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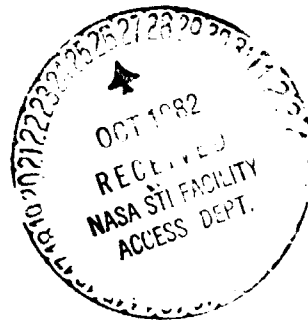
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Multifuel Evaluation of Rich/ Quench/Lean Combustor



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Work performed for
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ABSTRACT

The work described in this paper is a part of the DOE/LeRC "Advanced Conversion Technology Project" (ACT). The program is a multiple contract effort with funding provided by the Department of Energy and Technical Program Management provided by NASA LeRC. The emphasis in this paper is the fuel flexible combustor technology developed under the "Low NO_x Heavy Fuel Combustor Concept Program" for application to the Detroit Diesel Allison (DDA) Model 570-K industrial gas turbine engine. The technology, to achieve emission goals, emphasizes dry fuel-bound nitrogen (FBN), control of NO_x can be effected through a staged combustor with a rich initial combustion zone. A rich/quench/lean (RQL) variable geometry combustor utilizes the technology that will be presented to achieve low NO_x from alternate fuels containing FBN. The results will focus on emissions and durability for multifuel operation.

INTRODUCTION

Detroit Diesel Allison (DDA) is among five gas turbine engine manufacturers participating in the "Low NO_x Heavy Fuel Combustor Concept Program"(1). The technology focus at DDA is the Allison Model 570-K industrial gas turbine engine. This low- NO_x combustor must be capable of sustained, environmentally acceptable "dry" operation on minimally processed heavy petroleum residuals (RESID), synthetic coal derived liquids (CDL), petroleum distillate (ERBS) low-heating-value gaseous (LHV) fuels, and medium-heating-value gaseous (MwV) fuels. From a fuel flexibility viewpoint, the advanced combustion technology developed under this DOE/LeRC program, and presented in this paper, is essential to the future industrial engine market. Declines and uncertainties in the availability of petroleum distillate fuel and increasing demands for natural gas coupled with continually rising cost lead one to conclude that in the future industrial gas turbine users will require multifuel capability. As a result of fuel flexibility, uninterrupted operation will be preserved. Fuels such as petroleum residuals, "synthetics," or low/mid-heating-value gases are most likely to become prominent for the utility and industrial user. Often these fuels have significant levels of fuel-bound nitrogen (FBN). In developing a fuel flexible combustion system, the control of NO_x emissions from this pollutant source is a major challenge for the engine manufacturer. Significant technological advances from contemporary combustion systems are essential to operate gas turbine engines in an environmentally acceptable manner when using these fuels.

Because of general air pollution problems within the United States, the exhaust emissions from all fuel-burning devices have been or are planned to be regulated by both federal and state governments. Recently enacted federal regulations for stationary gas turbine engines specify pollutant emission concentration levels that are below the current applied technology. Pollutant emissions produced by gas turbines using petroleum distillate fuels are carbon monoxide (CO) and unburned hydrocarbons (UHC) at low-power conditions and oxides of nitrogen (thermal NO_x) at high-power conditions.

Reductions of CO and UHC in contemporary combustors can be achieved by relatively straightforward approaches(2,3). However, these approaches are subject to tradeoffs in operating range capabilities, combustion system complexities, and control of thermal NO_x . The reduction of thermal NO_x is not as straightforward because the most favorable conditions for minimum NO_x are in opposition to combustion stability, production of CO and UHC, and operating range. Control of NO_x from FBN is less understood but exploratory research(4) indicates control can be effected through a rich (excess fuel) combustion process. The flexibility to operate with nonstandardized liquid fuels presents performance problems apart from emissions. High viscosity makes atomization, vaporization, and distribution a difficult task, thus necessitating innovative fuel injector design and development. Distillation variations (residual fuel has end points in excess of 1100°F [867K]) require special consideration relative to combustor sizing. Reduced hydrogen content or high aromatics, especially for CDLs, present a problem in the area of liner durability due to high radiation loads. In essence, all facets of combustor design and development require careful review and advancements when multifuel capability is the goal.

The air-staged combustor(5) presented in this paper consists of an initial rich burning zone followed by a quench zone and lean reaction and dilution zone. This combustor is referred to as the

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RQL combustor. Unique to this RQL combustor is the feature that all air entries are regulated by variable geometry. This permits combustor performance/emission optimization over the entire engine operating range. Tradeoffs between the complexities of variable geometry and performance/emission results will determine the final design.

