Hydrogen content provides a qualitative characterization of the fuel in that, since the aromatic compounds have a high ratio of carbon to hydrogen atoms; increasing the aromatic content reduces the hydrogen content. For reference, a fuel devoid of aromatics has a hydrogen content of about 15 percent, while Jet A fuel at the specification limit of 20 percent aromatic content has a hydrogen content of about 13.7 percent. The lower hydrogen content of the tentative ERBS specification would permit the aromatic content to increase into the range of 35 to 40 percent.

The increase in the allowable aromatic content of ERBS is also reflected in the distillation temperature distribution with the high end of the distillation range occurring at higher temperature levels. The increase in aromatic content is also shown to necessitate an increase in the freezing point relative to Jet A - a consideration that is of significance in consideration of fuel storage and pumpability both in ground operations and on long duration high altitude flights. Since proximity of the fuel temperature to the freezing point has a strong influence on viscosity, deteriorated fuel atomization could compromise cold engine starting. Consequently, the ERBS specification also includes a limit on low temperature fuel viscosity. The differences in the maximum allowable breakpoint temperature imply that the thermal stability of ERBS fuel will be poorer than that of Jet-A. This reduction is consistent with, and an anticipated consequence of, the higher allowable aromatic content.

While the specifications of Table 2-I define the allowable limits on the composition and physical characteristics of these fuels, they do not define their nominal properties nor do they provide sufficient data for the purposes of the present study. Consequently, at the initiation of the study a more comprehensive tabulation of the composition and properties of Jet A and ERBS fuels was formulated and

TABLE 2-I

COMPARISON OF SPECIFICATIONS FOR JET A AND ERBS FUEL

	JET A	ERBS
Aromatic Content (% vol.)	20 max.	-
Hydrogen Content (% wt)	-	12.8 ± .2
Sulphur Mercaptan (% wt) max.	0.003 max.	0.003
Sulphur Total (% wt)	0.3 max.	0.3 max.
Naphthalene Content (% vol.)	3.0 max.	-
Distillation Temperature (°K)		
10 Percent	500 max.	477 max.
90 Percent	-	534 min.
Final Boiling Point	561 max.	-
Residue (% vol.)	1.5 max.	-
Loss (% vol.)	1.5 max.	-
Flashpoint (°K)	311 min.	311/321
Freezing Point (°K)	233 max.	244 max.
Maximum Viscosity (cs)	8 @ 253°K	12 @ 249°K
Heat of Combustion (J/kg)	42.8×10^6 min.	-
Thermal Stability:		
JFTOT Breakpoint Temperature (°K)	533 min.	511 min.
Method	Visual	TDR = 13.

provided the basis for the study. These data are listed on Table 2-II and were based on the following assumptions:

- The hydrogen content was selected to represent the upper bound of the specification of Table 2-I and the corresponding aromatic content would be expected to be about 35 percent. The increase in aromatic content was also assumed to lead to a proportionately greater increase in naphthalene concentrations.

- Since Jet A fuel currently provided from petroleum feed stocks has sulfur contents well below the specification limit and low nitrogen levels both fuels were assumed to have the same low concentrations of these constituents. This situation could change if the fuels were derived from shale or coal syncrude sources.

- The increase in the 90 percent and final boiling point temperatures results in the inclusion of more aromatic constituents in ERBS. Since the specification for ERBS also stipulates a low 10 percent boiling point and a flashpoint nearly identical to that required for Jet A the nominal 10 percent distillation temperatures were assumed equal but the initial boiling point of ERBS was assumed to be lower than that of Jet A. This assumption is consistent with the intent of producing ERBS from the widest allowable distillation cut.

- The nominal physical properties of the fuels, including the thermal stability characteristics, were assumed to be consistent with the specification limits. The heat of combustion of Jet A fuel is nominally somewhat above the specification limit of Table 2-I, but; as will be shown in Section 4.2; that of ERBS may be close to the assumed minimum.

2.3 PROGRAM PLAN AND OBJECTIVES

The objective of the study documented in this report was to assess the impact of the use of the ERBS specification fuel on combustors for current and intended future use in commercial aircraft gas turbine engines. To cover the entire spectrum of combustor technology levels that is or could be incorporated in these engines, the study addressed three basic combustor types in two different engine cycles. The reference combustors included conventional single stage annular burners, the low emissions dual stage Vorbix combustor evaluated under the NASA-PWA Experimental Clean Combustor Program and an advanced technology premixed-prevaporized combustor. The reference engine cycles were the currently in-service JT9D-7 engine and the advanced technology, high pressure ratio, Energy Efficient Engine. These engine cycles and the baseline configurations of the reference combustors, as they are or would be designed for operation on Jet A fuel are discussed in Section 3.0.

TABLE 2-II

NOMINAL PROPERTIES AND COMPOSITION OF JET A AND ERBS FUELS

	JET A	ERBS
Composition		
Aromatic Content (% vol.)	20	35
Hydrogen Content (% wt)	13.7	13.0
Naphthalene Content (% vol.)	3	7.5
Sulphur Content (% wt)	.05	.05
Nitrogen Content (% wt)	.001	.001
Volatility		
Distillation Temperature (°K)		
Initial Boiling Point	444	422
10 Percent	477	477
50 Percent	505	511
90 Percent	517	567
Final Boiling Point	561	589
Flash Point (°K)	311	311/321
Physical Properties		
Freezing Point (°K)	233	244
Viscosity (cs) at 253°K	8	-
at 249°K	-	12
Heat of Combustion j/Kg	42.8 x 10^6 min.	42.8 x 10^6
Specific Gravity (288/288°K)	.7753-.8299	.8348-.8448
Thermal Stability		
Coker P in hg. at 422/477°K	12	-
at 400/455°K	-	12
Cokertube Color Code at 422/477°K	3	-
at 400/455°K	-	3
JFTOT Breakpoint Temperature (°K)	533	511

Because of the diversity of the available data on the use of fuel of various compositions in combustion devices, the study was initiated with a survey of this information and a correlation effort to generalize the impact of fuel properties on combustor performance and operation. From this information revised design criteria consistent with the use of ERBS fuel were developed and influence coefficients, defining incremental changes in combustor performance and emissions when ERBS was substituted for the conventional Jet A fuel, were established. This effort was a major part of the overall study and the results are discussed in Section 4.0.

The second phase of the effort consisted of a design study, using the three reference combustor types in both engine cycles, to assess the impact of the use of ERBS fuel on the design and operation of these combustors. The influence of the change in fuel specification on the performance, emissions and operational capabilities of the reference combustors without design revisions was projected. Subsequent analyses addressed appropriate design revisions including changes in liner materials and cooling, stoichiometry and fuel injectors. The effect of reduced thermal stability of the fuel on fuel system design and the impact of the change of fuel specification on integration of the combustor into the engine, including its effect on fuel control systems and turbine design were analyzed in a general context. The results of this design study phase are summarized in Section 5.0.

The study was completed with an overall evaluation of the design revisions to the combustor and related systems that would be required to accommodate the use of the ERBS specification fuel. These conclusions and recommendations for areas of further study are presented in Section 6.0.

3.0 REFERENCE CYCLES AND COMBUSTORS

3.1 INTRODUCTION

The introduction of a fuel specification revision of the magnitude of that between Jet A and ERBS is a long term proposition involving redesign, development, substantiation, and retrofitting of engine components. To conduct the study in the most realistic scenario, it was necessary to project the evaluation to the types of engines and combustors that would be in commercial airline service both at and subsequent to the time of the change in fuel specification. Anticipating that such a change would occur in the 1990 time period, a substantial number of the more recently introduced engine models, such as the JT9D would still be in service in the commercial airline fleet. Likewise, more advanced engine models that are introduced into service after the JT9D would be expected to operate on the new specification fuel over part or the entirety of their service periods. Based on the current trends of evolution of engines for subsonic commercial aircraft, these advanced engines will be high bypass ratio engines of progressively higher pressure ratio that will offer significant reductions in thrust specific fuel consumption relative to current engine models. The Energy Efficient Engine currently being defined under joint NASA-PWA effort is representative of such an advanced engine cycle.

Promulgation of emissions constraints on aircraft gas turbine engines is expected to have a significant effect on combustor design philosophy in the future and each level of combustor technology must be considered with regard to the accommodation of a relax specification fuel such as ERBS. Moderate restrictions on the output of smoke, carbon monoxide and unburned hydrocarbon emissions would be expected to be satisfied with improved versions of the current single stage annular type of combustor. Should control of airport vicinity NO_x emissions become a necessity, staged combustors such as the Vorbix combustor evaluated under the NASA-PWA Experimental Clean Combustor Program would have to be incorporated. More stringent control of airport vicinity or cruise NO_x emissions would require the use of more advanced burner concepts such as lean premixed prevaporized combustion systems. Depending on the required degree of emissions constraints and the implementation date of the appropriate regulations, any or all three of these types of combustors could be in commercial airline service during the period that ERBS is projected to be the standard commercial aviation gas turbine fuel. Consequently, conducting this study in the most realistic scenario with regard to the gas turbine and combustor technology levels requires that all three combustor types; the single stage annular, the Vorbix and the lean premixed-prevaporized combustor be evaluated in the JT9D and a representative advanced higher pressure ratio cycle such as the Energy Efficient Engine.

3.2 REFERENCE ENGINE CYCLES

The JT9D-7 engine was selected as one of the references for the study. This engine is a current production version of the basic JT9D engine model, which was designed and developed by Pratt & Whitney Aircraft. Since its introduction into commercial service, this engine has acquired widespread use as the powerplant for both the Boeing 747 and the Douglas DC-10 aircraft.

The JT9D engine is a dual-spool, axial-flow turbofan engine designed with a high bypass ratio and an overall pressure ratio of 22.3 at sea level takeoff condition at which a thrust of 197 KN is produced at an engine airflow of 686 kg/sec. At cruise power levels at an altitude of 10,668 m and 0.85 flight Mach number it produces a thrust of 44.6 KN with a specific fuel consumption of 1.98×10^{-5} kg/Ns.

The Energy Efficient Engine, selected as a cycle representative of the advanced technology engines that will be introduced into service in the future is also a high bypass ratio axial flow turbofan engine. This engine, currently in the initial design phase under a joint NASA-Pratt & Whitney Aircraft Program is expected to substantiate the technology required to produce a reduction of more than 12 percent in the specific fuel consumption, while providing a 6 to 10 percent reduction in direct operating cost, relative to the JT9D-7 engine. This will be accomplished by optimizing the bypass ratio and operating at a higher pressure ratio; approximately 31.7 as opposed to 22.3 in the JT9D at sea level takeoff; and through the introduction of advanced technology concepts in many of the engine components. The latter include such features as improved turbomachinery aerodynamics. Further details on the design features of the Energy Efficient Engine may be found in Reference 2.

Table 3-I lists the combustor operating parameters for various sea level and flight conditions for both the JT9D-7 and the Energy Efficient Engine. Data are presented at the four power levels on the sea level operating line used to evaluate the Environmental Protection Agency's thrust weighted emissions parameter (EPAP) for net airport vicinity emissions output. The design cruise condition for these engines is also listed because long term steady state operation occurs at this condition and it could be critical to combustor durability considerations. Future needs to reduce high altitude NO_x emissions could also make this condition a critical combustor design point. The flight idle point represents the minimum fuel flow condition and, while normally encountered only during transient operation during descent, can be a critical condition from the point of view of thermal stability of the fuel. The data of Table 3-I shows the effect of the higher pressure ratio of the Energy Efficient Engine with the combustor inlet temperature being approximately 45°K higher than in the JT9D-7 at all operating conditions. In combination with the higher pressure environment, this reduction in cooling potential is expected

to produce more severe liner durability problems in the Energy Efficient Engine - a situation which will also be aggravated by the use of a fuel of higher aromatic content.

TABLE 3-I

TURBOFAN ENGINE COMBUSTOR OPERATING PARAMETERS

	Compressor Discharge				Combustor Airflow Kg/sec	Fuel/Air Ratio	Combustor Exit Temperature °K
	Total Pressure atm	Total Temperature °K	Airflow Kg/sec.	Velocity m/sec			
Energy Efficient Engine							
Idle (6% Thrust)	3.97	488	12.15	122 3	10 69	01184	925
Sea Level 30% Thrust (Approach)	11 82	620	33 31	142 3	29.05	01367	1106
Sea Level 85% Thrust (Climb)	27.52	780	65.84	151.4	57.51	02170	1510
Sea Level Takeoff (100% Thrust)	31 67	812	73.48	152.7	64 18	02381	1602
Cruise (10,668 m M = .8)	13.83	755	32.94	126 0	28 78	02311	1533
Flight Idle (10,668 m. M = .8)	3 06	501	9.89	132 2	8.64	00942	847
JT9D-7F Engine							
Idle (6.7% Thrust)	3 65	447	26 12	108 2	20.74	01093	861
Sea Level 30% Thrust (Approach)	8 84	582	52.94	117 4	42.04	.01558	1150
Sea Level 85% Thrust (Climb)	19 5	735	101.42	129.0	53 09	02259	1502
Sea Level Takeoff (100% Thrust)	22.3	767	112.42	151.7	89.00	02483	1595
Cruise (10,668 m. M = .9)	9 7	701	52 0	126.3	41 64	.02173	1447
Flight Idle (10,668 m. M = .8)	2.1	450	15.73	114.4	12.65	.00828	760

The introduction of ERBS fuel could dictate revisions to combustor design parameters that influence the overall geometry of the combustor, such as changes in front end height or flameholder surface area to maintain adequate combustion stability or changes in residence times in combustion zones or premixing passages which require alteration of the combustor length. Since changes to the combustor section length or the diffuser and burner case contours to accommodate a larger combustor would be extremely costly, a strong incentive exists to maintain the geometry of the redesigned combustor consistent with these constraints. Figures 3-1 and 3-2 show the critical dimensions of the combustor sections of the JT9D and Energy Efficient Engine respectively. The combustor section of the JT9D was designed to accommodate a single stage annular burner; c.f., Figure 3-3. The diffuser incorporates an inner ramp and an outer wall trip followed by a dump section. Ten struts span the dump section and provide not only structural support of the inner burner case but also form a conduit for oil and breather lines to a bearing compartment inboard of the combustor section. Twenty fuel injector mount pads are provided on the outer diffuser case in the dump region.

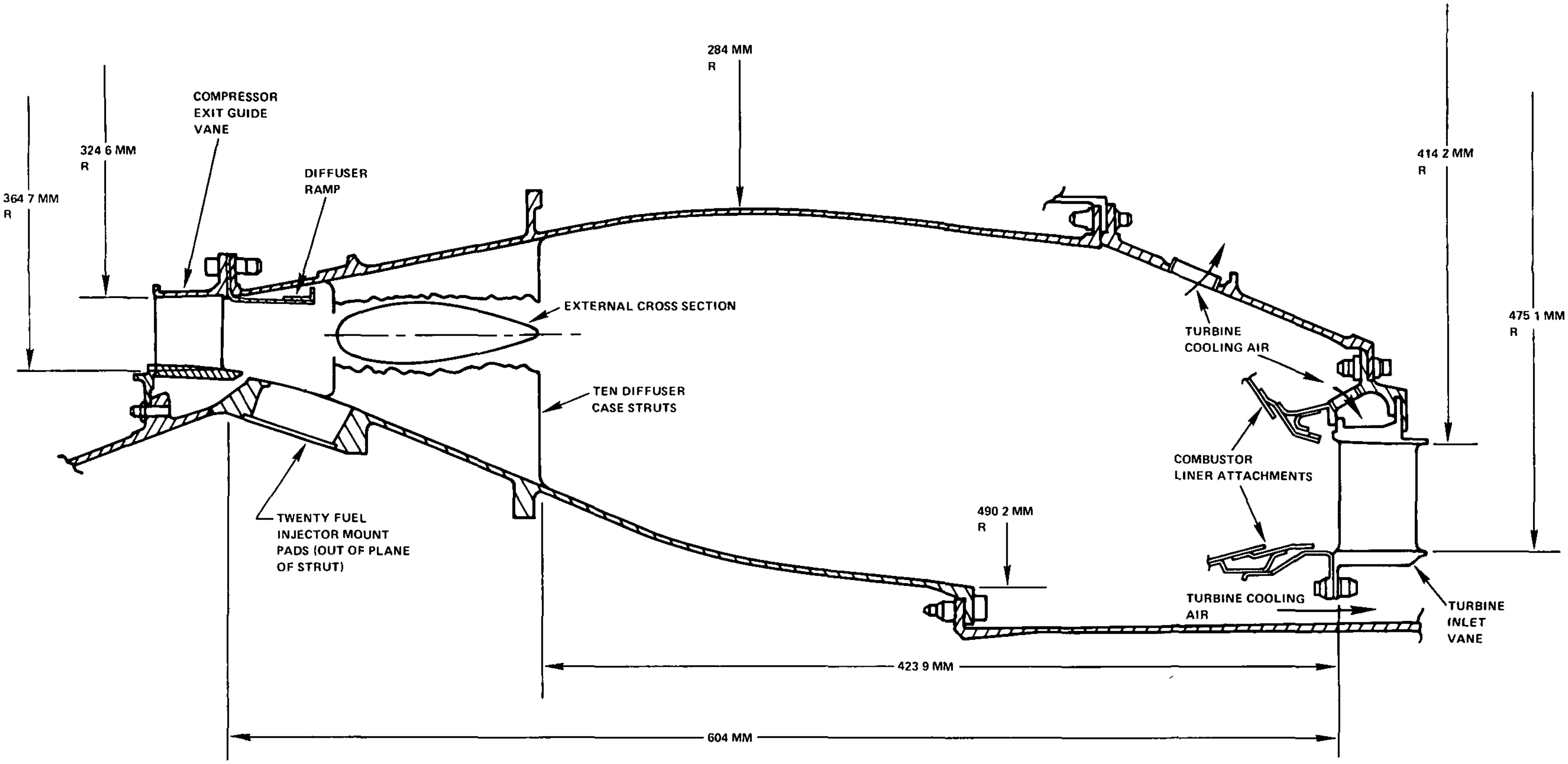


Figure 3-1 Combustor Section of JT9D Engine

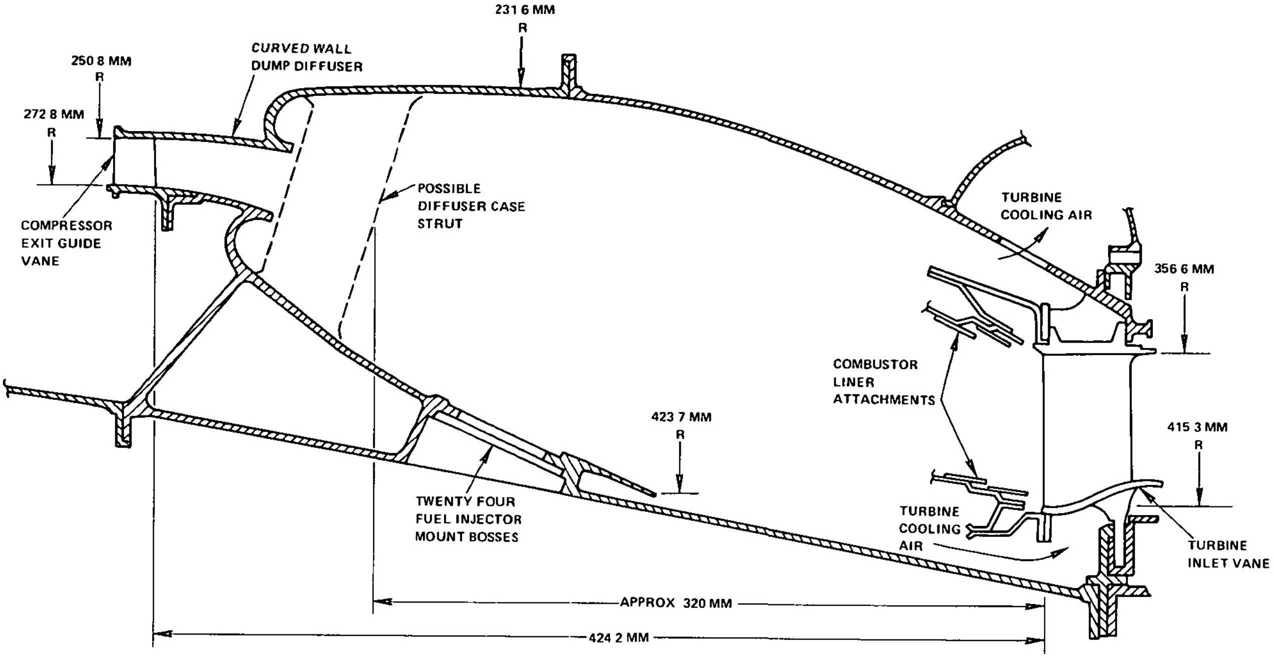


Figure 3-2 Combustor Section of Energy Efficient Engine

The combustor section of the Energy Efficient Engine is canted outward considerably more than in the JT9D because of the use of a single stage high pressure turbine. Flow control to the front end of the combustor is maintained, despite the high cant angle of the combustor, through the use of a curved wall diffuser. The dump at the discharge from this diffuser is also more pronounced than in the JT9D to minimize total pressure losses around the front end of the combustor. While the Energy Efficient Engine does not have a bearing compartment inboard of the combustor section, diffuser case struts may be necessary to support the inner burner case. These struts would be considerably thinner than those in the JT9D and will be located in the dump region. The primary combustor configuration in this engine is a Vorbix burner requiring fuel injection in both the front end and part way downstream. To minimize case penetrations, internally installed fuel injector support modules providing injectors at both axial positions from the same penetration will be employed, c.f., Figure 3-6. Both the JT9D and the Energy Efficient Engine cycles require that turbine cooling air be extracted from the inner and outer burner shrouds.

3.3 REFERENCE COMBUSTORS

The six reference combustors; a single stage annular burner, a Vorbix combustor and a lean premixed prevaporized burner in the JT9D and Energy Efficient Engine cycles; were all considered to be designed for operation on Jet A fuel. In most cases, existing designs were available for these combustors but in some situations, particularly those involving the Energy Efficient Engine, these designs had to be scaled from other engine configurations. In the remainder of this section, the design features of each of these combustors and the data base for establishing their performance and emissions when operating on Jet A fuel are enumerated.

JT9D Single Stage Combustor

The current JT9D-7 production combustor was selected as the reference single stage combustor in this engine because it provides a basis for estimating the impact of a change in fuel specification on engines currently in commercial airline service. As shown in Figure 3-3, the combustor employs a burner hood to provide a positive pressure feed to the combustor front end. The hood is indented locally in ten places downstream of each diffuser case strut. A film-cooled louver construction is used for the combustor liners. The liner assembly features inner and outer slipjoints to facilitate assembly as well as to allow for liner thermal expansion. The fuel system features direct liquid fuel injection through twenty duplex-pressure atomizing fuel nozzles. The nozzle portion of the fuel injector is enclosed in twenty short cone swirler modules, which provide primary zone flame stabilization.

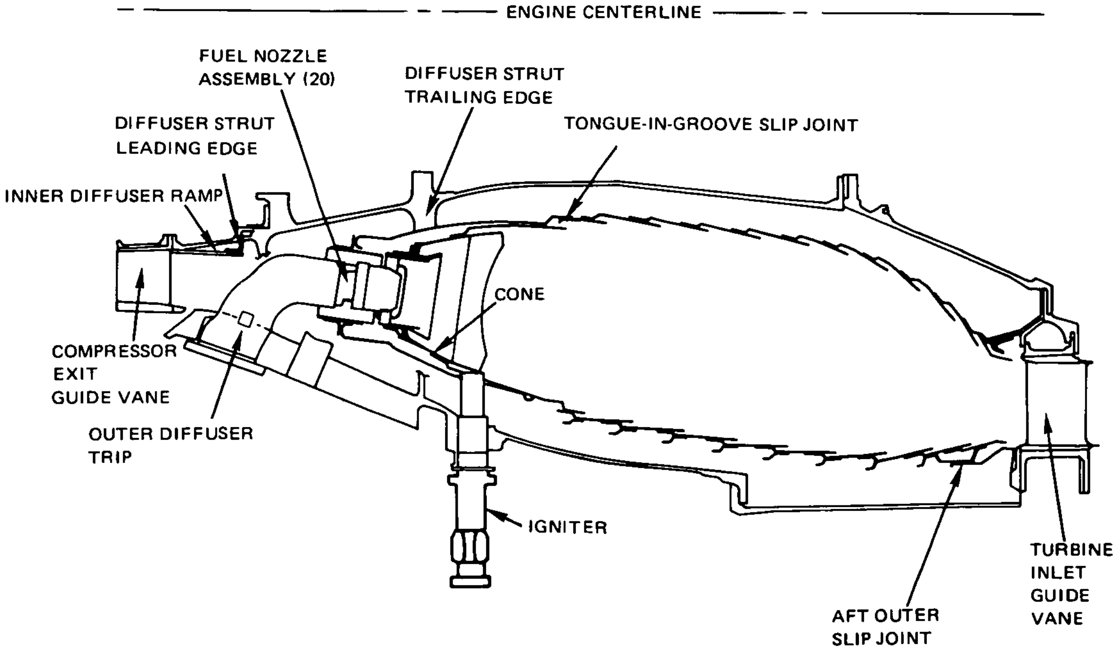


Figure 3-3 Single Stage Annular Combustor for the JT9D Engine

Since the JT9D engine and combustor system were designed prior to current concerns regarding gaseous pollutants, the combustor was not specifically intended to provide low emissions. However, the combustor does incorporate smoke reduction features and produces no visible smoke at any operation condition. An extensive data base on the performance of this combustor on Jet A fuel is available and includes data on the emissions of pilot lots of production engines (Reference 3) which were used as the basis for the projections of this study.

Energy Efficient Engine Single Stage Combustor

A more advanced single stage combustor was selected for evaluation in the Energy Efficient Engine cycle. Relative to the current JT9D single stage burner, this combustor has been designed to produce substantially lower emissions of carbon monoxide and unburned hydrocarbons at low power levels and could be representative of the type of combustor in service if constraints are imposed on the output of these emissions constituents. The combustor operates at a richer primary zone equivalence ratio than the production JT9D burner. The nominal primary zone equivalence ratio is about unity at idle operating conditions to provide a favorable environment for minimizing carbon monoxide and unburned hydrocarbons emissions. At takeoff power levels the equivalence ratio in the primary combustion zone is about two and excessive smoke production becomes a concern. This is offset by the use of aerating fuel injectors to provide better fuel atomization and to locally lean the high smoke production regions near the nozzle face. The stoichiometry-residence time history in the combustor is regulated through the scheduling of intermediate combustion air entry and is optimized on the basis of carbon monoxide and smoke oxidation rates.

Figure 3-4 shows the configuration of this type of combustor in the burner section of the Energy Efficient Engine. The combustor employs a louver cooled liner similar to the JT9D single stage combustor, but the use of an advanced liner material capable of sustaining higher temperature levels is assumed for the purposes of this study. The combustor also incorporates a bulkhead rather than multi-cone front end construction for the more effective utilization of cooling air. Experimental combustors incorporating these rich primary combustion zone, aerating fuel injection and bulkhead construction design philosophies have been evaluated at Pratt & Whitney Aircraft and provide the data for projecting the emissions and performance characteristics of this type of combustor when operating on Jet A fuel.

Vorbix Combustor

The vorbix combustor is representative of the technology level that would be required if emissions of oxides of nitrogen, in addition to those of carbon monoxide and unburned hydrocarbons are to be controlled in the airport vicinity. Combustors of this type were rig and engine tested in configurations compatible with the JT9D-7 engine under the NASA-PWA Experimental Clean Combustor Program (References 4, 5 and 6).The final engine tested configuration derived under Phase III of that program (Scheme S27E of Reference 6) was selected as the reference vorbix combustor in the JT9D engine.

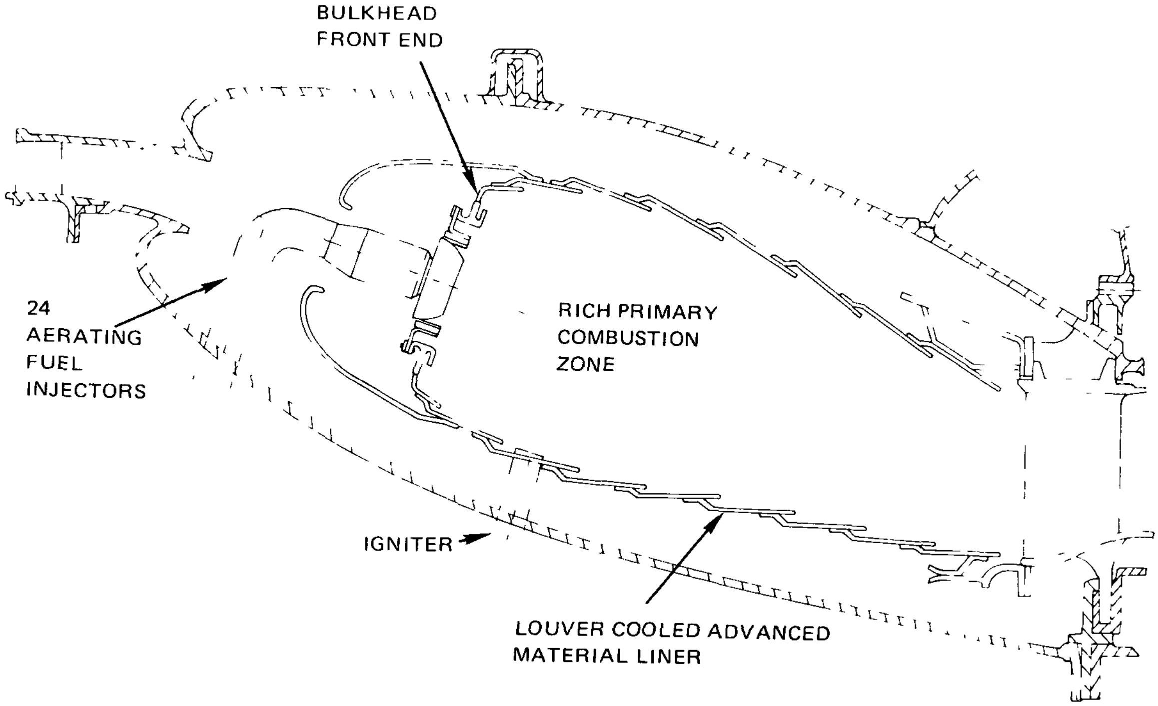


Figure 3-4 Single Stage Annular Combustor in the Energy Efficient Engine

Figure 3-5 shows the configuration of this burner which incorporates two axially separated combustion zones. The pilot zone is a conventional swirl-stabilized, direct-injection combustor employing thirty pressure atomizing fuel injectors. It is sized to provide the required heat release rate for idle operation at high efficiency. Emissions of carbon monoxide and unburned hydrocarbons are minimized at idle operating conditions by maintaining a pilot zone equivalence ratio of about unity. At high power conditions, the pilot exhaust equivalence ratio is reduced to as low as 0.3 (including pilot dilution air) to minimize formation of oxides of nitrogen. The minimum equivalence ratio for the pilot zone is determined by the overall lean blowout limits, combustion efficiency, and the need to maintain sufficient pilot zone temperature to vaporize and ignite the main zone fuel. Main zone fuel is introduced through fuel injectors located at the outer wall of the liner downstream of the pilot zone discharge location. Sixty pressure atomizing fuel injectors are used. Main zone combustion air is introduced through sixty swirlers positioned on each side of the combustor (120 total). Further details on the principle of operation of the Vorbix combustor may be found in Reference 7.

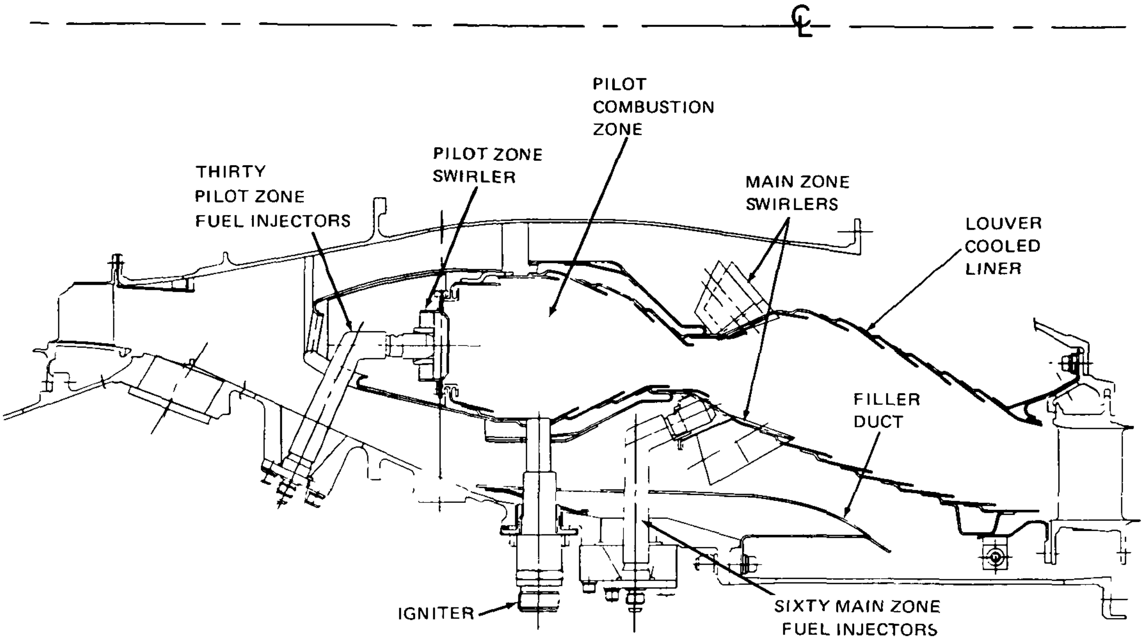


Figure 3-5. Vorbix Combustor for JT9D Engine

The Vorbix combustor is the baseline combustor for the Energy Efficient Engine and Figure 3-6 shows the initial definition of this combustor as it has been established under that program. The combustor has been designed to duplicate the stoichiometry of the Vorbix combustors evaluated under the Experimental Clean Combustor Program but reflects combustor operating conditions and geometry consistent with the Energy Efficient Engine cycle and engine size. Relative to the JT9D Vorbix combustor, this configuration has several unique features. The throat constriction between the pilot and high power stage has been eliminated to minimize potential durability problems and, as in the case of the single stage burner in this engine, the use of a high temperature capability liner material was assumed for this study. The fuel injection system employes twenty-four injector modules, each have one pilot and two main stage fuel injectors, providing a total of twenty-four pilot and forty-eight main stage injectors. In projecting the emissions and performance characteristics of the Vorbix combustor for the Energy Efficient Engine, the data obtained from testing Scheme S27E of Reference 6 was also used as the reference.

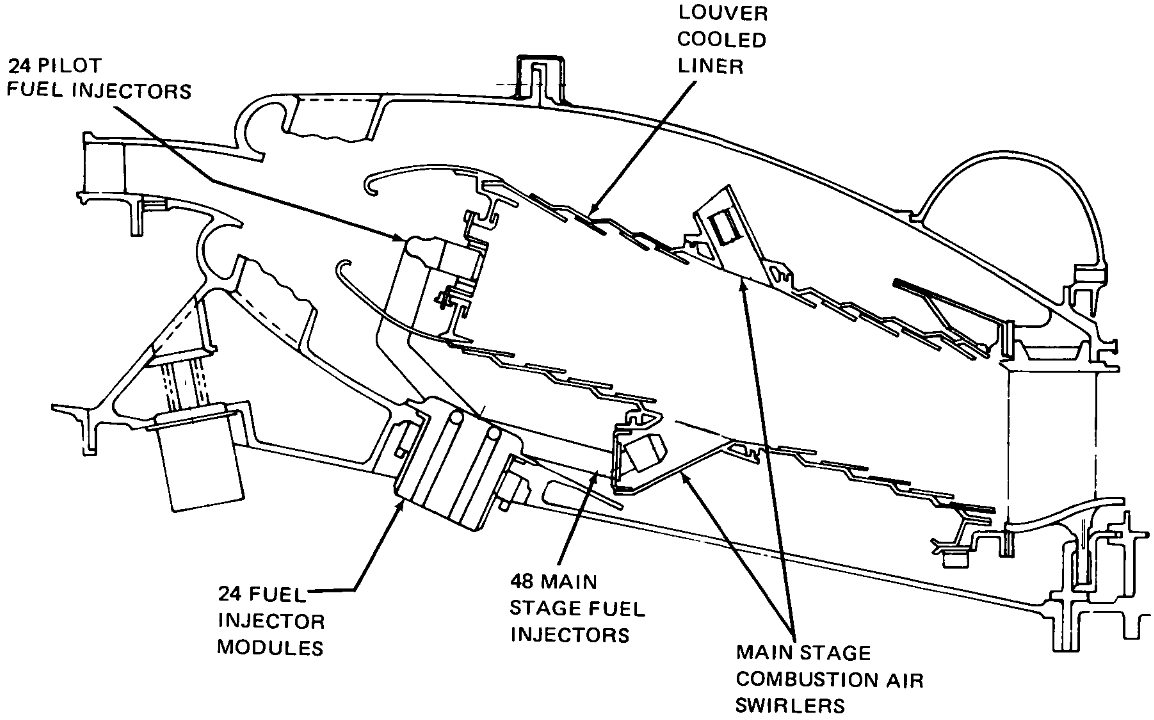
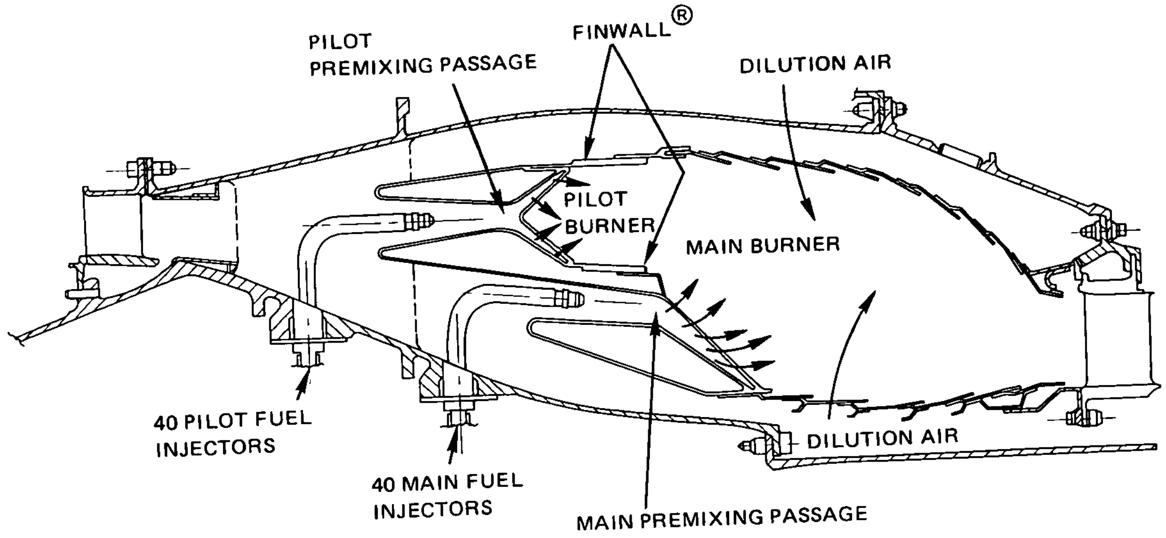


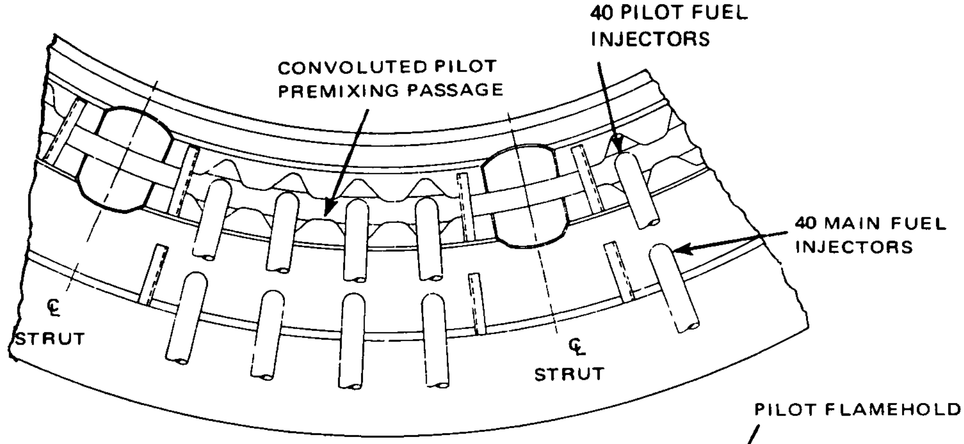
Figure 3-6 Vorbix Combustor for the Energy Efficient Engine

Premixed Combustors

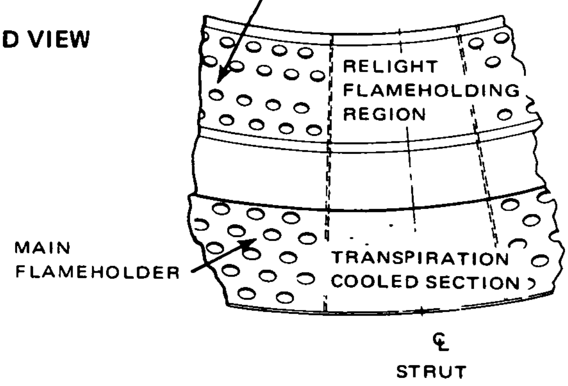
If environmental considerations dictate the need for extremely low NO_x emissions, in the airport vicinity and/or at cruise altitudes, future engines will have to employ lean premixed prevaporized combustion systems. Laboratory tests of idealized premixed combustors (References 8 and 9) have demonstrated that NO_x emissions can be minimized by conducting the combustion process in homogeneous fuel air mixtures at equivalence ratios approaching the lean extinction limit.

While the concept of premixed prevaporized combustion has been well established in controlled laboratory experiments, its translation into a viable combustion system for aircraft gas turbine engines is yet to be completed. Figure 3-7 shows an experimental combustor that is the most realistic approach made to date to incorporate the premixed combustion concept in an aircraft engine burner. This combustor was designed and evaluated under Phase I of the NASA-PWA Experimental Clean Combustor Program (Reference 4). The combustor uses two burning zones with premixing of the fuel and air prior to injection into each burning zones. The two combustion zones are required because such design variables as mixture preparation, residence time, and quench rate must be carefully controlled within narrow limits in premixing systems, and achievement of this control throughout the combustor operating range is difficult with a single combustion stage.





PREMIXING PASSAGE FRONT END VIEW



PILOT AND MAIN BURNER FLAMEHOLDERS

Figure 3-7 Staged Premixed Combustor

Each combustion system has its own independent fuel injectors, premix passage, flameholder, and combustion volume. High fuel source density in conjunction with pressure atomizing fuel injectors are used in both the pilot and the main premixing passages to promote fuel atomization and premixing with air. The two premixing passages and combustion zones are axially displaced, with the pilot burner system located further upstream. This displacement avoids rapid quenching of the pilot combustion process by the cool main burner air during low power operation.

In the staged premix combustor, fuel is furnished only to the pilot stage during idle operation and to both the pilot and the main stage during high power operation. Consequently, the equivalence ratio for the pilot stage is set at about unity to produce low levels of carbon monoxide and total unburned hydrocarbons, which are the predominant pollutants at low power, while the equivalence ratio for the combined pilot and main stage was selected to produce low levels of oxides of nitrogen, which is the main pollutant at high power levels. Considerations of adequate stability margin limit the minimum equivalence ratio to the range of 0.6 to 0.7 when operating on Jet A fuel.

Since the premixing passages contain a combustible mixture at high temperature, the residence time of the gases in the premixing passage is limited by the time required for autoignition to occur. At high power operating conditions, the autoignition delay time is sufficiently short that it constitutes a significant design factor. In this particular combustor, both the pilot and the main burner premixing passages were designed with an autoignition safety factor of two at maximum sea-level takeoff hot-day conditions of the JT9D engine. The combustor was designed, because of this constraint, to operate with a maximum premixing passage residence time of 1.8 milliseconds.

Both the pilot and the main flameholders must be independently stable. This is achieved by using perforated plate flameholders which provide a region for stable combustion in the wake of the web area between adjacent flameholder holes. The blocked surface area of the flameholder, in combination with the equivalence ratio of the premixed flow and the combustor inlet conditions are the critical parameters determining combustion stability.

The results of testing of combustors of this type indicate that two serious deficiencies are present relative to the performance achieved with idealized premixed combustors investigated in laboratory experiments:

o The range of equivalence ratio at which optimum emissions is achieved in a premixed system is limited. With two independent stages this type of combustor can be designed to two operating conditions but high emissions or inadequate stability will be encountered at other points in the operating envelope. Consequently, a variable geometry system is required to achieve the desired stoichiometry control over the entire operating envelope.

