DOE/NASA/0148-2
NASA CR-165615
DDA EDR 10950

Low NO_X Heavy Fuel Combustor Concept Program Addendum: Low/Mid Heating Value Gaseous Fuel Evaluation

A. S. Novick, D. L. Troth
Detroit Diesel Allison Division
General Motors Corporation

April 1982

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Under Contract DEN 3-148

for

U. S. DEPARTMENT OF ENERGY
Fossil Energy
Office of Coal Utilization

1. Report No. NASA CR-165615 DOE-NASA-0148-2	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Low NO_x Heavy Fuel Combustor Concept Program Addendum: Low/Mid Heating Value Gaseous Fuel Evaluation		5. Report Date April 1982 6. Performing Organization Code
7. Author(s) A. S. Novick, D. L. Troth		8. Performing Organization Report No. EDR 10950 10. Work Unit No.
9. Performing Organization Name and Address Detroit Diesel Allison Division General Motors Corporation P.O. Box 894 Indianapolis, IN 46206		11. Contract or Grant No. DEN3-148
12. Sponsoring Agency Name and Address Department of Energy Washington, D.C. National Aeronautics and Space Administration NASA Lewis Research Center 21000 Brookpark Road Cleveland, OH 44135		13. Type of Report and Period Covered Final Report April 1981-February 1982 14. Sponsoring Agency Code

15. Supplementary Notes

Project Manager, J. Notardonato
NASA Lewis Research Center
Cleveland, OH 44135

16. Abstract

The purpose of this program addendum was to experimentally evaluate combustion performance of a Rich/Quench/Lean (RQL) combustor when operated on low- and mid-heating-value gaseous fuels. Two synthesized fuels were prepared having lower heating values of 10.2 MJ/m^3 (274 Btu/scf) and 6.6 MJ/m^3 (176 Btu/scf). These fuels were configured to be representative of actual fuels, being composed primarily of nitrogen, hydrogen, carbon monoxide, and carbon dioxide.

A liquid-fuel air-assist fuel nozzle was modified to inject both of the gaseous fuels. The RQL combustor liner was not changed from the configuration used when the liquid fuels were tested.

Both gaseous fuels were tested over a range of power levels from 50% load to maximum rated power of the DDA Model 570-K industrial gas turbine engine. Exhaust emissions were recorded for four power levels at several rich zone equivalence ratios to determine NO_x sensitivity to the rich zone operating point. For the mid-Btu heating value gas, ammonia was added to the fuel to simulate a fuel-bound nitrogen-type gaseous fuel. Results at the testing showed that for the low-heating-value fuel NO_x emissions were all below 20 ppmc and smoke was below a 10 smoke number. For the mid-heating-value fuel, NO_x emissions were in the 50 to 70 ppmc range with the smoke below a 10 smoke number.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Gas Turbine Engines, Combustors, Gaseous Fuels, Exhaust Emissions, Fuel Bound Nitrogen, Low NO_x	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified		

*For sale by the National Technical Information Service, Springfield, Virginia 22151

TABLE OF CONTENTS

PRECEDING PAGE BLANK NOT FILMED

LIST OF ILLUSTRATIONS

LIST OF TABLES

SUMMARY

This report documents work performed under an addendum to DOE/NASA contract DEN3-148, "Low NO_x Heavy Fuel Combustor Concept Program."

The objective of this addendum, entitled "Low/Mid Heating Value Gaseous Fuel Evaluation," was to provide an evaluation of the modified rich/quench/lean (RQL) gas turbine combustor operating on low- and mid-heating-value simulated coal derived gaseous fuels.

Although generally classified as low- and mid-heating-value gases, the constituents of these fuels are highly dependent upon the source and processes used to produce them. Thus the gases contain large amounts of CO, CO_x, N_2, some H_2 and possible ammonia or other fuel bound nitrogen species. As a consequence two coal gas simulated fuels were selected for testing at 570-K engine conditions: low-heating-value gas, mid-heating-value gas, and mid-heating-value gas with ammonia (NH_3) added up to 2.8% by weight. The goal of the program was to demonstrate that the modified combustor rig hardware could operate with the gaseous fuels described above and achieve exhaust emission goals equal to or less than concentrations allowed by the EPA for industrial gas turbine engines. The NO_x goal for the gaseous fuel devoid of NH_3 addition was 50% of the maximum EPA NO_x level.