DESIGN FEATURES

The objective of this DOE/LeRC program is to generate and demonstrate the advanced technology required to develop a durable, low-emission gas turbine combustor for utility and industrial applications capable of operation on minimally processed petroleum residual, synthetic, or low/mid-heating-value gaseous fuels. Key properties of the five fuels tested in this program are enumerated in Table 1. Note that ERBS(6) is a research fuel that is a special blend of kerosene and hydrotreated catalytic gas oil. It represents a future fuel should it become necessary to broaden current kerojet specifications. Design criteria for multifuel operation are dictated by the program goals and are shown in Table 2.

The control of NO_x requires specific reaction zone stoichiometry. In general, oxides of nitrogen are formed when nitrogen in the atmosphere is subjected to high temperatures over a finite period of time in the presence of oxygen. The oxidation of atmospheric nitrogen can be minimized by operating at reaction-zone temperature levels below approximately 2500°F (1644K). Unfortunately, in the excess

oxygen state of lean combustion, FBN will react to produce excessive levels of NO_x. It has been postulated and later demonstrated in fundamental experiments that a fuel-rich combustion zone can be effective to minimize NO_x from FBN(4,7,8). The equivalence ratio for minimum NO_x has to be determined through experimentation and is a significant part of this program. The DDA design rationale was to inhibit NO_x formation from FBN in a rich burning zone and quickly/uniformly quench the exiting hot products so that a minimum of thermal NO_x will be formed in the final lean reaction zone. This staged-air RQL combustion process is illustrated through the temperature rise curve shown in Figure 1. Transition from a rich zone to a lean zone requires a very rapid uniform quench to prevent high temperatures resulting from stoichiometric streaks. The lean zone equivalence ratio can be selected as a function of thermal NO_x levels with due consideration for the consumption of CO and smoke. The reaction of CO requires time and temperature, which is in direct opposition to the NO_x reactions. Therefore, the operating equivalence ratio for this lean zone must also be carefully controlled to satisfy both emissions requirements. The dilution zone tailors the exit temperature pattern for turbine durability and receives the balance of air after combustion and cooling are satisfied.

Details of the design philosophy of the RQL combustor tested at DDA are presented in a previous paper(5). This current paper presents the results of the combustor rig testing on liquid and gaseous fuels.

Table 1.
Fuel Properties.

	Liquids			Gas mixtures	
	Petroleum distillate (ERBS)	Petroleum residual (RESID)	Synthetic-CDL (SRC-II)	Low-heating value	Mid-heating value
Elemental composition--wt %					
Hydrogen	12.88	11.24	8.81	1.92	3.60
Carbon	87.05	87.39	85.84	18.59	36.38
Oxygen	-	0.51	4.19	26.04	57.55
Nitrogen	0.013	0.27	0.88	53.45	2.45
Sulfur	0.09	0.56	0.28	-	-
10% dist.--°F (K)	375 (464)	572 (573)	410 (483)	-	-
End point--°F (K)	645 (614)	1026 plus (825)	597 (587)	-	-
Pour point--°F (K)	-35 (236)	40 (278)	-50 (228)	-	-
Lower heating value					
Btu/lb	18,327	17,933	17,349	2660.5	4852.1
(MJ/kg)	(42.63)	(41.71)	(40.35)	(6.19)	(11.29)
Stoichiometric fuel/air	0.0693	0.0718	0.0785	0.5972	0.3408
Gases in mixture--vol %					
Hydrogen, H ₂	-	-	-	17.4	36.4
Carbon monoxide, CO	-	-	-	29.7	50.2
Carbon dioxide, CO ₂	-	-	-	4.6	11.6
Methane, CH ₄	-	-	-	2.7	-
Nitrogen, N ₂	-	-	-	45.6	1.8

Table 2.
Emissions and performance goals.

Performance goals	
Combustion efficiency	99% (operating range)
Total pressure loss	6% (base load power)
Outlet temp. pattern factor	0.25 (base and peak load)
Outlet temp. profile	Equivalent to typical production
Emissions goals	
Oxides of nitrogen (at 15% O ₂)	90 ppm FBN ≤ 0.015% (ERBS) 140 ppm FBN > 0.25% (RESID) & SRC-II)
Sulfur dioxide	(Limits fuel sulfur content)
SAE smoke number	20

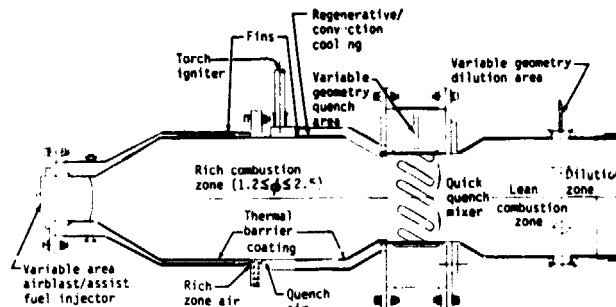


Figure 2. Schematic of rich/quench/lean combustor.