- The degree of mixture homogeneity and the extent of prevaporization is limited compared to that achieved in the more idealized premixed systems. More extensive development of the premixing components, possibly in conjunction with external preheating of the fuel will be required to achieve the degree of premixing necessary to accomplish the full NO_x reduction potential of the premixed prevaporized concept.

Recognizing these and other technology voids and the potential benefits of premixed combustion in the areas of emissions and smoke control, NASA is currently conducting the Lean Premixed-Prevaporized Combustor Technology (LPPC) Program (Reference 8) which will provide the technology base necessary to exploit the full potential of the premixed combustion concept in a variable geometry configuration compatible with the operating requirements of a flight engine. It is anticipated that the technology evolved in this program will provide the basis for the design of the premixed combustors that could be introduced into service in the time period when ERBS fuel is projected to be in use for commercial aircraft operation. Lacking this information, it was necessary to make several assumptions with regard to the design of the reference premixed combustors for the present study. These included:

- The basic configuration of Figure 3-7 was an adequate description of the LPPC technology combustor from the point of view of the liner and flameholder configuration. This design, and its corresponding scaled version for the Energy Efficient Engine would be adequate for evaluating the effect of changes in fuel composition on such design parameters as liner heat load, overall airflow distribution, flameholder stability and ignition.

- The front end of the advanced technology combustor; including all components upstream of the flameholder; would be substantially different from the configuration of Figure 3-7 in that it would include variable geometry components incorporating more advanced and yet to be defined fuel preparation and premixing concepts. Consequently, the effect of fuel composition on design parameters such as autoignition, mixture homogeneity and vaporization could only be assessed in a general sense and not in terms of specific designs.

- For the purposes of projecting the emissions characteristics when operating on Jet A fuel, it was assumed that, at high power levels, the performance of the advanced technology premixed combustor would approach that of the idealized laboratory combustors and the data of Reference 9 was used as the reference.

At low power levels, such as idle, the inlet air temperature is below the boiling point of many of the less volatile constituents of the fuel and it was assumed that the degree of prevaporization that could be achieved with even the advanced technology design concepts would be limited. Consequently, the performance of the staged combustor of Figure 3-7, as documented in Reference 4, was selected as the reference for the premixed combustors when operating on Jet A fuel at low power levels.

4.0 BACKGROUND SURVEY

4.1 INTRODUCTION

The study was initiated with a survey of prior experience in the use of alternate fuels in gas turbine combustors and of fundamental research into the effect of variations in the composition and properties of hydrocarbon fuels on combustion mechanisms. The objective of this survey was threefold:

- From measurements obtained on the performance characteristics of gas turbine combustors operating on various fuels, derive influence coefficients that could be used to predict the incremental changes in the performance, durability, and emissions of the study combustors when operated on ERBS rather than Jet A fuel.
- To define new design criteria or modify existing criteria for use in revising the configuration of the study combustors to correct deficiencies in the performance, durability, and emissions or reliability of those combustors associated with the use of ERBS.
- By examining the fundamentals of the combustion mechanism and their influence on the performance of gas turbine combustors, differentiate between the aspect of fuel composition that impose fundamental limitations on the performance of the combustor and those that are ammendable to resolution through changes in design philosophy or development.

Because of the volume and diversity of topic areas of the literature on alternate fuels and combustion processes, a computerized literature survey was conducted to collect the relevant background material. The majority of the references were collected through the Dialog computerized retrieval system maintained by Lockheed Aircraft Corporation with access through the computer system at United Technologies Research Center. Most of the search was conducted in three files: the Engineering Index and the National Technical Information Service; both of which include primarily information published in the United States; and the Institution of Mechanical Engineers which includes mostly material generated in Great Britain. Other files searched included Chemical Abstracts and the Energy Research and Development Administration files. In addition, the results of a search conducted by the National Aeronautics and Space Administration for the Government Products Division of Pratt & Whitney Aircraft Group in August 1977 was consulted.

In conducting the search the key words and topic areas were kept as general as possible to avoid excluding material of potential relevancy and the total number of citations produced by these searches was approximatly 6000. As expected, the majority of the useful information came from a small number of sources -- about 50 documents -- and most of these have been cited as references in this report.

In the following parts of this section, the critical aspects of gas turbine combustor performance and operation are discussed in the context of the effect of a change in fuel specification. Data obtained with a wide range of fuels is generalized to predict the impact of a relaxation of the fuel specification from the current Jet A to ERBS. Sections 4.2 and 4.3 include the fundamental aspect of the combustion chemistry, fuel properties and atomization. Emissions and smoke are discussed in Sections 4.4 and 4.5 while the effect of fuel composition on liner heat load is evaluated in Section 4.6. Ignition and the stability of the combustion process are reviewed in Sections 4.7 and 4.8, respectively. Section 4.9 includes a discussion of fuel thermal stability, and the effect of fuel composition of the design of fuel-air premixing systems is evaluated in Section 4.10.

4.2 FUEL PROPERTIES

Changes in the chemical composition of the fuel can alter the progression and eventual output from the combustion process. The energy released in combustion varies with the fuel composition and measurements of the heat of combustion of fuels derived from petroleum, shale and coal sources (Reference 10) indicate a decline in heating value of 1.16 percent for a reduction in the hydrogen content of one percent below the nominal 13.7 percent by weight in Jet A, a rate that is consistent with basic stoichiometry computations. In the case of ERBS, with anticipated hydrogen content of 13 percent, this results in a 0.8 percent reduction in the heat of combustion. Since the specific fuel consumption of engines is related directly to fuel heating value even a small decline in heating value can be of concern. In the definition of engine performance guarantees, fuel consumption is based on the minimum heat of combustion stipulated by the appropriate fuel specification, and the assumed properties for Jet A and ERBS on Table 2-II are identical in that both have a nominal heating value of 42.8×10^6 joules/kg. In this respect, the fuels are comparable for use in specific fuel consumption definition but, in reality, Jet A fuel has been supplied at heating values somewhat above the minimum; of the order of one percent; as it must if the hydrogen content is maintained at the 13.7 percent level. As indicated above, ERBS with 13 percent hydrogen would have a 0.8 percent lower heating value than Jet A, placing it extremely close to the specification limit. Consequently, the use of ERBS would not only impose a small reduction in in-service specific fuel consumption but also a greater potential for the production of deviate fuel with below specification heating value.

The effect of fuel composition on the flame temperature is also of interest because the latter dictates local reaction rates and is the source temperature for radiant heat transfer to the upstream components of the combustor liner. While the heat of combustion is expected to decrease slightly when the fuel hydrogen content is decreased the flame temperature can increase because the hydrogen reduction implies a shift in fuel composition toward more unsaturated compounds which are less stable and absorb less energy in decomposition to combustible molecules. Consequently, additional energy is available to heat the combustion products.

Computations were made, using the equilibrium composition analysis of Reference 11 to define the dependence of flame temperature on fuel composition. Because conventional combustors operate in essentially a diffusion burning mode, with the bulk of the reactions occurring at or near stoichiometic proportions the initial calculations were made at an equivalence ratio of unity. An additional mechanism increasing the flame temperature occurs at this condition because the stoichiometric fuel air ratio increases with decreasing hydrogen content. Figure 4-1 shows the results of this computation for combustor inlet conditions corresponding to takeoff and idle operation of the JT9D-7 and the Energy Efficient Engines. The results indicate that the change in fuel composition and the stochiometric fuel air ratio offset the reduced heat of combustion and lead to increases in the stoichiometric flame temperature with decreasing hydrogen content. The same trend is also evident in the results computed for an equivalence ratio of 0.5. Another analysis, reported in References 12 and 13, projected similar results for the maximum flame temperature in a combustor operating at takeoff conditions of the JT8D engine. While the increments of flame temperatures are small, being only about 7^{o}K for the Jet A to ERBS composition differences, it will be demonstrated that they provide reasonable correlation of observed changes in NO_x emissions from test combustors.

Physical properties of the fuel, such as viscosity, specific gravity and surface tension are of significance because of their impact on fuel atomization, metering of fuel in the control system and its lubricating and heat transfer properties. Values of these properties were computed over a range of fuel temperatures using the procedures of Reference 14 and are shown on Figure 4-2. The variation of viscosity with temperature is significant to atomization at cold engine starting conditions and the projection is shown to be in agreement with the specification limit of 12 centistokes at 250^{o}K.

4.3 ATOMIZATION

The differences in the physical properties of the fuel identified in Section 4.2, can influence the atomization processes in the fuel injector. Based on the data of Reference 15, the Sauter mean diameter (SMD) of the spray produced by a pressure atomizing injector is correlated in the form:

$$\mathrm{SMD} = K \frac{W_f^{0.25} \quad \nu_f^{0.20} \quad \sigma_f^{0.60}}{\Delta P^{0.40}} \tag{1}$$

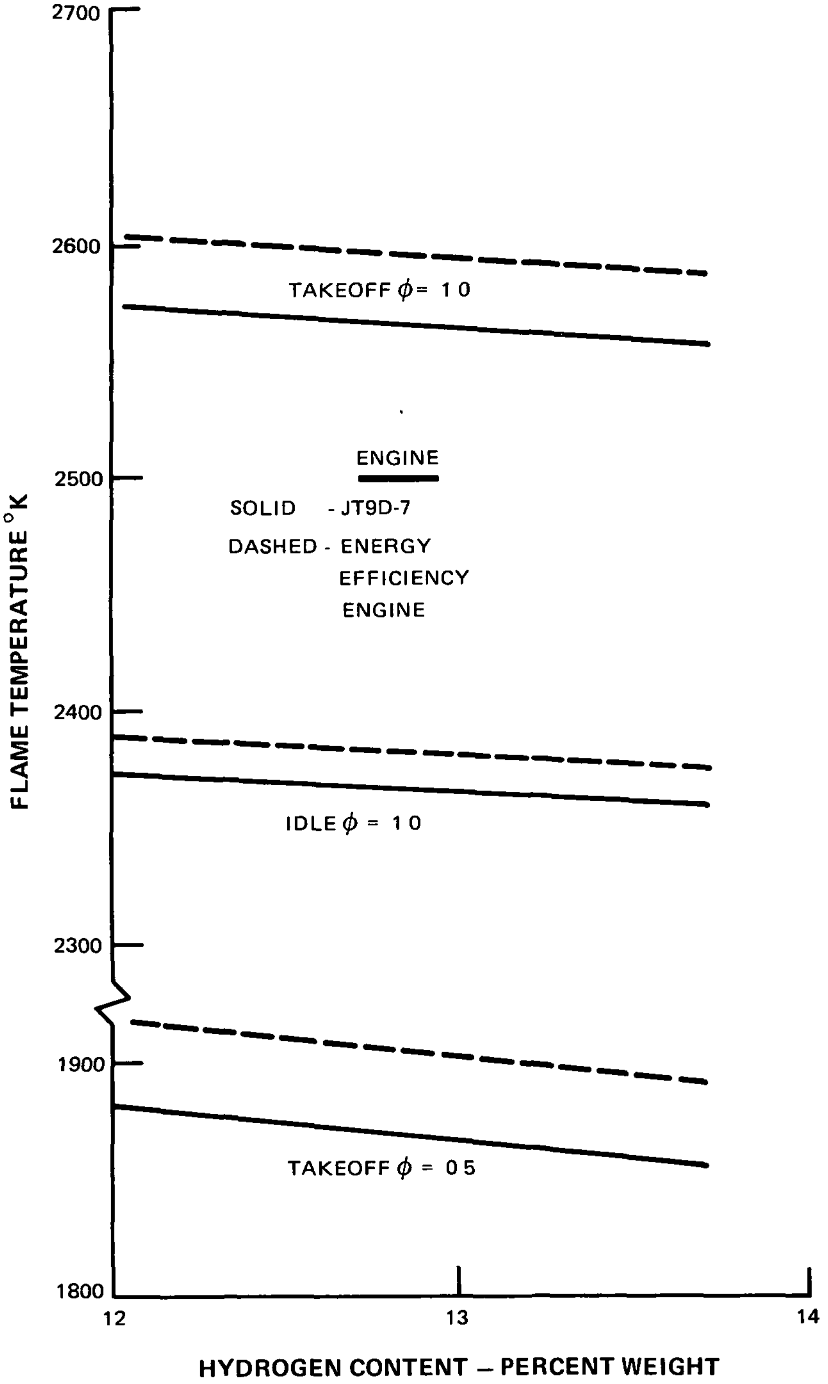


Figure 4-1 Effect of Fuel Hydrogen Content on Flame Temperature

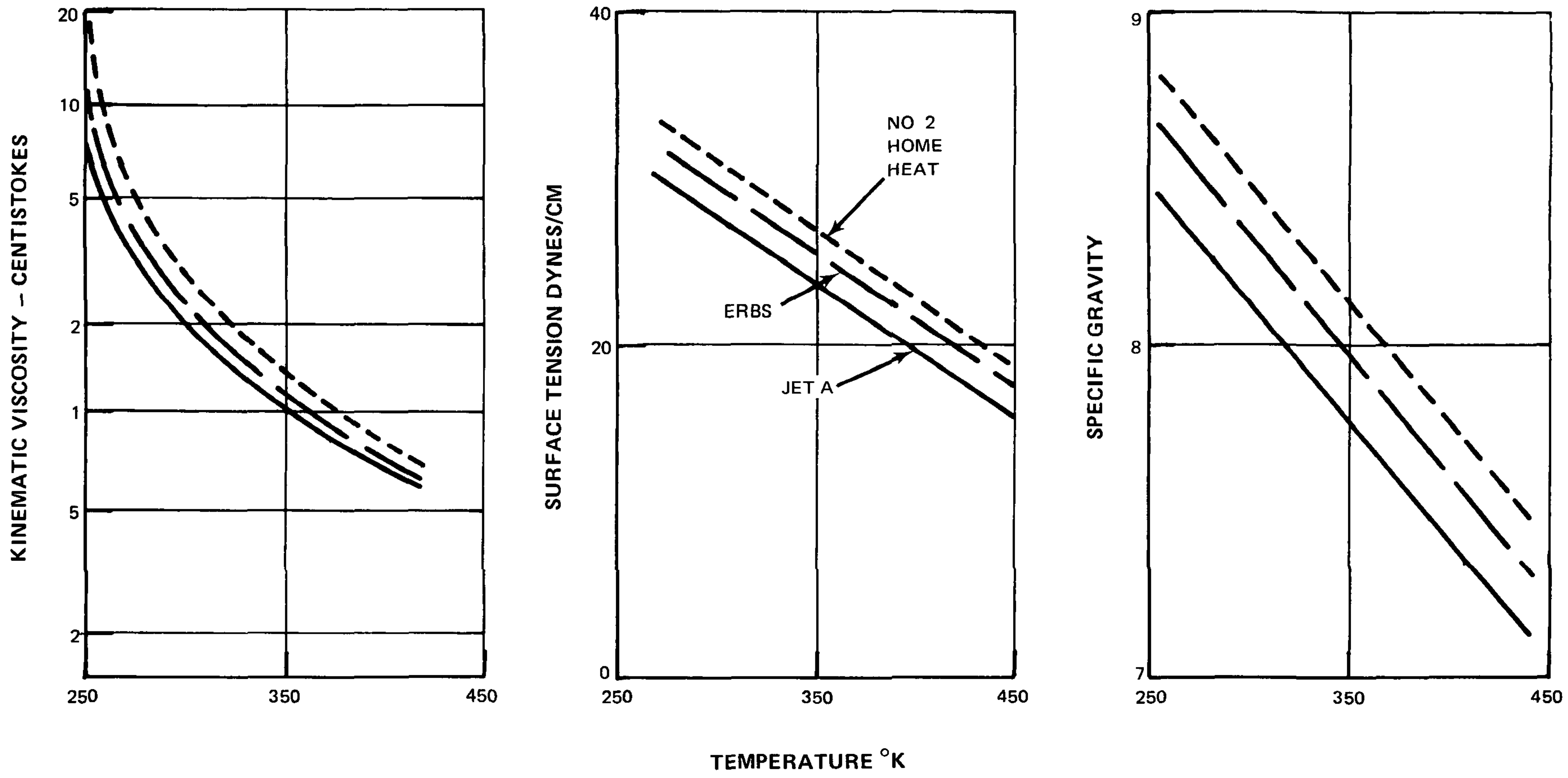


Figure 4-2 Physical Properties of Fuels

where the constant of proportionality K is dependent on injector geometric parameters such as spray angle and metering passage configuration. Other investigations (Reference 16) have confirmed the critical parameters of Equation 1 and magnitude of the exponents. Since both the surface tension and kinematic viscosity of ERBS are higher than those of Jet A, an increase in SMD, or equivalently a deterioration in atomization, is anticipated with the use of this fuel. Additional changes in atomization can result from the influence of the injector pressure drop term in Equation 1. The pressure drop is a combination of that due to frictional losses in the metering passages of the injector; and consequently dependent on the fuel viscosity; and the kinetic energy of the discharged fuel spray. Since only the latter component contributes to the atomization process, the ratio of these components are incorporated in the constant K. If it is assumed that the discharge kinetic energy of the fuel spray is the dominant component, it is related to the injector flow in the form:

$$\Delta P = \frac{W_f^2}{2g_c \quad A_N \quad \rho_f} = \frac{W_f^2}{2g_c \quad A_N \quad \rho_{H_2O} \quad \gamma_f} \qquad (2)$$

where A_N is the effective flow area of the discharge orifice of the injector. If A_N is not adjusted to compensate for the higher specific gravity of ERBS relative to Jet A, the pressure drop required to inject a fixed mass flow rate of fuel will decrease and as implied by Equation 1, further deterioration in atomization will occur.

The magnitude of the total deterioration in atomization has been estimated using the fuel properties derived in Section 4.2 and is shown on Figure 4-3. At fuel temperature levels encountered during normal engine operation, the SMD of the spray increases by 8 to 9 percent with the use of ERBS rather than Jet A while more severe atomization deterioration is shown at the lower fuel temperatures that are representative of those encountered in starting a cold engine when the fuel will be at essentially ambient temperature. The effect of variation in the injector pressure drop because of differences in the specific gravity of the fuels is shown to be small compared to that produced by the differences in viscosity and surface tension. Only a one to two percent difference in SMD deterioration is shown between an injector originally sized for operation on Jet A and subsequently operated on the more dense ERBS fuel as opposed to one that has been resized to reproduce the original flow rate - pressure drop characteristics when operated with ERBS. For comparative purposes the corresponding atomization characteristics for an injector operating on No. 2 Home Heat fuel are shown on this figure. Similar trends are evident but the magnitude of the deterioration in atomization is about double that projected for ERBS fuel.

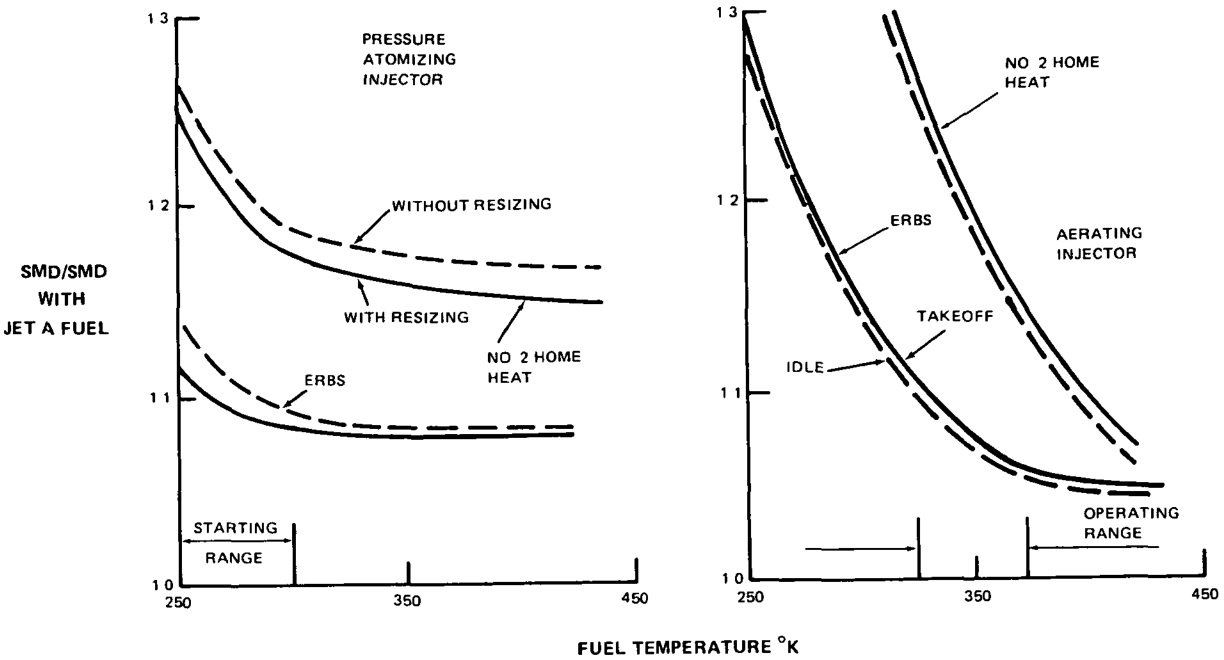


Figure 4-3 Effect of Fuel Composition on Atomization

In the event this deteriorated atomization is projected to have an adverse effect on the performance or emissions of the combustor, the injector could be redesigned to enhance atomization with ERBS. As indicated by Equation 1, the most evident approach is to increase the pressure drop across the injector by restricting the size of the flow passages. An increase in pressure drop of 20 to 25 percent would be required to offset the effect of the increased surface tension and viscosity and achieve the same SMD produced in the original injector with Jet A. However, such an increase in injector pressure drop significantly affects engine design because it requires higher fuel supply pressures with associated impact on fuel pump size and life and fuel manifold weight. The smaller metering passages in the injector would also be more susceptable to clogging. Furthermore, there is some evidence that, at high pressure levels, increases in the injector pressure drop will not produce the improvement in atomization projected by Equation 1. This equation, as well as most other correlations of atomization characteristics are based on data obtained in an atmospheric pressure environment. Measurements in a pressurized environment, such as those of Neya and Sato (Reference 17) indicate that the SMD produced by a pressure atomizing injector may increase with increasing pressure drop. This phenomena has been attributed to the increased drag on the fuel droplets; produced by the higher ambient density; which reduces the dispersion of droplets and collapses the spray angle allowing some droplets to coalesce. Other alternatives to improving atomization from a pressure atomizing injector include use of a different injector configuration having a lower value of the constant K in Equation 1 and, in the context of a major redesign of the combustor section, increasing the number of injectors in the combustor to reduce the per injector fuel flow. In general, it appears that it would be possible to improve the atomization characteristics of pressure atomizing injectors to the extent necessary to offset the adverse effect of higher viscosity and surface tension of ERBS fuel. However, this could involve not merely resizing of the injector, but redesign of the fuel system, use of a new combustor configuration or a significant injector development effort.

In the aerating fuel injector the fuel is atomized by shearing a thin film of fuel with high velocity air streams - the latter being generated by the air pressure drop across the front end of the combustor. As opposed to pressure atomizing injectors, the atomization characteristics of aerating injectors are dependent on the physical properties of the atomizing airflow as well as those of the fuel. The literature survey revealed reports of several experiments in which the atomization characteristics of aerating type injectors were assessed and correlated. The data accumulated by Rizkalla and Lefebvre (References 18 and 19) are of particular interest because the injector configuration was most representative of those employed in gas turbine applications and the tests were extremely comprehensive in nature, including extensive variations in the properties of the atomized liquid. The range of specific gravities tested was from 0.78 to 1.5 while the viscosity varied between 1.3 and 218 centipoises and surface tension between 24 and 73 dynes/cm. The tests were conducted in two series, the first of which was an atmospheric pressure and temperature environment (Reference 18) and the results were correlated in the form:

$$\mathrm{SMD} = \frac{\sigma_f^{0.5}\ \rho_f^{0.75}}{V_a}\left(1 + \frac{W_f}{W_a}\right) + 0.37\ \mu_f^{0.85}\ (\sigma_f\ \rho_f)^{1.2}\left(1 + \frac{W_f}{W_a}^{2}\right) \quad (3)$$

In the second series of tests (Reference 19), the atomization air pressure and temperature were also varied, over ranges of 1 to 8.5 atmospheres and 294 to 424°K respectively, and a somewhat different correation generated:

$$\mathrm{SMD} = \frac{6.5\mathrm{x}10^{-4}(\ \sigma_f\ \rho_f)}{\rho_a\ V_a}\left(1 + \frac{W_f}{W_a}\right) + 1.2\mathrm{x}10^{-4}\left(\frac{\mu_f^{2}}{\sigma_f\ \rho_a}\right)^{0.425}\left(1 + \frac{W_f}{W_a}\right)^{2} \quad (4)$$

As in the case of the pressure atomizing injectors, increases in the surface tension, viscosity and density of the fuel, all of which occur in the transition from Jet A to ERBS fuel, lead to an increase in the Sauter mean diameter of the spray.

Computations were made of the deterioration of the atomization of aerating fuel injectors using Equation 4 and the values of the physical properties of the fuel from Figure 4-2. The results are shown on Figure 4-3 where the Sauter mean diameter of the spray, relative to that produced at similar conditions which Jet A fuel are shown as a function of fuel temperature. For comparison purposes, the atomization quality with No. 2 Home Heat oil is also shown. The data were computed for injectors in a JT9D engine using 6.5 percent of the combustor airflow for atomization with a 4.3 percent pressure drop across the burner front end. Calculations were made for the takeoff and idle operating conditions of the JT9D as listed in Table 3-1 and, as shown on the figure, the relative deterioration in the atomization is essentially identical at these conditions. At the fuel temperatures encountered in normal engine operation the aerating injector is slightly less sensitive to the physical properties of the fuel than the pressure atomizing injector, having increases in SMD of 6 to 10 percent. However, as the fuel temperature is decreased into the range encountered in engine starting the deterioration in atomization is substantially higher reaching levels of about 30 percent at 250°K (6°K above the freezing point of ERBS). Similar trends, with a higher magnitude of deterioation are evident for the No. 2 Home Heat fuel.

Modification of the aerating injector to enhance atomization involves changes to the atomization air stream. Equation 4 indicates this may be accomplished by increasing the atomizing airflow and/or its velocity. The latter is related to the front end pressure drop and attempts to improve atomization in this manner could compromise combustor section pressure loss. However, the injector airflow may be increased by increasing its physical size. Figure 4-4 shows the increase in airflow required to reduce the SMD to that produced with Jet A fuel. In the case of ERBS fuel at normal engine operating fuel temperatures in the range of 325 to 365°K, an increase in the atomizing airflow of 25 to 50 percent appears adequate to return the atomization quality to a level consistent with that produced with Jet A. At low fuel temperatures, the results indicate substantially larger increases in atomizing airflow would be required to accomplish such an improvement and the practical limitations on increasing the airflow; i.e., the physical size of the injector becoming too large and the ability to have all of the injector airflow in intimate contact with the fuel film; would be exceeded.

Comparative measurements of the atomization characteristics of aerating and pressure atomizing injectors has shown that aerating injectors are capable of providing a fine spray - of the order of a 30 percent lower SMD - than a pressure atomizing injector. Lebefvre, et al (Reference 20) have performed comparative computations with fuels of varying composition and demonstrated that this advantage is valid over a wide range of fuel properties. Consequently, the substitution of aerating fuel injectors for pressure atomizing injectors can be considered an additional means for improving the atomization of ERBS fuel.

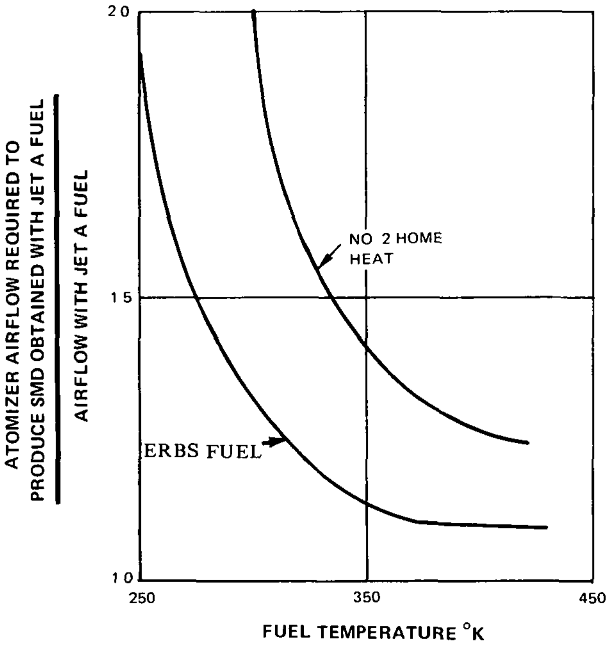


Figure 4-4 Atomizing Airflow Required to Obtain Same Atomization as Jet A Fuel

In summary, the following criteria and considerations are of significance relative to the atomization of ERBS fuel:

o With pressure atomizing injectors the use of ERBS will produce 8 to 14 percent increases in the SMD of the fuel spray relative to the same injector operating on Jet A with the higher deterioration occurring at the low fuel temperatures associated with engine starting. While correlations indicate this deterioration may be offset by increasing the injector pressure drop, more extensive injector or fuel system modifications might be necessary to accomplish this improvement.

o Aerating fuel injectors appear to offer the advantage of finer atomization than pressure atomized injectors. While they have comparable sensitivity to fuel properties in the range of fuel temperatures encountered in normal engine operation, the atomization may be improved by increasing the atomizing airflow. At low fuel temperatures the atomization produced by aerating injectors is much more sensitive to fuel properties and increasing the injector airflow does not appear to be an expedient means of enhancing atomization at these fuel temperature levels.

o With their apparently superior atomization characteristics, aerating fuel injectors could be substituted for pressure atomizing injectors and the improved atomization at engine operating fuel temperatures would more than offset the adverse effects of the physical properties of ERBS relative to Jet A fuel. However, their increased sensitivity to fuel properties at low fuel temperatures could comprise altitude relight and cold starting.

4.4 EMISSIONS

Emissions measurements have been obtained on a number of production and experimental aircraft gas turbine combustors operating on both conventional Jet A or JP-5 fuel and various alternate fuels; the latter generally including diesel, home heating oil and blends selected to produce specific composition variations. The majority of this data was obtained under the Alternate Fuels Addendums to the Experimental Clean Combustor Programs (References 21 and 22); which involved testing of experimental low emissions combustors designed for compatibility with the JT9D-7 and CF6-50 engines; and from the evaluation of JT8D combustors at NASA-Lewis Research Center (References 12 and 13). Limited additional data obtained on a T-56 engine combustor (Reference 23) and on other experimental combustors (Reference 24) was also discovered during the literature survey. In all of these investigations, the combustor geometry and operating conditions were maintained fixed and the test fuel was varied, i.e., no attempt was made to optimize the operating conditions or reconfigure the combustors for different fuel compositions. The tests were generally conducted at conditions representative of idle and takeoff operation of the appropriate engine, but those on the JT8D combustor also included simulated cruise conditions.

For the purposes of this study, the data was examined with two objectives. The first was to detect trends in the data that would indicate the mechanisms causing the change in emissions level with fuel composition. After identification of these mechanisms design modifications could be recommended to offset adverse changes in emissions or reduce the sensitivity of the combustion process to the particular mechanism. The second objective was to define influence coefficients that would be indicative of the change in the emissions indices when a particular combustor; designed for operation on Jet A fuel; was operated with ERBS.

The hydrogen content was selected as the principle variable reflecting fuel composition. While it will be demonstrated in Section 4.5 that hydrogen content is not a sufficiently specific parameter to correlate the smoke formation characteristics of the fuel, the limited extent of the emissions data and the complexity of the combustion mechanisms necessitates this simplification. Figure 4-5 shows a representative set of data correlated in this manner -- the data being that obtained for the carbon monoxide emissions from a Vorbix combustor operating at simulated JT9D-7 idle condition (Reference 21). (The properties of the test fuels used in the program of Reference 21 are listed on Table A-1 in the Appendix.) With the exception of the point obtained when operating on a blend of Jet A and naphthalene this data correlates well with hydrogen content and indicates a specific incremental increase in carbon monoxide emissions that may be associated with the operation of this combustor on ERBS fuel. From this increment an influence coefficient α is defined in the manner:

$$EI_{ERBS} = \alpha \ EI_{JETA} \qquad (5)$$

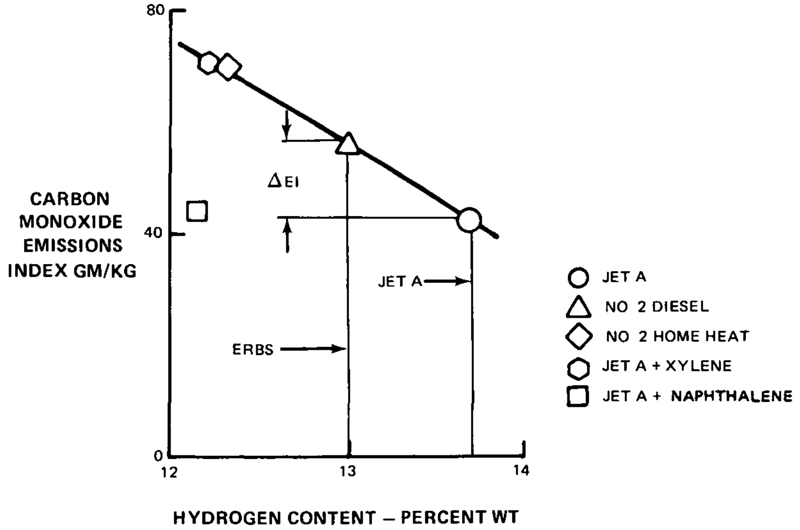


Figure 4-5 Representative Correlation of Emissions With Fuel Hydrogen Content (Vorbix Combustor of JT9D Idle)

In general, the data obtained on the unburned hydrocarbon emissions at idle operation revealed the poorest correlation with the hydrogen content of the fuel and was analyzed to establish the correct parameters and trends. Figure 4-6 shows idle unburned hydrocarbon data from the Vorbix combustor of Reference 21 and demonstrates the inadequacy of hydrogen content as a correlating parameter. However, when plotted against the viscosity of the test fuel an excellent correlation is obtained. Since fuel viscosity is critical to atomization this result implies that the differences in unburned hydrocarbon emissions of this combustor are not due to changes in fuel chemistry as it affects the combustion processes, but rather due solely to differences in atomization of the fuel. Consequently, redesign of the fuel injectors to improve the atomization of more viscous fuels according to the approaches outlined in Section 4.3 could be expected to reduce the unburned hydrocarbon emissions to the same level encountered with Jet A fuel. In the event that the fuel injector is not redesigned, this correlation may be used to predict the increase in THC emissions through the use of the appropriate fuel viscosity.

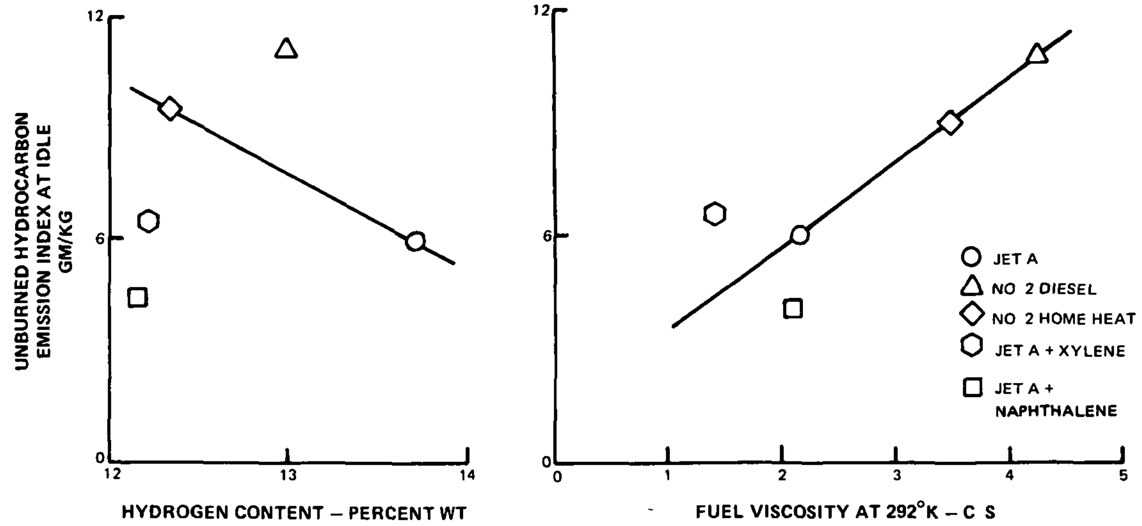


Figure 4-6 Correlation of Unburned Hydrocarbon Emissions From Vorbix Combustor at JT9D Idle

A similar sensitivity of the idle unburned hydrocarbon emissions to fuel atomization was evident in the data from a production CF6-50 and an experimental double annular combustor reported in Reference 22. Figure 4-7 shows the results from testing the double annular combustor with the viscosities of the test fuels indicated next to each data point. In this case the results indicate that the xylene and naphthalene fuel blends (which were similar in composition to those used in the Reference 21 tests) produced unexpectedly low THC emissions relative to their hydrogen content but that these fuels had low viscosities which would have enhanced their atomization. The diesel test fuel used in this experiment has a viscosity more consistent with its hydrogen content and it should be anticipated that, if this combustor is operated on ERBS without reconfiguring the fuel injectors, the increment in THC emissions should be defined by the line from this point to the JP-5 point. However, if the injector is redesigned to improve the atomization to the level produced with JP-5 fuel the characteristic will be flatter and the "improved injector" line shown on the figure was constructed based on a constant effective fuel viscosity of 1.56 cs.

The data on carbon monoxide emissions at idle generally correlated better with the hydrogen content of the fuel, with that of Figure 4-5 being representative. However, in some instances, most notably the Hybrid combustor of Reference 21 and the production CF-6-50 and double annular burners of Reference 22, the use of the blended xylene and naphthalene tests fuel led to lower emission levels than would be expected from the trend established by the other fuels. While the deviations are not as large as those observed in the case of the unburned hydrocarbon emissions they may be interpreted in the same context as the data of Figure 4-7 which implies that at least part of the increase in carbon monoxide emissions from these combustors may also be attributed to deteriorated atomization as opposed to being inherent in the fuel chemistry.

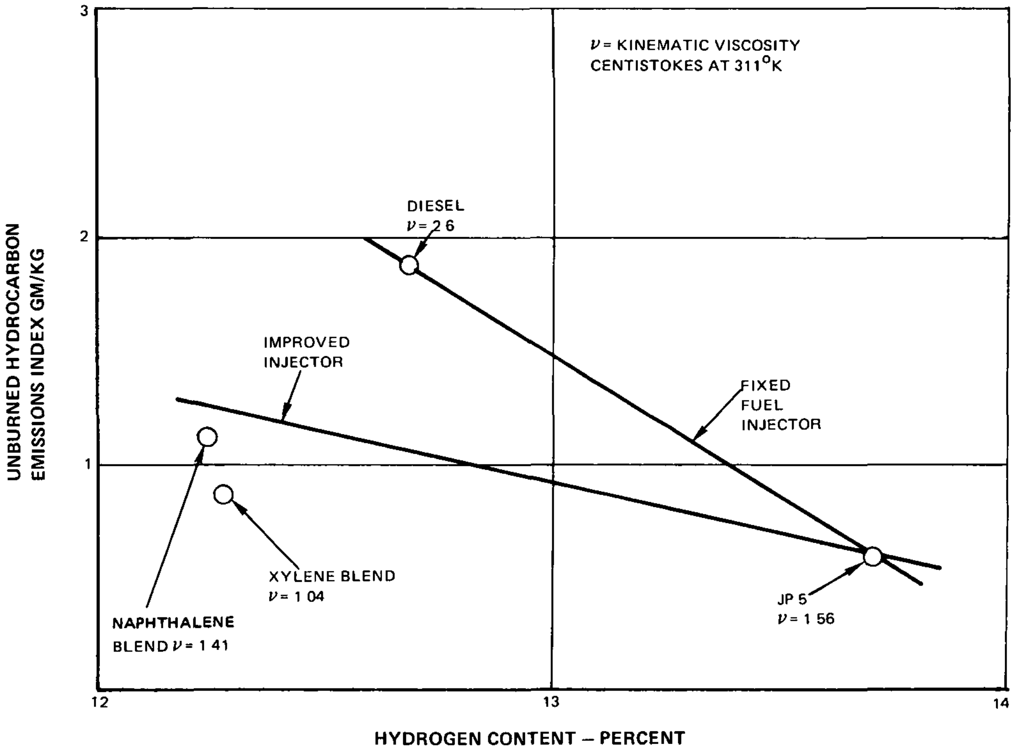


Figure 4-7 Unburned Hydrocarbon Emissions From Double Annular Combustor of CF-6-50 Idle Conditions

In general, the accumulated data obtained at idle conditions indicated that the emissions of both carbon monoxide and unburned hydrocarbons were more sensitive to fuel composition in the experimental low emissions combustors than they were in the more conventional type of combustor such as the JT8D burners of References 12 and 13. Measurements of carbon monoxide and THC emissions at simulated takeoff conditions indicated that in combustors with reasonable performance levels, the emissions concentration were not significantly affected by changes in fuel composition, variations in the carbon monoxide and THC emissions at these power levels do not contribute significantly to the overall emissions problem.

The available data also reveals a sensitivity of the NO_x emissions to the fuel composition with the emissions generally increasing with reduction in the hydrogen content of the fuel. The consistency of this trend with the increase in flame temperature with reduced hydrogen content, as cited in Section 4.2, suggests that this may be the governing mechanism. Kinetic analysis of the NO_x formation in a combustor leads to the following relation between NO_x emissions and flame temperature (Reference 25):

$$\frac{EI_{NO_x}}{EI_{NO_{x_{ref}}}} = \left(\frac{T_{fl}}{T_{fl_{ref}}}\right)^{-0.53} \exp\left(\frac{67,400}{T_{fl_{ref}}} - \frac{67,400}{T_{fl}}\right) \tag{6}$$

The majority of the combustors involved in the emissions data base employ a swirl stabilized primary combustion zone with direct fuel injection. In such a configuration the combustion occurs primarily in a diffusion burning mode with the majority of the reactions occurring at or near stoichiometric proportions. Using the computed flame temperatures at equivalence ratio of unity from Section 4.2, the variation in NO_x emissions with fuel hydrogen content was computed from Equation 6. The results of this calculation and the experimental data on NO_x emissions are shown on Figure 4-8 for both takeoff and idle operating conditions. While there are deviations of sizable proportions in some instances, the data from several of the combustors substantiate the rate of change of NO_x emissions predicted from Equation 6 and provide at least qualitative confirmation of the increased flame temperature as the significant mechanism causing the increased NO_x emissions.

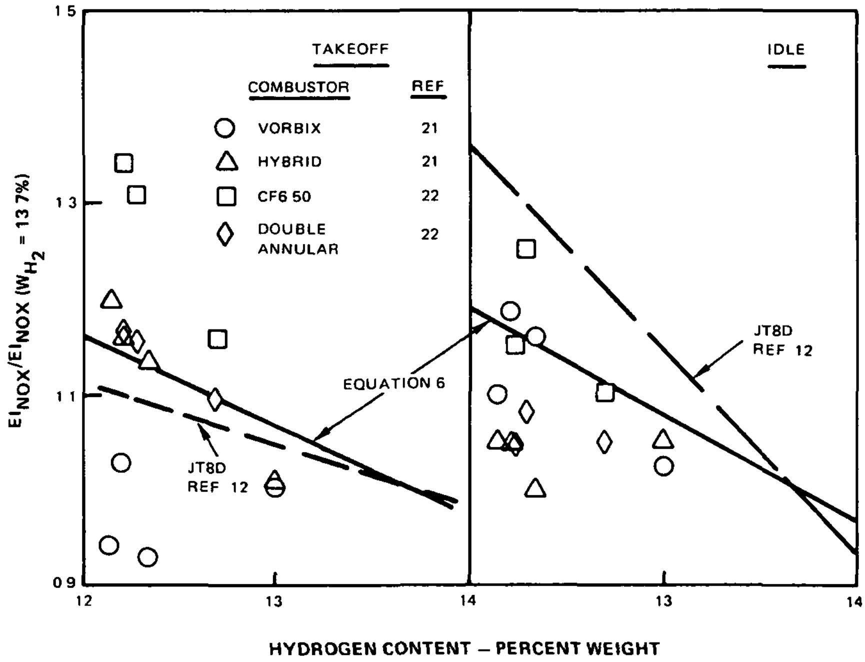


Figure 4-8 Effect of Fuel Composition of NO_x Emissions

This theoretical dependence of NO_x emissions on fuel composition through the flame temperature has unusual implications for advanced premixed-prevaporized burners. Since the combustion process in these burners occurs at essentially the equivalence ratio of the premixed system, rather than at locally stoichiometric proportions, the flame temperature will be lower and the nominal NO_x production significantly less than in the diffusion burning systems. At a representative premixed equivalence ratio of 0.5 the use of Equation 6 with the flame temperature data of Figure 4-1 indicates that combustion of ERBS fuel will produce a 21 percent increase in the NO_x emissions over that obtained with Jet A. This is about three times the sensitivity predicted with diffusion burning systems and must be attributed to the low nominal level of the flame temperature with fuel composition. While the higher flame temperature could be offset by operating at a leaner equivalence ratio, premixed prevaporized combustors are expected to be designed as close as possible to the lean stability limits and, until the rationale can be developed for improved lean stability margin (c.f., Section 4.8), this penalty must be accepted.