After a very brief development test period to verify that the modified Concept-I RQL combustor had no significant problems burning gaseous fuels, the gas phase combustor test program was initiated. This incorporated a series of performance tests on both gaseous fuels and parametric testing on the mid-heating-value gas with various amounts of NH_3 addition.

The RQL combustor demonstrated consistently low NO_x emissions (fewer than 70 ppmv corrected to 15% O_2) from both fuels. These levels met or exceeded the contract goals for NO_x levels. The smoke goal of 20 SAE smoke number was easily met with measured smoke below 5-10 SAE smoke number. These minimum emissions were achieved at rich zone equivalence ratios in the range of 1.5 to 2.2.

Parametric testing of the modified RQL combustor using mid-heating-value gaseous fuel with NH_3 addition showed that the combustor was essentially insensitive to the level of FBN at the minimum NO_x setting of rich zone equivalence ratio. NO_x variation with lean zone equivalence ratios between 0.5 and 0.6 revealed no significant change in NO_x emission levels. Again the exhaust smoke was between 5-10 SAE smoke number.

Exhaust carbon monoxide was high (~300 ppmv) only at the 50% power level on the low-heating-value gas. Increasing the rich zone equivalence ratio and power levels decreased this to 30 ppmv. Carbon monoxide emissions on the mid-heating-value gas were fewer than 30-40 ppmv for all operating conditions. Exhaust hydrocarbons were fewer than 6 ppmv for all performance and parametric test points with the combustion efficiency concurrently above 99.6%. Maximum combustor wall temperatures occurred in the fuel rich primary zone. Maximum measured metal temperatures were 1089 K (1500°F) and 1047 K (1425°F) for the low-heating-value and mid-heating-value fuels respectively at their minimum NO_x emission level equivalence ratio settings.

I. INTRODUCTION

Detroit Diesel Allison (DDA) is among the five gas tubine engine manufacturers participating in the Department of Energy (DOE)/NASA Lewis Research Center (LeRC) "Low NO_x Heavy Fuel Combustor Concept Program" (Ref. 1). This combustor development program is part of the DOE/LeRC "Advanced Conversion Technology Project" (ACT).

At DDA, the contract objective was to evolve a combustion technology base for a potentially durable, fuel-flexible combustor based on the operating conditions of the Allison Model 570-K, 4470 kW (6400 shp) industrial gas turbine engine (Refs. 2 and 3). This combustor must be capable of sustained, environmentally acceptable dry operation on minimally processed heavy petroleum residuals, synthetic coal-derived liquids, and petroleum distillate fuels. The purpose of this addendum program for contract DEN3-148 is to provide a data base for the program's RQL combustor when using low- and mid-heating-value gaseous fuels.

Liquid fuels such as petroleum residuals or synthetics have significant levels of fuel-bound nitrogen (FBN). In developing a fuel-flexible industrial engine combustion system, the control of NO_x emissions from this pollutant source is a major challenge for the engine manufacturer. Consequently, significant technological advances from contemporary combustion systems are essential to operate gas turbine engines in an environmentally acceptable manner when using these fuels.

Gaseous fuels produced from coal are receiving increasing attention. In general, the coal gases that are easiest and most economical to produce are those that have a relatively low heating value. This gas production is primarily limited to on-site power production applications because of the high cost of all energy transportation and a special unwillingness to transport inert materials in the gas.

The DDA design rationale for liquid fuel flexibility is to inhibit NO_x formation from FBN in a rich burning zone and quickly and uniformly quench the exiting hot products so that a minimum of thermal NO_x will be formed in the final lean reaction zone. To accomplish this, a unique staged-air combustor has been developed. This combustor is referred to as the RQL combustor, signifying an initial rich-burning zone followed by a quench zone and a lean reaction and dilution zone.