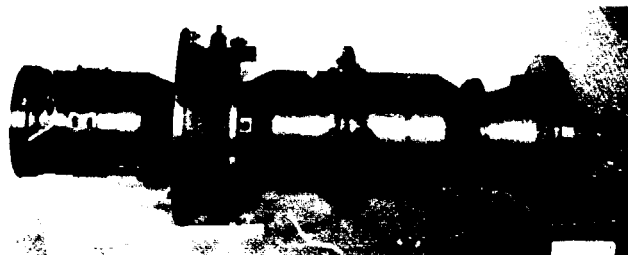


Figure 3. Assembled rich/quench/lean combustor.

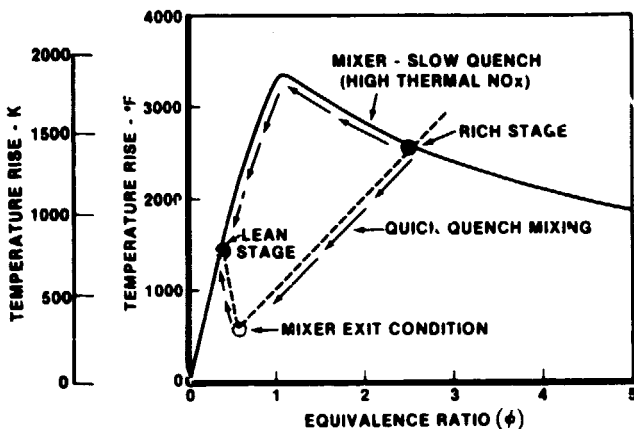


Figure 1. Operational considerations for rich/quench/lean staged combustor.

RQL COMBUSTOR DESCRIPTION

A schematic of the RQL fuel flexible combustor that depicts its key features is shown in Figure 2. A photograph of the RQL combustor is presented in Figure 3. Unique features of this combustor are its air staging, variable geometry, and regenerative/convective cooling. Three axial locations of variable geometry are used to vary rich/lean zone equivalence ratios in concert or independently while maintaining a specified pressure drop. A description and illustration of the key features of this combustor are given in the previous paper(5).

Shown in Figure 4 is the variable-area airblast fuel injector designed by Parker Hannifin Corp. Gas Turbine Fuel Systems Division. This injector includes two constant-area air orifices, two variable-area air swirlers and a fuel prefilming orifice. The area variation is accomplished through meshing of the swirlers and is shown in figure 5. The photo at the top depicts the maximum airflow configuration while the minimum airflow configuration is shown at the bottom. The center shroud and fuel entry point traverses approximately 0.25 inches (0.64 cm) axially when operating over the airflow (equivalence ratio) range. In the closed position the air-to-air fuel ratio of 3:1 acceptable for good atomization.



Figure 4. Variable area airblast fuel injector.

For gaseous fuels (low- and mid-heating-value) a liquid fuel nozzle was modified to handle the gas flows required. The combustor liner required no modification, being able with the ranges of its variable-geometry components to operate satisfactorily on any of the liquid or gaseous fuels used in the test program.

TEST FACILITIES AND PROCEDURES

Airflow calibration and combustion testing of the fuel flexible RQL combustor was carried out in a DDA high-pressure test facility. The test cell dedicated to this program is capable of operation at the Model 570-K rated engine conditions. High-pressure filtered facility air is supplied to the test rig through indirect gas-fired heaters, which



Full open



Full closed

Figure 5. Variable area airblast fuel injector.

are used to elevate inlet temperatures to simulate compressor discharge characteristics. The operating conditions at which the combustor was evaluated are enumerated in Table 3.

A plenum-type test rig, shown in Figure 6, accommodates the variable geometry combustor. Unique to its test section are three remotely controlled, variable-geometry actuators. These permit independent sizing of the nozzle, quench, and dilution air entries from the control room. Thus, many configurations can be examined in an efficient test procedure.