While the data shown on Figure 4-8 was obtained with fuels having low nitrogen content (less than 0.01 percent by weight) higher levels of fuel bound nitrogen can lead to substantial increases in NO_x emissions. If completely converted to NO_2, one percent fuel bound nitrogen would produce an emissions index of about 33 gm/kg beyond the thermal NO_x. Measurements on a T-56 combustor (Reference 23) have shown that the conversion efficiency is highest at the inlet air temperatures representative of idle operation; 400 to 550°K at which it reaches levels of 70 percent at nitrogen contents of 0.1%. Increased inlet temperature and higher fuel bound nitrogen contents reduce the conversion efficiency, but levels of 40 to 50 percent efficiency were still observed. Similar trends and levels of conversion efficiency were also deduced from the results of tests conducted on a CF6-50 combustor and reported in Reference 22.

While the tentative specification for ERBS fuel shown on Table 2-1 does not stipulate a limit on fuel bound nitrogen, for the purposes of this study it was assumed that nitrogen concentrations would be maintained consistent with the current Jet A composition and, consequently, does not create an additional NO_x generation situation. The fuel bound nitrogen problem may become more acute when fuels are derived from shale sources rather than the current petroleum feed stocks. However, as will be shown later in this report, high nitrogen concentrations may also have an adverse effect on the thermal stability of the fuel and the nitrogen content will, most likely, have to be reduced to sufficiently low levels to alleviate these stability problems that the impact on NO_x emissions will be of secondary importance.

The process of identifying incremental changes in the emissions constituents for each of the six combustors that would be analyzed during the design study required evaluation of experimental data in the form of Figures 4-5 through 4-8 and definition of the appropriate value of the influence coefficients as defined by Equation 5. To provide realistic estimates of these increments, they had to be made from data obtained on a combustor that was reasonably consistent with the configuration to which the influence coefficients would later be applied. The following considerations entered this selection:

Single Stage Annular Burner for JT9D-7 Engine

The production JT9D-7 combustor employs a duplex pressure atomizing fuel injector nearly identical to that used in the JT8D combustor of References 12 and 13. However, the stoichiometry of these combustors differ considerably with the primary zone of the JT9D combustor being much leaner. The data from the CF-6-50 combustor of Reference 22 appears to be a more realistic reference for projecting the sensitivity of the JT9D burner to fuel composition in that it has comparable primary combustion zone stoichiometry and, at least, a similar fuel injection system. Since the data from the CF-6-50 combustor indicates the potential for reduced sensitivity of the carbon monoxide and THC emissions through improved fuel atomization, influence coefficients for the situation where atomization of ERBS was comparable to that obtained with Jet A were also computed in the manner defined on Figure 4-7.

Single Stage Annular Burner for Energy Efficient Engine

This combustor is considered to employ an aerating fuel injector system and a rich primary combustion zone having a nominal equivalence ratio of about unity at idle to minimize the carbon monoxide and unburned hydrocarbon emissions. The low power stage of the double annular combustor of Reference 22 was optimized to a similar equivalence ratio for idle emissions control and also employed an aerating type of fuel injection system. Consequently, the data from this combustor was used to estimate the sensitivity of the Energy Efficient Engine single stage combustor to fuel composition at idle. The data from the double annular combustor also indicated potential reduction of the sensitivity of the low power emissions to fuel composition through improved atomization and influence coefficients for this situation were also derived from the data.

At takeoff power levels, the Energy Efficient Engine single stage combustor will operate with a primary zone equivalence ratio of about two which is comparable to that of the JT8D combustor evaluated in Reference 12 and that combustor was selected as the appropriate reference.

Vorbix Combustors

The fuel composition sensitivity of the Vorbix combustors for both the JT9D and Energy Efficient Engine cycles were determined from the data on the Vorbix combustor evaluated in the program of Reference 21. The unburned hydrocarbons emissions from this combustor were shown to correlate with fuel viscosity rather than hydrogen content implying that the sensitivity of this emissions constituent to fuel composition could be eliminated by improving atomization.

Premixed-Prevaporized Combustors

As indicated in Section 3-3, the performance of the staged premixed combustor and the Hybrid combustor evaluated under Phases I and II of the PWA-NASA Experimental Clean Combustor Program (References 5 and 6) is considered representative of that of an advanced premixed prevaporized combustor when operating at low power levels where the inlet air temperature is insufficient to sustain or produce a prevaporized fuel state. On this basis, the data from the Hybrid combustor of Reference 16 was used to determine the sensitivity of the idle emissions of the advanced premixed prevaporized combustor to fuel composition. The data from this burner revealed sensitivities to fuel viscosity that have been interpreted in the context of changes in atomization. However, in this type of premixed system the dominant source of atomization is uncertain. The fuel could be atomized at the injector and remain in a fine droplet state until the mixture enters the combustion zone or the droplets could impinge on the flameholder and reatomize off the edges of the flameholder. If the latter situation dominated, redesign of the fuel injector would not produce the expected reduction in sensitivity to fuel composition. The reverse situation was also noted in the THC emissions at idle in that the more viscous diesel and home heating fuels produced consistently lower THC emissions than the other test fuels. Because of these uncertainties and anomalies no attempt was made to project the effect of revised fuel injection on the sensitivity of the premixed prevaporized combustor.

In projecting the effect of a change of fuel composition on the high power emissions characteristics of the premixed prevaporized combustor, it would be desirable to employ data obtained on a research combustion rig of the type described in Reference 9. However, the literature survey did not reveal any experiments in which an apparatus of this type was used to investigate the effect of fuel composition on emissions. Since most of the combustors that were discussed previously were found to have minimal sensitivity of the high power carbon monoxide and THC emissions to fuel composition, it appeared reasonable to assume that an advanced premixed prevaporized combustor would have similar characteristics. The sensitivity of the high power NO_x emissions to fuel composition were determined from Equation 6 assuming that the flame temperatures would be those associated with premixed combustion at an equivalence ratio of 0.50.

Table 4-I presents a summary of the influence coefficients defining the sensitivity of the emissions to a change in fuel composition from Jet A to ERBS at idle and takeoff operating conditions. The design study of Section 5 required projecting the effect of fuel composition on the thrust weighted Environmental Protection Agency Parameter for the aircraft takeoff-landing cycle for which values of the influence coefficients were needed at the 85 percent thrust; climb; and 30 percent thrust; approach; conditions. The only available data obtained at intermediate power levels is that from the JT8D combustor of Reference 1 which was also operated at simulated cruise conditions. In terms of combustor inlet conditions and fuel air ratio, the cruise condition is similar to a point at about 40 percent rated thrust on the sea level operating line. The data of Reference 19 indicated that the sensitivity of the emissions to fuel composition at the cruise condition was essentially identical to that observed at takeoff. Consequently, it was assumed that at the climb condition the influence coefficients were equal to those at takeoff while the assumption of a linear variation in the magnitude of the influence coefficient between idle and 40 percent thrust permitted estimating the influence coefficients at approach.

TABLE 4-I

INFLUENCE COEFFICIENTS FOR EMISSIONS SENSITIVITY OF STUDY COMBUSTORS

	Combustor Type			
Idle	JT9D Single Stage	EEE Single Stage	Vorbix	Premixed-Prevaporized
CO	1.14 (1.05)	1.12 (1.03)	1.16	2.04
THC	1.16 (1.08)	1.46 (1.13)	1.66 (1.00)	0.75
NO_x	1.07	1.03	1.03	1.02
Takeoff				
CO	1.00	1.00	1.00	1.00
THC	1.00	1.00	1.00	1.00
NO_x	1.14	1.05	1.004	1.21

Numbers in parenthesis indicate improved atomization configurations.

In summary, the evaluation of the available emissions data has led to the following conclusions regarding the effect of relaxation of the fuel specification on emissions:

- Operation of a combustor designed for use of Jet A fuel on ERBS results in an increase in the low power emissions of carbon monoxide and unburned hydrocarbons. Correlation of the data with fuel viscosity, as well as hydrogen content, suggests that in some situations, part of the increase might be reduced by redesign of the fuel injector to improve atomization of the more viscous ERBS fuel.

- The NO_x emissions correlate qualitatively with increases in flame temperature caused by the reduction in hydrogen control of relaxed specification fuels. Increase in NO_x emissions from less than one half to more than twenty percent are projected when the study combustors are operated on ERBS fuel.

4.5 SMOKE

The majority of the investigations cited in Section 4.4 also involved measurement of the smoke formation in the combustors and this data was used in analyzing the effect of relaxing the fuel specification on smoke formation. The objectives of this analysis were identical to those of Section 4.4 namely; to identify mechanisms causing changes in smoke formation with fuel composition and to define influence coefficients relating the incremental change in smoke output to changes in fuel composition for the combustor configurations evaluated in the design study.

The approach employed was also similar to that used in the analysis of the emissions in that the experimental data was correlated against the hydrogen content. However, unlike the emissions characteristics, there is considerable evidence that hydrogen content, by itself is an inadequate parameter for correlation of the smoke formation propensity of a fuel. The smoke point test is perhaps the most fundamental experiment for isolating the effect of fuel chemistry on smoke formation. The apparatus consists of a simple wick type burner. As the wick is raised more surface area of the fuel wetted wick is exposed to the air and the quantity of fuel evaporated increases, producing a richer and higher flame. In operation, the wick height is progressively increased until smoke is observed above the flame. The height of the wick is called the smoke point of the fuel being evaluated. The fact that a smokefree flame can be produced at low wick heights and the qualitative correlation between flame height and equivalence ratio implies the existence of a threshold equivalence ratio for smoke formation that is a characteristic of the particular fuel.

Figure 4-9, reproduced from Reference 10, shows the variation of the smoke point with the aromatic content of the fuel. The test fuels used in generating this data came from diverse sources and included those made from shale oil, coal and tar sands as well as petroleum based fuels. The data indicate a consistent correlation in which the smoke point decreases with increasing aromatic content implying that the aromatic constituents exert a dominant influence on smoke production and that lean equivalence ratios, i.e., lower wick heights, are required to avoid smoke formation with fuels that have high concentrations of these constituents. The data also indicate that a group of six of the test fuels do not fit the correlation well. These fuels have aromatic contents of less than ten percent and would have been expected to produce smoke points in excess of thirty millimeters, but the test results revealed that smoke was already visible at wick heights of about twenty millimeters. These six fuels were unique in that, while the aromatic content was low, they consisted of more than eighty percent cycloparaffins. These hydrocarbons have the carbon ring structure similar to aromatics rather than the chain structure of paraffins and all of the carbon atoms are saturated with hydrogen. These saturated bonds are weak and promote the stripping of the hydrogen with the resultant formation of free carbon. Based on this evidence it must be concluded that the inherent smoke formation propensity of a fuel is dependent, not only on its overall aromatic content, but also on the other constituents.

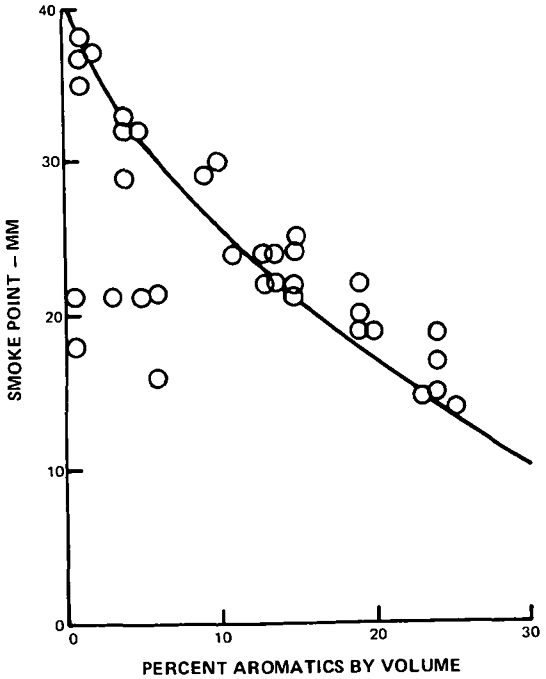


Figure 4-9 Effect of Aromatic Content on Smoke Point

Further evidence of the dependence of smoke formation on the detailed composition of the fuel was found in the testing of the Vorbix combustor of Reference 21. Figure 4-10 shows the variation of smoke number observed with four different test fuels at conditions simulating takeoff operation of the JT9D engine except that the inlet total pressure level was reduced to about 6.8 atmospheres. Table 4-II shows the composition of these fuels and further details on the properties are provided in Table A-1 in the Appendix. The xylene blend has a very high aromatic content but most of these are of the single carbon ring type. In contrast the naphthalene blend has an aromatic content similar to the home heating fuel but the blending stock had a high concentration of naphthalenes which have double carbon ring structures.

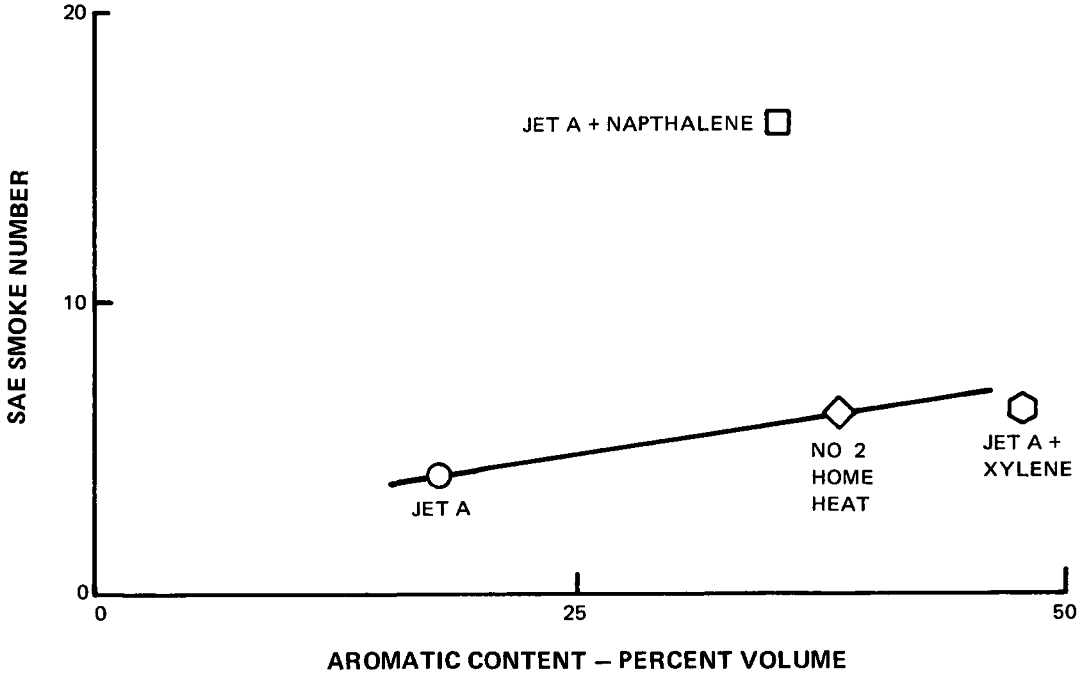


Figure 4-10 Effect of Fuel Composition on Smoke Produced by Vorbix Burner

TABLE 4-II

COMPOSITION OF TEST FUELS

Fuel	Jet A	Home Heat	Jet A +Xylene	Jet A +Naphthalene
Percent Hydrogen (wt)	13.71	12.33	12.20	12.15
Percent Aromatics (vol)	18.0	38.5	47.9	35.5
Percent Naphthalenes (vol)	2.1	10.9	1.3	16.2

The data of Figure 4-10 indicate a correlation of increasing Smoke Number with increasing aromatic content but several anomalies exist. Based on the trend of increasing smoke formation established by the Jet A and home heating fuels a higher smoke level would be anticipated from the xylene blend because of its substantially higher aromatic content. In addition, the naphthalene blend produced more than twice the Smoke Number of the home heating fuel despite a slightly lower aromatic content. The source of these deviations is, in this case, the types of aromatics in the particular fuels. As shown on Table 4-II, the naphthalene content of the xylene blend was very low and despite a high aromatic content most of these aromatics were of a single ring structure. Nearly half of the aromatics in the naphthalene blend were naphthalenes with the more complex double ring structure. While the data do not imply that naphthalene content be selected as the correlating parameter, it does support the conclusion that the types as well as the overall level of aromatics are significant and that the presence of high concentrations of the more complex multi-ring aromatics increase the propensity for smoke production.

On the basis of these data, it is apparent that while, of necessity, hydrogen content must be used as the characteristic parameter of the fuel for the purposes of this analysis, the smoke formation propensity of hydrocarbon fuels is strongly dependent on more detailed aspects of its composition. Consequently, in examining the data from various test combustors, an effort was made to concentrate the establishment of trends on the basis of measurements obtained with fuels having overall compositions representative of their hydrogen content. In this context, in assessing the data obtained during the Alternate Fuels Addendum to the Experimental Clean Combustor Program (References 21 and 22), more weight was given to the diesel, home heat, Jet A and JP-5 fuels and the naphthalene and xylene blends were considered relevant only in a manner consistent wth their unusual composition.

In defining the influence coefficients for projecting the incremental change in smoke output when the study combustors were operated on ERBS, rather than Jet A fuel, the data from the same reference combustor selected in Section 4.4 for the emissions projections was employed. The only exception was the definition of the sensitivity of the single stage combustor for the JT9D engine at takeoff power level. The influence coefficients for sensitivity of the emissions were based on data from the CF-6-50 combustor, but because of the low pressure level at which the tests were conducted the nominal magnitude of the smoke number at takeoff was extremely low. Because the accuracy of differentials would be questionable at these conditions, the data from the JT8D combustor of Reference 12 was used to define the influence coefficient at takeoff for this combustor despite the differences in primary combustion zone stoichiometry between these combustors.

As in the case of the emissions, no data was available on the sensitivity of the smoke production from a lean premixed prevaporized combustor to fuel composition. Since these combustors have been shown to have inherently very low smoke production, it is not likely that a change in fuel specification to ERBS would increase the smoke output to a level of concern.

Table 4-III lists the influence coefficients for smoke production sensitivity of the study combustors. Since experience with the study combustor types indicates that the maximum smoke output usually occurs at takeoff, no attempt was made to interpolate the data to intermediate power levels. However, influence coefficients for idle conditions are shown because they reveal some unusual trends. While the increases in smoke output associated with the use of ERBS as opposed to Jet A fuel are relatively moderate at takeoff, the data bases used to project the idle sensitivity of the single stage combustors indicate a very strong sensitivity to fuel composition and could imply that the idle condition may become the more critical operating condition. Examination of this data indicates the same type of sensitivity of the smoke number to fuel viscosity that was shown on Figure 4-7 with the xylene and naphthalene blends producing much lower smoke numbers than would be anticipated from their composition. As in the case of carbon monoxide and unburned hydrocarbon emissions from these combustors, it appears that this viscosity sensitivity reflects deteriorated atomization and alternative values of the influence coefficients have been derived based on improved fuel injector design.

TABLE 4-III

INFLUENCE COEFFICIENTS FOR SMOKE SENSITIVITY OF THE STUDY COMBUSTORS

	Combustor Type			
	JT9D-7 Single Stage	EEE Single Stage	Vorbix	Premixed Prevaporized
Smoke Number				
Idle	4.5 (3.2)	2.35 (1.2)	ND	ND
Takeoff	1.15	1.15	1.09	ND

ND = No data available

Numbers in parenthesis are with improved atomization.

Based on these observations, the following conclusions are drawn regarding the effect of relaxing the current Jet A fuel specification:

- Smoke formation is strongly dependent on the detailed composition of the fuel including not only the fractional aromatic content but also the composition of both aromatic and nonaromatic constituents.
- When estimated on the basis of data from fuels having compositions representative of those currently derived from petroleum feedstocks, the use of ERBS fuel in direct injection type combustors is projected to result in a nine to fifteen percent increase in the Smoke Number at high thrust levels.
- Data from some of the combustors reveals that the smoke formation at idle operating conditions is more strongly dependent on fuel composition, with the use of ERBS projected to lead to increases in SAE Smoke Number by factors of as much as four relative to that obtained with Jet A. The same data also indicate a sensitivity to fuel viscosity that could imply that the high smoke formation rate is caused, at least in part, by deteriorated atomization.

4.6 LINER HEAT LOAD

Increases in the aromatic content of the fuel can have a substantial impact on the radiant heat transfer to the combustor liner because of the increased concentrations of highly luminous carbon particulates in the combustion gases. This phenomena is most significant in the primary combustion zone where the local fuel/air ratios, particulate concentrations and gas temperatures are the highest.

The literature survey revealed considerable evidence of sensitivity of liner temperature to changes in the fuel composition. References 12, 13, 23, 26, 27 and 28 report results of tests conducted to measure the metal temperatures on louver cooled combustors at simulated high power engine operating conditions using fuels of varying composition. In each case, the measured liner temperatures were found to show correlation with the hydrogen content of the fuel. The increase in liner temperature varied widely between investigations with the increments equivalent to a change in fuel hydrogen content from 13.7 to 13.0 percent; corresponding to Jet A and ERBS respectively; being between a minimum of 10°K and as high as 50°K. The spread in temperature increases is obviously a function of operating environment, the louver design and the axial location of the thermocouple along the louver. Blazowski (Reference 23) has reduced the data scatter significantly by correlating it in terms of the liner temperature parameter:

$$\frac{T_L - T_{LO}}{T_{LO} - T_{TI}} \qquad (7)$$

where T_{LO} is the liner metal temperature with the reference fuel which was JP-4 with a hydrogen content of 14.5 percent. Figure 4-11 shows the correlation of data obtained at simulated cruise conditions. Based on this correlation, the change from Jet A to ERBS fuel would be projected to cause an increase in the liner temperatures of about 35°K. However, as Blazowski notes, all of the data on Figure 4-11 was obtained on single stage combustors having pressure atomized fuel injectors and rich primary combustion zones. Data was also obtained on experimental low emissions combustors under the Alternate Fuels Addendums to the Experimental Clean Combustor Program. Measurements on Vorbix and hybrid premixed-swirl cup burners (Reference 21) and double annular staged combustors (Reference 22) indicated less sensitivity of liner temperature to fuel composition than the correlation of Figure 4-11. However, these burners were tested at pressures less than half the design levels, and consequently, the liners were not exposed to the high nominal gas radiation levels encountered in actual engine operation. The gas radiation was further reduced because these combustors were designed for lean combustion zone equivalence ratios, and hence lower flame temperatures, to minimize NO_x production at the high power levels.

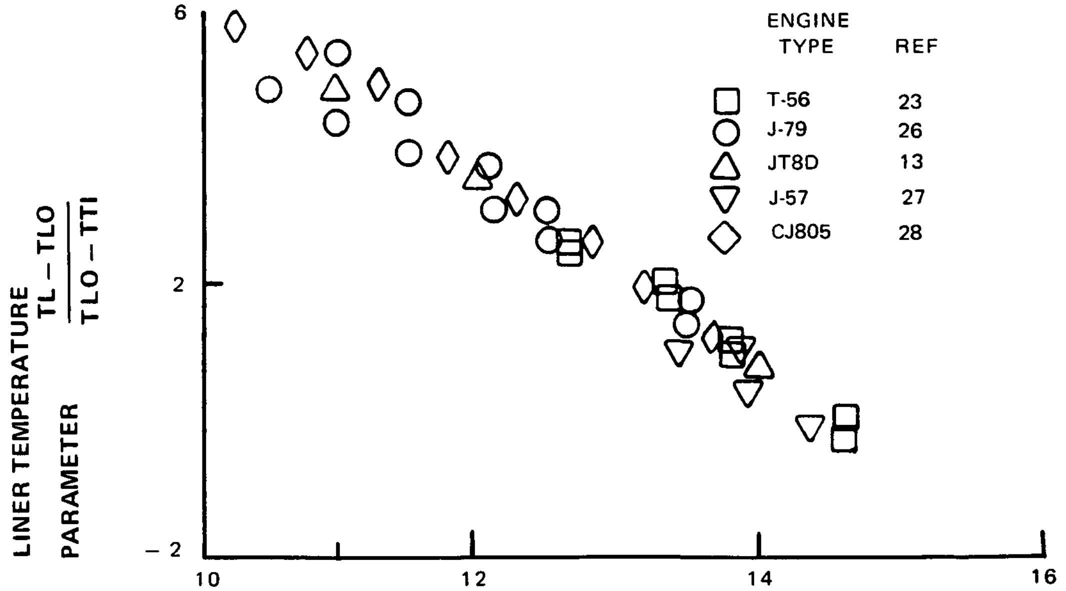


Figure 4-11 Correlation of Effect of Fuel Composition on Liner Temperature

Because these differences in the stoichiometry and fuel preparation in advanced combustors can modify the radiant heat transfer to the liner, correlations of the form of Figure 4-11 are generally inadequate for projecting the sensitivity of liner temperatures to fuel composition. Liner thermal studies are conducted using computerized analyses that are based on an energy balance between the various modes of heat transfer to and from the liner to compute local metal temperatures. To provide sufficient generality, the gas radiation computations in these analyses must be modified to properly account for the effect of fuel composition.

In these thermal analyses, the radiant heat transfer from the combustion gases to the liner are defined by:

$$q = S\,F \left(\frac{1 + \epsilon_w}{2}\right) \left(\epsilon_g\, T_g^4 - a_g\, T_w^4\right) \qquad (8)$$

where the gas emissivity and absorptivity are defined by the empirical relations (Reference 29):

$$\epsilon_g = 1 - \exp\left(-3064\ PL \sqrt{\frac{B\ F/A}{T_g^{1.5}}}\right) \qquad (9)$$

$$a_g = 1 - \exp\left(-3064\ PL \sqrt{\frac{B\ F/A}{T_g^{1.5}}}\right) \qquad (10)$$

The luminosity factor, L, relates the radiation from a luminous flame to that from the nonluminous products of perfect combustion, i.e., carbon dioxide and water vapor, and is the parameter that must be adjusted in the analysis of liner heat loads to account for the increased concentration of luminous particles in the combustion products when the burner operates on fuels of higher aromatic contents.

The values of the luminosity factor for combustors operating on Jet A or JP-5 fuel have been determined from experience with instrumented burners. For conventional combustors, i.e., those with fuel injected through individual pressure atomizing nozzles into swirl stabililized primary combustion zones, the appropriate values of the luminosity factor is 1.4 when the combustor is operating on JP-5 or Jet A fuel. Similar measurements have been obtained from experimental premixed combustors, such as the staged premixed burner evaluated under Phase I of the NASA/PWA Experimental Clean Combustor Program (Reference 4). On these configurations, a luminosity factor of 1.2 provides the best correlation between predicted liner temperatures and those measured when the combustor was operating on Jet A or JP-5 fuel. Relative to the combustors with direct fuel injection, the premixing of the fuel and combustion air produced a substantially homogeneous mixture, thereby eliminating fuel rich pockets where high concentrations of carbon particulates are formed and consequently producing a less luminous flame with lower radiation to the combustor liner. In both the conventional direct fuel injection combustors and the premixed combustors, the value of the luminosity factor was found to be relatively independent of combustor fuel/air ratio, size and operating conditions suggesting that it is a unique function of the general combustor type and the fuel composition.

Two different approaches are available to determine the appropriate values of the luminosity factors to be used in the analysis of liners of combustors operating on ERBS. The previously cited liner temperature measurements obtained in the testing of combustors with different fuels could be used in conjunction with back calculation through the liner design energy balance to define the luminosity factor for these fuels. However, this procedure requires a precise definition of several boundary conditions, including the cooling airflow distribution and information on the axial gas temperature distribution as inferred from stoichiometry. All of the tested combustors employed louvered liner constructions which produce significant axial temperature gradients along the length of the louver panel and precise definition of the axial location of the thermocouple is required. A more accurate approach appears to be the use of data from experiments in which radiometers were employed to measure the radiant heat transfer to the liner directly. The change in luminosity can then be obtained directly from Equations 8, 9 and 10 for the known increment in heat flux. The survey revealed a few experiments of this type and the most applicable data appears to be that generated by Schirmer and Aldrich (Reference 30), who measured the radiant heat flux to the liner of J-57 and J-79 burner cans and a smaller research burner. The measurements were obtained in the primary zone of the combustors at a nominal inlet pressure level of 5 atmospheres and inlet air temperatures of 475 to 555°K. Figure 4-12 shows the variation of the measured radiant heat transfer with the hydrogen content of the test fuels and indicates substantial increases in heat transfer as the hydrogen content of fuel was decreased. Assuming that the radiant energy is emitted from a region burning at stoichiometric proportions, the use of Equations 8, 9 and 10 indicate that the appropriate value of the luminosity factor for the combustion of ERBS in a conventional burner is 1.8, whereas this factor would be 1.4 when operating on Jet A fuel. The corresponding values for a premixed combustor having a luminosity factor of 1.2 for Jet A fuel would be 1.53 when operating on ERBS.

To verify the magnitude of the increases in flame luminosity, a preliminary thermal analysis was conducted on the liner of the JT9D-7 engine combustor at the sea level takeoff standard day condition. Figure 4-13 shows the incremental increases in liner metal temperatures at the critical louver knuckle location when ERBS and a fuel of about 12.3 percent hydrogen content (equivalent to No. 2 Home Heating oil) are substituted for the usual Jet A Fuel. The results indicate increases in the metal temperature in the primary zone of about 40°K when operating on ERBS and of the order of 60°K with No. 2 Home Heating oil. In the downstream section of the combustor where the combustion products have been diluted and the radiant heat transfer to the liner is less significant the predicted metal temperature increases follow the same trend, but are of lesser magnitude. The predicted liner temperature increases in the primary zone are consistent with, but slightly higher than those estimated from the correlation of Figure 4-11. The deviation is apparently due to the differences in the combustor inlet and operating conditions.

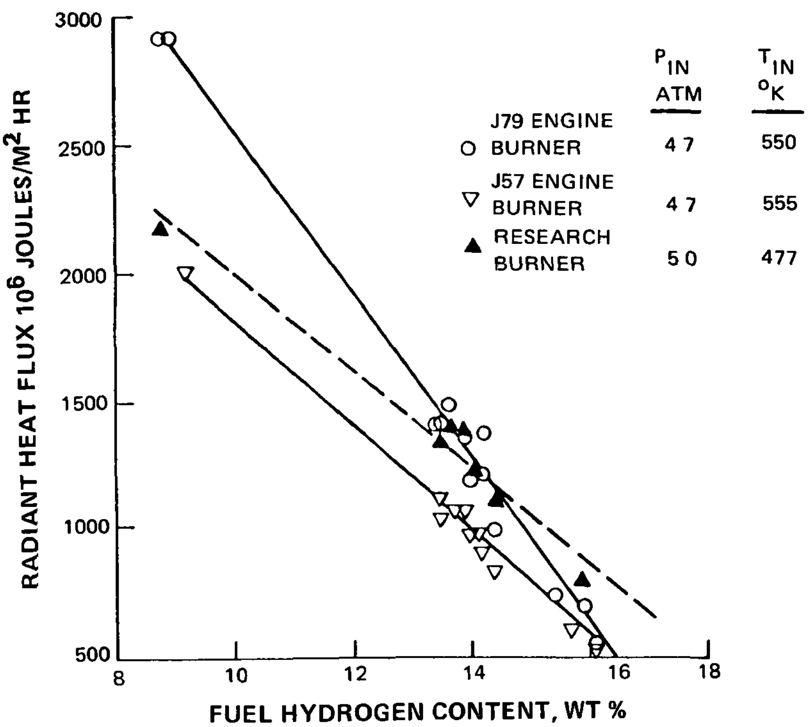


Figure 4-12 Effect of Fuel Composition on Radiant Heat Transfer to Combustor Liner

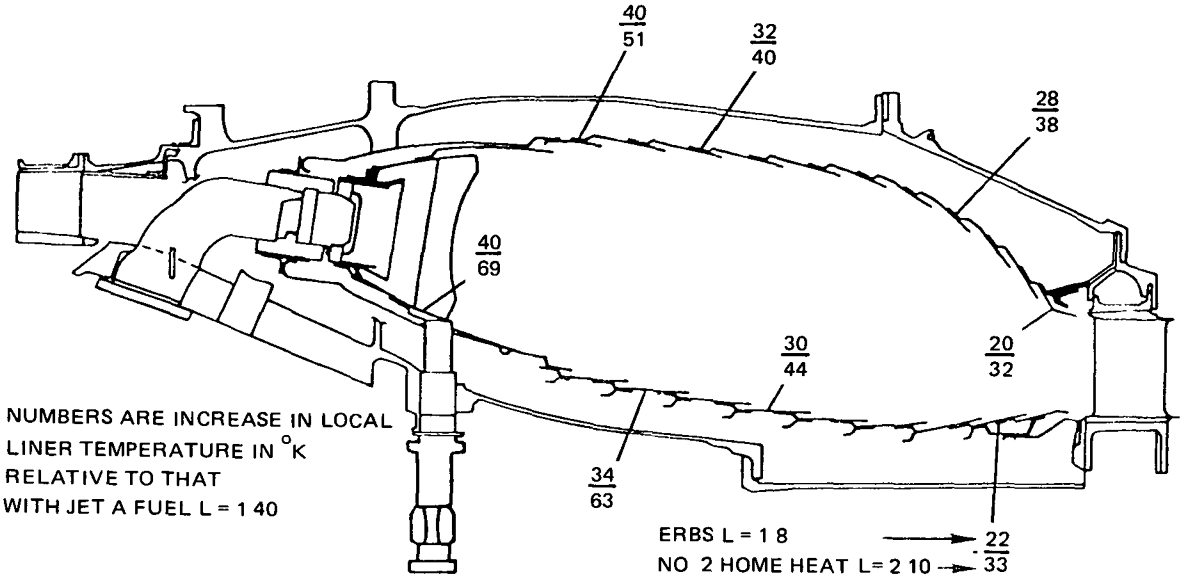


Figure 4-13 Effect of Luminosity on JT9D-7 Combustor Liner Temperatures at Takeoff

Based on these observations, the following design criteria were established for combustors operating on the ERBS specification fuel:

- The luminosity factor employed in predicting the radiant component of heat transfer from the combustion gases to the liner must be increased to account for the increased luminosity of the combustion products of ERBS relative to those of Jet A. The appropriate values are:

	Jet A	ERBS
Conventional Direct Injection Combustor:	1.4	1.8
Premixed Combustors:	1.2	1.53

- Increases in the liner temperature of the order of 40°K are to be expected in the primary zone of the JT9D burner at takeoff when the fuel is changed from Jet A to ERBS.

4.7 IGNITION

The ignition mechanism in a gas turbine engine is critically dependent on the evaporation of fuel to produce a locally combustible mixture capable of being readily ignited and subsequently sustaining combustion. While the pressure and temperature of the inlet air strongly influence evaporation, fuel properties relative to volatility are also important. The composition of the fuel influences volatility through the distillation temperature distribution. Parameters characterizing the low end of the distillation range, such as the initial boiling point and low fraction points in the 10 to 25 percent range, would be expected to correlate ignition data because the low boiling point constituents are the first to vaporize and actively participate in the ignition process.

The significance of the distillation temperature range on the ignition characteristics of a swirl stabilized combustor is shown in Figure 4-14 which presents data obtained from a T-63 engine combustor (Reference 31). The time required to achieve ignition is shown as a function of the combustion zone equivalence ratio with various fuels. The basic test fuels consisted of JP-4, Jet A and a diesel fuel, the later having a 25 percent distillation temperature of about 540°K. The combustor could not be started on the diesel fuel, but ignition was accomplished when the diesel fuel was blended with pentane to lower the distillation temperature. In general, rapid ignition was achieved at progressively lower equivalence ratios as the 25 percent distillation temperature of the fuel was decreased.

A similar dependence on the low end of the distillation temperature range is evident for bluff body stabilized combustion. Figure 4-15 shows the ignition boundaries for combustion in the wake of a disc (Reference 32). While the fuel was injected into the wake rather than being premixed, the results are of interest in generalizing data on ignition to both swirl stabilized combustors and premixed systems that rely on bluff body flame stabilization. The three test fuels had final boiling points in the range of 505 to 511°K but widely divergent initial boiling points. The results show that the more volatile JP 4 fuel has a wider ignition envelope; both in terms of fuel flow range and limiting velocity; than the JP-5 and JP-1 fuels with the higher initial boiling points. The existance of a rich ignition boundary implies excessive accumulation of liquid fuel in the wake which has a quenching effect because the energy released when combustion is initiated is absorbed in vaporizing some of the remaining liquid fuel rather than in flame propagation into a surrounding fuel vapor-air mixture.

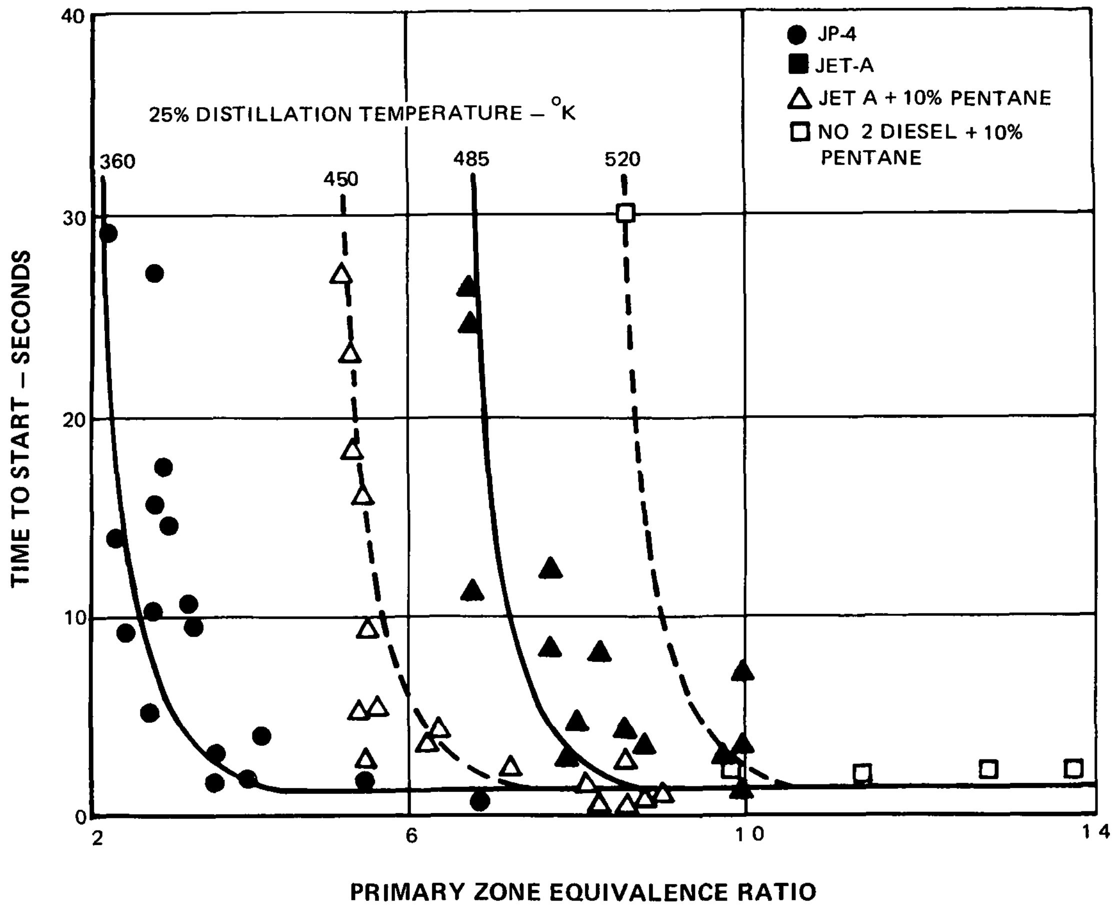


Figure 4-14 Effect of Fuel Volatility on Ignition of a T-63 Combustor

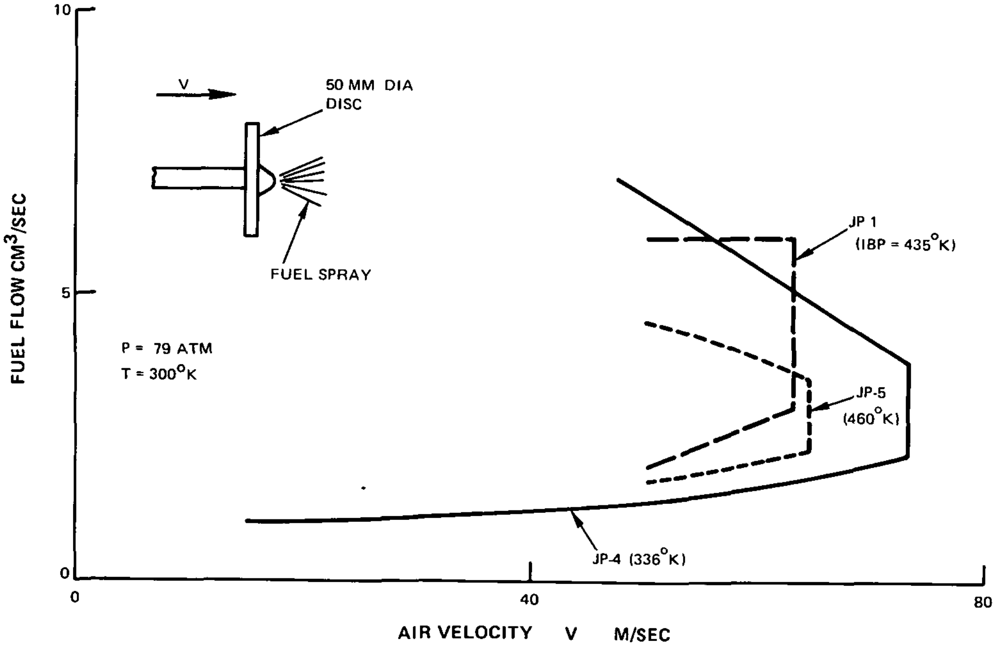


Figure 4-15 Effect of Fuel Volatility on Ignition With Buff Body Flameholder

Atomization of the fuel can also have a significant effect on ignition through its influence on evaporation. Lefebvre (References 20 and 33) and others have formulated analytical models of the process of evaporation from a droplet in motion relative to the air in a combustor. The size of the droplet enters these models because the rate of evaporation is dependent on the surface are of the fuel droplet. Computations of the droplet lifetimes indicated a square relation with the initial droplet diameter. The influence of atomization is of particular concern with reference to the starting of engines on cold fuel since the surface tension, specific gravity and particularly the viscosity increase with decreasing temperature. The literature survey revealed only minimal data on the effect of fuel properties on ignition at low temperatures. Tests were conducted on a J-33 combustor in the early 1950's in which the air and fuel temperature were varied over the range 233 to 300°K and the minimum spark energy required for ignition was determined (Reference 34). As shown on Figure 4-16, with one exception, the data correlated with the 10 percent distillation temperature, and shows as much as a fivefold variation in the minimum ignition energy over the range of inlet temperature tested. The increased difficulty in sustaining ignition with decreasing inlet temperature can be interpreted in the context of the above cited evaporation models in terms of reduced evaporation caused by lower potential for mass transfer and/or deteriorated atomization because of the lower fuel temperatures. Some indication of the relative magnitude of these influences is found in the properties of the single test fuel that deviates from the trends of the remainder. Relative to this fuel, the other five test fuels had viscosities 1.3 to 1.7 times higher, which would have produced poorer atomization. On this basis it appears that the improvement in atomization was equivalent to as much as a 30°K increase in fuel and air temperature. The data on this figure also indicate that increasing the ignition energy can be an effective means of expanding the ignition boundary.

More direct evidence of the significance of atomization and the influence of ignition energy is shown on Figure 4-17 which is based on tests that included direct measurement of the Sauter mean diameter of the injector spray (Reference 35). Acceleration of fuel evaporation by reducing the SMD of the spray is shown to extend the range of equivalence ratio over which ignition may be accomplished. The data also indicate an upper bound on ignition energy, about 10 millijoules in this experiment, beyond which no additional gain in ignition capability was observed.

Measurements were also obtained on the altitude ignition characteristics of a CF-6-50 and several experimental low emissions combustors under the Experimental Clean Combustor Program Alternate Fuel Addendum (Reference 22). The tests were conducted at ambient air and fuel temperatures but at pressures and combustor airflows that simulated the high altitude boundary of the engine ignition envelope.