Although generally classified as low- and mid-heating-value gases, the constituents of these fuels are highly dependent upon the source and processes used to produce them. Of major concern to pollutant formation is the ammonia content of the initial gas and its fate in a sulfur cleanup process. Contemporary combustion systems are not adequate when presented with the task of burning gases containing bound nitrogen, such as ammonia, in an environmentally acceptable manner. The flexibility to operate with low- and mid-heating-value gases presents other problems apart from the ammonia content:

- Thermal NO_x increases as a result of high diffusion flame temperatures for mid-heating-value gases.
- Difficulty in fuel/air mixing, caused by high fuel flow requirements for low-heating-value gases and low flame temperatures, results in increased CO emissions and a possible degradation in blowout and efficiency.

- o Decreased combustor residence time, caused by high through-put flow rates coupled with slow reaction rates for the major low-heating-value gas constituent CO, also results in increased CO emissions.
- o Varying properties of gases dependent on coal sources and gasification processes affect combustor performance and emissions.

Although low- and mid-heating-value coal-derived gaseous fuels present different problems than synthetic and original heavy liquids, the combustor design approach is generally compatible with the original heavy liquid fuel design approach. Sufficient combustion volume must be provided because of the relatively low reaction rates of these gaseous fuels. In the heavy liquid fuel design case, a large combustion volume is necessary to achieve fuel vaporization prior to reaction. The resulting combustion volume for either case is similar. Combustor air distribution (stoichiometry) is also similar in that uniformly lean mixtures and low-temperature reactions are required for the control of thermal NO_x emissions; in the case of FBN an initial rich burning zone approach applies equally well to control NO_x with gaseous as well as liquid fuels. Fuel injector design must necessarily be different to handle the high-volume gaseous fuel flows; however, the basic concept of fuel/air premix within the injector is a valid approach to combustion control. With a goal of multifuel capability, all facets of combustor design and development require careful review to accommodate the requirements for both liquid and gaseous fuels.

From a fuel readiness viewpoint, the advanced combustion technology and low- and mid-heating-value gas data base developed under this DOE/LeRC program is essential to the future industrial engine market. Declines and uncertainties in the availability of petroleum distillate fuel and increasing demands for natural gas, coupled with the continually rising cost, lead to the conclusion that future industrial gas turbine users will require multifuel capability. Uninterrupted operation will be preserved as a result of fuel flexibility.

II. THE RQL COMBUSTOR

COMBUSTOR DESCRIPTION

A schematic of the RQL combustor is shown in Figure 1. The combustor features air staging, variable geometry, and regenerative/convective cooling. Three axial locations of variable geometry are used to vary rich and lean zone equivalence ratios in concert or independently while maintaining a specified pressure drop and overall fuel-air ratio.

A composite of the RQL combustor hardware is shown in Figure 2. Included in this figure is the airblast/air-assist fuel injector that was modified for gaseous fuel. Following is a brief description and illustration of the key features of this RQL combustor.

Figure 3 shows the variable area airblast fuel injector designed by Parker Hannifin Corporation's Gas Turbine Fuel Systems Division to operate with residual fuel. This injector includes two fixed area orifices, two variable area swirlers, and a fuel prefilming orifice. The area variation is accomplished through axial meshing of the swirlers. All the rich zone air is admitted to the combustor through this single fuel nozzle. This single point injection allows for intimate mixing between the rich zone air and fuel.