Data of interest are the inlet and exit pressures and temperatures, emissions, internal static pressures, combustor metal temperatures, and variable geometry positions. Inlet measurements are consistent with standard DDA test procedures, including sharp-edged orifices and appropriate pressure and temperature instrumentation. Exit instrumentation consists of five equally spaced five-element platinum/platinum-rhodium thermocouple rakes with one rake having a sixth element on the centerline. These are used to evaluate temperature rise and pattern factor. Water-cooled emission probes are arranged in a similar manner, with the exclusion of a centerline port. The emission probes are manifolded to a common, heated sample line leading to the exhaust gas measurement instruments given in

Table 3.
Engine/combustor operating conditions.

Power point	Airflow --lb/sec (kg/sec)	Inlet temp-- °F (K)	Inlet pressure-- psia (kPa)	Fuel flow --lb/hr (g/sec)
Max rated	3.87 (1.75)	688 (638)	177.1 (1221.1)	331.4 (41.8)
Max cont.	3.70 (1.68)	661 (623)	165.6 (1141.8)	296.9 (37.4)
70% load	3.22 (1.46)	592 (584)	135.4 (933.6)	212.2 (26.7)
50% load	2.89 (1.31)	547 (559)	116.2 (801.2)	164.2 (20.7)
Idle	1.61 (.73)	342 (445)	52.0 (358.5)	40.8 (5.1)

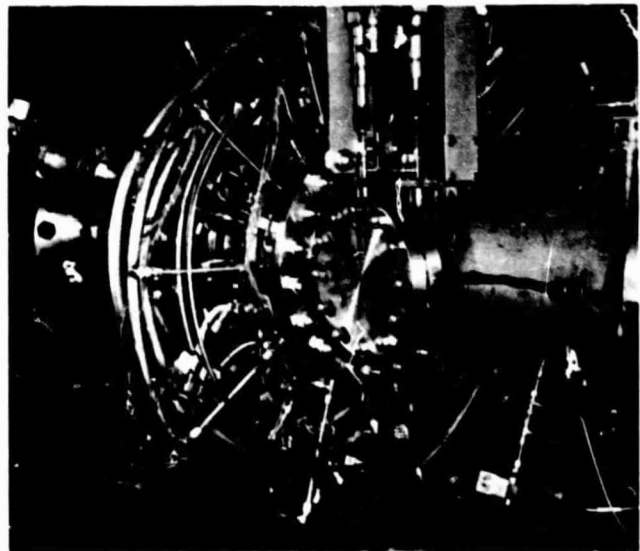


Figure 6. Test rig for remotely actuated variable-geometry RQL combustor.

Table 4. If necessary, the emission probes can also be used as total pressure instrumentation. This exit instrumentation provides sufficient coverage for meaningful evaluation of the combustor's performance. Each combustion zone and plenum section of the RQL combustor is instrumented for static pressures; the plenums also include thermocouples to measure the cooling air temperature rise. Combustor liner durability is monitored through 29 embedded wall thermocouples.

All performance and emissions data are computer recorded with on-line display in the control room. Calibration of the variable-geometry actuators as a function of percent open permit digital readout and computer recording of the combustor configuration.

The liquid-fuel storage system entails three 275-gallon (1041 L) tanks for the RESID, ERBS, and SRC-II fuels. To maintain a uniform nonstratified temperature, an internal heater and recirculating system are part of the RESID tank. The rig fuel delivery system includes electrically heated lines, filters, recirculation circuits, and a high-pressure

Table 4.
On-line exhaust gas measurement instruments.

<u>Exhaust Gas</u>	<u>Instrument</u>	<u>Accuracy</u>
Carbon monoxide (CO)	Beckman Model 865-NDIR	$\pm 1.0\%$
Unburned hydrocarbons (UHC)	Beckman Model 402-heated FID	$\pm 1.0\%$
Total nitrogen oxides (NO _x)	TECO Model 10A-CL	$\pm 1.0\%$
Carbon dioxide (CO ₂)	Beckman Model 864-NDIR	$\pm 1.0\%$
Smoke	ARP 1179 procedure	± 3 SN

steam heater to elevate the RESID temperature immediately upstream of the fuel nozzle. Also, the capabilities to inject pyridine into the fuel line through a metered, low-flowing, high-pressure pump and to blend any two fuels during testing are part of this system. Flotrons are used for all fuel flow measurements.

The gaseous fuel system supplied filtered and remotely controllable gas flow and was measured by an ASME orifice. The system's essential components included a vented high-pressure trailer, a high-pressure volume reducing station, filters, safety controls, and a flow control and measuring station. The reduced operating pressure of the system was 350 lb/in.² gage (2413 kPa), which provides a usable gas volume of 70,000 ft³ (1982 m³). Ammonia could be added to gaseous fuel to simulate FBN.

