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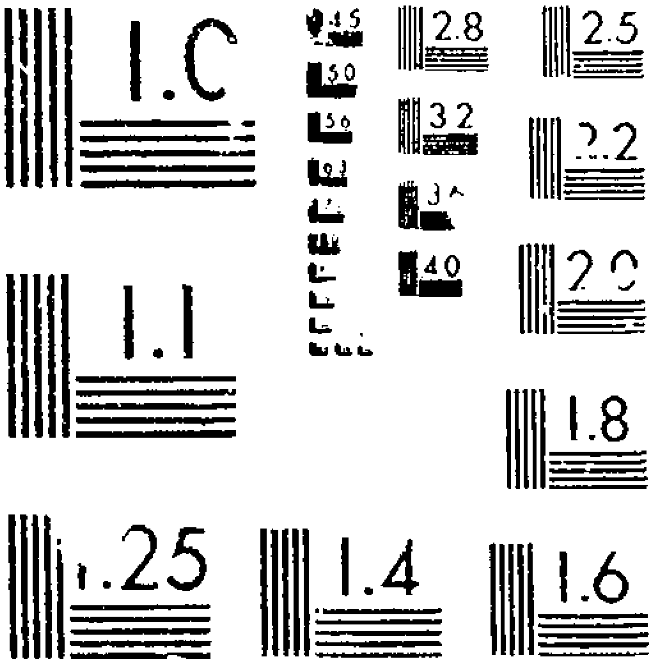

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Low NO_x Heavy Fuel Combustor Concept Program Phase IA — Combustion Technology Generation Coal Gas Fuels

Final Report

Westinghouse Electric Corporation
Combustion Turbine Systems Division

February 1982

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Under Contract DEN 3-146

for
U.S. DEPARTMENT OF ENERGY
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DOE/NASA DE-AI01-77ET13111

FOREWORD

Funding for this program was provided by the United States Department of Energy. The Program Manager is Warren Bunker, DOE Heat Energy and Heat Recovery Division, Office of Coal Utilization. Technical program management is provided by the Lewis Research Center of NASA. J. Notardonato is the Technical Program Manager

The work was performed by Westinghouse Electric Corporation under direction of the Combustion Turbine Systems Division. K. L. Rieke and T. P. Sherlock are the Program Managers. The test work was performed at the Synthetic Fuels Division under the direction of J. Schwab.

This report includes the combined efforts of the following Westinghouse Electric Personnel:

T. P. Sherlock	Combustion Turbine Systems Division
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CONTENTS

Illustrations

Tables

SUMMARY

This paper describes the results of combustion tests of two scaled burners using actual coal gas from a 25 ton/day fluidized bed coal gasifier. The two combustor configurations studied were a ceramic-lined, staged rich/lean burner and an integral, all metal multi-annular swirl burner (MASB). The tests were conducted over a range of temperatures and pressures representative of current industrial combustion turbine inlet conditions. Tests on the rich lean burner were conducted at three levels of product gas heating values: 104, 197 and 254 Btu/Scf. Corresponding levels of NO_x emissions were 5, 20 and 70 ppmv. Nitrogen was added to the fuel in the form of ammonia, and conversion efficiencies of fuel nitrogen to NO_x were found to be on the order of 4 to 12 percent, which is somewhat lower than the 14 to 18 percent conversion efficiency when SRC-II liquid fuel was used. The MASB was tested only on medium Btu gas (220 to 270 Btu/Scf), and produced approximately 80 ppmv NO_x at rated engine conditions. It is concluded that both burners operated similarly on actual coal gas and ERBS fuel, and that all heating values tested can be successfully burned in current machines.

Section 1
INTRODUCTION

Under contract DEN 3-146, Westinghouse is participating in Phase I and Phase IA of the DOE/NASA Low NO_x Heavy Fuel Combustor Concept Program. The Phase I program dealt with low emissions-producing burners using petroleum and coal-derived liquid fuels; and the final report has been issued.[1] The Phase IA program deals with combustor concept development for low emissions using low and medium Btu coal gas. This report summarizes the findings of the Phase IA effort.

The Phase IA addendum requires that two combustor concepts developed in the original program be modified to burn low (80 to 180 Btu/SCF) and medium (180 to 350 BTU/SCF) Btu gas. The proximity of the Westinghouse Test Development Center and the Westinghouse/Department of Energy 25 ton/day fluidized bed coal gasifier provided an opportunity to test on actual coal gas. Permission was given to use the gasifier in conjunction with the combustion tests by DOE (D.C. Cicero, Project Manager).

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[1] "Low NO_x Heavy Fuel Combustor Concept Program Phase I," Final Report, Westinghouse Electric Corporation, October 1981, NASA Report CR 165482.

Section 2

PROGRAM OBJECTIVES

The objectives of this program are as follows:

- Modify two combustor concepts from the initial program to burn low and medium Btu coal gas. One of the configurations will be a staged rich/lean combustor. The modifications to the combustors will be minimal and restricted to such items as fuel injectors, air distribution systems, fuel systems and instrumentation.
- Provide actual (preferred) and/or simulated coal derived gaseous fuels. These fuels should have compositions representative of existing coal derived fuels with the constitutents shown in Table 2-1.
- Provide for the addition of ammonia (NH_3) to the selected test fuels.
- Test the two selected configurations using gases of different heating values. The tests will be conducted at conditions representative of rated engine peak power and pressure as well as reduced operating conditions.
- Conduct design analysis studies of the data generated during the test program, which will provide input to engine-combustor applications of the derived technology. Comparisons of combustor concept performance on liquid versus gaseous fuels will be made.
- Issue a Final Report and a separate Comprehensive Data Report covering all work and analysis performed under this contract.

Table 2-1

TYPICAL COAL-DERIVED GAS PROPERTIES

	Low Btu Gas (80-180 Btu/SCF)	Medium Btu Gas (180-350 Btu/SCF)
SPECIFIED	RANGE - %	RANGE - %
H_2	11-17	26-41
CO	9-30	35-53
CH_4	0-4	0-7
CO_2	3-11	6-22
H_2O	0-33	0-27
N_2	31-64	0-1
NH_3	0-1	0-1

Section 3
COMBUSTOR DESIGNS

In the Phase I Final Report, four candidate configurations that met EPA emissions requirements for liquid petroleum (ERBS) fuels were identified. Two of these were selected for further development in the Phase IA program:

- A modular, staged rich/lean, ceramic-lined combustor with a rapid venturi quench section. This will be referred to as the rich/lean (R/L) burner.
- An integral, all metallic, rich/lean combustor, referred to as the Multi-Annular Swirl Burner (MASB).

These configurations were described in detail in the Phase I final report, and only a brief description will be given here. Modifications required to burn low and medium Btu gas will also be discussed.

3.1 MODULAR RICH/LEAN BURNER

The staged rich/lean burner tested in Phase I is a modular design as shown in Figure 3-1. The rich burn module is based on the Westinghouse B-4 combustor. It uses an air-assist fuel nozzle, convective cooling for the ceramic-lined walls, and a radial jet-induced recirculation zone. The quench module is based on jet mixing at the throat of a reduced cross-sectional area. The lean burn module is an open, ceramic-lined tube.

In Phase I tests with ERBS fuel, this configuration produced approximately 70 ppmv NO_x corrected to 15 percent O_2. In tests with SRC-II middle distillate, containing 0.8 weight percent nitrogen, this configuration produced an additional incremental 70 ppmv of NO_x, which corresponds to approximately 17 percent fuel bound nitrogen conversion to NO_x.

The modifications required for this burner to burn low and medium Btu coal gas were minimal. The basic configuration remained unchanged; only the air-assist nozzle was replaced with a medium Btu coal gas nozzle that was designed for this program and is shown in Figure 3-2. The nozzle assembly was retrofitted without modifying the test assembly.

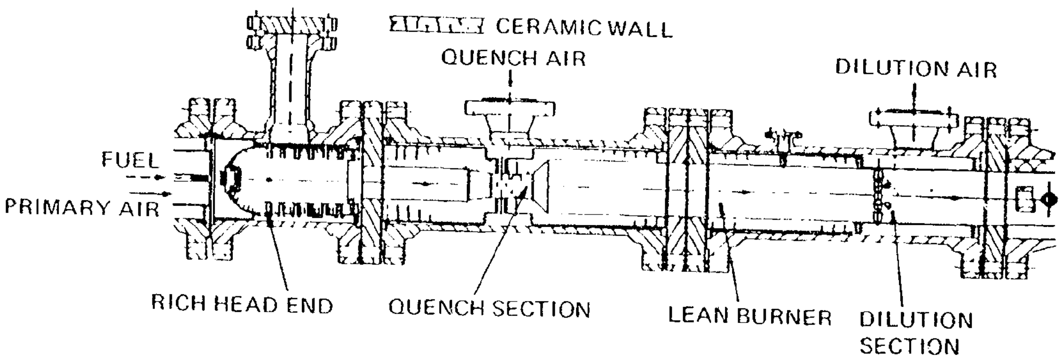

Figure 3-1. Modular, Staged Rich/Lean Burner

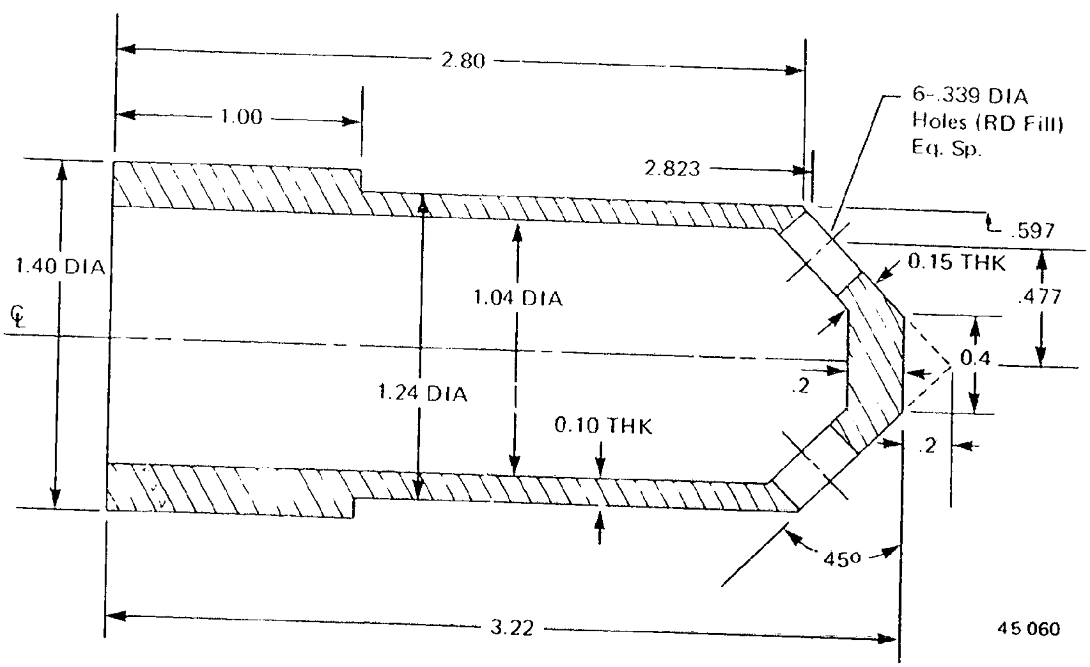

Figure 3-2. 90° Enclosed Injection Angle Nozzle for B-4 Combustor with Coal Gas

3.2 MULTI-ANNULAR SWIRL BURNER (MASB)

The MASB used during Phase I is shown in Figure 3-3. It is an all-metal, integral burner consisting of a system of axially displaced concentric rings. The desired tangential velocity is produced and controlled by rows of vanes in the individual annuli, which are created by pairs of radially adjacent rings. Rich burn, quench, lean burn and dilution can thus be implemented by controlling the axial and radial spacing of the rings. The Phase I MASB had provisions for injecting liquid fuel in a central nozzle and/or radial nozzles (Figure 3-3). That configuration produced 80 to 90 ppmv NO_x on ERBS fuel, and 160 to 170 ppmv NO_y on SRC-II, which represents a conversion efficiency of FBN in the SRC-II fuel of approximately 20 percent.

The MASB was modified to accept low and medium Btu coal gas as shown in Figure 3-4. Experience with liquid fuel in Phase I indicated that the central nozzle alone reduced NO_x emissions. The additional separate fuel supply to the second row of vanes in the Phase 1A burner was justified because the large relative volume of low Btu gas necessary for full rated power may have been too great for the central nozzle to handle alone.

Although no physical change was made for the gas test in the dilution section downstream of the MASB, it should be mentioned that the dilution section was used somewhat differently from the liquid fuel tests. This difference was in the amount of dilution air. In order to protect the downstream sections, as well as sampling probes and instrumentation from 1300 to 1425°C temperatures, the dilution air flow was held at a level where the exhaust gases were on the order of 800°C. The NO_x and the gas temperature upstream of the dilution section (in the actual exhaust of the MASB) was calculated from the test data obtained in the diluted low temperature gas stream. As NO_x formation is negligible at temperatures below 1540°C, dilution air was introduced under conditions where no chemical change was expected.

