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Low NO_x Heavy Fuel Combustor Concept Program

Final Report

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FOREWORD

This final report was prepared by the Power Systems Division of United Technologies Corporation (PSD/UTC) under contract DEN3-149 "Low NO_x Heavy Fuel Combustor Concept Program". It encompasses the work associated with the base program (23 October 1979 to July 1981).

Contract DEN 3-149 was sponsored by the Department of Energy under the administration of the National Aeronautics and Space Administration/Lewis Research Center (DOE/NASA-LeRC). Donald Schultz of NASA/LeRC was the technical manager.

The Power Systems Division Program Manager was Fred Kemp and Technical Manager was Richard Sederquist. Paul L. Russell was Primary Investigator for the project at the Government Products Division of the Pratt & Whitney Aircraft Group. He was assisted by George W. Beal and Bruce Hinton.

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SUMMARY

This report describes results of a systematic evaluation of bench-scale hardware concepts intended to provide technology for environmentally clean combustion of minimally processed fuels, as well as synthetic fuels. Pratt & Whitney Aircraft/Government Products Division (P&WA/GPD) experience and results of computer studies were drawn upon to select the concepts evaluated in this program. Twelve concepts were initially designed and included many variations of basic strategies such as rich/lean combustion, preburning, premixing, and rich product recirulation. An assessment of the pollutant levels of individual concepts was made using a combined computer model including combustor aerodynamics, emission predictions, and fuel droplet vaporization. The design approach considered cost, time, and the interchangeability of parts within the same rig test duct.

The combustor testing was conducted within a cylindrical pressure cell with instrumentation providing for measurement of critical combustor parameters including exhaust gas analysis. A data reduction program was formulated for on-line data analysis and provided rapid cost effective technical knowledge concerning the particular configurations being tested.

During the course of testing the various concepts, durability problems were encountered which delayed the work effort and this unpredictable cost impact prevented the testing of all concepts. However, enough concepts were evaluated to supply the necessary design information for the design of full-scale combustors which will operate below the pollutant limits established for industrial gas turbine engines.

An extensive analysis of all test data was carried out to determine the best overall configuration. The results were very promising and are summarized as follows:

- NOx goal achieved and surpassed (50 ppmv range obtained with all fuels).
- High Burner efficiencies obtained by control of overall fuel-air ratio.

- Smoke levels below SAE 20 achieved for all fuels.
- Excellent Burner Pattern Factor of 0.045 achieved.

The major conclusions from the test effort are:

- A water-cooled rich zone wall has little or no effect on exhaust emissions.
- Fuel preparation is very important in rich combustion, especially for controlling smoke levels.
- NOx levels are independent of pressure in a rich/lean combustion system.
- Control of lean zone stoichiometry is required to control CO levels.
- NOx levels show a strong dependence on rich zone residence time and stoichiometry.
- Sufficient information was obtained to design a full-scale combustor which will have pollution levels below the EPA requirement.

SECTION I
INTRODUCTION

The program discussed in this report has provided an opportunity to study rich-lean combustion processes and their effects on pollutant levels. The work performed was part of the Department of Energy/National Aeronautics and Space Administration - Lewis Research Center (DOE/NASA-LeRC) "Low NO_x Heavy Fuel Combustor Concept Program." The intent of this program was directed toward the development of a fuel flexible combustor which achieves published Environmental Protection Agency (EPA) emissions goals. Emphasis was placed on NO_x reduction techniques for all fuels, including fuels with high levels of fuel-bound nitrogen.

A continued development of combustion technology is needed to provide the users of utility and industrial gas turbine engines the capability of operating in an environmentally acceptable manner. Results from this program could be used to provide design tools necessary for the full-scale combustion of a variety of fuels, including residual, synthetic and blends of each with distillate fuel.

Rich-lean combustion proved to be an effective technique for achieving the goals of this program. In addition, techniques have also been developed which help to reduce smoke levels so that program goals were achieved.

In this exploratory development program, the overall goals were defined by the contractor (Table I) with the primary emphasis on NO_x reduction techniques. The effort was accomplished by completion of the tasks defined below.

Task I - Provided for the preparation of preliminary combustion design drawings, test rig assembly drawings, and a test program plan.

Task II - Provided for the generation of final design drawings of the combustion components, test rig assembly, and all rig instrumentation.

Task III - Provided for the fabrication and procurement of all parts required for baseline testing and installation of test equipment in the test stand. Task III has been expanded to include fabrication of that hardware necessary to conduct fuel property variation testing under Tasks IV, V, and VI.

Task IV - Experimental testing of the hardware designed in Task II using residual fuel, as well as blends of distillate and residual fuels.

Task V - Experimental testing of selected hardware using distillate fuel, as well as blends of distillate and residual fuels and distillate and synfuels.

Task VI - Experimental testing of selected hardware using synfuel, as well as blends of synfuel and distillate fuels.

Task VII - Provided for design analysis using the derived technology gained from combustor testing under Tasks IV, V, and VI.

Task VIII - Identified and documented the characteristics of combustor designed hardware that materially influence integrity and performance.

Task IX - Provided for technical, financial, and schedular reports, as required.

This report documents the work accomplished under Contract DEN3-149 and presents the analysis of the results.

TABLE I - DESIGN EMISSION SPECIFICATIONS

Pollutant	Maximum Level	Operating Conditions
Oxides of Nitrogen	75 ppm @ 15% O_2*	All
Sulfur Dioxide	150 ppm @ 15% O_2**	All
Smoke	S.A.E. Smoke Number = 20***	All

* These levels are subject to the constraints and corrections contained in the Environmental Protection Agency Proposed Rule for Stationary Gas Turbines, Federal Register, 40 CFR Part 60, pp. 53782-53796, October 3, 1977 which rule is hereby incorporated by reference.

** Since the conversion of fuel sulfur to sulfur oxides is total, this design specification represents a practical limit of fuel sulfur content of approximately 0.8%.

*** The smoke measurement technique shall be in accordance with SAE recommended practice as contained in "Aircraft Gas Turbine Engine Exhaust Smoke Measurement, Aerospace Recommended Practice 1179, May 4, 1970" and hereby incorporated by reference.

SECTION II
SUBSCALE COMBUSTOR TESTS

A. BASELINE CONFIGURATIONS

Twelve configurations were initially selected for baseline testing. In addition, two configurations were utilized near the end of the test program. Table II lists the 14 configurations including figure identification when a figure is being used for configurative delineation.

TABLE II - BASELINE CONFIGURATIONS

Configuration	Description	Figure No.
1	Baseline RBQQ*	1
2	RBQQ -- Short Rich Zone	11
3	RBQQ -- Small Dia. Quench Zone	17
4	RBQQ -- Large Dia. Quench Zone	20
5	RBQQ -- Non-Metallic Linear	25
6	Catalytic Fuel Preparation	--
7	Preburner Fuel Preparation	31
8	Variable Geometry	32
9	Graduated Air Addition	35
10	Rich Product Recirculation	--
11	Rich Product Recirculation with Alternate Quench	--
12	Rich-Lean Annihilation	--
13	RBQQ -- Very Short Rich Zone	37
14	RBQQ -- Conf. 13 with Air Blast Fuel Nozzle and Swirler	40

*RBQQ -- Rich-Burn/Quick-Quench Combustor

Configurations 6, 10, 11 and 12 did not undergo baseline testing due to cost limitations which resulted from durability problems encountered early in the test program.

All other configurations underwent testing on one or all of the fuels listed in Table III including some blends of these fuels.

TABLE III - FUEL PROPERTIES

	ERBS	Residual	Synthetic
Viscosity (CS) @ 100°F (38°C)	1.0	200.0	3.56
%FBN	0.02	0.3	0.74
Specific Gravity 60/60°F (15°C)	0.831	0.955	0.98
% Carbon	87.0	87.5	86.1
% Hydrogen	12.5	11.3	9.00
% Sulfur	0.10	0.22	0.028
Initial Boiling Point (°F, °C)	310,154	~600,315	356,180
Heating Value (Btu/lb, j/kg)	18,323; 42.7×10^6	71,850; 41.6×10^6	16,730; 38.9×10^6

B. CONFIGURATION DESCRIPTIONS AND RESULTS

A short summary of each configuration tested and test results are included in this section. Table IV gives a complete breakdown of minimum NO_x levels obtained for all configurations tested. Table V is a test summary of all configurations evaluated. Testing was done at 3.4 atmospheres unless otherwise specified.

TABLE IV. TEST SUMMARY OF ERBS/SRC-II FUEL BLEND

			CONFIGURATION ID				
			NO_x at 15% O_2/ϕ_{pri}				
f/a	T_{inlet} (°F,°C)	ERBS	0.9/0.1	0.7/0.3	0.5/0.5	0.1/0.9	SRCII
0.012	500,260	22/1.56	40/1.49	49/1.52	35/1.55	56/1.45	-
0.016	600,315	26/1.57	35/1.59	32/1.56	37/1.53	37/1.43	-
0.021	700,371	36/1.55	42/1.55	49/1.52	53/1.58	47/1.40	44/1.60
0.024	750,399	-	53/1.66	55/1.54	65/1.52	68/1.47	-

ϕ_{pri} = Primary Zone Equivalence Ratio

TABLE V. TEST SUMMARY

Configuration-Description		Fuel	Min NO_x/Rich Equiv. Ratio	Approx. Run Hours	Comments
1	o Rich-Lean Burn (Rich-Burn/Quick-Quench) o 18-in. (45.7 cm) Rich Zone Length o Premix Tube	ERBS	35/1.4	5	Burned hole in Rich Zone at High Pressure.
1A	o Rich-Lean Burn o 18-in. (45.7 cm) Rich Zone Length o Recessed Air Swirler	ERBS SRC-II	40/2.0 68/1.37	7.5	Burned Hole in Rich Zone.
1B	o Rich-Lean Burn o 18-in. (45.7 cm) Rich Zone Length o Recessed Air Swirler o Copper Coiling Coil	ERBS	39/1.53	3	Burned Hole in Rich Zone.

TABLE V. TEST SUMMARY (Cont'd)

Configuration Description		Fuel	Min NO_x/Rich Equiv. Ratio	Approx. Run Hours	Comments
1C	o Rich-Lean Burn				
	o 18-in. (45.7 cm) Rich Zone Length	ERBS	35/1.56	8	SAE SN = 5.0 to 8. Overheated Rich Zone.
	o Recessed Air Swirler	SRC-II	51/1.64		
	o Thicker Liner Material				
2A	o Rich-Lean Burn	ERBS	47/1.90		
	o 12-in. (30.5 cm) Rich Zone Length	SRC-II	77/1.41	13	SAE SN = 2.0-3.0 on No. 2 & SRC-II. Overheated Rich Zone.
	o Recessed Air Swirler				
2B	o Rich-Lean Burn				
	o 12-in. (30.5 cm) Rich Zone Length	ERBS	39/1.53	4	Burned Hole in Rich Zone at High Pressure Due to Low Steam Flow.
	o Recessed Air Swirler				
	o Steam Cooled Liner				

TABLE V. TEST SUMMARY (Cont'd)

Configuration Description		Fuel	Min NO_x/Rich Equiv. Ratio	Approx. Run Hours	Comments
2C	o Rich-Lean Burn	ERBS	49/1.73		
	o 12-in. (30.5 cm) Rich Zone Length	RESID (0.3%FBN)	90/2.25	10	No Cooling Problems.
	o Recessed Air Swirler	RESID (0.4%FBN)	89/1.74		
	o Water Cooled Liner	RESID (0.5%FBN)	98/2.2		
3A	o Rich-Lean Burn				
	o 18-in. (45.7 cm) Rich Zone Length	RESID (0.3%FBN)	61/1.59		
	o Recessed Air Swirler	RESID (0.4%FBN)	75/1.35	15	No Cooling Problems.
	o Water Cooled Liner	RESID (0.5%FBN)	64/1.43		
	o Small Dia. Quench Zone				

TABLE V. TEST SUMMARY (Cont'd)

	Configuration Description	Fuel	Min NO_x/Rich Equiv. Ratio	Approx. Run Hours	Comments
4A	o Rich-Lean Burn o 18-in. (45.7 cm) Rich Zone Length o Recessed Air Swirler o Water Cooled Liner o Large Dia. Quench Zone	RESID (0.3%FBN) RESID (0.4%FBN) RESID (0.5%FBN)	57/1.6 49/1.6 55/1.52	15	No Cooling Problems. Heavy Coking at Entrance of Rich Zone.
8A	o Rich-Lean Burn o 18-in. (45.7 cm) Primary o Recessed Air Swirler o Water Cooled Liner o Variable Quench Zone	ERBS RESID (.3%FBN) RESID (.4%FBN) RESID (.5%FBN) SRC II	192/1.54* 423/1.36* 80/1.59 106/1.56 82/1.60	12	No Cooling Problem. Variable Area Stuck at Low Temps. *Fuel Nozzle Tip Bent.

TABLE V. TEST SUMMARY (Cont'd)

Configuration Description	Fuel	Min NO_x/Rich Equiv. Ratio	Approx. Run Hours	Comments
5A o Rich-Lean Burn				
o 18-inch (45.7 cm) Primary	ERBS	34/1.55 28/2.09		SAE SN = 13.9 @ ϕ_{pri} = 2.0.
o Recessed Air Swirler	ERBS	27/1.78	13 (2 Hr High Pressure)	No Cooling Problems at 600°F (315°C) Inlet.
o Non-Metalic & Water Cooled Primary	ERBS	42/1.69		180 psia (1237 kPa).
	50/50 ERBS RESID	46/1.60		SAE SN = 21.9 @ ϕ_{pri} = 2.0.
	RESID (.3%FBN)	77/1.66		Non-Metalic Liner Ablated; Started in Cone Exit about 6 hrs into Testing after Blowout Instability at 300°F (149°C) Inlet Condition with Residual Fuel.
	RESID (.5%FBN)	75/1.54		

TABLE V. TEST SUMMARY (Cont'd)

Configuration Description	Fuel	Min NO_x/Rich Equiv. Ratio	Approx. Run Hours	Comments
9A o Graduated Air Addition	RESID (.3%FBN)	55/1.88		
o 12-in. (30.5 cm) Primary	RESID (.5%FBN)	64/1.85		
o Recessed Air Swirler	SRC-II	92/1.99	10	SAE SN = 51.
o Water Cooled Liner	70/30 ERBS/SRC-II	58/1.75		
o Rich-Rich-Lean-Burn				
7A o Preburner Fuel Prep.	ERBS	214/1.01*		*Fuel Nozzle Tip Bent.
o 12-in. (30.5 cm) Primary	SRC II	106/0.56	5	
o Water Cooled Primary Liner				
o Lean-Rich-Lean Burn				

TABLE V. TEST SUMMARY (Cont'd)

Configuration Description	Fuel	Min NO_x/Rich Equiv. Ratio	Approx. Run Hours	Comments
1D o Rich-Lean Burn	RESID (0.3%FBN)	46/1.54	20	Fuel Prop Var Tests.
o 18 in. (45.7 cm) Rich Zone Length	90/10 RESID/ERBS	43/1.56 38/1.61		
o Recessed Air Swirler	70/30 RESID/ERBS	38/1.61		
o Water Cooled Liner	30/70 SRCII/ERBS	52/1.57		
	50/50 RESID/ERBS	49/1.56		
	50/50 SRC II/ERBS	53/1.58		
	90/10 SRC II/ERBS	47/1.41		

TABLE V. TEST SUMMARY (Cont'd)

Configuration Description		Fuel	Min NO_x/Rich Equiv. Ratio	Approx. Run Hours	Comments
2C	o Rich-Lean Burn	SRC-II	48/1.53	50	180 psia (1237 kPa).
	o 12-in. (30.5 cm) Rich Zone Length	ERBS	32/1.50		180 psia (1237 kPa).
	o Recessed Air Swirler	RESID	67/1.49		50 psia (343 kPa).
	o Water Cooled Liner				Smoke Numbers (approx) ERBS 3-10 RESID 50.
13	o Rich-Lean Burn	SRC-II	150/1.56	14	180 psia (1237 kPa).
	o 6-in. (15.2 cm) Rich Zone Length	ERBS	43/1.51		180 psia (1237 kPa).
	o Recessed Air Swirler	RESID	88/1.42		50 psia (343 kPa).
	o Water Cooled Liner	50/50 ERBS/ RESID	87/1.61		50 psia (343 kPa).

TABLE V. TEST SUMMARY (Cont'd)

Configuration Description	Fuel	Min NO_x/Rich Equiv. Ratio	Approx. Run Hours	Comments
14 o Rich-Lean Burn	SRC-II	88/1.62	4	50 psia (343 kPa).
o 6-in. Rich Zone Length	ERBS	46/1.56		50 psia (343 kPa).
o Air Blast Atomizer	RESID	48/1.51		180 psia (1237 kPa).
o Water Cooled Liner				

1. Configuration 1 - Baseline Rich-Burn/Quick-Quench Combustor (RBQQ)

Summary

Figure 1 illustrates the original geometry of this configuration. Early tests with this configuration resulted in durability problems in the rich zone. Initially this configuration utilized a premix tube (Figure 2) to prevaporize the fuel; however, flashback occurred and the premix tube was abandoned in favor of a carburetor tube with a recessed fuel nozzle and recessed air swirler as shown in Figures 3 and 3A. This configuration displayed the best overall performance of any concept tested, and easily met and surpassed the NO_x goals set forth in the contract.

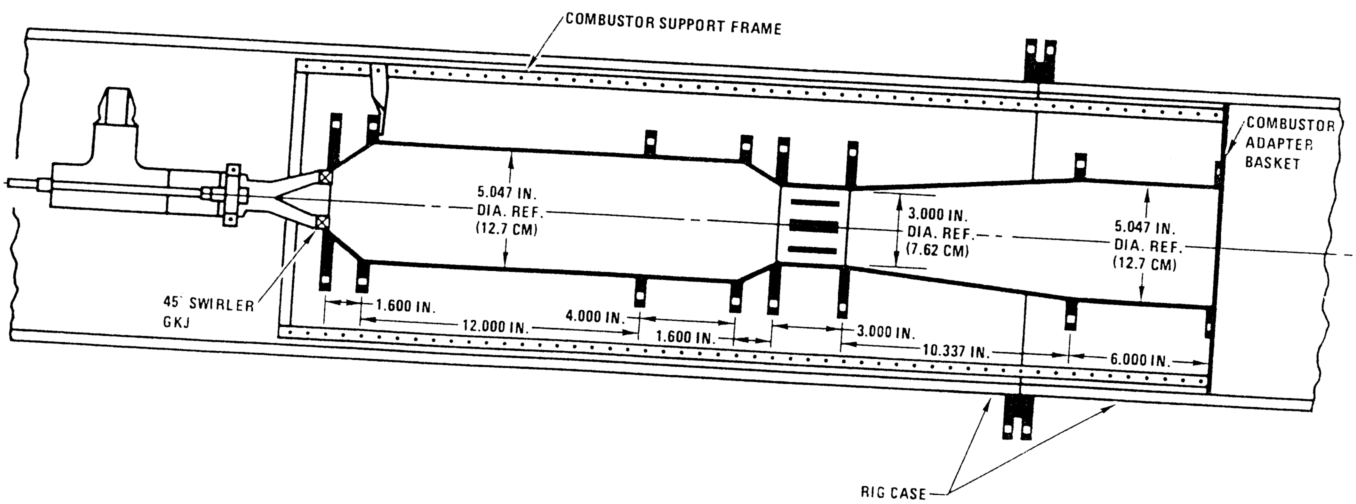


Figure 1. Configuration 1 - Baseline Rich-Burn/Quick-Quench (RBQQ) Combustor

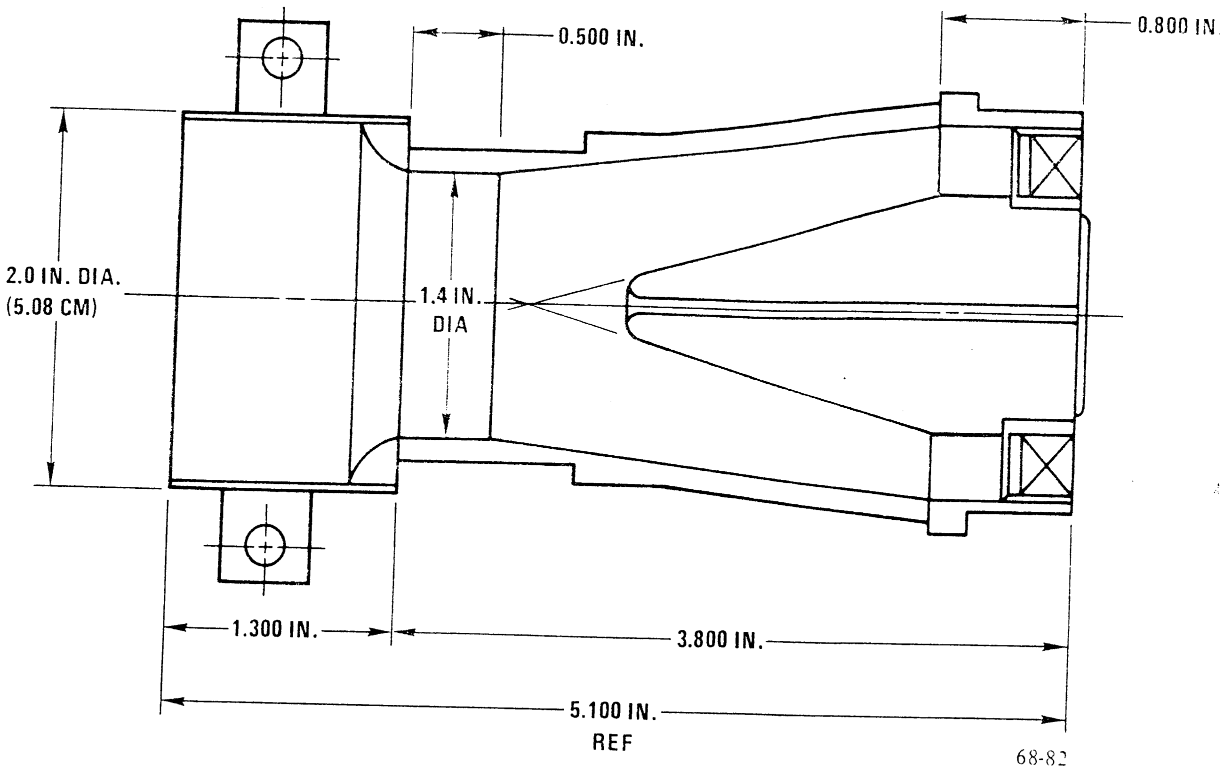


Figure 2. Configuration 1 - Premix Tube

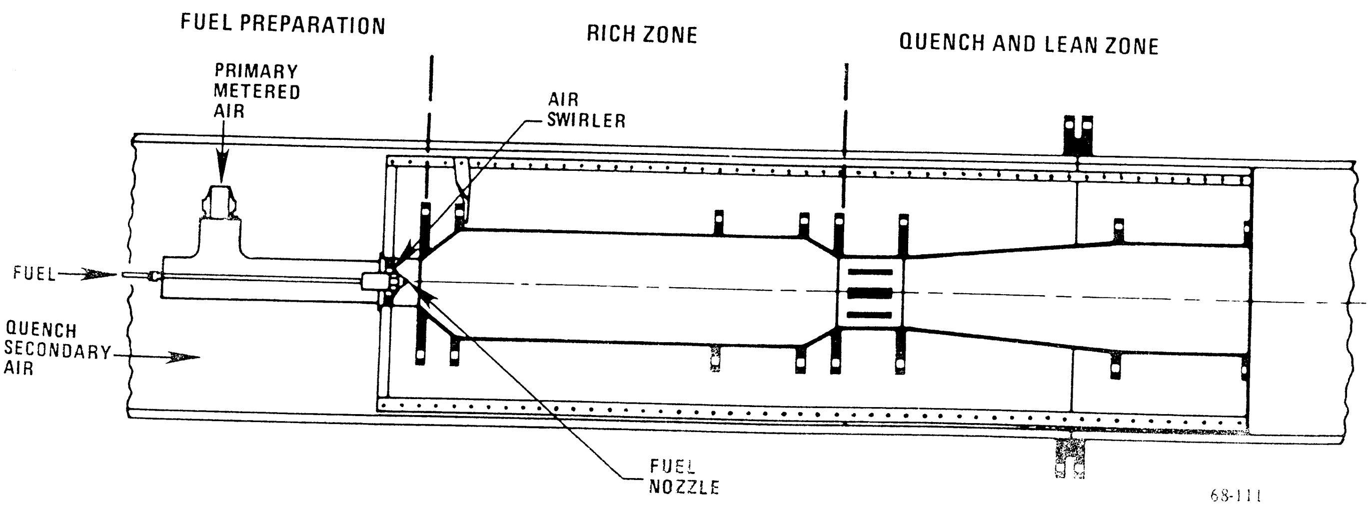


Figure 3. Configuration 1 - RBQQ Combustor with Recessed Air Swirler

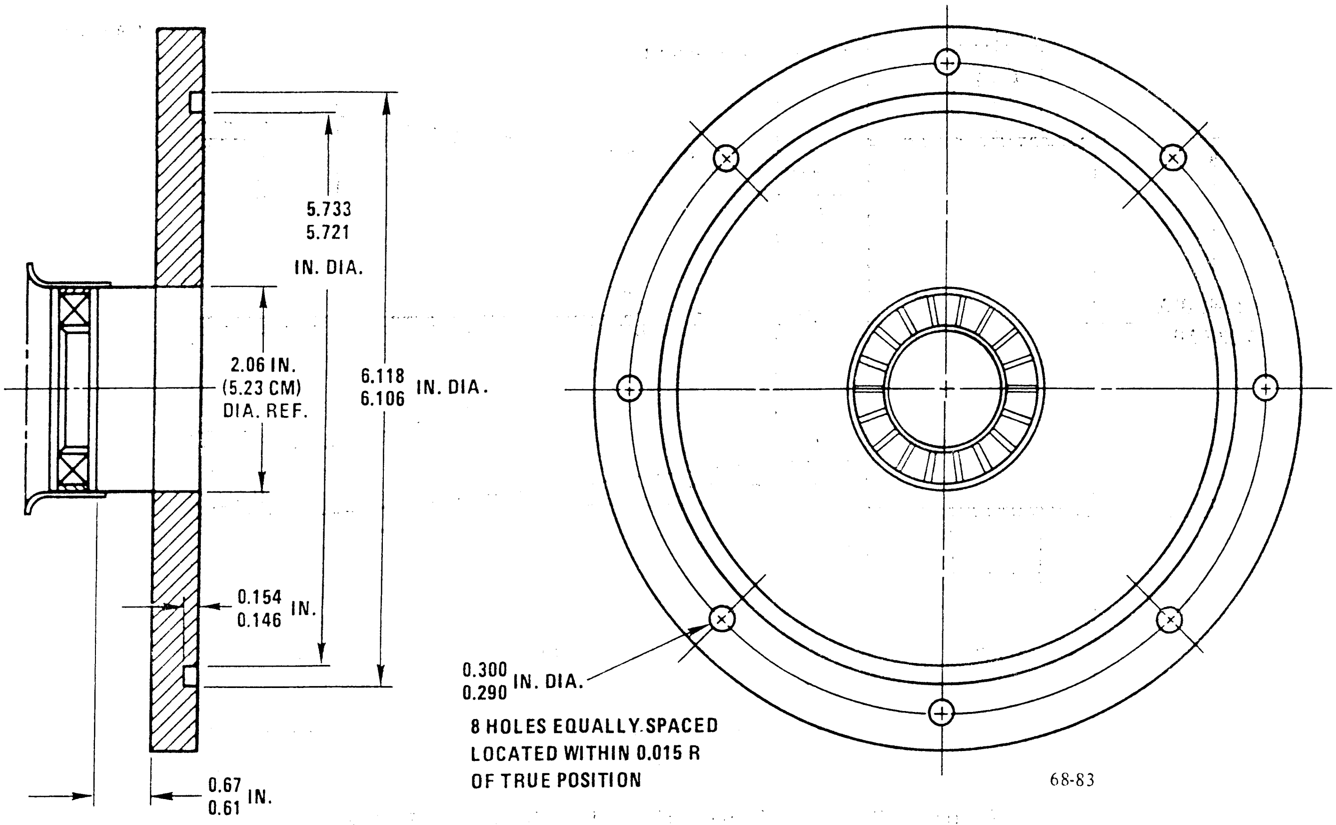


Figure 3A. Configuration 1 - Recessed Air Swirler Assembly

Five iterations were required to fix the durability problems associated with the rich zone of this combustor and are described as follows:

- Configuration 1 - Same as Figure 1 but with the carburetor tube replaced with a premix tube.
- Configuration 1A - Premix tube replaced by recessed air swirler.
- Configuration 1B - copper cooling coil added to reduce metal temperatures.
- Configuration 1C - thicker rich zone liner material added.
- Configuration 1D - Water cooled rich zone utilized.