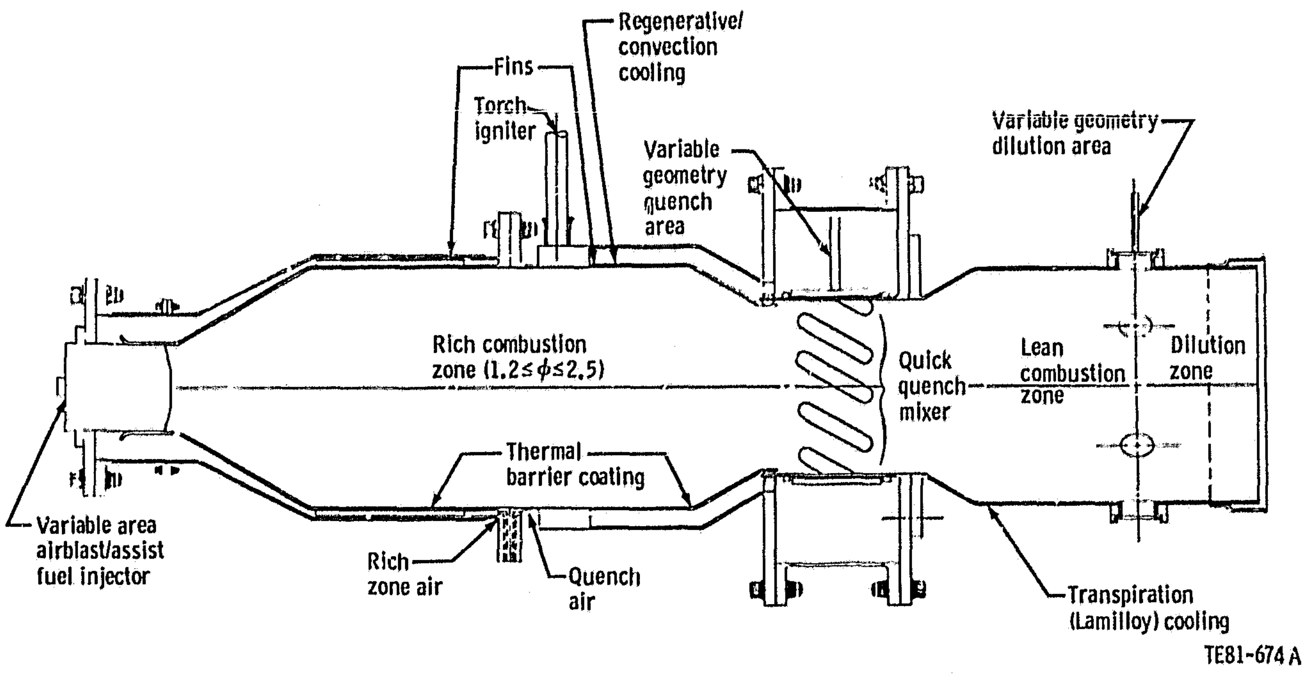


Figure 1. Schematic of RQL combustor.