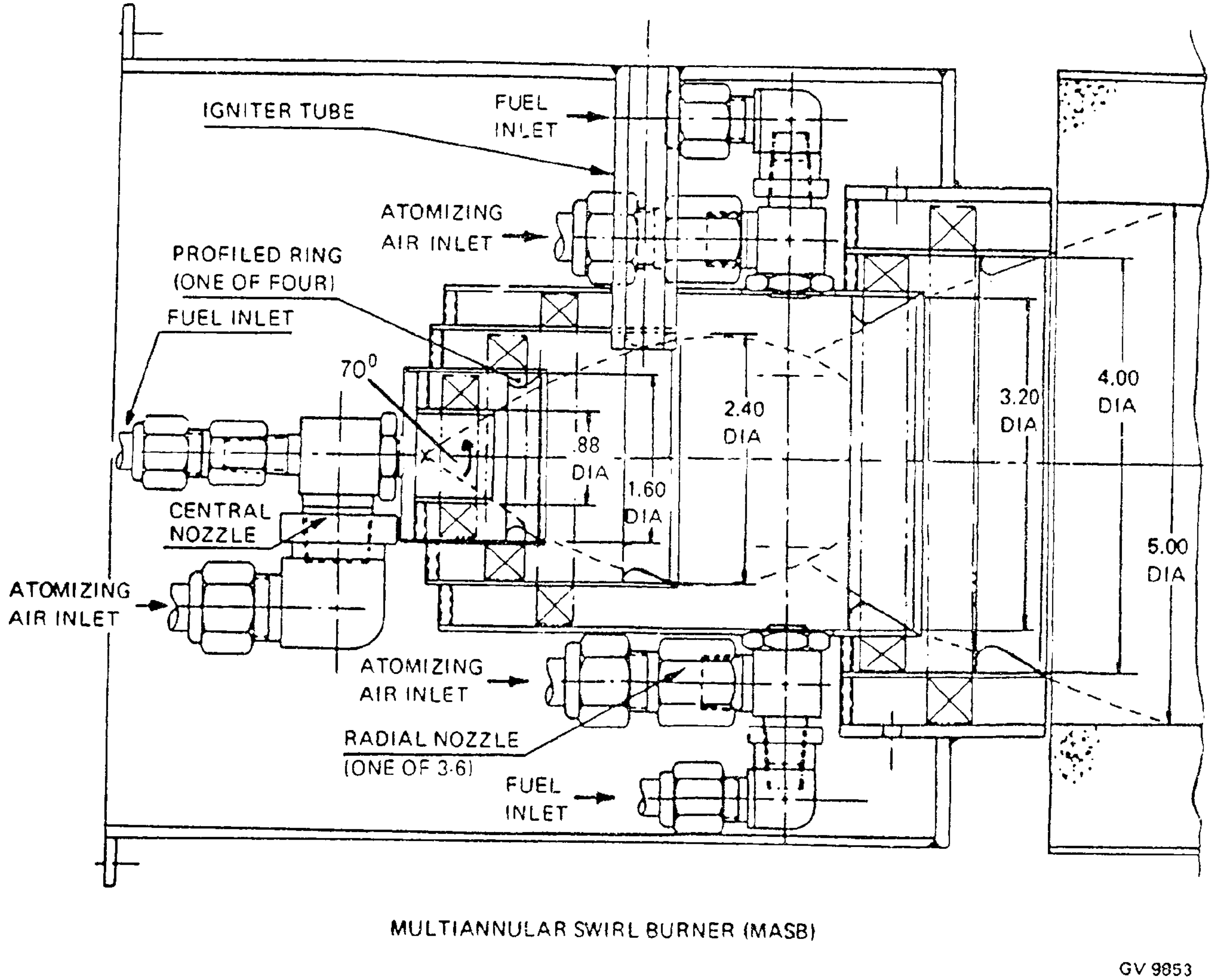

Figure 3-3. Phase I Multiannular Swirl Burner (MASB) for Liquid Fuels

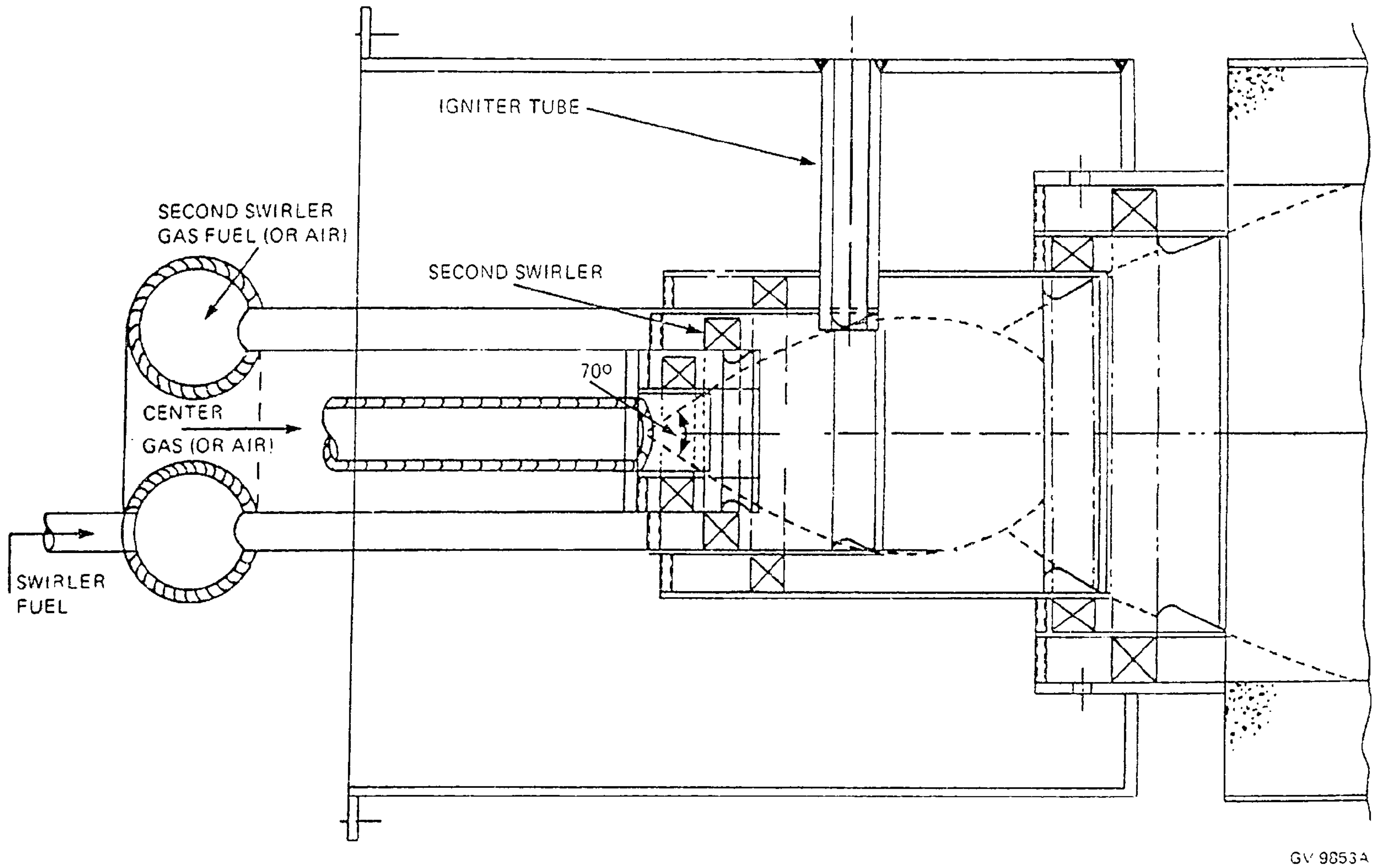

Figure 3-4. Modified Phase IA Multi-Annular Swirl Burner (MASB) for Coal Gas Fuels

Section 4
TEST FACILITY

The test facilities used for this program were the same as those used in Phase I. A detailed description is given in that final report and a brief review follows:

4.1 TEST PASSAGE

The passage for these tests, shown in Figure 4-1, is a modular structure of 8-inch stainless steel pipe designed for 2 MPA operation at 540°C. Separate sections are removable if any module needs to be changed to create a new configuration.

4.2 FUEL SYSTEM

Coal gas delivery conditions from the DOE coal gasification Process Development Unit (PDU) to the combustion laboratory are as follows:

- Pressure - Gas is available at a pressure slightly lower than the PDU operation range of 0.5 MPA to 1.5 MPA (80 to 225 psig).
- Flow - Product gas flows of 725 to 900 Kg/hr (1600 to 2000 lb/hr) are available for combustion testing.
- Temperature - Gas is cooled to a nominal 50°C in the system of aqueous venturi scrubbers located at the PDU site. Further cooling of the gas occurs in the piping from the gasifier to the test facility.

4.3 INSTRUMENTATION

Instrumentation is provided to monitor rig inputs and to determine rig section and overall performance. Flow rate, temperature and pressure are

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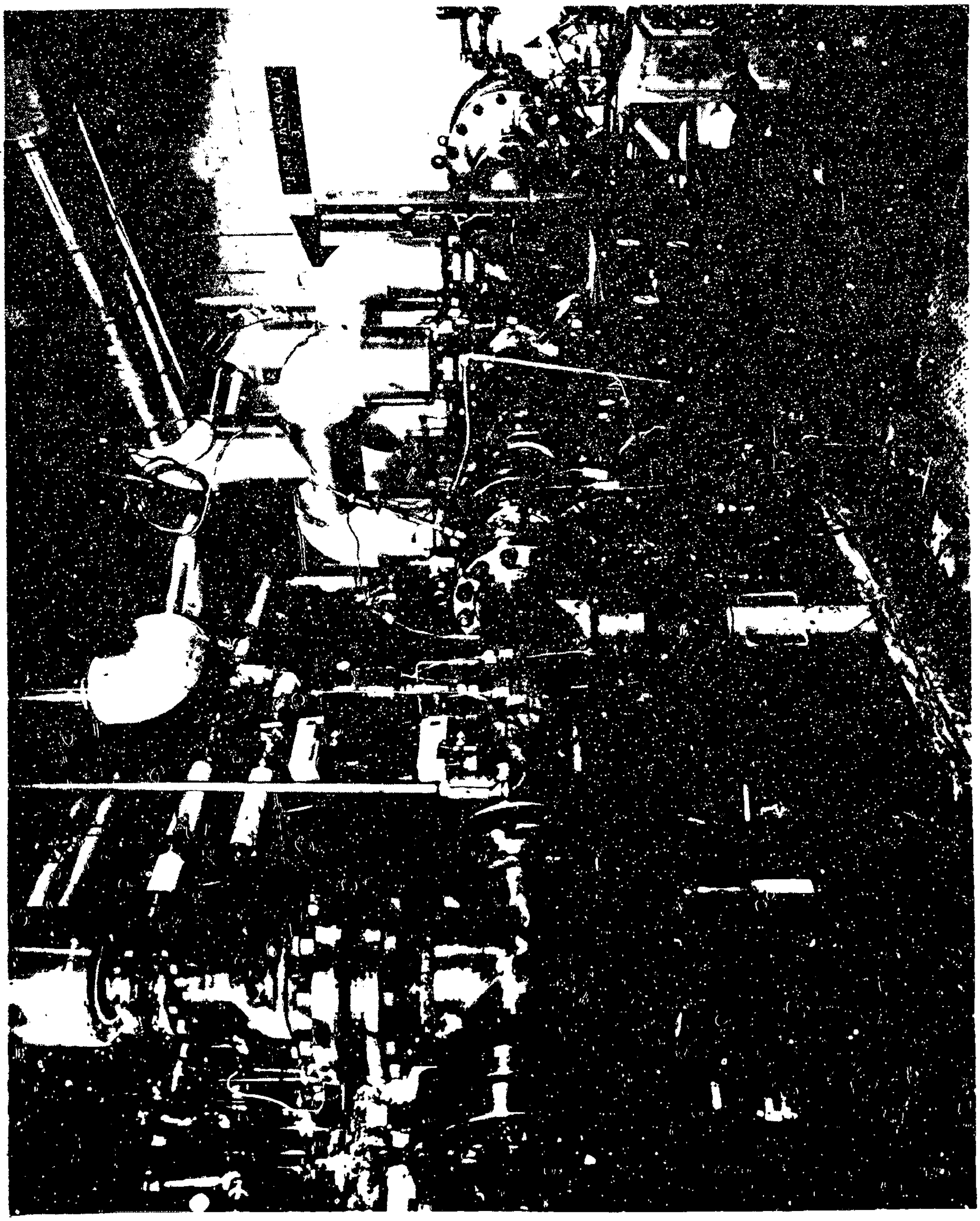

Figure 4-1. High Pressure Combustor Test Passage

measured for fuels, primary air, secondary air, and cooling air. Coal gas fuel pressure drop is measured across the fuel nozzles. Inlet air humidity is also determined at the compressor exit.

Test rig performance is determined by measurements taken at instrumentation stations. Each station consists of a water-cooled, 127 mm (5-inch) unit housed in a 203 mm (8-inch) flange. There are multiple penetrations for a static pressure tap, thermocouples that measure temperature, and water-cooled sampling probes that collect products of combustion for emissions analysis. There are flanged instrumentation stations at the rich burner outlet, the quench module outlet, and the lean burner outlet so that each module can be evaluated. Monitoring the combustor duct metal surface and ceramic internal temperatures reduces the possibility of burnout and indicates both radial and axial temperature profiles. Surface-mounted thermocouples measure metal surface temperature.

All of these conditions are continuously monitored. Selected variables are recorded on strip chart recorders and trend recorders. All data is fed to the data acquisition system.

4.4 DATA ACQUISITION SYSTEM

A PDP 11/34 computer system supports data acquisition. This system includes 128K words of MOS memory, 7.5 million bytes of mass storage (disk) capacity, magnetic tape drive, video CRT, a hard copy terminal, a line printer and an interface to process instrumentation through A/D converters with mutliplexers and digital sensor inputs.

Raw data is collected at regular intervals, analyzed for high/low limits to generate appropriate alarms, and reduced on line to generate various flows, temperature averages and fuel/air ratios. The CRT display and printer continuously monitor the system during a test. Raw data and reduced data, including all process constants needed for data reduction, are stored on magnetic tape for permanent off-line data retrieval and further data reduction.

Section 5
GASIFIER OPERATION

The Westinghouse/DOE Process Demonstration Unit (PDU) schematic is shown in Figure 5-1. Components shown are for the single-stage, medium Btu (oxygen blown) gasification process utilized during combustion tests. A brief description of gasifier/combustion system operation follows.

Pulverized, dried coal is pneumatically fed into the gasifier through lockhoppers and rotary feeders. Recycled product gas is used to transport the feed coal, as well as recycled char fines, from two downstream cyclone separators. Untreated coal is injected into the gasifier along its centerline.

Combustion occurs when oxygen, fed through a central feed tube, combines with the coal. Steam, fed with oxygen in other parts of the gasifier, reacts with coal and char to form hydrogen and carbon monoxide. As the bed of char recirculates, carbon in the char is consumed by combustion and gasification, leaving particles rich in ash. The ash particles contain mineral compounds that melt between 820 K (1000°F) and 1370 K (2000°F). The liquid in the char extrudes through pores to the surface and sticks to other liquid droplets on adjacent char particles. The ash agglomerates that form are larger and more dense than the char and coal in the bed. These agglomerates settle from the fluidized bed and are continuously removed by a rotary feeder to lockhoppers. Recycled product gas partially fluidizes and cools the ash as it is withdrawn.

Raw product gas containing methane, hydrogen, carbon monoxide, carbon dioxide and gaseous impurities exits the reactor at approximately 1260 K (1800°F). Refractory-lined cyclones remove char particles for reinjection into the gasifier. The gas is then quenched and cooled in a water scrubber to remove remaining particulate matter. The scrubber also removes all but a few ppm of the ammonia and cyanide compounds contained in the product gas. Sulfur compounds in the product gas are not removed by the scrubber. Part of the product gas flow enters a carbon steel pipeline to the TDC combustion rig. Operating conditions for typical gasifier setpoints are summarized in Table 5-1. Coal feedstock for all setpoints was Wyoming C.