Only the results of Configuration 1D are shown in this report due to the rich zone damage to the others incurred during testing, which created some doubt as to the data validity. All results are summarized in the Comprehensive Data Report (GTR-3235).

Results

NO_x Levels - Figure 4 displays the NO_x emissions data taken during baseline testing on residual fuel. Note that the minimum NO_x levels are at an equivalence ratio of approximately 1.55 in the rich zone.

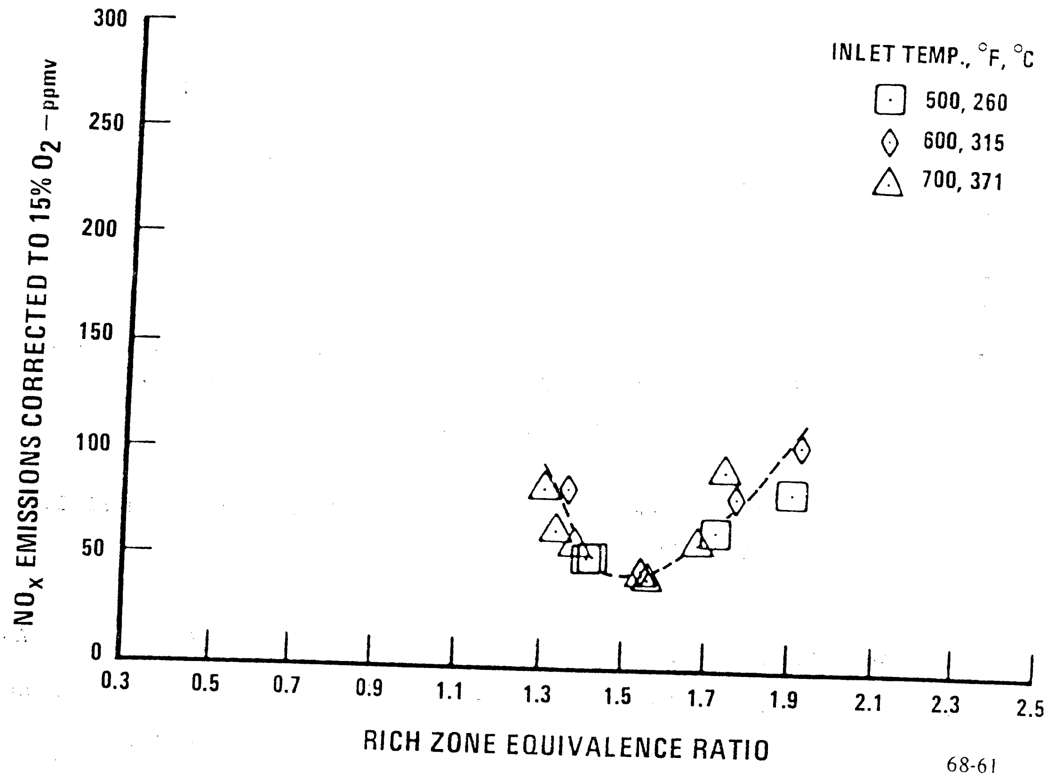


Figure 4. Configuration 1 - NO_x Emissions with Residual Fuel

Tests with Other Fuels - Tests were conducted to determine the effects of fuel properties on burner performance and emissions. Figure 5 shows data for a 90/10% mixture of Residual/ERBS (Experimental Referee Broadened-Specification) fuel; for properties see Table III. The results indicated no appreciable difference in the NO_x "bucket" as compared to straight residual fuel.

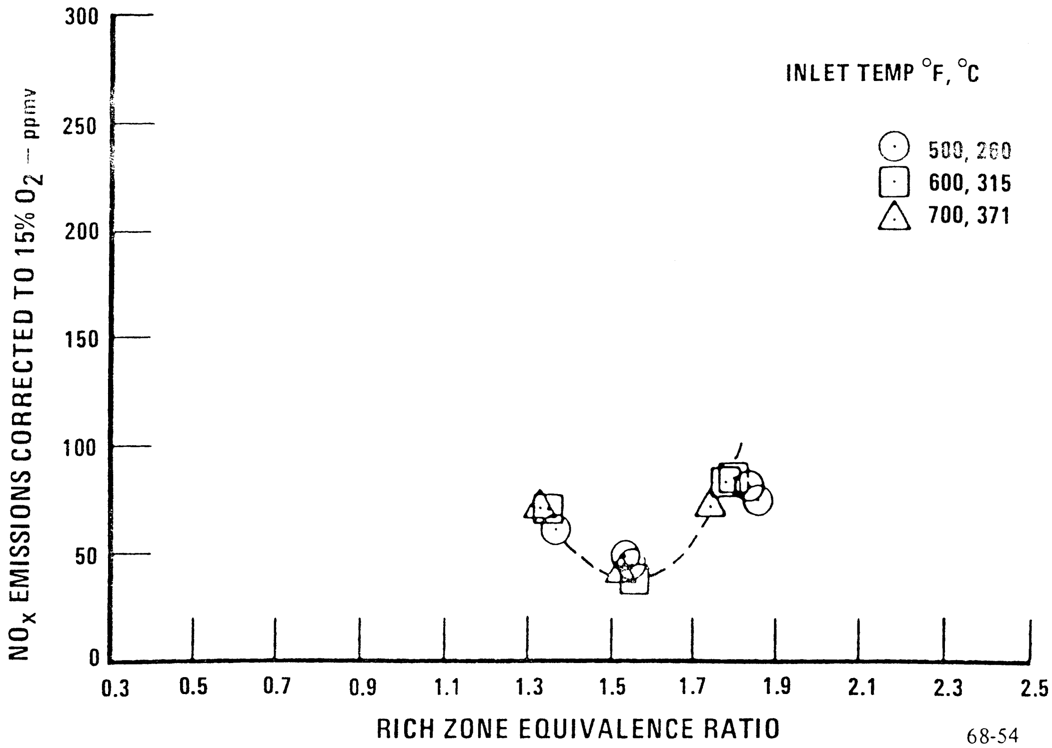


Figure 5. Configuration 1 - NO_X Emissions with 90/10 Residual/ ERBS Fuel

Figure 6 shows results for a 70/30 mix of Residual/ERBS fuel. At this mixture ratio, a general flattening of the NO_X bucket was observed and increasing equivalence ratio did not show a dramatic increase in NO_X.

Test results with a 50/50 mixture of Residual/ERBS fuel are shown in Figure 7. These results were very similar to the 70/30 mixture test results.

Tests were also conducted with ERBS, and SRC-II (Solvent Refined Coal from the Pittsburg and Midway Coal Mining Company, Denver, Colorado) fuels and blends of these. Table IV gives NO_X results obtained with this configuration.

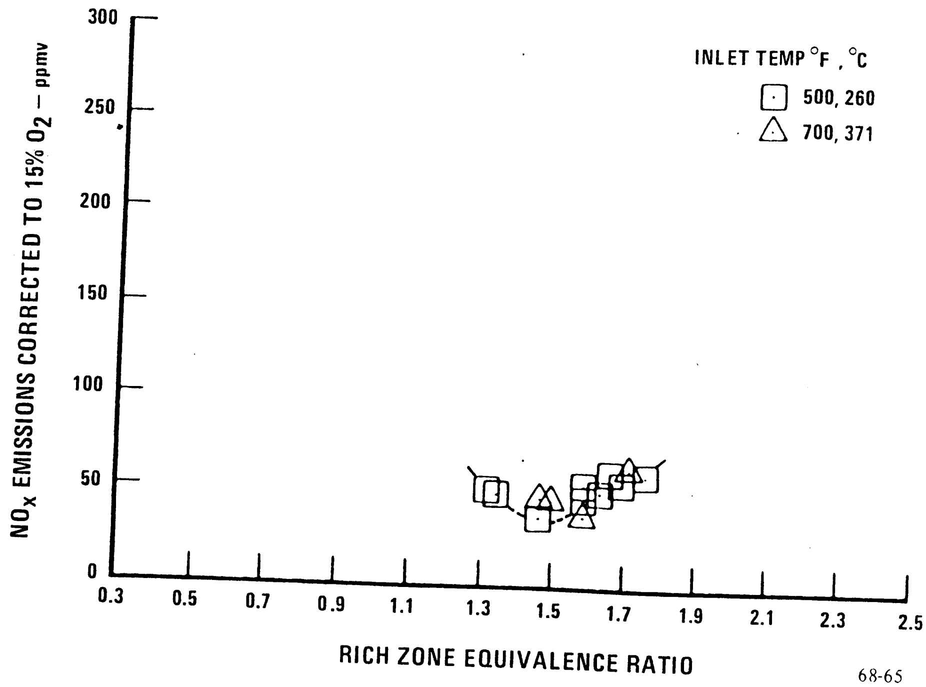


Figure 6. Configuration 1 - NO_x Emissions with 70/30 Residual/ ERBS Fuel

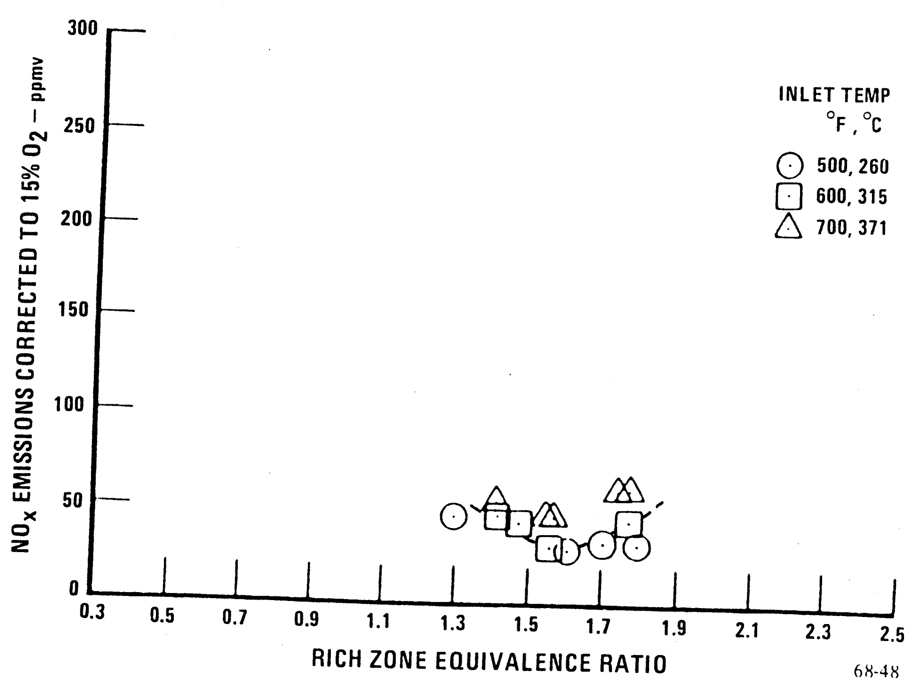


Figure 7. Configuration 1 - NO_x Emissions with 50/50 Residual/ ERBS Fuel

Carbon Monoxide Levels - The CO levels obtained with this configuration on residual fuel are shown in Figure 8. It can be seen that overall fuel/air ratio has a dramatic effect on the levels of this pollutant, minimum levels are obtained when the lean zone downstream of the quench module is kept above 0.021 fuel/air ratio. Similar levels were obtained with all fuels tested.

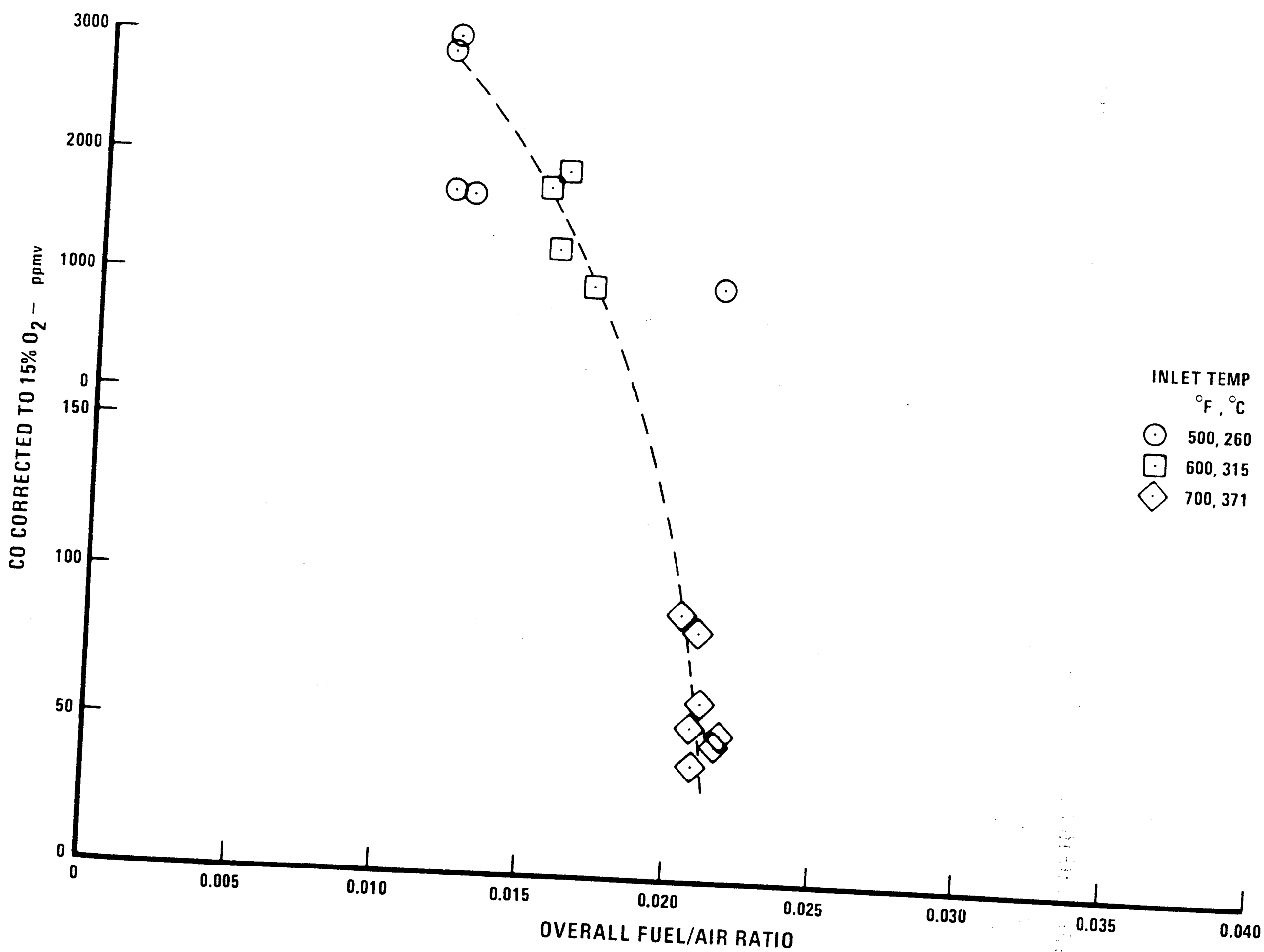


Figure 8. Configuration 1 - CO Emissions with Residual Fuel

Burner Exit Temperature Pattern - The pattern factor for this configuration was 0.060 at simulated idle conditions and 0.045 at high power. Figures 9 and 10 display a very uniform temperature pattern for this configuration. Temperatures outside the circle are outside of the hot gas stream.

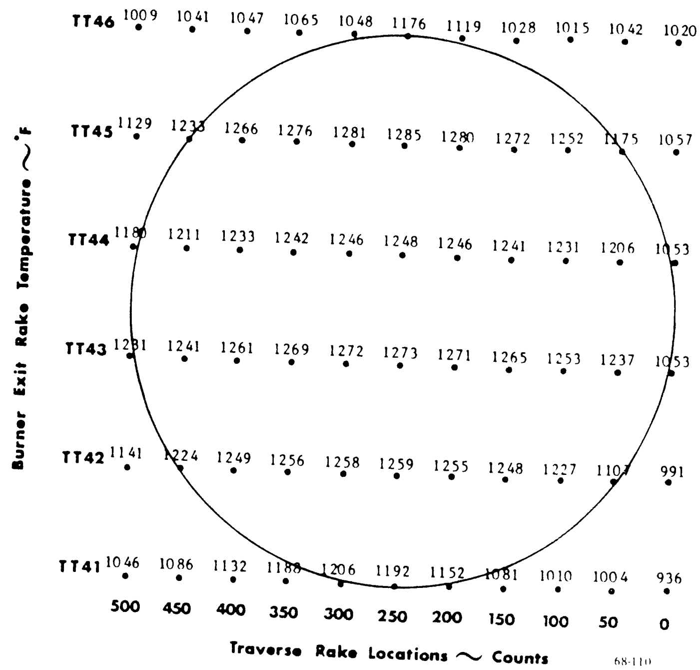


Figure 9. Configuration 1 - Temperature at the Combustor Exit - Low Power

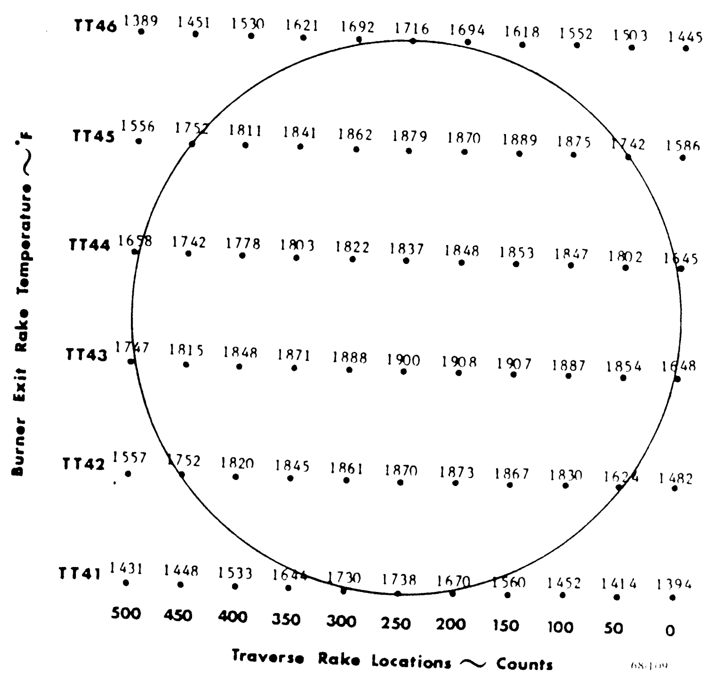


Figure 10. Configuration 1 - Temperature at the Combustor Exit - High Power

Burner Efficiency - Efficiencies greater than 99% were evident when exit fuel-air ratios were 0.021 and greater for all fuels tested. Lower efficiences were obtained when the exit fuel/air ratio was less than 0.021. This problem can be solved by the addition of a tertiary zone to the burner to allow for CO oxidation in the lean zone when a full-scaled combustor design is required.

2. Configuration 2 - RBQQ Combustor with 12-inch (30.5 cm) Rich Section

Summary

This configuration was the same as Configuration 1 with the exception of the 12-in. vs. 18-in. (30.5 cm vs. 45.7 cm) length of the rich zone. Figure 11 illustrates the geometry of this configuration. Durability problems were also encountered with this configuration and eventually a water cooled rich zone had to be utilized to prevent front-end combustor damage.

This configuration displayed low NO_x values with ERBS fuel similar to Configuration 1; however NO_x levels with SRC-II and residual fuels were slightly higher due to shorter rich zone residence times.

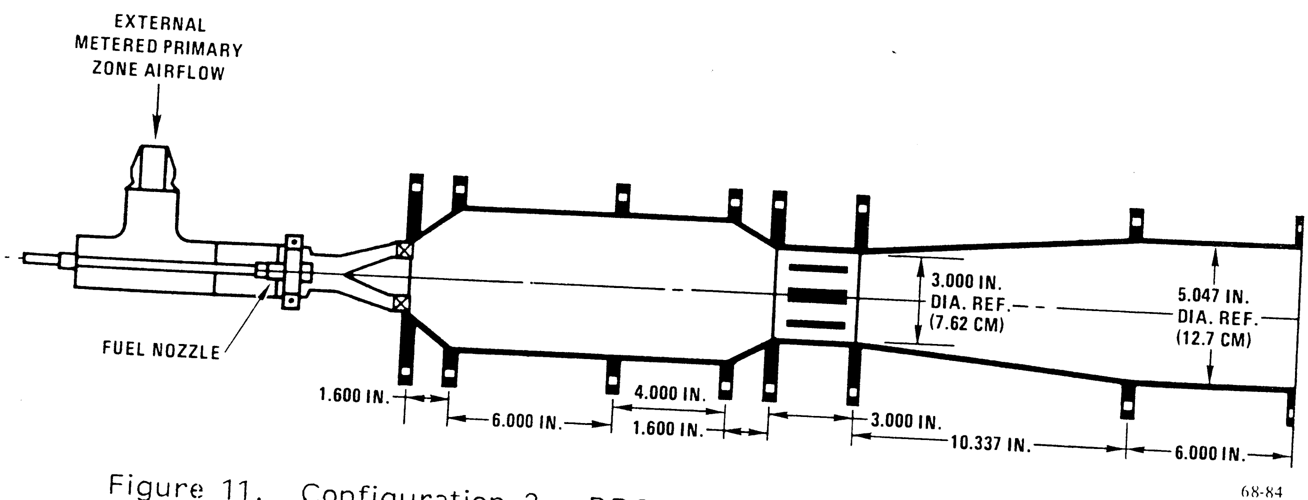


Figure 11. Configuration 2 - RBQQ Combustor with Short Rich-Zone

Results

Figure 12 displays NO_x levels obtained with three different fuels (ERBS, SRC-II, and Residual) vs. front-end equivalence ratio with the SONICORE 086H fuel nozzle manufactured by Sonic Development Corporation, Upper Saddle River, New Jersey. Figure 13 displays the same type of data taken with the 125H SONICORE fuel nozzle. A first impression of this data is that it appears to be scattered; however, an analysis indicated that as the front-end equivalence ratio was varied, the hot residence times were changing and as burner inlet pressure was increased a dramatic effect on residence times was evident. Figure 14 displays some of the data taken (in the ranges indicated) with NO_x levels plotted vs. rich-zone residence times. It can be seen that the residence times played a very important role in the NO_x levels obtained.

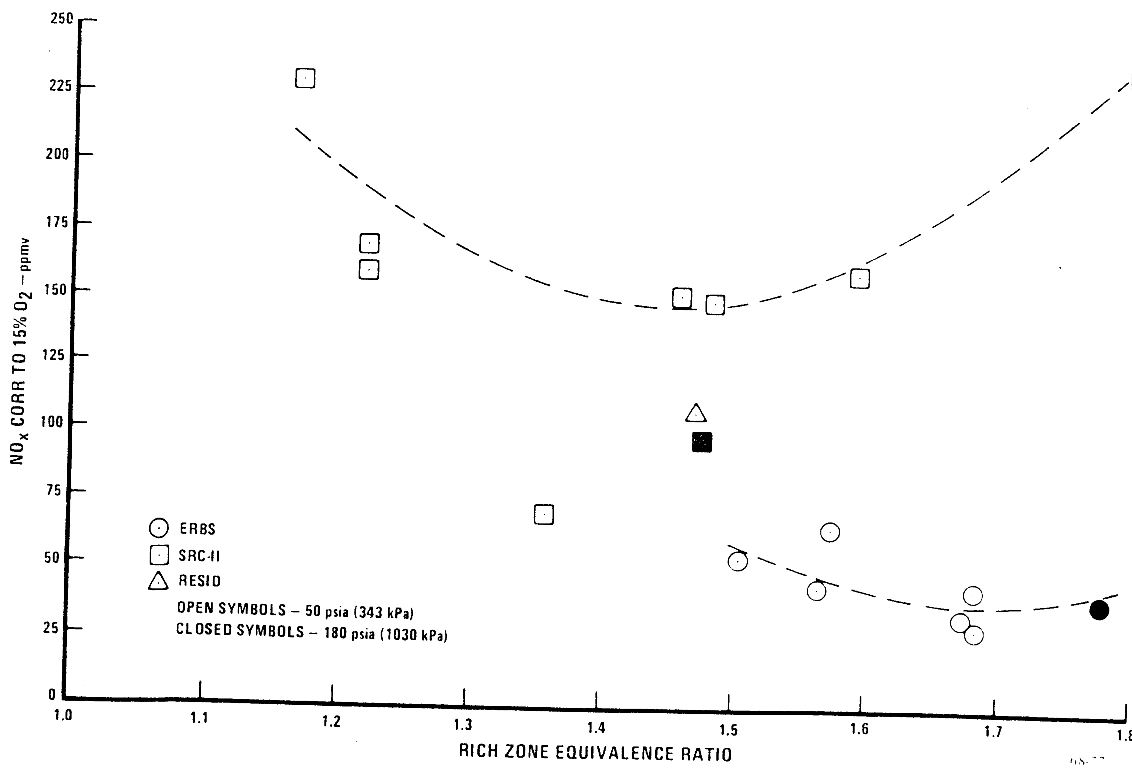


Figure 12. Configuration 2C - NO_x Emissions vs Rich Zone Ratio Equivalence Ratio (086H Fuel Nozzle)

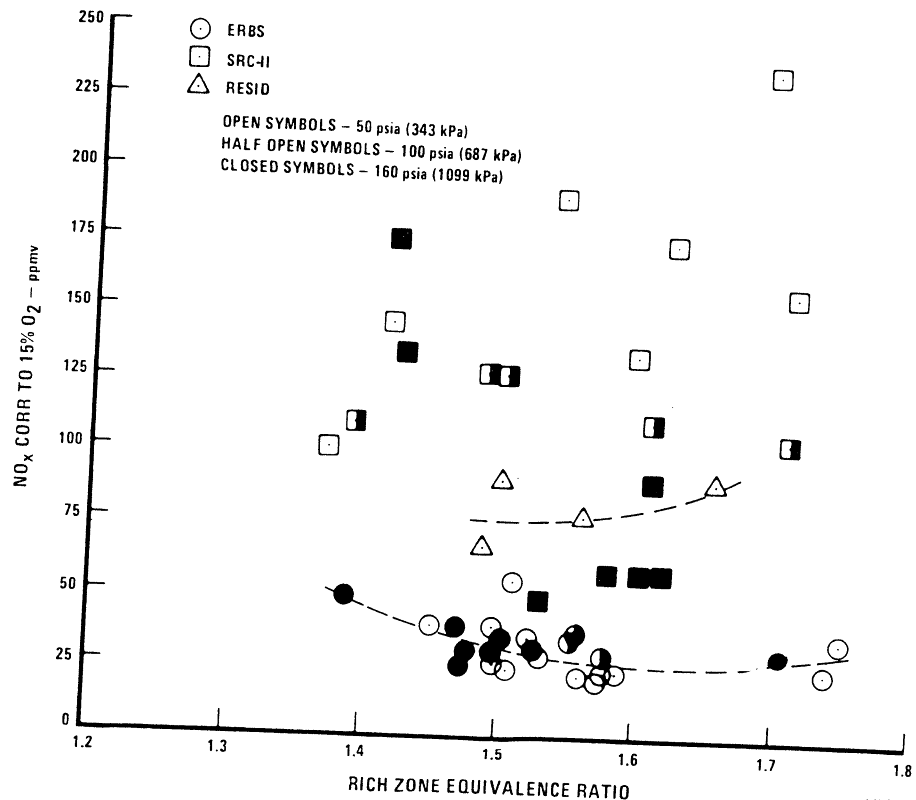


Figure 13. Configuration 2C - NO_x Emissions vs Rich Zone Equivalence Ratio (125H Fuel Nozzle)

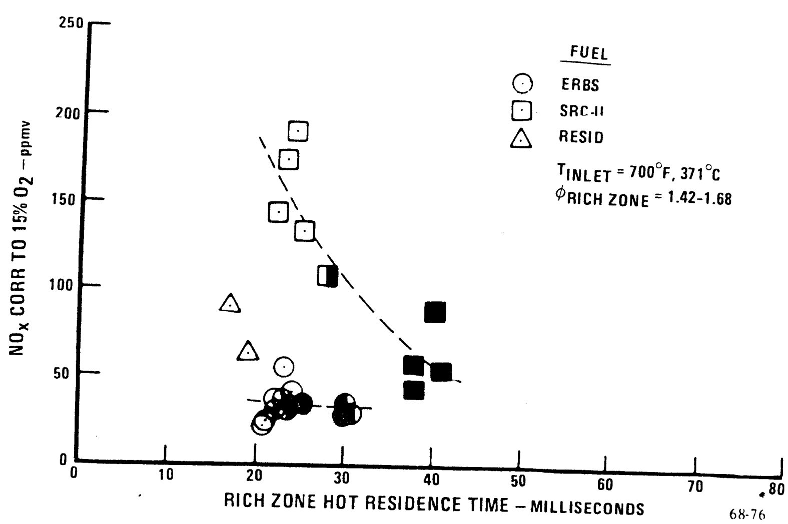


Figure 14. Configuration 2C - NO_x Emissions vs Rich Zone Residence Time

NO_x levels were found to be very dependent on fuel preparation. This can be seen in Figure 15 where data with a bent fuel nozzle tip is compared to data with a geometrically correct fuel nozzle when burning ERBS fuel.