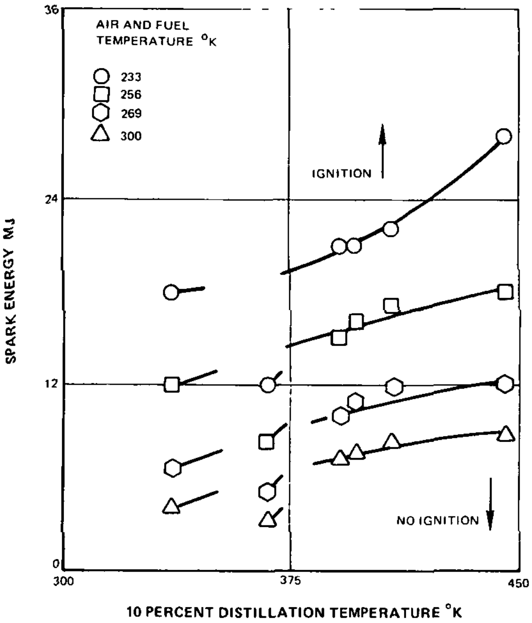


Figure 4-16 Cold Air and Fuel Temperature Ignition Characteristics of a J-33 Combustor

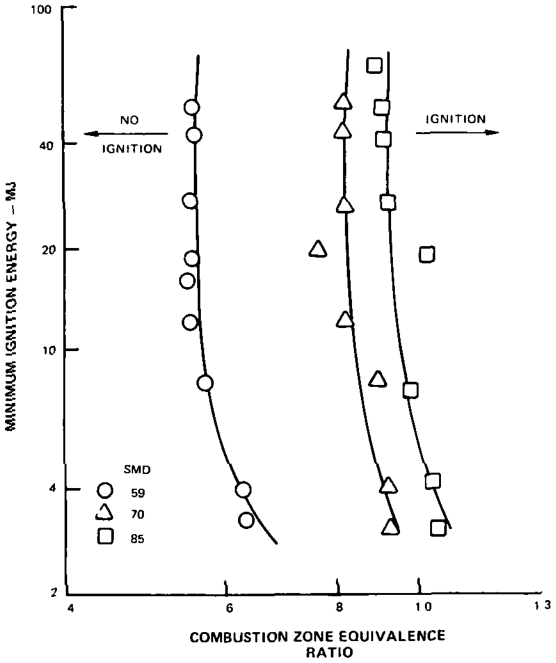


Figure 4-17 Effect of Atomization on Ignition

Relative to the JP-5 baseline fuel, the three other fuels, No. 2 Diesel and blends of Xylene and Naphthalene with Jet A, exhibited minor deterioration in the altitude at which ignition could be achieved. Based on the foregoing discussion, this performance would be anticipated with the diesel fuel because of the higher initial and low end boiling points as well as the higher viscosity but the Xylene and Naphthalene - Jet A blends had both lower initial distillation temperatures and lower viscosity than the Jet A. In the testing of a double annular combustor, it was demonstrated that the loss in relight altitude could be offset by increasing the starting fuel flow.

In applying this experience to the relaxing of the current Jet A specification to ERBS the low end of the distillation temperature range and the low temperature atomization characteristics appear to be the most significant fuel parameters. However, the specifications for Jet A and ERBS listed on Table 2-I indicate the same 483°K maximum temperature for the 10 percent distillation point. Consequently, the low temperature fractions of both fuels should not differ substantially and this aspect of fuel composition should not compromise ignition. However, in Section 4.3 it was projected that the differences in physical properties between these fuels could produce significant deterioration in atomization at low fuel temperatures. The experiments cited in this section have indicated several means by which inadequate ignition could be corrected, but each of these approaches have limitations or require additional development or operational complications. These include:

- The atomization characteristics of the fuel injectors could be improved to produce the atomization quality currently obtained with Jet A. This approach has been discussed in Section 4.3.

- The primary zone equivalence ratio could be increased to facilitate ignition. However, in the tests leading to the data shown on Figure 4-14, enrichment still did not permit ignition of a high initial boiling point diesel fuel. Primary zone enrichment could be readily accomplished by modifying the combustor starting fuel flow schedule but limits exist on the amount the schedule can be increased. Extremely high starting fuel flows must be avoided because they could cause "hot starts" that are capable of damaging turbine components or generate large pressure pulses which could initiate compressor stall when ignition is accomplished. Local enrichment techniques such as use of a fuel injector with larger fuel flows at the ignitor position or primary zone airflow reductions in the vicinity of the ignitor could also be employed within limits. The addition of more fuel at the injector location could provide more positive ignition in marginal situations but cannot alleviate a circumferential propagation problem. Likewise, local reduction of the primary zone airflow in a fixed geometry combustor could cause maldistribution of the combustor exit temperature and exposure of the turbine inlet vanes immediately downstream of the ignitors to more severe gas temperature levels.

- Ignition could be enhanced by the use of a higher energy ignition system. Again, while tests have demonstrated increased ignition energy can improve cold starting situations other data indicate limiting conditions beyond which no further improvement in ignition capability is achieved.

- The fuel could be preheated or volatile additives used during the ignition sequence. This approach increases the complexity of the fuel supply/control system and could cause concern over system reliability during an inflight engine relight.

4.8 STABILITY

The stability of the combustion process refers to the ability to sustain combustion over a wide range of combustor inlet conditions, i.e., pressure, temperature and Mach number; and fuel air ratio. The extinction limit is attained when there is insufficient excess heat generated in the combustion zone to accomplish the evaporation and initial pyrolisis of the incoming fuel or when the residence time becomes inadequate for these processes to be completed. Since the fuel composition influences the evaporation and pyrolisis reactions, variations in the stability limits of combustion systems can be anticipated with different fuels.

Under the Alternate Fuels Addendums to the Experimental Clean Combustor Program (References 21 and 22) tests were conducted to evaluate the stable operating range of several different combustors operating on various fuels. Figure 4-18 shows the stability boundary for a production CF-6-50 combustor operating at inlet fuel and air temperatures of approximately 300^{o}K (Reference 22). With the exception of some conflicting data points in the range of a loading parameter of 9 to 16; which correspond to high altitude low power level conditions; the results indicate essentially no sensitivity of the stability to fuel composition. In the limited area of uncertainty all of the data indicating deteriorated stability was obtained with the xylene and naphthalene - Jet A blended fuels while the tests conducted with the No. 2 diesel and Jet A fuels produced nearly identical stability limits. Since the physical and chemical properties of the diesel fuel used in these tests is more nearly representative of ERBS that those of the blended fuels, for the purposes of this study, the stability can be considered independent of fuel composition over the entire range of the loading parameter. A similar insensitivity of stability to fuel composition was noted in the evaluation of a Vorbix combustor (Reference 21) on comparable fuels. Testing of a JT8D combustor (Reference 12 and 13) with a wide range of fuels having hydrogen contents between 11 and 15.3 have confirmed that at least, the minimum pressure boundary of the stability boundary (the vertical part of the boundary at a loading parameter value of 8 to 10 on Figure 4-18) was also insensitive to fuel composition. Since all three of the above cited combustors employed swirl stabilized primary combustion zones with direct fuel injection through a pressure atomizing fuel nozzle, it can be concluded that the stability characteristics of combustors of this type should not be sensitive to a change of fuel composition from Jet A to ERBS.

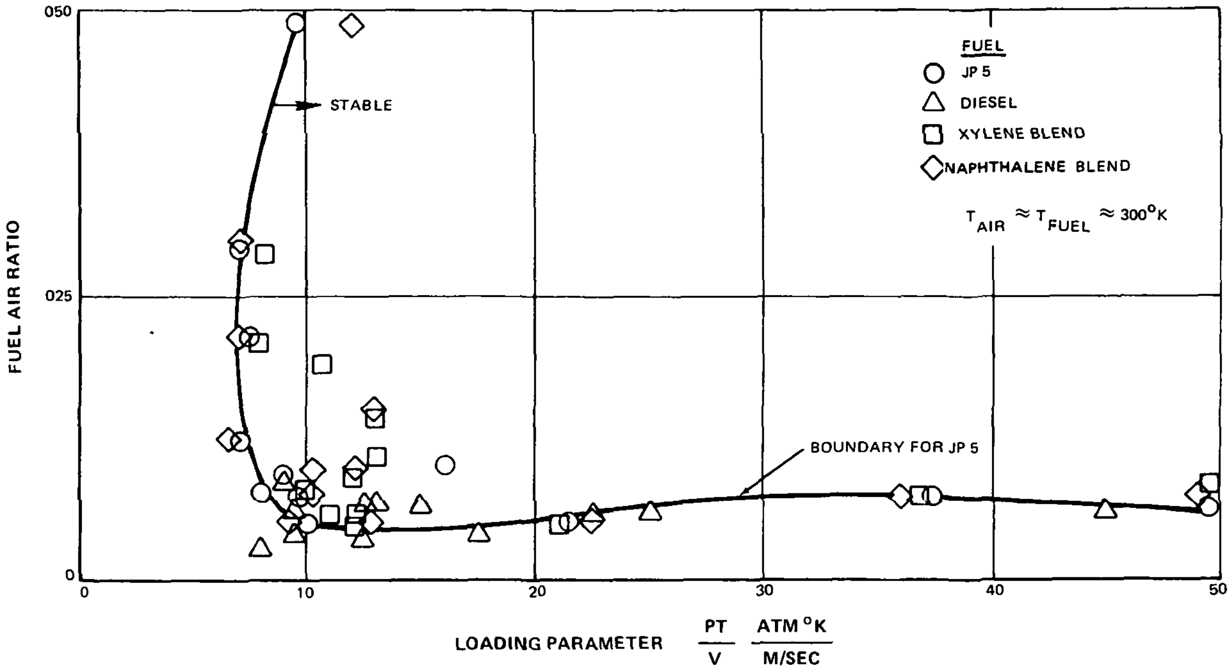


Figure 4-18 Stability Characteristics of Swirl Stabilized CF6-50 Combustor

The investigations reported in Reference 22 also included the evaluation of the stability characteristics of a double annular combustor which employed aerating fuel injection into a swirl stabilized primary combustion zone. Relative to the data of Figure 4-18 this combustor had reduced stability at high values of the loading parameter, i.e., above 20 atm °K/m/sec; and exhibited some sensitivity to fuel composition in this range with the lean blowout fuel air ratios achieved with the diesel fuel being 10 to 30 percent higher than those with JP-5. At these test conditions, the pressure drop across the combustor was extremely low - less than one percent. At these conditions, the atomization characteristics of the aerating fuel injectors would be poor and more sensitive to the physical properties of the fuel. Deteriorated atomization would be expected to produce a reduction in the stability because the larger fuel droplets would evaporate at a slower rate providing less fuel in the vapor phase to sustain combustion.

The stabilization mechanisms are somewhat different in a pre-mixed combustion system because the reaction zone is generally stabilized by the recirculation of combustion products in the wake of bluff body flameholders. The hybrid combustor tested under the Alternate Fuels Addendum to the Experimental Clean Combustor Program (Reference 21) employed a pre-mixed combustion mode in the pilot stage with bluff body flame stabilization accomplished with a perforated plate flameholder. Figure 4-19 shows the stability characteristics of this burner when operating on Jet A, No. 2 diesel and No. 2 home heating fuels. The use of No. 2 home heating fuel is shown to lead to a significant reduction in the high altitude stability but an improvement in the stability at high values of the loading parameter. Interpolating between the data obtained with Jet A and with No. 2 home heating fuel on the basis of hydrogen content indicates that the use of ERBS would lead to a 50 percent increase in the minimum allowable loading parameter at high altitudes and a ten percent decrease in the fuel air ratio at lean blowout. The altitude stability margin could be re-established by increasing the surface area of the flameholder. Correlations of bluff body stability characteristics (Reference 36) indicate that a 50 percent increase in this area would be sufficient to achieve the high altitude stability obtained with Jet A when operating on ERBS fuel. The improvement in lean stability at high values of the loading parameter, corresponding to those encountered in engine operation at low altitudes, implies the capability of operating at leaner primary combustion zone equivalence ratios. This would reduce the NO_x emissions from the combustor and tend to offset the increased NO_x emissions projected in Section 4.4.

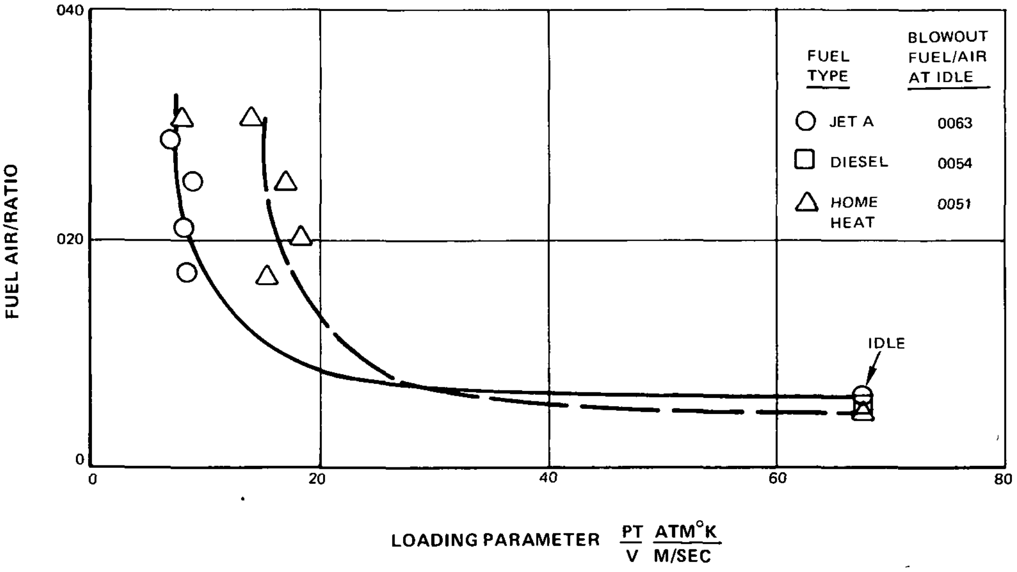


Figure 4-19 Stability Characteristics of Hybrid Combustor With Premixed Pilot Stage

Based on the data discussed in this section, it is concluded that the effect of using ERBS fuel as opposed to Jet A on the stability characteristics will depend on the type of combustor. In particular:

- No change in stability is anticipated for swirl stabilized combustors using direct pressure atomizing fuel injection.

- Combustors employing direct injection of fuel with aerating injectors could encounter reduced stability at operating conditions where the combustor pressure drop is low because the atomization is more sensitive to fuel properties at these conditions.

- The stability of premixed combustion systems is expected to be more sensitive to the composition of the fuel and will require larger flameholder areas to achieve adequate altitude stability margin. The lean stability margin is projected to improve with the use of ERBS fuel and could lead to operation at lower primary combustion zone equivalence ratios with more favorable NO_x emissions characteristics.

4.9 THERMAL STABILITY

Modification of the fuel composition can alter its thermal stability and lead to changes in the propensity for deposit formation on the surfaces of fuel passages in manifolds, injectors and their supports. The reactions causing deposit formation are sensitive to changes in fuel composition including components normally present in only trace concentrations. These reactions are also extremely sensitive to temperature and consequently the primary approach in suppressing deposit formation is to maintain fuel and component surfaces at sufficiently low temperatures. The sensitivity of thermal stability to fuel composition is understood in only a qualitative sense. Jet fuels with increased aromatic and heterocompound content can undergo accelerated thermal decomposition for a number of reasons. Some aromatic and heterocompounds initiate or participate in free radical chain reactions easily thus accelerating the homogeneous chain decomposition of the fuel and the formation of insolubles through secondary reactions. For example, acenapthene, a naturally occurring constituent of petroleum and found in abundance in Diesel fuel is particularly harmful because of its ability to initiate free radical reaction (Reference 37). Likewise high molecular weight, resonance stabilized, radicals are formed easily from many substituted, condensed ring molecules . Since these stable radicals do not pyrolyze to any significant extent they exist at high concentrations and under appreciable absorption on surfaces where they subsequently undergo dimerization or polymerization reactions (Reference 38). In addition, some polar aromatic compounds can undergo homogeneous condensation reactions with themselves or with polar oxidation products leading to the formation of high molecular weight insoluble products.

Although the overall effect of increased heterocompound content will be to reduce the thermal stability of jet fuels, at low levels some heterocompounds and aromatics function as natural inhibitors and can retard the decomposition of the fuel. For example, a compensating effect of the formation of stable free radicals is to inhibit the oxidative decomposition of the fuel. Thus, homogeneous formation of insolubles may actually be retarded by low levels of certain oxygen, nitrogen, and sulfur compounds, phenols, thiophenes, and quinolines (References 39 and 40).

The problems of deposit formation in aircraft gas turbine fuel systems can be identified in three distinct areas:

Inactive Fuel Systems

Deposition in fuel injectors and supports is generally precluded by maintaining adequately low surface temperatures with the flow of fuel through the component providing the necessary cooling of the surrounding components. When the fuel flow is stopped, the cooling effect is eliminated and residual fuel in the component exposed to excessive temperature forms carbon deposits. This problem is most acute in staged combustors and occurs when the power level is decreased, shutting down a high power stage; while other stages remain operational. This type of problem appears to be primarily one of combustor design and, while the thermal stability characteristics of the fuel may influence the deposit formation mechanism, the environmental effects probably dominate.

Long Term Deposit Formation

If the thermal isolation of the fuel passage in an injector or its support are inadequate, carbon deposits can be formed. While the deposition rates may be low, if this situation exists over long terms the accumulation can become severe. This problem is most likely to occur at the end of cruise-start of decent part of the flight because fuel flows are low and may provide inadequate cooling of the fuel system components. A change in fuel specification to one of lower thermal stability will lead to an increase in deposition rate which must be offset by improving the thermal isolation of the injector surfaces or reducing the fuel supply temperature.

Fuel Vaporizors

The use of heat input to prevaporize the fuel prior to injection into a premixed combustor is being considered as a means of accomplishing the full NO_x emissions reduction potential of this type of combustor. Experience with systems of this type is extremely limited and, even if the heating process is conducted above the critical pressure to avoid boiling, severe thermal stability problems may be encountered. As in the case of the inactive fuel system, the thermodynamic environment in the fuel preheater is expected to be so severe that relatively small differences in the thermal stability characteristics of the fuel are probably of second order significance.

Of the three problem areas, the one of greatest immediate concern with regard to relaxation of the fuel specification, and fortunately also that most ammenable to analytical treatment, is that of long term deposition in active fuel systems -- item 2 above. A common method of rating the thermal stability of hydrocarbon fuels is afforded by measurement of fuel "breakpoint" temperature using the JFTOT apparatus per ASTM D 3241. In this procedure, the loss in reflectance of a polished metal surface which has been exposed to heat fuel is used as a measure of the fuel instability. Breakpoint temperature is defined as that temperature for which a Tube Deposit Rating (TDR) of 13 is registered following a 2.5 hr test at a specified fuel flow. The TDR is defined as zero for a clean tube and 50 for a "dark" deposit. The fuel specifications of Table 2-I indicate that the maximum breakpoint temperatures of the tentative ERBS specification fuel is 22°K lower than that of Jet A, implying a reduction in the thermal stability. Similar evidence of reduced stability is shown in the anticipated coker tube pressure and color code results of Table 2-II in which similar results are projected at 28°K lower nominal temperature levels.

To substantiate these increments and further assess the impact of fuel composition on breakpoint temperature a correlation was made of available data. Unfortunately limited data was available on the composition-breakpoint characteristics of petroleum based fuels but recently both Exxon and Atlantic Richfield have synthesized a number of coal and shale derived fuels with widely different compositions which provide a basis for estimating the dependence of breakpoint temperature on composition. Breakpoint temperatures of the ARCO samples have been measured by Reynolds (Reference 41) and of the Exxon samples by Kalfadelis (Reference 42). The samples produced by Atlantic Richfield were selected for correlation in this study and consisted of 16 shale and 16 coal derived fuels processed at two levels of hydrotreating severity and at two yield levels. The range of chemical properties of the fuel samples were extensive and are listed on Table 4-IV. The breakpoint temperatures of the samples were in the range of 490 to 590°K.

TABLE 4-IV

RANGE OF COMPOSITION VARIATION IN THE ATLANTIC RICHFIELD FUEL SAMPLES

Constituent	Concentration Range	Symbol In Equation 11
Oxygen	0.03-0.14 (% wt)	
Sulphur	0.0001-0.0044 (% wt)	S
Nitrogen	0.0001-0.2233 (% wt)	N
Hydrogen	12.47-13.98 (% wt)	
Naphthalenes	0.055-1.20 (% vol.)	Na
Olefins	0.50-1.80 (% vol.)	Ol
Aromatics	5.5-33.8 (% vol.)	Ar

Because the samples had been hydrotreated to reduce their nitrogen content, the variations in the composition listed in Table 4-IV were not random, but in general the samples having high sulphur and nitrogen contents were also those with the higher aromatic and naphthalene levels. This complicated the process of identifying the constituents having the greatest impact on thermal stability but a correlation of breakpoint temperature with fuel composition was achieved using a multiple linear regression analysis in which the significant valuables were identified by the computer at a prespecified confidence level. Correlations were generated for the coal and shale derived fuels independently and in aggregate. The most general correlation was derived for the latter and indicated that:

$$TB = 255 + 259[S]^{-.024}[N]^{-.00415}[Na]^{-.0149}[Ol]^{-.082}[Ar]^{-.067} \qquad (11)$$

where the square brackets indicate the concentrations of the constitutents in the units shown on Table 4-IV. Figure 4-20 shows the overall accuracy of this equation. The negative exponents on the correlated constituents indicate that increased concentrations of these components reduce the breakpoint temperature.

Estimates of the breakpoint temperature were made for Jet A and ERBS using Equation 11 and compositions that appear to be nominal for these fuels. The assumed fuel compositions and the corresponding breakpoint temperatures are listed in Table 4-V.

While the computed breakpoint temperatures are about $40^{o}K$ below the minimum levels stipulated in the specifications of Table 2-I, the difference between them is of the magnitude anticipated from the specifications. The overall low level of the breakpoint temperatures of the fuel samples used in generating this correlation is probably due to their being derived from shale and coal sources which produced inherently high aromatic and olefin contents. In the present analysis, the differences in, rather than magnitudes, of the breakpoint temperature are of greater significance because they identify the propensity for an individual constituent to contribute to the thermal stability of the fuel.

Table 4-VI shows the incremental changes in breakpoint temperature associated with the change in concentration between the nominal Jet A and ERBS compositions. The increase in the aromatic content itself is shown to be a major contributor to the reduction in thermal stability. The naphthalenes contribute less to the change in breakpoint temperature but, because naphthalene concentrations normally vary with aromatic content, the effects of both of these components should be considered in combination. The presence of olefins in even low concentrations has been shown to have a significant adverse effect on thermal stability and the relatively small differences in the assumed concentration of this constituent in the nominal compositions of Jet A and ERBS is shown to have a substantial effect on the breakpoint temperature computed from this correlation.

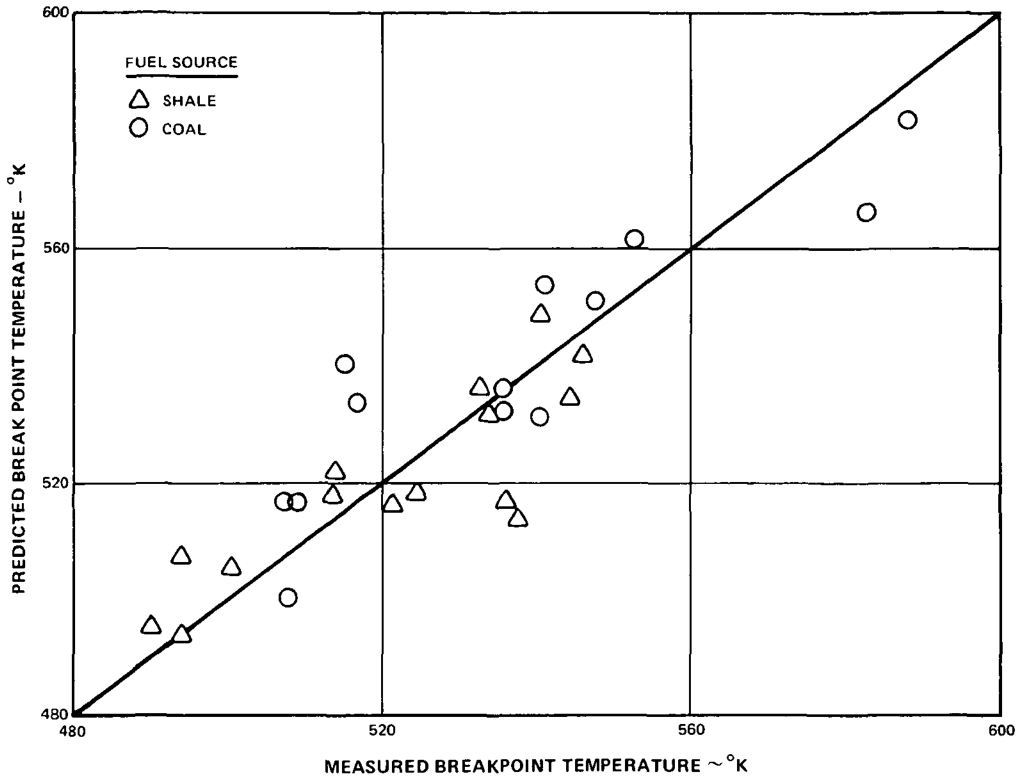


Figure 4-20 Accuracy of Breakpoint Temperature Correlation

TABLE 4-V

NOMINAL FUEL COMPOSITION AND BREAKPOINT TEMPERATURES

	Nominal Jet A	Nominal ERBS
Aromatics (% vol.)	20	35
Naphthalenes (% vol.)	3	7.5
Olefins (% vol.)	0.5	0.8
Sulphur (% wt)	.05	.05
Nitrogen (% wt)	.001	.001
Breakpoint Temperature - °K	500	474

TABLE 4-VI

INCREMENTAL CHANGE IN BREAKPOINT TEMPERATURE FOR VARIOUS CHANGES IN FUEL COMPOSITION

Composition Change Relative to Jet A of Table 4-5	Breakpoint Temperature Increment Relative to Jet A at 500°F (°K)
Increase Aromatics to ERBS Level	-9.9
Increase Naphthalene to ERBS level	-4.2
Increase Olefins to ERBS level	-9.4
Increase Sulphur to 0.3 percent	-11.2
Increase Nitrogen to 1.0 percent	-7.8

The table also shows the effect of variations in the concentrations of sulphur and nitrogen in the fuel. Increasing the sulphur content six fold to the ERBS specification limit is shown to have a pronounced effect, reducing the breakpoint temperature even more than the change in aromatics or olefins. Surprisingly, the correlation reveals a relatively low sensitivity to nitrogen content with a thousand fold increase to levels approaching those of untreated shale derived fuels decreasing the breakpoint temperature by only 7.8°K.

Based on these computations from the correlation of Equation 11 it appears that; despite the disparity in the nominal breakpoint temperature level between the test fuels and those derived from conventional petroleum feedstocks; the anticipated reducton in thermal stability of ERBS fuel is of the correct magnitude and that it will be due in large part to the increase in aromatic content of the fuel. Even small changes in the concentrations of olefins and sulphur contents approaching the specification limit have been shown to have a significant adverse effect on the breakpoint temperature.

The temperature dependence of the coking rate of a particular fuel can be determined from knowledge of the breakpoint temperature, the coking rate at the breakpoint temperature, and assuming an Arrhenius type dependence on temperature, knowledge of the mean activation energy. The coking rate at the breakpoint temperature has been estimated by Hazlett (Reference 43) from measurements obtained by means of ellipsometry, of the deposit film thickness as a function of the Tube Deposit Rating. Since these measurements were for dodecane fuel, it is necessary to assume that the film thickness/TDR relationship is not a function of fuel type. This implies that all fuels exhibit the same coking rate at the breakpoint temperature. At the breakpoint these measurements indicated the film thickness is 1.3×10^{-5} mm. Since the test time is 2.5 hrs, this corresponds to a growth rate of 5.2×10^{-6} mm/hr. Assuming a deposit density of 1 gm/cm^3, the deposit growth rate is approximately 0.52 $\mu gm/cm^2$ hr at the breakpoint temperature. Published values for JP-5 obtained in nonisothermal experiments (Reference 44) indicate a deposit rate of approximately 1.5 $\mu gm/cm^2$ hr while other measurements, obtained under isothermal conditions using Jet A fuel, indicate a deposit rate of 1.1 $\mu gm/cm^2$ hr. In view of the fact that the experimental measurements of coking rate and deposit thickness have been made under different experimental conditions, and that the deposit density is not known the agreement between these estimates is surprisingly good. A value of 1.1 $\mu gm/cm^2$ hr at the breakpoint temperature was used as a reference point in comparing the coking rate at other temperatures.

To estimate deposit formation rate as a function of temperature it is necessary to assume that the formation rate exhibits Arrhenius type dependence on temperature and that the activation energy is known. Data on jet fuel generally indicate an overall mean activation energy for deposit formation in the range of 10-20 kcal per mole, with values of 15-20 kcal per mole more likely. Assuming a value of the activation energy of 20 kcal/mole the temperature dependence of the coking rate from Jet A fuel has been constructed on Figure 4-21 using the breakpoint temperature from the specification of Table 2-I. A similar assumption regarding the activation energy for ERBS fuel could be made but a better estimate of the coking rate is afforded by making use of the observation that; in the temperature range of 700 to 800°K; many fuels of lower thermal stability exhibit the same coking rate as Jet A (References 44 and 45). Proceeding on this basis and using the above established coking rate at the breakpoint temperature of ERBS from Table 2-I, a straight line is constructed on Figure 4-21 defining the temperature dependence of the coking rate for ERBS. The reduced slope of this characteristic, relative to that of Jet A, implies a lower activation energy and a weaker temperature dependence.

Based on experience with Jet A fuel, coke formation in fuel injectors, supports and manifolds is minimal or nonexistant when the wall temperatures of these components are maintained at temperatures below 375°K. In the context of Figure 4-21 this implies the existance of an "acceptable" coke formation rate of about 10^{-5} $\mu gm/cm^2$ hr. To achieve this "acceptable" level with ERBS fuel it is necessary to reduce the maximum fuel passage temperatures to 345°K. This reduction in allowable surface temperature is about 36 percent greater than the difference in breakpoint temperatures and is a consequence of the reduced temperature sensitivity of coke formation of ERBS relative to Jet A.

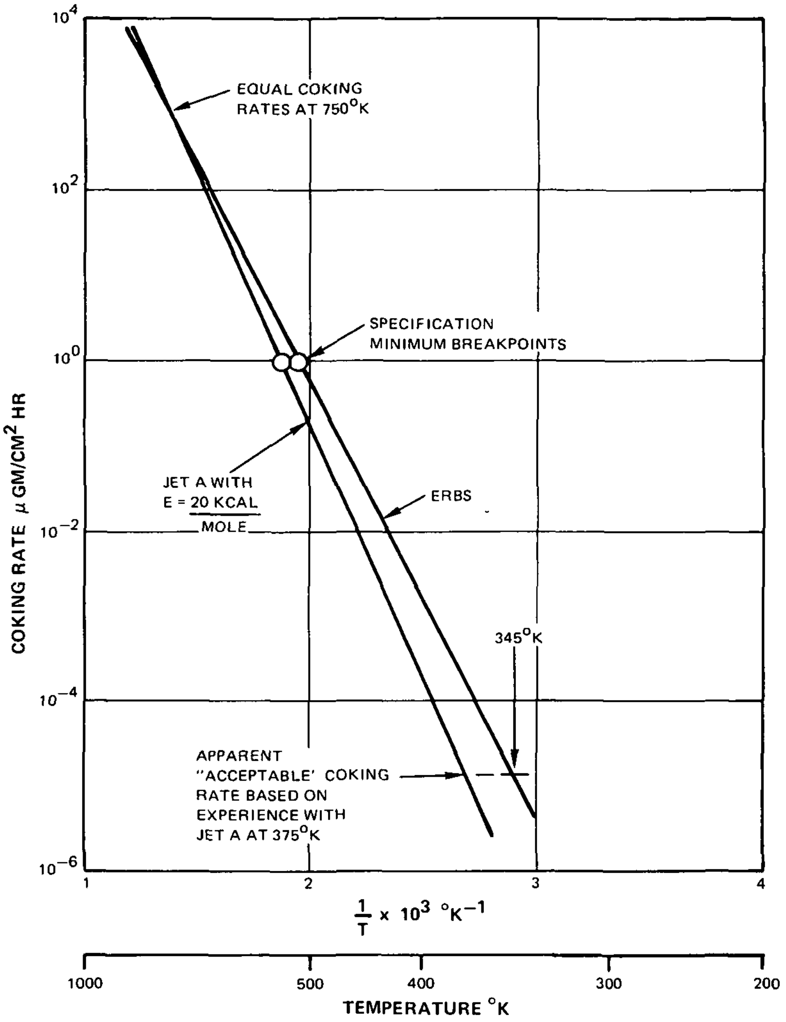


Figure 4-21 Predicted Coking Rates of Jet A and ERBS Fuel

Based on these observations, the following conclusions and design criteria are derived relative to the thermal stability of relaxed specifications fuels:

- o Coke formation in inactive fuel systems or fuel vaporizors may be sensitive to the thermal stability characteristics of the fuel but the extreme thermal environment may be the dominant mechanism in these situations.

- o In active fuel systems, the coking rate has a strong temperature dependence. The reduced thermal stability of ERBS fuel will require a reduction in surface temperatures in the fuel system components of about 30°K to achieve the level of coking protection currently obtained with Jet A fuel.

- Correlation of data on the breakpoint temperature of fuel samples indicates a strong dependence on fuel composition including both major constituents and those normally present in only trace quantities. For the particular fuel samples analyzed, the aromatic, olefin and sulphur contents were dominant while the influence of the nitrogen content was not as severe as anticipated.

4.10 PREMIXING SYSTEMS

Premixed-prevaporized combustors rely on the supply of an extremely homogeneous fuel/air mixture to the primary combustion zone. By burning this mixture at lean proportions - approaching the lean stability limits - flame temperatures are maintained low throughout the reaction zone and minimal quantities of NO_x will be formed. In this respect, the premixing section of the combustor is the most critical component in achieving the expected low NO_x emissions. To accomplish the goal of homogeneous combustion, the fuel must be dispersed uniformly in the flowing combustion air from a discrete number of sources. After premixing, the fuel must at least approach a completely vaporized state or the ensuing combustion process may be dominated by diffusion burning in the vicinity of the residual fuel droplets rather than the intended premixed mode of combustion. Two approaches to prevaporization may be considered: The fuel can be injected into the passage in a liquid state and vaporize as it mixes with the combustion air, with the heat of vaporization being drawn from the combustion air. The alternative is to preheat the fuel in an external heat exchanger and introduce it into the premixing passage in a vapor phase. While obviously more complex, the latter approach eliminates the problems associated with evaporation of the fuel in the premixing passage permitting concentration on the fuel dispersion aspects. Regardless of the fuel vaporization approach employed, the fuel dispersion processes in the premixing passage must be accomplished in short residence times to minimize combustor section lengths and satisfy autoignition margins. The design of the premixing passage must also be integrated with that of the flameholder to avoid flashback risks. The properties of the fuel become design considerations because of their potential influence on fuel droplet dispersion and evaporation rates, external heating requirements, autoignition margins and flashback risks.

For combustors in which liquid fuel is injected into the premixing passage, the progress of the vaporization process can be critical in achieving the low emissions goal. Evaporation of fuel from droplets has already been shown to be strongly dependent on atomization with smaller droplets having significantly higher evaporation rates. The previously discussed effect of fuel properties on the performance of fuel atomizers is also relevant to the design of premixed combustors and must be considered in combination with the unique requirements for fuel dispersion in the premixing passage. Assuming that the same degree of atomization and dispersion can be accomplished with Jet A and ERBS, the rate of evaporation of fuel becomes dependent only on their thermodynamic properties. An analysis was conducted to define the evaporation histories in a representative engine environment using an analytical model of droplet evaporation. The results of this computation are shown on Figure 4-22. Since the analytical model recognizes the vapor pressure of the fuel as only a single species and not a mixture of constituents having a continuous range of boiling points, separate calculations were made for ficticous fuels having vapor pressures corresponding to the initial and final boiling points of Jet A and ERBS. Based on the assumed values of these boiling point temperatures on Table 2-II, from which ERBS is expected to have a slightly lower initial boiling point than Jet A (427°K as opposed to 449°K for Jet A) the analysis predicts that the more volatile components of ERBS will evaporate more rapidly than those in Jet A. Conversely, with the final boiling point of ERBS expected to be about 28°K higher than that of Jet A, evaporation of the heaviest constituents is slower than with Jet A fuel. Regardless of the fuel type, the majority of the evaporation occurs over the range of lengths of 20 to 30 cm downstream of the point of fuel injection. As will be shown later in this section, the residence time in passages of these lengths is of the same magnitude or exceeds that allowable from autoignition constraints. Consequently, with liquid fuel injection the evaporation of the fuel must be considered the limiting process in achieving the desired premixing passage performance.

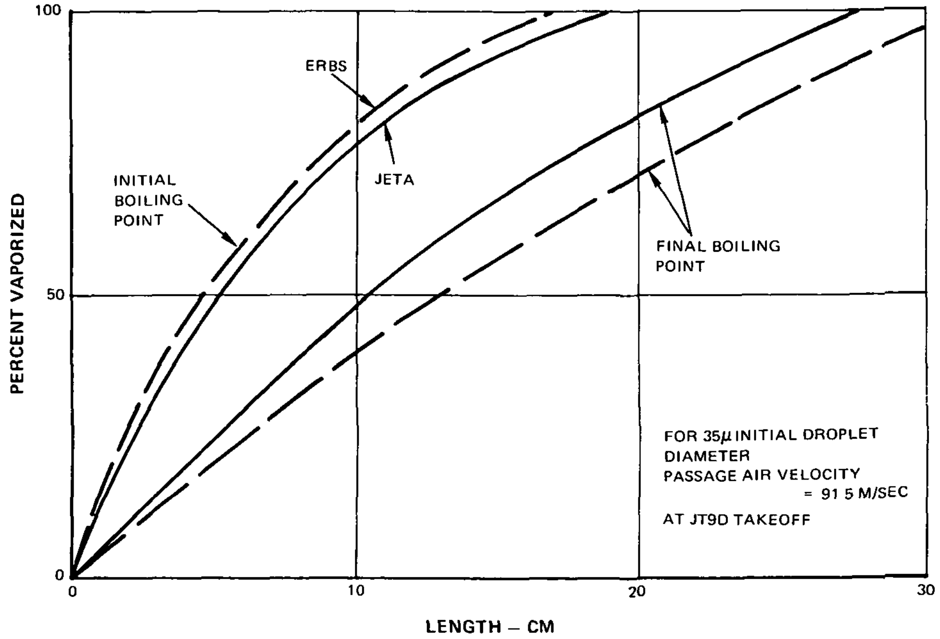
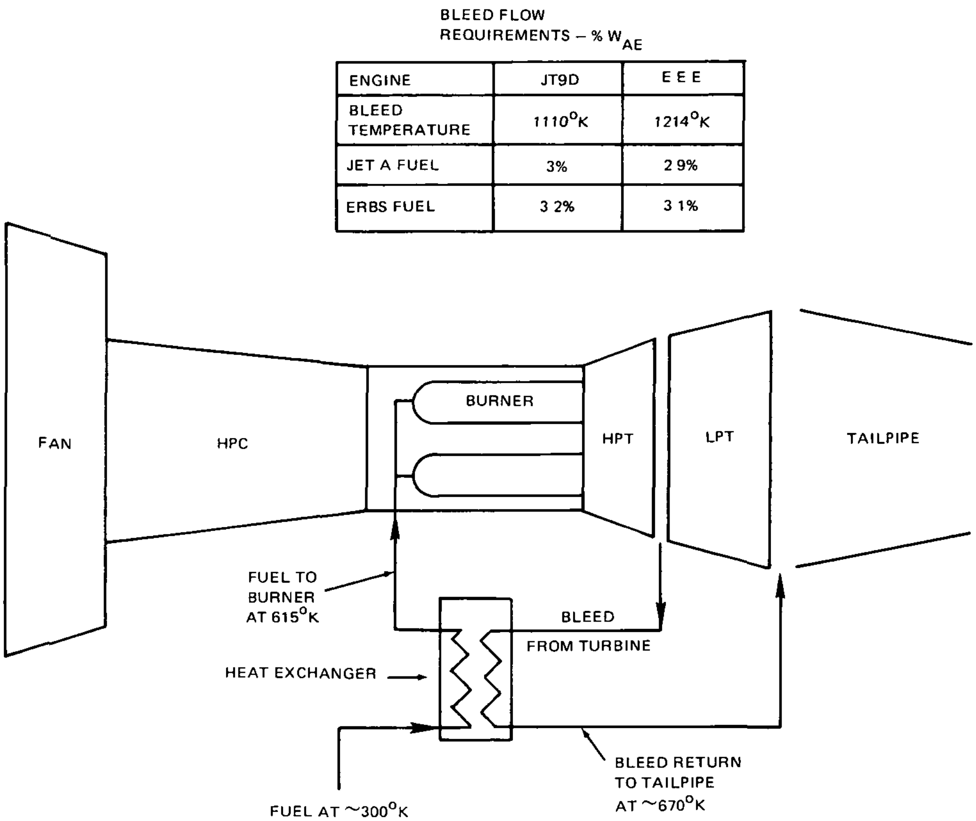


Figure 4-22 Rate of Fuel Vaporization in a Premixing Passage

Vapor phase fuel injection systems circumvent the evaporation time limitations by preheating the fuel in an external heat exchanger and, as long as the combustor inlet air temperature is sufficiently high to prevent condensation of the vapor, prevaporized combustion is assured. The external heating requirements of such a system depend on the method of fuel preheating as well as the composition of the fuel. It is anticipated that the fuel heater would operate at pressures in excess of the critical pressure; approximately 22 atmospheres for Jet A; to avoid boiling the fuel in the heat exchanger. Boiling can not only lead to severe vibratory problems in the heat exchanger but there is also evidence that thermal stability problems become acute in the presence of two phase flow (Reference 46) and could lead to rapid formation of carbon deposits on the heat transfer surfaces. After heating at pressures above the critical pressure, the fuel can be flash vaporized by throttling either across a distribution valve or the fuel injectors proper. Estimates have been made of the fuel heating requirements for Jet A and ERBS fuel based on a fuel supply temperature of 300°K and sufficient heating that the least volatile constituents will remain in a vapor state when mixed with combustion air at conditions representative of takeoff operation of the JT9D-7 engine. Heating rates of 153 and 169 kilocalories/kilogram of fuel are required for Jet A and ERBS respectively.

The heat source for fuel preheating could be the combustion gases in the burner; i.e., a regeneratively cooled combustor liner could be employed as the heat exchanger. An alternative source would be the use of combustion gases bled from the turbine of the engine. Figure 4-23 shows a schematic diagram of this fuel preheating system in which the hot gases are bled from the high-low turbine interface and returned to the tailpipe downstream of the low pressure turbine. An analysis of this type of fuel heating system was conducted under a previous study (Reference 47) and was used as a basis for estimating the effect of the difference in heating requirements between Jet A and ERBS on the bleed gas quantity and heat exchanger size. As shown in the table on Figure 4-23 an essentially direct proportionality between bleed flow and fuel enthalpy rise exists with the bleed flow increasing about 10 percent in the JT9D-7 cycle. Slightly lower bleed flows are required in the Energy Efficient Engine cycle because of the higher bleed temperature. Analysis of the heat exchanger surface area or volume requirements on an NTU-effectiveness basis (Reference 48) for an unmixed multipass crossflow heat exchanger indicated that there would be no need to increase the size of a heat exchanger designed for operation on Jet A if it were to be operated on ERBS. This is attributed to the increase in bleed gas flow required with ERBS that reduces the required effectiveness of the heat exchanger so that the existing surface area is adequate.



BLEED FLOW REQUIREMENTS – % W_{AE}

ENGINE	JT9D	EEE
BLEED TEMPERATURE	1110°K	1214°K
JET A FUEL	3%	2.9%
ERBS FUEL	3.2%	3.1%

Figure 4-23 External Fuel Preheating With Low Turbine Bypass Flow

It should be noted that the feasibility of external fuel vaporization systems from premixed combustors, particularly with respect to thermal stability considerations, has yet to be established and only limited experience, such as that derived in the tests of Reference 49, has been obtained with systems of this type. Deposit formation problems may be substantial and, in such a situation, the use of a fuel with reduced thermal stability, such as ERBS, could aggrevate these difficulties significantly.