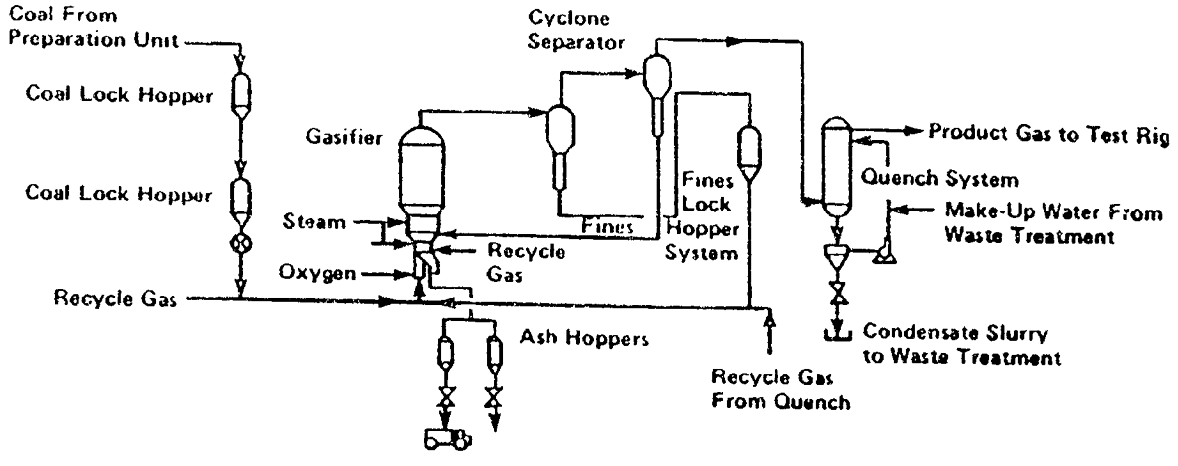

Figure 5-1. Process Development Unit (PDU) Schematic)

Table 5-1

PDU OPERATING SUMMARY

Operating Parameters

Mode	Air Blown	Enriched Air	O_2 Blown
Coal Feed Rate, lb/hr (Kg/hr)	1710 (776)	1916 (869)	2184 (991)
Oxygen/Coal Ratio (MAF)*	3.1**	---	0.83
Steam/Coal Ratio (MAF)*	0.11	0.27	0.24
Recycle Gas/Coal Ratio (MAF)*	1.80	1.43	1.35
System Pressure, psig (kPa)	216 (1590)	216 (1590)	216 (1590)
Freeboard Temperature, °F (°K)	1527 (1104)	1560 (1122)	1581 (1134)
Gas Composition	Table 6-1	Table 6-3	Table 6-5
Gasmake/Coal Ratio, scf/lb (m^3 @ STP/Kg)	63.8 (4.0)	38.9 (2.5)	38.9 (2.5)
Net Gas Rate, lb/hr (Kg/hr)	5059 (2295)	2922 (1325)	3060 (1388)
Ash Rate, lb/hr (Kg/hr)	53 (24)	49 (22)	74 (34)

* MAF - Based on Moisture and Ash Free Coal

** Air/Coal Ratio

Section 6
COMBUSTION TEST RESULTS

6.1 MODULAR RICH/LEAN BURNER TEST RESULTS

The modular rich/lean combustor was tested in conjunction with a scheduled PDU test run using Wyoming Sub-C coal. Additional steady state PDU conditions were used in the gasifier operation to accommodate the requirements of this program.

The product gas composition from a gasifier operating at steady state has more variance in the concentration of individual species than is expected from gas provided by a typical commercial synthetic coal gas installation. For the R/L tests, this variance was not severe enough to warrant data adjustments. The data analysis for the R/L tests is, in general, a parametric study of results collected over a relatively short time span. For example, the effect of pressure was ascertained from results obtained over a period of several hours, and the effect of velocity was ascertained over a different time span. Slight inconsistencies between the two studies can be attributed to different test periods; however, a check of carbon and oxygen balances throughout testing rarely showed more than a five percent difference.

The emission results are reported corrected to a 15% O_2 basis. The corresponding emissions values calculated on a pounds per million Btu basis are plotted on some of the figures for comparison. Differences in emission levels using the two methods are not significant.

6.1.1 R/L AIR BLOWN GASIFIER RESULTS

The product gas of the PDU when operated in an air blown mode had a heating value of 104 Btu/SCF, which is the lowest value tested in this program. The composition of the fuel is given in Table 6-1, and symbols used in plotting are given in Table 6-2.

With the low heating value fuel, no special precautions were taken to prevent overtemperature of the walls as the maximum adiabatic flame temperature was below 1535°C (2800°F) for the operating conditions. The size of the fuel nozzle limited the maximum input for this fuel to a lower equivalence ratio than was measured for the other fuels.

The evaluation of the ammonia injection results was complicated by the formation of a precipitate of ammonium bicarbonate, which occurs when ammonia is added to a cold mixture of CO and H_2O, as shown below.

$$NH_3 + CO_2 + H_2O = NH_4\ HCO_3$$

This ammonium salt decomposes at temperatures above approximately 60°C. Since the fuel gas temperature was typically 15° to 25°C, the precipitate probably did form in the mixing lines prior to injection into the burner.

The NO_x results for this fuel are given in Figure 6-1. The NO_x results with no ammonia injection are on the order of three to four ppm at all operating points. The ammonia injection points are also plotted (Figure 6-1), and conversion effeciencies were calculated and plotted in Figure 6-2. It was not possible to test at rich equivalence ratios greater than 1.8 with ammonia injection, but the results seem to indicate that the optimum operating condition would be at an equivalence ratio of approximately 1.8. If a precipitate was forming during the test, then the calculated amount of ammonia in the fuel was higher than the actual amount. This would cause the calculated conversion efficiencies to be lower than actual. However, in the tests immediately following the ammonia injection tests, the NO_x levels were not higher than expected, which would occur if a larger amount of precipitate was left in the lines. Therefore it is concluded that the conversion efficiencies are somewhat low, but reasonable.

The emission results related to combustion efficiencies (UHC and CO) are plotted in Figures 6-3 and 6-4, and are indicative of combustion efficiencies greater than 99 percent. Neither inlet temperature nor pressure

Table 6-1

AIR BLOWN GASIFIER OPERATION

FUEL COMPOSITION

Element	Average Compostion (%)	Range of Composition (%)
CO	16.0	15.3 - 16.2
CO_2	16.75	16.6 - 17.5
H_2	11.5	11.4 - 11.7
CH_4	2.25	2.15 - 2.4
N_2	53.3	52.7 - 53.4
H_2S	0.08	0.07 - 0.08
H_2O	0.13	0.09 - 0.15
NH_3	0.01	- -
LHV (BTU/SCF)	103.8	102.6 - 104.2

Table 6-2

AIR BLOWN GASIFIER OPERATION

R/L BURNER PLOTTING SYMBOLS

Symbol	Inlet Pressure MPa (psia)	Avg. Inlet Temperature °C (°F)	Rich Inlet Temperature °C (°F)	Quench Air / Rich Air	Inlet Velocity M/S (Fps)
◒	0.79 (114)	464 (867)	347 (657)	5.0	13.4 (44)
○	1.18 (171)	464 (867)	347 (657)	5.0	9.7 (32)
□	1.18 (171)	476 (890)	381 (718)	4.3	12.2 (40)
⬓	1.18 (171)	476 (890)	381 (718)	4.3	12.2 (40)*
⬒	1.18 (171)	476 (890)	381 (718)	4.3	12.2 (40)**

⬓* Has 0.2 volume % NH_3 added to fuel.

⬒** Has 0.5 volume % NH_3 added to fuel.

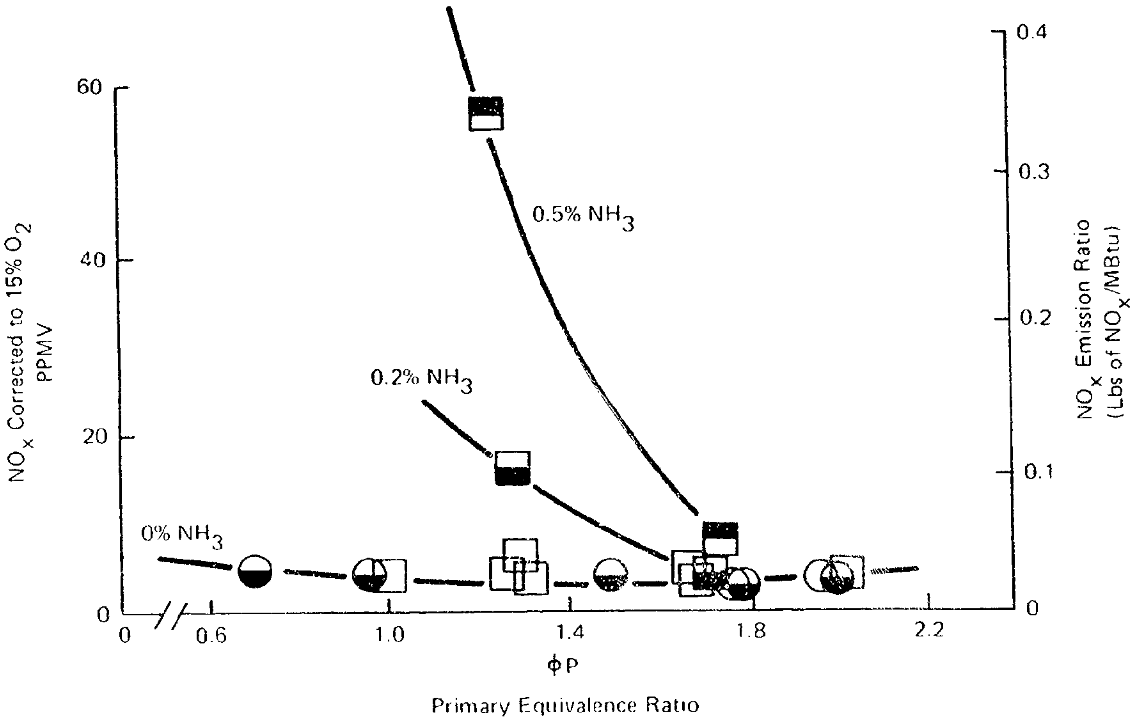

Figure 6-1. ' ir Blown Gasifier NO_x Results for the R/L Burner

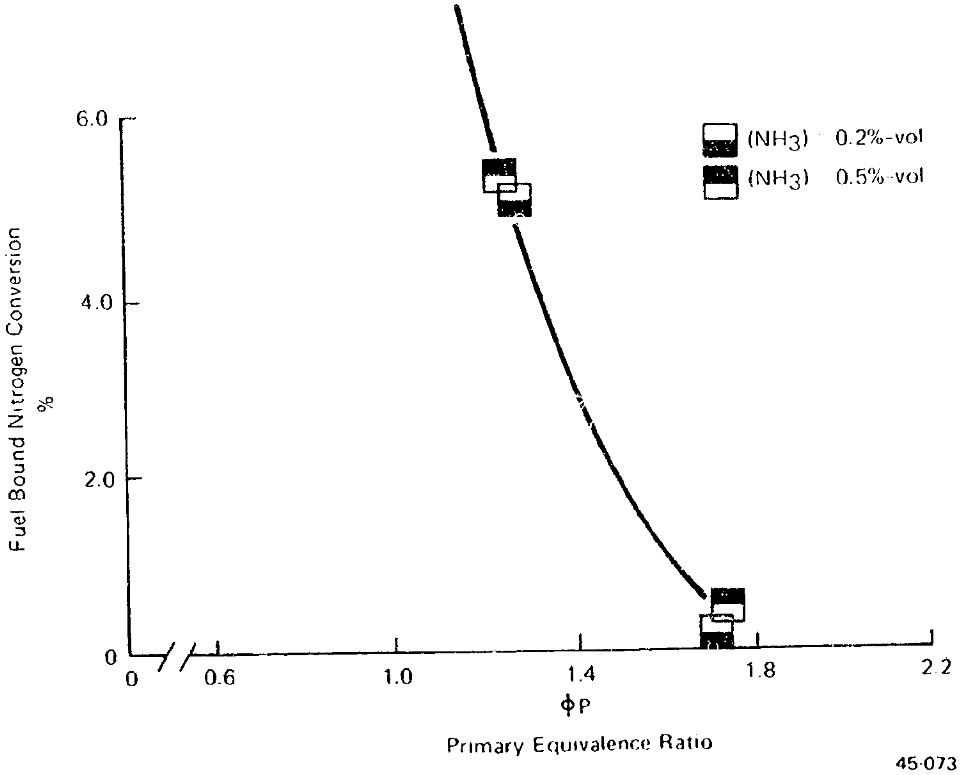

Figure 6-2. Air Blown Gasifier FBN Conversion for the R/L Burner

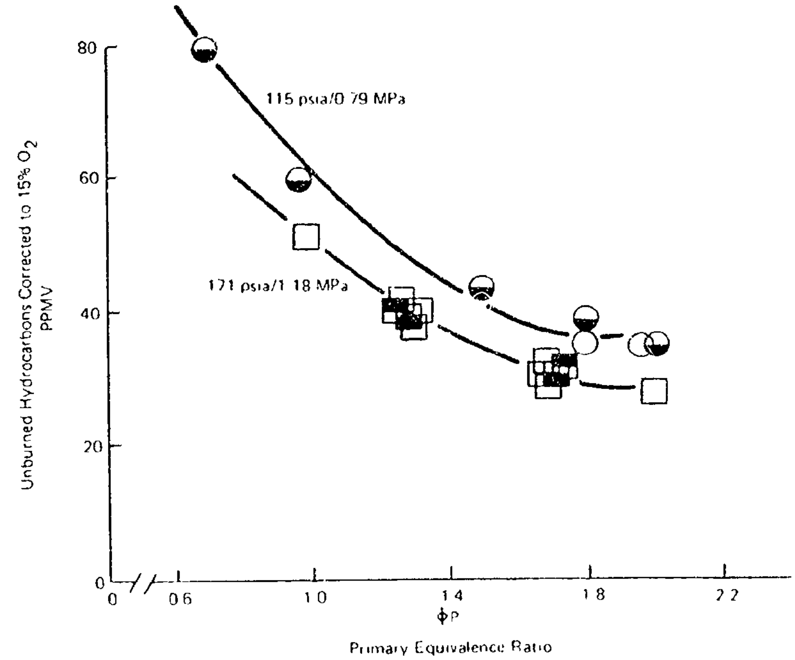

Figure 6-3. Air Blown Gasifier UHC Results for the R/L Burner

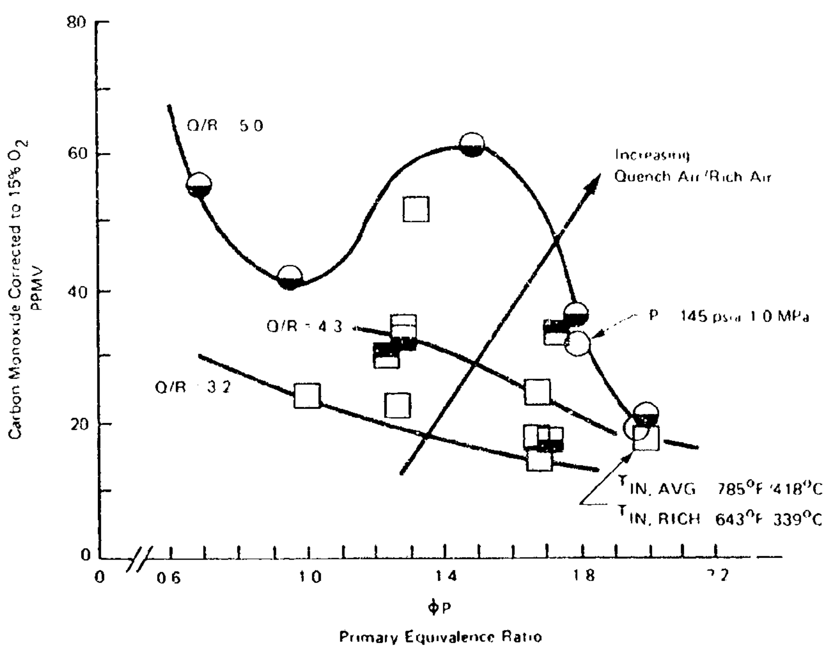

Figure 6-4. Air Blown Gasifier CO Results for the R/L Burner

appears to have a significant effect on CO results, but increasing inlet temperature resulted in lower UHC levels. In addition, increasing the quench air flow resulted in higher CO levels due to colder lean zone temperatures and less CO burnout.