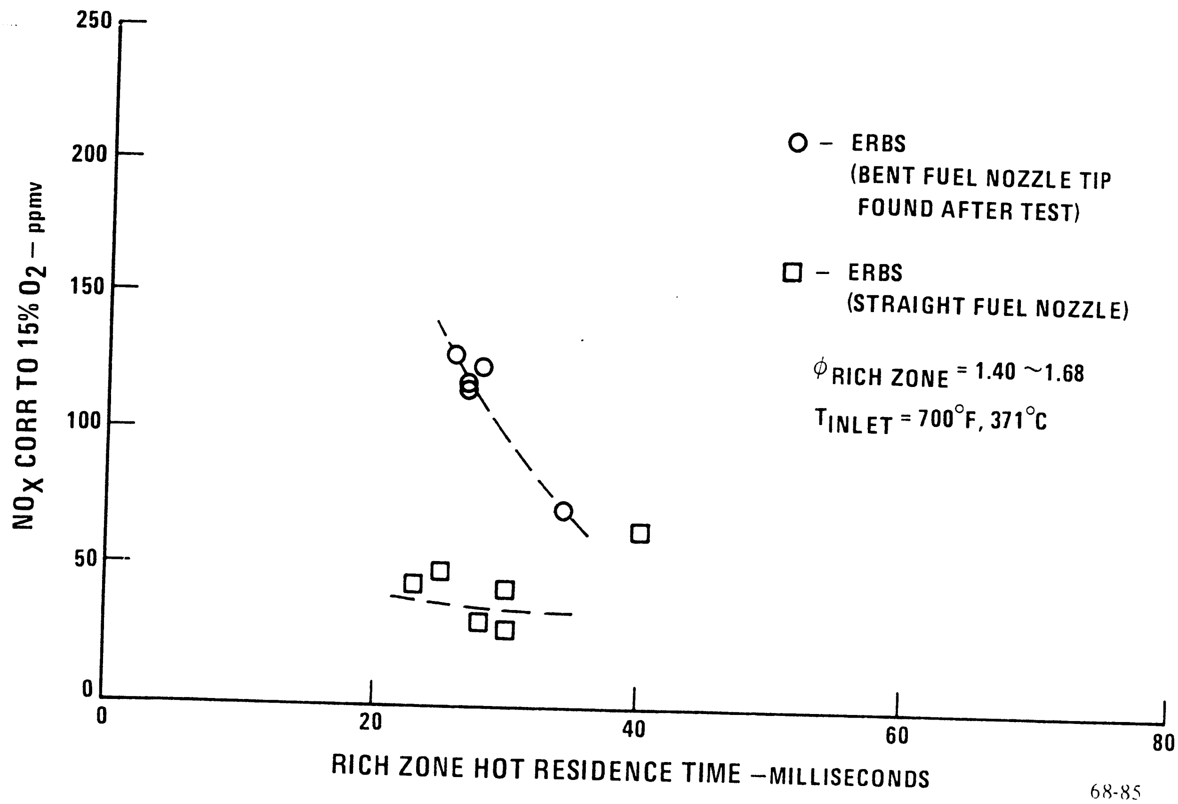


Figure 15. Configuration 2C - NO_x Emissions vs Rich Zone Residence Time (Bent vs Straight Nozzle)

Carbon Monoxide Levels - The CO levels obtained with this configuration were similar to those obtained with Configuration 1. Again it was evident that the fuel/air ratio at the exit of the quench zone had to be kept above 0.021 in order to obtain minimal CO levels.

Smoke Levels - Considerable effort was made with this configuration to reduce smoke levels. An analysis of early smoke data taken with this configuration showed that smoke levels were affected by the atomizing fluid/fuel ratio. This data is shown in Figure 16 for three burner pressure levels. It can be seen that the residual fuel smoke levels were not affected; however, the atomizing fluid used was cold nitrogen (since high pressure hot air was not available at the test site) and it is believed that this had an adverse effect on the atomization of the highly viscous residual fuel. SAE smoke numbers below 20 were obtained with ERBS and SRC-II fuels when sufficient atomizing fluid was used.

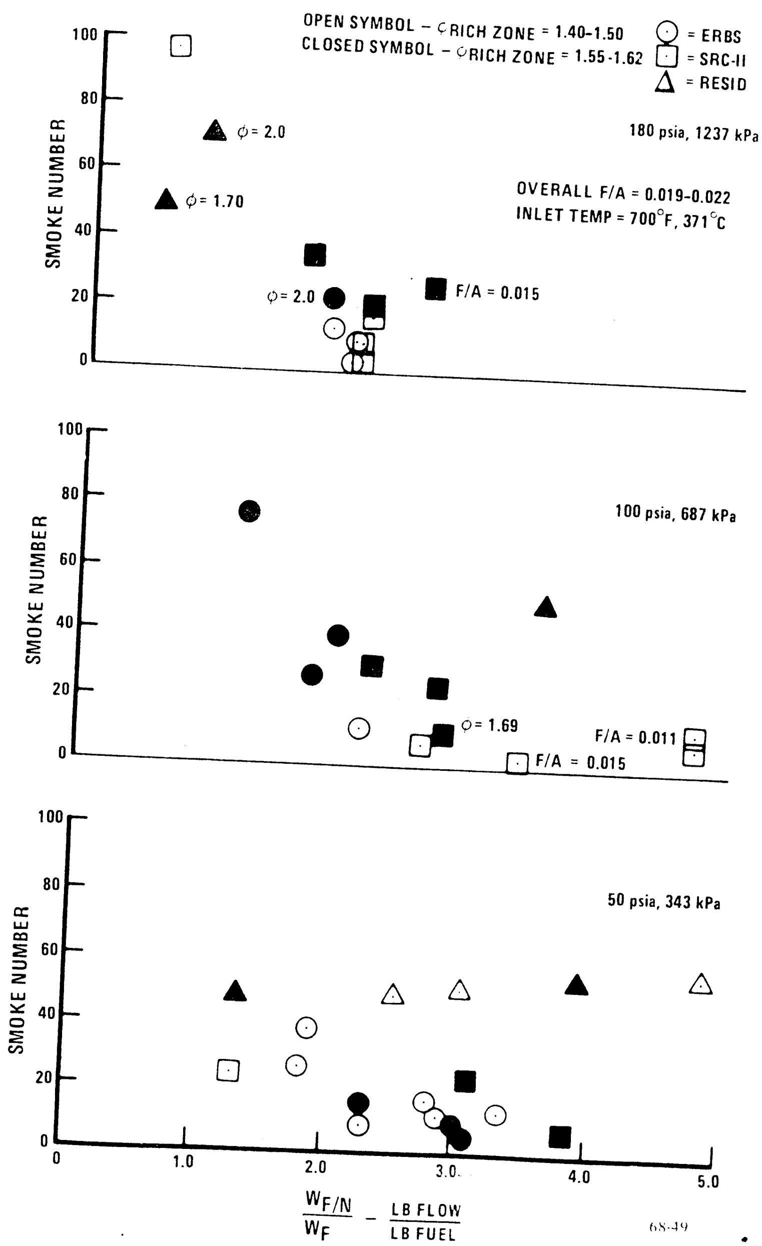


Figure 16. Configuration 2C - Effect on Smoke Level of Atomizing Fluid/ Fuel Ratio

Unburned Hydrocarbon Levels - The UHC levels were minimal for this configuration on all fuels tested.

3. Configuration 3 - RBQQ Combustor With Small Diameter Quench Zone

Summary

Figure 17 illustrates the original geometry of this configuration. The development and test results of Configuration 1 and 2 led to utilizing the water cooled rich zone and recessed swirler instead of the premix tube as originally planned. This configuration was tested to determine the effects of rich-zone/quench-zone area ratios on NO_X emissions. The slot area for the quench air was the same as for Configurations 1 and 2. This configuration was only tested on the baseline residual fuel and residual fuel with pyridine added (for fuel-bound nitrogen effects).

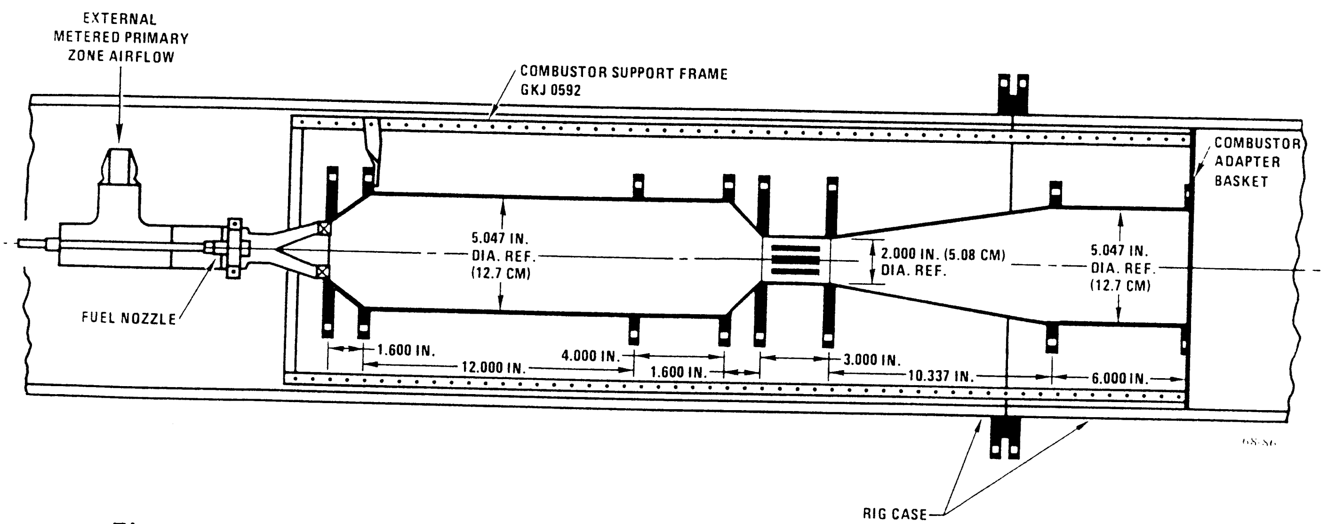


Figure 17. Configuration 3 - RBQQ Combustor with Small Diameter Quench Zone

Results

NO_X Levels - With this configuration the levels were slightly higher than those obtained with Configuration 1. Figures 18 and 19 display data of NO_X

levels vs. rich zone residence time with residual fuels containing 0.4% FBN and 0.5% FBN, respectively. The resulting minimum NO_x levels were on the order of 60 ppm.

CO Levels - The levels were similar to Configuration 1 with minimum levels occurring at overall fuel/air ratios greater than 0.021 at the burner exit.

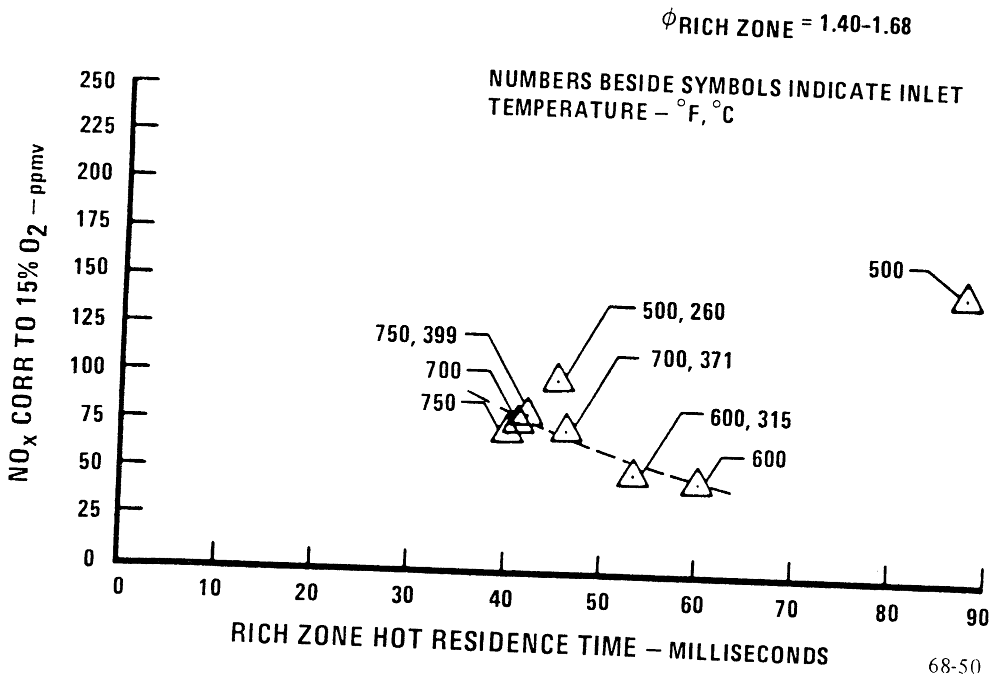


Figure 18. Configuration 3A - NO_x Emissions vs Rich-Zone Residence Time (Residual w/ 0.4% FBN)

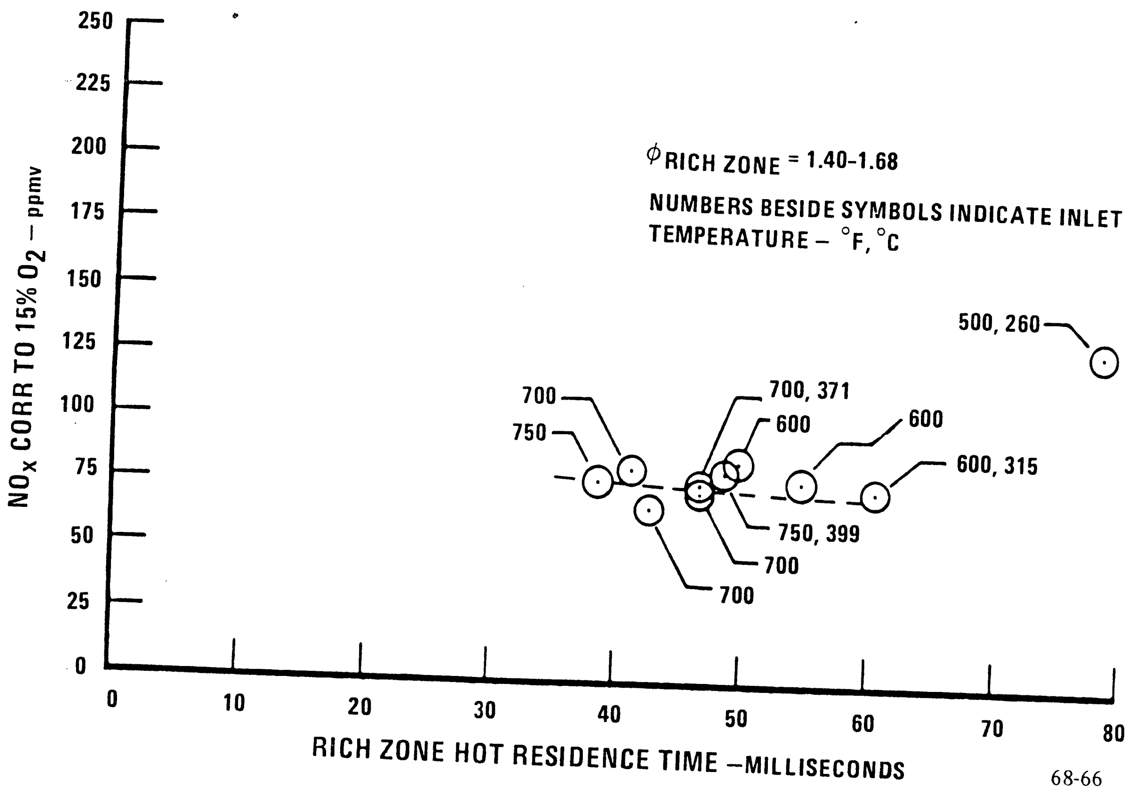


Figure 19. Configuration 3A - NO_X Emissions vs. Rich-Zone Residence Time (Residual w/ 0.5% FBN)

4. Configuration 4 - RBQQ Combustor With Large Diameter Quench Zone

<u>Summary</u>

Figure 20 illustrates the original geometry of this configuration. Changes made before testing were the same as with Configuration 3, the addition of water cooling and the recessed swirler. This test was conducted also to determine the effects of rich-zone/quench-zone area ratios on NO_X levels.

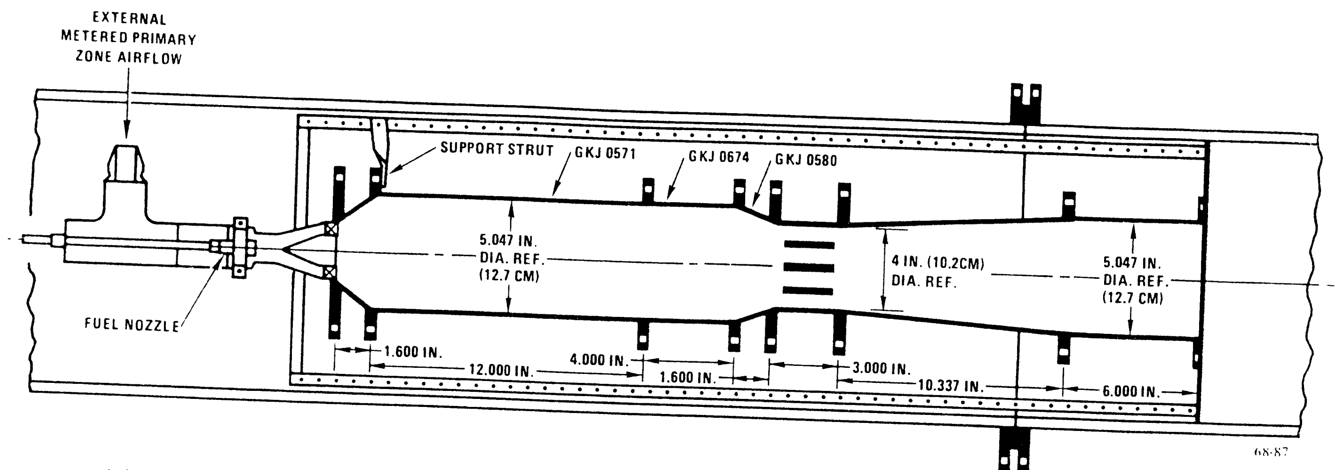


Figure 20. Configuration 4 - RBQQ Combustor with Large Diameter Quench Zone

Results

NO_x Levels with this configuration were slightly higher than Configuration 1 and slightly lower than Configuration 3 with minimum levels on the order of 55 ppm with residual fuel. Figures 21, 22 and 23 display data obtained of NO_x levels vs. rich zone residence time with residual fuels containing 0.4% FBN and residual with 0.5% FBN fuels, respectively.

CO Levels - The results were similar to Configuration 1 at overall fuel/air ratios above 0.021.

Other Comments - Some heavy coking in the front end of the combustor was evident after test completion. The reason for this is unknown.

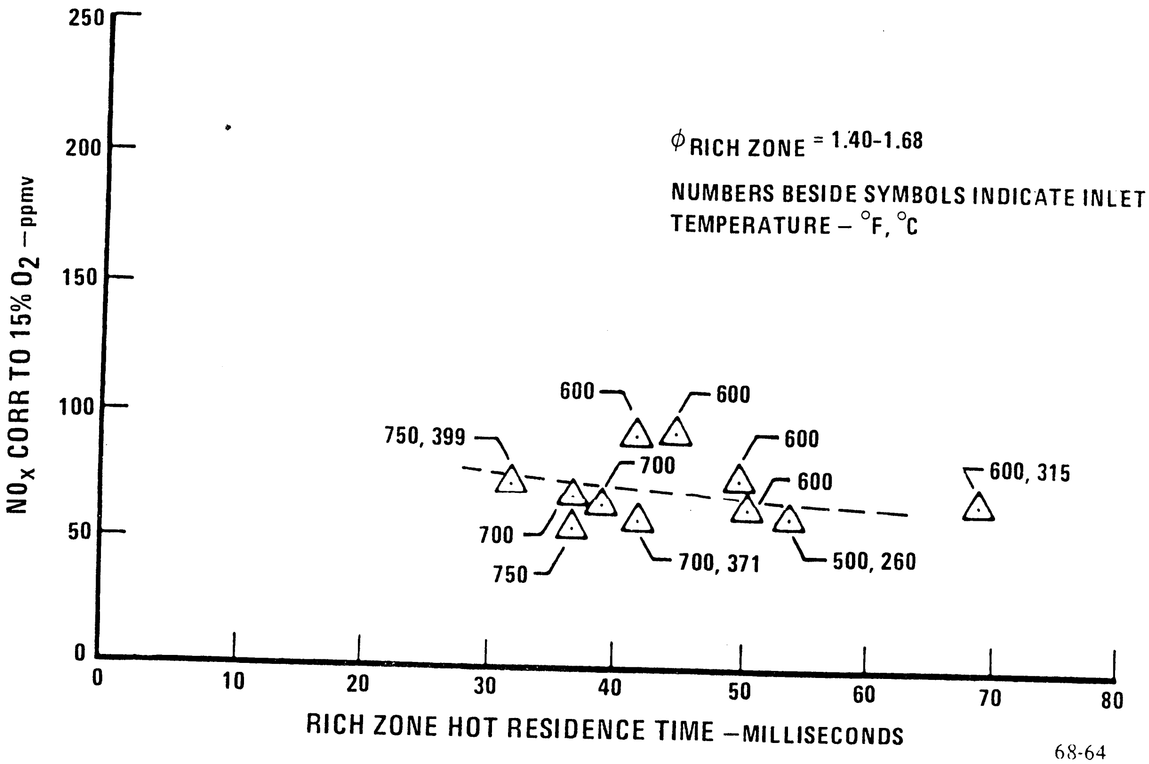


Figure 21. Configuration 4A - NO_x Emissions vs. Rich-Zone Residence Time (Residual w/0.4% FBN)

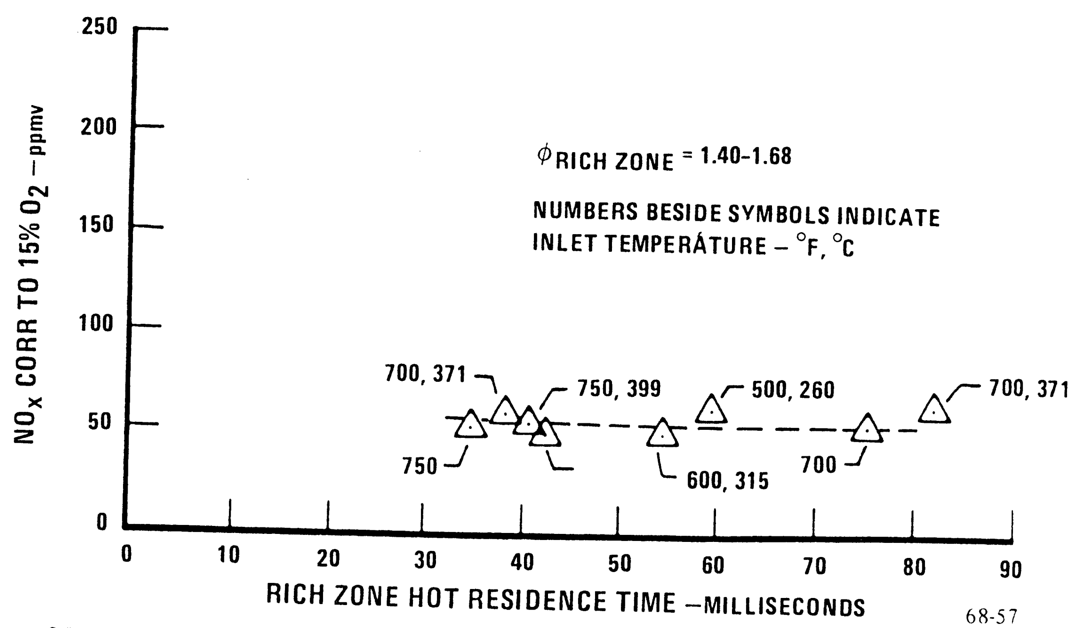


Figure 22. Configuration 4A - NO_x Emissions vs. Rich-Zone Residence Time (Residual w/ 0.4% FBN)

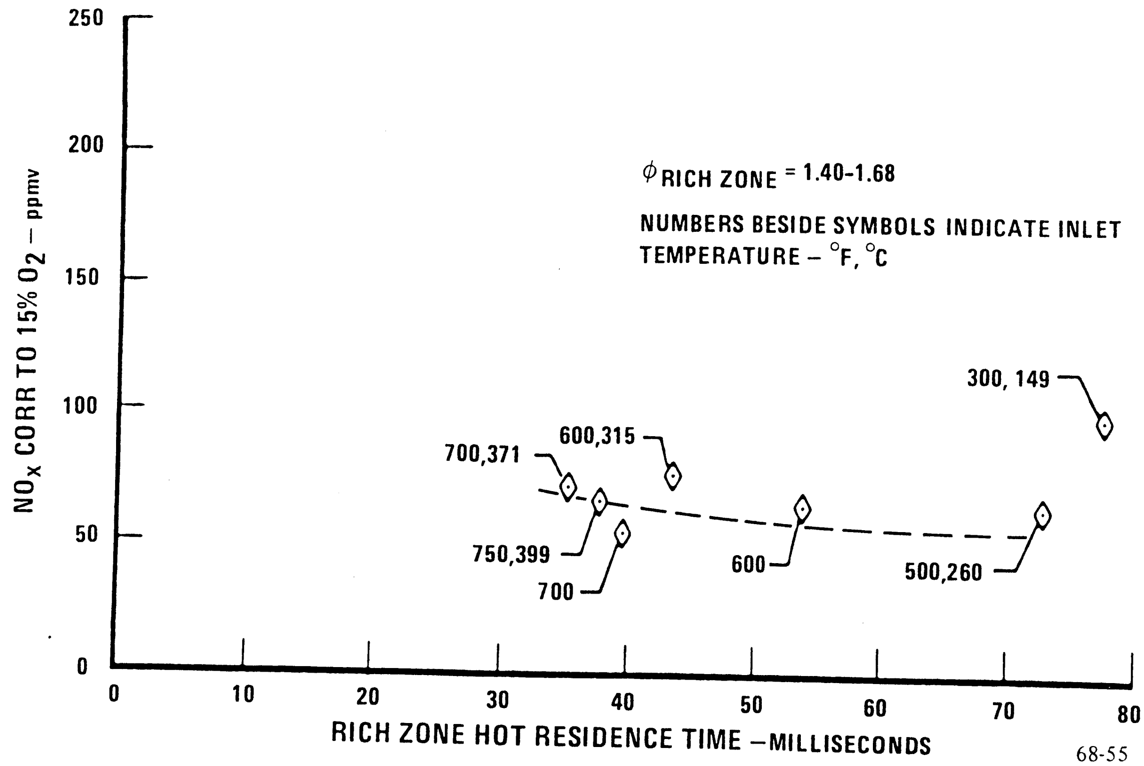
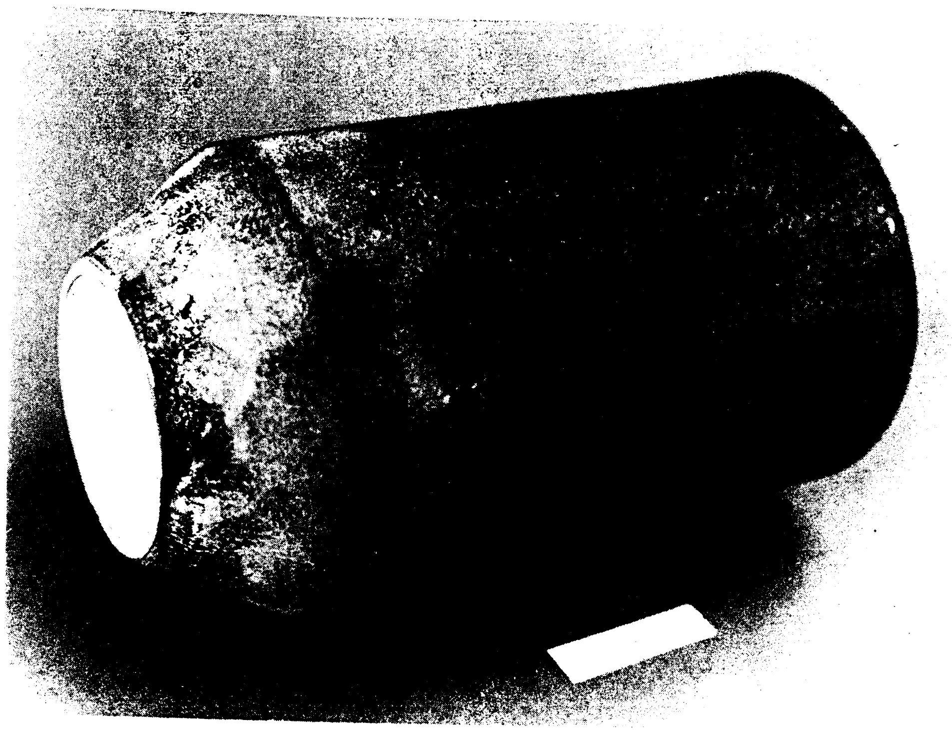


Figure 23. Configuration 4A - NO_x Emissions vs. Rich-Zone Residence Time (Residual w/ 0.5% FBN)

5. Configuration 5 - RBQQ Combustor With Non-Metallic Liner

Summary

The carbon-carbon liner, shown in Figure 24, was tested under fuel rich conditions in the RBQQ combustor and operated satisfactorily for six hours at temperatures over 4000°R (2222°K), but failed rapidly after a short period of unstable operation. The most likely failure mechanism was judged to be loss of the oxidation resistant coating during unstable operation followed by reaction of the carbon with H_2O and CO_2. The test results and supporting analysis show that for high temperature applications carbon-carbon will require a suitable oxidation resistant coating, even when operated at fuel rich conditions.