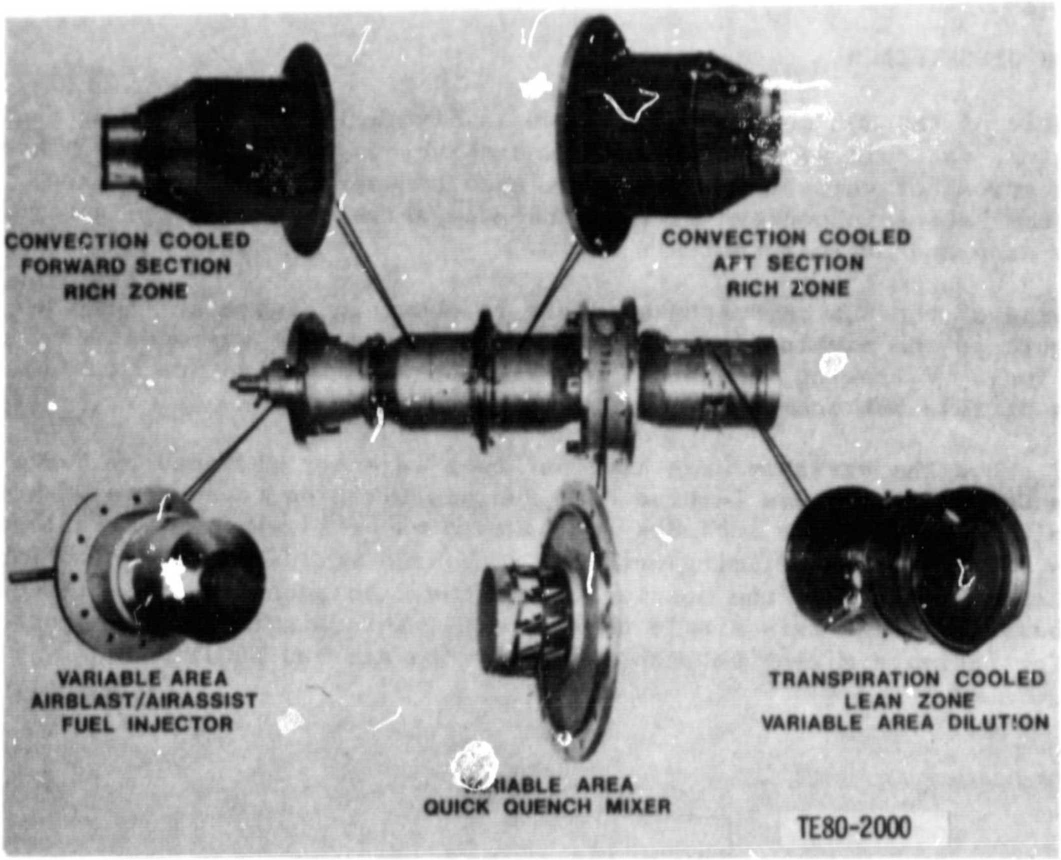


Figure 2. Assembled RQL combustor.

Prior to entering the nozzle, the air is used to convectively cool the forward portion of the augmented surface area rich zone. Regenerative use of cooling air provides the potential for improved fuel vaporization and added combustion stability within the rich stage because of the elevated inlet temperature. It also allows a wider range of parametric operation since air specifically designated for cooling is minimized.

The variable geometry quick quench zone is shown in Figure 4. Two rows of 12 circumferentially inclined slots having a 4:1 aspect ratio (in the full open position) define the quench air entry ports. Inclining the slots with respect to the axial direction serves a twofold purpose. First, the arrangement results in more uniform mixing over a shorter length when compared with circular holes or axial slots. Second, the inclined slots contribute a tangential component of velocity to the hot rich zone combustion products, providing flame stabilization in the lean zone. Similar to the combustion air, the quench air convectively cools the aft section of the rich zone. The lean combustion and dilution zone are shown in Figure 5. The dilution variable geometry consists of circular holes metered by an elevated rotating band.