Due to the importance of precise zone equivalence-ratio control, experimental airflow calibrations were carried out to determine the complex combustor airflow circuits and the three variable-area air entries. The effective area of each entry and zone pressure drops were determined through sequential testing. Thus, during combustor testing, zone equivalence ratios are determined by using the variable geometry positions and design pressure drop as input to the performance maps. Throughout the testing this is a set-and-confirm procedure, i.e., test configurations are selected utilizing the maps and subsequent confirmation of the test point is determined based on the experimental measurements. All data transfers, reductions, and correlations are processed through the DD computer system.

The principal procedure for combustor evaluation testing involved operating at inlet conditions representative of a fixed engine operating point while varying the combustor configuration. Since there are three stations of variable geometry, many configurations can be evaluated during a single rig buildup. Also, the ability to vary reaction-zone equivalence ratios while maintaining the overall fuel/air ratio and pressure drop permits correlation of all configurations without scaling. Since durability is paramount in this program and novel cooling schemes are being used, continuous real-time monitoring of liner temperatures was carried out. The first test requirement of an acceptable configuration is liner integrity. Based on satisfaction with this criteria, performance and emissions data are acquired and a new configuration initiated.

RESULTS AND DISCUSSION

Evaluation of the RQL combustor has been carried out using three liquid fuels and two gaseous fuels.

The liquid fuels tested on the RQL combustor were ERBS, RESID, and SRC-II. In addition to the three fuels themselves, which contained varying levels of FBN, higher levels of FBN were simulated by adding 2-vinyl pyridine to the base fuels. The RQL combustor was operated from idle to maximum rated power on each of the liquid fuels with much of the testing occurring at the maximum continuous (90% maximum rated) power condition. Combustor rig testing comprised three test series for the RQL combustor.

Development testing accumulated 209 data points, during which the minor development problems of the RQL concept were solved. Some of these data were presented in the previous paper(5) on the RQL combustor. The second test series, accounting for 174 data points, was the performance testing of the RQL combustor from idle to maximum rated power using each of the three liquid fuels plus some testing of each fuel with pyridine added to increase the FBN levels. These are the data that will be presented in this paper. The final test series of the RQL combustor on liquid fuels accounted for 211 data points of parametric tests on the ERBS and RESID fuels.

The RQL combustor NO_x emissions when operating on ERBS fuel are shown in Figure 7. The NO_x emissions are plotted as a function of the rich-zone equivalence ratio, which was accomplished by adjustments in the rich-zone (fuel nozzle) and mixer variable-geometry air distribution systems. As can be seen, NO_x levels are minimal in the 1.2 to 1.4

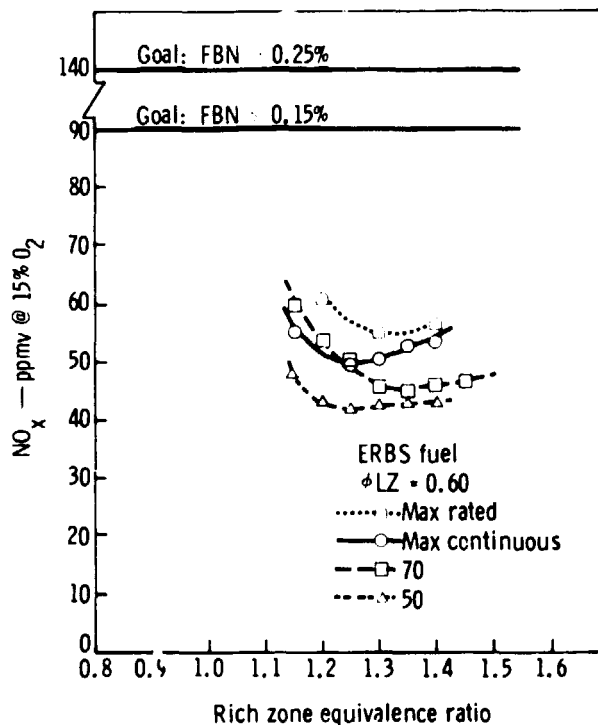


Figure 7. NO_x response to power level.

rich-zone equivalence ratio range and gradually increase with increasing power level.

Minimum NO_x levels were approximately the same at maximum continuous power conditions for all three of the liquid fuels at 52 to 53 ppmv, as shown in Figure 8, even though the FBN varied widely from fuel to fuel. The minimum NO_x points occurred in the 1.3 to 1.4 rich-zone equivalence ratio range, demonstrating the insensitivity of NO_x emissions to fuel type or to inherent FBN levels. The window for low NO_x emissions is fairly narrow. To be below 75 ppmv NO_x , the rich-zone equivalence ratio had to be between 1.15 and 1.55.