(WO-1247)

Figure 24. Photograph of Carbon/Carbon Liner

The liner, shown schematically installed in Figure 25, was approximately 5-in. (12.7 cm) in diameter, 9-in. (22.9 cm) long and was located in the convergent section of the rich-burn zone. The liner had a diffusion bonded silica carbide coating on the inside and outside diameter and end areas for oxidation resistance and a zirconium oxide thermal barrier on the inner diameter and end areas.

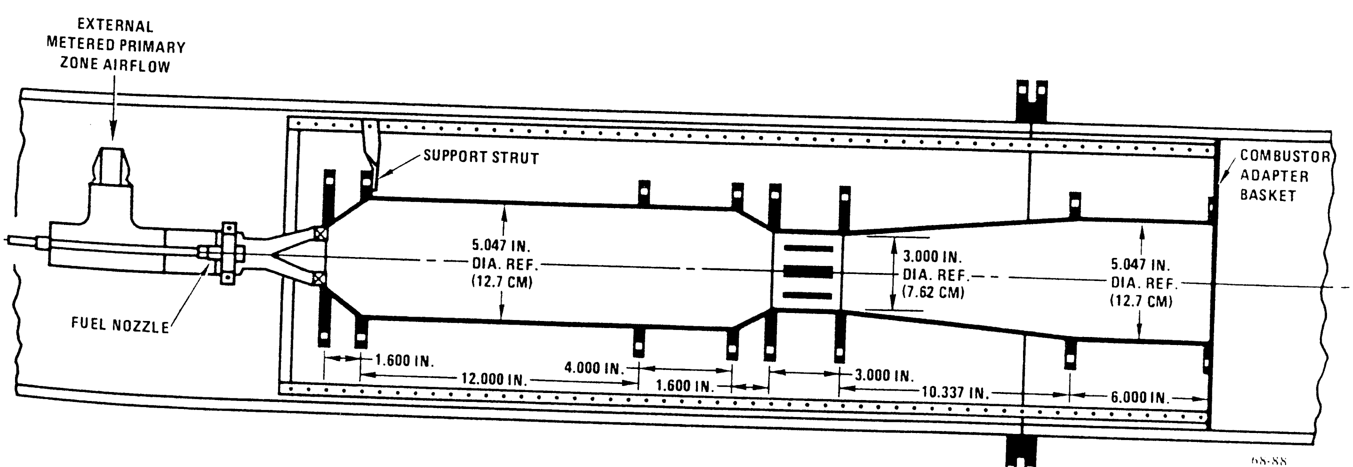


Figure 25. Configuration 5 - RBQQ Combustor with Non-Metallic Liner

Results

The liner operated satisfactorily without apparent deterioration for approximately six hours. The primary zone temperature was approximately 4000°R (2222°K) and combustion pressure varied from 50 to 125 psia (343 to 859 kPa). After six hours of testing, a blowout occurred followed by a hard relight and a short period of unstable operation. As combustion was restablished, a deterioration of the carbon-carbon liner was noted visually. The highly luminous spalling and erosion of the liner appeared to last approximately two minutes. After this period, test conditions appeared normal and testing was continued for an additional four hours.

After ten hours of testing, inspection of the rig revealed that the liner had completely disintegrated up to the flange which separated the uncooled portion of the rich burn zone from the water cooled portion (see Figure 26). The liner upstream of the flange was partially eroded on the exposed surface.

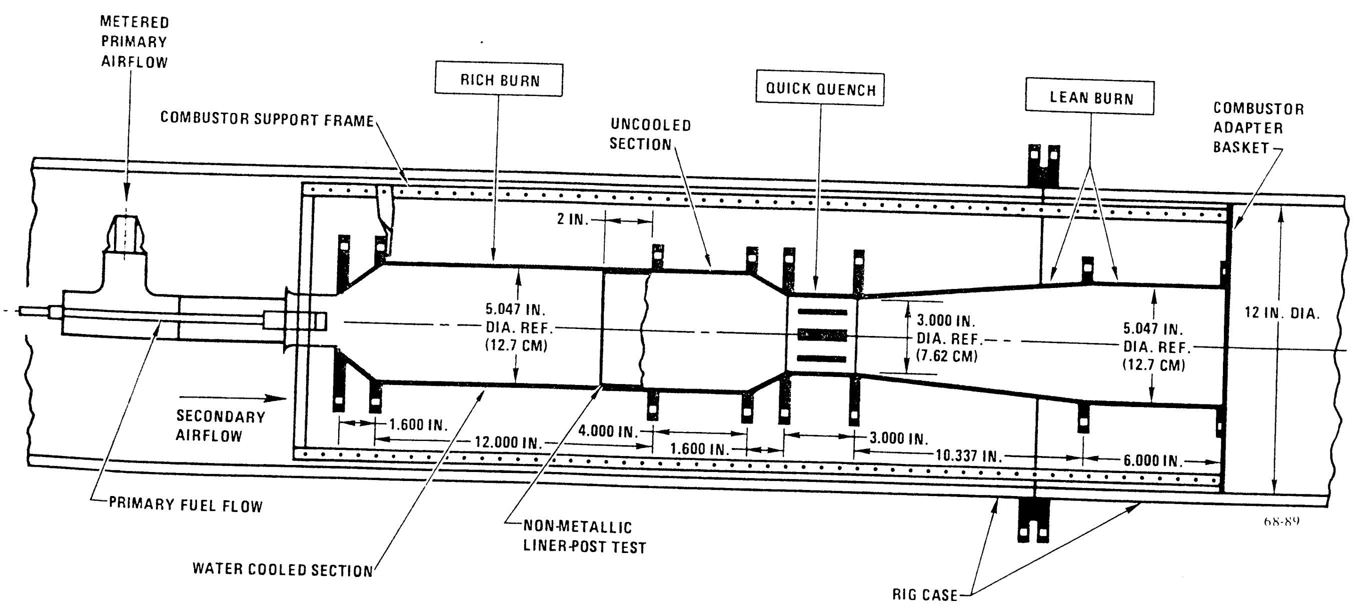


Figure 26. Configuration 5C - RBQQ Combustor Non-Metallic Liner Disintegration

NO_x Levels - Several fuels were tested with this configuration and the NO_x levels vs. front-end equivalence ratio are shown in Figure 27 for these fuels. Figures 28 and 29 display NO_x levels as a function of rich-zone residence time.

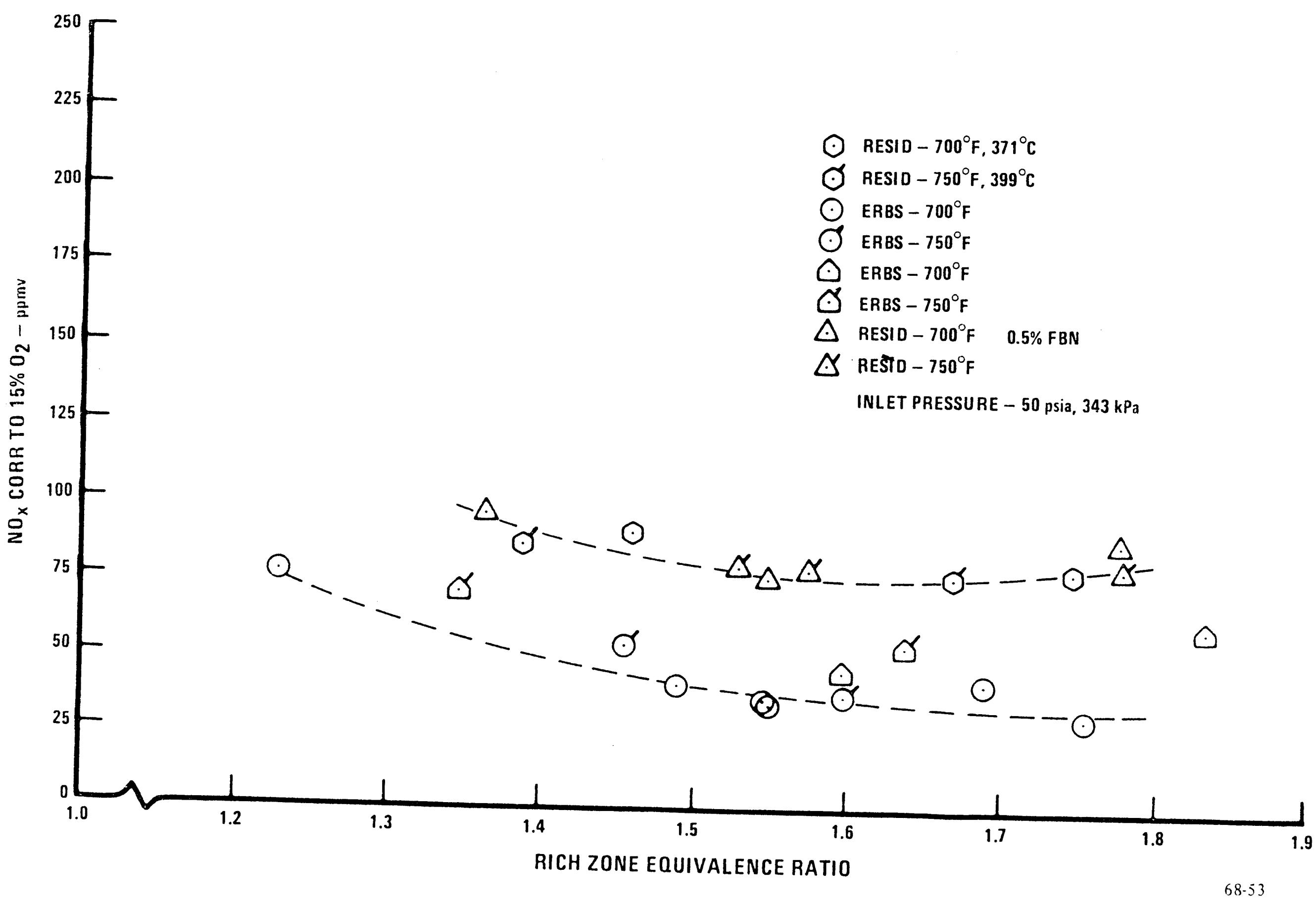


Figure 27. Configuration 5C - NO_x Emissions vs. Rich-Zone Equivalence Ratio

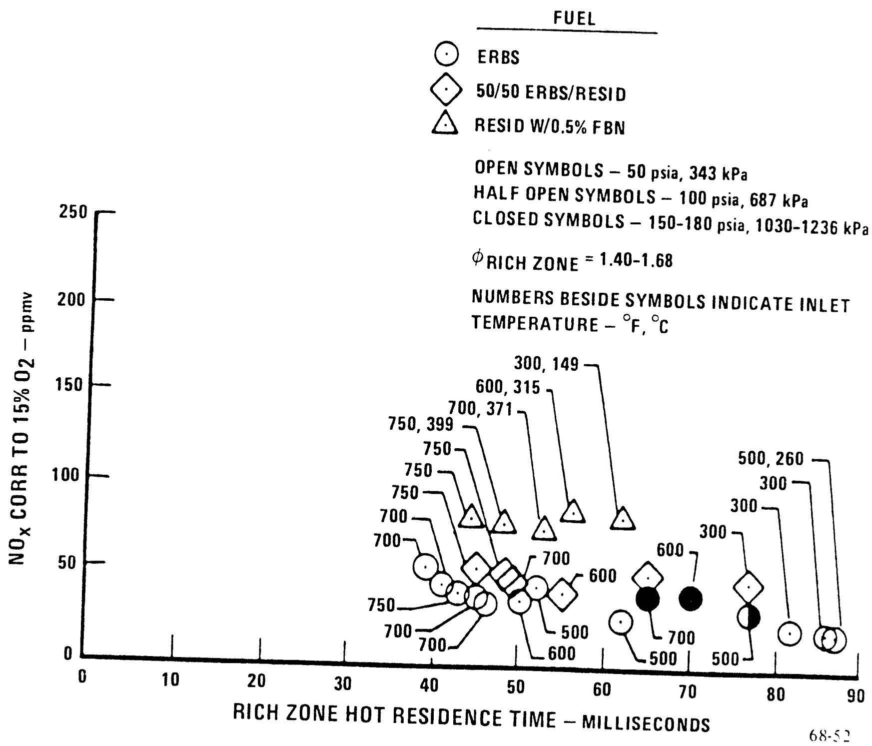


Figure 28. Configuration 5A - NO_X Emissions vs. Rich-Zone Residence Time

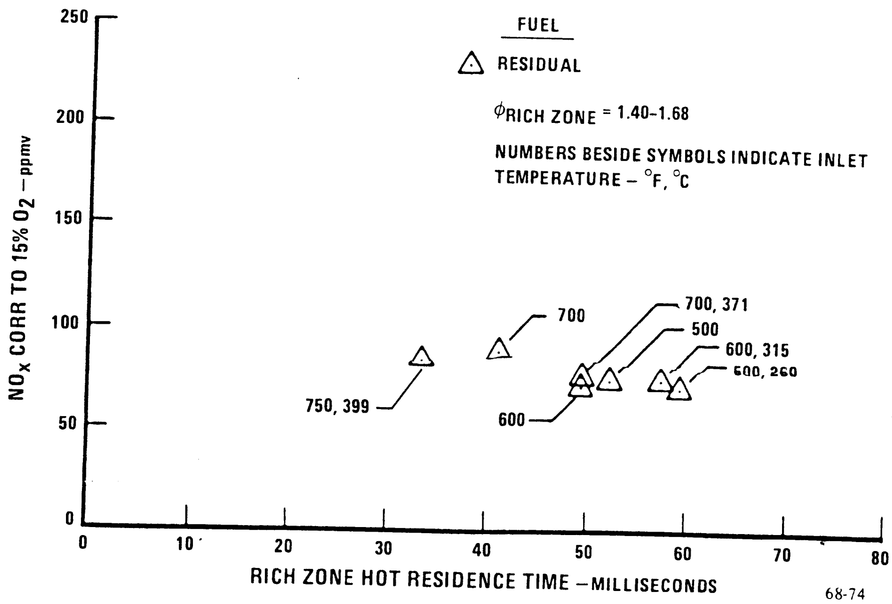


Figure 29. Configuration 5A - NO_X Emissions vs. Rich-Zone Residence Time

CO Levels - CO levels were again shown to be dependent on overall fuel/air ratio with minimum levels occurring at values greater than 0.021.

Comments - CO_2 and H_2O are considered to be completely stable molecules; however, at elevated temperatures either may react with carbon to produce CO, i.e.,:

$$CO_2 + C \rightarrow 2CO + 41.25 \text{ Kcal/mole} \quad (1)$$

$$H_2O + C \rightarrow H_2 + CO + 31.4 \text{ Kcal/mole} \quad (2)$$

Both reactions are highly endothermic. The results of equilibrium calculations showing the extent of the reaction as a function of temperature are shown in Figure 29. As shown, at temperatures above 1500 to 2000°R (833 to 1111°K) the carbon is completely reacted. As the concentration of CO_2 relative to C increases the temperature at which the carbon is reacted is reduced. This trend is illustrated by comparing lines A and B of Figure 30. Addition of water to CO_2 makes the carbon even more reactive as seen by comparing lines A and C. In practice, reaction rates may limit the rate at which the carbon reaction proceeds.

Reactions (1) and (2) form the basis for the production of two types of commercial fuel gasses, i.e., water gas and producer gas. Water gas is obtained from the reaction of steam with a carbonaceous material such as coal or coke. The fuel is brought to a high temperature by blasting it with hot air after which the air supply is cut off and steam is injected. Producer gas is generated by blasting deep hot beds of coal or coke continuously with a mixture of air and steam. Typically reaction temperatures for production of these gases range from 1800 to 2500°R (1000 to 1389°K).

It is judged that the most likely cause of the carbon-carbon liner failure in the RBQQ combustor was a failure of the oxidation resistant coating during unstable operation followed by a water gas type oxidation of the liner under fuel rich conditions.

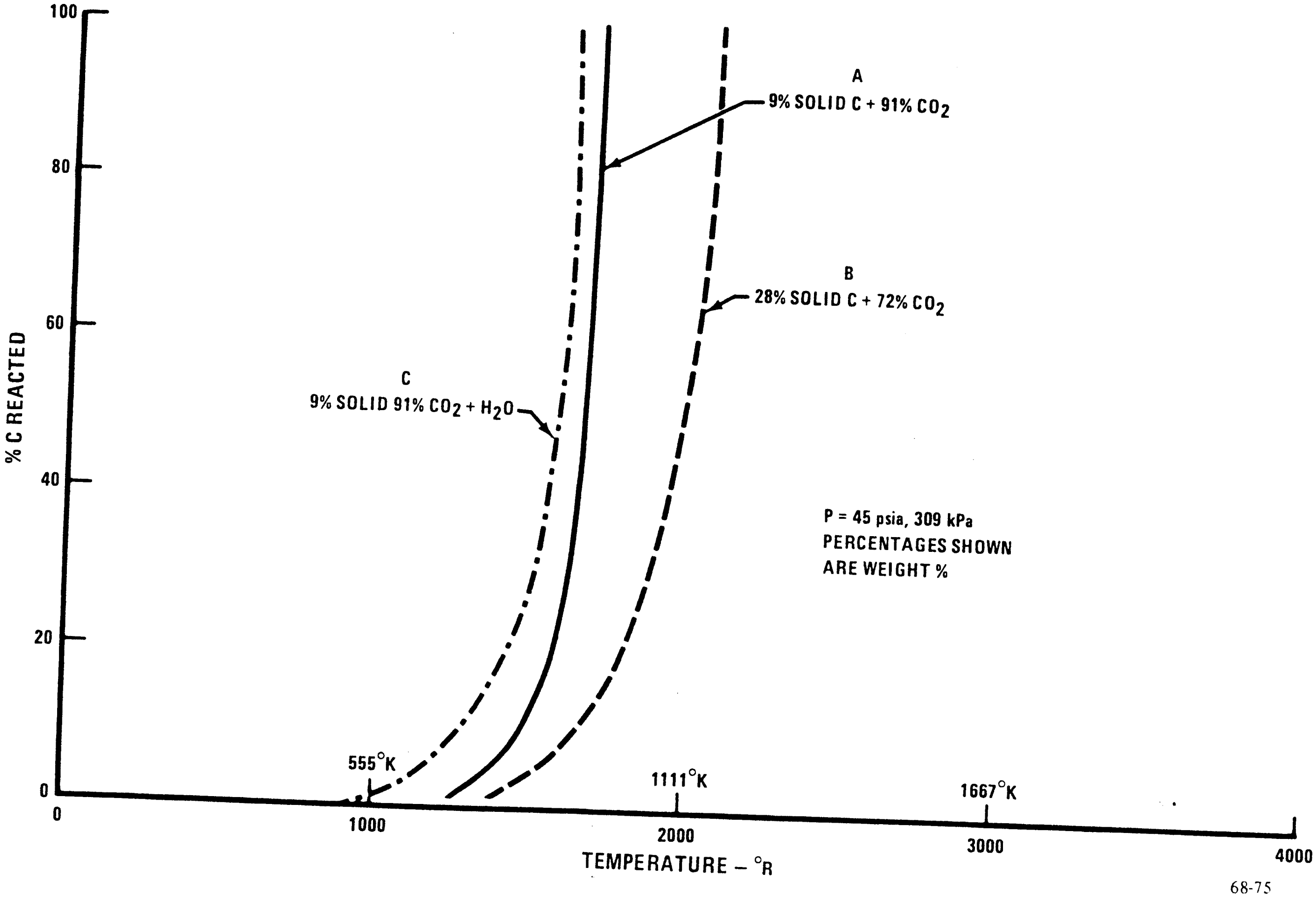


Figure 30. Reaction of Carbon with CO_2 and H_2O

6. Configuration 7 - Preburner Fuel Preparation

<u>Summary</u>

Figure 31 illustrates the original geometry of this configuration. Changes made during testing to try and improve performance included using only two instead of four fuel nozzles in the secondary fuel zone, as well as use of a water cooled rich zone. This configuration displayed very poor performance and was abandoned after several attempts to improve its operating characteristics.

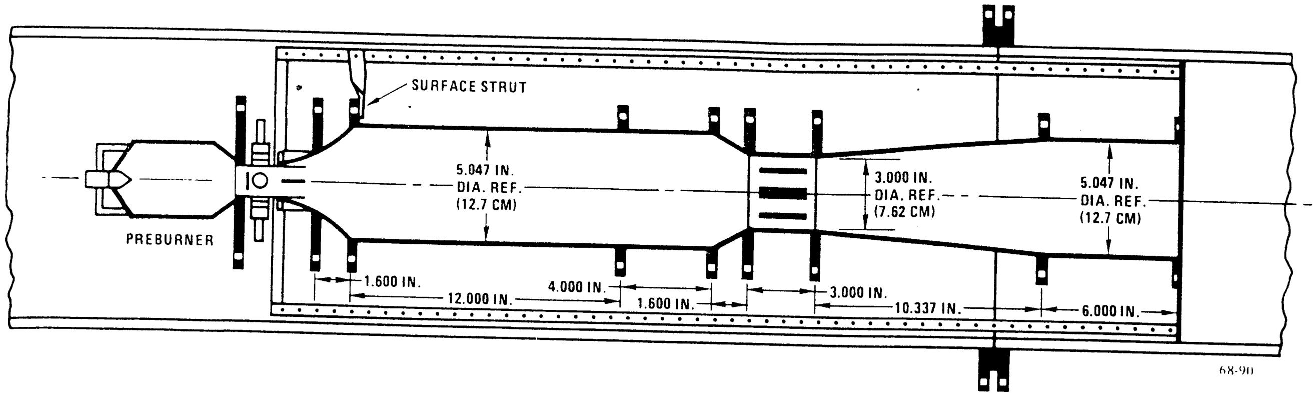


Figure 31. Configuration 7 - RBQQ Combustor with Preburner Fuel Preparation

Results

NO_x Levels - These levels were very high and on the order of 300 ppmv for ERBS fuel.

Smoke - Smoke was highly visible at the rig exhaust.

Comments - This concept was judged as needing extensive development effort to meet the contract goals and was abandoned as this was not within the scope of the program.

7. Configuration 8 - Variable Geometry Combustor

Summary

Figure 32 illustrates the original geometry of this configuration. The quench module consisted of 8 openings, 4 of which could be closed off by means of movable pistons within the module. Troubles with this configuration were encountered during testing, for the pistons would freeze up in both open and closed positions due to thermal growth. To add to this problem, it could not be determined which pistons were opening and closing and how many were operating properly. It was the opinion of the author that variable geometry devices would require a substantial development effort if they were to be used in full-scale combustors for stationary gas turbines.

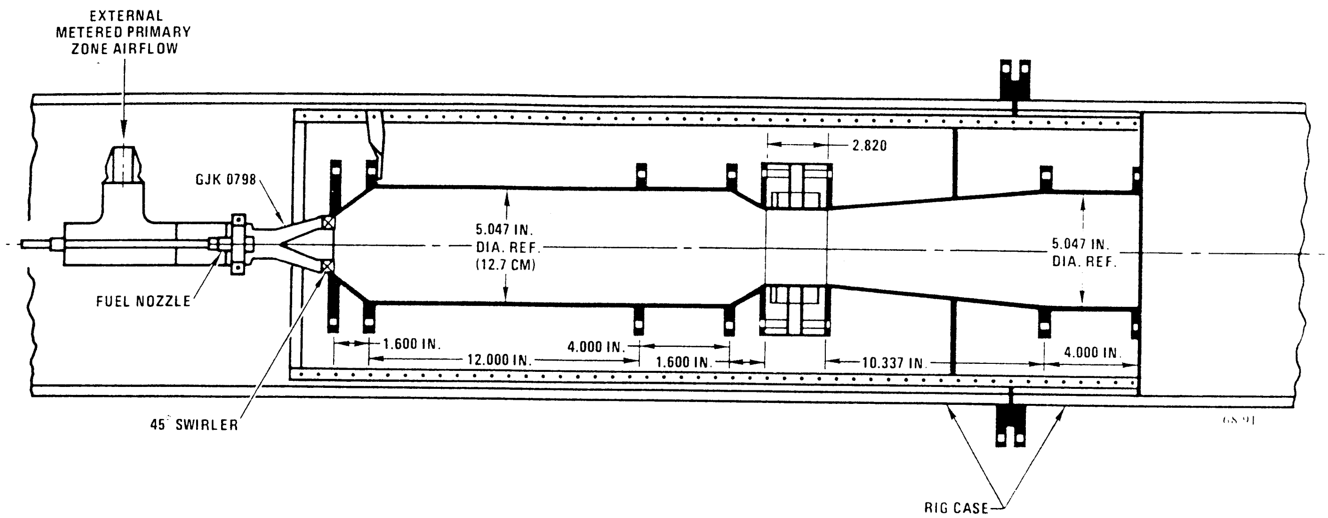


Figure 32. Configuration 8 - RBQQ Combustor with Variable Geometry

Results

NO$_x$ Levels - The NO$_x$ levels vs. rich-zone residence times for SRC-II and residual fuels (with pyridine) are shown in Figures 33 and 34. Data obtained with ERBS and residual fuel (without pyridine) was marred by the discovery of a bent fuel nozzle tip after tests with these fuels.

CO Levels - The results levels were similar to Configuration 1 at fuel/air ratios above 0.021 as expected.

Comments - Due to the effort required to develop this concept, attempts to fix the thermal growth problems were not attempted during the course of these tests.