Another design consideration for fuel-air premixing systems is the problem of autoignition. After the initial contact between the fuel and the combustion air, a finite time interval-the ignition delay time is available for fuel dispersion and evaporation before spontaneous combustion is initiated. This ignition delay time is strongly dependent on the air pressure and temperature and to some extent on the composition of the fuel. Wentzel (Reference 50) was one of the first investigators to conclude that the ignition delay time comprises a series of overlapping physical and chemical processes. The physical delay is the time required for droplet formation, heating, vaporization, diffusion and mixing with the air. The chemical delay is the time elapsed from the instant a combustible mixture has been formed until the appearance of a hot flame; it involves the kinetics of preflame reactions which result in the decomposition of high molecular weight hydrocarbon species and the formation of critical concentrations of intermediate free-radial species, so called ignition precursors. It is believed that the chemical processes start immediately upon the introduction of the fuel into the air; however, initially they proceed at a very slow rate and consequently the mass of fuel vapor which undergoes chemical reaction is very small compared to the mass necessary to cause a detectable temperature or pressure rise due to combustion. Therefore, the very early stages of the preignition processes are probably dominated by the physical processes and the late stages by the chemical processes. The relative effects of the physical and chemical processes on the magnitude of the ignition delay have been studied by many investigators (References 51, 52 and 53), and it has been concluded that in conventional combustion system (e.g., gas turbine and diesel engines) the chemical delay is typically the more important of the two periods. Ample evidence has been derived from theoretical analyses and experimental investigations to indicate that chemical reaction is the rate controlling factor for autoignition. For example, Henein (Reference 54) has calculated the time required to form a combustible mixture at the droplet surface (i.e., droplet heating, evaporation and mass transfer) for conditions representative of the start of injection in an open-chamber diesel engine and concluded that it is very short compared to the ignition delay. In addition, several investigators (References 54, 55 and 56) have measured longer ignition delay times for certain of the relatively high-volatility fuels than for diesel fuel and distillate fuel oil. There is no doubt that the rate of the physical processes increases with the fuel volatility; but if physical processes control the ignition delay, one would expect the opposite result. Also, it is a well known fact that the addition of small amounts of tetraethyl lead to gasoline significantly affects the ignition delay without having any known effect on the physical delay. Consequently, the ignition delay time can be considered an inherent property of the fuel and the mixing environment but is not dependent on the state of the fuel, i.e. whether it is introduced in the liquid or vapor phase.

A survey of the available data on ignition-delay times for hydrocarbon fuels was recently conducted (Reference 57) and revealed more than fifty independent experiments. These were conducted on different types of apparatus including constant volume bombs, reciprocating engines and steady flow systems. Anticipating some forms of apparatus sensitivity, the steady flow experiments are of greatest interest because they were conducted in an environment and configuration similar to a premixing passage in a combustor. Figure 4-24 shows a collection of data from these experiments and demonstrates that the ignition delay times of lower hydrogen content fuels such as No. 2 Home heating and Diesel fuel are generally lower than conventional aircraft gas turbine fuels like JP-4 and Jet A in similar environments. Figure 4-25 shows further details of the data from the tests of Reference 55 in which JP-4 and No. 2 Home Heating fuels were evaluated at identical conditions and indicates the ignition delay time for the No. 2 Home heating oil is only half that of JP-4. Extrapolating these ignition delay times to the pressure level of the JT9D-7 combustor at takeoff conditions, according to the pressure scaling exponents of Reference 55, leads to ignition delay times of 4.5 and 2.6 milliseconds respectively for JP-4 and No. 2 Home heating fuel. Interpolating between these values on the basis of hydrogen content, assuming values of 14.5 and 12.3 percent for the JP-4 and No. 2 Home Heat yields values of the ignition delay time of 3.8 and 3.2 milliseconds for Jet A and ERBS respectively.

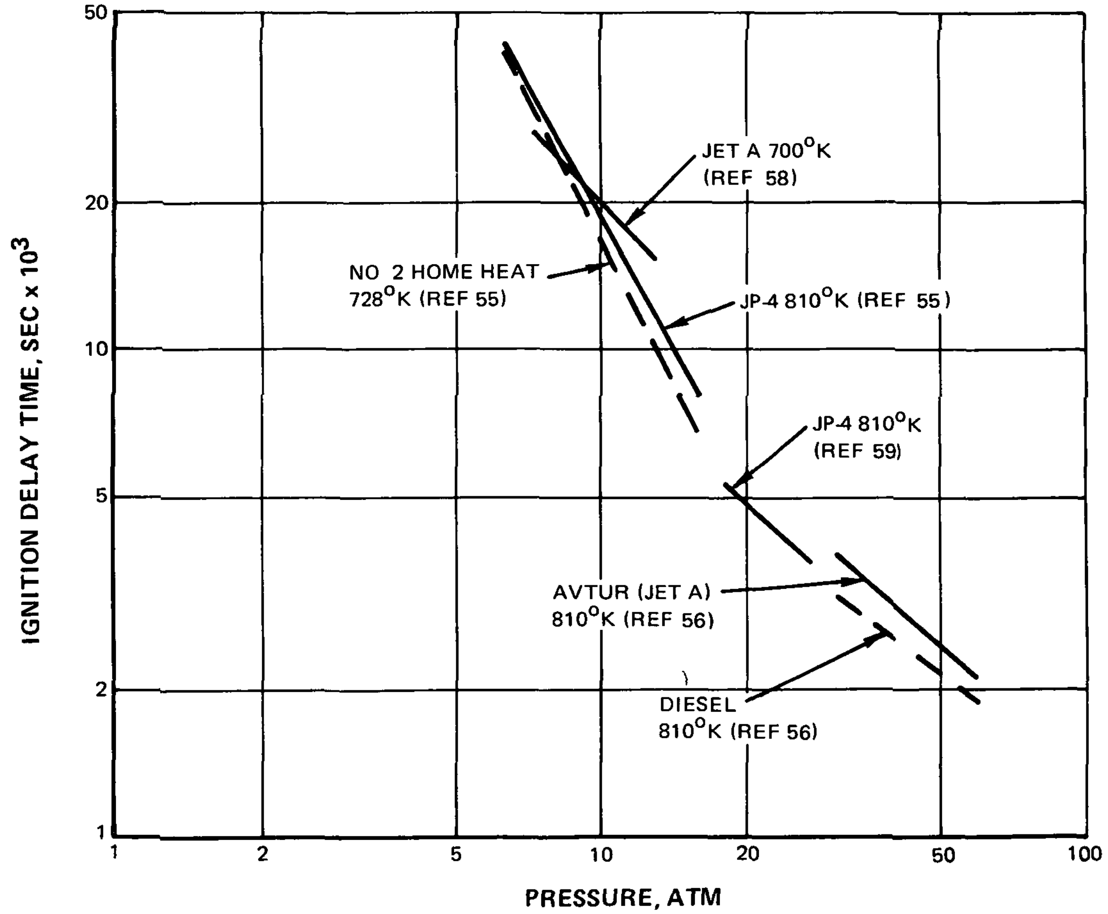


Figure 4-24 Ignition Delay Times for Various Fuels

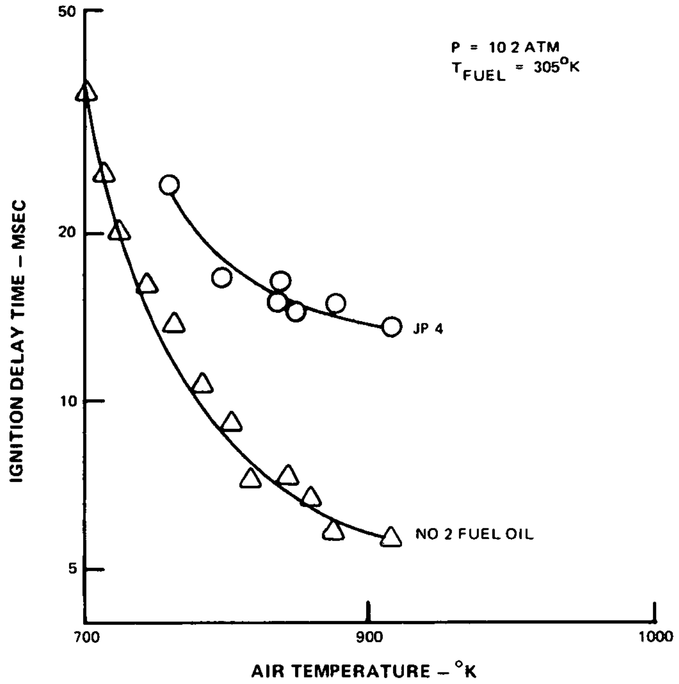


Figure 4-25 Ignition Delay Times of JP-4 and Fuel Oil

This result indicates that for the same factor of safety against autoignition the residence time in premixing passages of a combustor designed for operation on ERBS must be about 16 percent less than those in combustors operating with Jet A fuel. In the case of a combustor with vapor phase fuel injection the reduction in allowable passage length translates into an increment in the extent to which the mixture homogeneity can approach the ideal uniform composition. Since the approach toward homogeniety would most likely be exponential with mixing distance, a 16 percent reduction in passage length might not have a severe effect on mixture homogeneity in a system that was well mixed in the base length. However, by the same rationale, if the mixture produced by the base system operating on Jet A fuel was not homogeneous, the reduction in passage length to comply with the more stringent autoignition constraints of ERBS can be expected to have a large effect on mixture homogenity.

In a liquid phase fuel injection system, the fuel evaporation process in the premixing passage has been shown to require considerable residence time. Applying a factor of safety of 1.7 to the above estimates of the ignition delay times for Jet A and ERBS to assure preclusion of autoignition in the premixing passagae, the allowable passage lengths for the JT9D burner situation of Figure 4-22 are 20.5 cm and 17.2 cm for Jet A and ERBS respectively. With reference to that figure, at these lengths the fuel fractions having the lowest boiling points have just completed evaporation while those at the final boiling of Jet A are 83 percent vaporized and the least volatile components of ERBS are 61 percent vaporized. Based on these computations, an approximate profile of the vaporization fraction has been constructed on Figure 4-26. Only the most volatile fractions of ERBS have sufficient time to completely vaporize in the 17.2 cm long passage, and it is estimated that of the total mass of the fuel about 81 percent will be in the vapor phase at the end of the passage. The longer passage length allowed with Jet A permits components having distillation temperatures below about 475°K; approximately 8 percent by volume; to completely vaporize and the total mass fraction of the fuel vaporized is about 94 percent.

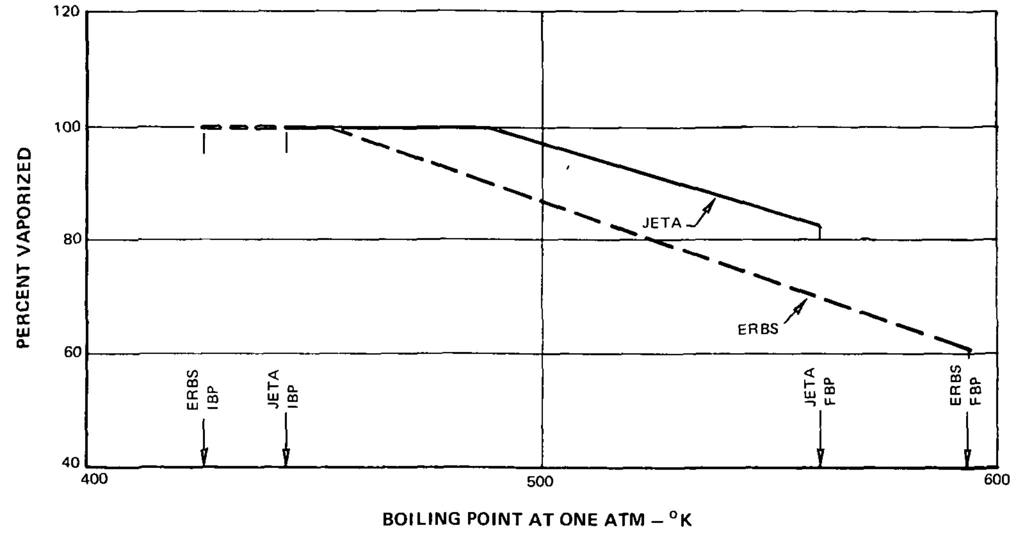


Figure 4-26 Approximate Vaporization Profile at Discharge From a Premixinq Passage

There is not sufficient data available to estimate the effect of this change in the fraction of fuel vaporized on the emissions characteristics of a premixed combustion system. However, limited data is available from comparative tests of a combustor operated on mixtures of liquid Jet A and gaseous propane fuel in various proportions (Reference 60). Interpreting the gaseous fuel as equivalent to vaporized Jet A the results indicated that over the range of 75 to 100 percent "vaporized" fuel the NO_x emissions increased about 0.7 percent for each percent of fuel in the liquid phase. This would imply a 9 percent increase in NO_x emissions from the above cited combustor designed for operation on ERBS relative to that obtained with the longer premixing passage consistent with the Jet A autoignition margin.

An additional area of concern in the design of premixed combustion systems is the risk of flashback which can occur in the situation where the local mixture velocities are less than the flame propagation velocity. The flashpoint temperature of ERBS is projected on Table 2-I to be the same as the lower limit for Jet A fuel and flashback avoidance appears to be more a matter of combustor design than sensitivity to differences in these fuels. The pressure drop across flameholders in premixed combustor are expected to be sufficiently high that the velocity of the mixture in the flameholder aperatures will be as much as an order of magnitude higher than the flame propagation velocities. Length constraints will also force high velocities in the premixing passages which will minimize flashback risks. The presence of regions of recirculating separated flow, particularly in the vicinity of the upstream face of a flameholder that is being heated by the combustion zone presents the greatest risk of flashback and must be eliminated by proper design of the interface region between the premixing passage and the flameholder.

The data and analyses discussed in this section indicate that relaxation of the current Jet A fuel specification to ERBS would have several impacts on the design and anticipated emissions characteristics of premixed prevaporized combustors. These include:

- Reduced ignition delay time requires that premixing passages be designed to about 16 percent less residence time, or equivalently passage length, to provide the same autoignition margin as obtained with Jet A fuel.
- For systems designed for liquid phase fuel injection, evaporation times with good initial atomization of the fuel are of similar magnitude to the allowable premixed passage residence time with reasonable autoignition safety margins. The above reduction in passage length can significantly alter the extent of prevaporization accomplished.
- If the fuel is introduced into the premixing passage in a vapor phase and reasonable homogeneity is achieved with Jet A fuel, the reduction in premixing passage length to satisfy more the stringent autoignition criterion should not compromise the homogeneity significantly.
- The use of ERBS rather than Jet A fuel leads to an increase of about 10 percent in the external heating requirements to preheat fuel for vapor phase injection but heat exchanger surface area requirements are unchanged. The feasibility of such a system, particularly with regard to thermal stability, is yet to be established and additional fuel related problems could be encountered.
- The risk of flashback with ERBS fuel does not appear to be significantly greater than with Jet A fuel and flashback avoidance appears to be more of a design problem than one related to the composition of these fuels.

5.0 DESIGN STUDY

5.1 INTRODUCTION

The influence coefficients and revised design criteria of Section 4.0 were used to conduct design studies on the six reference combustors identified in Section 3.0. The objectives of the design studies were to define the revisions that would be necessary to achieve acceptable performance, emissions, durability and operational characteristics when the reference combustors were operated on ERBS fuel and to identify the areas of uncertainty and those where additional development or improved technology would be necessary.

The approach involved an assessment of each configuration, examining combustor related parameters such as liner durability, emissions, smoke, ignition and stability characteristics and the ability to control the exit temperature distribution. Problems associated with integration of the redesigned combustor with the engine, including revisions to the fuel system and concerns over turbine durability when the fuel specification is relaxed, are considered common to all of the combustors and are discussed in general in the latter parts of this section.

The results of the study indicated that, in the case of single stage and Vorbix combustors, there was no need to change the basic aerothermal definition, i.e., the envelope of the combustor, the number of fuel injectors or the gross characteristics of the airflow distribution, to accommodate the use of ERBS fuel. The discussion of the analysis of these combustors, in Section 5.2, 5.3 and 5.4 follows a common format and includes evaluation of the unaltered reference combustor operating on both Jet A and ERBS followed by perturbations to the configuration to assess the effect of improvements in combustor design and available technology. The lean premixed prevaporized combustors were found to require revision of the basic aerothermal definition to achieve optimum operation on ERBS fuel and the redesign of these combustors is discussed in Section 5.5.

The problems associated with the use of ERBS fuel in regard to the fuel system and turbine durability are discussed in Section 5.6 and 5.7. The design study is concluded in Section 5.8 with an evaluation of the fuel flexibility of the different types of combustors and comments on the general problems associated with relaxing fuel specifications.

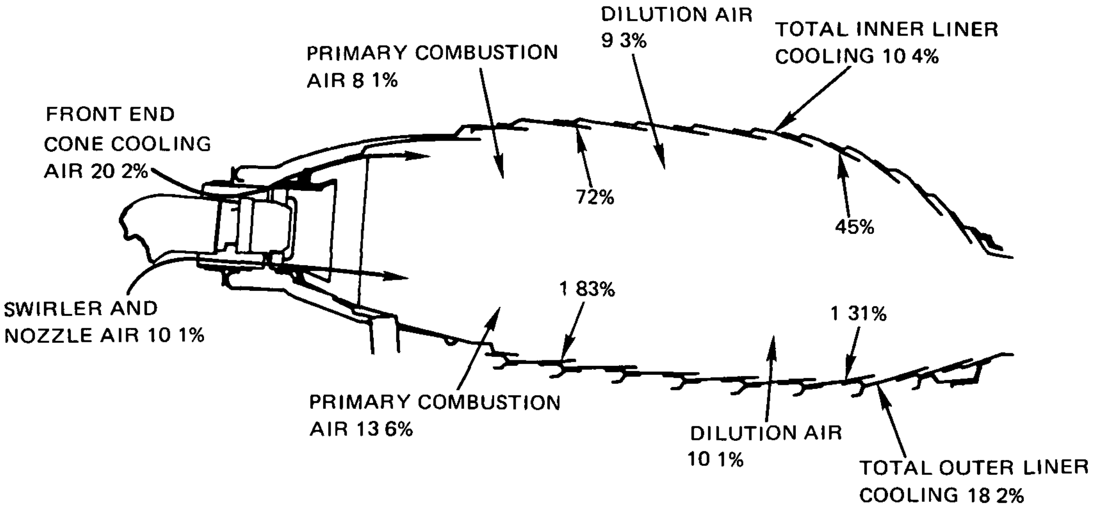
It should be noted that the performance and emissions characteristics of the reference combustors cited in this section are based, in large part, on limited data obtained from experimental combustors, many of which were not evaluated in an actual engine environment. Data on the emissions characteristics are based on nominal conditions and do not reflect margins for engine-to-engine variations or deterioration. It is intended that this information be used primarily to define the relative change in these parameters for the particular design perturbations under consideration.

5.2 JT9D SINGLE STAGE ANNULAR COMBUSTOR

Figure 5-1 shows the airflow distribution and pertinant design and performance parameters for the JT9D-7 single stage combustor as it is currently configured to operate on Jet A fuel. Part A of this figure shows the combustor airflow distribution with the local flows expressed as a percent of the total combustor airflow. The latter is defined as the total airflow entering the turbine inlet vane row and includes a small fraction of the total engine air that enters the gaspath at the downstream end of the combustor liner for the purpose of cooling the leading edge of the turbine inlet vane platforms. This bypass air, amounting to about 4.5 percent of the total combustor airflow is, for the purpose of this analysis, included in the liner cooling airflow. The combustor employs a relatively lean primary combustion zone with 31.8 percent of the combustor air entering through the nozzle swirler and the primary combustion air aperatures in the liner. Nearly 50 percent of the combustor airflow is used for cooling with a large fraction of this being consumed in cooling the swirler cones and falsehead in the front end of the burner. Typical cooling flows to individual louvers are shown on the figure. Other performance parameters, including nominal pressure drops, the primary zone equivalence ratio, exit temperature pattern factor and reference velocity are listed on the table in Figure 5-1. The reference velocity is defined as the velocity that would occur if all of the combustor airflow passed through the maximum crossectional area of the liner at a density corresponding to the compressor exit stagnation condition. The emissions, including the landing-takeoff cycle weighted EPA Parameters and the smoke output from this combustor when operated on Jet A are listed on Table A-2 in the Appendix.

The initial perturbation considered in the study was the situation occurring when this combustor was operated on ERBS fuel without incorporating any revisions to the combustor design. Comparative computations were made to define the change in liner temperatures when operating on the two fuels. The analysis incorporates an energy balance between the various modes of heat transfer to and from the liner to compute local metal temperatures and the radiant heat transfer from the combustion gases was computed from Equations 8, 9 and 10 of Section 4.6 and the values of the luminosity factors defined in that section. In the primary combustion zone, the radiant source is assumed to be the combustion product of stoichiometric proportions, while further downstream this source has a temperature consistent with a hot streak superimposed on the local mixed gas temperature. The incremental increases in liner temperature when the fuel is changed from Jet A to ERBS are shown on Part B of Figure 5-1. The cited temperature increases are those occurring at the knuckle of the louver

A. AIRFLOW DISTRIBUTION WITH JET A FUEL



C. AIRFLOW DISTRIBUTION REQUIRED TO MAINTAIN CURRENT LINER TEMPERATURES WITH ERBS FUEL

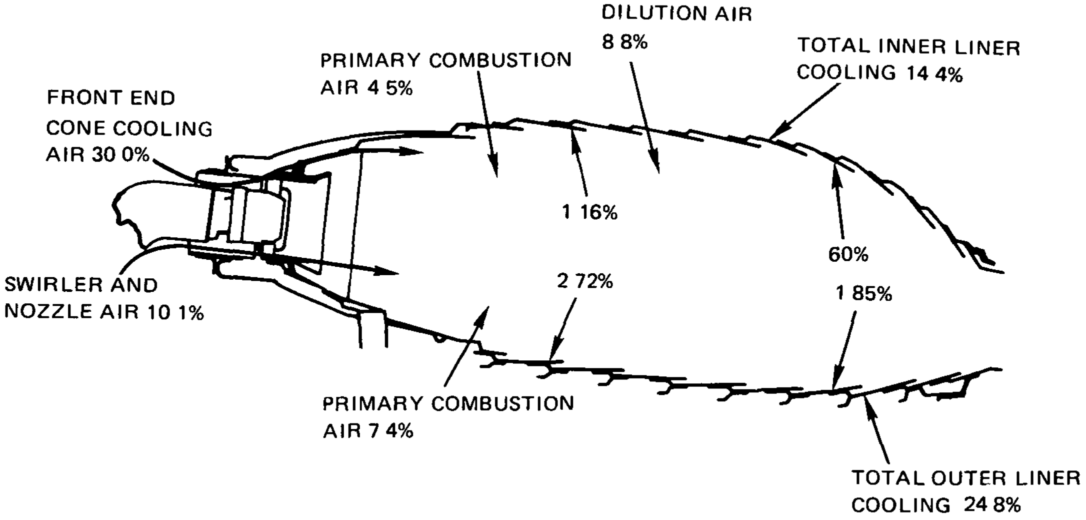
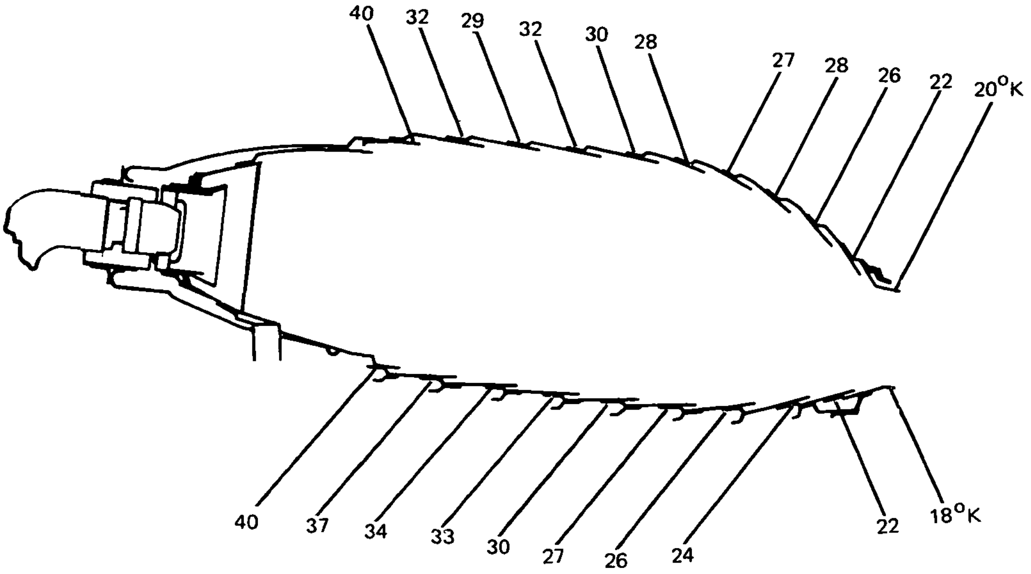


Figure 5-1 Design Variations of Single Stage Combustor for JT9D Engine

B. INCREASE IN LINER TEMPERATURES WITH ERBS FUEL AND AIRFLOW DISTRIBUTION OF A.



COMBUSTOR DESIGN AND PERFORMANCE PARAMETERS FOR CONFIGURATION OF PART A WHEN OPERATING ON JET A FUEL

PRESSURE DROPS AT TAKEOFF	
DIFFUSER LOSS TO BURNER FRONT END	1 0%
DIFFUSER LOSS TO BURNER SHROUDS	3 4%
FRONT END DROP	4 4%
LINER DROP	2 0%
OVERALL SECTION LOSS	5 4%
REFERENCE VELOCITY AT TAKEOFF	25 m/sec
FUEL SYSTEM	20 DUPLEX PRESSURE ATOMIZING INJECTORS
FUEL FLOW PER INJECTOR	
IDLE	41 Kg/hr
TAKEOFF	399 Kg/hr
PRIMARY ZONE EQUIVALENCE RATIO	
IDLE	0 51
TAKEOFF	1 16
PATTERN FACTOR AT TAKEOFF	0 45

Figure 5-1 Design Variations of Single Stage Combustor for JT9D Engine (Cont'd)

which is the critical section for structural integrity of the liner. The results indicate increases in the metal temperature from 18 to 40°K with the higher increases occurring in the louvers around the primary combustion zone. From the point of view of liner life, increases in the metal temperature of 40°K at the takeoff condition would be unacceptable because when weighted over nominal flight profiles, they would produce a 40 percent reduction in the cyclic fatigue life of the liner.

The emissions and smoke formation characteristics of this combustor when operating on ERBS fuel were estimated using the influence coefficients defined in Sections 4.4. and 4.5 and are listed on Table A-3 of the Appendix. Idle carbon monoxide and unburned hydrocarbons and the high power NO_x and smoke output are all shown to increase about 15 percent when this combustor is operated on ERBS.

The tests conducted under the Alternate Fuel Addendum to the Experimental Clean Combustor Program (References 21 and 22) demonstrated that, with a number of different types of combustors and test fuels, the exit temperature pattern factor and radial temperature profile were insensitive to fuel type. Consequently, the use of ERBS fuel in an otherwise unaltered JT9D single stage combustor would not be expected to produce changes in these parameters unless it increased the long term streak production propensity of the fuel injectors.

Based on the discussions of Sections 4.7 and 4.8 the conversion from Jet A to ERBS fuel would not be expected to compromise the acceptable stability characteristics of the JT9D single stage combustor and any deterioration in ignition capability would be attributable to deteriorated atomization of the more viscous ERBS fuel.

In general, the most severe consequence of operating the current JT9D single stage combustor on ERBS fuel appears to be the increase in liner temperatures. While leaning of the primary combustion zone might be considered an approach to reduce, at least, the higher increases in liner temperature, this approach does not appear to be a realistic alternative. The liner thermal analysis is based on the assumption of gas radiation from a locally stoichiometric region in the primary combustion zone regardless of the bulk equivalence ratio. This assumption is realistic for a direct injection combustor and it is doubtful that large benefits in reduced liner heat load through reduction of the primary zone equivalence ratio could be achieved without exploiting a premixed type of fuel induction system to actually eliminate locally higher than nominal equivalence ratios. Reducing the primary combustion zone equivalence ratio through increases in the airflow admitted to this zone could also have adverse effects on the stability and ignition characteristics. Furthermore, it would tend to increase the low power carbon monoxide and unburned hydrocarbon emissions but could be employed to offset the increase in smoke production associated with the use of ERBS.

On this basis, it appears that a more realistic approach to adapting the combustor to the use of ERBS fuel would involve redesigning the liner cooling system to achieve acceptable metal temperature levels. An analysis was conducted to establish the impact of such a change on the performance characteristics. The analysis was subject to the following constraints:

- The liner configuration was unchanged, but the cooling flow to each louver was increased sufficiently to reduce the knuckle temperature to the level obtained when operating on Jet A.
- The stoichiometry of the primary combustion zone was maintained constant to avoid additional impact on emissions, smoke and ignition. Consequently, the increased quantity of liner cooling air had to be offset by a reduction in dilution air.
- The influence of increased cooling on reaction quenching and its effect on emissions was recognized.
- The redistribution of the combustor airflow was accomplished by resizing the liner aperatures to maintain the overall combustor section total pressure loss and liner pressure drops consistent with those tabulated on Figure 5-1.

Part C of Figure 5-1 shows the combustor airflow distribution defined by this analysis. Increases in liner cooling flow of the order of 65 to 35 percent are required in the primary combustion and dilution zone of the combustor respectively to eliminate the excess liner temperatures associated with the use of ERBS and the total fraction of combustor air used for cooling increases to nearly 70 percent of the combustor airflow. At least part of the cone and falsehead cooling air must be assumed to participate in the primary combustion zone reactions and, to maintain the stoichiometry of that zone, the quantity of combustion air entering through the combustion air aperatures on the liner has been reduced proportionately. Some concern exists over this change because it could affect the recirculating flow structure in the primary zone with an adverse effect on stability or ignition. Likewise, the large increase in swirler cone cooling air required to maintain current metal temperature levels could have an adverse effect on ignition by inhibiting fuel dispersion into the vicinity of the ignitor.

The reduction in the quantity of dilution air, from 19.4 percent in the initial configuration to the 8.8 percent indicated on Part C of Figure 5-1 is expected to have a significant effect on the ability to control the combustor exit temperature pattern factor. Data obtained from the testing of experimental JT9D combustors has been used to define the effect of increased cooling and decreased dilution flow on pattern factor and the results are shown on Figure 5-2. The data on the single stage combustors were obtained from comparative tests on experimental JT9D liners in which the liner cooling flow had initially been maintained at current levels and then increased by about 30 percent while simultaneously reducing the dilution flow to maintain a constant liner pressure drop. Data obtained from a Vorbix combustor, tested under Phase II of the Experimental Clean Combustor Program (Reference 5) is also shown. The changes in dilution air on this combustor were made to offset variations in both the liner cooling and combustion zone airflow. As the results indicated both the lean primary zone single stage and the vorbix combustors have similar sensitivities to the quantity of dilution flow with the pattern factor increasing about 0.035 for each percent of combustor airflow removed from the dilution jets. The rich single stage combustor exhibited only about one third of this sensitivity which is probably due to the larger nominal quantity of dilutant air and a rather massive air addition in the intermediate combustion zone of this type of burner which would tend to reduce the intensity of hot streaks entering the dilution zone. It is noted that no effort was expended to optimize the dilution air jet schedule at the lower dilution flow levels during these tests. Consequently, while the trends of Figure 5-2 have been used as a basis for estimating the effect of diluent flow quantity on pattern factor, the sensitivity after development might not be as severe as these data indicate.

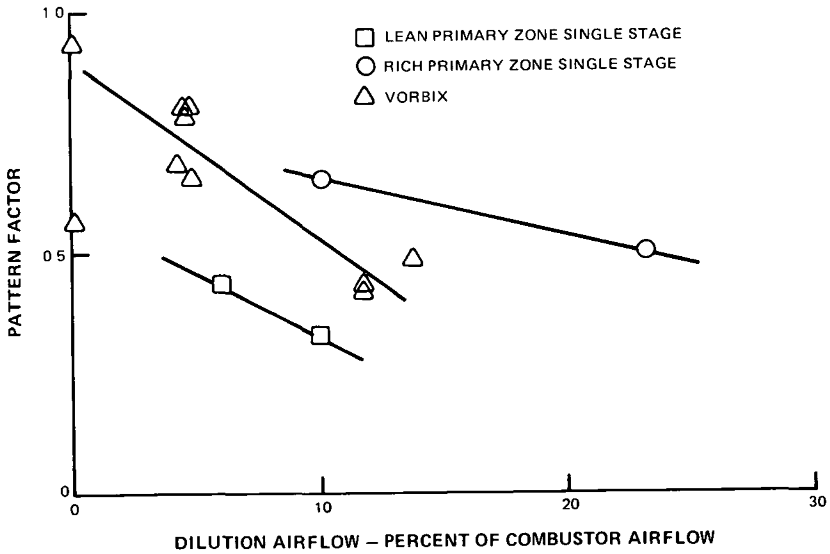


Figure 5-2 Effect of Dilution Air Quantity on Combustor Exit Temperature Pattern Factor

Using the trend of Figure 5-2 for the lean primary zone single stage combustor, the projected decrease of 10.6 percent combustor airflow in the available dilution air in the JT9D single stage combustor would lead to an increase in the pattern factor from the base level of 0.45 to 0.82 - an unacceptable increase from the point of view of turbine inlet vane durability. While similar data has not been generated for the ability to control the exit radial temperature profile, this parameter would not be expected to be as sensitive to available dilution flow as the pattern factor. However, there is most likely, a threshold diluent level below which there is inadequate air available for temperature profile control. Based on experience with experimental combustors, this threshold is probably in the range of 5 to 10 percent of the combustor airflow and this configuration, having 8.8 percent of the airflow available for dilution, has marginal capability of meeting the exit radial temperature profile requirements.

The increase in liner cooling flow would also be expected to have an effect on the emissions characteristics of the combustor, beyond that produced by the change in fuel composition, because of the increased propensity for reaction quenching. Using the measured emissions characteristics of the two lean primary zone combustors discussed above in the context of Figure 5-2, influence coefficients were derived for the change in emissions indices associated with an incremental change in liner cooling flow. The influence coefficients are defined in the form:

$$EI_2 = EI_1 \beta \frac{W_{A\ COOLING\ 2}}{W_{A\ COOLING\ 1}} \tag{12}$$

where values of β, the influence coefficients, are listed in Table 5-I below.

An Entry of NC in Table 5-I indicates that the particular constituent was found to be insensitive to a change in liner cooling flow. Considerable increases in the low power carbon monoxide and unburned hydrocarbons are indicated by these coefficients while the NOx emissions, having influence coefficients significantly below unity tend to decrease with increasing liner cooling flow because of the quenching effect. Based on the liner cooling flows of Parts A and C of Figure 5-1, Equation 12 indicates that the idle carbon monoxide, unburned hydrocarbons and smoke will increase by 47 percent, 136 percent and 50 percent, respectively, while the NOx will decrease by 11 percent. These changes in emissions are beyond those already associated with the change from Jet A to ERBS. A complete tabulation of the emissions indices, EPA Parameters and smoke numbers is provided on Table A-4 of the Appendix.

TABLE 5-I

INFLUENCE COEFFICIENT FOR THE EFFECT OF LINER COOLING FLOW ON THE EMISSIONS FROM LEAN PRIMARY ZONE COMBUSTORS

	Unburned Hydrocarbons	Carbon Monoxide	NO_x	Smoke
Idle	1.73	1.08	0.65	1.09
Approach	1.30	0.80	0.59	NC
Climb	1.27	NC	NC	NC
Takeoff	1.27	NC	NC	NC

In general, increases in the liner cooling flow to return the metal temperature levels in the liner to those obtained with Jet A fuel is not a satisfactory approach to resolving the problem of the increased liner heat load produced by ERBS fuel. Increased cooling flow, while maintaining primary combustion zone stoichiometry, has substantial adverse effects on emissions and may compromise combustion stability and ignition. The required reduction in dilution air also leads to excessively high exit temperature pattern factors and limited capability to control the exit temperature profile.

An additional alternative pursued in the design study was the use of a liner material capable of withstanding higher metal temperatures, or in the absence of such a material, the use of thermal barrier coated on the existing liner. A thermal analysis was conducted, using radiant heat transfer parameters consistent with ERBS fuel, for the case of the current Hastelloy-X liner coated with a thermal barrier of Magnesium-Zirconate. The results indicated that, with the airflow distribution of Part A of Figure 5-1 and at the takeoff operating condition, the metal temperatures underneath the coating would be slightly lower than those encountered with an uncoated liner and Jet A fuel. Consequently, assuming that the coating would be retained over long term operation of the combustor or that an uncoated liner was fabricated from a material having a 40°K higher temperature capability than Hastelloy-X with the same mechanical properties, the airflow distribution of Part A of Figure 5-1 could be retained while using ERBS fuel without compromising the liner life. Other parameters, such as pattern factor, stability and ignition capability would be the same as those indicated previously when the Part A combustor configuration was operated on ERBS fuel. The emissions characteristics would also be consistent with those projected for the use of ERBS fuel in the reference combustor configuration, as listed on Table A-3 of the Appendix except that some improvement in the unburned hydrocarbons might be produced by the hotter walls in the primary combustion zone. It is also noted that the improvement in combustor operation achieved with the introduction of an improved liner material or thermal barrier coating could be accomplished with an improved liner cooling concept having a higher effectiveness.

It was indicated in Sections 4.4 and 4.5 that, at idle power levels, some of the sensitivity of the emissions and smoke to fuel composition may have been due to differences in atomization. Influence coefficients were derived in those sections for the increment in emissions associated with the use of ERBS fuel on the assumption that the atomization of ERBS could be improved to the level currently achieved with Jet A. Improvement in atomization was also shown in Section 4.7 to be desirable from the point of view of ignition, particularly with cold fuels. The discussion of Section 4.3 indicated that the atomization produced by the duplex pressure atomizing fuel injectors in the single stage JT9D combustor in current service could be improved by increasing the fuel pressure drop across the injector and that an increase in the pressure drop of 20 to 25 percent would be required to obtain the degree of atomization achieved with Jet A fuel when operating on ERBS. The mechanics of producing the increase in fuel pressure drop and its implication on the design of the engine fuel system are discussed in a subsequent part of this section. Estimates were made of the performance characteristics of the JT9D single stage burner with the improved fuel atomization produced by higher fuel pressure drops assuming that this approach would be employed in conjunction with an improved liner employing either high temperature capability material, thermal barrier coating or an advanced cooling concept. This combination of design revisions produced the configuration that most successfully offsets the problems associated with the use of ERBS fuel. As indicated in the foregoing discussion of the improved liner design, this approach eliminates compromises in the area of liner life, combustor exit temperature distribution control and local shifting of the stoichiometry or flow-recirculation in the primary combustion zone. The improved atomization characteristics of the higher pressure drop fuel injector are projected to regain the ignition characteristics achieved with Jet A and reduce the sensitivity of the idle emissions to fuel composition. The projected emissions and smoke characteristics of this combustor are listed on Table A-5 of the Appendix.

The design variations to the single stage JT9D annular combustor are summarized on Table 5-II. The need to improve liner or material cooling to accommodate the increase in liner heat load produced by ERBS fuel is evident. Increasing the liner cooling flow to maintain constant liner life is shown to be ineffective in that it produced substantial deterioration in the ability to control pattern factor, increases low power emissions by increments considerably larger than those associated with the change in fuel composition and, if primary combustion zone stoichiometry is maintained constant, may seriously compromise stability and ignition. Improvement in atomization of ERBS fuel also appears desirable from the point of view of low power emissions and ignition capability but would be of secondary significance relative to the liner life/cooling air utilization problem.

TABLE 5-II

SUMMARY OF JT9D SINGLE STAGE COMBUSTOR DESIGN VARIATIONS

Configuration	Fuel	Airflow Distribution On Figure 5-1	Emissions Indices			Takeoff Smoke	Liner Life	Pattern Factor	Stability/Ignition
			Idle CO	Idle THC	Takeoff NO_x				
Reference	Jet A	A	58	27	42.4	4	Base	0.45	Acceptable
Reference	ERBS	A	66	31.3	48.3	4.6	59% of Base	0.45	May require development
Increased Liner Cooling	ERBS	C	97	74	48.3	4.6	Base	0.72	Potentially serious problem
Improved Liner or Thermal Barrier Coating	ERBS	A	66	31.3	48.3	4.6	Base	0.45	May require development
Improved Liner and Fuel Atomization	ERBS	A	61	29	48.3	4.6	Base	0.45	Acceptable

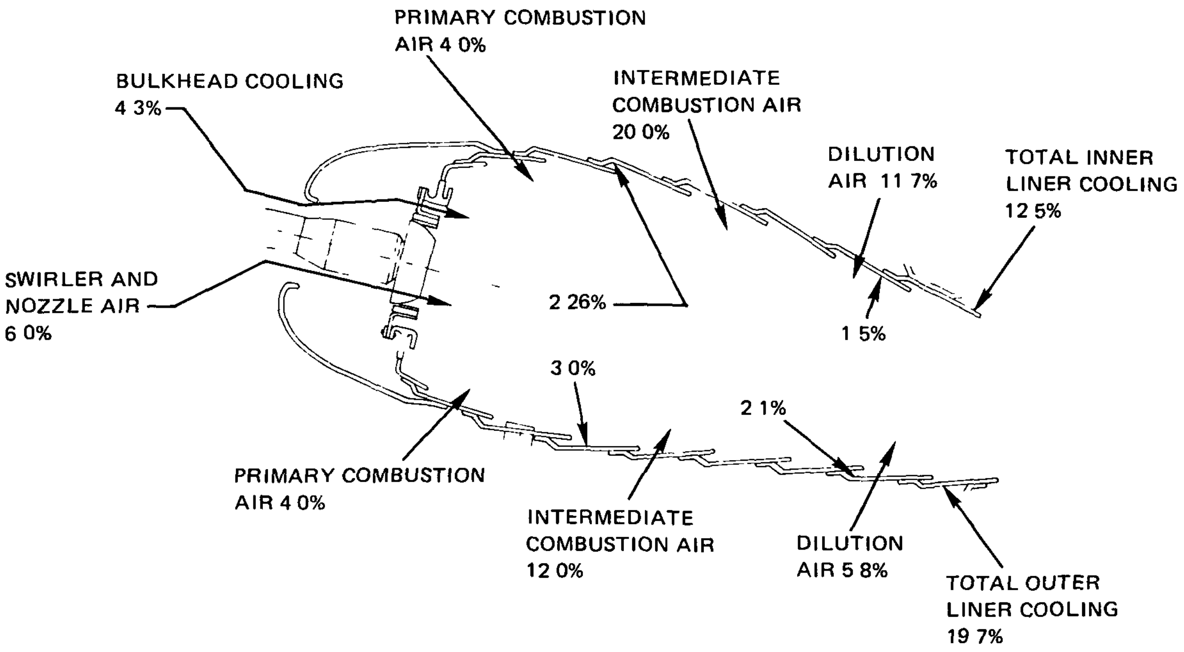
5.3 ENERGY EFFICIENT ENGINE SINGLE STAGE COMBUSTOR

Figure 5-3 shows the airflow distribution and pertinent design and performance parameters for the single stage annular burner in the Energy Efficient Engine. Part A of the figure shows the airflow distribution when the combustor is designed for operation on Jet A fuel. As indicated in Section 3.3, relative to the JT9D-7 single stage combustor, this burner incorporates several advanced features. These include an aerating, as opposed to duplex-pressure atomizing, fuel injector and revised stoichiometry. The airflow to the primary combustion zone; including that through the aerating injector, the primary combustion air holes and part of the bulkhead cooling flow; was selected to produce stoichiometric proportions in this zone at idle power levels to minimize carbon monoxide and unburned hydrocarbon emissions. At takeoff power levels, the equivalence ratio in this zone is about 2.0 and a rapid quench with 32 percent of the combustor air is employed to avoid high NOx production. The combustor liner was also assumed to be fabricated from an Oxide Dispersion Strengthened (ODS) material having the capability of meeting the Energy Efficient Engine liner life goals while operating at liner temperature levels 165^{o}K high that the Hastelloy-X used in the liners for the JT9D combustor. When combined with a shorter combustor length and a bulkhead, rather than cone, front end construction the use of ODS material permits substantial reduction in the total cooling air despite the higher pressure ratio of the EEE cycle.

The design variations considered for this combustor paralleled those analyzed for the JT9D single stage combustor and the results are summarized on Table 5-III. Further details on the projected emissions from this combustor, including the EPA landing and takeoff cycle thrust weighted parameters are listed on Table A-2, A-3, A-4 and A-5 in the Appendix.

The particular experimental combustor selected as the reference for this study produced low carbon monoxide and unburned hydrocarbon emissions at idle but, because of the rich primary zone equivalence ratio, the smoke production at takeoff was very high. Combustors of this type are sensitive to primary zone equivalence ratio and as shown by the data from experimental JT9D combustors on Figure 5-4, a potential tradeoff between idle emissions and takeoff smoke is available with minimal impact on NOx emissions. Further reduction in smoke output and idle carbon monoxide emissions, at the expense of high power NOx emissions, could be achieved by shifting the introduction of part of the intermediate combustion air downstream to permit additional residence time at higher temperature levels to enhance oxidation of these species.