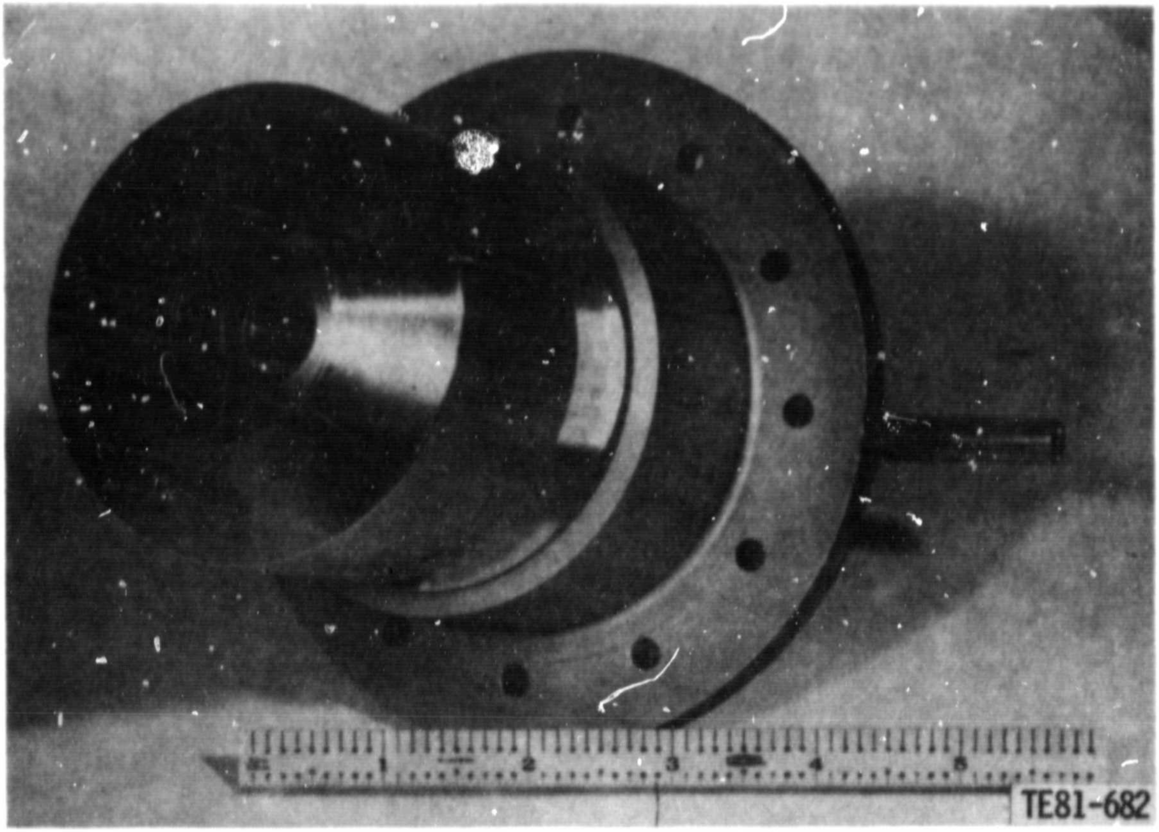


Figure 3. Variable area airblast fuel injector.

As previously described, the rich zone is regeneratively, convectively cooled. The use of a convective cooling scheme is necessary because any air entering into the rich zone that has not been intimately mixed with the fuel will result in local lean zones, minimizing the benefit of rich burning and causing high-temperature streaks.