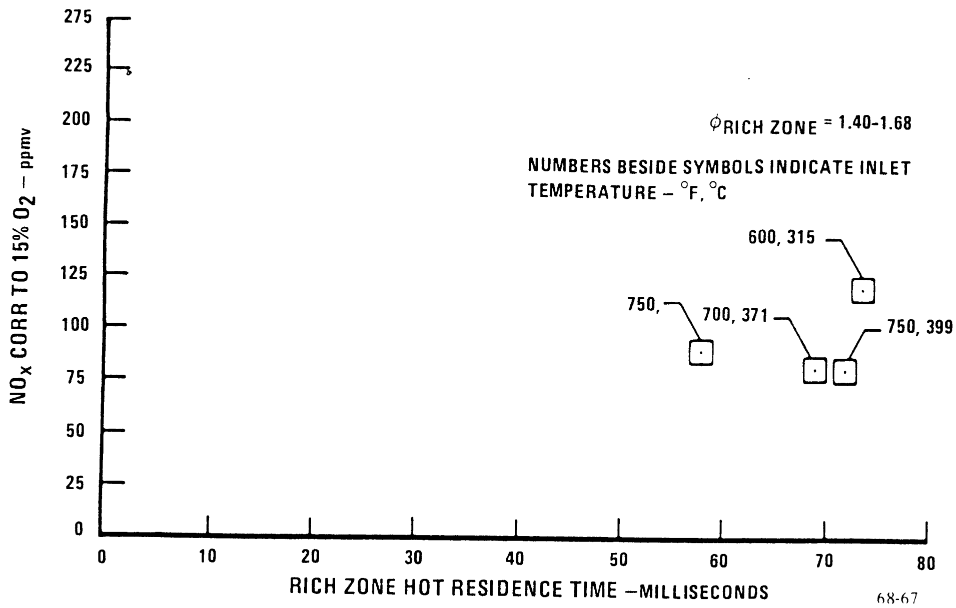


Figure 33. Configuration 8A - NO_X Emissions vs. Rich-Zone Residence Time (SRC-II Fuel)

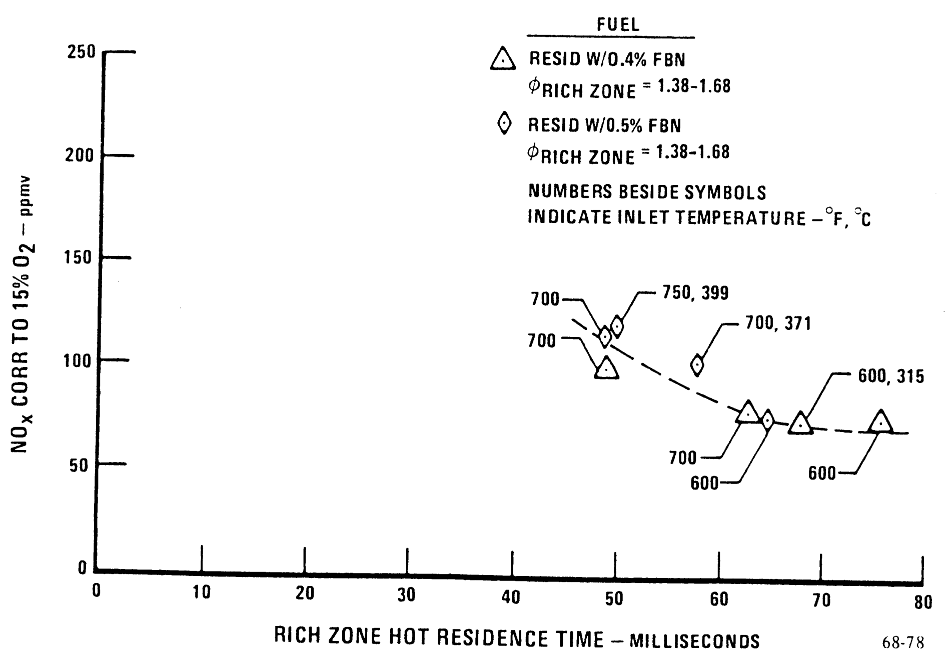


Figure 34. Configuration 8A - NO_X Emissions vs. Rich-Zone Residence Time (Residual Fuel)

8. Configuration 9 - Graduated Air Addition Combustor

Summary

Figure 35 illustrates the original geometry of this configuration. Water cooling was added to the rich-zone walls for durability purposes. Smoke levels were excessively high with this configuration and attempts to improve performance were fruitless.

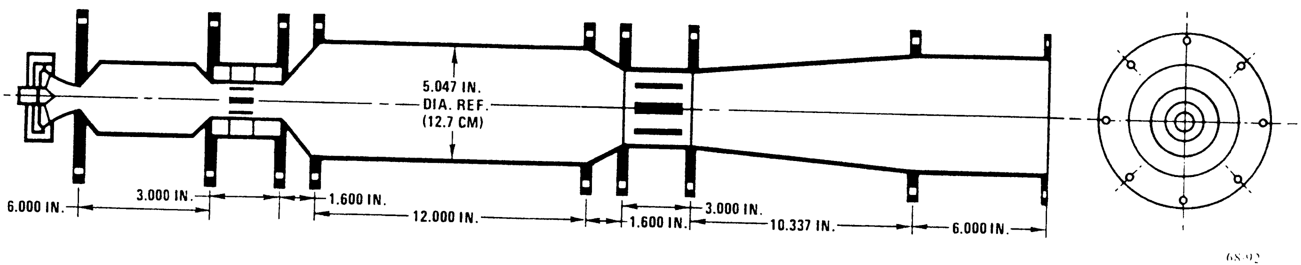


Figure 35. Configuration 9 - RBQQ Combustor with Graduated Air Addition

Results

NO_x Levels - Figure 36 illustrates the NO_x levels vs. rich-zone residence time for this configuration for the fuels tested. To obtain the low NO_x levels, the preburners had to be operated at equivalence ratios between 1.80 and 2.50 which resulted in high smoke levels.

Comments - This concept showed no potential due to the high smoke levels obtained.

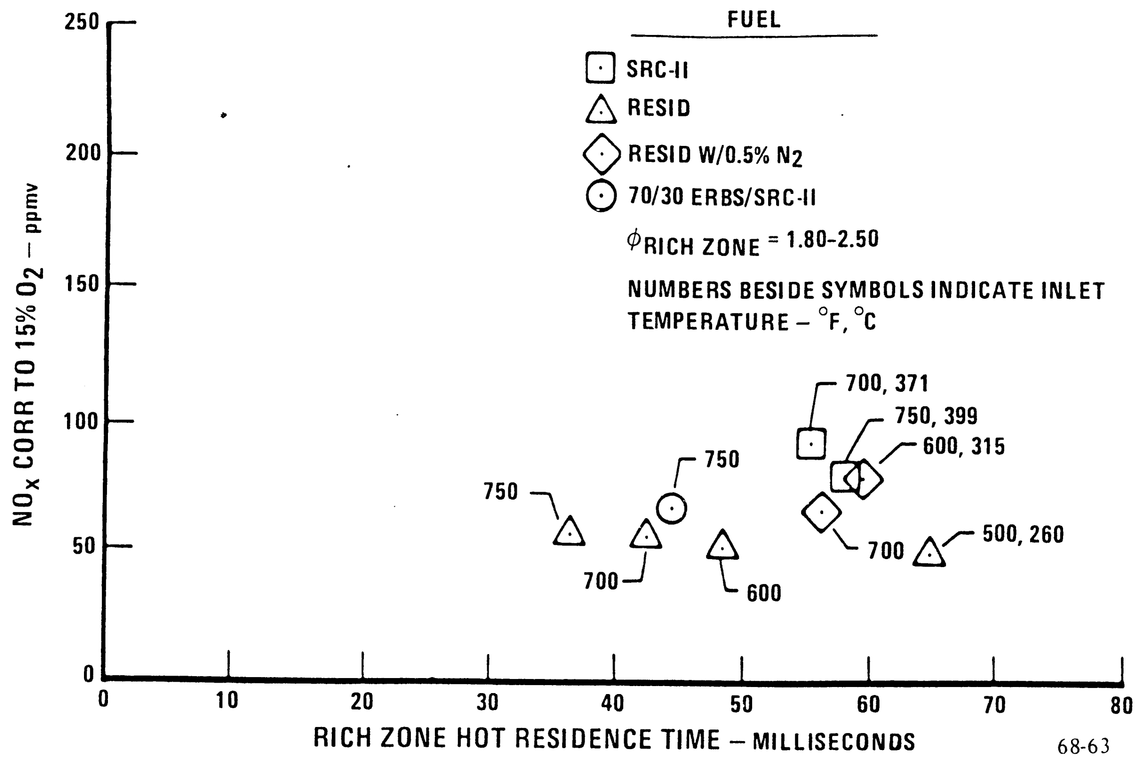


Figure 36. Configuration 9A - NO_x Emissions vs. Rich-Zone Residence Time (SRC-II, Residual w/o 0.5% FBN, 70/30 ERBS/SRC-II)

9. Configuration 13 - RBQQ with 6-inch (15.2 cm) Rich-Zone

<u>Summary</u>

Figure 37 illustrates the geometry of this configuration. This configuration was added near the end of the test program to help define rich-zone residence time effects on the RBQQ emissions levels. Tests were conducted with ERBS, SRC-II, Residual, and a 50/50 mixture of ERBS/Residual fuels.

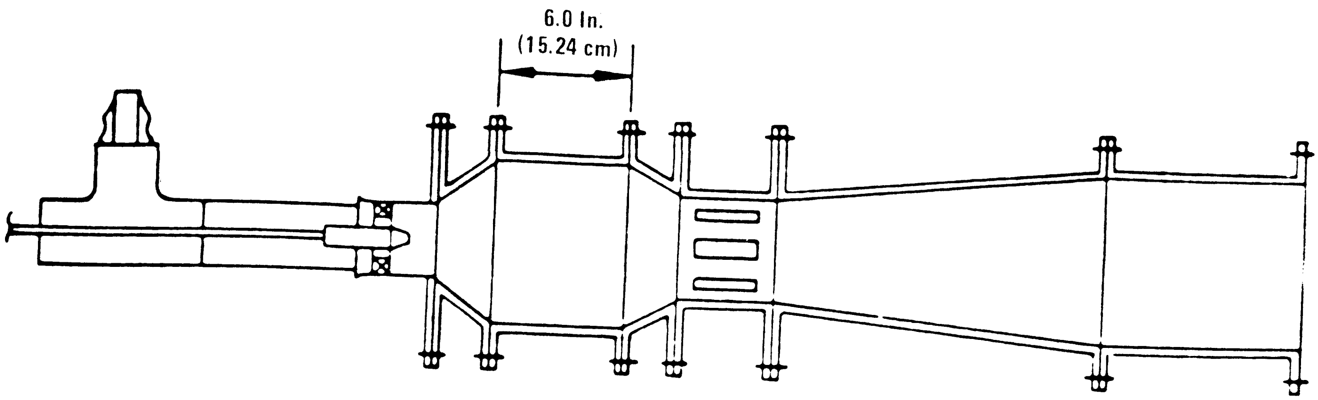


Figure 37. Configuration 13A - RBQQ Combustor with Very Short Rich-Zone

Results

NO_x Levels - Were similar to Configuration 1 on ERBS fuel only. The short residence times of this combustor resulted in dramatic increases in NO_x levels with the SRC-II fuel (approximately 1% FBN) and moderate increases were noted with the residual fuel (approximately 0.3% FBN). Figure 38 illustrates this where NO_x levels are shown vs. rich zone residence time. Figure 39 illustrates these NO_x levels as a function of rich-zone end equivalence ratio. From these curves it is observed that the NO_x levels are a strong function of residence time in the rich zone.

CO Levels - CO levels were comparable to Configuration 1 and suggests that rich zone length (in the ranges tested) have little or no effect on overall CO levels.

Comments - This configuration showed potential for meeting NO_x standards when combusting residual and ERBS fuels, but does not have acceptable NO_x levels with SRC-II fuels.

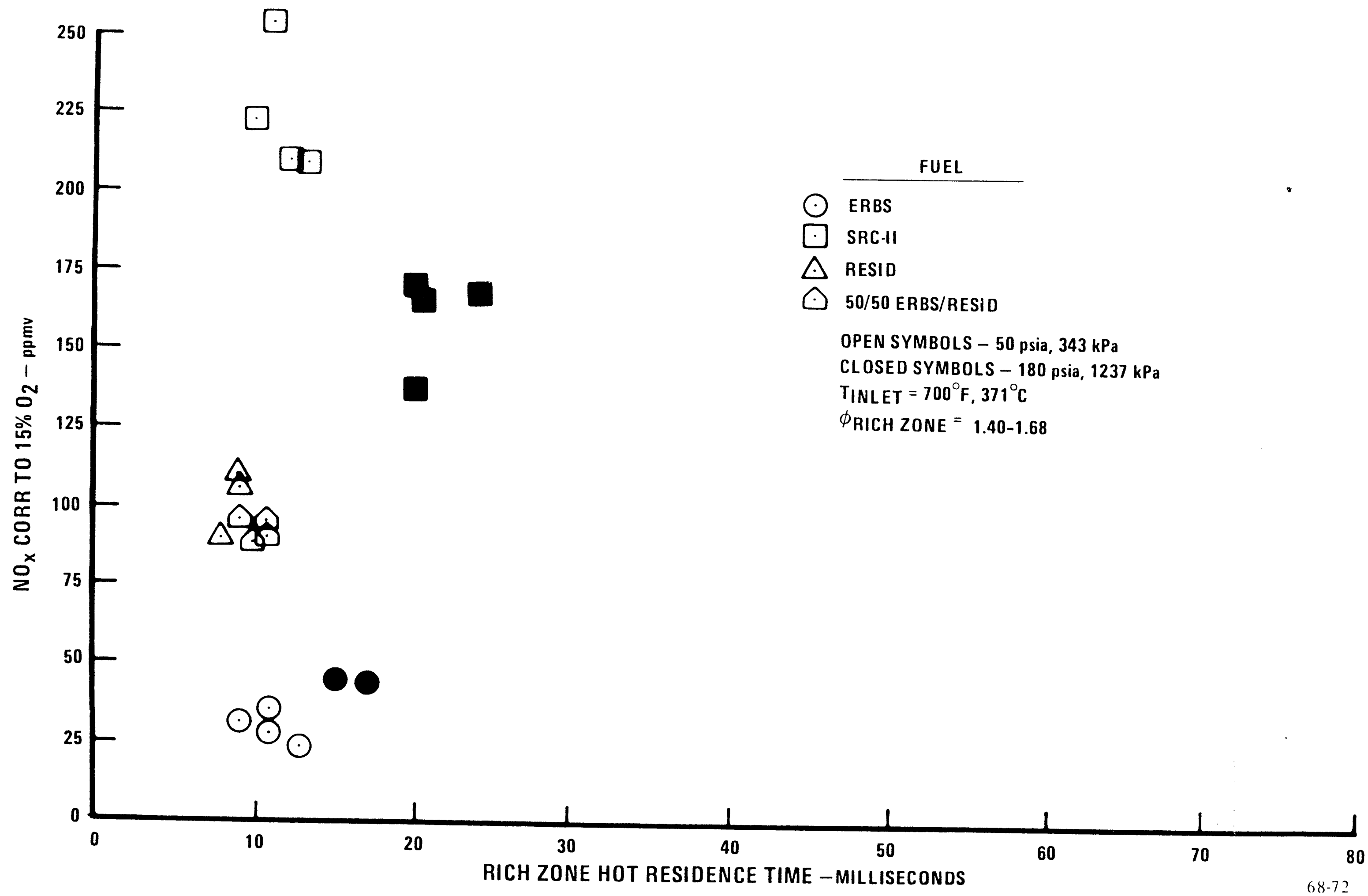


Figure 38. Configuration 13 - NO_x Emissions vs. Rich-Zone Residence Time (ERBS, SRC-II and Residual Fuels)

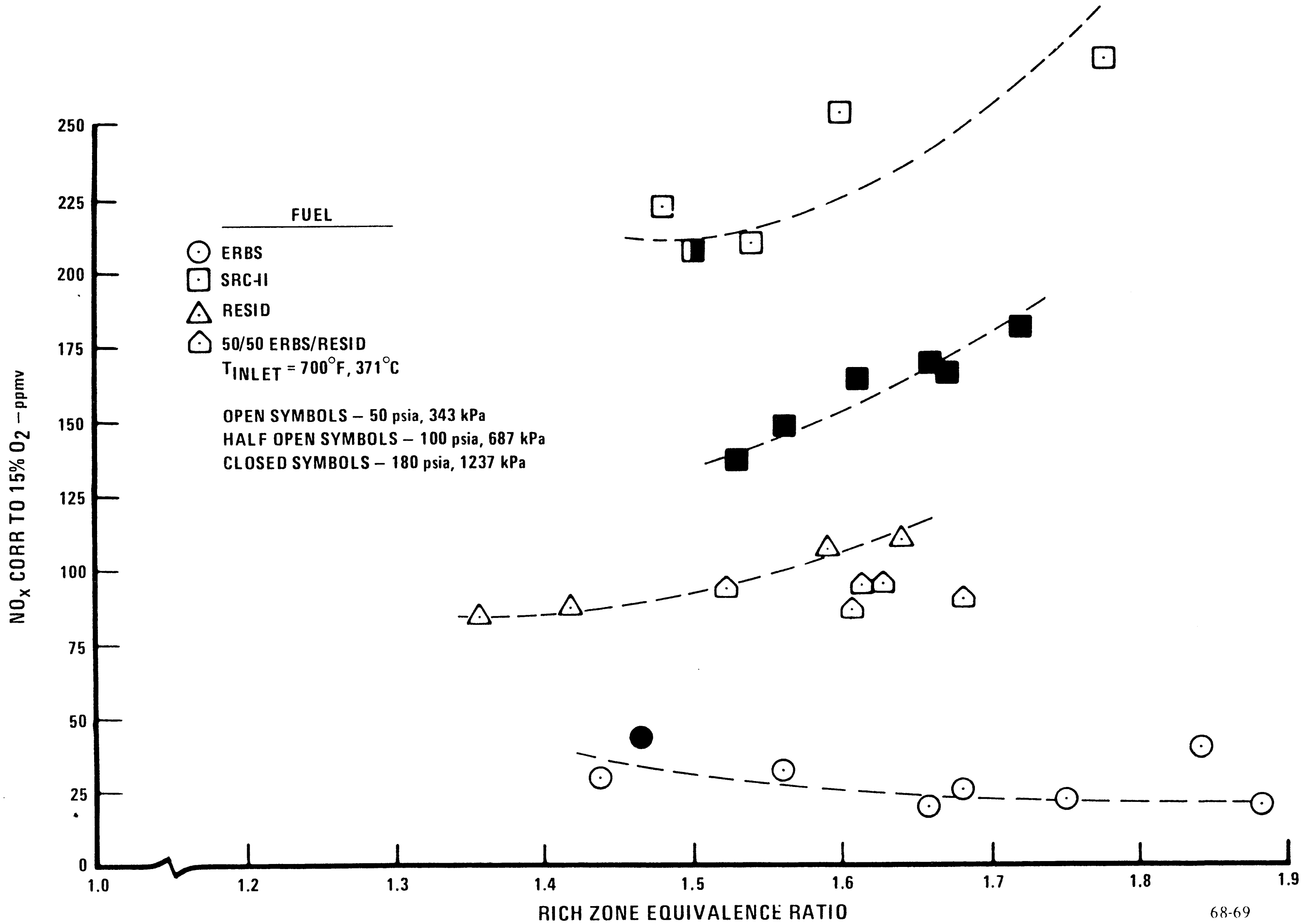


Figure 39. Configuration 13 - NO_x Emissions vs. Rich-Zone Equivalence Ratio (ERBS, SRC-II and Residual Fuels)

10. Configuration 14 - RBQQ with 6-inch (15.2 cm) Rich-Zone and Air-Blast Nozzle

Summary

This configuration is the same as Configuration 13 (Figure 37) with the exception of replacing the recessed swirler assembly and air-boost fuel nozzle with the air-blast fuel nozzle and swirler shown in Figure 40. Tests were conducted with ERBS, SRC-II and residual fuel. The main purpose of the tests were to try and reduce smoke levels, especially with residual fuels.

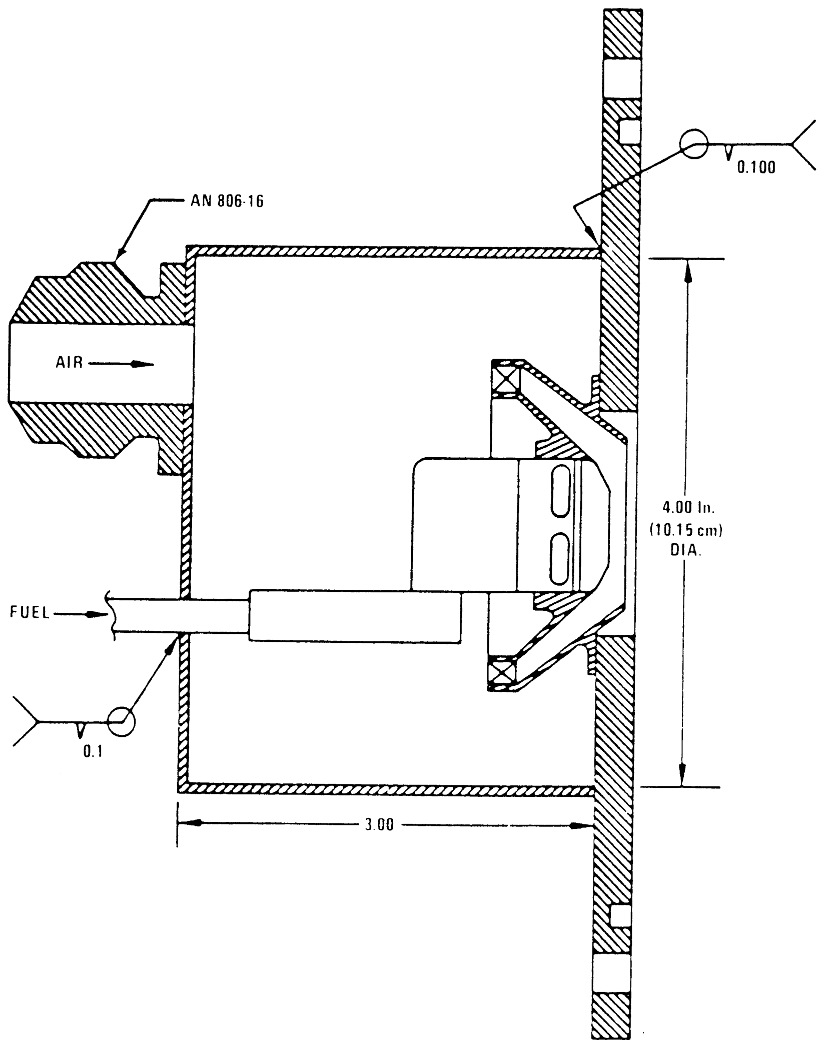


Figure 40. Configuration 14 - Air Blast Fuel Nozzle Atomizer Configuration

Results

NO_x Levels - Figure 41 displays results obtained for all fuels tested as a function of rich-zone residence time. Figure 42 displays NO_x versus rich-zone equivalence ratio. These NO_x levels were within the expected range based on previous configuration results.

Smoke Levels - Table VI summarizes the smoke levels obtained with this configuration. Lower smoke levels were obtained with this fuel nozzle on residual fuels than with the air-boost nozzle.

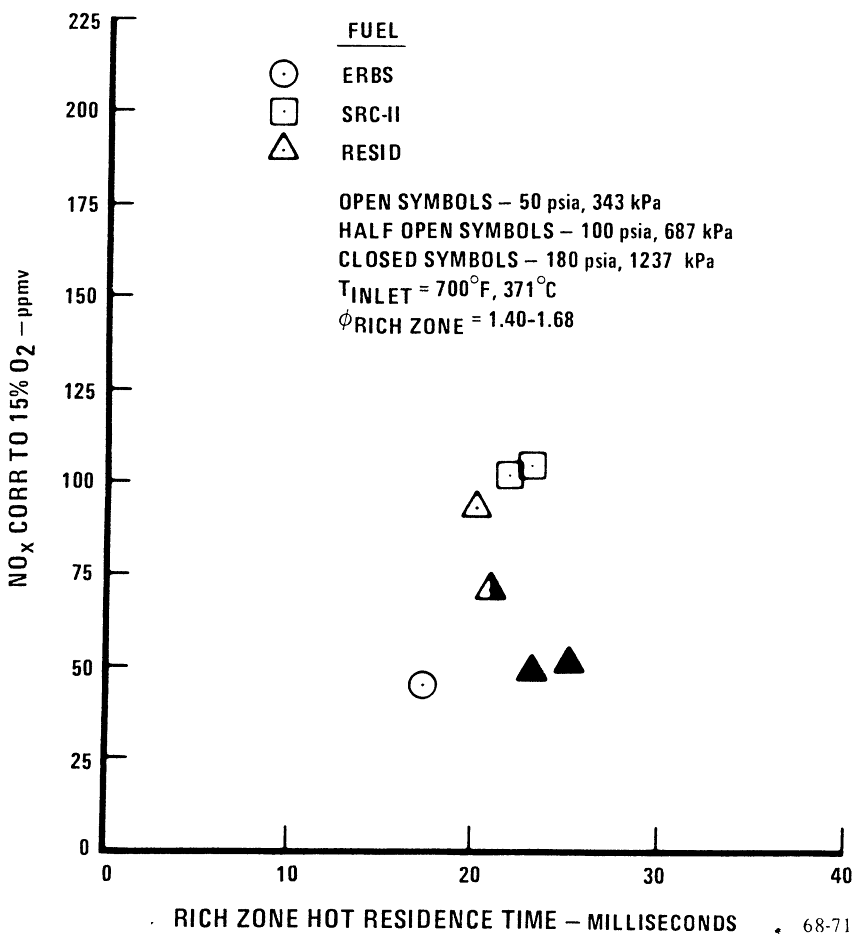


Figure 41. Configuration 14 - NO_x Emissions vs. Rich-Zone Residence Time (ERBS, SRC-II and Residual Fuels)

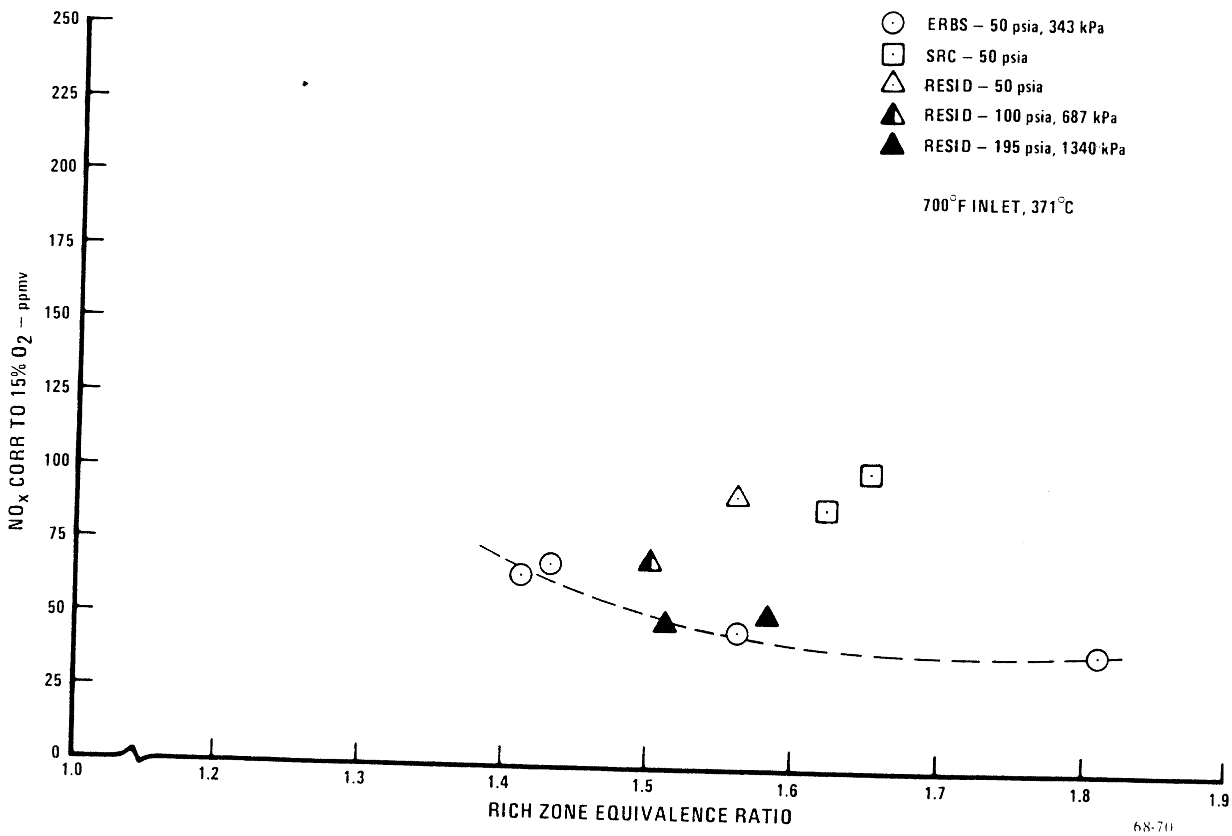


Figure 42. Configuration 14 - NO_x Emissions vs. Rich Zone Equivalence Ratio (ERBS, SRC-II and Residual Fuels)

TABLE VI. TEST SUMMARY OF SMOKE DATA FROM CONGIGURATION 14

Fuel Type	Burner Pressure (psia, kPa)	Front-end Equivalence Ratio	Burner Inlet Temperature (°F,°C)	SAE Smoke Number
ERBS	50, 343	1.56	700, 371	2.2
Residual	50, 343	1.56	700, 371	28.6
Residual	100, 687	1.50	700, 371	29.9
Residual	195, 1340	1.58	700, 371	19.5
SRC-II	50, 343	1.65	700, 371	11.9

C. DATA CORRELATIONS

This section describes the results of a comprehensive data analysis to determine the most important parameters affecting burner emissions and performance. Some of this section is also reported in the Comprehensive Data Report (GTR-3235) and is presented in this document due to the importance of what the test data revealed. The summary test data is contained in Table V.