A. AIRFLOW DISTRIBUTION FOR OPERATION ON JET A FUEL



C. REVISED AIRFLOW DISTRIBUTION FOR OPERATION ON ERBS FUEL

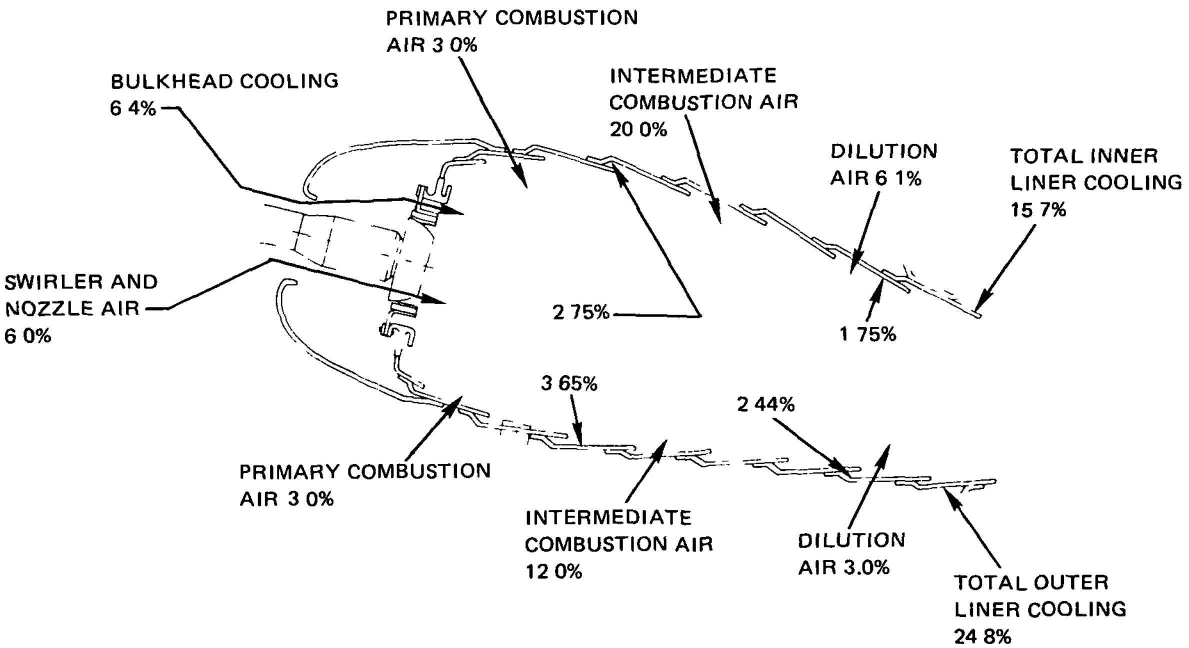
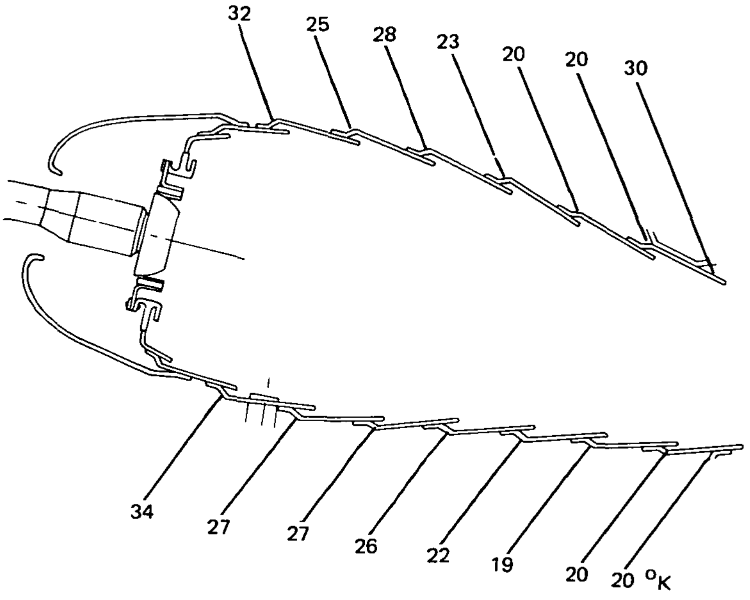


Figure 5-3 Design Variations of Single Stage Combustor for Energy Efficient Engine

B. INCREASE IN LINER TEMPERATURE WHEN COMBUSTOR OF A. IS OPERATED ON ERBS FUEL AT TAKEOFF



COMBUSTOR DESIGN AND PERFORMANCE PARAMETERS FOR CONFIGURATION OF PART A WHEN OPERATING ON JET A FUEL

PRESSURE DROPS AT TAKEOFF	
DIFFUSER LOSS TO BURNER FRONT END	1 0%
DIFFUSER LOSS TO BURNER SHROUDS	3 0%
FRONT END DROP	4 5%
LINER DROP	2 5%
OVERALL SECTION LOSS	5 5%
REFERENCE VELOCITY AT TAKEOFF	19 2 m/sec
FUEL SYSTEM	24 AERATING FUEL INJECTORS
FUEL FLOW PER INJECTOR	
IDLE	19 Kg/hr
TAKEOFF	230 Kg/hr
PRIMARY ZONE EQUIVALENCE RATIO	
IDLE	1 0
TAKEOFF	2 01
PATTERN FACTOR AT TAKEOFF	0 37

Figure 5-3 Design Variations of Single Stage Combustor for Energy Efficient Engine (Cont'd)

TABLE 5-III

SUMMARY OF DESIGN VARIATIONS OF THE SINGLE STAGE COMBUSTOR IN THE ENERGY EFFICIENT ENGINE

Configuration	Fuel	Airflow Distribution On Figure 5- 3	Emissions Indices				Liner Life	Pattern Factor	Stability/Ignition
			Idle CO	Idle THC	Takeoff NO_x	Takeoff Smoke			
Reference	Jet A	A	9.7	0.5	31	61	Base	0.37	Acceptable
Reference	ERBS	A	10.9	0.73	32.5	70	Approx. 63% of Base	0.37	May require development
Increased Liner Cooling	ERBS	C	16.1	1.0	32.5	70	Base	0.47	May require development
Improved Liner Material or Thermal Barrier Coating	ERBS	A	10.9	0.73	32.5	70	Base	0.37	May require development
Improved Liner Material and Fuel Atomization	ERBS	A	10.0	0.56	32.5	70	Base	0.37	Acceptable

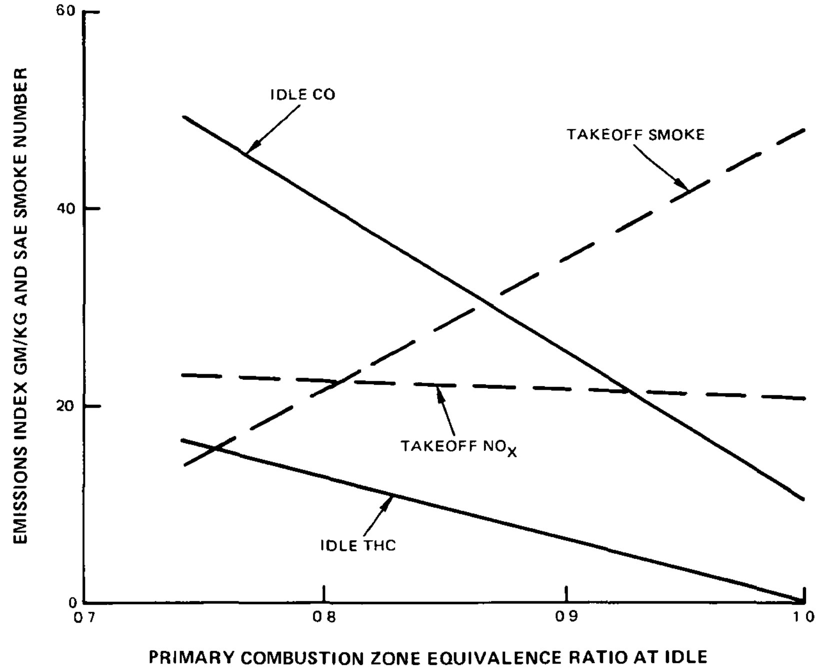


Figure 5-4 Effect of Primary Zone Equivalence Ratio on Emissions and Smoke From Experimental Rich Primary Zone Combustors

As in the analysis of the single stage JT9D-7 combustor, the first perturbation considered was the operation of the reference combustor on ERBS without introducing any combustor design changes. The projected changes in the emissions and smoke production, as listed on Tables 5-III and in more detail on Tables A-2 and A-3, are comparable to those computed for the JT9D single stage combustor. Likewise no deterioration in exit temperature pattern factor or radial profile is anticipated and, if the ignition margin were to deteriorate, it would be caused by the poorer atomization of the more viscous ERBS fuel. Because this burner has considerably less combustion and cooling air in the primary zone than the JT9D single stage combustor, it would be expected to have better ignition capability and, consequently, the ignition margin may not be as severely compromised by deteriorated fuel atomization.

The results of a thermal analysis of the combustor liner, conducted at the sea level takeoff operating condition for the EEE engine are shown on Part B of Figure 5-3 and indicate that the increased luminosity of the combustion products of ERBS will lead to increases in the liner temperature of 19 to 34°K, with the greatest increase occurring in the louvers containing the primary combustion zone. The increments are slightly lower than those predicted for the JT9D combustor. Since the detailed definition of the configuration of the ODS combustor liner was not available at the time of this study, accurate estimates of the deterioration in the cyclic fatigue life because of these increases in liner temperature could not be made. However, assuming that the life deteriorations trend parallels that of the Hastelloy-X liner of the JT9D combustor, the most severe metal temperature increases would result in a 37 percent reduction in liner life.

Redistribution of the combustor airflow to increase the liner cooling flow to the levels necessary to reduce the metal temperatures to the same level projected for operation on Jet A fuel was also analyzed. The perturbation was made subject to the same constraints applied to the similar analysis of the JT9D single stage combustor, i.e., the overall combustor pressure drop and primary combustion zone stoichiometry were maintained at the same level. Comparison of the results of this perturbation in Part C of Figure 5-3 and Table 5-III with the corresponding situation in the JT9D single stage combustor indicates that the change induced in other combustor operating parameters are not as severe as they were in that case. While it was still necessary to increase the total cooling airflow by 28 percent, as opposed to 42 percent in the JT9D combustor, to achieve the required metal temperature reduction, the impact of this increase on the overall airflow distribution is reduced. The dilution airflow available for exit temperature distribution control is reduced from 17.5 to 9.1 percent of the combustor airflow and would be expected to be adequate for radial temperature profile adjustment. The change in pattern factor was estimated from the data of Figure 5-2 using the trend for this type of rich primary zone combustor. Because of the lower slope of this characteristic and the smaller incremental change in dilution air, the projected increase in pattern factor is substantially less than that for the JT9D single stage combustor. While still unacceptable from a turbine durability point of view, the pattern factor could be reduced to the reference level by diverting some of large quantity of intermediate combustor air downstream into the dilution zone of the combustor. While reducing the intensity of the quenching in the intermediate zone might have a slight adverse effect on NOx emissions, the effect of this diversion on both carbon monoxide emissions and smoke output would be expected to be favorable.

Because of the bulkhead front end construction, the nominal cooling flow in the primary combustion zone is much lower than in the JT9D single stage combustor and the increase in this cooling required to accommodate the use of ERBS is not expected to have as significant an effect on ignition, recirculation zone stability or emissions as it did in that combustor. Data from experimental rich primary zone burners was used to define influence coefficients for the effect of liner cooling flow level on the emissions characteristics of this type of combustor in the manner of Equation 12 and Table 5-I. The corresponding values are shown in Figure 5-IV.

TABLE 5-IV

INFLUENCE COEFFICIENTS FOR THE EFFECT OF LINER COOLING FLOW ON THE EMISSIONS FROM RICH PRIMARY ZONE COMBUSTORS

	Unburned Hydrocarbons	Carbon Monoxide	NO_x	Smoke
Idle	1.10	1.20	0.98	.28
Approach	NC	0.87	0.90	.49
Climb	NC	NC	NC	NC
Takeoff	NC	NC	NC	NC

Relative to the coefficients for a lean primary zone combustor, the unburned hydrocarbon and NO_x emissions at low power are less sensitive to increases in cooling flow. The low power carbon monoxide emissions are more sensitive to quenching by the cooling air while the smoke output at these power levels is projected to decrease. Detailed tabulations of the emissions and smoke characteristics are provided in Table A-4 of the Appendix.

The arbitrary assumption of an incremental increase in the liner material temperature capability, cooling system effectiveness or the use of a thermal barrier coating on the liner permitting the retention of the reference airflow distribution while meeting EEE goal liner life and operating on ERBS fuel was introduced into the analysis. As in the case of the JT9D single stage combustor, this assumption permitted resolution of the liner life problem, reduction of the emissions levels to those of Table A-3 in the Appendix and the same exit temperature distribution control capability as the reference combustor operating on Jet A fuel. The ignition characteristics of this type of combustor could still be compromised to some extent by poor atomization of ERBS fuel and the final perturbation considered was an improvement in the atomization by redesigning the aerating fuel injector. As indicated in Section 4.3, a 50 to 70 percent increase in the atomizing airflow through the injector might be required to produce a fuel spray having the same Sauter Mean Diameter as Jet A at a cold fuel ignition condition. This would require a 20 to 30 percent increase in the diameter of the fuel injector. Based on a reference injector diameter of 37 mm the redesigned configuration would be 44 to 48 mm in diameter. Some redesign of the injector support, because of the increased injector mass and of the burner hood to permit injector insertation and removal might be necessary; but these would be expected to be minor. The additional atomization air would be diverted from the primary combustion air jets introduced through the liner to maintain the stoichiometry of that zone and some development would be necessary to assure adequate stability and optimize emissions after this modification. However, relative to the fuel system revisions required to improve the atomization characteristics of a pressure atomizing injector through an increase in pressure drop (c.f., Section 5.6), these changes are of a minor nature.

The improved atomization not only offsets any problems associated with the use of ERBS fuel with regard to ignition but also reduces the low power emissions. As shown on Table 5-III, and in more detail on Table A-5 in the Appendix, the idle carbon monoxide and unburned hydrocarbon emissions are projected to be only slightly higher than those obtained with Jet A fuel.

In summary, the analysis of a more advanced single stage combustor in the Energy Efficient Engine cycle indicates that some of the problems associated with the use of ERBS fuel are not as acute as they are in the more conventional current JT9D single stage combustor. Unacceptable liner life is the most critical problem despite the assumed use of an ODS liner material to be compatible with the EEE cycle and durability goals. Attempting to design the combustor with increased cooling flow to achieve acceptable liner life results in increased low power emissions, but the ability to control pattern factor and radial profile, the stability and the ignition characteristics do not appear to be as adversely affected by the increased liner cooling flow as they were projected to be in the JT9D single stage combustor.

The differences in the impact of the change in fuel specification are attributable primarily to the differences in combustor configuration rather than those of the JT9D and the Energy Efficient Engine cycle. The use of a bulkhead rather than multicone burner construction reduces the cooling air requirements in the primary zone, and in combination with the rich primary zone stoichiometry, minimizes the impact of increased cooling levels on stability, ignition and to some extent, low power emissions. Similarly the shorter liner length with a lower nominal cooling flow level and the availability of excess air in the intermediate combustion zone reduce the sensitivity of exit temperature profile control. Since a combustor of this basic type could be retrofit into the JT9D engine, the reduced sensitivity to change in fuel specification should also be translatable into that engine. The comparative effect of the JT9D and Energy Efficient Engine cycles on the impact of a fuel specification change will be more evident in the discussion of Vorbix and premixed-prevaporized combustors in the following sections. In these cases, the reference combustors in both cycles are more nearly identical.

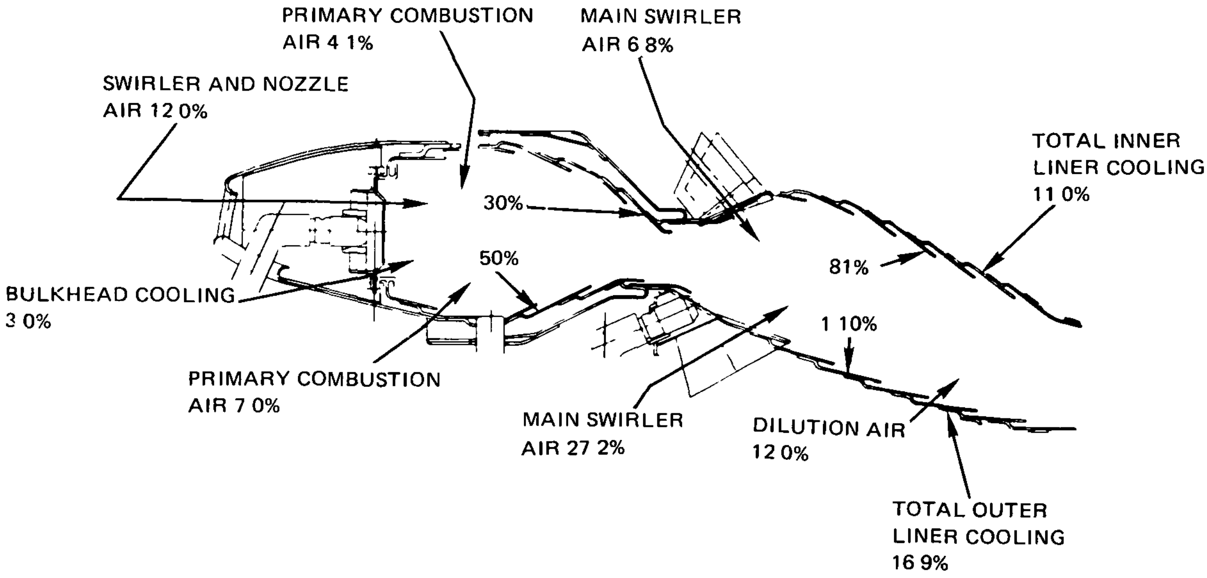
5.4 VORBIX COMBUSTORS

The airflow distribution and pertinent design and performance parameters for the Vorbix combustors for the JT9D and Energy Efficient Engine are shown on Figures 5-5 and 5-6 respectively. As indicated in Section 3.3, the JT9D Vorbix combustor designed for operation on Jet A fuel is that evaluated during Phase III of the NASA-PWA Experimental Clean Combustor Program (Reference 6). The reference EEE Vorbix combustor is, essentially, this configuration adjusted to the airflow size and combustor requirements of the Energy Efficient Engine. As shown on Figures 5-5 and 5-6, critical design parameters such as combustion zone equivalence ratios, fuel source and swirler tube densities and reference velocities have been maintained identical to those of the JT9D counterpart. The only significant differences between the reference designs are:

- An aerating fuel injector is used in the pilot stage of the EEE combustor while the JT9D combustor was evaluated with a pressure atomizing injector in this stage. The aerating injector is used primarily to provide fuel flow turndown capability in the higher pressure ratio cycle.
- The high velocity throat section incorporated at the exit of the pilot stage has been eliminated to minimize possible durability problems. This is not expected to impact the emissions characteristics which have been projected from those of the JT9D combustor with appropriate adjustments for combustor inlet conditions.
- The liner was assumed to be fabricated from an ODS material, rather than the Hastelloy-X used in the JT9D combustor, to be consistent with EEE life goals.
- The liner pressure drops and the sizing of the cooling air louvers, swirler tubes and other liner aperatures reflect the combustor section pressure loss constraints of the EEE program.

The design perturbations on these combustors paralleled those evaluated for the single stage combustors and the results are summarized on Table 5-V and 5-VI. Further details of the emissions characteristics are provided on Table A-2 through A-5 in the Appendix.

A. AIRFLOW DISTRIBUTION FOR OPERATION ON JET A FUEL



C. REVISED AIRFLOW DISTRIBUTION FOR OPERATION ON ERBS FUEL

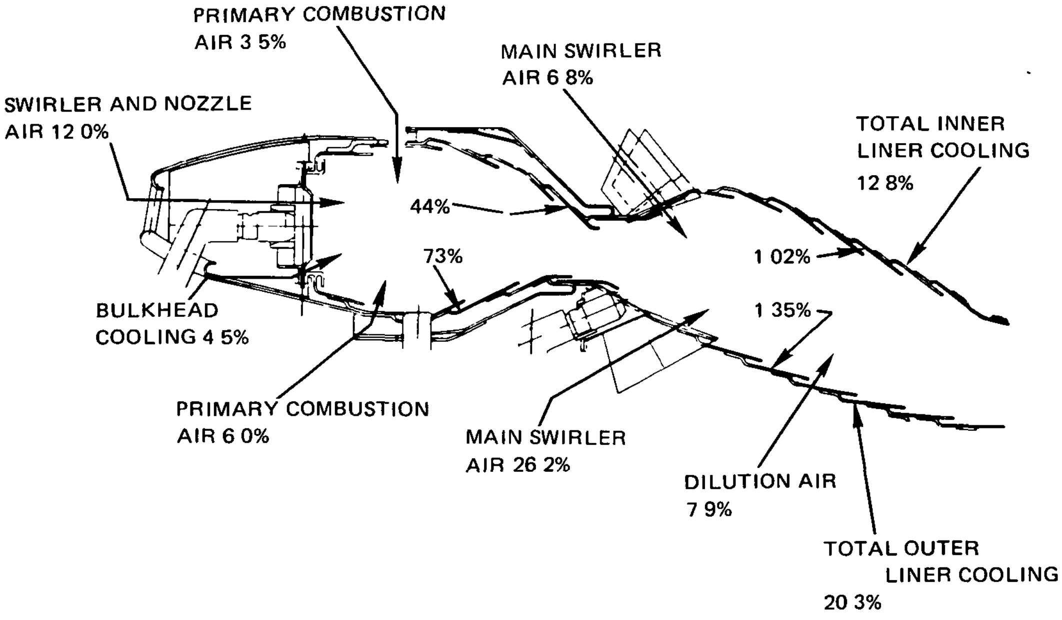
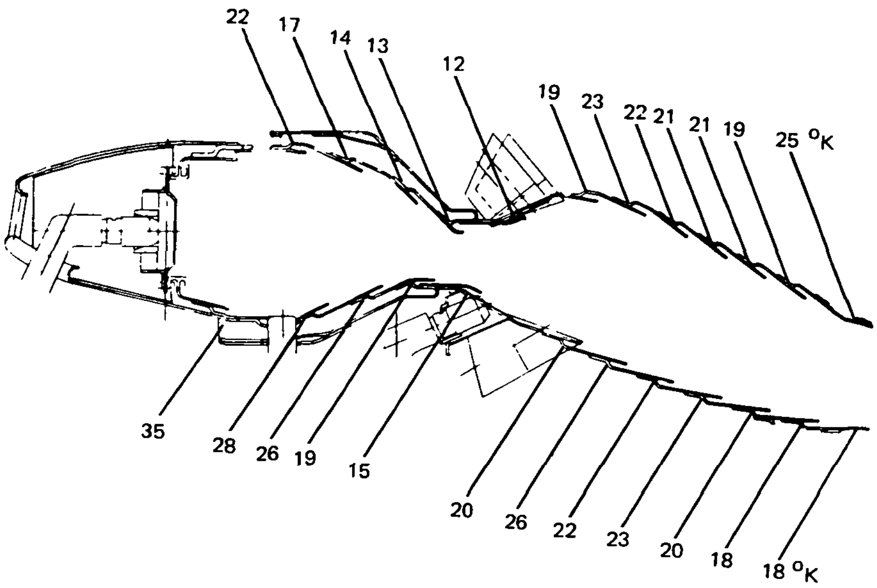


Figure 5-5 Design Variations of the Vorbix Combustor for the JT9D Engine

B. INCREASE IN LINER TEMPERATURE WHEN COMBUSTOR OF A. IS OPERATED ON ERBS AT TAKEOFF

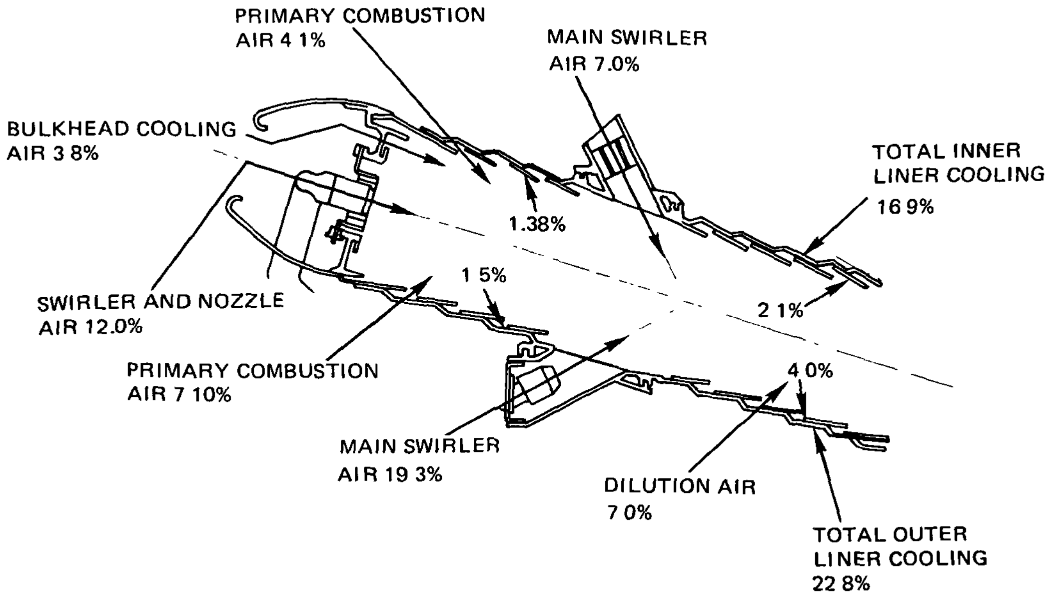


COMBUSTOR DESIGN AND PERFORMANCE PARAMETERS FO CONFIGURATION OF PART A WHEN OPERATING ON JET A FUEL

PRESSURE DROPS AT TAKEOFF		
DIFFUSER LOSS TO BURNER FRONT END	0 9%	
DIFFUSER LOSS TO BURNER SHROUDS	3 5%	
FRONT END DROP	4 6%	
LINER DROP	2 0%	
OVERALL SECTION LOSS	5 5%	
REFERENCE VELOCITY AT TAKEOFF		
PILOT STAGE	21 5 m/sec	
MAIN STAGE	45 m/sec	
FUEL SYSTEM		
PILOT STAGE	30 PRESSURE ATOMIZING INJECTORS	
MAIN STAGE	60 PRESSURE ATOMIZING INJECTORS	
FUEL FLOW PER INJECTOR	PILOT STAGE	MAIN STAGE
IDLE	27 4 Kg/hr	0
TAKEOFF	80 Kg/hr	93 Kg/hr
ZONE EQUIVALENCE RATIOS		
PRIMARY ZONE AT IDLE	0 70	
PRIMARY ZONE AT TAKEOFF	0 47	
PRIMARY AND MAIN ZONE AT TAKEOFF	0 54	
PATTERN FACTOR AT TAKEOFF	0 45	

Figure 5-5 Design Variations of the Vorbix Combustor for the JT9D Engine (Cont'd)

A. AIRFLOW DISTRIBUTION FOR OPERATION ON JET A FUEL



C. REVISED AIRFLOW DISTRIBUTION FOR OPERATION ON ERBS FUEL

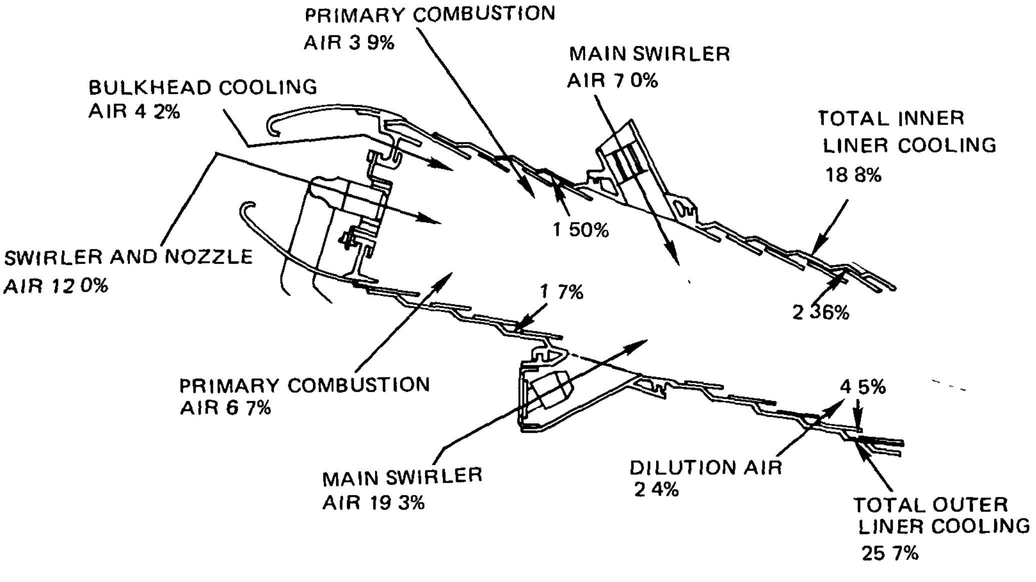
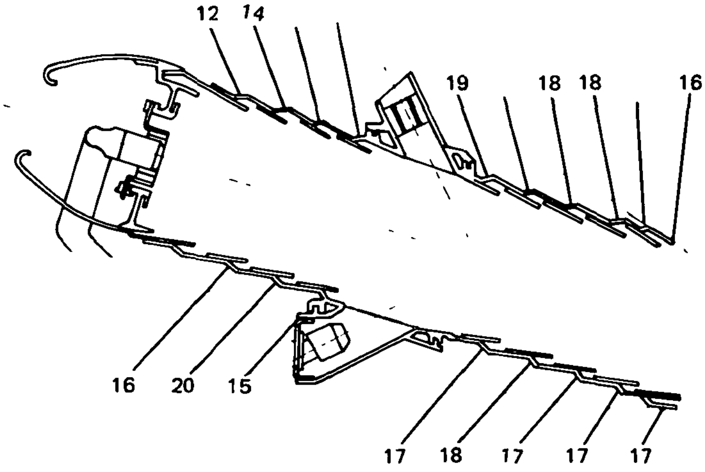


Figure 5-6 Design Variations of the Vorbix Combustor for the Energy Efficient Engine

B. INCREASE IN LINER TEMPERATURE WHEN COMBUSTOR OF A IS OPERATED ON ERBS FUEL AT TAKEOFF



COMBUSTOR DESIGN AND PERFORMANCE PARAMETERS FOR CONFIGURATION OF PART A WHEN OPERATING ON JET A FUEL

PRESSURE DROPS AT TAKEOFF		
DIFFUSER LOSS TO BURNER FRONT END	1 0%	
DIFFUSER LOSS TO BURNER SHROUDS	3 0%	
FRONT END DROP	4 5%	
LINER DROP	2 5%	
OVERALL SECTION LOSS	5 5%	
REFERENCE VELOCITY AT TAKEOFF		
PILOT STAGE	17 6 m/sec	
MAIN STAGE	34 8 m/sec	
FUEL SYSTEM		
PILOT STAGE	24 AERATING INJECTORS	
MAIN STAGE	48 PRESSURE ATOMIZING INJECTORS	
FUEL FLOW PER INJECTOR	PILOT STAGE	MAIN STAGE
IDLE	19 kg/hr	0
TAKEOFF	68 kg/hr	80 kg/hr
ZONE EQUIVALENCE RATIOS		
PRIMARY ZONE AT IDLE	0 75	
PRIMARY ZONE AT TAKEOFF	0 45	
PRIMARY AND MAIN ZONE TAKEOFF	0 55	
PATTERN FACTOR AT TAKEOFF	0 37	

Figure 5-6 Design Variations of the Vorbix Combustor for the Energy Efficient Engine (Cont'd)

TABLE 5-V

SUMMARY OF JT9D VORBIX COMBUSTOR DESIGN VARIATIONS

Configuration	Fuel	Airflow Distribution On Figure 5-5	Emissions Indices Idle CO	Emissions Indices Idle THC	Emissions Indices Takeoff NO_x	Takeoff Smoke	Liner Life	Pattern Factor	Stability/Ignition
Reference	Jet A	A	14.0	1.0	13	30	Base	0.45	Acceptable
Reference	ERBS	A	16.3	1.67	13	33	68% of Base	0.45	May require development
Increased Liner Cooling	ERBS	C	23.0	2.2	13	33	Base	0.60	May require development
Improved Liner or Thermal Barrier Coating	ERBS	A	16.3	1.67	13	33	Base	0.45	May require development
Improved Liner and Fuel Atomization	ERBS	A	16.3	1.0	13	33	Base	0.45	Acceptable

TABLE 5-VI

SUMMARY OF ENERGY EFFICIENT ENGINE VORBIX COMBUSTOR DESIGN VARIATIONS

Configuration	Fuel	Airflow Distribution On Figure 5-6	Emissions Indices Idle CO	Emissions Indices Idle THC	Emissions Indices Takeoff NO_x	Takeoff Smoke	Liner Life	Pattern Factor	Stability/Ignition
Reference	Jet A	A	6.0	0.9	19	41	Base	0.37	Acceptable
Reference	ERBS	A	7.0	1.5	19	45	Approx 75% of Base	0.37	May require development
Increased Liner Cooling	ERBS	C	9.3	1.85	19	45	Base	0.56	May require development
Improved Liner or Thermal Barrier Coating	ERBS	A	7.0	1.5	19	45	Base	0.37	May require development
Improved Liner and Fuel Atomization	ERBS	A	7.0	0.9	19	45	Base	0.37	Acceptable

As in the case of the single stage combustors, when the reference combustors were assumed to be operated on ERBS fuel without introducing any design revisions, some concern arose over the ignition capabilities of the combustors, particularly at cold fuel conditions, because of poorer fuel atomization. Increases in the emissions and smoke were also projected, but the high power NO_x was found insensitive to changes in fuel composition. The most profound increase in emissions is a nearly 70 percent increase in the unburned hydrocarbons at idle, but this increment has been associated with an atomization sensitivity that might be minimized by fuel injector modification.

The thermal analysis of the liners in these combustors was conducted at the sea level takeoff operating condition of the appropriate engine and the incremental increase in liner temperature when the combustor is operated on ERBS rather than Jet A fuel are shown on Part B of Figures 5-5 and 5-6. In general, the increases in liner temperatures are not as pronounced as those predicted for the corresponding single stage combustors. In the EEE Vorbix combustor, the highest liner temperature rise is 20°K while the maximum temperature increase in primary combustion zone area of the corresponding single stage combustor was 34°K. Likewise, in the JT9D Vorbix combustor, with the exception of one louver in the pilot stage, the local metal temperature increments are 28°K or less while nearly two thirds of the louvers in the corresponding single stage combustor were projected to experience temperature increases of more than 28°K. This difference is due in part to the lean combustion occuring in both stages of the Vorbix burner when operating at high power levels. The reference velocities in the Vorbix combustors are also higher than in the single stage combustors which leads to increased convective heat load on the liners. As a result, the increment in radiant heat load produced by the change from Jet A to ERBS fuel is a smaller fraction of the total heat load and results in a smaller increase in metal temperature.

Higher liner cyclic lives are also projected as a consequence of the reduced metal temperature increments. Assuming that the 35°K temperature increase on one louver in the pilot of the JT9D combustor can be reduced by a minor adjustment of the cooling flow, the life of the liner was estimated on the basis of the 28°K increase in metal temperature. Based on the cyclic endurance properties of Hastelloy-X liners, the deterioration in liner life associated with this temperature increment was projected to be 32 percent. Lacking complete information on the configuration of the ODS liner in the combustor for the EEE, a similar projection could not be made for this liner but a 25 percent reduction in cyclic life is estimated based on the assumption of cyclic life deterioration characteristics paralleling that of the Hastelloy-X liner.

The effect of the change in heat load is more evident on considering the design perturbation in which the cooling flow was increased to the level necessary to reduce the liner metal temperatures to the levels encountered when operating on Jet A fuel. Using the same constraints applied to the analysis of the single stage burners, the corresponding combustor airflow distributions are shown on Part C of Figures 5-5 and 5-6. The increases in liner cooling are not as pronounced as in the single stage combustor, increasing by factors of only 1.22 and 1.12 in the JT9D and EEE combustors, respectively. The corresponding factors for the increase in cooling flow in the single stage combustors were 1.42 for the JT9D combustor and 1.28 for the advanced single stage burner in the EEE. In addition to demonstrating a reduced sensitivity of the combustion products to changes in the luminosity, these results also indicate a dependence on the engine cycle. The liner temperature increments, life deterioration increments and quantity of additional cooling air required to offset these increments are all lower in the higher pressure ratio Energy Efficient engine cycle. This occurs because the increase in radiant heat load produced by the change in fuel composition is a smaller increment relative to the total heat load imposed on the liner in the higher pressure ratio cycle.

While the changes in cooling flow necessary to reduce the liner temperatures to the levels encountered with Jet A are smaller than those required in single stage combustors, they still are of sufficient magnitude to influence the ability to control the exit temperature distribution, the emissions and ignition characteristics. The nominal dilution flow is low in Vorbix combustors because of the need to maintain lean mixture strengths in the main combustion zone to minimize NO_x production, but pattern factor control can be accomplished because the higher fuel source density and vigorous mixing produced by the swirling main combustion air apparently produces a more homogeneous discharge flow than encountered in single stage combustors. Increments in pattern factor were defined on the basis of the data of Figure 5-2 and, while being lower than those projected for the JT9D single stage combustor are still unacceptable from the point of view of turbine inlet vane durability. The 2.4 percent of combustor airflow available for dilution in the EEE combustor is probably also inadequate for control of the exit radial temperature profile and some flow would have to be diverted from the secondary swirler tubes, with an adverse effect on NO_x production, to satisfy this requirement.

The projected changes in the emissions characteristics were based on the influence coefficients of Table 5-IV because at idle conditions, where the quenching effect of increased liner cooling is significant, the pilot zone of the Vorbix combustor operates at relatively rich proportions. The increases in low power emissions listed on Table 5-V and 5-VI are not as large as those encountered in single stage combustors because the change in liner cooling flow is not as large. The increase in cooling in the primary combustion zone could also influence stability and ignition but, because of the bulkhead construction of the pilot stages, the effect of greater cooling is not expected to have the profound effect anticipated in the JT9D single stage combustor. The ignition enhancement concepts discussed in Secion 4.7 might have to be employed to provide adequate margin.

As in the case of the single stage combustors, analyses were conducted of perturbations involving improved liner materials or cooling effectiveness and improved fuel atomization both independently and in combination. Improved atomization concepts were considered only in the pilot stage because they are projected to benefit only ignition and idle emissions. The data analyzed in Section 4.4 indicated that the idle carbon monoxide emissions were not atomization sensitive but that the entire increment in unburned hydrocarbon emissions at idle may be attributable to deteriorated atomization and not to fuel chemistry. The improvement in atomization would be accomplished by the same means proposed for the single stage combustors; i.e., increasing the pressure drop across the pressure atomizing-injector in the JT9D vorbix burner and increasing the atomizing airflow in the aerating injector in the EEE combustor by increasing the physical size of the injector. The corresponding projections of the emissions characteristics are shown on Table 5-V and 5-VI and in more detail on Table A-5.

In summary, the analysis of the Vorbix combustors have indicated that because of high reference velocities and lean combustion processes, the incremental increases in liner temperature, liner life deterioration and the increases in cooling air required to offset them are not as severe as in the single stage combustors. Nonetheless, the imposition of higher heat load on the liner through the use of ERBS rather than Jet A still causes severe decreases in liner cyclic life that must be offset by the introduction of improved liner materials, coatings or advanced cooling concepts. Attempting to circumvent the liner life problem by increasing cooling flow reduces the ability to control exit temperature distribution, leads to projected increases in the low power emissions beyond those associated with the use of ERBS fuel and could aggravate the ignition characteristics. While the magnitude of these penalties are not as severe as in a single stage combustor because the increase in cooling flow required is not as severe, they are of sufficient size to be of major concern.

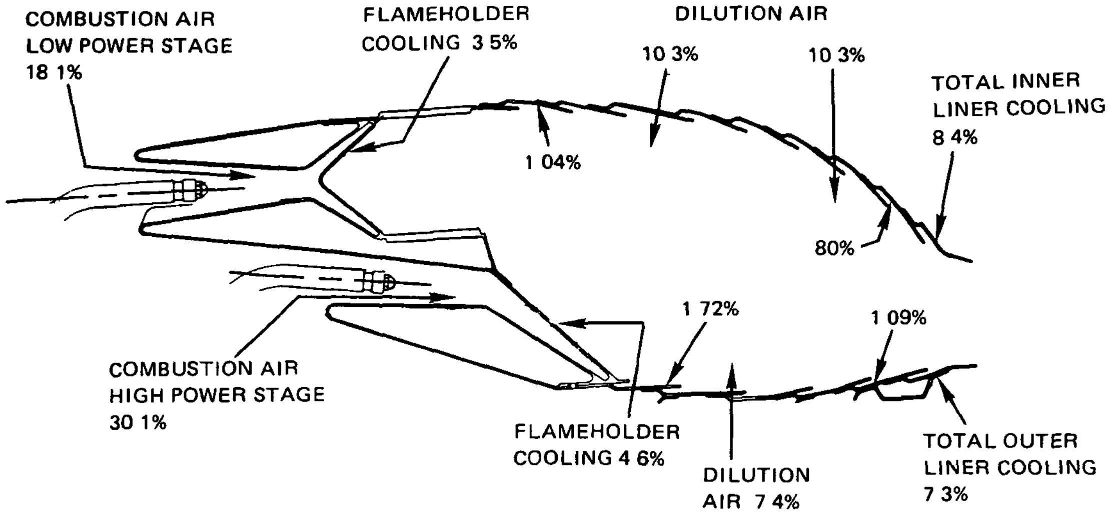
The analysis of similar combustors in the JT9D and Energy Efficient Engines indicates that; assuming liner material is available that is compatable with the thermal environment and life requirements when the combustor is operating on Jet A fuel; the change in liner temperatures and life associated with the use of ERBS fuel will be less in higher pressure ratio cycles.

The impact of a change of fuel specification from Jet A to ERBS on the overall performance of Vorbix type combustors would be minimized by the introduction of two new technology features: A liner capable of withstanding the more severe thermal environment without an increase in cooling flow or a deterioration in life and an improved pilot stage fuel injector producing the degree of atomization achieved with Jet A while operating on ERBS. With the incorporation of these concepts, it appears that from the viewpoint of combustor performance, durability, emissions and operation characteristics, the penalties associated with the use of ERBS are limited to a 16 percent increase in carbon monoxide emissions at idle and a 10 percent increase in high power smoke output. Both of these appear, at this time, to be fuel chemistry dependent and their response to development without compromising other parameters cannot be assured.

5.5 PREMIXED COMBUSTORS

As indicated in Section 3.3, it is anticipated that the lean premixed prevaporized type of combustors, that could be incorporated in commercial aircraft engines in the future to permit compliance with stringent regulation of the NO_x emissions, will benefit from technology currently being evolved under the NASA Lean Premixed Prevaporized Combustor Technology (LPPC) Program (Reference 8). Consequently, the configuration of these combustors is expected to deviate considerably from those that have been designed to date. It was also indicated in that section that the aspects requiring the greatest improvement are fuel preparation and stoichiometry control over the entire engine operating range. It was anticipated that the latter would require the use of variable geometry components. Despite these conceptual differences it was concluded that the two stage premixed combustor designed for compatability with the JT9D engine and evaluated under Phase I of the PWA-NASA Experimental Clean Combustor Program (Reference 4) could be used as the reference configuration for the purposes of this study. Analysis of the effect of fuel composition could be conducted in the context of this configuration and the results generalized to advanced technology premixed prevaporized combustors.