The SRC-II and RESID fuels were tested with increased FBN levels by adding 2-vinyl pyridine. Figures 9 and 10 present the data from the increases in FBN in the SRC-II and RESID fuels. Basically the minimum NO_x concentration was not affected by the increase in FBN, but effects from FBN are noted at equivalence ratios above and below the minimum NO_x point. At equivalence ratios less than the minimum NO_x value, the addition of increasing levels of FBN reduced the NO_x concentration. At equivalence ratios more than the minimum NO_x value, the addition of more FBN increased the NO_x concentrations.

Measured exhaust smoke from the RQL combustor was less than a 20 smoke number (SN) at all conditions for all fuels and for all but a few data points was below 10 SN. Carbon monoxide in the exhaust was measured at concentrations of 20 to 50 ppmv. Combustion efficiency exceeded 99.9 percent at all test conditions above idle. The range of operation of the RQL combustor did not permit satisfactory operation at idle conditions.

The gaseous fuels tested on the RQL combustor are described in Table 1. Equilibrium temperatures were computed for both gaseous fuels as shown in Figure 11. The mid-heating-value gas produced temperatures that were 460°F (255K) higher than the low-heating-value gas at unity equivalence ratio. Also plotted in Figure 11 are the calculations for a middle distillate oil containing 14 percent hydrogen by weight. The maximum temperature of the mid-heating-value gas is higher than the oil due to the high percentage (36 percent) of hydrogen gas in the mixture.

Corrected NO_x emissions from the RQL combustor operating on low-heating-value gaseous fuel are shown in Figure 12. Nine data points were recorded with successful performance achieved at all four power levels. Corrected NO_x levels varied from 11 to 20 ppmv. Carbon monoxide emissions were high (200-400 ppmv) at 50% load power due to the lack of variable-geometry range to enrich the lean zone sufficiently for efficient oxidation of the CO. No smoke was measured in the exhaust. Combustion efficiencies exceeded 99.9 percent above 70 percent load power conditions.

The mid-heating-value gaseous fuel was tested in the RQL combustor at each of the four test conditions with and without ammonia addition to simulate FBN effects. The NO_x emissions for no ammonia addition, shown in Figure 13, vary from 85 to 53 ppmv, which are the same levels as from the liquid fuels. As with the low-heating-value fuel, definite minimum NO_x equivalence ratios were not observed, but increasing equivalence ratios for the gaseous fuels generally produced decreasing NO_x emissions.

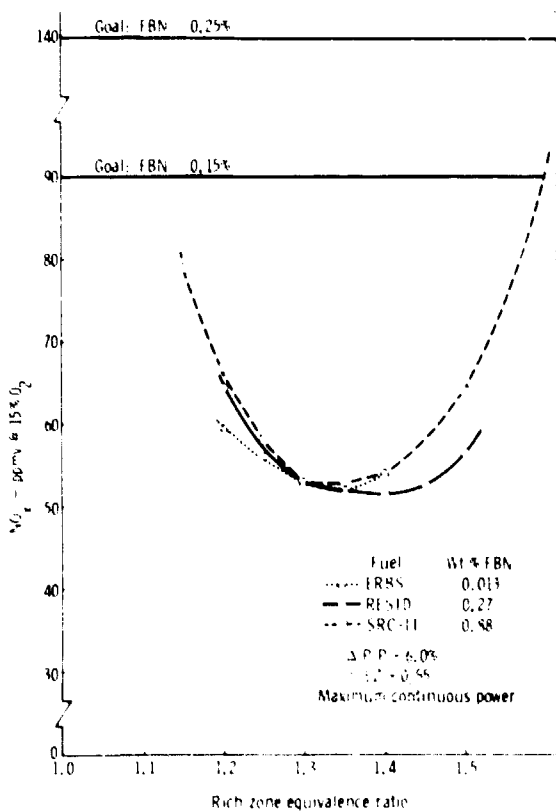


Figure 8. NO_x response to base fuel FBN content.