1. Effect of Residence Time on NO_x Emissions

Data from Configuration 1, 2, and 13 were compared due to similar geometries in every location except for rich zone length. Figure 43 displays these data and reveals an extremely important relationship. Fuels containing fuel-bound nitrogen can be burned with minimal NO_x levels given sufficient residence time.

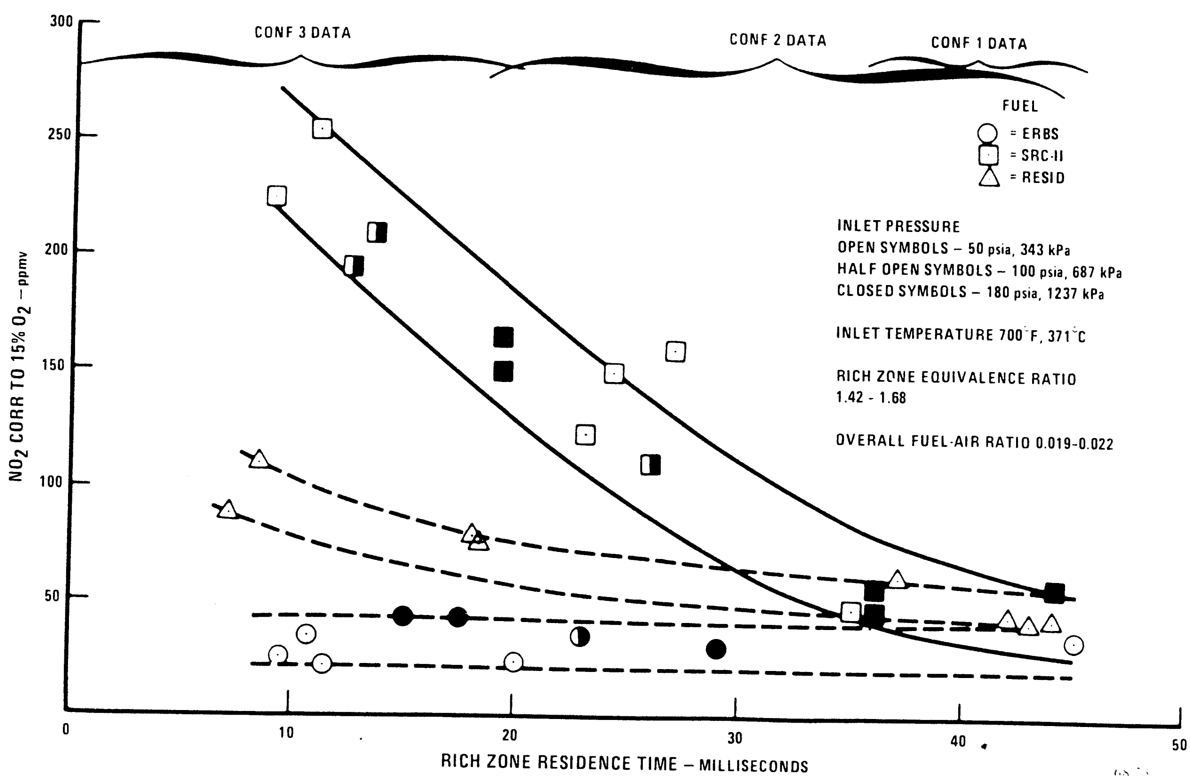


Figure 43. Summary of NO_x Emissions vs. Rich-Zone Residence Time (ERBS, SRC-II, and Residual Fuels)

2. Effect of Quench Module Size on NO_x Emissions

Data from configurations 1, 3, and 4 were compared due to similar geometries except for quench module size. Figure 44 displays this data and reveals that configuration 1 gave the lowest NO_x levels in the bucket region of the curve. This corresponds to a rich zone/quench zone area ratio of 2.77.

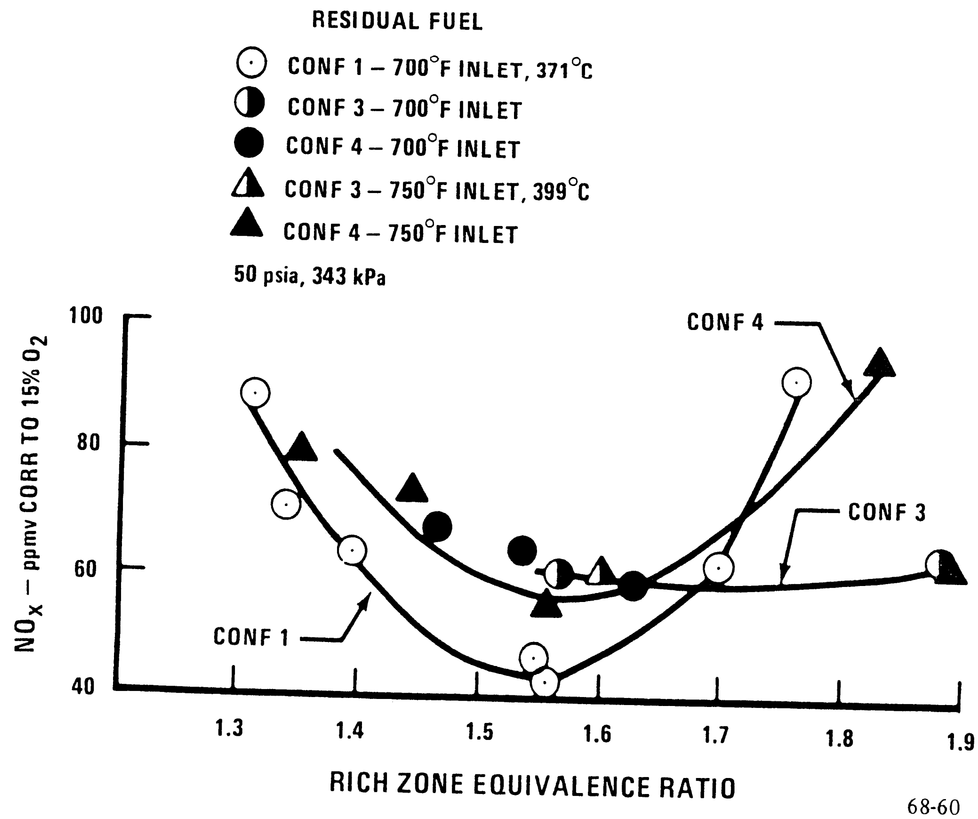


Figure 44. Effect of Quench Module Size on NO_x Levels

There was some concern over scaling a bench scale combustor to a full-scale design, and the major concern with scaling was to insure proper mixing in the quench module section. The parameters considered most critical when scaling are the rich/quench zone area ratio, the pressure drop across the quench module, the length/width ratio of the quench slots, and proper length of the quench module to insure complete mixing. Analysis of data indicates that if these parameters are matched, the mixing process will be very similar in both cases. The data from the three configurations did not display major differences, and NO_x levels were within the goals of the program for all three, which alleviates some of the concern over scaling.

3. Effect of Rich Zone Equivalence Ratio on NO_x Emissions

Effects varied depending on type of fuel used and can be related to amount of fuel-bound nitrogen (FBN). For the ERBS fuel (no fuel-bound nitrogen), NO_x decreased with increasing equivalence ratio up to equivalence ratios of approximately 1.6 and remain relatively constant thereafter as shown in Figure 45. For residual fuel (0.3% FBN) a minimum NO_x level occurs at an equivalence ratio of approximately 1.55 as shown in Figure 46. The SRC-II fuel (approximately 1.0% FNB) also displays a minimum at a front end equivalence ratio of approximately 1.55 as shown in Figure 47.

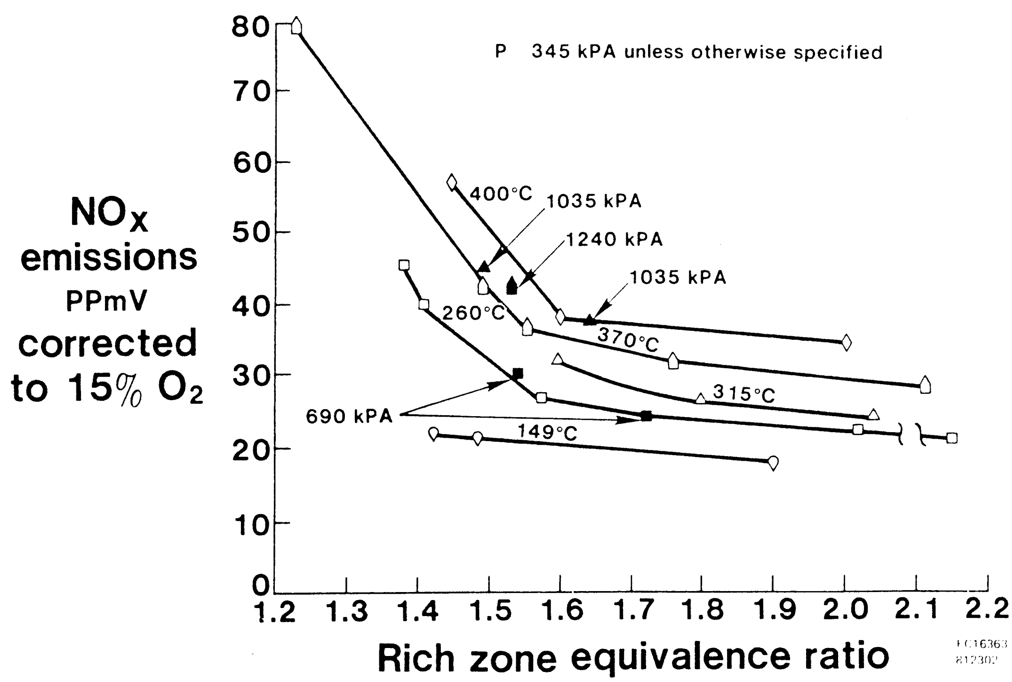


Figure 45. NO_x Emissions with Configuration 5 Combustor Using Distillate Fuel

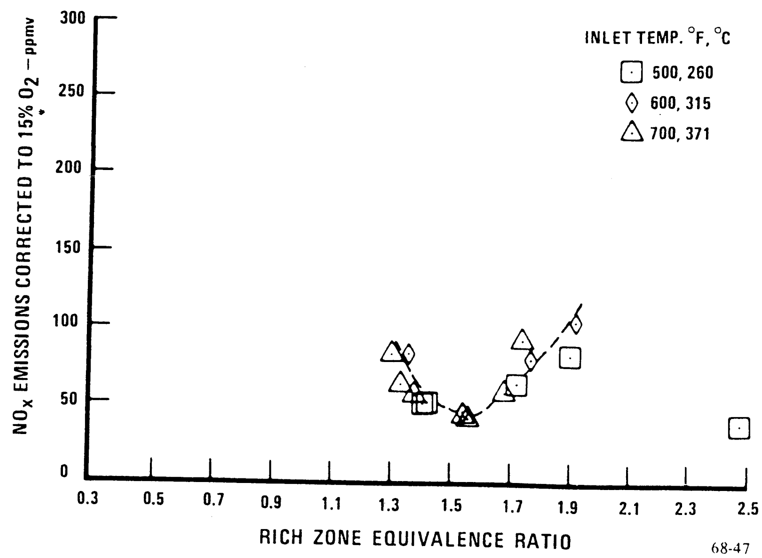


Figure 46. NO_x Emissions with Residual Fuel

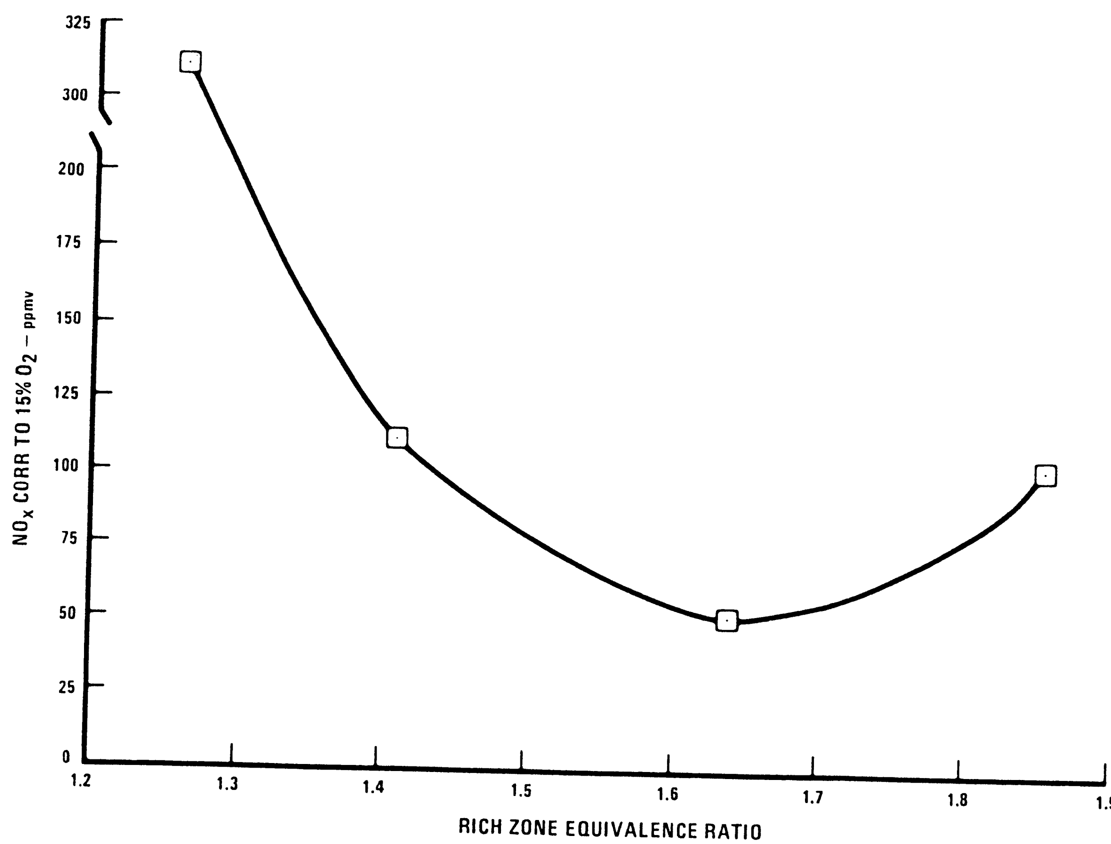


Figure 47. NO_x Emissions with SRC II Fuel

4. Effect of Rich Zone Wall Temperature on NO_x Emissions

Cooled walls down to 150°F (65°C) had minimal effect on NO_x levels. This is a very significant discovery in that it allows for longer burner life and use of steam or water in a combined cycle power plant, where the lost heat can be recovered. Figure 48 displays typical data for water cooled walls (200°F, 100°C range) and uncooled walls (2000°F, 1100°C range), as can be seen, very little variation in NO_x levels is evident.

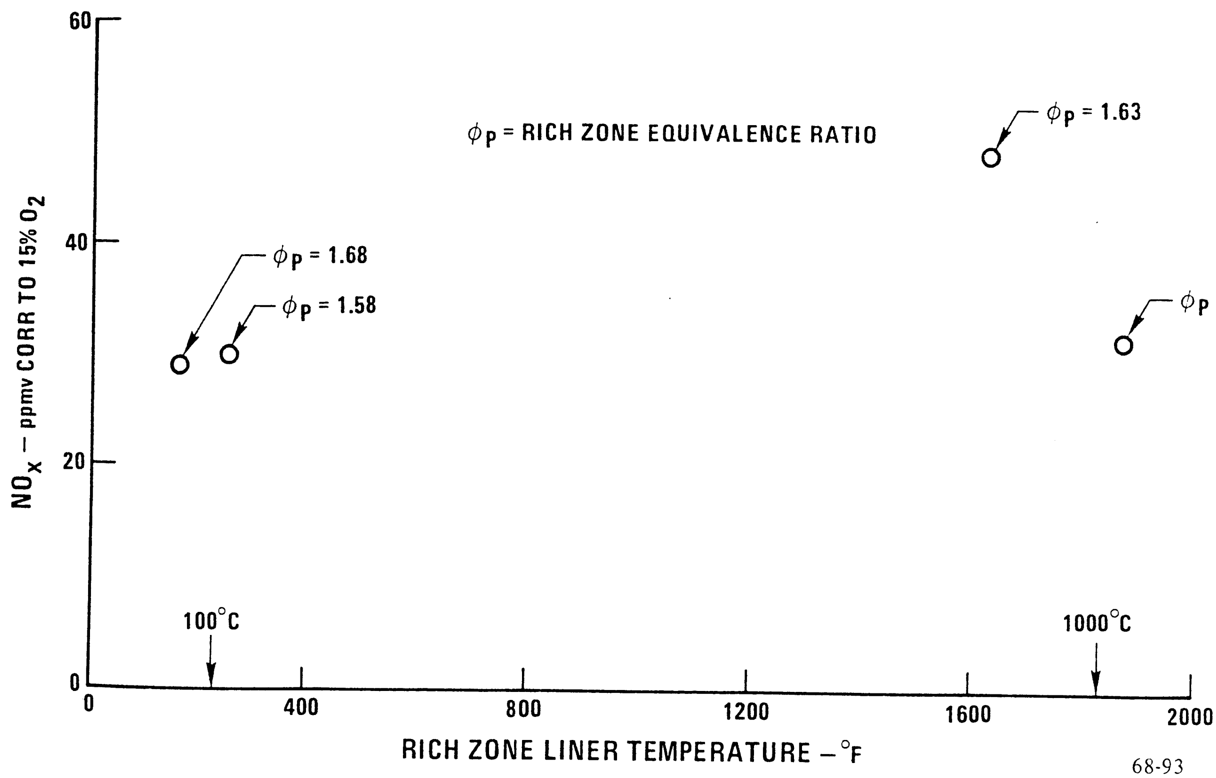


Figure 48. Effect of Liner Wall Temperature on NO_x Levels

5. Effect of Overall Fuel/Air Ratio on CO Emissions

The majority of data indicated that at a 700°F (371°C) inlet condition, the fuel/air ratio at the quench module exit had to be kept above 0.021 to achieve minimal CO emissions for all configurations. Figure 49 displays typical data taken during the course of testing. CO levels drop rapidly as the 0.021 fuel/air ratio is approached. This important finding provides valuable information for a full-scale design.

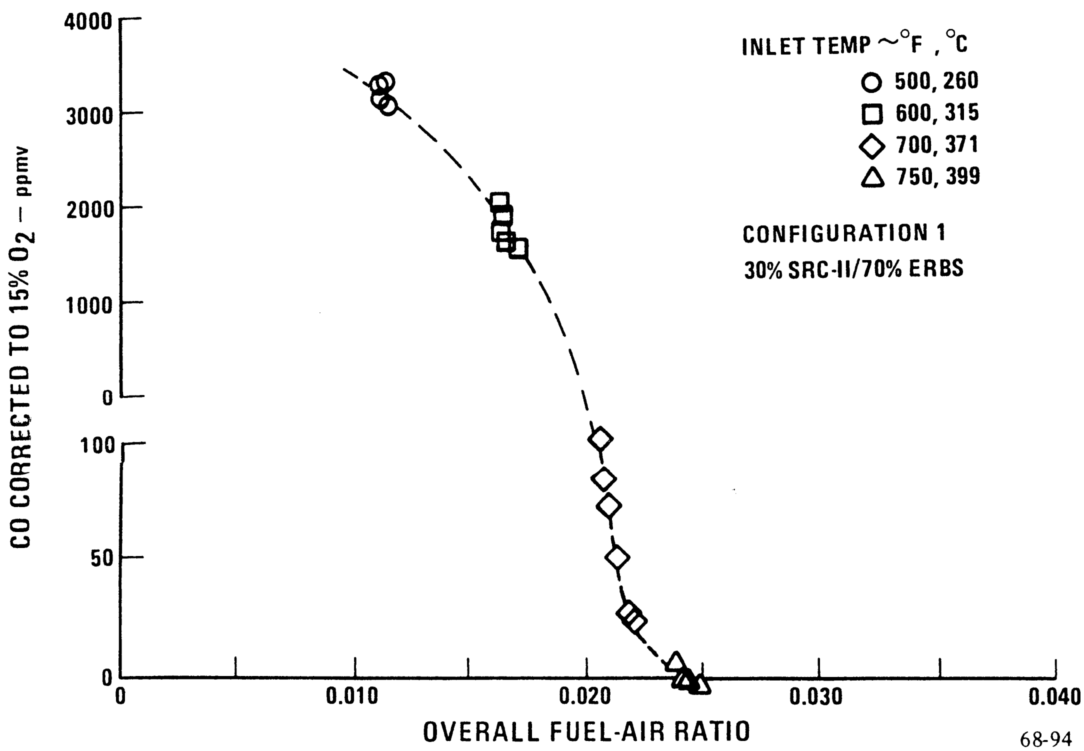


Figure 49. CO Emissions vs Overall Fuel Air Ratio

D. CONCLUSIONS - BENCH SCALE TESTS

The Rich-Burn/Quick-Quench Combustor concept has successfully demonstrated substantial emissions reductions, representing improvements better than the emissions goals of the program for all fuels tested.

Emissions

NO_x Levels - Given sufficient residence time, NO_x levels can be kept in the range of 50 ppmv by use of the rich-burn/quick-quench combustor geometry.

This applies to fuels containing fuel-bound nitrogen; clean fuels require shorter residence times. Front end equivalence ratios must be controlled and kept in the range of 1.5 to 1.6 for optimum operation.

CO Levels - The mixture temperature at the exit of the quench zone for a RBQQ combustor must be kept high enough to provide for CO oxidation.

UHC Levels - The RBQQ combustor displayed no problems in keeping these emissions low.

Smoke Levels - If proper atomization and good front end mixing are present, smoke levels can be kept in the invisible range.

Durability

Liner Wall Temperatures - Liners can be steam or water cooled for long life with no detriment to emission levels.

Non-Metallic Materials - The coated carbon-carbon liner, manufactured by Vought Corporation, operated satisfactorily for six hours at temperatures in excess of 4000°R (2220°K). All planned test objectives were met. The following observations were made after testing the carbon-carbon liner:

- Once the liner coating was lost, deterioration of the liner occurred very rapidly.
- Conditions in the fuel-rich zone of the RBQQ strongly favor carbon oxidation by H_2O and CO_2. Conditions are in fact much more severe than those used for commercial preparation of water gas and producer gas from carbonaceous materials.
- The reduced erosion of the liner in the water cooled section illustrates the temperature dependence of the reaction process.

- The use of carbon-carbon under fuel rich conditions will require an oxidation resistant coating.

Performance

Burner Pattern Factor - The RBQQ displayed excellent pattern factor at both low and high power, indicating a homogenous mixture at the burner exit.

Burner Efficiency - Efficiencies on the order of 100% were displayed by the RBQQ.

Combustor Geometry

Variable Area - Requires extensive development, but will be required if NO_x levels are to be kept to a minimum at all power settings. The use of multiple staged (fuel on-off) rich-burn quick-quench elements for direct-drive constant-speed gas turbine systems might be used to avoid the need for variable geometry.

Rich Zone - Must be of sufficient length to provide proper residence times for NO_x reduction when operating on fuels containing bound nitrogen.

Quench Zone - Must provide vigorous mixing to insure CO oxidation and uniform temperature patterns.

SECTION III
CONCEPTUAL ENGINE COMBUSTOR DESIGN

The successful techniques demonstrated during this program were used to conceptually design two full-scale combustors which could be incorporated into the United Technologies Corporation FT4 industrial stationary gas turbine engine. This section describes the procedures used in preparing the designs and a description of each concept is given.

A. REVIEW OF RESULTS

A review and analytical study of bench-scale hardware test results was conducted to determine the optimum configurations for full-scale hardware that had potential for reducing the production of pollutants, including smoke. Of the concepts tested, Configuration ID gave the best overall performance and emerged as the most successful in meeting the design goals. This concept is the rich-burn/quick-quench (RBQQ) with a sufficient rich-zone length to provide residence time for reduction of NO_x levels, including thermal and fuel-bound sources of NO_x.

Figure 50 illustrates the key features of the RBQQ combustor concept. At the front-end of the burner, where fuel and air are admitted, a combustor tube with a recessed air swirler is provided in which the fuel is atomized and mixed with air to form a rich mixture. This mixture then enters into a primary rich-zone of the combustor where combustion occurs without any further addition of air or fuel. This mixture then travels into a dilution zone called the quench section where very rapid dilution occurs with the remaining airflow, which is further combusted in the lean zone. The success of this concept resulted from the refinement of techniques, during the test program, to solve durability problems and provide for good fuel and air mixing in the rich-zone.

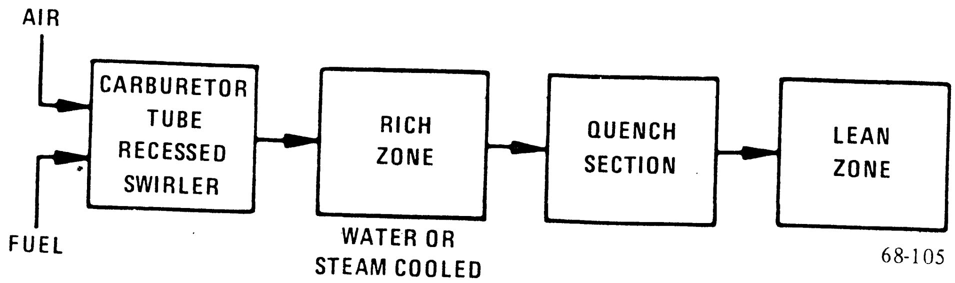


Figure 50. Key Features of RBQQ Combustor Concept

The rich-burn/quick-quench combustor geometry, with the modifications which were made during the test program, are shown in Figure 51. This geometry resulted in minimal NO_x levels. The recessed swirler was added during the test program and replaced the original premix tube arrangement which had durability problems. Water cooling was added to the rich section after structural damage occurred because of high flame temperatures and poor heat transfer which resulted from low back side cooling air velocities.

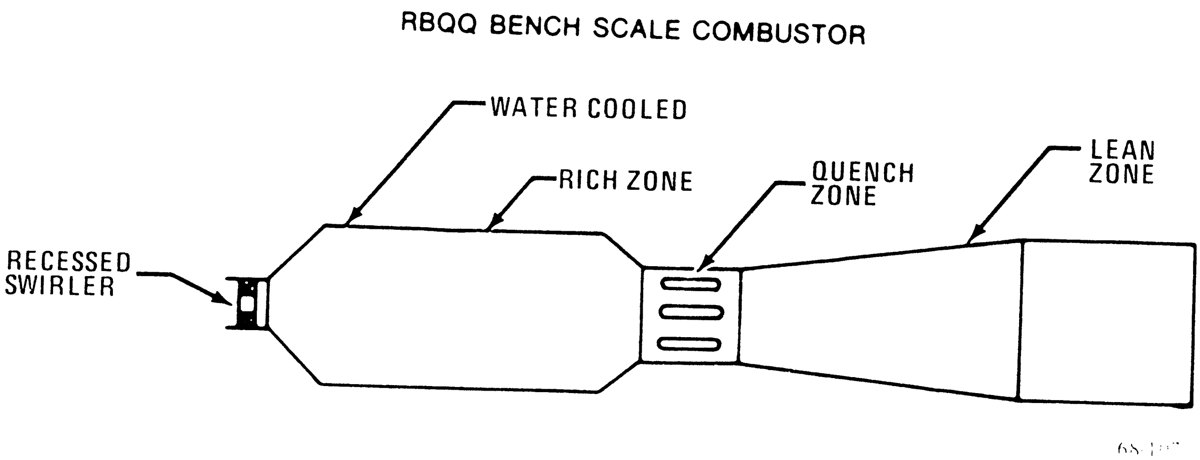


Figure 51. RBQQ Bench-Scale Combustor Geometry

Tests were conducted at several simulated operating points, including elevated pressures and temperatures. By controlling the amount of air that entered the rich zone, it was determined that low NO_x concentrations could be achieved over a wide range of overall fuel-air ratios. Carbon monoxide levels were high at overall fuel/air ratios below 0.021 and were minimal above this level.