6.1.2 R/L OXYGEN ENRICHED GASIFIER RESULTS

The product gas composition of the oxygen enriched gasifier was between the air blown and oxygen blown operating modes. The heating value of the gas was 197 Btu/SCF, and its composition, displayed in Table 6-3, was again reasonably stable during the period of testing. Table 6-4 displays the plotting symbols used in this section.

The NO_x results and the theoretical lean zone temperature for this fuel are plotted in Figure 6-5. There was no intentional variation in velocity, preheat temperature or relative quench air flow rates. The pressure effect was not measurable. The NO_x results over the range of equivalence ratios tested were consistently in the 20 to 25 ppmv range despite lean zone temperatures approaching 1425°C (2600°F). No ammonia injection tests were conducted with this fuel.

The emission levels related to combustion efficiencies indicated >99% efficiency. The effect of pressure on CO and UHC levels was neglible.

6.1.3 R/L OXYGEN BLOWN GASIFIER RESULTS

The product gas of the oxygen blown gasifier had a heating value of 254 Btu/SCF, which was the highest value tested. More tests were run with this gas than the other two. Results were collected at two different PDU steady state conditions, and as a result, there is somewhat more variation in the gas composition as shown in Table 6-5. Plotting symbols are given in Table 6-6.

NO_x results and the theoretical lean zone temperature for both PDU conditions are displayed in Figure 6-6. The results show a minimum NO_x value of approximately 60 to 70 ppmv at a rich equivalence ratio of

Table 6-3

OXYGEN-ENRICHED GASIFIER OPERATION
FUEL COMPOSITION

Element	Average Composition (%)	Range of Composition (%)
CO	31.9	30.2 - 33.2
CO_2	23.1	22.7 - 23.7
H_2	20.9	20.2 - 21.4
CH_4	4.0	3.9 - 4.1
N_2	19.2	17.3 - 21.5
H_2S	0.13	0.13
H_2O	0.12	0.12
NH_3	nil	nil
LHV (BTU/SCF)	196.5	189.2 - 202.2

Table 6-4

OXYGEN ENRICHED GASIFIER OPERATION
R/L BURNER PLOTTING SYMBOLS

Symbol	Inlet Pressure MPa (psig)	Avg. Inlet Temperature °C (°F)	Rich Inlet Temperature °C (°F)	Quench Air / Rich Air	Inlet Velocity M/S (F/S)
	1.14 (166)	380 (717)	286 (547)	4.6	11.6 (38)
	1.25 (181)	380 (717)	286 (547	4.6	11.0 (36)
	1.30 (188)	380 (717)	281 (538)	4.6	10.4 (34)

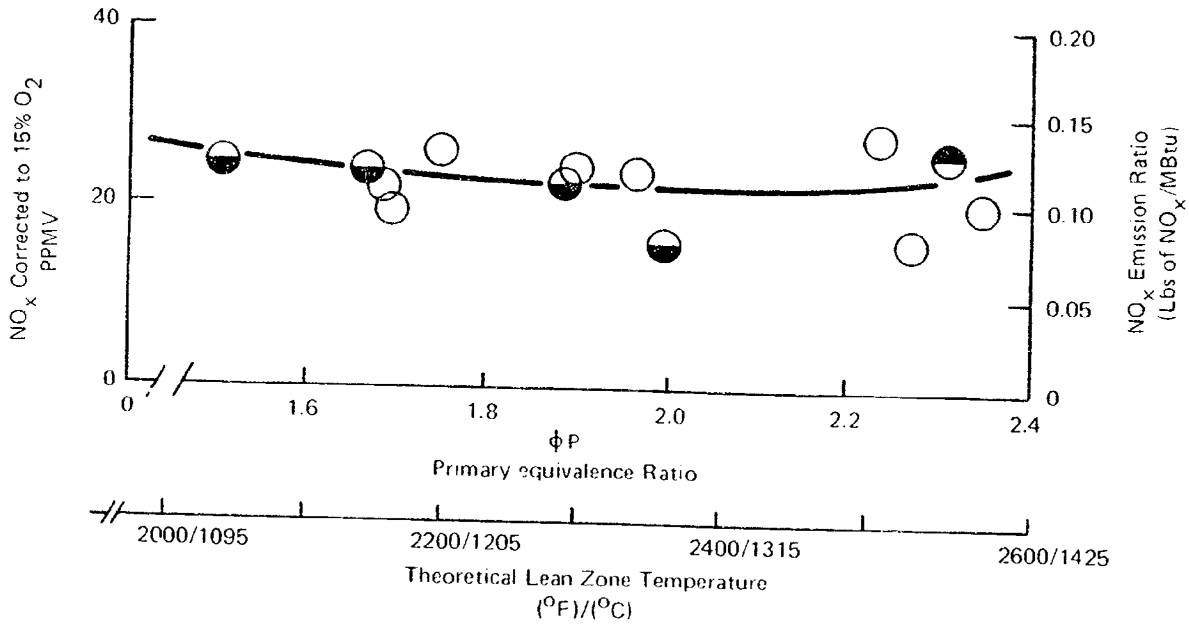

Figure 6-5. Oxygen Enriched Gasifier - NO_x Results

Table 6-5

OXYGEN BLOWN GASIFIER OPERATION
FUEL COMPOSITION

Element	Average Composition (%)	Range of Composition (%)
CO	41.3	38.2 - 45.2
CO_2	27.6	24.2 - 30.4
H_2	25.0	23.5 - 26.1
CH_4	5.7	4.8 - 7.3
N_2	0.17	0.16 - 0.23
H_2S	0.17	0.15 - 0.21
H_2O	0.12	0.10 - 0.15
NH_3	nil	nil
LHV (BTU/SCF)	253.7	243.8 - 261.9

Table 6-6

OXYGEN BLOWN GASIFIER OPERATION
R/L BURNER PLOTTING SYMBOLS

The shape of the symbol denotes reference velocity and is consistent within all figures.

Symbol	Reference Velocity M/S	(fps)
○	10.7	(35)
□	13.1	(43)
△	15.2	(50)
◇	18.3	(60)

Shading of symbols will be explained in each individual Figure and indicates changes in pressure, inlet temperature, etc. Ratios of quench to primary air varied from 4.4 to 4.6.

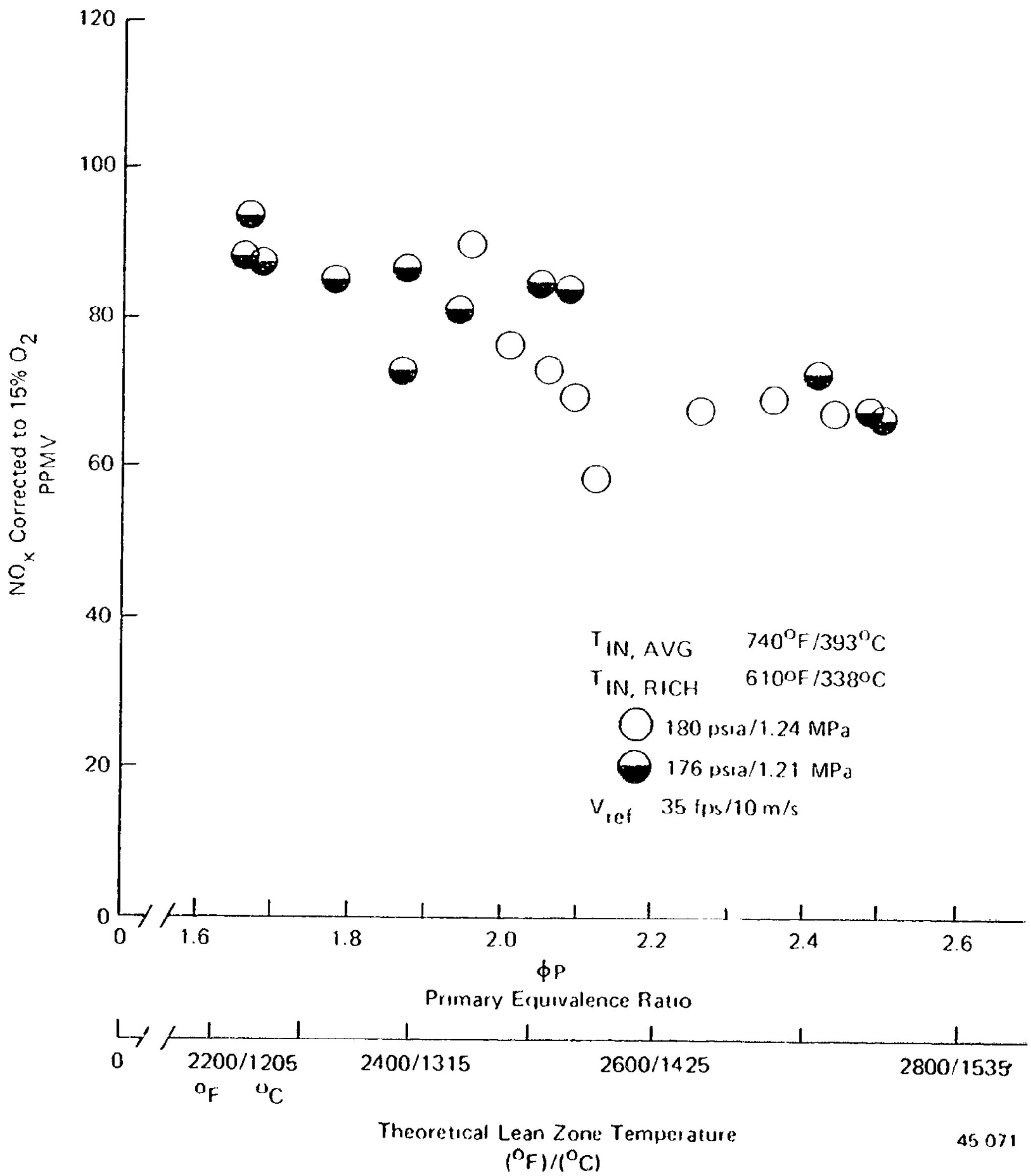

Figure 6-6. Oxygen Blown Gasifier - NO_x Results - 740°F

approximately 2.3. These results include three different levels of quench air flow, which did not affect the results.

This NO_x value is consistent with the results from the Phase 1 program where the minimum NO_x concentrates using ERBS fuel was about 70 ppmv at a rich equivalence ratio of 1.8. The apparent difference in optimum equivalence ratio for the two fuels if the definition of Φ is changed to emphasize the chemistry of the rich zone rather than the fuel and air flow rates. By definition, "valence equivalence ratio is essentially the ratio of reducing atoms (such as C or H) to oxidizing atoms (O)[2]. While this valence - Φ has a one-to-one correspondence with the conventional Φ defined using stoichiometric fuel air ratios, the valence - Φ is a more accurate representation of the species concentration in the rich zone. With ERBS fuel the valence - Φ is identical to the Φ normally computed. However, the oxygen in the CO and CO_2 present in coal gases causes the valence - Φ to be less than the Φ normally computed. For this reason, the optimum valence - Φ for minimum NO_x formation is 1.8 for the ERBS fuel and 1.9 for the oxygen blown gasifier product gas.

Emissions results related to combustion efficiencies indicated >99% efficiency for all tests. The only variable that had a noticeable effect was primary equivalence ratio, and consequently, the lean zone temperature, with higher ratios producing slightly better combustion efficiencies.

The effect of inlet temperature on NO_x values is significant. Figures 6-7 and 6-8 display NO_x versus primary equivalence ratio for inlet temperatures other than those already discussed (Figure 6-6). These results indicate increasing NO_x levels with increasing inlet temperature, implying that appreciable NO_x is being formed by a thermal (i.e. Zeldovich-type) mechanism.

[2] S. Gordon, B. McBride, "Computer Program for Calculation of Complex Chemical Equalibrium Compositions," NASA SP-273 (1971)