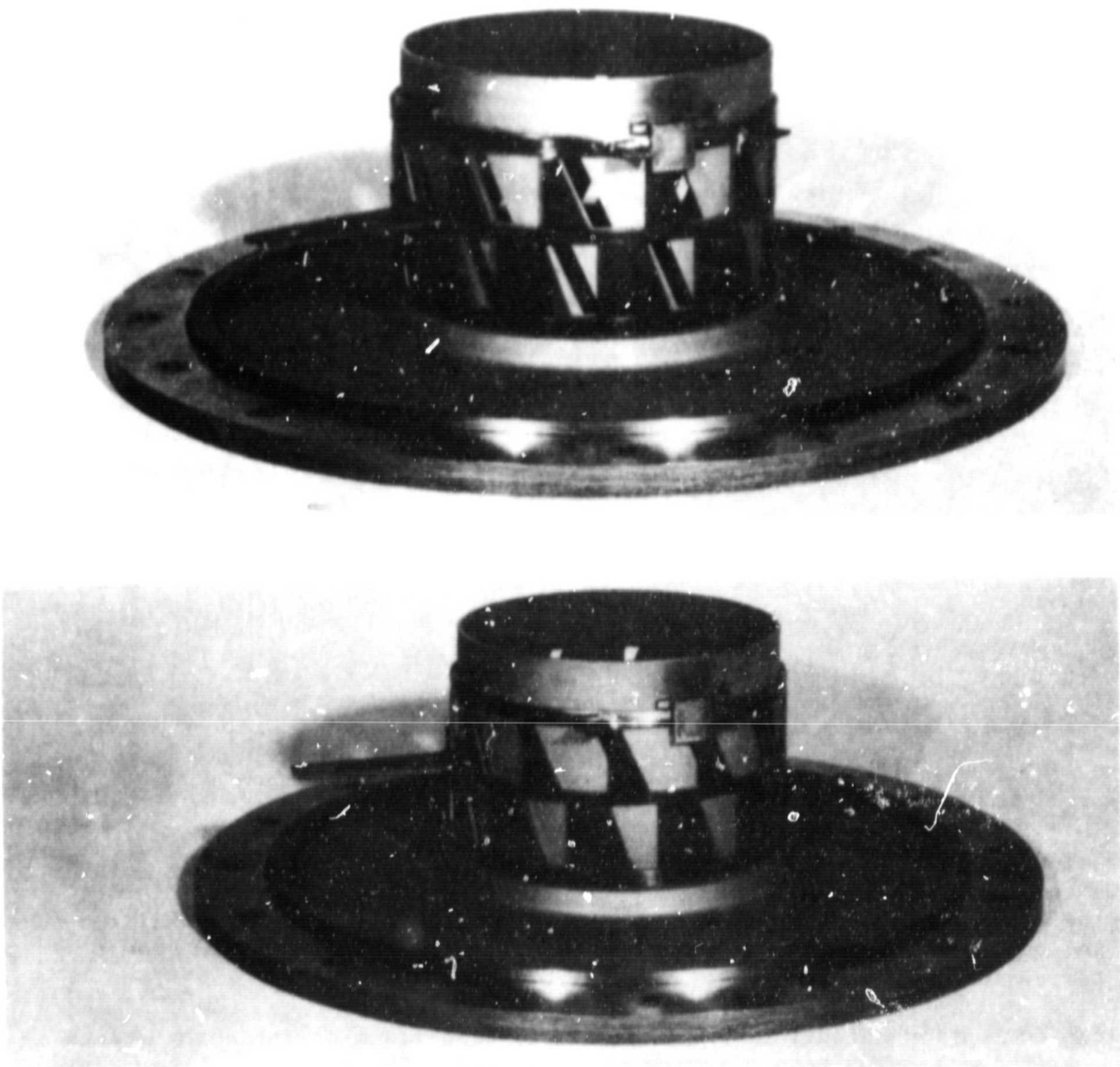
The lean combustion and dilution zone section, downstream of the quick quench mixer, uses Lamilloy®* transpiration wall cooling. The use of Lamilloy minimizes cooling air requirements for fuel-flexible combustors. Lamilloy hole sizes, patterns, and passage heights are specifically designed to satisfy the wall cooling requirements.