B. DESIGN APPROACH

The NO_x reduction technology generated in the bench-scale tests was heavily relied upon to provide data for the full-scale designs. In addition, the information gathered on carbon monoxide and smoke production was used extensively in the design approach. It was felt that the combustor should reflect the requirements of conventional stationary gas turbine combustion systems and should be capable of being used in combined-cycle power plants. The design requirements for the combustor are presented in Table VII along with the applicable engine operating conditions.

TABLE VII. DESIGN REQUIREMENTS

Type Combustor: Can or Annular

Design Point Requirements:

	Base	Idle
Airflow	257 lb/sec (116.5 kg/s)	72 lb/sec (32.7 kg/s)
Inlet Temperature	735°F (390°C)	280°F (138°C)
Inlet Pressure	207.5 psia (1425 kPa)	43.0 psia (295 kPa)

Pressure Drop: 3.0%

Exhaust Emissions: (Max. corrected to 15% O_2)

	Distillate (ppmv)	1.0% Fuel N (ppmv)
NO_x	50	140
CO	75	75

Efficiency: 99.9% or greater

Smoke: SAE SN 20 or less

Pattern Factor: Less than 0.25

In the design of the basic features of the combustors, in the areas of rich zone stoichiometry, aerodynamics, liner cooling, and residence times, an attempt was made to reproduce the essential processes of the rich burning concept as defined parametrically from bench-scale testing.

C. DESIGN FEATURES

The basic features of the rich-burn/quick-quench designs are summarized and discussed below.

1. Arrangement

Three combustion zones are arranged in series, a fuel-rich primary zone, a fuel-lean secondary zone, and tertiary dilution zone. The tertiary zone was not utilized in bench-scale tests; however, bench-scale tests revealed that carbon monoxide levels could not be controlled below an overall fuel-air ratio of 0.021 without the use of a tertiary zone.

2. Emissions Features

Four requirements for low pollutant levels have been identified from bench-scale test results:

- Smoke levels were heavily dependent upon the proper mixing and combustion of fuel and air in the rich zone. Proper fuel atomization was very important in the clean combustion of all fuels, as shown in the results section of this report (Section I).

- Minimal carbon monoxide levels require keeping the lean zone fuel-air ratio above 0.021 downstream of the quench zone. The temperature in this region must not be allowed to become excessive as NO_x formation from lean combustion could become predominant. This implied the need to dilute the fuel-rich products of combustion in the rich zone to a fuel-air ratio slightly above 0.020. Consequently, it is desirable to introduce only part of the remaining airflow into the quench region, leaving the final quantity to be introduced in a tertiary zone to achieve the final mixture. For ideal operation of the combustor at low power settings, the quench airflow area will have to be varied to maintain efficient combustion.

- Fuel-bound nitrogen required longer residence times and rich zone stiochiometry control as was shown in the bench-scale results. The results showed that minimum NO_x occured at rich zone equivalence ratios near 1.55 and hot rich zone residence times of 35-45 milliseconds. Fuels containing no fuel-bound nitrogen displayed a levelling off of NO_x levels at rich zone stoichiometry levels above 1.55; however, smoke levels could become unacceptable at equivalence ratios exceeding this level.

- Quench air - Must be admitted in a manner which promotes vigorous mixing to insure a homogenous mixture for the complete combustion of the remaining carbon monoxide.

3. Emission Signature

The emission signature of the bench-scale configuration is shown in Figure 52. This signature was generated by keeping combustor airflow constant and varying only the fuel flow. This signature is for a residual fuel with fuel-bound nitrogen (0.3%), for fuels containing higher levels of fuel-bound nitrogen a minimum NO_x level is also obtained at a front-end equivalence ratio of approximately 1.55 and then the NO_x levels begin to rise again more rapidly.

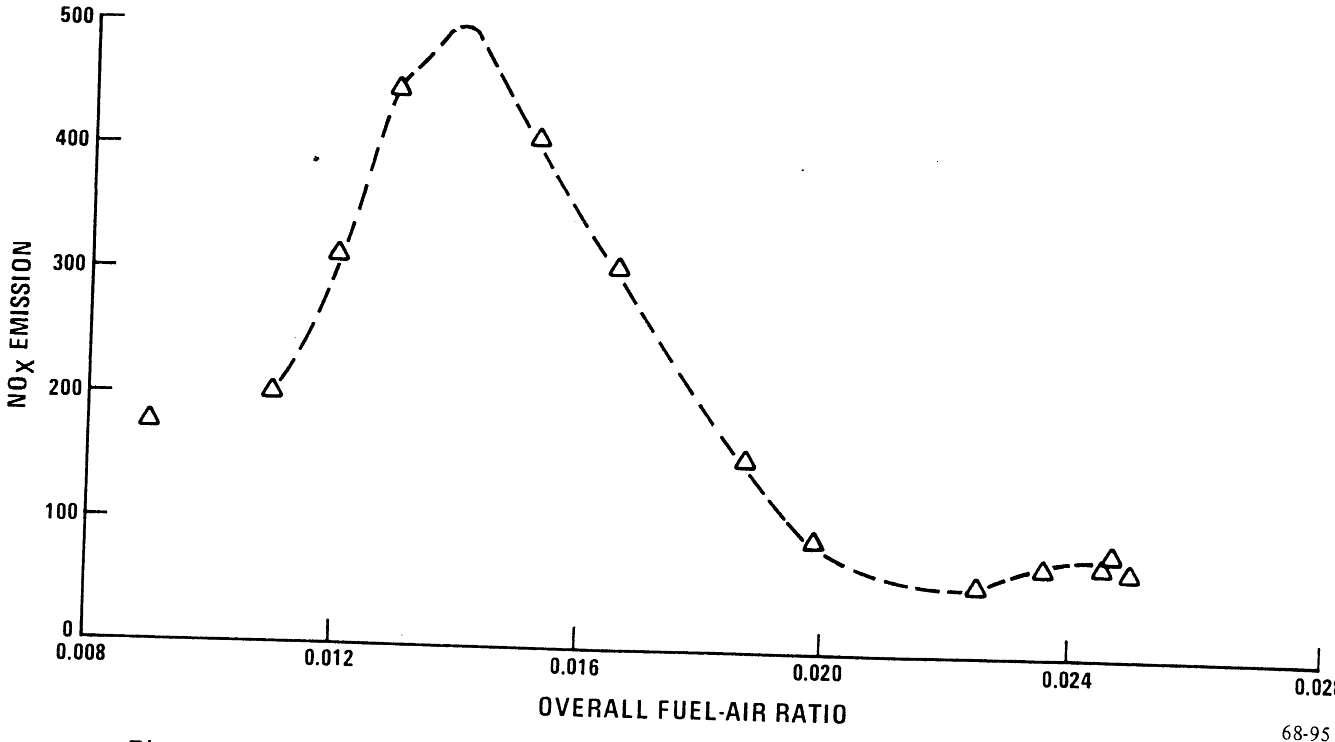


Figure 52. Emission Signature of Bench-Scale Baseline Configuration

4. Residence Time Requirements

Minimum NO_x levels were shown to decline with increasing primary zone residence time with fuels containing fuel-bound nitrogen. Hot residence times of approximately 40 milliseconds are required to keep NO_x levels in the 50 ppmv range for these fuels.

5. Variable Geometry

This technique failed in the bench-scale tests and is considered to be a high risk item for future development; however, if NO_x levels are to be kept at a minimum at all power conditions it would be necessary to use this configuration. Although not considered in this study, the use of an off-board combustor or silo burner with a direct-drive constant-speed gas turbine-generator would allow the flexibility of using multiple rich-lean combustor elements with on-off fuel staging to achieve turndown without variable geometry. Fuel to the individual elements would be turned on as power increases, with each element operating over only a discrete fuel-air range. Sufficient downstream combustor length must be provided to allow thermal mixing of burning and non-burning combustor element effluents to achieve a low overall pattern factor.

The designs submitted in this report do not have variable geometry and hence will not have low NO_x levels at all power conditions. However, they will have low pollutant levels at baseload and peak power settings. Idle power settings will also have low pollutant levels due to lean burning in the primary zone. Cycling of the combustor between idle and base power results in the rich zone varying in stoichiometry between lean and rich conditions. With good fuel preparation (atomization and mixing) and low smoke and low soot operation the problem of carbonaceous deposits building and removal during these cycles would not be expected since even under rich conditions, the environment is still an oxidizing one, as explained previously in the results for the carbon/carbon liner test (Configuration 5). The formation of carbonaceous deposits due to poor fuel preparation must be avoided since this could lead to cycling between carburizing and decarburizing conditions which would lead to liner corrosion and failure.

D. COMBUSTOR SIZING

1. Residence Time Considerations

The parameters which displayed the greatest effect on NO_x emissions were used to size the full-scale combustor. To achieve the low emissions displayed by the bench-scale hardware, it was necessary to reproduce the critical parameters and duplicate the same basic processes. The area ratio of the rich-zone/quench-zone of Configuration 1 displayed the lowest emissions, and it was felt that the area ratio would provide the best mixing and performance.

Initial rich-zone sizing calculations indicated that a can combustor configuration, which would fit into the FT4-scale combustor section, would not be capable of producing emission levels as low as 50 ppmv of NO_x when burning fuels containing fuel-bound nitrogen. However, a can combustor could be sized which could meet the EPA requirements of 140 ppmv of NO_x. This conclusion is based on the bench-scale data of Configurations 1, 2, and 13 in which the rich-zone length was varied as shown in Figure 53. The results obtained were shown previously in Figure 43 in terms of tradeoffs between rich zone hot residence time and NO_x concentrations corrected to 15% oxygen.

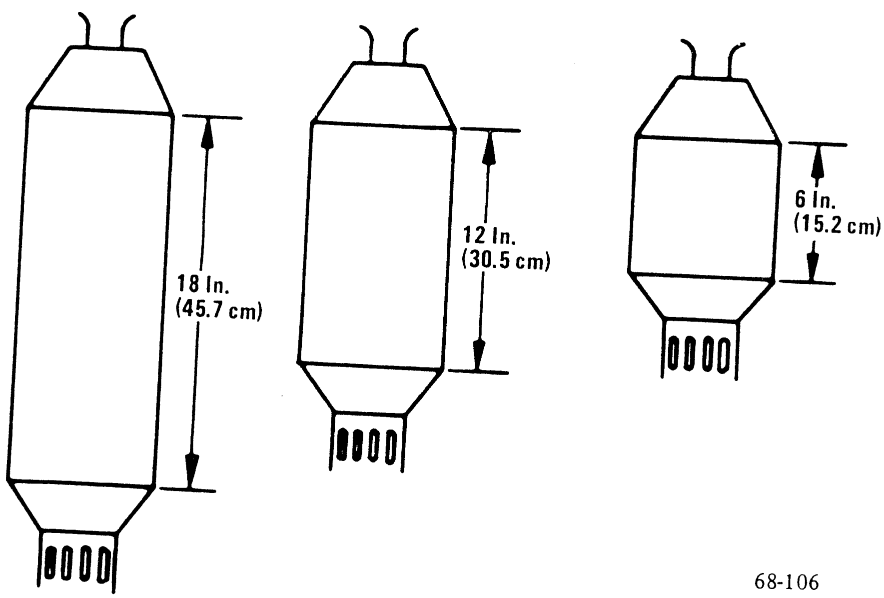


Figure 53. Bench-Scale Combustor - Various Rich-Zone Lengths Tested

2. Stablity and Efficiency Considerations

The correlation of Odgens and Carrier were used for designing for stable and efficient combustion (ref. 1). Figure 54 shows the correlation for combustion stability and the design point for the full-scale can combustor. Based upon this correlation, the full-scale combustor will have very stable combustion over a wide range of fuel-air ratios. Figure 55 shows the correlation for combustor recirculation zone efficiency and the design point for the full-scale can combustor. This correlation only applies to the recirculation zone of the burner and does not apply to overall burner efficiency. Figure 56 shows the correlation for overall combustion efficiency of rich zones and the associated design point for the full-scale can combustor. Also shown in the figures is the range of values tested with bench-scale hardware.

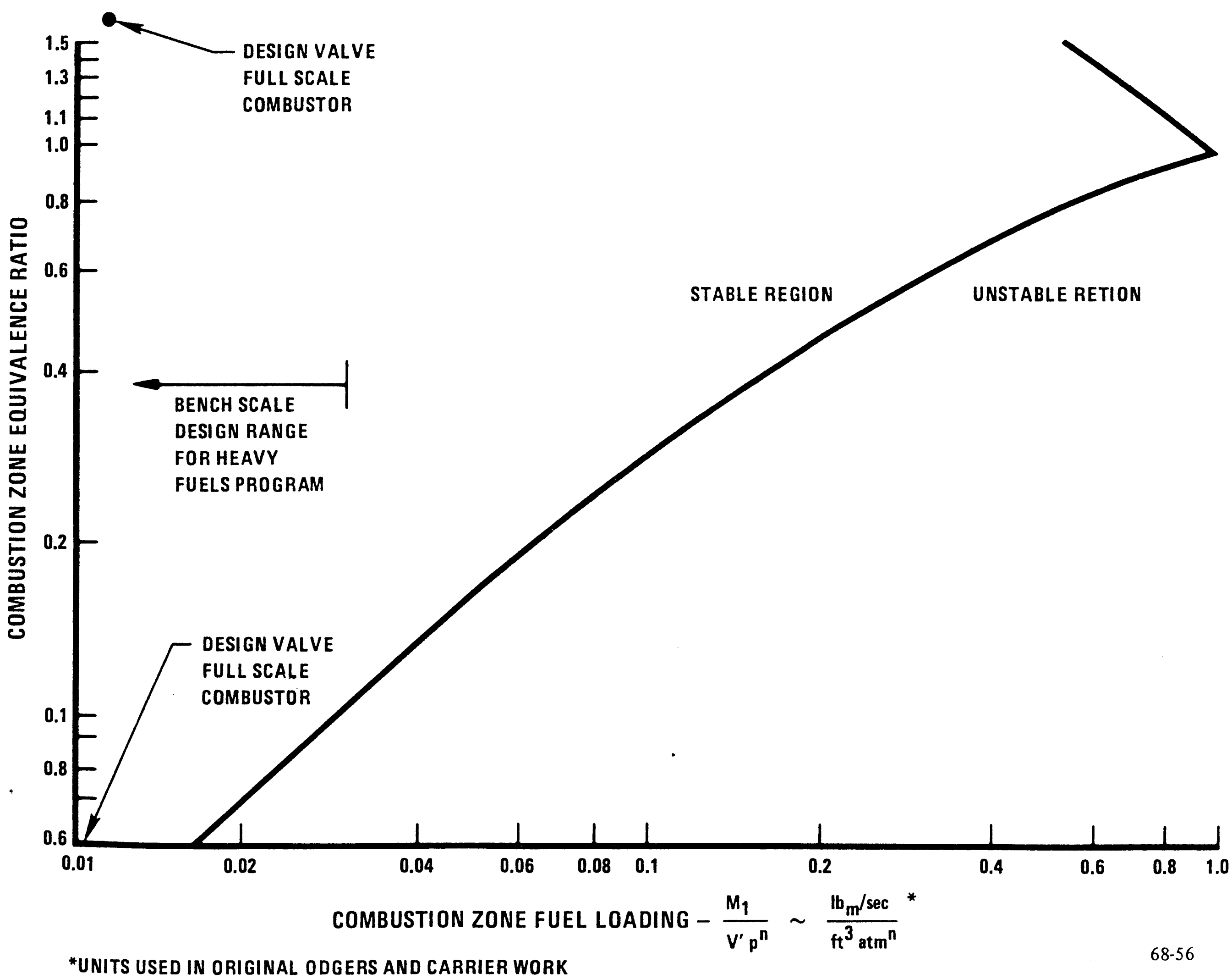


Figure 54. Combustion Stability Correlation

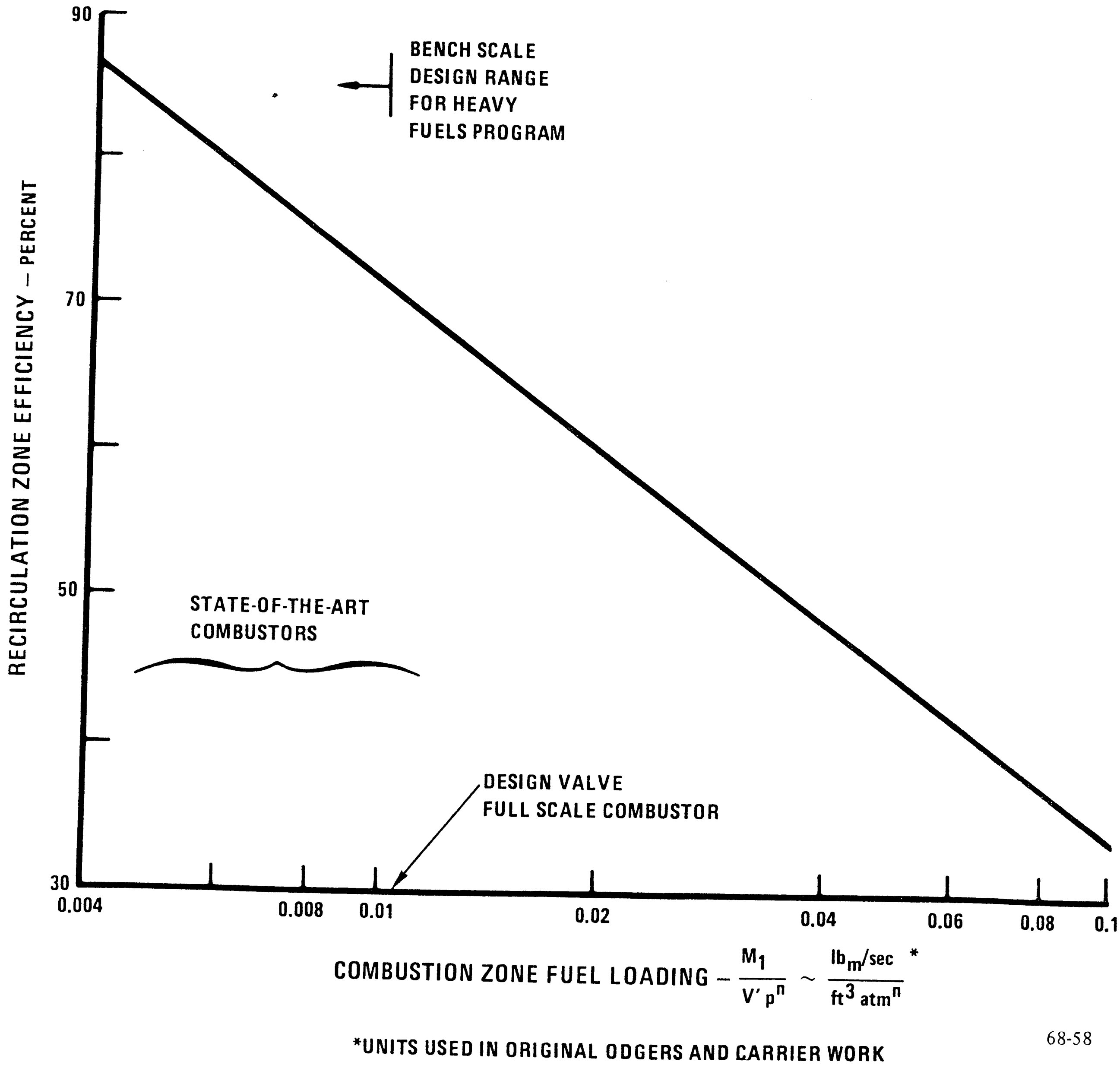
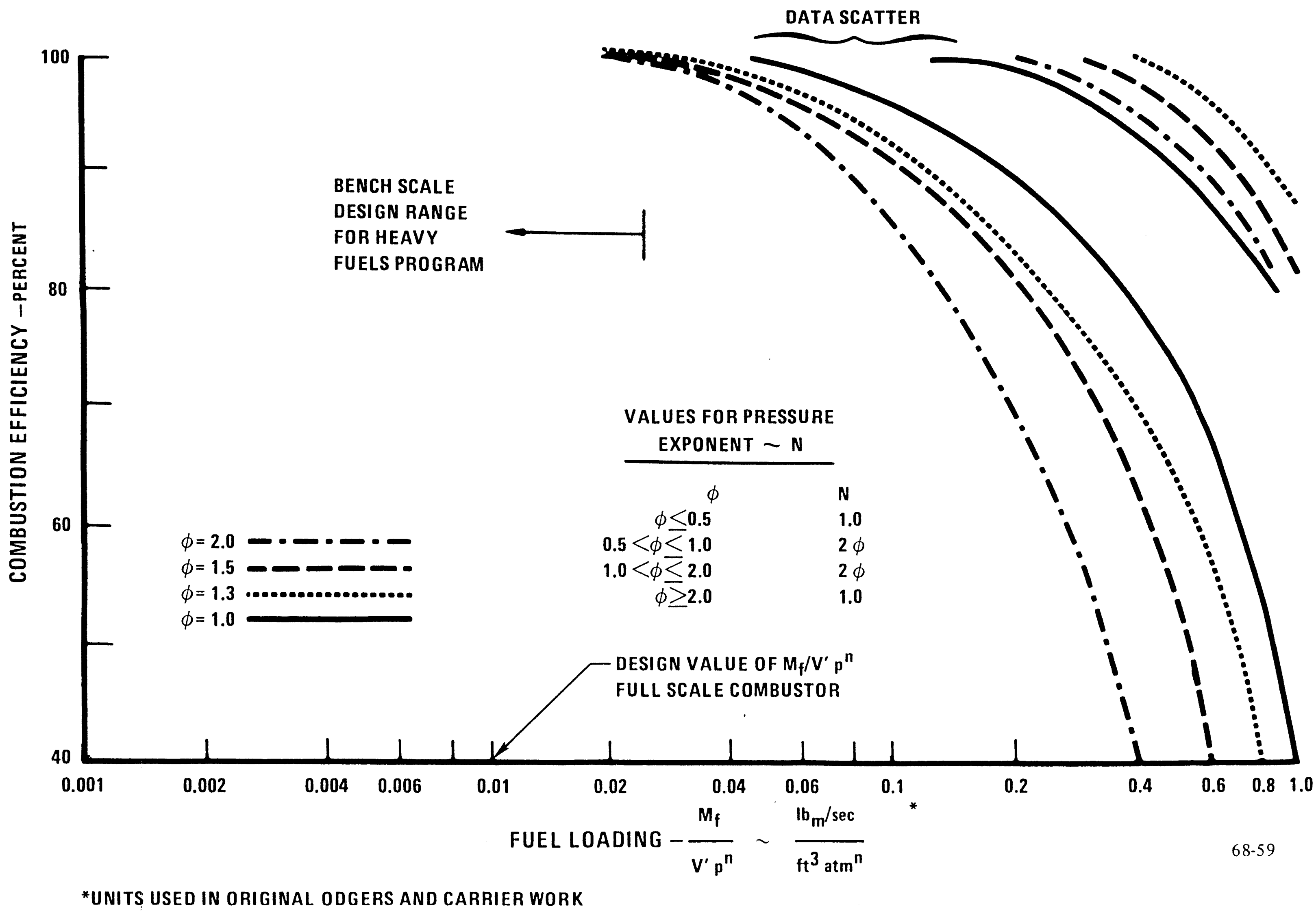


Figure 55. Rich Combustor Recirculation Zone Efficiency Correlation



*UNITS USED IN ORIGINAL ODGERS AND CARRIER WORK

Figure 56. Overall Combustion Efficiency Correlation

3. Combustor Aerodynamics, Emission Predictions, and Fuel Vaporization Model

This model was used to predict combustor flow fields and emission characteristics performance of the full-scale combustor. The model employs a modular approach to the prediction of combustor emissions. Submodels are used for the internal flowfield, physical combustion, hydrocarbon thermochemistry, and NO_x kinetics. The parabolic region of the internal flowfield for both can and annular combustors are modeled with several streamtubes, which exchange mass and energy via a turbulent eddy viscosity model. The recirculation zone is modeled as an embedded well-stirred reactor. Stabilization of this primary combustion region is through either flow or bluff body flameholding.

The physical combustion model incorporates a fuel droplet vaporization model and a droplet burning model. It is assumed that fuel droplets are uniformally distributed within a streamtube, that interaction between burning droplets is negligible, and that fuel droplets within a given streamtube are adequately described by a single value of Sauter Mean Diameter (SMD). The droplet burning model approximates the combustion of fuel vapor immediately following vaporization from injected fuel droplets in the early stages of combustion in the primary zone. The hydrocarbon thermochemistry model is a quasi-global model which provides for partial equilibrium products of combustion. The rate constants for these quasi-global reactions are obtained by fitting these reactions to the results of the full kinetics, perfectly stirred reactor, solution over a range of initial temperatures, pressures and fuel-air ratios. This system provides for the rate-controlled conversion of raw fuel-air mixture to partial equilibrium products both directly and through an unburned hydrocarbon intermediate. Subsequent conversion to full equilibrium products is controlled by a single reaction. The combustion temperature species concentrations are determined by interpolation between the partial and full equilibrium states. The model for the formation of the oxides of nitrogen is basically the Zeldovich mechanism, modified by the addition of the reaction between the species N and OH (ref. 2). The model is capable of handling fuel-bound nitrogen according to the Fenimore mechanism (ref. 3).

Figure 57 illustrates the results of the model predictions for the full-scale can combustor. The predictions are slightly lower than bench-scale results would indicate for fuels containing fuel-bound nitrogen, and slightly higher for fuels with no fuel-bound nitrogen. This is due to the fact that the kinetic reactions are not completely understood and would require analysis beyond the scope of this program. For this reason, the results of the bench-scale test results were heavily relied upon for the design of the full-scale combustors.

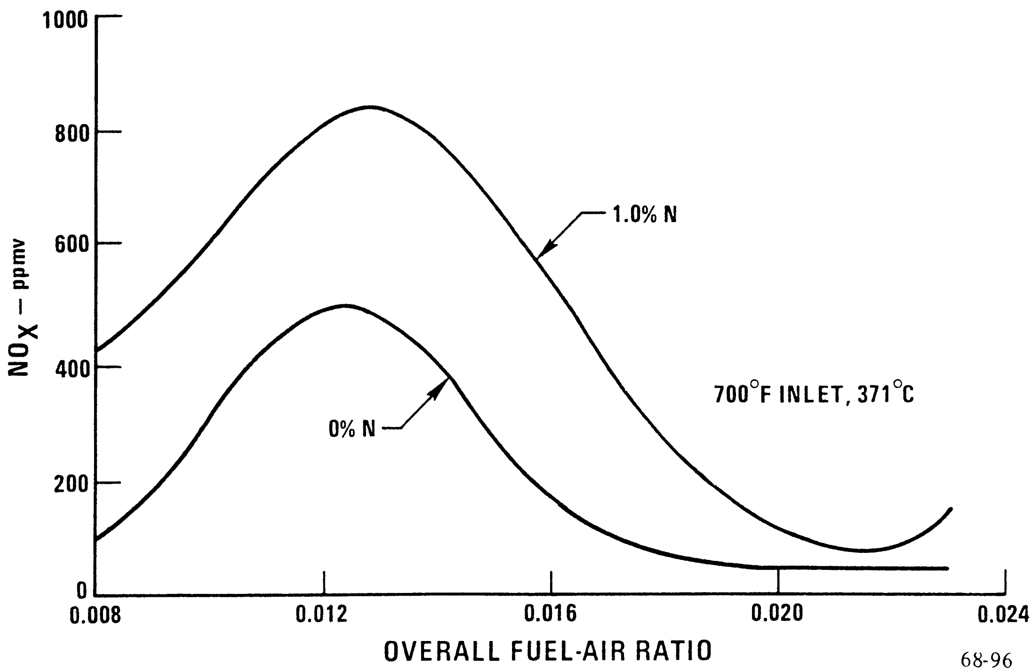


Figure 57. Predicted NO_x for the Full-Scale Can Combustor Design

The aerodynamics of the RBQQ combustor differ from the conventional combustor. It must be designed for an operating point where the primary zone is fuel-rich and the equivalence ratio must be controlled. The airflow distribution is determined by several factors, including the relative areas of each section, the pressure/velocity distribution of the approach airflow, and the internal geometry of the combustor.