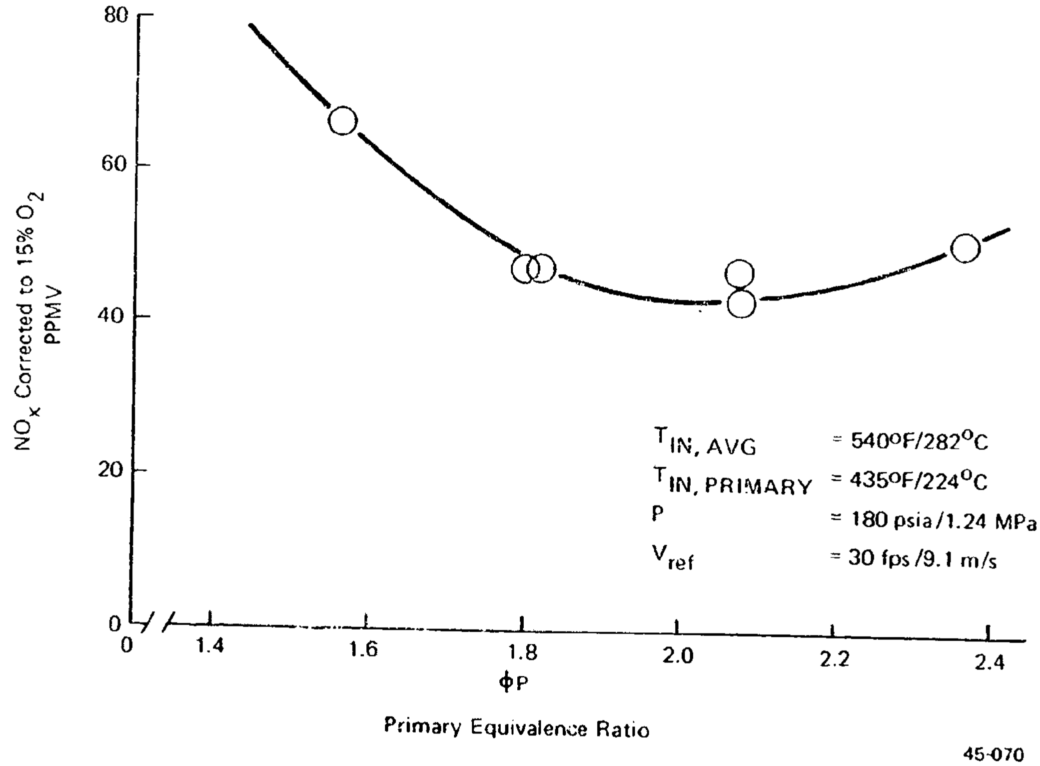

Figure 6-7. Oxygen Blown Gasifier NO_x Results - 540°F

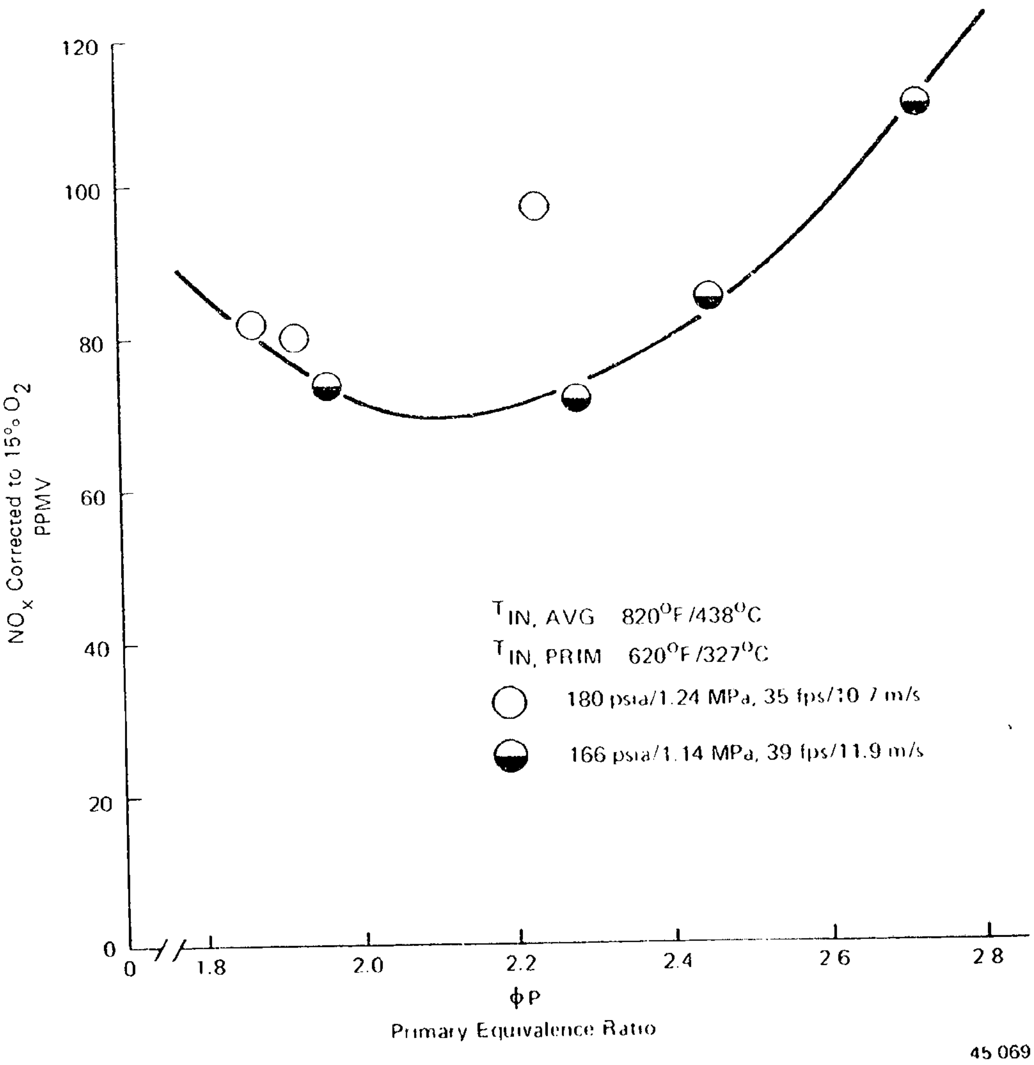

Figure 6-8. Oxygen Blown Gasifier NO_x Results - 820°F

Pressure effects are also measurable as seen in Figure 6-9. This increase in NO_x values at higher pressure is also consistent with a thermal mechanism.

The effect of velocity, shown in Figure 6-10, is also consistent with a thermal-type mechanism. The higher velocity values yield a lower residence time, which tends to reduce the time available for thermal NO_x formation.

The magnitude of this thermal NO_x is comparable with that found for the Phase 1 program using ERBS fuel. When the NO_x values shown in Figures 6-4 through 6-10 were adjusted to the same basis of temperature, pressure, and velocity using the procedure reported by Vermes[3], it was found that they reduced to a common value. Since the procedure was developed and experimentally verified based on thermal NO_x formation, the inference here is that most, if not all, NO_x formed by the R/L burner is thermal NO_x. Since this thermal NO_x is undoubtedly formed at the quench zone, the NO_x emission could probably be reduced moresignificantly if the quench zone were improved than if the rich zone were altered.

Ammonia injection tests demonstrated the rich/lean nature of the burner. Two ammonia injection rates were tested at two velocities. The results for the lower velocity are given in Figure 6-11, and for the higher velocity in Figure 6-12. The meaningful aspect of these tests is the conversion of the ammonia to NO_x as shown in Figures 6-13 and 6-14. Figure 6-13 indicates that the optimum rich equivalence ratio is approximately 2.1. Figure 6-14 shows the significant effect that rich zone residence time has on fuel bound nitrogen conversion levels. As with the results of ammonia injection for the air blown gasifier tests, the conversions are probably somewhat low, but realistic.

[3] G. Vermes, "A NOx Correlation Method for Gas Turbine Combustors based on NOx Formation Assumption," ASME Paper 74-WA/GT-10 (1974).