Figure 5-7 shows the airflow distribution in and the pertinent performance parameters of the two stage premixed combustor as it was designed for operation on Jet A fuel. The airflow in the premixing passages has been established on the basis of providing optimum primary zone stoichiometry at idle and at takeoff. At idle, only the pilot stage is fueled and the airflow to that stage is consistent with a combustion zone equivalence ratio of about .8 to provide an optimum carbon monoxide - NO_x emissions tradeoff at that condition. The airflow in the main stage is based on achieving an equivalence ratio of 0.65 in this zone at sea level takeoff - this equivalence ratio being selected on the basis of minimizing NO_x emissions while



COMBUSTOR DESIGN AND PERFORMANCE PARAMETERS

PRESSURE DROPS AT TAKEOFF		
DIFFUSER LOSS TO BURNER FRONT END	1 0%	
DIFFUSER LOSS TO BURNER SHROUDS	3 2%	
FRONT END DROP	5 1%	
LINER DROP	2 9%	
OVERALL SECTION LOSS	6 1%	
REFERENCE VELOCITY AT TAKEOFF	25 m/sec	
PREMIXING PASSAGES	LOW POWER STAGE	HIGH POWER STAGE
RESIDENCE TIME AT TAKEOFF	1 47 m sec	1 8 m sec
VELOCITY AT TAKEOFF	66 m/sec	66 m/sec
LENGTH	97 mm	119 mm
FUEL FLOW AT IDLE	820 Kg/hr	0
FUEL FLOW AT TAKEOFF	3060 Kg/hr	4920 Kg/hr
PRIMARY ZONE EQUIVALENCE RATIOS		
IDLE	0 8	0
TAKEOFF	0.65	0 65

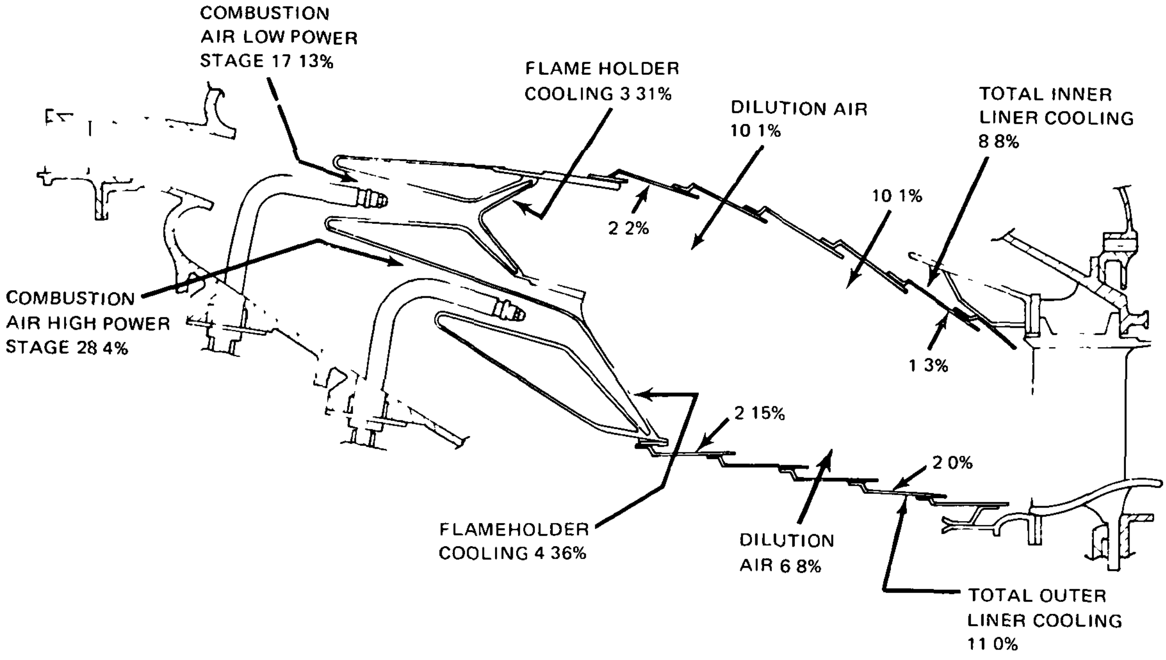
Figure 5-7 Premixed Combustor Designed for Operation on Jet A Fuel in the JT9D Engine

retaining adequate flameholder stability margin. In the advanced technology premixed prevaporized combustor this stoichiometry control would probably be provided by employing a single variable geometry premixing passage. The airflow through this passage would be coordinated with the power setting and provide a range of primary combustion zone airflows between about 20 percent at idle and 56 percent at maximum power. It is likely that the Lean Premixed Prevaporized Combustor Program will also lead to enhanced flameholder stability concepts permitting operation at primary zone equivalence ratios below .65 at high power levels which would require extending the maximum airflow capacity of the premixing passage beyond 56 percent of the combustor airflow. The air not admitted into the primary zone at low power levels would enter the combustor through variable area apertures in the liner in the vicinity of the dilution air holes shown on Figure 5-7 so as to maintain a relatively invariant overall combustor section pressure drop.

The premixing passages on this combustor have been designed for a maximum residence time of 1.8 milliseconds to provide adequate margin against autoignition of the Jet A fuel. The passages operate at an air velocity of 66 meters/sec at sea level takeoff and velocities of this magnitude are required if the premixing section of the combustor is to be compatible with the geometry of existing diffuser and burner cases and combustion section length constraints.

Figure 5-8 shows the corresponding premixed combustor designed for the Energy Efficient Engine. As indicated on the tables on the figures, this combustor has been designed to the same basic concepts as that for the JT9D engine and critical parameters such as stage equivalence ratios, reference velocities and fuel injector density are maintained consistent with that design. Requirements such as flameholder surface area and combustion zone lengths and volumes have been adjusted to reflect the higher pressure ratio of the EEE cycle. In particular, the data of Reference 55 indicates that, because of the higher combustor inlet pressures and temperatures, the residence time in the premixing passages must be reduced to less than half that allowed in the JT9D combustor to maintain the same autoignition margin. In the design of Figure 5-8 this has been accomplished by a combination of reducing the length of and increasing the velocity in these passages.

As in the previously analyzed combustors, the liner of the premixed burner for the Energy Efficient Engine was assumed to be louver cooled and fabricated of ODS material while that for the JT9D engine was made from Hastelloy-X.



COMBUSTOR DESIGN AND PERFORMANCE PARAMETERS

PRESSURE DROPS AT TAKEOFF		
DIFFUSER LOSS TO BURNER FRONT END	1 0%	
DIFFUSER LOSS TO BURNER SHROUD	3 0%	
FRONT END DROP	4 5%	
LINER DROP	2 5%	
OVERALL SECTION LOSS	5 5%	
REFERENCE VELOCITY AT TAKEOFF	21 6 m/sec	
PREMIXING PASSAGES	LOW POWER STAGE	HIGH POWER STAGE
RESIDENCE TIME AT TAKEOFF	0 8 m sec	0 8 m sec
VELOCITY AT TAKEOFF	82 m/sec	82 m/sec
LENGTH	66 mm	66 mm
FUEL FLOW AT IDLE	455 kg/hr	0
FUEL FLOW AT TAKEOFF	2115 kg/hr	3385 kg/hr
PRIMARY ZONE EQUIVALENCE RATIOS		
IDLE	0 80	0
TAKEOFF	0 65	0 65

Figure 5-8 Premixed Combustor Designed for Operation on Jet A Fuel in the Energy Efficient Engine

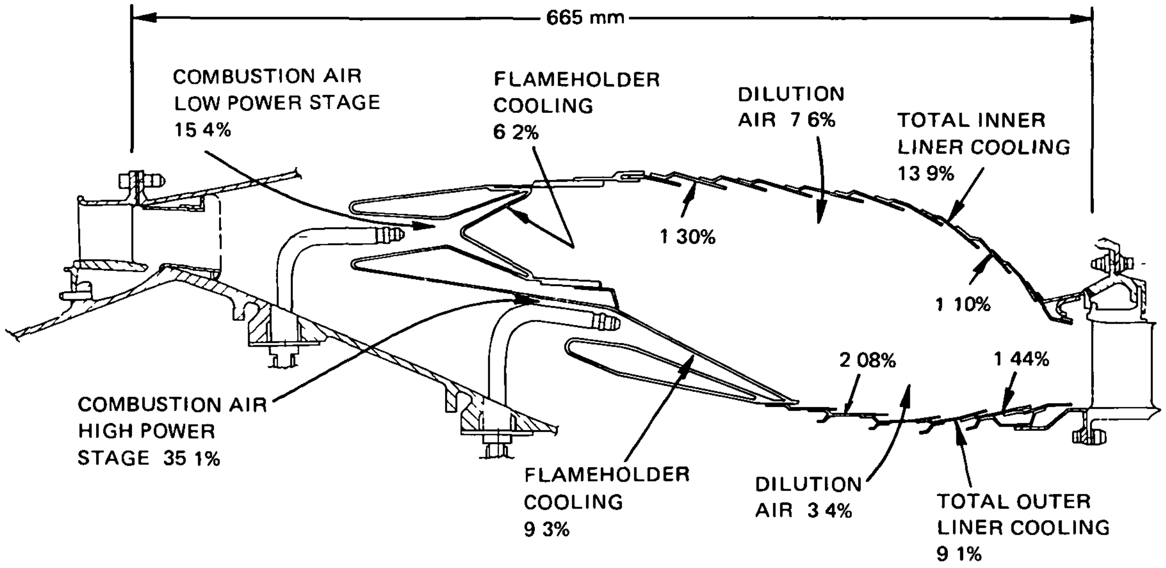
Operation of the premixed combustor on ERBS fuel requires consideration of several aspects developed in Section 4.0 of this report. These include:

- Assesssment of the effect of fuel composition on the stability characteristics of premixed combustors indicated sensitivity that will require redesign of the combustor. The use of ERBS fuel was projected to cause a reduction in the low pressure stability of bluff body flameholders and could lead to blowout at high altitudes. It was also indicated in that discussion that the stability characteristics achieved with Jet A fuel could be obtained with ERBS if the blocked surface area of the flameholder was increased by 50 percent.

- While the use of ERBS fuel was projected to reduce altitude stability; at the higher airflow loadings associated with high power operation of the combustor it enhanced stability. It was projected that the primary combustion zone equivalence ratio could be reduced by about 17 percent while maintaining the stability margin achieved with Jet A fuel. By taking advantage of this improvement in stability and redesigning to an increased primary zone airflow at higher power levels the NO_x emissions may be reduced.

- ERBS fuel is projected to have a greater propensity for autoignition than Jet A and to maintain equal safety margins the residence time in the premixing passages must be reduced by 16 percent relative to those permitted with Jet A. While this modification will not have a profound effect on the geometry of the combustor, it further limits the ability of achieving the homogeneous prevaporized mixture necessary to minimize NO_x production.

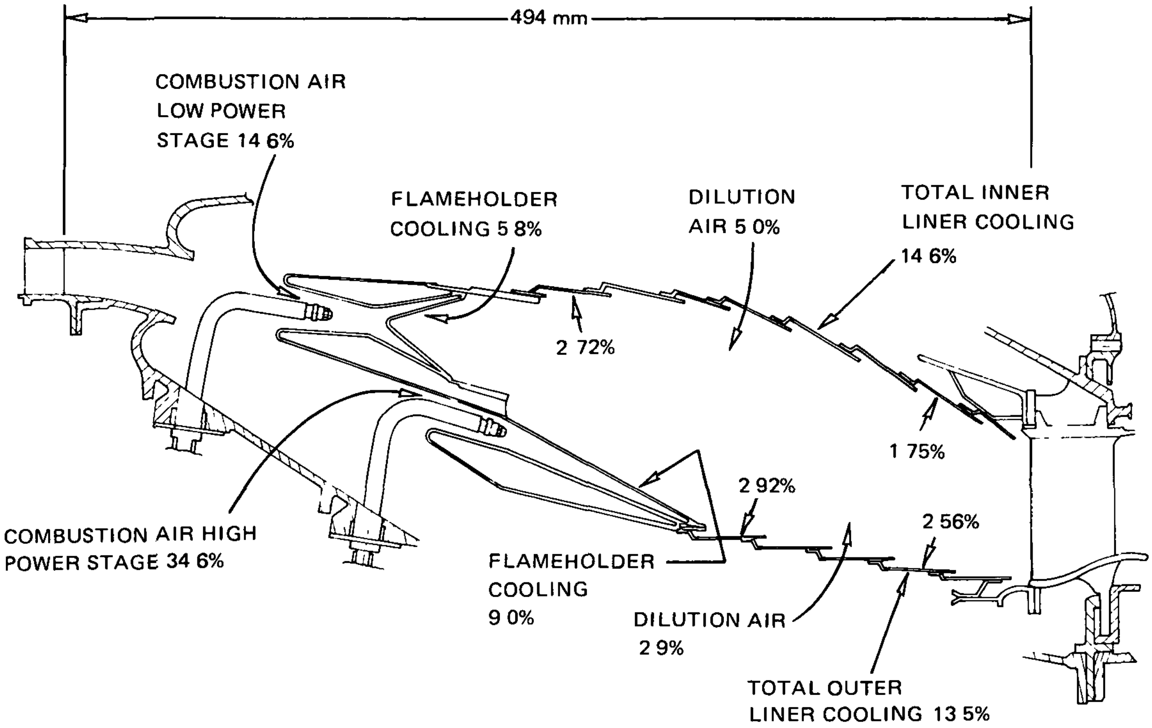
Figures 5-9 and 5-10 show the configurations of the premixed combustors as redesigned for operation on ERBS. The airflow distributions reflect the increase in allowable primary zone combustion air because of the enhanced high power stability anticipated with ERBS. The full extent of the 17 percent increase in airflow does not appear in the premixing passages because the flameholder cooling air is also assumed to participate in the reactions in the primary zone and this airflow has also been increased in proportion to the surface area being cooled. Since the stoichiometry of the pilot stage is dictated by optimum low power emissions, the airflow to this stage has been maintained constant and the excess air is introduced through the premixing passage on the main stage. The fuel split between stages would have to be adjusted at high power levels so that both stages operate at the same 0.54 equivalence ratio at the takeoff condition. When interpreted in the context of a variable geometry premixing section, the reduction in the equivalence ratio in the primary zone at high power levels and the need to increase the flameholder cooling flow results in the requirement of a greater range of variability in the airflow capacity of the premixing section.



COMBUSTOR DESIGN AND PERFORMANCE PARAMETERS

PRESSURE DROPS AT TAKEOFF		
DIFFUSER LOSS TO BURNER FRONT END	1.0%	
DIFFUSER LOSS TO BURNER SHROUS	3 2%	
FRONT END DROP	5 1%	
LINER DROP	2 9%	
OVERALL SECTION LOSS	6 1%	
REFERENCE VEOCITY AT TAKEOFF	25 m/sec	
PREMIXING PASSAGES	LOW POWER STAGE	HIGH POWER STAGE
RESIDENCE TIME AT TAKEOFF	1 5 m sec	1 5 m sec
VELOCITY AT TAKEOFF	66 m/sec	66 m/sec
LENGTH	97 mm	95 mm
FUEL FLOW AT IDLE	820 kg/hr	0
FUEL FLOW AT TAKEOFF	2610 kg/hr	5370 kg/hr
PRIMARY ZONE EQUIVALENCE RATIOS		
IDLE	0 80	0
TAKEOFF	0 54	0 54

Figure 5-9 Premixed Combustor Designed for Operation on ERBS Fuel in the JT9D Engine



COMBUSTOR DESIGN AND PERFORMANCE PARAMETERS

PRESSURE DROPS AT TAKEOFF		
DIFFUSER LOSS TO BURNER FRONT END	1 0%	
DIFFUSER LOSS TO BURNER SHROUDS	3 0%	
FRONT END DROP	4 5%	
LIKNER DROP	2 5%	
OVERALL SECTION LOSS	5 5%	
REFERENCE VELOCITY AT TAKEOFF	21 6 m/sec	
PREMIXING PASSAGES	LOW POWER STAGE	HIGH POWER STAGE
RESIDENCE TIME AT TAKEOFF	0 67 m sec	0 67 m sec
VELOCITY AT TAKEOFF	82 m/sec	113 m/sec
LENGTH	56 mm	76 mm
FUEL FLOW AT IDLE	455 kg/hr	0
FUEL FLOW AT TAKEOFF	1752 kg/hr	3748 kg/hr
PRIMARY ZONE EQUIVALENCE RATIOS		
IDLE	0 80	0
TAKEOFF	0 54	

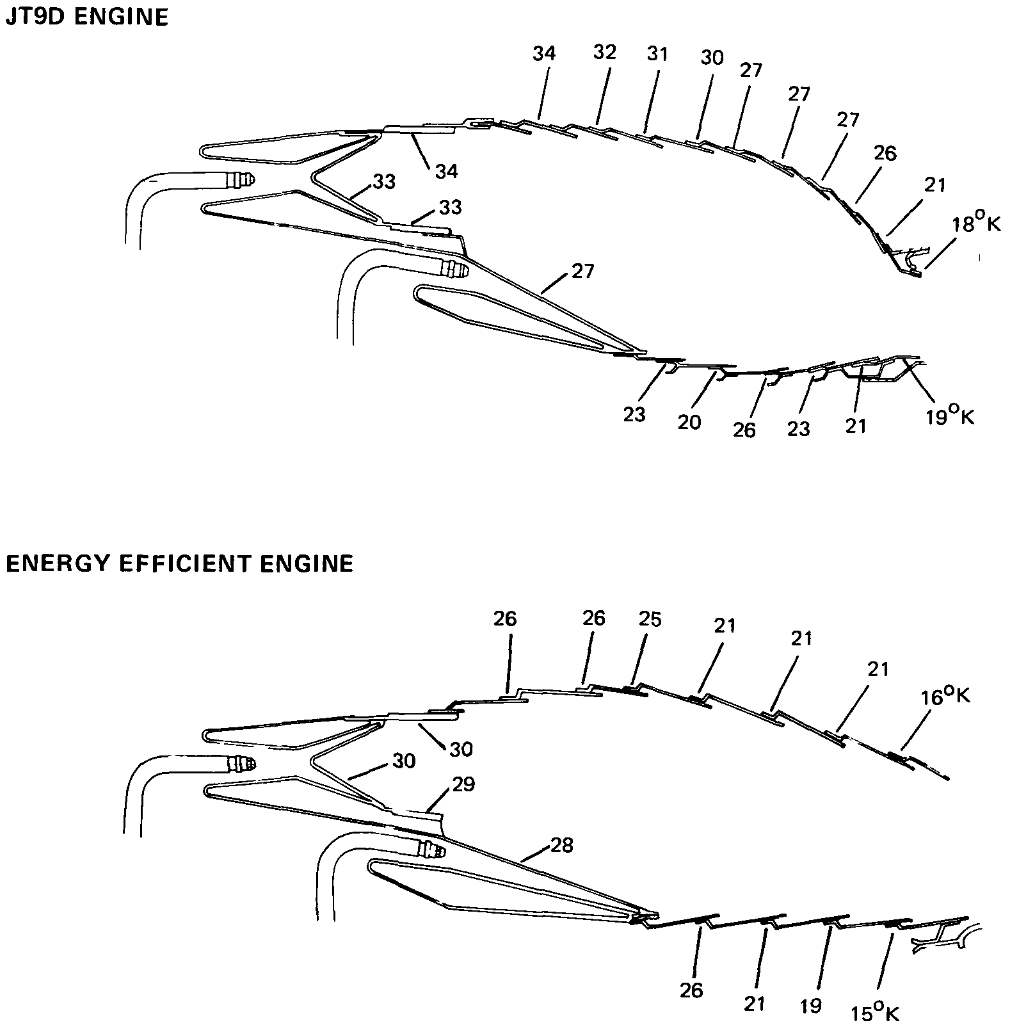
Figure 5-10 Premixed Combustor Designed for Operation on ERBS Fuel in the Energy Efficient Engine

The airflow in the main stage of the combustors has been increased by the order of 20 percent and a proportionate increase in the surface area of that flameholder is necessary to maintain the initial loading. In addition, retention of the high altitude stability characteristics achieved with Jet A requires that the flameholder surface area be increased by 50 percent when the combustor is operating on ERBS. Consequently, in both combustors the surface area of the pilot stage flameholder has been increased by 50 percent while that of the main stage flameholder has been increased by about 80 percent.

As shown on Figures 5-9 and 5-10 the increase in area has been accomplished by increasing the cant angle and length of the main stage flameholder. This approach leads to substantial increases in the length of the combustor. Alternate approaches exist, such as maintaining the cant angle and extending the flameholder surface radially outward, but this approach would be constrained by burner case radii. With the magnitude of the flameholder area increases involved, it appears that the need to alter the diffuser and burner cases is inevitable.

A thermal analysis of the combustor liner, similar to those presented in the discussion of the single stage and vorbix combustors was also conducted as part of the redesign effort. The computation was made using the lower values of the combustion gas luminosity defined in Section 4.6 as appropriate to premixed combustion systems. In the foregoing analysis of direct injection burners the source of radiant heat transfer to the louvers surrounding the primary combustion zone was assumed to be a locally stoichiometric region. In analyzing the premixed combustor, it was assumed that the premixing would eliminate locally stoichiometric mixtures and that the dominant radiation source in the primary combustion zone would be the products of combustion of a mixture having an equivalence ratio 20 percent higher than the bulk primary zone equivalence ratio.

Figure 5-11 shows the results of comparative computations of the liner temperature distribution for both the JT9D and EEE premixed combustor; based on the cooling air distributions of Figures 5-7 and 5-8 where the temperature increment represents the increase in liner temperature when ERBS fuel is used in place of Jet A. In the downstream portion of the liner, enclosing the dilution zone and turbine entry region, the metal temperature rises are comparable to those projected for the vorbix and single stage combustor. This is to be anticipated because the thermal environments are essentially identical to those encountered in those burners and the only variance in the analysis of this region is the use of lower values of the gas luminosity in the computation of the radiant heat load with each fuel. However, in the primary combustion zone the metal temperature increases are quite large despite the assumption of a low radiant source temperature and consequently lower net radiant heat transfer. This phenomena is essentially the inverse of the situation encountered when comparing the effect of the JT9D and EEE cycles on the metal temperature increments in vorbix combustors. The assumption of a reduced source temperature and a lower nominal luminosity, both of which appear valid for application to the analysis of a well premixed system, have reduced the nominal heat load on the liner and the cooling system has been optimized to that heat load. Thereafter, the incremental increase in heat load associated with the use of ERBS becomes a proportionately larger fraction of the nominal load and produced larger metal temperature increases.



FOR COMBUSTOR GEOMETRIES OF FIGURES 5-9 AND 5-10 WITH PER LOUVER COOLING FLOWS CONSISTENT WITH USE OF JET A FUEL

Figure 5-11 Incremental Increase in Liner Metal Temperatures for Premixed Combustors Operating on ERBS Fuel at Takeoff

For the purposes of this design perturbation of the premixed combustor, the liner cooling flow was increased to the level necessary to offset these incremental increases in metal temperature and the resultant distributions are included in the configurations of Figures 5-9 and 5-10. The cooling air flow to the louvered liners are of the order of 50 percent higher than those in combustors designed for operation with Jet A fuel. These increments are as large as those required in the single stage combustors of Section 5.2 and 5.3 but are due, in part, to the need for two additional louvers in the inner liner to accommodate the increase high power stage flameholder length.

The tradeoff between air availability for liner cooling and dilution purposes in a premixed combustor is expected to be different from that in direct injection combustors. In the latter, dilution air is needed to attenuate hot streaks associated with individual fuel injectors or combustion air apertures and the availability of air for this purpose is critical to exit temperature pattern factor control.

Anticipating that the advanced technology premixed combustor will achieve its goal of an extremely homogeneous mixture, the temperature distribution in the combustion products leaving the primary combustion zone would also be expected to be uniform. While some inner to outer bias in the introduction of the dilution air will be necessary to produce the desired radial temperature profile at the combustor exit the achievement of reasonable pattern factor goals should not be difficult. The availability of dilution air is probably more critical to emissions control in that its introduction would be scheduled to provide an abrupt quenching of the combustion products after sufficient time has elapsed for the desired degree of carbon monoxide oxidation. An inadequate quantity of dilutant air, because of excessively high liner cooling requirements, could lead to poor dispersion of the dilutant across the cross-section of the combustor permitting continuing NO_x production in the unquenched regions. While the quantity of dilution air in both the JT9D and EEE premixed combustors has been reduced by more than half during the redesign of the combustor for operation on ERBS it should be noted that about two thirds of this reduction has been made to accommodate the increase in primary combustion zone airflow. Since reducing the equivalence ratio of that zone; achievable only because of the projected enhanced combustion stability with ERBS; has a strong favorable impact on NO_x emissions, the part of the reduction in dilution air caused by this shift must not be considered a penalty.

The projected emissions characteristics of the referenced premixed combustors operating on Jet A fuel and the combustors as redesigned for operation on ERBS are summarized on Table 5-VII. Further details on the projected emissions, including the EPA Parameters are listed on Tables A-2, A-4 and A-5 of the Appendix. The effect of quenching of the reactions leading to consumption of the low power emissions constituents by the increase in liner cooling air has been estimated using the influence coefficients of Table 5-II. As in the case of the single stage and vorbix combustors, the emissions characteristics have also been estimated independently on the assumption that an improved liner material or increased effectiveness cooling concept, permitting reduction in the cooling flow level to that of the reference combustor, was available.

TABLE 5-VII

PROJECTED EMISSIONS CHARACTERISTICS OF LEAN PREMIXED-PREVAPORIZED COMBUSTORS

JT9D Engine

Configuration	Fuel	Liner Cooling Air	Primary Zone Equivalence Ratio at Takeoff	Liner Life	Emissions Indices		
					Idle CO	Idle THC	Takeoff NO_x
Reference - Figure 5-7	Jet A	15.7%	0.65	Base	3.9	2.9	7.88
Redesign - Figure 5-9	ERBS	23.0%	0.54	Base	11.0	4.8	2.64
Redesign - Figure 5-9 With Improved Liner	ERBS	17.8%	0.54	Base	8.0	2.2	2.64

Energy Efficient Engine

Configuration	Fuel	Liner Cooling Air	Primary Zone Equivalence Ratio at Takeoff	Liner Life	Emissions Indices		
					Idle CO	Idle THC	Takeoff NO_x
Reference - Figure 5-8	Jet A	19.8%	0.65	Base	3.6	2.7	13.8
Redesign - Figure 5-10	ERBS	28.1%	0.54	Base	9.3	4.1	4.56
Redesign - Figure 3-10 With Improved Liner	ERBS	22.7%	0.54	Base	7.4	2.0	4.56

The most profound change in the projected emissions is in the NO_x output at high power levels. While the analysis of Sections 4.2 and 4.4 had indicated an increase in the adiabatic flame temperature with the introduction of ERBS and an attendant 21 percent increase in NO_x emissions, the ability to reduce the primary zone equivalence ratio because of improved stability with ERBS reverses this trend and leads to three-fold reductions in the NO_x generation.

The sensitivity of the low power emissions to quenching by increased liner cooling is consistent with the trends established by the other combustors analyzed. After adjusting for this situation by the assumption of an improved liner, the increase in idle carbon monoxide emissions is still shown to be substantial and the more than two-fold increase was the greatest sensitivity of any emissions constituent to the change in fuel composition observed in the entire study.

No attempt was made to estimate the smoke output from premixed prevaporized combustors operating on ERBS fuel because of a lack of data on the sensitivity of ideal premixed combustors to fuel composition. However, when operated on Jet A fuel, these combustors are projected to produce minimal smoke because of the lean homogeneous vapor phase combustion process; and since the use of ERBS rather than Jet A fuel has been projected to produce increases of the order of 10 to 15 percent in the high power smoke output of direct injection combustors, it is doubtful that its use in premixed prevaporized burners would raise the smoke output to excessive levels.

The ignition characteristics of bluff body stabilized combustion systems were examined in Section 4.7 and it was concluded that these burners should have sensitivity to the low range of the distillation temperature distribution similar to that observed with direct injection swirl stabilized combustors. While other sensitivities were observed in the swirl stabilized burner, such as the effect of atomization of cold fuel, no additional information was available on ignition in the premixed-bluff body stabilized combustors. Assuming that an advanced technology premixed combustor is established that has adequate ignition margin when operating on Jet A and recognizing that the differences in the low range distillation temperatures of Jet A and ERBS are small, some development effort may still be required to obtain these ignition characteristics in a combustor designed for operation on ERBS because of the uncertainties regarding the influence of other parameters. It would be anticipated that the ignition capability would be responsive to one or more of the enhancement approaches identified in Section 4.7.

In summary, the analysis of lean premixed-prevaporized combustors operating on Jet A and ERBS fuel has indicated that the stability characteristics of the combustor changes with fuel composition and has strong impacts, both positive and negative, on the combustor necessitating redesign to accommodate the use of ERBS fuel. Reduced low pressure stability with ERBS requires increasing the flameholder area to avoid potential blowout following deceleration at high altitude and to assure adequate stability after an altitude relight. The necessary increase in flameholder area alters the geometry of the combustor front end sufficiently that may not be compatible with existing diffuser and burner case hardware. The use of ERBS fuel enhances the stability of the combustor in the high loading level range, permitting a reduction in the equivalence ratio in the primary combustion zone at high power levels with an attendant and substantial reduction in high power NO_x emissions.

Adequacy of liner materials and cooling concepts is a concern in lean premixed prevaporized combustors and, based on comparable liner technology and cooling levels, reductions in liner cyclic fatigue life of 30 to 35 percent are anticipated with the use of ERBS fuel. While increasing the cooling flow to the liner to offset the increased heat loading can return the liner life to baseline levels and is projected to have minimal impact on the ability to achieve patter factor goals, it compromises the low power emissions to extents similar to those projected for more conventional combustors.

5.6 FUEL SYSTEM REVISIONS

Revisions to the engine fuel system are to be anticipated with the change in fuel specification from Jet A to ERBS. These will involve changes to offset the reduced thermal stability of ERBS, modification of the fuel control and pump to accommodate changes in fuel properties and, in the case of combustors employing pressure atomizing fuel injectors, possible increases in the fuel supply pressure to enhance atomization of the more viscous ERBS. These revisions are discussed in this section. Because of the as yet undefined configuration of the fuel system for premixed prevaporized combustors, the revisions are discussed primarily in the context of current fuel system designs which are particularly relevant to the single stage and vorbix type combustors.

The analysis of Section 4.9 revealed three different classes of thermal stability problem areas encountered in fuel system design. Two of these; carbon deposition in inactive fuel systems during low power operation of a multi-stage combustor and those associated with preheating fuel prior to its introduction into the combustor; were considered to be more dependent on the thermal environment than fuel composition and must be resolved independently regardless of the fuel employed. The third area was that of long term deposition in an active fuel system and was demonstrated to be critically dependent on fuel composition and strongly temperature dependent. In particular, the analysis of Section 4.9 indicated that the use of ERBS fuel would require a reduction in the maximum surface temperatures in the fuel passages in fuel injectors and their supports if carbon formation is to be avoided. Based on the estimated minimum breakpoint temperatures and the temperature dependence of the coking rate the analysis indicated that, if no significant coke formation is encountered at fuel passage surface temperatures of 375°K with Jet A, an equivalent degree of protection with ERBS would require these surfaces be maintained at temperatures below 345°K.

The fuel injector supports are a critical component in this regard in that the cooling effect produced by the fuel flow through the support is required to maintain the fuel passage surfaces at a safe temperature while the external surface of the support is exposed to potentially high convective heat transfer from the compressor discharge flow. This effect is demonstrated in Figure 5-12 which shows the results of a previously conducted thermal analysis of the production JT9D fuel injector support. The support consists of an internal structural member; containing separate fuel passages for the primary and secondary fuel; and surrounded by a sheet metal heat shield. The temperature distribution in the support was computed for the 50 percent of cruise thrust condition - a situation encountered near the end of cruise on a long flight after much of the aircraft fuel load has been depleted. The condition is the most severe steady state environment because the fuel flow through the support is low.

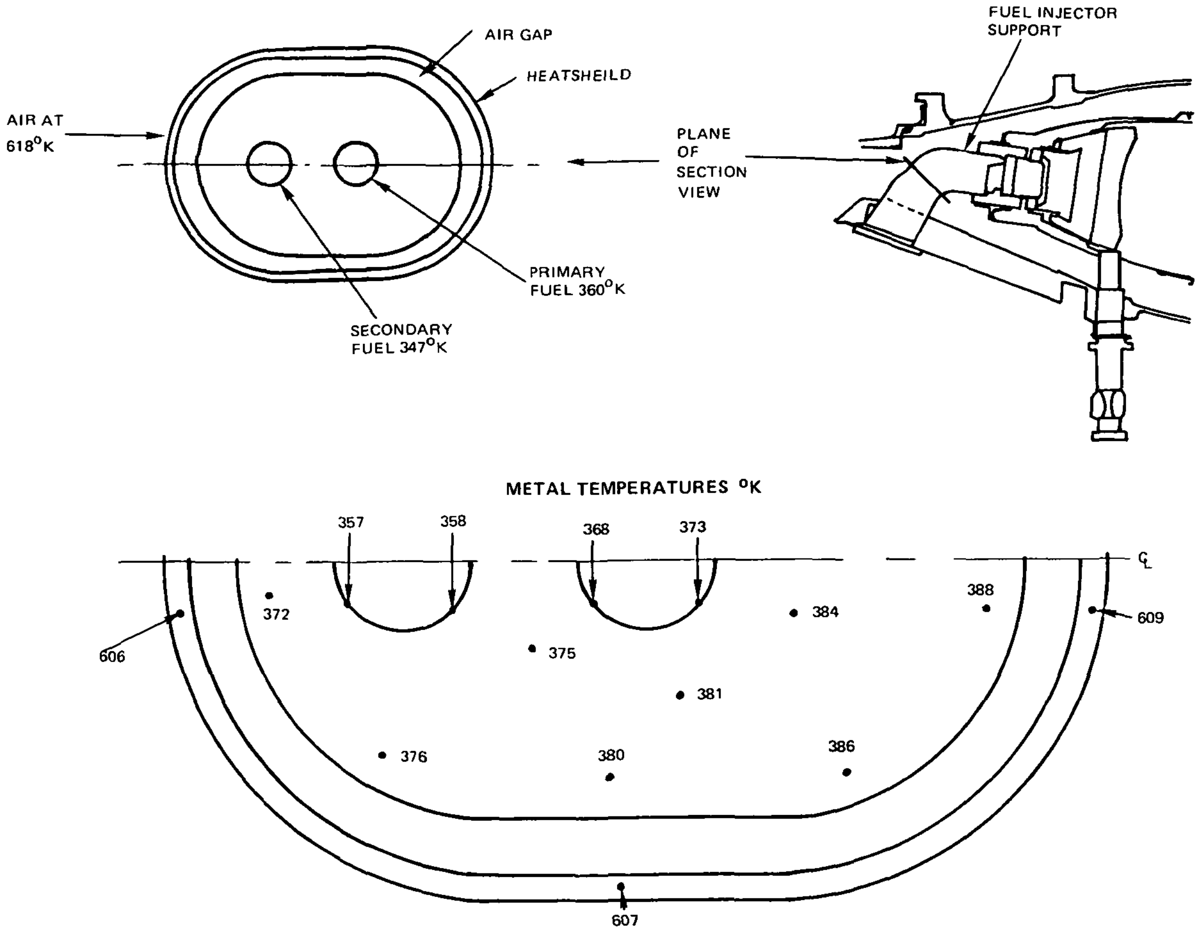


Figure 5-12 Temperature Distribution in JT9D-7 Fuel Injection Support

The results indicate that the combination of the heat shield and fuel cooling is effective in maintaining low support temperatures with the maximum temperature in the support being less than 390°K. On the critical surfaces of the fuel passages, the temperatures are only 8 to 13°K above the bulk fuel temperature and on the basis of protecting these surfaces from the 618°K compressor discharge air, the support has an efficiency in excess of 95 percent.

Perturbations to the support configuration, including reduction in the support cross-section, reduced fuel passage diameters, and the use of low conductivity insulation in the air gap under the heat shield, were found analytically to increase the efficiency of fuel passage surface isolation to at best 97 to 98 percent - i.e., reducing the passage surface to bulk fuel temperature difference to the order of 4 to 6°K as opposed to 8 to 13°K with the current support configuration. Based on the results of this analysis, it is concluded that the current fuel injector support has essentially the limit of thermal isolation of the fuel passages; and that if a 30°K reduction in the surface temperature is necessary to preclude coking with ERBS fuel, it must be accomplished entirely by reducing the temperature of the fuel being supplied to the manifold.

The major sources of fuel heating are the fuel pump and the use of the fuel as the coolant for the engine lubricating oil. Figure 5-13 shows the temperature of the fuel in the supply system during a representative flight. The fuel tank temperature history was obtained from analyses conducted by the Boeing Company (Reference 61). The particular flight schedule selected was a short 900 kilometer mission with high ambient temperature levels. Because the fuel is cooled by convective heat rejection from the airframe at high altitudes, the combination of a short mission with high loading temperatures produced the highest fuel supply temperatures. The figure shows this supply temperature history and the superimposed fuel heating produced by the fuel pump and the oil cooler based on current JT9D-7 engine accessories.

The temperature rise across the fuel pump varies considerably with operating condition and is the highest at the low fuel idle and decent conditions. This occurs because the pump is a fixed displacement configuration sized to provide the maximum fuel flow required at takeoff. At lower power levels, the fuel control bypasses the excess fuel back into the pump at the high pressure stage inlet (c.f., Figure 5-14). Consequently, while the bulk fuel temperature rise across the pump is only about 6°K, the fuel may be recirculated through the high pressure stage several times before being delivered to the engine at low power levels and experience temperature rises of 40°K or more. The temperature rise in the oil cooler is also somewhat fuel flow sensitive, with minimum temperature rises occurring at high power levels, but relative to the fuel pump heating, there is less variation in the temperature rise across this component during the flight.

The net result of the fuel heating mechanisms shown on Figure 5-13 are to produce a fuel temperature history at the manifold that exceeds the previously established steady state limit of 375°K for Jet A fuel only during the brief transient at the start of decent. However, this temperature level is in excess of the corresponding limit for ERBS fuel over nearly the entire duration of the mission. Several possible modifications to the fuel system appear evident to circumvent this problem. These are identified on the schematic diagrams of Figure 5-14.

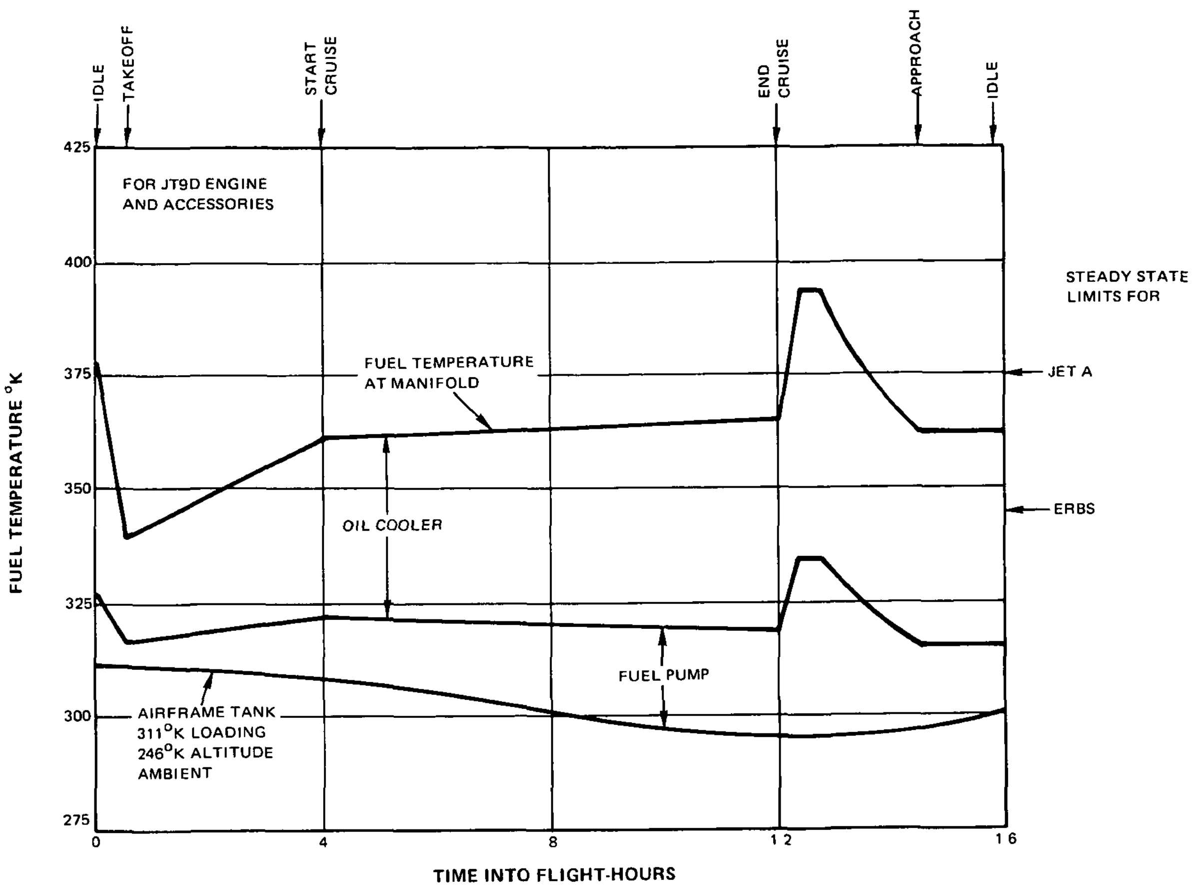


Figure 5-13 Fuel Temperature History in JT9D Engine Fuel System

The excess fuel pump flow, currently recirculated to the pump inlet line could be diverted back to the airframe fuel tanks to avoid repetitive heating of the fuel in the pump. This would reduce the net temperature rise across the pump to the previously cited 6°K at all operating conditions and would be most effective in reducing the peaks in fuel temperature occurring at ground idle and the start of decent. An alternative approach, producing the same net effect on fuel temperature, would be to employ a variable displacement fuel pump capable of responding to changes in engine fuel flow demand and eliminating the need to bypass excess fuel. To date, variable displacement fuel pumps have not been incorporated in engines for commercial aircraft because of concerns over complexity and durability. By itself, the process of eliminating fuel recycling through the pump is inadequate to produce the desired reduction in manifold temperatures and they would still exceed the stipulated limits for ERBS over the entire cruise portion of the mission.

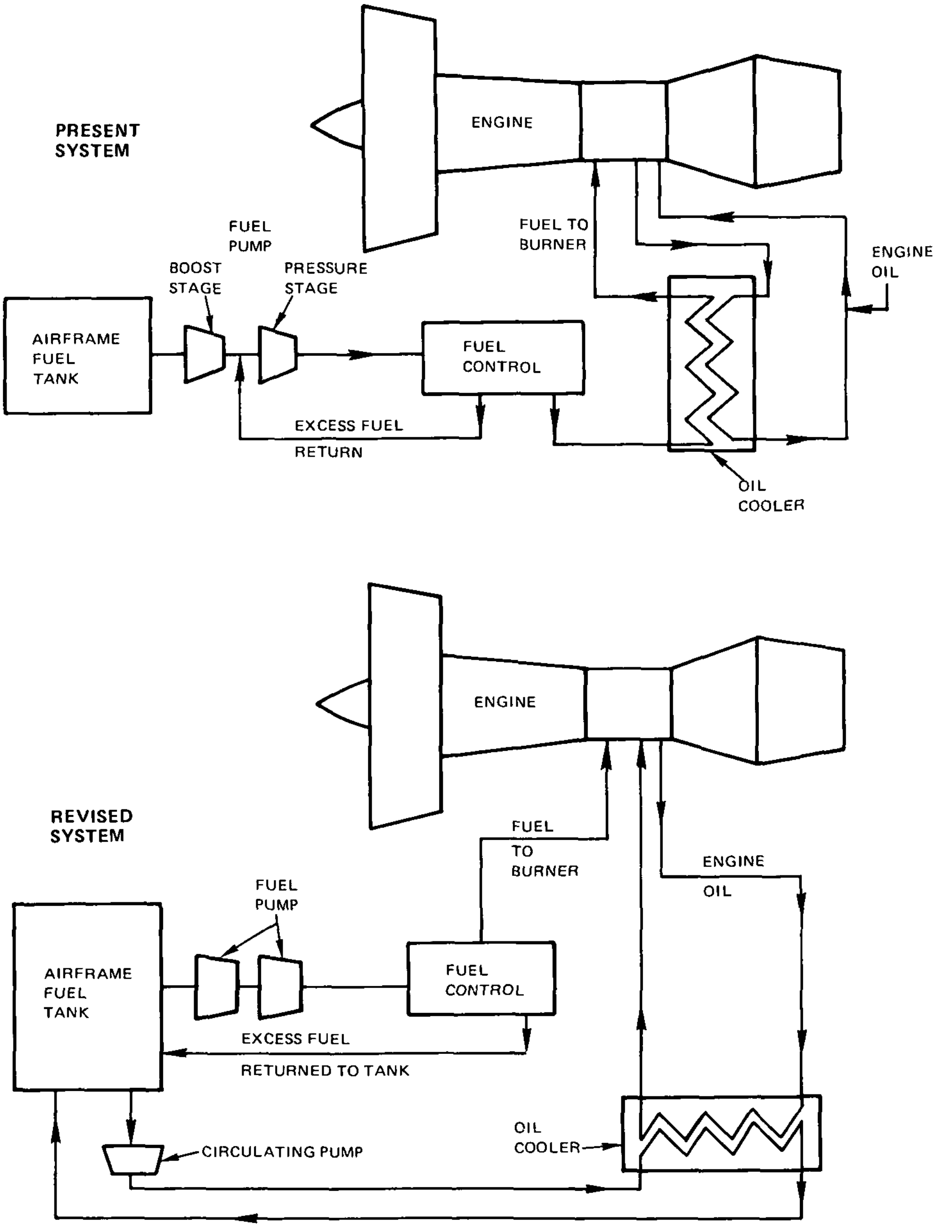


Figure 5-14 Revisions to Engine Fuel System to Reduce Fuel Temperature at Combustor Manifold

A more attractive alternative appears to be to operate the oil cooler on a separate fuel recirculating loop independent of the engine fuel supply. The heat absorbed from the lubrication system - of the order of 2400 kJ/minute from a JT9D-7 engine at cruise - would be carried to the airframe fuel tanks from which it would be disipated to the atmosphere. This approach would eliminate the oil cooler as a fuel heat source and reduce the fuel temperature by as much as 60^{o}K at the critical low fuel flow start of decent condition. As shown on Figure 5-13, the reduction in fuel heating would be sufficient to bring the fuel manifold temperature well below the 345^{o}K limit stipulated for ERBS over the entire mission. This approach was also found of interest in the study of Reference 61 in that it provided a means of avoiding fuel freezing in the airframe tanks during long duration flights. Some potential problems; such as overheating of the fuel in the airframe tanks during lengthy ground idle/taxi operations or near the end of the mission when the fuel supply in the tanks is nearly depleted; are evident with this approach and warrant further study because of the ability to circumvent both the fuel freezing and thermal stability problem simultaneously.