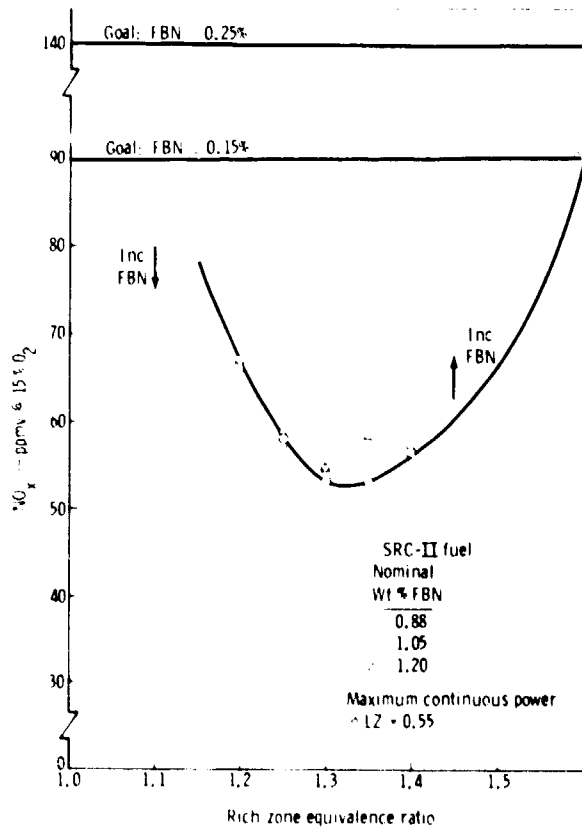


Figure 9. NO_x response to FBN content SRC-II fuel.

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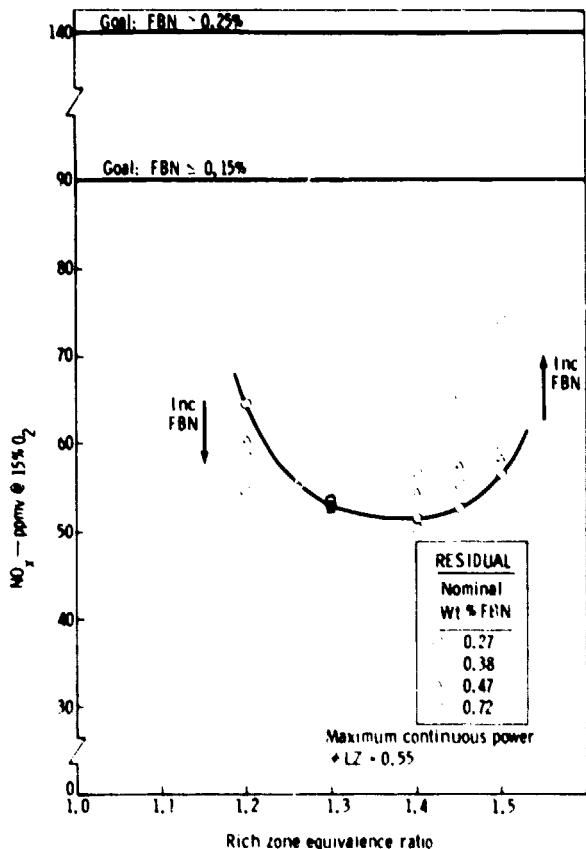


Figure 10. NO_x response to FBN content RESID fuel.

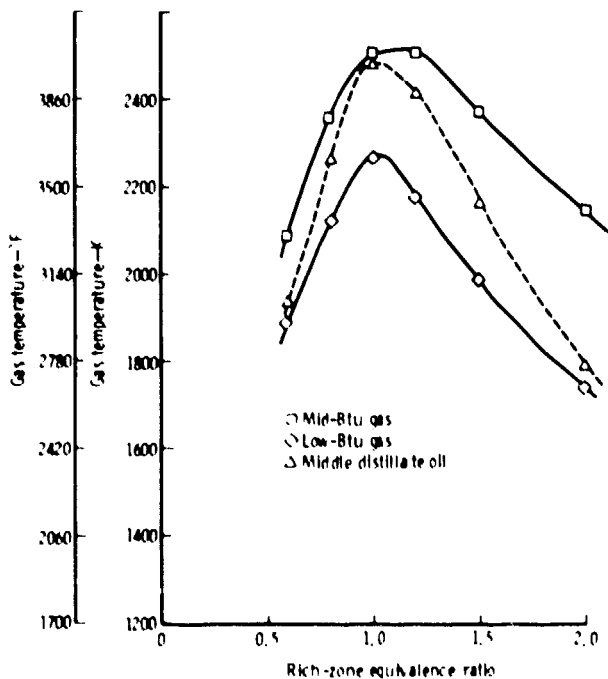


Figure 11. Equilibrium temperatures for gaseous fuels.