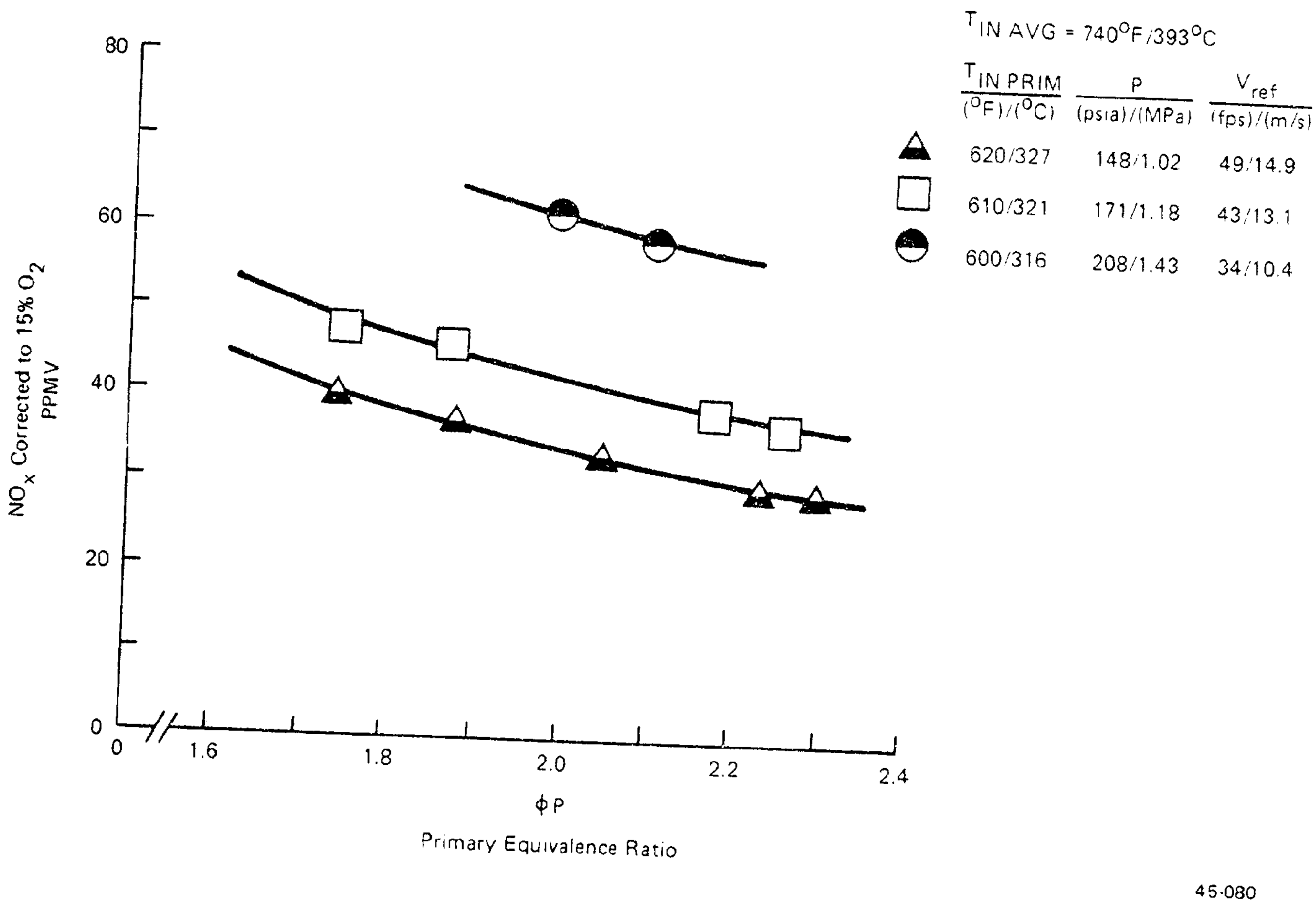

Figure 6-9. Oxygen Blown Gasifier NO_x Results - Pressure Effects

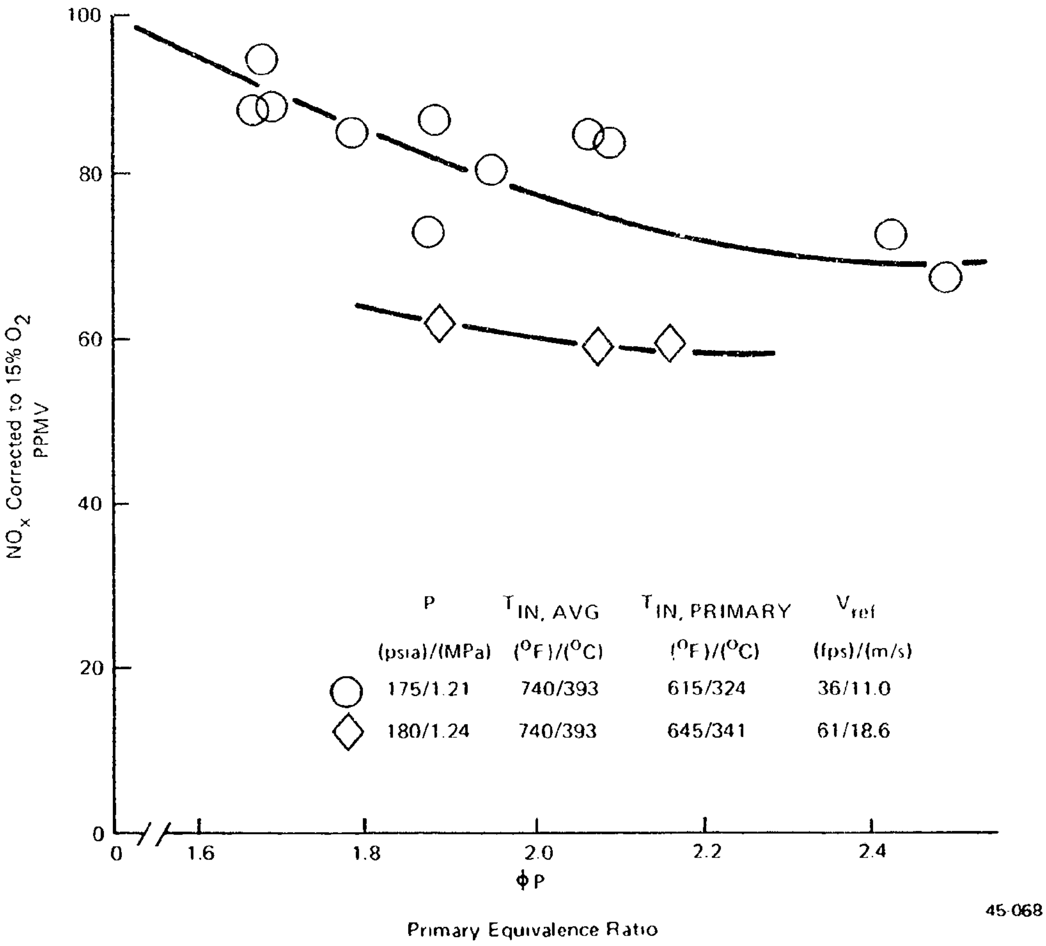

Figure 6-10. Oxygen Blown Gasifier NO_x Results - Velocity Effects

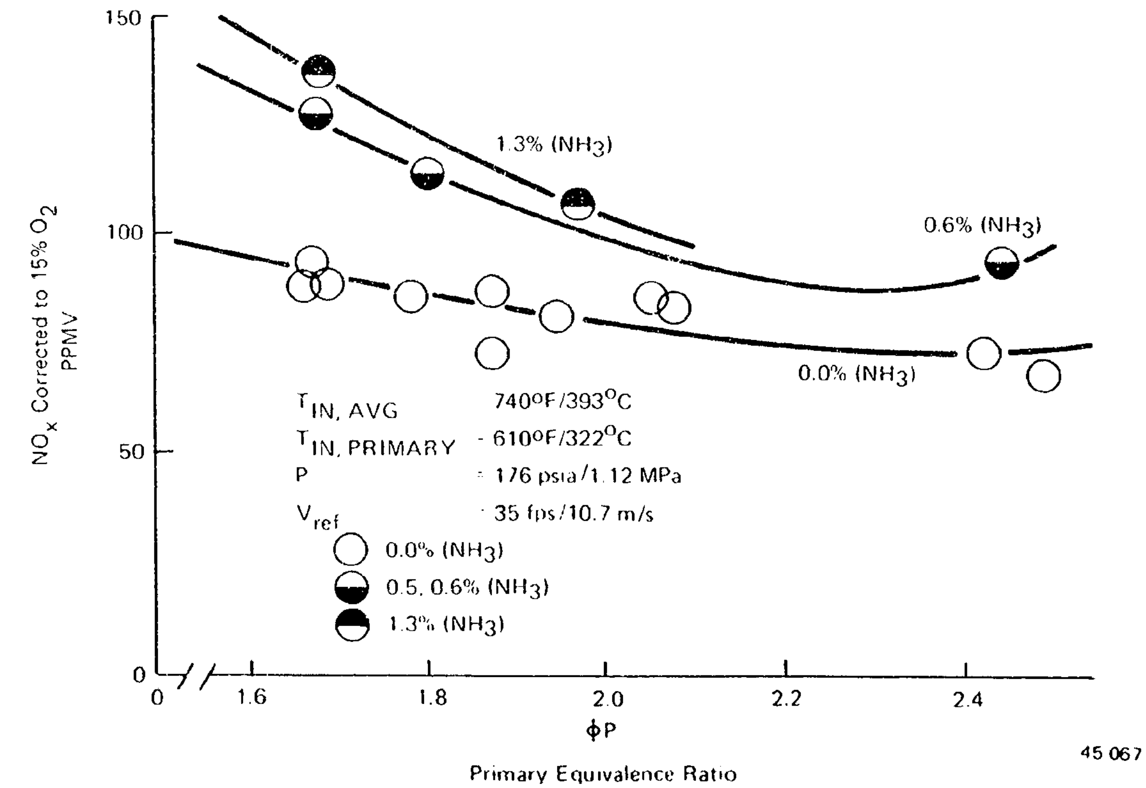

Figure 6-11. Oxygen Blown Gasifier NO_x Results - FBN - 35 fps

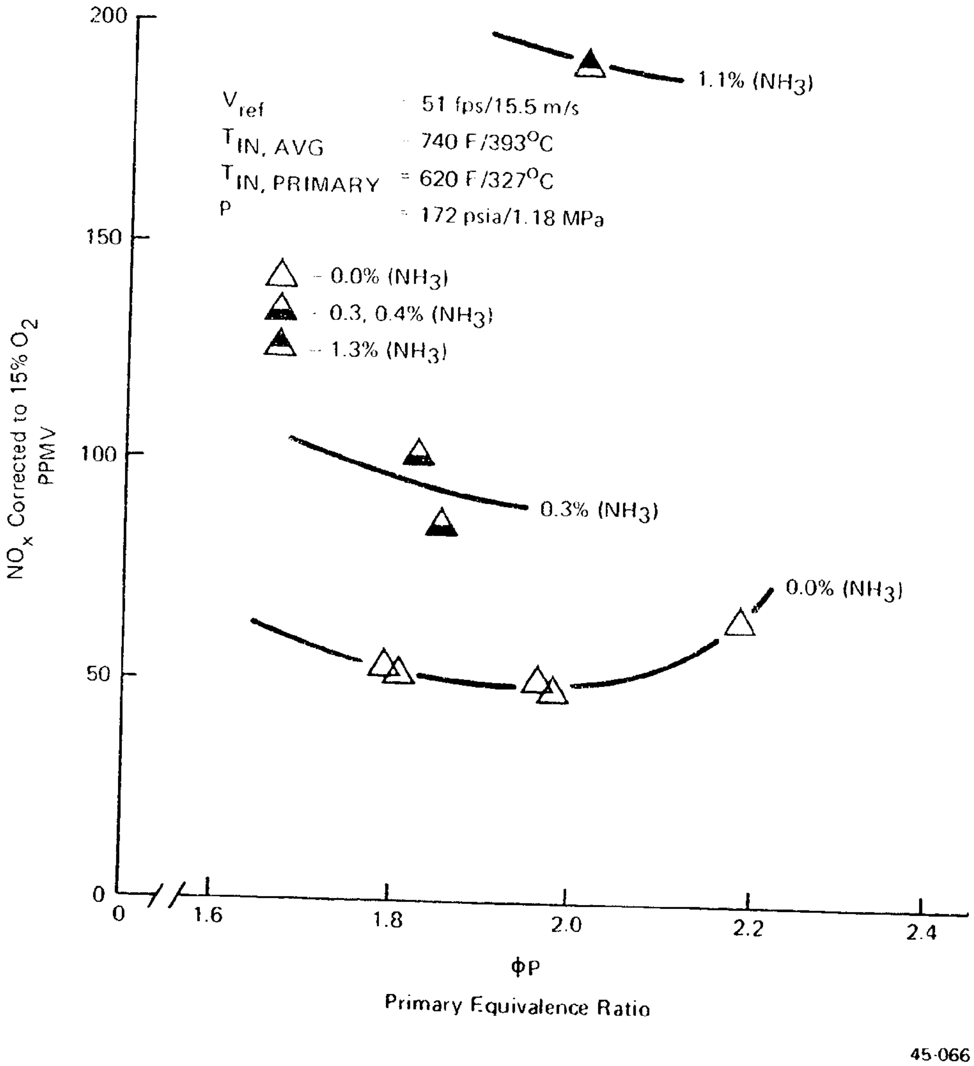

Figure 6-12. Oxygen Blown Gasifier NO_x Results - FBN - 51 fps

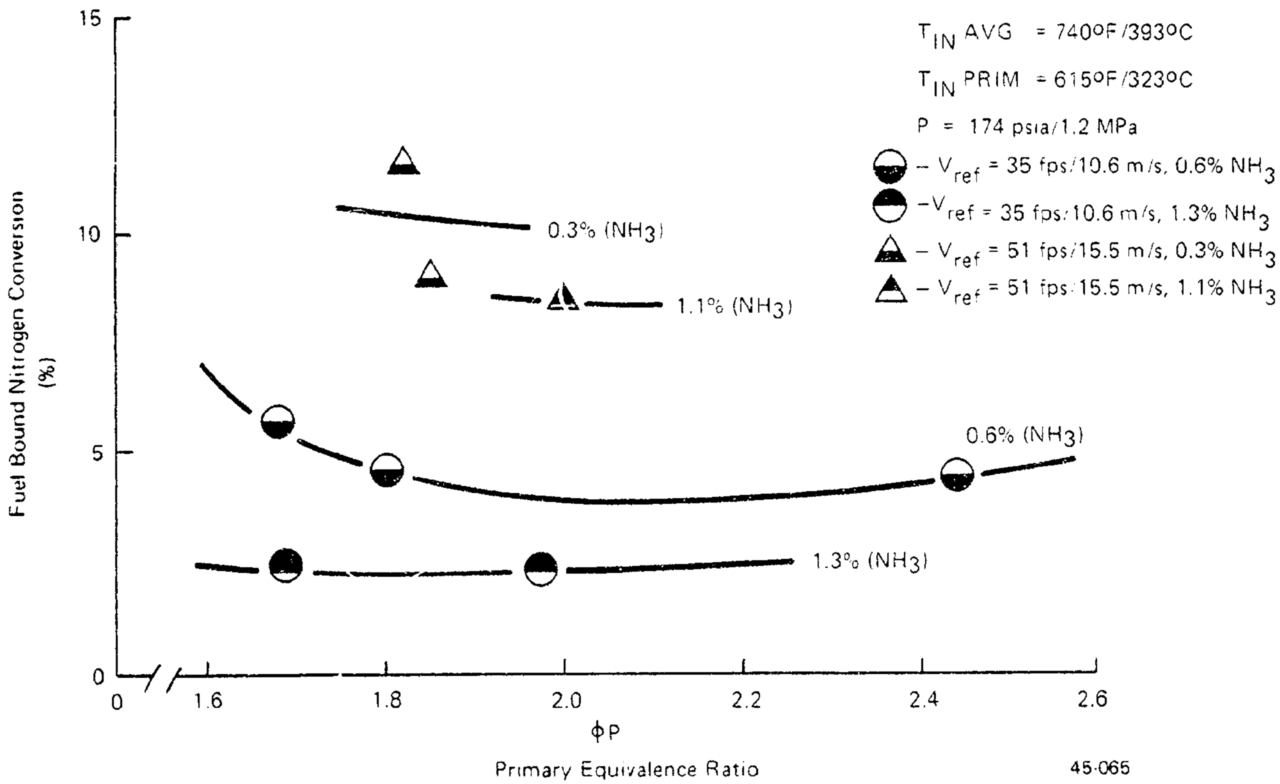

Figure 6-13. Oxygen Blown Gasifier FBN Conversion

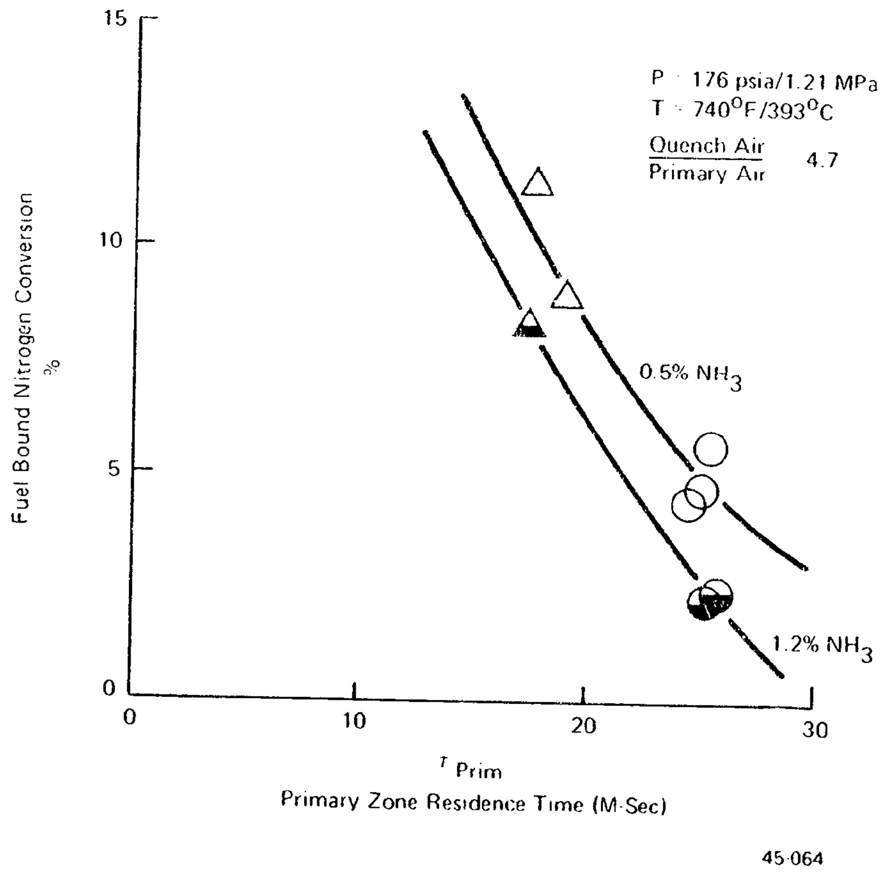

Figure 6-14. Oxygen Blown Gasifier FBN Conversion - Residence Time

The results from the ammonia injection tests indicate that the rich zone is functioning properly. Otherwise the fuel bound nitrogen conversion level would have been about 50% by analogy with conventional lean combustors. This reinforces the earlier conclusion that the rich zone is performing well and that most of the NO_x measured for the R/L burners was formed by a thermal mechanism at the quench air inlet region.

6.2 MULTI ANNULAR SWIRL BURNER RESULTS

The MASB was tested in conjunction with a scheduled PDU test run using South African coal. Table 6-7 gives the composition of the product gas during the test.

Table 6-7

GAS COMPOSITION, MASB, OXYGEN BLOWN OPERATION

Element	Average Composition (%)	Range of Compositions (%)
CO_2	25.0	19.0 - 33.6
H_2S	0.2	0.19 - 0.22
H_2	24.5	25.2 - 19.5
N_2	0.6	0.6 - 0.58
CH_4	1.62	1.58 - 1.64
CO	48.0	53.3 - 44.4
LHV (BTU/SCF)	258	268 - 222

The range of compositions indicates that the operation of the PDU during the test changes sufficiently enough to influence MASB emissions levels. Carbon dioxide was particularly influential, as discussed below.

The gasifier is characterized by fuel/air reactions that occur in a nominal 7-meter (22-foot) bed and random changes in operating reactions should be averaged out by the time the product gas reaches the exhaust manifold of the gasifier. The notable exception is CO_2, intentionally introduced into the bed. This measure was occasionally necessary when problems with the coal feeder occurred during gasifier operation. To isolate the feeder from the reactive bed, a CO_2 blanket was applied at the feeder, and this flow of CO_2 changed the absolute level from the gasifier.

Operating problems also occured with the ammonia injection system, and only four data points were obtained with fuel bound nitrogen. Because of the gasifier scheduling constraints, only twenty-six test points were obtained; these results are tabulated in Table 6-8. In order to assess

Table 6-8

MULTIANNULAR SWIRL BURNER TEST ON COAL GAS

Run No.	Air Temp. In (Nom.) °F	Air Temp. In (Nom.) °C	Air Press. In PSIA	Air Press. In MPa,a	Airflow (w/o Dil. Air) PPS	Airflow (w/o Dil. Air) Kg/sec	F/A w/o Dil. Air	NOx w/o Dil.Air Measured ppm(v)	NOx w/o Dil.Air @ 166 psia, 761°F ppm(v)	CO_2 In Fuel %/(v)	NOx/(NOx)norm	NOx @ 26% CO_2 ppm(v)	2nd Ring Fuel / Total Fuel %	Remarks
1	792	422	117.7	0.811	1.74	0.791	0.104	94	103	19.5	1.78	58	32	
2	789	421	167.6	1.155	1.75	0.795	0.107	68	64	23.0	1.24	52	32	
3	789	421	167.0	1.151	1.98	0.900	0.099	44	41	24.4	1.18	35	34	
4	767	408	155.4	1.071	2.00	0.909	0.104	81	82	24.4	1.18	68	36	
5	763	406	167.2	1.152	2.00	0.909	0.134	35	35	26.5	0.95	37	29	
6	762	406	166.1	1.144	1.49	0.677	0.190	60	60	31.8	0.46	130	29	
7	762	406	165.6	1.141	1.48	0.673	0.154	76	76	32.3	0.42	181	35	
8	762	406	155.4	1.071	1.49	0.677	0.125	46	47	29.5	0.64	73	46	
9	761	405	165.9	1.143	1.48	0.673	0.106	37	39	26.5	0.95	41	100	
10	761	405	165.6	1.141	1.48	0.673	0.148	105	105	25.5	1.06	99	100	
11	761	405	166.1	1.144	1.48	0.673	0.159	173	173	23.2	1.32	131	100	
12	761	405	165.6	1.141	1.48	0.673	0.133	98	98	22.8	1.36	72	100	
13	761	405	165.7	1.142	1.49	0.677	0.116	79	79	24.9	1.12	71	100	
14	761	405	166.1	1.144	1.50	0.682	0.120	188	188	-	-	-	100	0.48% NH_3
15	761	405	165.4	1.140	1.49	0.677	0.151	234	234	-	-	-	100	0.48% NH_3
16	761	405	165.0	1.137	1.49	0.677	0.104	197	197	-	-	-	100	1.06% NH_3
17	761	405	165.2	1.138	1.50	0.682	0.087	157	157	-	-	-	100	0.51% NH_3
18	761	405	162.8	1.122	1.49	0.677	0.135	118	118	24.0	1.23	96	100	
19	761	405	164.8	1.135	1.49	0.677	0.126	164	164	22.4	1.40	117	46	
20	786	419	163.7	1.128	1.53	0.695	0.165	87	83	24.9	1.13	74	37	
21	788	420	185.5	1.278	1.53	0.695	0.154	79	78	25.7	1.04	75	38	
22	791	422	131.3	0.905	1.53	0.695	0.159	64	66	27.5	0.84	79	37	
23	791	422	111.9	0.771	1.53	0.695	0.158	53	60	27.7	0.82	73	37	
24	791	422	105.8	0.729	1.53	0.695	0.155	68	80	27.7	0.82	98	32	
25	791	422	148.8	1.025	1.34	0.609	0.152	55	54	28.8	0.71	70	43	
26	791	422	175.5	1.209	1.35	0.614	0.161	50	45	29.9	0.60	75	42	

the influence of CO_2 on NO_x generation, the NO_x output from a conventional burner was calculated using the nominal product gas composition as the fuel. The calculation is based on the Zeldovich mechanism, and Figure 6-15 displays the results. It can be seen that the CO_2 level had a very significant influence on the NO_x level. The calculation was repeated changing the relative amount of CO and H_2, and within the range of compositions encountered, only CO_2 significantly influenced the results. The justification for using the Zeldovich mechanism (assuming thermal NO_x only) is based on the assumption that the majority of NO_x measured in the combustor exhaust was generated during an incomplete quench; some of the combustion air supported a lean flame, and the lean flame temperature changed with CO_2 content. The role of CO_2, a high molecular weight gas, is similar to the role of H_2O molecules with water or steam injection. Figure 6-16 is a replot of the results in Figure 6-15, with the NO_x values normalized to 26 percent CO_2 in the product gas. Values obtained from this curve were used to normalize the NO_x results in Table 6-8.