The RBQQ full-scale combustor must have a necked down quench region where locally high velocities are present to produce vigorous mixing. Significant mixing losses are present in this section and these losses were accounted for in determining the required airflow splits. These mixing losses are desirable to provide a homogeneous mixture to combust the remaining carbon monoxide from the rich zone.

Figure 58 displays the predicted pressure drops throughout the RBQQ combustor. Note that high pressure drops are expected across the quench section.

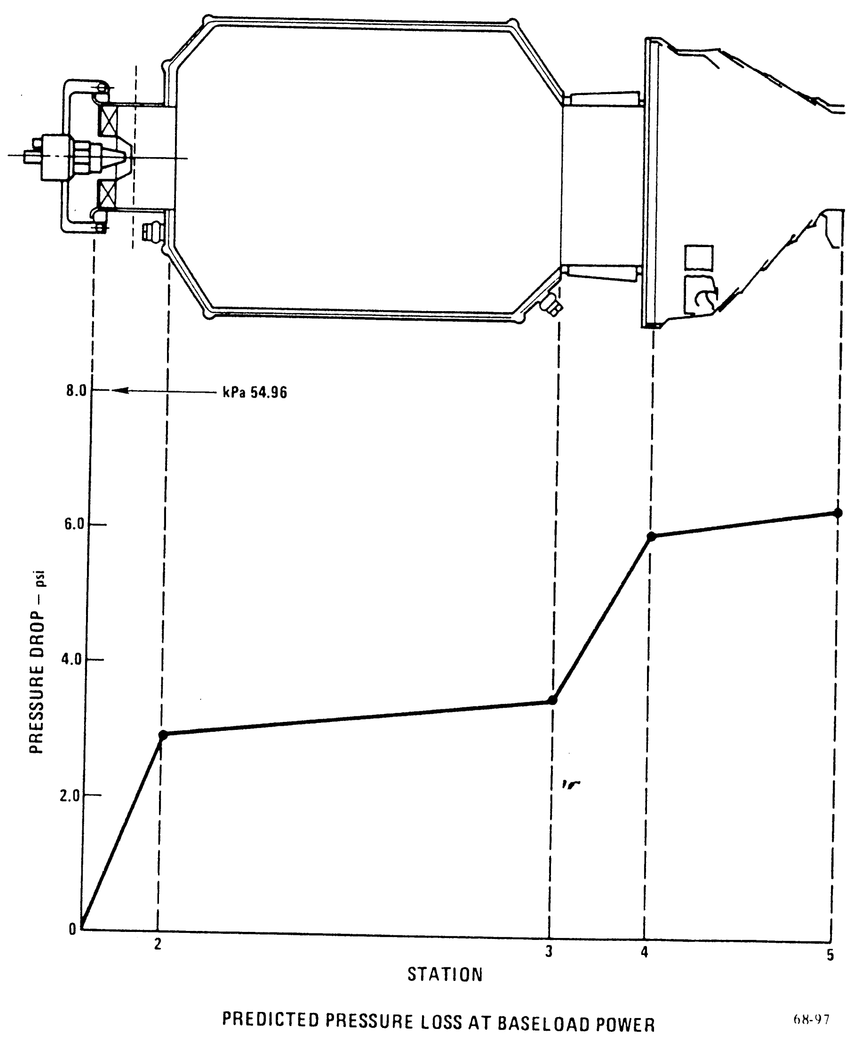


Figure 58. Predicted Pressure Loss at Baseload Power

4. Rich Zone Geometry

Because of the problems encountered in early bench-scale tests with the premix tube arrangement, the carburetor tube with recessed swirler was chosen for the front-end of the combustor. This type of arrangement has shown consistent ability to provide high performance and low pollutant levels throughout the bench-scale testing effort. The premix tube, the preburner, and the graduated air addition concepts displayed either poor performance or durability problems. Figure 59 displays these concepts.

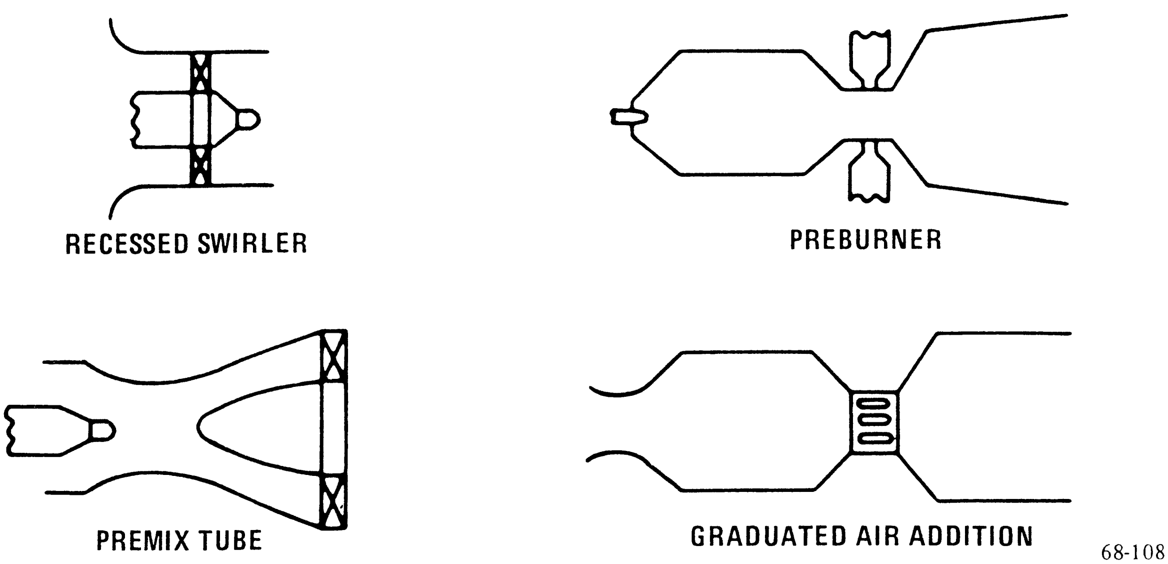


Figure 59. Various Front-End Configurations Tested

Consideration was also given to fuel nozzle selection which fits into the swirler in the combustor front end. Two fuel nozzle types were tested, an air boost which requires external compressed air and an air blast which utilizes combustor inlet air to atomize the fuel (Configurations 13 and 14, respectively). NO_x data from these two tests was shown previously in Figures 38 and 41. Smoke data indicated that the air-blast fuel nozzle was slightly better on residual fuel. However, these fuel nozzles may operate differently when scaled-up to full engine conditions, thus, it was felt both types should be tested at full-scale conditions. The recessed swirler can be easily replaced during testing and the air-blast swirler/fuel nozzle combination installed. All concepts presented in this report show the air-boost fuel nozzle installed to simplify the discussion.

Considerations of combustion efficiency (which essentially is the attempt to control carbon monoxide emissions at the exhaust) led to the conclusion that a tertiary combustion dilution zone was required. As shown previously in Figure 8, carbon monoxide emissions can be kept to a minimum if the quench zone fuel/air ratio can be kept above 0.020 so that sufficient temperature is available for the oxidation process. Unburned hydrocarbon emissions were not a problem during bench-scale tests and are not expected to affect burner efficiency in the full-scale combustor.

5. Rich Zone Cooling Design

After consideration of the sizing and basic features of the full-scale combustor, subsequent design work was directed toward cooling the rich zone wall. Bench-scale testing indicated that the wall temperature had little or no effect on NO_x emissions, and in a combined-cycle power plant steam is readily available for cooling the rich zone wall.

Analytical efforts were undertaken to design a steam cooled combustor liner compatible with the FT4 engine cycle. To meet this requirement, the heat load to the rich zone wall was calculated assuming the most severe condition (stoichiometric flame temperature) at the peak engine operating pressure and inlet temperature. The rich zone heat release rate was calculated to be 5.4×10^6 Btu/h-ft^3 atm (55.9×10^6 W/m^3 atm). Results indicate that a steam flow of 1.84 lb/s (0.83 Kg/s) at a pressure of 150 psia (1030 kPa) is sufficient to cool the metal to 1500°F (815°C), with a steam exit (superheat) temperature of 800°F (426°C).

6. Rich Zone Area Requirements

The bench-scale results have shown that minimum NO_x levels occur when the primary zone equivalence ratio is approximately 1.55. This corresponds to approximately 20% of total burner airflow in the rich-zone combined with total burner fuel flow, indicating that the effective area of the recessed swirler must be in the range of 20% of total burner effective area.

7. Quench Zone Area Requirements

The quench zone area had to be such as to limit the quench exit fuel-air ratio to an allowable range. As stated previously, a fuel-air ratio of 0.020 or greater is necessary to insure limiting the carbon monoxide emissions from the products of rich combustion. When sizing these slots, the reduced static pressure in the throat of the quench section, due to the accelerating fluid stream from the rich zone was taken into account.

8. Tertiary Zone Area Requirements

The remaining effective area of the combustor was utilized in the tertiary zone for cooling and dilution.

E. FUEL PREPARATION

During the course of testing the bench-scale hardware, fuel preparation was found to play an extremely important role in both NO_x emissions and smoke characteristics. As was shown previously, boost air played a very important role in smoke levels when the air-boost fuel nozzle is utilized. If the air and fuel entering the rich zone have not been sufficiently mixed, local pockets of stoichiometric burning are possible with resultant high NO_x levels combined with very rich pockets and high smoke levels.

It has been shown that the recessed swirler design provides a near homogeneous, well-atomized mixture into the rich zone. Limited testing with the airblast design also displayed excellent results. Both of these concepts are recommended for further evaluation in full-scale combustors.

Fuel atomization has been shown to play an important part in combustor performance. Figure 60 shows a correlation for the effect of boost air on droplet size. During the course of bench-scale testing, increasing boost air displays a significant reduction in smoke levels as shown in Figure 16.

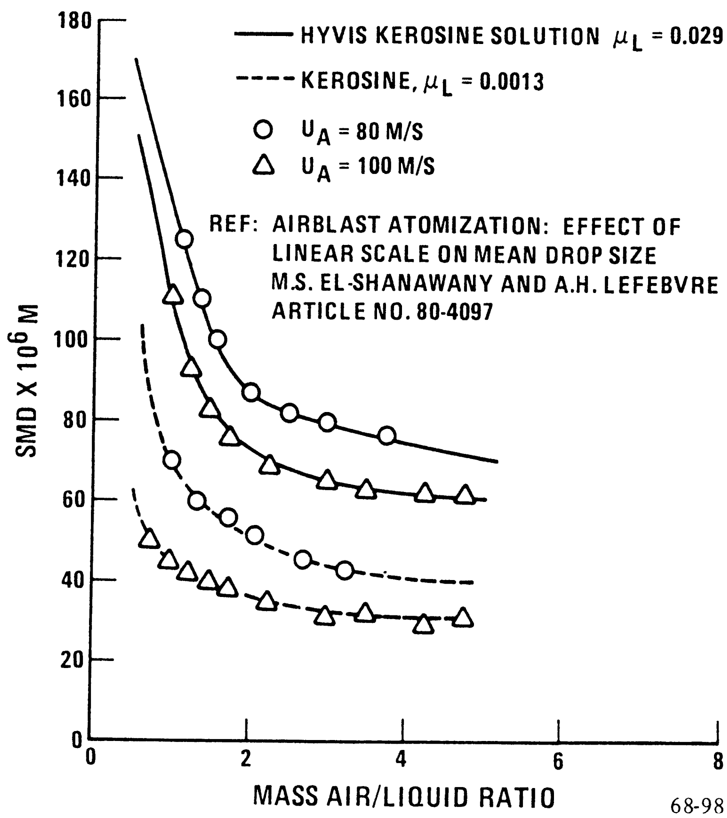


Figure 60. Correlation Effect of Boost Air on Droplet Size

F. COMBUSTOR DESIGN FINAL PARAMETERS

The above review and analysis led to the first full-scale combustor design which has the following basic features:

- A centrally mounted carburetor tube with recessed swirler having a scaled-up area schedule similar to that used in the bench-scale tests.

- A primary zone length was provided which will meet the minimum EPA NO_x regulations. This length was based on bench-scale rich zone residence time results.

- A rich-zone cooling scheme was provided which will supply long life to the combustor. Analysis indicates that a steam cooled wall will properly cool the combustor rich zone wall. Water cooling was also considered, since it was used in the bench scale tests.

- A quick-quench section with an area ratio of 2.77 to 1 was provided, matching the value from Configuration 1 in the bench-scale tests.

- A lean-burn section was provided to allow for the oxidation of CO to CO_2. The design fuel/air ratio at base load in the lean burn section is 0.021 to allow for minimal CO emissions.

- The tertiary zone was adapted from the present engine transition duct and is air-cooled.

The burner configuration, shown in Figure 61, consists of a double-wall primary liner made of cylindrical/conical pieces. These pieces are separated by a string of weld wires to guide the steam coolant flow. This concept was successfully tested with bench-scale hardware using water as the coolant, no structural damage or erosion of the inner wall was noted throughout the bench-scale tests. Both convective and radiative heat transfer processes were included in the analysis. Predictions indicate that the proper flowrate within the convective cooling passage will easily cool the walls to acceptable levels.

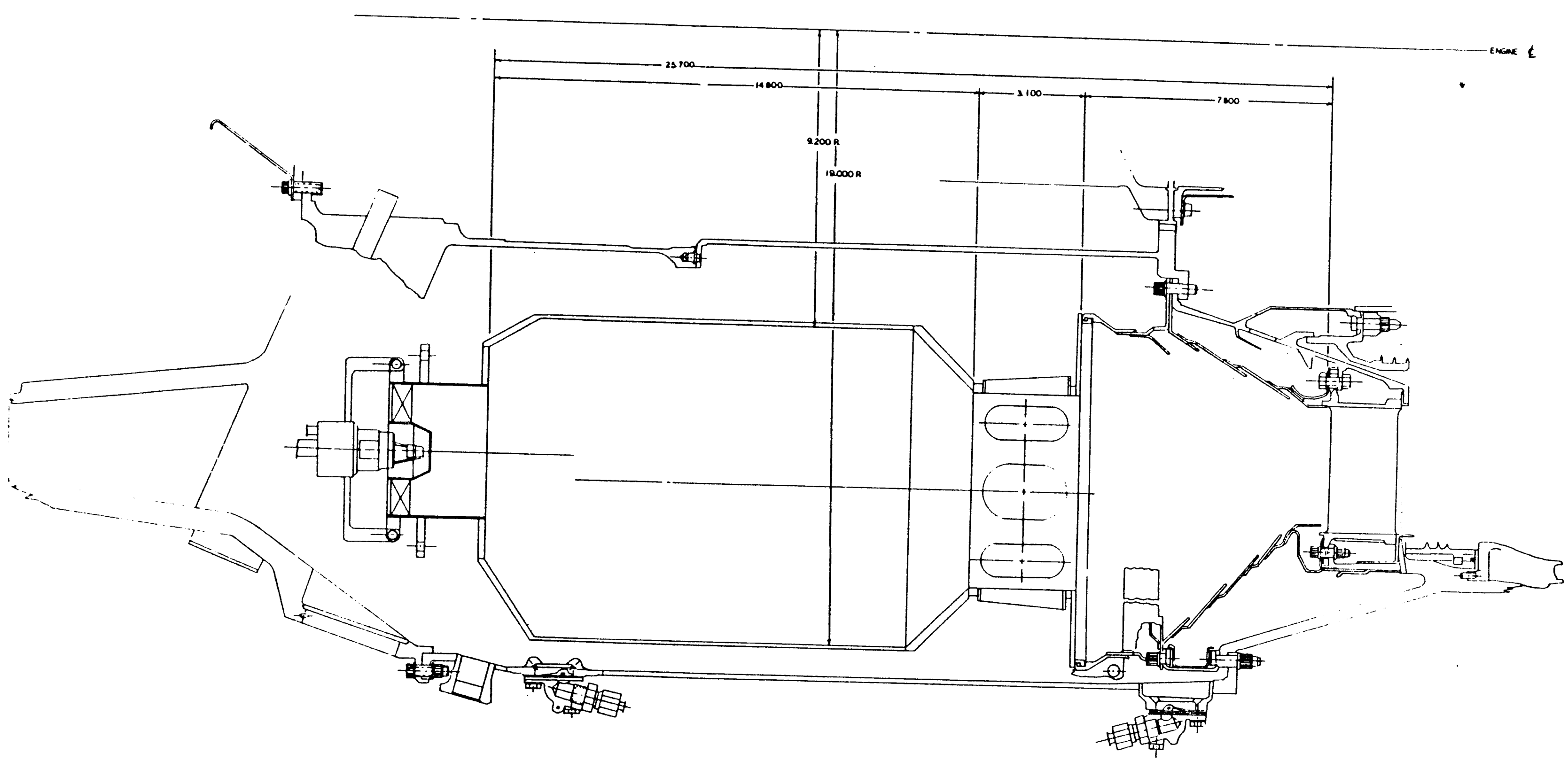


Figure 61. Full Scale Can Annular Combustor Design

The following is a breakdown of combustor operating parameters for the single can burner.

Single Can Burner at Base Condition

Fuel Nozzle	Airblast with Airboost Alternative
Liner Material	Hastalloy X
Burner Airflow	32.1 lb/s (14.56 Kg/s)
Inlet Pressure	207.5 psia (1426 kPa)
Inlet Temperature	735°F (390°C)
Front End Swirler Effective Area	5.74 in^2 (37.03 cm)
Quench Slot Area	19.90 in^2 (128.4 cm^2)
Tertiary Zone Area	7.25 in^2 (46.8 cm^2)
Burner Pressure Loss	3.0%
Rich Zone Wall Temperature	1500°F (816°C)
Lean Zone Wall Temperature	1500°F (816°C)
Heat Release Rate (Rich-Zone)	5.4×10^6 Btu/hr-ft^3-atm $\left(55.9 \times 10^6 \frac{W}{m^3\ ATM}\right)$
Coolant Flow (Stream)	1.84 lb/s (0.83 kg/s)

The following shows the individual zone stoichiometries at the indicated power setting:

Power Setting	Fuel Flow (pph, kg/h)	Air Flow (pph, kg/h)	Rich-Zone Fuel-Air/ϕ	Lean Zone Fuel-Air/ϕ	Tertiary Zone Fuel-Air/ϕ
Idle	2020, 916	72, 32.7	0.045/0.65	0.010/0.14	0.008/0.12
5MW	5860, 2658	148, 67.1	0.063/0.91	0.014/0.20	0.011/0.16
15MW	11260, 5106	207, 93.9	0.087/1.25	0.019/0.28	0.015/0.22
Base	17276, 7835	257, 116.5	0.107/1.55	0.024/0.35	0.019/0.27
Peak	18429, 8350	263, 119.3	0.112/1.61	0.025/0.36	0.0195/0.28

G. ALTERNATIVE FULL-SCALE COMBUSTOR DESIGN

An alternative full-scale combustor was designed which will meet the minimal 50 ppmv levels of NO_x production. The configuration is a full annular burner. The major difference between this combustor and the can combustor is in rich zone hot residence time. This design will require more development effort than the single-can engine burner; however, fuels containing high concentrations of fuel-bound nitrogen can be burned with low pollutant levels in this combustor. The design includes provisions for the use of steam coolant.

The full annular combustor design is shown in Figure 62 with Figure 63 showing a fronted view of the swirler arrangement. This burner will require considerably more development work than the can combustor arrangement shown previously; however, it will provide lower emissions levels. The following is a breakdown of combustor operating parameters for the full annular burner:

Full Annular Burner at Base Condition

Fuel Nozzle	Airblast with Airboost Alternative
Liner Material	Hastalloy X
Burner Airflow	257 lb/s (116.5 kg/s)
Inlet Pressure	207.5 psia (1425 kPa)
Inlet Temperature	735°F (390°C)
Front End Swirler Effective Area	45.92 in^2 (296 cm^2)
Quench Slot Area	159.2 in^2 (1027 cm^2)
Tertiary Zone Area	58 in^2 (374 cm^2)
Burner Pressure Loss	3.0%
Rich Zone Wall Temperature	1500°F (815°C)
Lean Zone Wall Temperature	1500°F (815°C)
Heat Release Rate (Rich-Zone)	3.31×10^6 Btu/h-ft^3-atm $\left(34.3 \frac{W}{m^2 ATM}\right)$
Coolant Flow (Steam)	14.72 lb/s (6.47 kg/s)

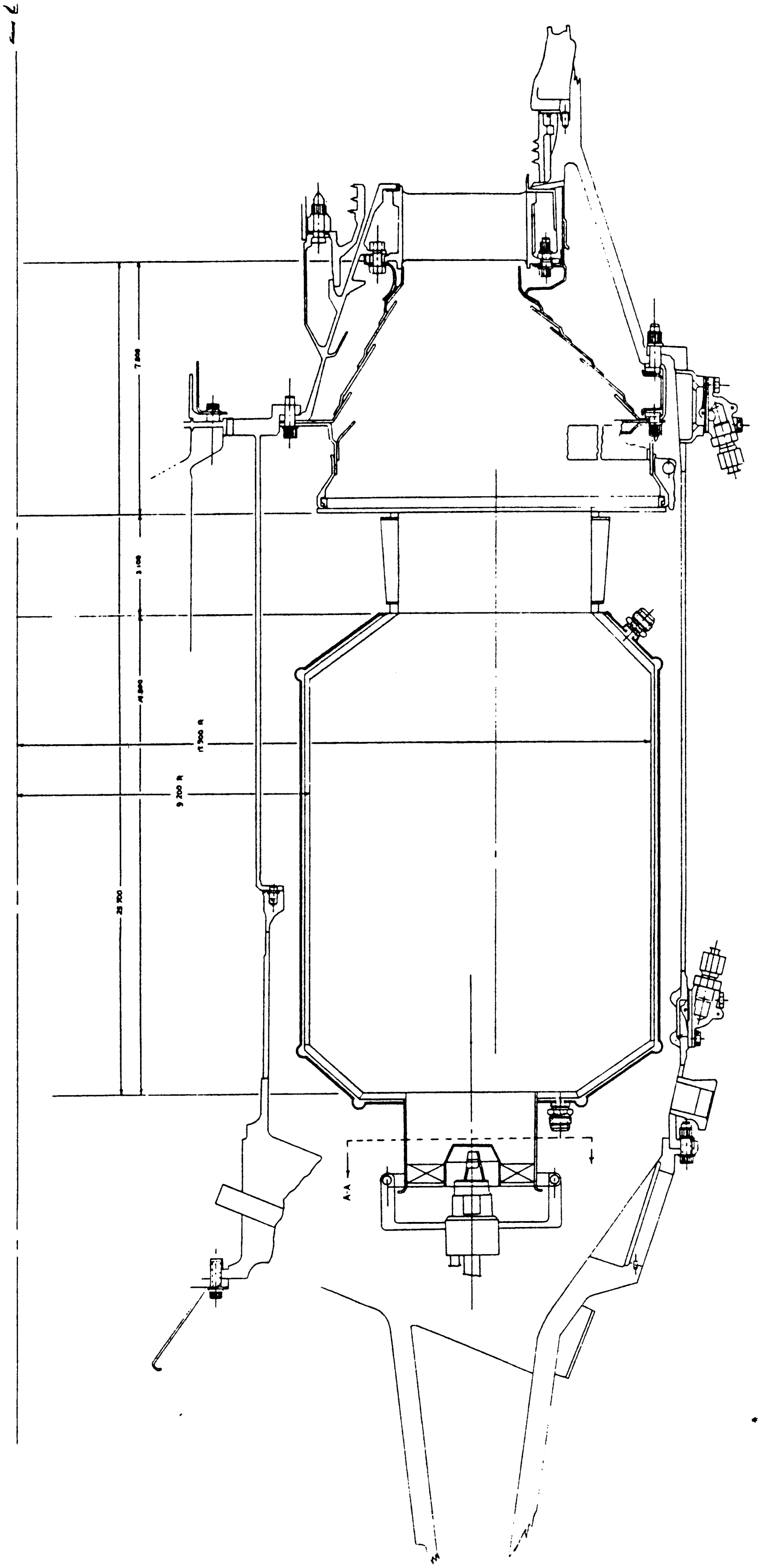


Figure 62. Full Scale Full-Annular Combustor Design

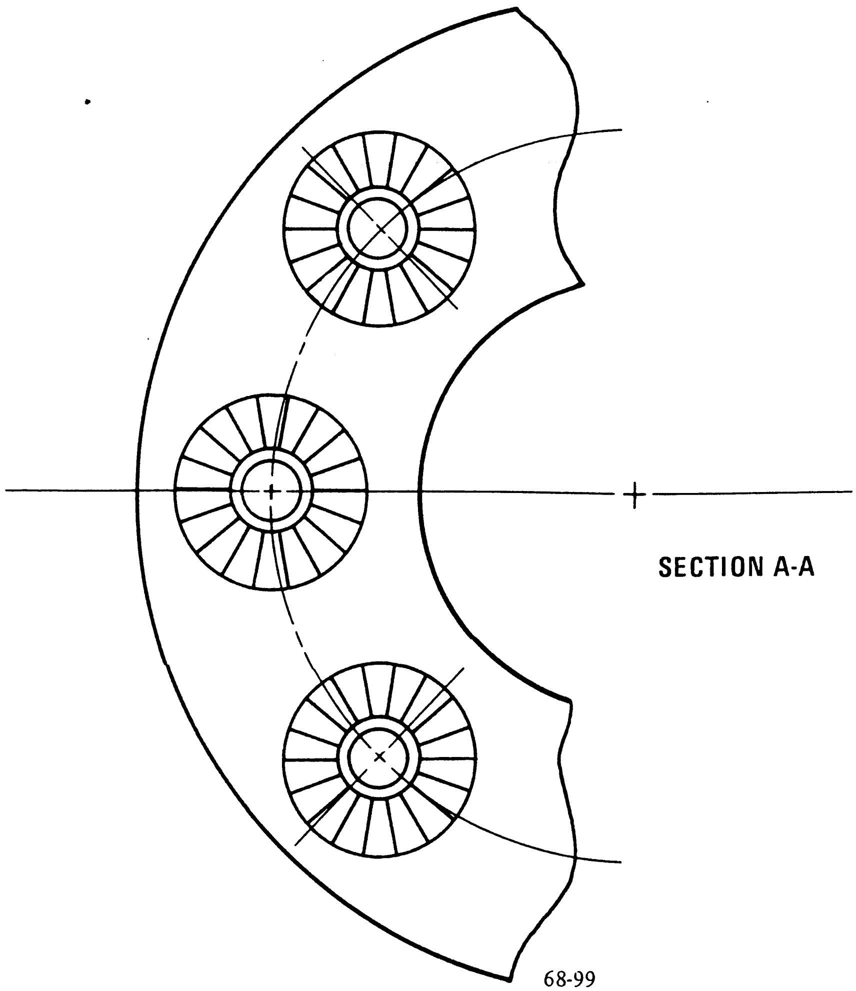


Figure 63. Front View of Annular Combustor

Although the annular burner design requires more engine disassembly to change combustors than the can design, when compared to present day air cooled burners, engine disassembly would not be required as often due to the long life expectancy of the liner.

The individual zone stoichiometries at different power settings is the same as the can burner design shown previously.

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

This report describes results of a systematic evaluation of bench-scale hardware concepts intended to provide technology for environmentally clean combustion of minimally processed fuels, as well as synthetic fuels. Pratt & Whitney Aircraft/ Government Products Division (P&WA/GPD) experience and results of computer studies were drawn upon to select the concepts evaluated in this program. Twelve concepts were initially designed and included many variations of basic strategies such as rich/lean combustion, preburning, premixing, and rich product recirculation. An assessment of the pollutant levels of individual concepts was made using a combined computer model including combustor aerodynamics, emission predictions, and fuel droplet vaporization. The design approach considered cost, time, and the interchangeability of parts within the same rig test duct.

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