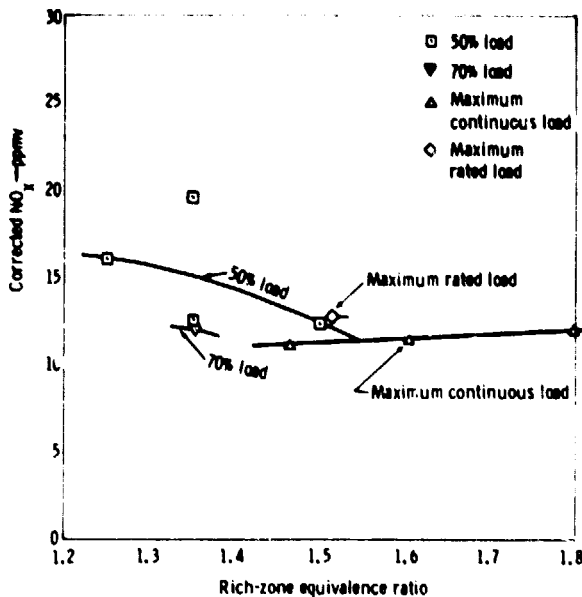


Figure 12. Corrected NO_x emissions for low-heating-value gas fuel.

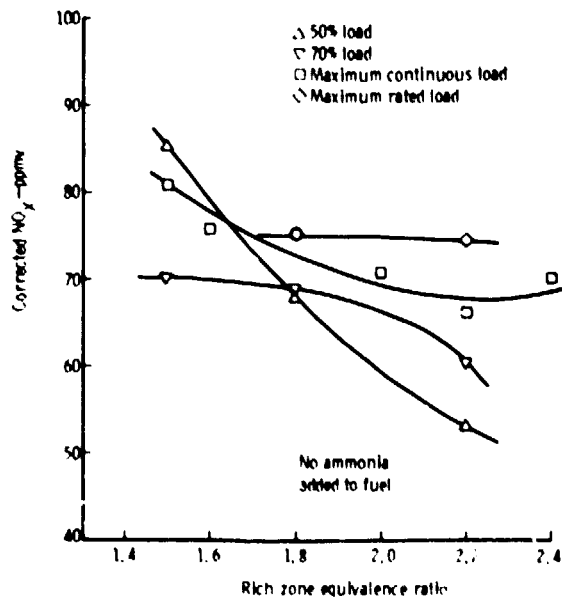


Figure 13. Corrected NO_x emissions for mid-heating-value gas fuel.

The widest range in FBN addition was evaluated at the 50 percent load power condition. The NO_x emissions in Figure 14 show only a minimal effect of the added ammonia. Carbon monoxide emissions at all operating conditions were in the 20 to 30 ppmv range, and there was no measurable smoke in the exhaust at any condition. Combustion efficiencies exceeded 99.93 percent at all conditions for the mid-heating-value gaseous fuel.

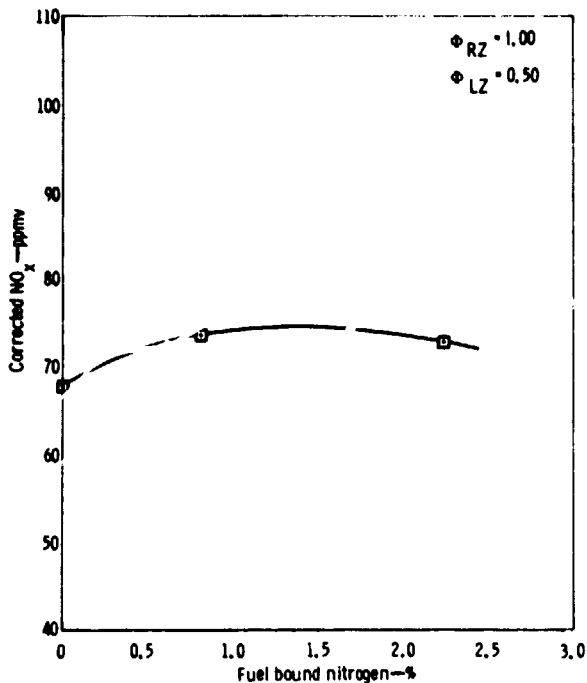


Figure 14. Corrected NO_x emissions for mid-heating-value gas fuel versus FBN content at 50% load conditions.

CONCLUSIONS

A fuel tolerant, variable-geometry, regenerative/convectively cooled staged-air combustor has been designed and tested on a variety of fuels: ERBS, SRC-II, RESID, low-heating-value gas, and mid-heating-value gas. The RQL combustor liner performed satisfactorily on all of the fuels tested, producing low NO_x emissions and very low smoke and operating at high combustion efficiencies. For both liquid and gaseous fuels the combustor demonstrated an insensitivity to FBN levels.

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