The normalized test data is plotted in Figure 6-17, and the majority of these ata fall into two groups. The first group (line A) was obtained when fuel was injected to the second swirler only. The other group (line B) had a central fuel flow of 29 to 46 percent of the total. Two test points (6 and 7) were obtained during a major gasification upset, and the high level of CO_2 content that was measured disappeared quickly. It is not clear how much of the 3:1 normalization of the NO_x value is justifiable.

There is one additional point (19) that did not fit with the rest of the data, and no ready explanation is available.

The nature of the data recalls the Phase I results in which the ERBS data followed a "base-line" behavior and then suddenly rose to higher NO_x values. This departure could be delayed to occur at higher temperature rise values by increasing the primary equivalence ratio as shown in Figure 6-18. After reviewing the gas test results, it seemed possible that the onset of the increased slope was not so much connected with

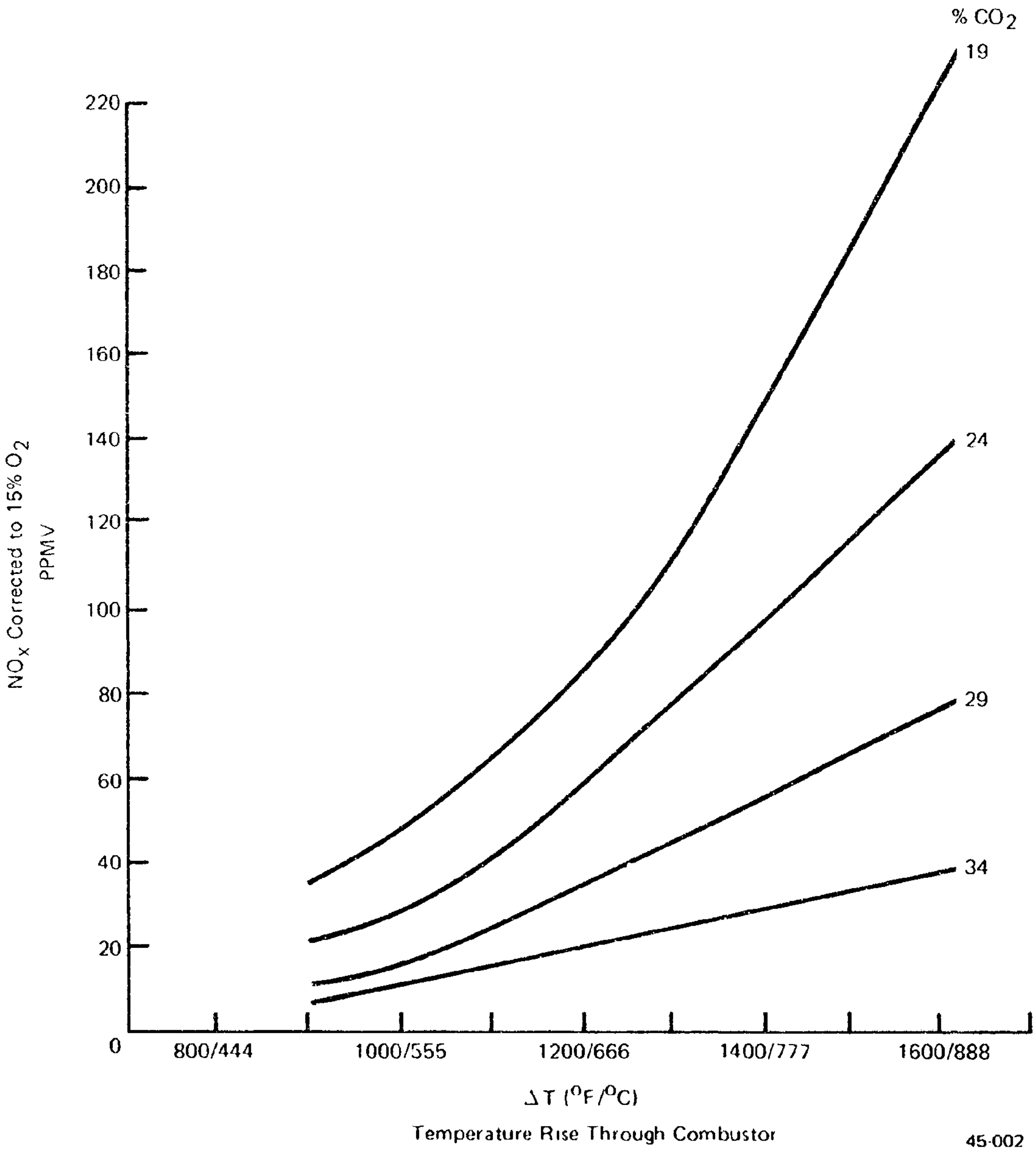

Figure 6-15. Calculated Influence of CO_2 on NO_x (State-of-the-Art Combustor)