It is also noted that the mechanisms producing fuel heating can be of benefit during engine starting. Recirculation of fuel through the pump at the low fuel flow starting condition and thermal inertia of the oil cooler during altitude relight can heat the cold fuel improving its atomization in the combustor. The above cited revisions to the fuel system to eliminate these heat sources because of thermal stability considerations might compromise ignition and require the use of some of the ignition enhancement concepts discussed in Section 4.7.

While the JT9D-7 engine cycle was used as a reference in the discussion of the thermal stability problem and the possible revisions to the fuel system, the situation is essentially identical in the Energy Efficient Engine. The gaspath temperatures are about 45^{o}K higher than at corresponding operating conditions in the JT9D-7 and slightly lower fuel supply temperatures - of the order of 5^{o}K - will have to be stipulated to maintain injector support surface temperatures below the allowable level for ERBS. This engine also has higher temperature environments around the bearing compartments and lower fuel flows, both of which tend to increase fuel temperature rises in the oil cooler. However, the heat load on the lubrication system is reduced by improved design features and the net fuel temperature rises across the fuel system components, as well as the in-flight temperature histories are projected to be essentially identical to those of the JT9D-7. Since removal of the oil heat rejection from the fuel system heat load was shown to be more than adequate to accomplish the desired reduction in fuel supply temperatures at the manifolds of the JT9D-7, such an approach would also be expected to be satisfactory in the Energy Efficient Engine.

With regard to fuel pump operation, there are two major areas of concern when changes in fuel composition are encountered; the lubricating quality of the fuel and the vapor handling capability of the boost stage of the pump. Lubricity is a property of fuel that influences the friction and wear behavior of rubbing surfaces. Tests conducted to determine a fuel's lubricity have not been very conclusive, except to show that a property of fuel that is in the direction to cause better adherence to the metal surface is in the direction to increase lubricity. It is speculated that increasing a fuel's surface tension increases its ability to adhere to metallic surfaces. In addition, a higher final boiling point would indicate that the fuel contains higher molecular weight molecules which also enhances lubricity. Since ERBS is projected to have both a higher surface tension and a higher final boiling point than Jet A, its lubricating quality in the fuel pump is expected to be superior to that of Jet A.

The concern over the vapor handling capability of the boost pump stage is primarily one that is aggravated by the use of a fuel of lower initial boiling point. At extreme operating conditions, this pump stage can operate with a high inlet suction and fuel entering the stage can have a high vapor content. Reduction in the lower boiling point of the fuel increases the potential vapor content at a fixed suction pressure causing increased difficulty in pumping the fuel and durability problems in the stage due to surface erosion when the vapor bubbles collapse. While ERBS is projected to have a slightly lower initial boiling point than Jet A, the distillation temperature curves are shown on Table 2-2 to cross at 10 percent and; except at the low extremes of vapor fraction, ERBS would be expected to produce lower vapor fractions than Jet A at a specified suction pressure. Consequently, the use of ERBS specification fuel in fuel pumps originally designed for operation on Jet A does not appear to present any problems.

Changes in the fuel specification may also require modification of the fuel control. The metering elements in the control operate on a volumetric flow basis and changes in the specific gravity alters the gravimetric flow through these components. Most of the fuel controls in current use, including that on the JT9D engine, have external adjustments to compensate for changes in fuel density. While modification of these components might be necessary to extend the range of specific gravity to the higher levels of ERBS, this modification is relatively straightforward. Consequently, existing fuel controls should be capable of operating on ERBS or be readily modified to do so and the external adjustment features could be retained to provide fuel flexibility during a transition period.

The metering elements in the fuel injectors also regulate the fuel flow on a volumetric basis and the higher specific gravity of ERBS fuel will lead to a reduction in the pressure drop across the injector for a given gravimetric flow rate. Since this was shown in Section 4.3

to lead to deterioration of the atomization produced by pressure atomizing injectors, it may prove desirable to reduce the size of the fuel injector orifices if the pressure drop-flow characteristics of the injector are to be maintained identical to those when operating on Jet A. However, based on the preceeding discussions of the single stage and Vorbix combustors in the JT9D engine, improved atomization of ERBS fuel appears desirable from the point of view of ignition and emissions at low power level. Additional increases of 20 to 25 percent in the pressure drop across the injector, which would require further reduction in the orifice size, were found necessary if the desired improvement in atomization is to be achieved. In addition to increasing the potential for injector clogging and higher erosion rates on the critical metering surfaces, this approach has implications regarding the remainder of the fuel system. Increasing the fuel supply pressure will increase the rate of wear in the gear stage of the fuel pump. Pump wear has been correlated with a characteristic temperature known as the Kelly Flash Temperature:

$$T_F = K_1 T_{fuel} + K_2 (PV)^{1/3},$$

where:
T_F = Kelly Flash Temperature
T_{fuel} = Fuel temperature at gear stage inlet
P = Max hertz stress = f (pump discharge pressure)
V = Max sliding velocity = f (pump speed)

Some correlations have been made for gear stage pumps, and the general trend is that the wear rate increases as the Kelly Flash Temperature increases. There is also a sharp rise in wear rate beyond a specific Kelly Flash Temperature. A pump is normally designed to be below the sharp rise; but an increase in discharge pressure could increase the Flash Temperature into the high wear rate regime and would require redesign of the pump to assure reasonable life. The higher operating pressure could require redesign of the entire fuel system including the pump, control and fuel manifolds. All components would have to be proofed at higher pressures and could require redesign with increased wall thicknesses, and consequently, higher weight. Seals in the pump and control might also have to be revised.

It is also noted that the operating conditions at which improved atomization of ERBS is desired, i.e., ignition and idle, are low fuel flow conditions. Consideration might be given to increasing the fuel pressure in a primary fuel system for this reason while maintaining current pressure levels in a secondary fuel system that is operational only at higher total fuel flows. An additional pressurizing pump would be required in the primary system downstream of the stage flow split control if this were to be accomplished without imposing additional pressure loads on the main fuel pump and the control housing. The additional complexity of this approach makes the potential benefit of improved atomization questionable, particularly on considering that the atomization produced by aerating injectors may be enhanced by manipulating aerodynamic parameters without modifying the fuel system.

In summary, a change in the fuel specification from Jet A to ERBS has been shown to require modifications to the engine fuel system. The impact on the fuel pump and fuel control are minor and the use of ERBS may actually improve gear pump durability. Significant reductions in the heat load on the fuel prior to delivery to the fuel manifolds are necessary to offset the lower thermal stability of ERBS. While the elimination of fuel recirculation through the pump can reduce this heat load somewhat, more elaborate measures, such as rejecting heat from the engine lubrication system directly into the airframe tanks, are necessary if the fuel temperature is to be reduced sufficiently to avoid long term carbon deposition. This approach also appears attractive from the point of view of avoiding fuel freezing in the tanks but problems associated with overheating the tanks and possible adverse effects on altitude relight must be given further consideration. Increasing the fuel pressure to enhance the atomization of the more viscous ERBS fuel in combustors employing pressure atomizing injectors could require extensive redesign of and increased weight in the fuel system components making the net benefit of such an approach very questionable.

5.7 TURBINE DURABILITY

The use of broad specification fuels will also have impacts on the durability of airfoils in the turbine section of the engine. These airfoils employ a coating to prevent oxidation of the base metal and corrosion of this coating, the rate of which is extremely temperature sensitive, is currently the life limiting mechanism for these components. Assuming that the combustor provided design levels of exit temperature pattern factor and an acceptable radial temperature profile when operating on ERBS fuel, other mechanisms exist which could lead to locally elevated airfoil surface temperature, and consequently, more rapid coating deterioration.

The high pressure turbine inlet guide vanes are subject to radiant heat transfer from the combustion products and, based on the increase in luminosity projected in Section 4.6, the use of ERBS fuel is estimated to produce a $14^{o}K$ increase in the vane leading edge temperature in the JT9D engine at sea level takeoff. When integrated over typical missions for this engine, this temperature increase would be expected to produce a 25 percent reduction in vane life. Radiant heat transfer does not have a significant effect on the high pressure turbine blade temperatures or on the airfoils in the lower pressure stages because the inlet guide vanes block the line of sight to the primary reaction zone of the combustor and work extraction reduces the static temperatures of the combustion products in the immediate vicinity of the airfoils.

Because of the thin boundary layers on their surfaces, the convective heat transfer to turbine airfoils is extremely sensitive to surface roughness. The roughness of the surface can be increased either by local erosion of the coating or by deposition on the surfaces.

Deposition occurs primarily on the pressure surface of the airfoils and may be caused by several factors including: dirt ingestion during ground operation, trace quantities of metallic constitutents or salts in fuel and ash or carbon particle accumulation. Erosion of the coating, most likely to occur on the leading edges of airfoils or on the suction surface of blades, is caused by impact with ingested dirt or hard carbon particulates generated in the combustor. Regardless of the source, increased surface roughness has a severely detrimental effect on airfoil lives. Analysis of the convective heat transfer to the first stage vane and blade of the JT9D high pressure turbine indicate that the imposition of a 0.015 mm. nominal surface roughness will lead to an increase in the surface temperature of 55°K, relative to a hydraulically smooth airfoil at sea level takeoff operation. If the roughening occurred as a step change at the start of service, it is projected that the increased surface temperature would lead to a 60 percent reduction in the corrosion life of the coating.

Allowing for a more realistic gradual build up in surface roughness moderates the life deterioration somewhat but this mechanism must still be considered to be a significant factor in determining overall component life.

The effect of fuel composition on the rate of airfoil surface roughening cannot be established directly. However, high concentrations of metallics or salt forming constitutents in the fuel and the propensity for ash or particulate carbon formation must be considered the significant factors. Neither the current Jet A nor the tentative ERBS specifications stipulate limits on metallic or salt contents and it must be assumed that the degree of control of these constitutents would be maintained. On this basis, it appears that the only characteristic of ERBS that would contribute to accelerated airfoil coating erosion or surface deposition is the increase in carbon particulate formation as evidenced by the higher projected smoke output relative to engines operating on Jet A fuel.

In the absence of an improved coating material having the corrosion resistance to withstand the projected higher surface temperatures, it would be necessary to redesign the cooling system in the air foils to reduce the surface temperatures to the same level encountered with Jet A fuel, if comparable component lives are to be achieved. The cooling flow through the high pressure turbine inlet guide vanes of the JT9D engine is 6.9 percent of the engine flow and it is projected that when the airfoil is redesigned this flow would have to be increased to about 7.5 percent to offset the higher radiant heat load produced by the combustion of ERBS. The inlet vane in this turbine employs a leading edge cooling system with small cooling air holes which can be susceptible to plugging by carbon particles generated in the combustor. With the recognized higher smoke formation characteristics of ERBS, consideration might be given to increasing the size of these cooling air holes during redesign of the vane. This could compromise the effectiveness of the cooling of the leading edge region, increasing the cooling air requirements further.

Increased convective heat transfer produced by airfoil surface roughness can also be offset during redesign of the cooling system, at the expense of a higher turbine cooling air requirement. While it appears such a redesign may be necessary to maintain current airfoil coating life while operating on ERBS fuel the extent of increase in surface cooling cannot be established. However, by way of example, in the above cited case of an initially hydraulically smooth JT9D high pressure turbine first stage vane and blade deteriorated to a surface roughness of 0.015 mm on the pressure surface; increases in the cooling air of 25 and 35 percent would be required in the vane and blade respectively to maintain the initial surface temperature, and hence, the coating life. This represents an extreme situation but the results provide some measure of the impact on the total turbine cooling flow. Combining these cooling flow increases with that required to offset the higher radiant heat load on the first stage inlet guide vane leads to a need for a 13 percent increase in the total turbine cooling air requirement in the JT9D engine which will produce a 0.25 percent increase in thrust specific fuel consumption at cruise.

The analysis of turbine airfoil life and cooling air increments was based on the JT9D engine. At the time this study was conducted, the design of the turbine for the Energy Efficient Engine was not sufficiently defined to permit a similar analysis. However, the incremental deterioration in airfoil life and the fractional increases in cooling flow to maintain coating lives are expected to be similar to those projected for the JT9D engine. Because the Energy Efficient Engine has a single stage high pressure turbine and higher local Mach numbers in the vicinity of the blade surface, the increases in turbine cooling air will have a larger impact on cruise specific fuel consumption.

It should be noted that, in the present analysis of turbine durability, airfoil coating erosion has been assessed only in the context of increased surface roughness and its effect on convective heat transfer to the surface. If the use of broad specification fuels were to lead to more severe erosive environments in which the coating were abraded to the base metal, severe and rapid oxidation would be encountered and airfoil life would have to be assessed on this basis.

5.8 FUEL FLEXIBILITY AND EXTENT OF SPECIFICATION MODIFICATION

From the point of view of aircraft operational capability, particularly during a period of transition when the commercial aircraft jet fuel specification is being changed from Jet A to ERBS, it would be desirable to have the flexibility necessary to use these two fuels interchangeably. Since it has been shown in this study that the use of ERBS fuel will require extensive revision to the engine fuel system, and, at least, redesign of the combustor liner and turbine inlet guide vanes to avoid fuel thermal stability problems and deteriorated component lives, it only appears realistic to consider the fuel flexibility situation from the point of view of a combustor that has been designed to operation on ERBS as the reference.

In the following, the various aspects of combustor operation are considered on the basis of a burner, designed for operation on ERBS, but temporarily operating on Jet A fuel:

Liner and Turbine Durability

It is assumed that the combustor liner and the turbine inlet vane have been fabricated from an improved material; employ an improved cooling concept or the cooling flow has been increased to provide acceptable component lives when operating on ERBS. In this situation, operation on Jet A would lower the metal temperatures in these components and, if a significant part of the operating time were spent with Jet A fuel, could produce an increase in life.

Thermal Stability

It has been projected that it will be necessary to remove some of the thermal stress from the fuel if long term carbon deposition is to be avoided when operating on ERBS fuel. If fuel system modifications are incorporated to reduce the manifold temperatures to levels low enough to preclude coking with ERBS, the more stable Jet A fuel should have additional margin against deposition.

Combustion Stability

The lean premixed-prevaporized combustor is the least flexible in this respect in that, if the primary combustion zone equivalence ratio at high power levels is reduced to take advantage of the enhanced combustion stability with ERBS, the combustor will have inadequate stability margin at high power levels when operated on Jet A. In a variable geometry premix-prevaporized combustor, it might be possible to introduce a limit in the actuating mechanism to prevent the primary zone air induction system from accepting the full quantity of combustion air and thereby maintain a higher primary combustion zone equivalence ratio when the burner is temporarily operated on Jet A fuel. Designing the combustion zone to a higher equivalence ratio consistent with the stability characteristics of Jet A to accommodate fuel flexibility would not be desirable becaue it would compromise the ability to achieve significantly lower NO_x emissions when operated on ERBS. The stability of direct injection combustors does not appear to be sensitive to the Jet A-ERBS fuel property changes.

Ignition

The ignition characteristics of combustors are dependent on the volatility of the fuel which is related to the distillation temperature distribution of the low boiling point fractions. Since ERBS and Jet A are projected to have similar distillation temperature characteristics in this range, including equal distillation temperatures at the 10 percent fraction, the volatility effect on ignition is expected to be minimal. Other mechanisms influence ignition, such as the poorer atomization of ERBS relative to Jet A, and are suspected of making ignition more difficult with ERBS particularly at cold fuel conditions. As a result, a combustor designed for adequate ignition on ERBS fuel would be expected to have better ignition capability when operated on Jet A.

Emissions and Smoke

Data from comparative testing of combustors operating on different fuels has indicated that the emissions and smoke output from otherwise identical combustors generally increase as the hydrogen content of the fuel is decreased. Consequently, it might be suspected that a combustor that has been designed to meet specific regulations on emissions and smoke when operating on ERBS should have greater margins relative to these regulations when operating on Jet A. However, with Jet A fuel the radiant heat load to the liner will diminish and the liner temperatures will be lower than intended. This could increase reaction quenching with a possible adverse effect on low power emissions particularly those of unburned hydrocarbons.

Exit Temperature Profile and Pattern Factor

The available data does not reveal any sensitivity of the exit temperature radial profile or pattern factor when an otherwise unaltered combustor is operated on different fuels. Since streaking and carbon deposition that might increase the pattern factor would be expected to be more likely when operating on ERBS, a combustor designed for that fuel should be capable of meeting the same criteria when operating on Jet A.

Fuel System

The differences in specific gravity of the fuels alters the gravimetric flow - pressure drop characteristics of the metering orifice in the fuel control and in the individual fuel injectors in the combustor. Because of its lower specific gravity, the pressure drop across these orifices are about 3 percent higher for the same gravimetric flow of Jet A. Existing fuel controls generally feature external adjustments to compensate for fuels of different specific gravity and these could be designed to provide adjustment over the Jet A-ERBS range. Fuel injectors have no such compensation and if the injectors have been sized to the design pressure limit of the fuel system when operating on ERBS, it would be necessary to overpressurize the system to achieve the peak fuel flow rates.

In general, the design criteria for a combustor operating on ERBS are more stringent than those used in conjunction with Jet A fuel and the use of ERBS as opposed to Jet A has generally a negative impact on combustor performance, emissions and operational parameters. The results of the preceeding examination of fuel flexibility indicate that a direct injection combustor designed for satisfactory operation on ERBS; by adherence to the more stringent design criteria and incorporating features to offset the negative impacts of the use of this fuel; should be capable of operating on Jet A fuel. However, an adverse effect on low power emissions, particularly those of unburned hydrocarbons, might be encountered because of the overcooling of the liner; and, operation at peak fuel flows would have to be reviewed to ascertain the effect of higher fuel supply pressures.

Lean premixed prevaporized combustors designed for optimum emissions characteristics with ERBS fuel would not have the capability of operation on Jet A because of inadequate stability margin. If this problem were circumvented by compromising the NO_x emissions reduction capability with ERBS, or in the case of a variable geometry burner, use of a temporary change in the airflow schedule limit, the fuel flexibility situation of a lean premixed prevaporized combustor would be comparable to that cited above for direct injection combustors.

With regard to the extent to which the current Jet A fuel specification may be relaxed without excessively compromising the performance, emissions, durability or operational aspects of the combustor, there are two reference points on which such an estimate would have to be based: current experience with combustors operating on Jet A and the analytical projection derived from this study for burners operating on ERBS. The limited amount of data available on the subject of combustors operation on fuels of different hydrogen content was shown to correlate in a generally linear manner between these two reference points. Changes in combustor performance parameters and design impacts were progressive with hydrogen content and no thresholds, beyond which these changes increased abruptly, were detected. If such thresholds had been observed, it would have been possible to identify the fuel composition at which they occurred as a limit which, only if exceeded, would necessitate a revision in combustor design. Since this is not the case, it appears that any relaxation of the current specification would produce adverse impacts on the combustion system, the acceptability of which would have to be weighed against other considerations. These considerations generally fall into three cataegories. In the first of these, involving operational aspects such as a change in fuel specification that compromises altitude relight, correction of the deficiency would be mandatory and the cost of development and retrofitting a combustor of improved ignition capability must be weighted against advantages in fuel cost and availability. The deterioration of emission and smoke output produced by a relaxation of the fuel specification presents a different situation. The levels of emissions control advocated by the Environmental Protection Agency (Reference 62) are stringent and combustors satisfying these controls will do so with small margins which could be negated when operating on a higher aromatic content fuel. Regulatory agencies must be informed of pending relaxation of fuel specifications and the emissions/smoke requirements modified to reflect the effect of fuel composition. The final category consists of those aspects, such as liner and turbine durability, where fuel cost and availability must be traded against engine operating costs - in this case increased maintenance and replacement parts costs. While evaluation of these situations were beyond the scope of the current study, the results of this effort, hopefully reinforced by additional analyses and experimental substantiation, could provide the basis for such an assessment.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Based on the analytical projections made during this study, the following major conclusions were reached regarding the use of the ERBS, rather than Jet A specification fuel, in both current and advanced technology combustors for commercial aircraft gas turbine engines.

- The use of ERBS fuel will not require alteration of the basic aerothermal definition of direct injection swirl stabilized combustors such as the single stage and Vorbix burners. These combustors may be designed for operation on ERBS without altering the diffuser-burner case or combustor liner contours, fuel injector density or other pertinent geometric parameters. With the exception of minor adjustments to optimize the overall performance, there would be little incentive to modify the pressure loss or the stoichiometry of reaction zones from those found acceptable with Jet A fuel. In the case of lean premixed prevaporized combustors, the differences in stability characteristics with Jet A and ERBS fuels leads to the need for more profound combustor design modifications that could require alteration of the diffuser-burner case geometry.

- The increased radiant heat load produced by ERBS fuel will cause substantial deterioration in the life of the combustor liner. The projected increases in liner temperature diminish with increasing nominal liner heat load and are the least in combustors with high reference velocities in high pressure ratio engines. Increasing the liner cooling airflow to maintain acceptable metal temperature levels has been projected to compromise low power emissions and, in some configurations, the ability to control exit temperature pattern factor.

- The use of ERBS fuel is projected to have adverse effects on the durability of turbine airfoils. The increased radiant heat transfer produced by the more luminous combustion products will lead to increased surface temperature on the high pressure turbine inlet guide vanes and the projected higher particulate carbon concentrations may accelerate erosion or deposition on airfoil surfaces with an attendant increase in convective heat transfer rates. The cooling system in the airfoils must be redesigned with an increase in cooling air requirements, and a consequent increase in thrust specific fuel consumption if deteriorated airfoil life and its impact on hot section maintenance costs is to be avoided.

- The use of ERBS fuel has been projected to lead to increased carbon monoxide and unburned hydrocarbon emissions levels at low power. The data examined under this study indicates that, in some combustor configurations, part of these increases may be attributable to variation in fuel atomization as opposed to being inherent in the chemistry of the fuel. The use of improved fuel injector concepts may be found to reduce the sensitivity of low power emissions to the higher fuel viscosity.

- The effect of fuel composition on NO_x emissions is correlatable in terms of change in the adiabatic flame temperature. The use of ERBS is projected to increase the flame temperature leading to higher NO_x emissions. This effect is more pronounced in lean premixed combustors than in those employing the more conventional diffusion burning.

- The use of ERBS has been projected to lead to increases in smoke production. While smoke output may be moderated by conventional approaches, such as leaning the primary combustion zone, this could compromise combustion stability, ignition and low power emissions. The smoke formation propensity of fuels has been found to be strongly dependent on the detailed composition of the fuel; including both cyclic and non-cyclic species; and the use of hydrogen content, as in the tentative ERBS specification is an inadequate parameter for characterizing fuel composition in this regard.

- Because the low distillation temperature range of ERBS is comparable to that of Jet A, the effect of volatility on ignition is expected to be comparable. However, ignition with cold fuel will be more difficult because of the deteriorated atomization of ERBS. Should ignition problems be encountered, it may be possible to resolve them by relatively straightforward approaches, such as local enrichment, modified starting fuel flows or increased ignition energy.

- The combustion stability characteristics of direct injection burners, such as the single stage and Vorbix combustors do not appear to be sensitive to fuel composition in the Jet A - ERBS range. However, the use of ERBS fuel in lean premixed prevaporized combustors modifies these characteristics, necessitating redesign of the combustor to achieve optimum performance. Low pressure stability is reduced with the use of ERBS and increased flameholder areas are required to maintain adequate stability margin at high altitude-low power level conditions. The use of ERBS is projected to have a favorable impact on the lean stability of premixed systems at high pressure levels, permitting operating the primary combustion zone at lower nominal equivalence ratios. This can lead to significantly reduced NO_x emissions, more than that required to offset the above cited increase associated with the higher adiabatic flame temperatures.

o The use of ERBS has several impacts on the design of premixing systems for lean premixed prevaporized combustors. The slower vaporization of the higher boiling point constitutents of ERBS, combined with an apparently greater propensity for autoignition may limit the degree of premixing attainable with this fuel relative to Jet A. This could affect the capability of achieving the full NO_x reduction potential of this combustion concept.

o The reduced thermal stability of ERBS fuel is projected to require reducing the allowable metal temperatures in fuel manifolds and injector supports by as much as 30°K during steady state operation to preclude carbon deposition. Since the thermal isolation of fuel passages in current injector supports is already very effective, this reduction must be accomplished by lowering the fuel supply temperature. Rejection of lubrication system generated heat to the airframe fuel tanks and the use of variable displacement fuel pumps or returning excess pump fuel to the airframe tanks may provide a means of accomplishing this reduction but consideration must also be given to the effect of these revisions on ignition because the fuel heating provided by these components in this situation may be critical to atomization of the otherwise cold fuel.

o While design changes will be required to produce a combustor capable of operating on ERBS fuel with minimal impact on emissions, performance and durability, a redesigned direct injection combustor would have the basic flexibility to continue operation on Jet A fuel. The most significant effect of the use of Jet A fuel in a combustor designed to the more conservative criteria dictated by the ERBS specification appears to be the overcooling of the combustor liner and turbine. While this would have a favorable effect on component life, it could cause increases in the low power emissions.

o With regard to the extent to which the fuel specification could be relaxed without compromising the operating characteristics of existing in-service combustors, relaxation of the fuel specification to permit a lower hydrogen content would result in a deterioration in combustor performance. The decline is largely a matter of degree rather than approaching a threshold beyond which further reductions are unacceptable. Because of the proximity of current combustor designs to the limits appropriate for Jet A; the desire to further improve the emissions and durability of these combustors; and the lack of specific thresholds of influence of fuel properties, it is impossible to identify precise limits on the extent to which the current Jet A fuel specification may be relaxed. These must be established by more comprehensive trade studies in which factors such as the economics of development, retrofitting and maintenance are evaluated against fuel availability and cost.

- The technology improvements required to employ a relaxed specification fuel; such as improved fuel atomization, more durable combustor liner materials or more effective liner cooling concepts; could also be used in conjunction with the current Jet A specification fuel to produce improvements in emissions, durability or performance of the combustor. In applying this technology to accommodate relaxation of the fuel specification similar improvements in these combustor operating parameters are not to be expected.

With regard to recommendations for future research activities, the literature survey and design studies conducted under this program revealed numerous areas of inadequacy of existing data, insufficient information to understand fundamental mechanisms and the need for technology improvement, all of which must be resolved if serious consideration is to be given to the use of broad specification fuels in the future. In the following parts of this section, these recommendations are discussed in the context of the various combustor performance and operational characteristics:

Liner and Turbine Heat Load

The projected decreases in component life and the severe penalties in emissions, and combustor exit pattern factor control associated with attempting to offset these decrements with increasing cooling airflow is one of the most severe problems that would be expected to be encountered with the use of ERBS fuel. Technology programs should be undertaken to address this problem from two directions: improving the heat load capability of combustor liners and turbine airfoils in general and identifying means of minimizng the additional heat load generated by the use of broad specification fuels.

Improvement of the heat load capability of hot section components would be accomplished through research activities to provide materials and coatings having higher temperature capabilities while retaining favorable mechanical properties and to identify liner and turbine airfoil cooling schemes with high effectiveness levels. Efforts in this area are also critical to the successful evolution of high pressure ratio, energy efficient engines. The effect of combustor design and operating parameters on liner heat load should be assessed through comprehensive combustor rig testing at high pressure levels. High radiant heat transfer to the combustor liners is known to be caused by increased luminous particulate concentrations particularly in the primary zone of the combustor and these concentrations are directly related to the smoke output. Improvements to the direct injection type of combustor that minimize smoke output when operating on higher aromatic content fuels could be on effective means of moderating the increase in liner heat load and should be pursued in these programs. To avoid compromising ignition and emissions, these efforts should concentrate on smoke and heat load reduction through improved fuel atomization, localized leaning of and enhanced mixing in particulate carbon formation regions rather than through global reductions in the primary zone equivalence ratio.

The data obtained to date on the effect of fuel composition on liner heat load has consisted primarily of measured liner metal temperatures. While measurements of that type are useful in qualitatively assessing the effect of combustor perturbations, greater emphasis should be placed on direct measurement of the heat transfer rate in future tests. The latter may be more readily incorporated into combustor design procedures and provides a more fundamental measurement for the identification of the mechanisms involved.

Thermal Stability

The data on the thermal stability of fuels, even that from simple JFTOT tests, is extremely limited and a more comprehensive evaluation of fuels even to correlate break point temperatures with fuel composition is required. Additional fundamental research on the effects of pressure, temperature, fluid mechanical aspects and surface properties have on coking rate is necessary before accurate projections can be made of fuel system requirements to avoid carbon deposition. While not addressed directly in this study, further research on the mechanism of carbon formation in fuel injectors is necessary to avoid fuel streaking or maldistribution when operated on broad specification fuels.

The results of the design study conducted under this program indicated that, if carbon deposition is to be avoided by lowering the fuel supply temperature at the engine manifolds, extensive revisions to the engine and airframe fuel system will be necessary. These revisions may also have a beneficial effect on potential fuel freezing problems during long duration flights but could adversely affect ignition characteristics or lead to overheating of the fuel in the airframe tanks under certain situations. The overall feasibility of this approach requires additional study.

Ignition

Ignition has been shown to be sensitive to both the volatility of the fuel and its atomization characteristics. The area of greatest concern is the cold fuel ignition situation and the literature survey conducted under this program indicated the available information on the effect of fuel composition on this aspect of combustor operation was extremely limited. Concern has also been expressed over the adequacy of ignition enhancement approaches such as local enrichment, increased ignition energy or modified fuel schedules and their impact on overall combustor performance. A comprehensive experimental program, involving testing of combustors in a facility capable of providing variable fuel and air temperatures and pressure levels consistent with ground and altitude starting conditions, should be conducted. In addition to the fuel composition, injector atomization characteristics, primary zone air loading and ignition energy should be varied over sufficient range to define the sensitivity of the ignition process to those parameters.

Emissions and Smoke

The use of higher aromatic content fuels has been found, in general, to lead to an increase in the output of all emissions constituents as well as smoke. While some of the incremental increases appear to be related to combustor design parameters, and consequently may be responsive to development, others are apparently inherent in the fuel chemistry. Extensive documentation of the effect of fuel composition on the emissions and smoke characteristics of aircraft engines is necessary and air quality regulatory agencies at the local and federal levels must be made aware of this data because of their participation in environmental-energy availability tradeoff assessments. The most realistic documentation would be achieved by comprehensive emissions/smoke measurements obtained from engines operating on fuels of progressively varying composition. Engines evaluated should include not only newly manufactured production engines, but deteriorated performance engines and prototypes or experimental versions of anticipated future models.

Premixed Combustion Systems

The results of this study indicate that fuel composition can have a profound effect on many of the mechanisms critical to the achievement of optimum performance of a lean premixed prevaporized combustor. These include combustion stability of bluff body flameholders, autoignition constraints and vaporization rates. At the present time, fundamental research is being conducted on these mechanisms under the Lean Premixed Prevaporized Combustor Technology Program (Reference 8) and will provide the framework for the eventual design and development of this type of combustor. Since the maturation time scale for the premixed prevaporized combustor concept parallels that for the introduction of a fuel specification comparable to ERBS, technology programs in this area should emphasize the use of such a fuel. The fundamental research efforts currently underway in this area should be expanded to include the effect of fuel composition. While premixed-prevaporized combustors are considered a long range technology area, expansion of these programs is particularly timely because of the availability of existing research apparatus which permits more economical data acquisition and the opportunity for obtaining data on fuel related phenomena under otherwise identical conditions.

Atomization

The atomization characteristics of fuel injectors for swirl stabilized direct injection combustors appear to strongly influence several combustor operating parameters including low power emissions, ignition and, through the particulate carbon formation processes, liner heat load and turbine airfoil durability. Since increased aromatic content of the fuel alters physical properties so as to produce deteriorated atomization, research efforts to evolve injectors capable of higher levels of atomization in combination with combustor testing to document their effectiveness would appear warranted.

Test Fuels

Accurate assessment of the impact of the use of broad specification fuels will require standardization of and improvements in the availability of test fuels. While the definition of the tentative ERBS specification is a significant step toward standardization, additional test fuels should be identified. Since two fuels, Jet A and ERBS, by themselves are inadequate to substantiate trends and define nonlinearities in the effect of composition, additional standardized test fuels should be identified. A fuel having a hydrogen content intermediate between Jet A and ERBS and one with a lower hydrogen content than ERBS would appear adequate. The composition of these fuels would have to be controlled to assure that all pertinent chemical and physical properties varied in a manner consistent with the Jet A-ERBS trends. Blends produced by the addition of a high aromatic content additive to Jet A must be selected carefully to avoid problems such as the inconsistently low viscosity of the Naphthalene and Xylene blended fuels used in the tests of Reference 21 and 22. After specifications for these test fuels are established, a source for the test fuels in sufficient quantity for large scale combustor rig and engine testing must be established.

APPENDIX A

TABLE A-1

ANALYSIS OF TEST FUELS USED IN THE REFERENCE 21 INVESTIGATION

	Jet A Baseline	No. 2 Diesel	No. 2 Home Heat	Jet A + Xylene	Jet A + Naphthalene
Specific Gravity 289/289 K	0.8151	0.8519	0.8623	0.8358	0.8571
Viscosity @ 311K, (cs.)	1.57	2.75	2.32	1.05	1.50
@ 292K, (cs.)	2.16	4.23	3.47	1.37	2.08
Flash point K	327	347	327	316	333
Heat of Combustion (10^6 j/kg)	43.2	42.7	42.5	42.3	42.2
Freezing Point K	228	253	257	216	229
Sulfur (wt. %)	0.034	0.24	0.18	0.02	0.03
Nitrogen (ppm)	5	42	93	6	5
Aniline Point (K)	335	335	324	300	315
Luminometer Number	44	33	21	23	24
Distillation (K)					
Initial Boiling Point	441	456	437	422	442
10%	459	495	474	437	468
20%	467	508	493	442	476
30%	477	517	507	446	483
40%	483	524	518	451	487
50%	489	532	528	458	491
60%	496	540	538	468	495
70%	503	550	550	480	499
80%	513	562	561	493	505
90%	524	580	579	506	514
Final Boiling Point	548	605	607	533	536
Recovery (vol. %)	98.0	97.5	98.0	98.0	98.5
Residue (vol. %)	1.2	2.1	2.0	1.0	0.9
Loss (vol. %)	0.8	0.4	0.0	1.0	0.6
Aromatics (vol. %)	18.0	27.0	38.5	47.9	35.5
Olefins (vol. %)	0.4	0.3	0.7	0.5	0.4
Hydrogen (wt. %)	13.71	12.97	12.33	12.20	12.15
Hydrogen to Carbon Ratio	1.89:1	1.78:1	1.68:1	1.66:1	1.65:1
Naphthalenes (vol. %)	2.1	7.1	10.9	1.3	16.2

TABLE A-2

PROJECTED EMISSIONS AND SMOKE CHARACTERISTICS OF THE REFERENCE COMBUSTOR OPERATING ON JET A FUEL

Single Stage Combustors

	JT9D Engine			
	Emissions Indices gm/Kg			SAE Smoke Number
	CO	THC	NO_x	
Idle	58.0	27.0	3.1	0.4
Approach	3.3	0.6	7.4	-
Climb	0.4	0.3	31.6	-
Takeoff	0.4	0.3	42.4	4
EPAP (gm/KN)	99.0	45.7	62.0	-

Energy Efficient Engine			
Emissions Indices gm/Kg			SAE Smoke Number
CO	THC	NO_x	
9.7	0.5	4.1	3.6
2.0	0.05	11.0	-
0.4	0.05	25.0	-
0.4	0.05	31.0	61
12.4	0.62	44.1	-

Vorbix Combustors

	JT9D Engine			
	Emissions Indices gm/Kg			SAE Smoke Number
	CO	THC	NO_x	
Idle	14.0	1.0	3.0	-
Approach	10.0	0.5	4.5	-
Climb	1.5	0.2	11.0	-
Takeoff	1.0	0.2	13.0	30
EPAP (gm/KN)	30.4	1.91	25.7	-

Energy Efficient Engine			
Emissions Indices gm/Kg			SAE Smoke Number
CO	THC	NO_x	
6.0	0.9	3.8	-
7.5	0.4	8.2	-
1.0	0.15	15.5	-
0.7	0.15	19.0	41
11.5	1.15	29.2	-

Premixed-Prevaporized Combustors

	JT9D Engine			
	Emissions Indices gm/Kg			SAE Smoke Number
	CO	THC	NO_x	
Idle	3.9	2.9	2.8	-
Approach	7.4	0.7	4.3	-
Climb	0.7	0.5	5.95	-
Takeoff	0.7	0.4	7.88	-
EPAP (gm/KN)	12.5	5.7	17.2	-

Energy Efficient Engine			
Emissions Indices gm/Kg			SAE Smoke Number
CO	THC	NO_x	
3.6	2.7	3.5	-
5.5	0.5	6.0	-
0.3	0.3	10.2	-
0.3	0.3	13.8	-
7.5	3.5	22.0	-

TABLE A-3

PROJECTED EMISSIONS AND SMOKE CHARACTERISTICS OF THE REFERENCE COMBUSTORS OPERATING ON ERBS FUEL

Single Stage Combustors

	JT9D Engine				Energy Efficient Engine			
	Emissions Indices gm/Kg			SAE Smoke Number	Emissions Indices gm/Kg			SAE Smoke Number
	CO	THC	NO_x		CO	THC	NO_x	
Idle	66.0	31.3	3.3	1.8	10.9	0.73	4.2	8.5
Approach	3.4	0.6	7.4	-	2.0	0.05	11.0	-
Climb	0.4	0.3	33.2	-	0.4	0.05	26.0	-
Takeoff	0.4	0.3	48.3	4.6	0.4	0.05	32.5	70
EPAP (gm/KN)	112.8	52.5	66.3	-	13.3	0.88	46.5	-

Vorbix Combustors

	JT9D Engine				Energy Efficient Engine			
	Emissions Indices gm/Kg			SAE Smoke Number	Emissions Indices gm/Kg			SAE Smoke Number
	CO	THC	NO_x		CO	THC	NO_x	
Idle	16.3	1.67	3.1	-	7.0	1.5	3.9	-
Approach	10.2	0.6	4.5	-	7.7	0.5	6.2	-
Climb	1.5	0.2	11.0	-	1.0	0.15	15.5	-
Takeoff	1.0	0.2	13.0	30	0.7	0.15	19.0	45
EPAP (gm/KN)	34.3	2.86	25.9	-	13.3	2.12	29.2	-

TABLE A-4

PROJECTED EMISSIONS AND SMOKE CHARACTERISTICS OF COMBUSTORS WITH INCREASED LINER COOLING AIR AND OPERATING ON ERBS FUEL

Single Stage Combustor

	JT9D Engine				Energy Efficient Engine			
	Emissions Indices gm/Kg			SAE Smoke Number	Emissions Indices gm/Kg			SAE Smoke Number
	CO	THC	NO_x		CO	THC	NO_x	
Idle	97.0	74.0	2.9	2.7	16.1	1.0	5.2	5.0
Approach	3.7	1.1	6.6	-	2.2	0.05	12.4	-
Climb	0.4	0.5	33.2	-	0.4	0.05	26.0	-
Takeoff	0.4	0.5	48.3	4.6	0.4	0.05	32.5	70
EPAP (gm/KN)	164.0	124.0	65.0	-	19.4	1.24	49.5	-

Vorbix Combustors

	JT9D Engine				Energy Efficient Engine			
	Emissions Indices gm/Kg			SAE Smoke Number	Emissions Indices gm/Kg			SAE Smoke Number
	CO	THC	NO_x		CO	THC	NO_x	
Idle	23.0	2.2	3.7	-	9.3	1.85	5.5	-
Approach	10.8	0.6	5.0	-	7.5	0.53	6.3	-
Climb	1.5	0.2	11.0	-	1.0	0.15	15.5	-
Takeoff	1.0	0.2	13.0	33	0.7	0.15	19.0	45
EPAP (gm/KN)	44.9	3.8	27.6	-	15.0	2.65	30.9	-

Premixed-Prevaporized Combustors

	JT9D Engine				Energy Efficient Engine			
	Emissions Indices gm/Kg			SAE Smoke Number	Emissions Indices gm/Kg			SAE Smoke Number
	CO	THC	NO_x		CO	THC	NO_x	
Idle	11.0	4.85	2.34	-	9.3	4.1	2.7	-
Approach	8.8	1.2	3.30	-	6.0	0.8	4.0	-
Climb	0.7	0.5	2.00	-	0.3	0.3	3.4	-
Takeoff	0.7	0.40	2.64	-	0.3	0.3	4.56	-
EPAP (gm/KN)	25.2	9.5	7.4	-	14.3	5.5	10.2	-

TABLE A-5

PROJECTED EMISSIONS AND SMOKE CHARACTERISTICS OF COMBUSTORS
OPERATING ON ERBS FUEL WITH IMPROVED LINER AND FUEL ATOMIZATION

Single Stage Combustor

	JT9D Engine				Energy Efficient Engine			
	Emissions Indices gm/Kg			SAE Smoke Number	Emissions Indices gm/Kg			SAE Smoke Number
	CO	THC	NO_x		CO	THC	NO_x	
Idle	61.0	29.0	3.3	1.3	10.0	0.56	4.2	4.3
Approach	3.4	0.6	7.4	-	2.0	0.05	11.0	-
Climb	0.4	0.3	33.2	-	0.4	0.05	26.0	-
Takeoff	0.4	0.3	48.3	4.6	0.4	0.05	32.5	70
EPAP (gm/KN)	104.6	49.8	66.3	-	12.2	0.68	46.5	-

Vorbix Combustors

	JT9D Engine				Energy Efficient Engine			
	Emissions Indices gm/Kg			SAE Smoke Number	Emissions Indices gm/Kg			SAE Smoke Number
	CO	THC	NO_x		CO	THC	NO_x	
Idle	16.3	1.0	3.1	-	7.0	0.9	3.9	-
Approach	10.2	0.5	4.5	-	7.7	0.4	6.2	-
Climb	1.5	0.2	11.0	-	1.0	0.15	15.5	-
Takeoff	1.0	0.2	13.0	33	0.7	0.15	19.0	45
EPAP (gm/KN)	34.3	1.91	25.9	-	13.3	1.15	29.2	-

Premixed-Prevaporized Combustors

	JT9D Engine				Energy Efficient Engine			
	Emissions Indices gm/Kg			SAE Smoke Number	Emissions Indices gm/Kg			SAE Smoke Number
	CO	THC	NO_x		CO	THC	NO_x	
Idle	8.0	2.2	2.8	-	7.3	2.0	3.5	-
Approach	8.5	0.7	4.3	-	6.0	0.5	6.0	-
Climb	0.7	0.5	2.0	-	0.3	0.3	3.4	-
Takeoff	0.7	0.4	2.64	-	0.3	0.3	4.56	-
EPAP (gm/KN)	20.0	4.8	8.90	-	12.0	3.2	12.0	-

NOMENCLATURE

A - Absorbtivity
B - Beam length (meters)
D - Characteristic Diameter (cm)
EI - Emission Index (gm/Kg of fuel)
F/A - Fuel Air Ratio
F - View Factor
P - Pressure (atmospheres)
q - Heat flux (joules/m^2)
S - Stefan Boltzman Constant
SMD - Sauter Mean Diameter (microns)
T - Temperature (^{o}K)
V - Velocity (m/sec)
W - Mass Flow Rate (gm/sec)
α, β - Influence Coefficients
ϵ - Emissivity
γ - Specific Gravity
ρ - Density (gm/cm^3)
σ - Surface tension (dynes/cm)
ν - Kinematic viscosity (centistokes)

Subscripts:

a - Air
f - Fuel
fl - Flame
g - Gas
w - Wall
i - Inlet
B - Breakpoint
L - Liner
IBP - Initial Boiling Point
FBP - Final Boiling Point

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