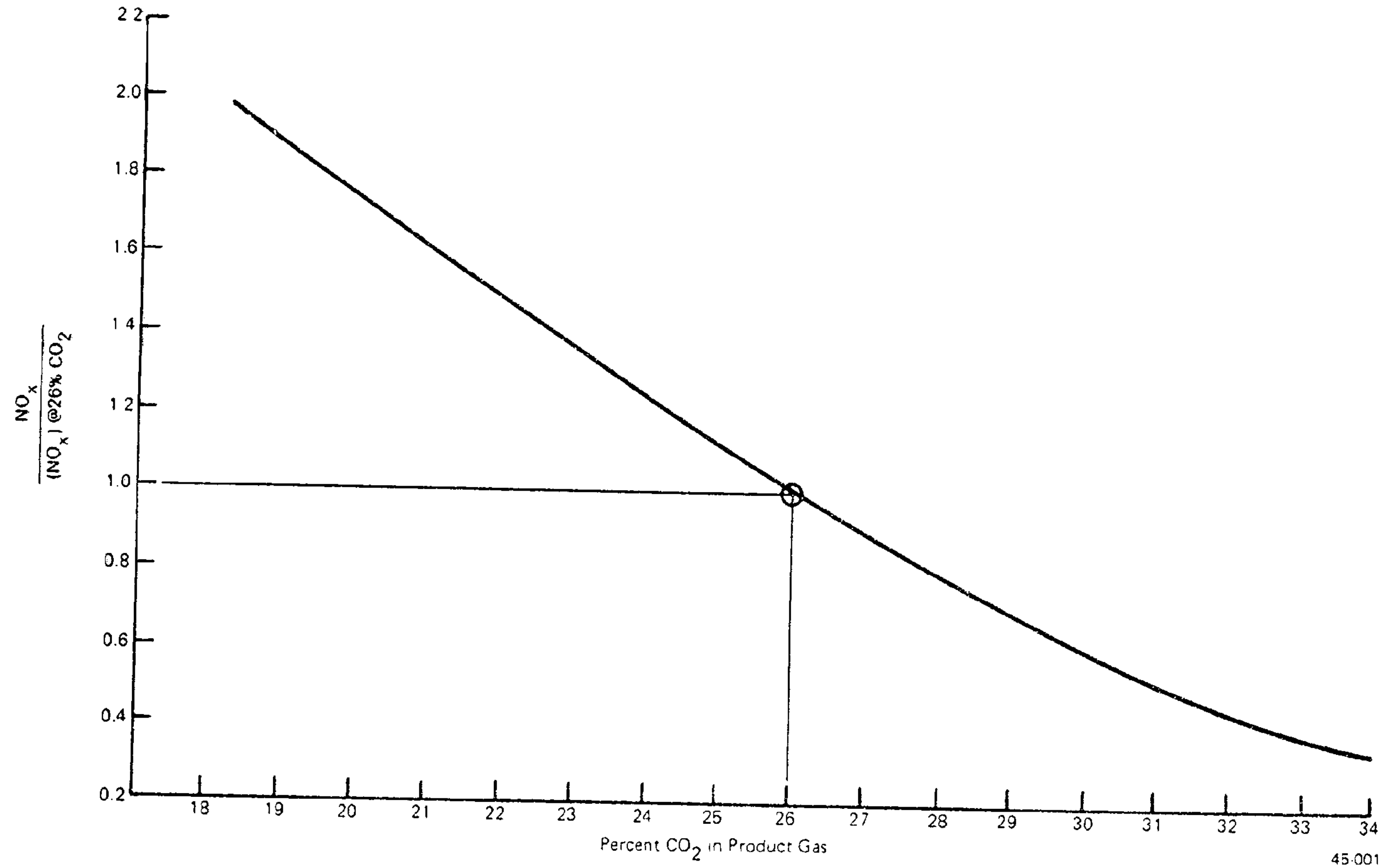

Figure 6-16. NO_x Normalized to 26% CO_2

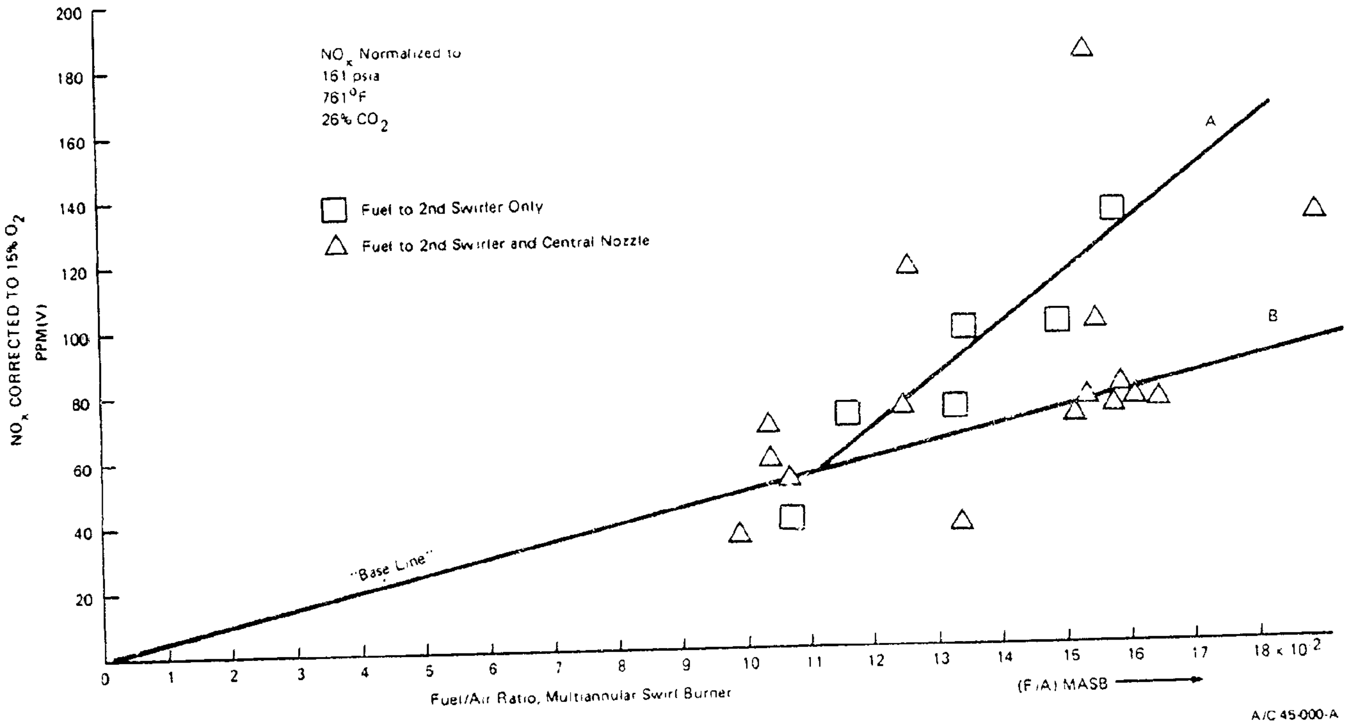

Figure 6-17. Multi-Annular Swirl Burner - NO$_x$ Performance, Coal Gas

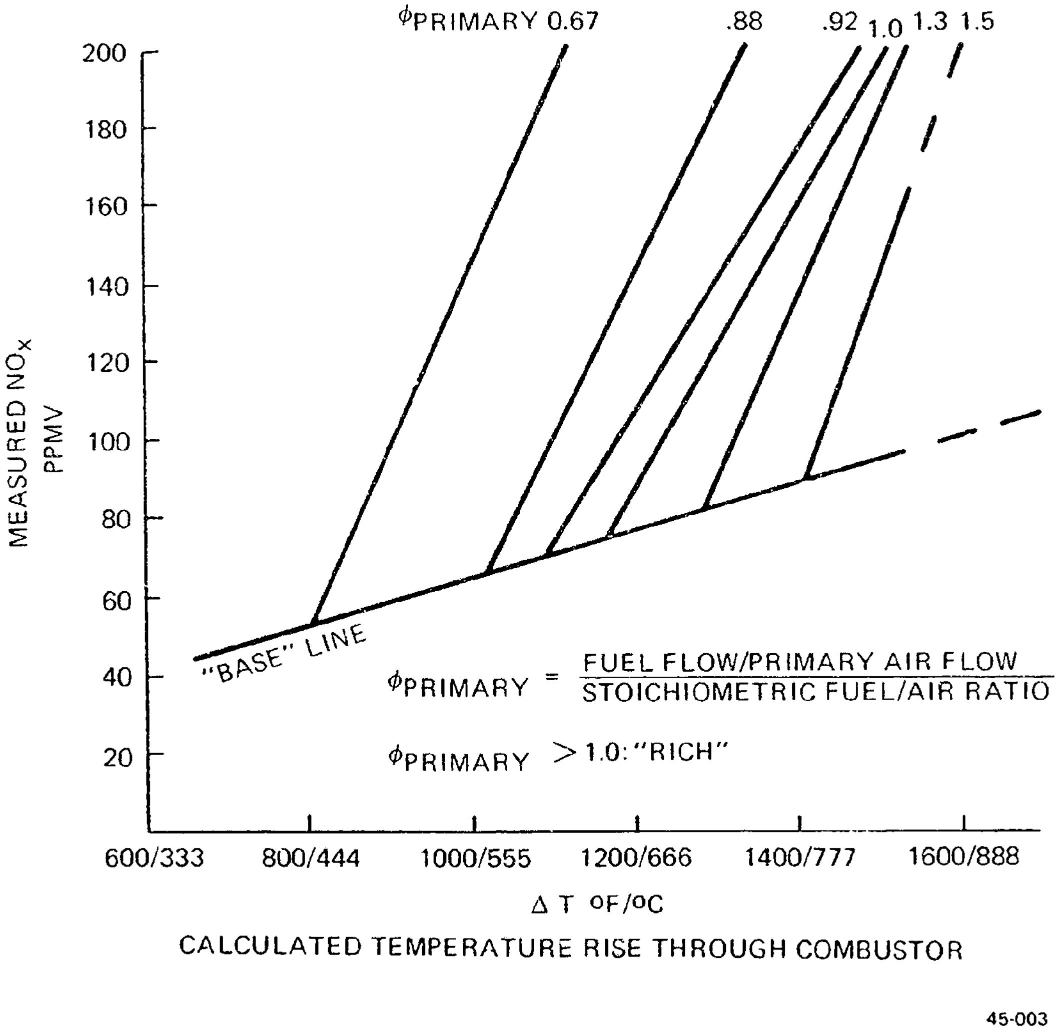

Figure 6-18. Multiannular Swirl Burner on No. 2 GT Oil

increasing the primary equivalence ratio, but with the manner in which it was obtained. For instance, although there was no test on fuel oil using only radial nozzles (low ϕp), Figure 6-18 suggests that such a line reflecting this test would be located in the far left of the plot. The radial nozzles not only lower the primary equivalence ratio, but also inject fuel into the outer regions of the burner where there is no recirculation. The results show that fuel in the outer regions of the burner creates additional NO_x regardless of using radial oil nozzles or swirler gas injection. The desired fuel injection pattern for the MASB is as central as possible.

The four ammonia injection tests indicate low NO_x conversion efficiencies (10 to 24 percent). As with the R/L burner, it was thought that some ammonia precipitates in the injection lines, and the conversion efficiencies quoted are realistic but somewhat optimistic.

Section 7
DISCUSSION

7.1 RICH/LEAN BURNER

The results of the oxygen blown gasifier can be compared to those in the Phase I program. On ERBS fuel, the R/L combustor produced a minimum NO_x value of approximately 70 ppmv at a primary equivalence ratio of approximately 1.8 and a maximum quench flow rate. The oxygen blown gasifier results showed approximately 70 ppmv at a primary equivalence ratio of approximately 2.3 independent of quench flow rate. The difference in optimum rich equivalence ratio is probably related to both the reaction rate of hydrogen, carbon monoxide and methane with regard to distillate oils and the relatively low heat release rates possible with dilute coal gas.

The three gasifier fuels were compared using a fixed geometry combustor as shown in Figure 7-1. Different air flow splits to the primary, quench and dilution sections are permitted for each fuel, but the split is not varied with simulated load. Design parameters for the three combustors are given in Table 7-1.

Based on the data generated in this program, the performance of the three fuels was compared over the normal load range of a combustion turbine. The reference velocities differ because it was assumed that the air blown and oxygen enriched gasifiers bleed air from the compressor and reduce the velocity in the combustor shell.

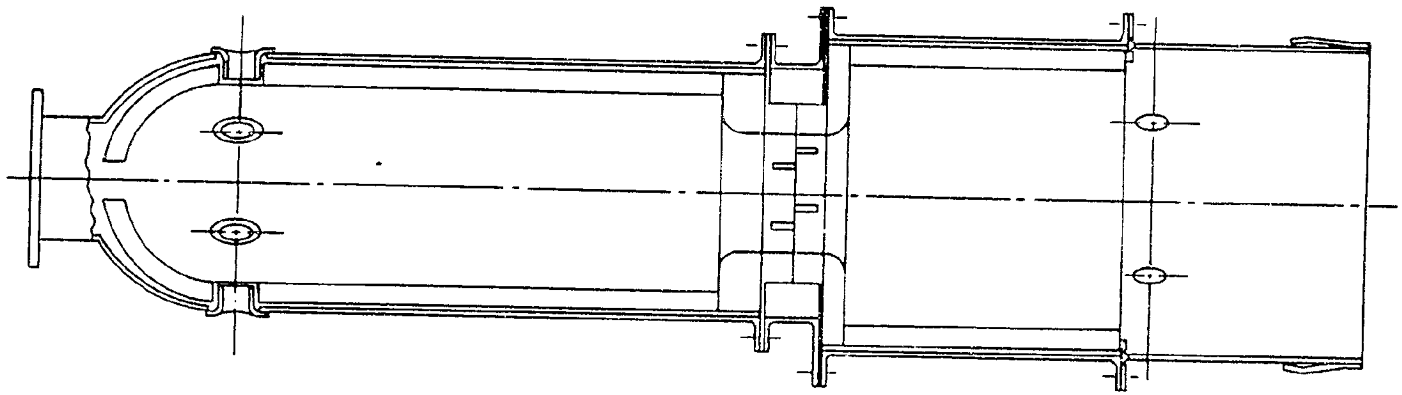

Figure 7-1. Full Sized Rich Lean Combustor

Table 7-1

DESIGN PARAMETERS FOR FUEL COMPARISON STUDY

Fuel	Test Inlet Temperature °C (°F)	Test Pressure MPa (psia)	Design Air Distribution-% Primary	Quench	Dilution	Velocity M/S (fps)
Oxygen Blown	393 (740)	1.24 (181)	12	54	34	16.2 (53)
Oxygen Enriched	380 (717)	1.24 (181)	13	60	27	15.2 (50)
Air Blown	477 (890)	1.18 (171)	18	78	4	12.5 (41)

The results for NO_x are given in Figure 7-2. Because of the fixed geometry, the combustor cannot be operated much below 70 percent load for the oxygen blown and oxygen enriched fuels without overheating the rich zone walls. The results for the conversion of fuel nitrogen to NO_x are shown in Figure 7-3. There is an apparent difference in the trend between the air blown and oxygen blown modes although the magnitudes are comparable. Comparisons of combustion efficiencies for the three fuels showed insignificant differences.

There were no operational or startup problems on any of the fuels tested with the R/L burner, and it is reasonable to assume that these fuels could be burned in a combustion turbine.

7.2 MASB

The behavior of the MASB on medium Btu gaseous fuel was also very similar to that observed on ERBS fuel in Phase I of the program. This can be clearly seen by comparing Figures 6-17 and 6-18, both of which exhibit the base-line behavior and sudden departure from the baseline, depending on the ratio of fuel to the central nozzle and secondary nozzles.

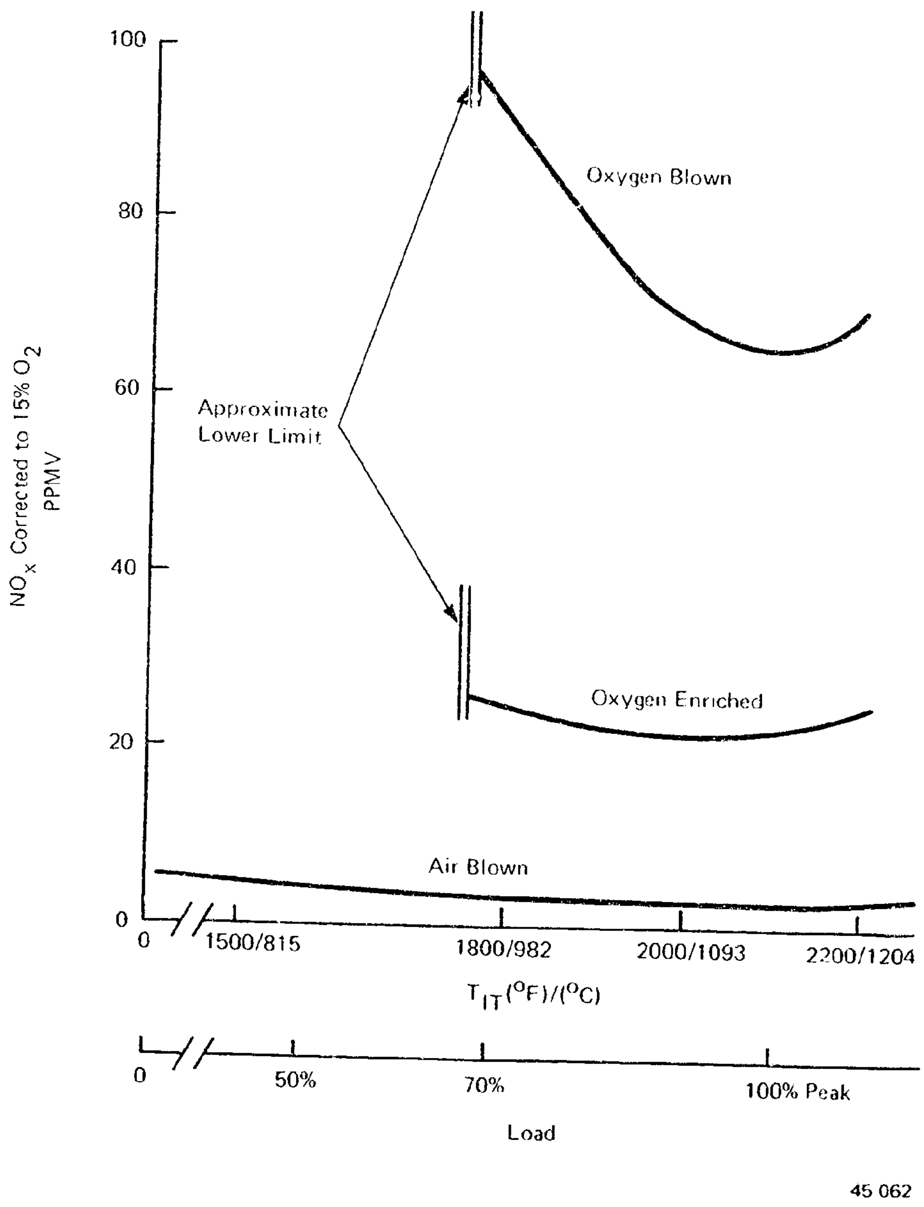

Figure 7-2. NOx Results - Load Variation

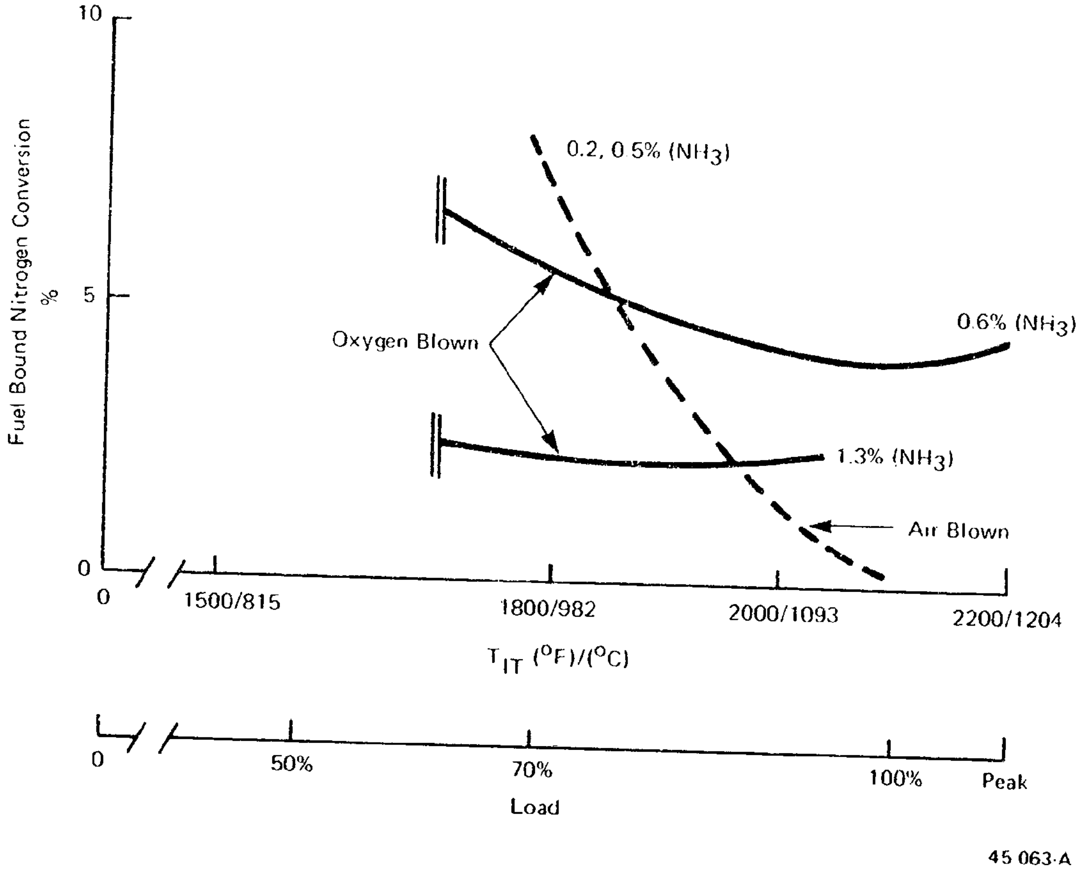

Figure 7-3. FBN Conversion - Load Variation

Section 8

CONCLUSIONS AND RECOMMENDATIONS

The program to test promising combustor concepts on actual coal gas achieved the majority of the program goals and highlighted some of the problems associated with combustor testing in conjunction with gasifier operation. Specific conclusions include:

- The behavior of both the rich/lean and multi-annular swirl burners on medium Btu coal gas was similar to behavior on distillate oil. NOx levels were slightly lower with the medium BTU gas and are within EPA regulations.
- The rich/lean burner operated successfully on coal gas in the range of 105 to 255 Btu/SCF as expected: the lowest heating values generated very little NOx.
- Conversion efficiencies of fuel bound nitrogen were lower for coal gas containing ammonia than for liquid fuels. This can be attributed to the fact that the nitrogen was not really chemically bound with the fuel and the different reaction kinetics of liquid versus gaseous fuels.

Recommendations for future development include:

- Comparison of results on actual versus simulated coal gas to determine effects of gas composition
- Scaling of combustors to utility engine size
- Development of improved wall cooling techniques and variable geometry for the rich/lean concept