The RQL combustor is designed in a building block concept for ease of fabrication, assembly, and modification. All sections are bolted together.

COMBUSTOR MODIFICATIONS

The RQL combustion system was analyzed to determine what modifications were necessary to change from liquid fuels to low- and mid-heating-value gaseous fuels. Based on the existing airblast fuel nozzle and the RQL combustor liner

*Lamilloy is a registered trademark of the General Motors Corporation.



TE81-680

Figure 4. Variable area quick quench zone.

used in the liquid fuel testing, investigations were conducted for the two gaseous fuels (6.15 MJ/m^3 [165 Btu/scf] and 9.76 MJ/m^3 [262 Btu/scf]) at the four steady-state test conditions (maximum rated, maximum continuous, 70% base load, and 50% base load) to determine if any changes were required for the air systems of the RQL combustor liner or the fuel nozzle. The results of this study indicated that both the liner and nozzle air systems were adequate to run the gaseous fuels. Figures 6 through 9 depict the operational range of the RQL combustor at the operating conditions mentioned above for the two gaseous fuels to be tested. As power is increased the equivalence ratio range in the rich zone becomes restricted. However, since it remains within the desired parametric range, no difficulties were anticipated.

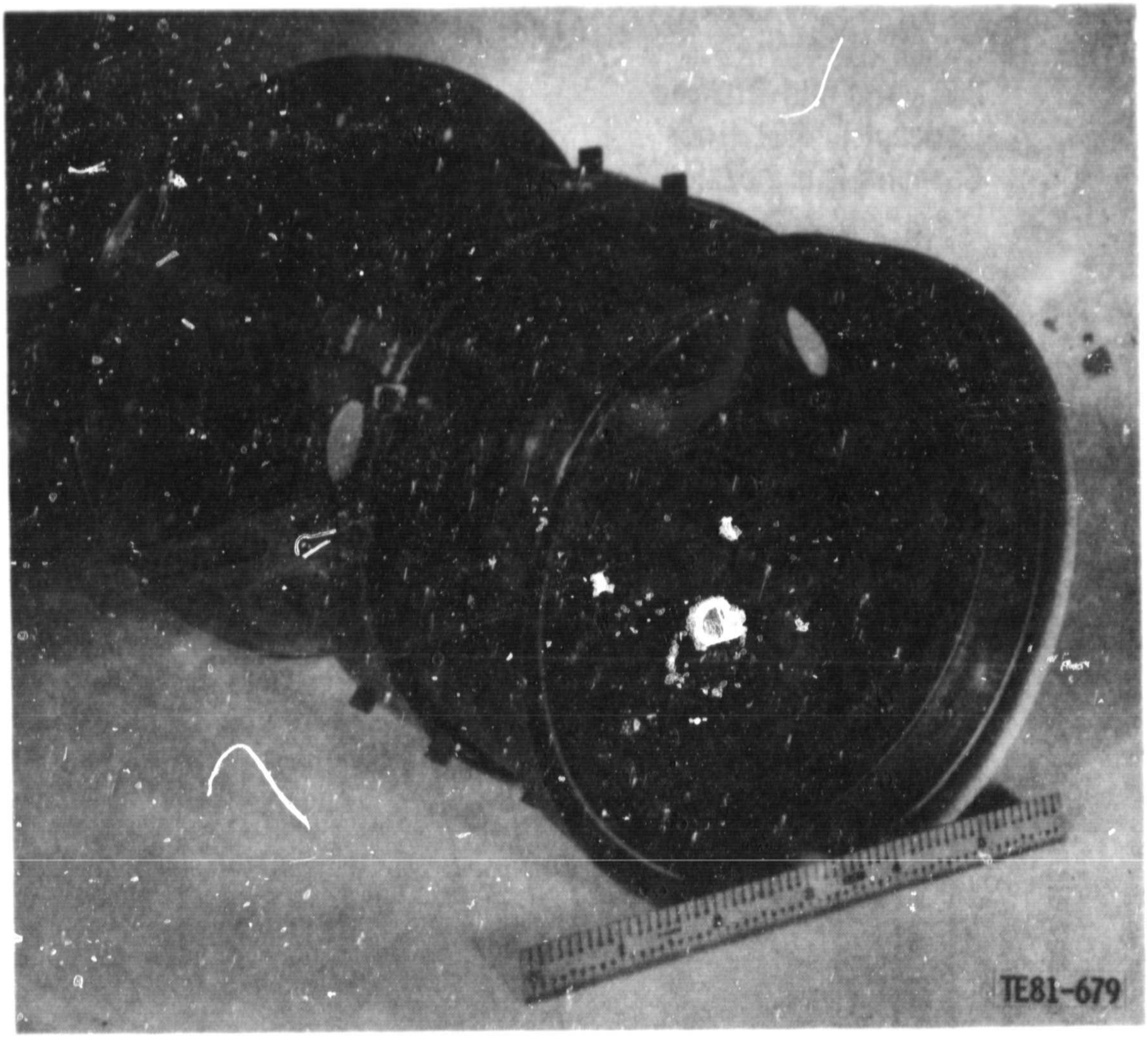


Figure 5. Transpiration-cooled lean combustor variable area dilution zone.

Consequently, the major effort required was to modify the fuel nozzle to properly handle gaseous fuels. It was found that the air-assist liquid fuel nozzle used earlier in the program and shown in Figure 2 could be modified to serve as the gaseous fuel nozzle for this addendum program. The modifications to the nozzle tip are shown in Figure 10. The air-assist details were removed and a gaseous fuel transfer tube and plenum cover (detail 1) were provided to permit the fuel to be injected through the existing fixed axial swirler and radial holes.

The modified nozzle is shown in Figure 11. The top photograph has the variable geometry full open while in the lower photograph the setting is closed for minimum airflow. Note that the variable geometry movement only controls the airflow and not the fuel. Overall combustor equivalence ratio is maintained while zonal distribution is varied.

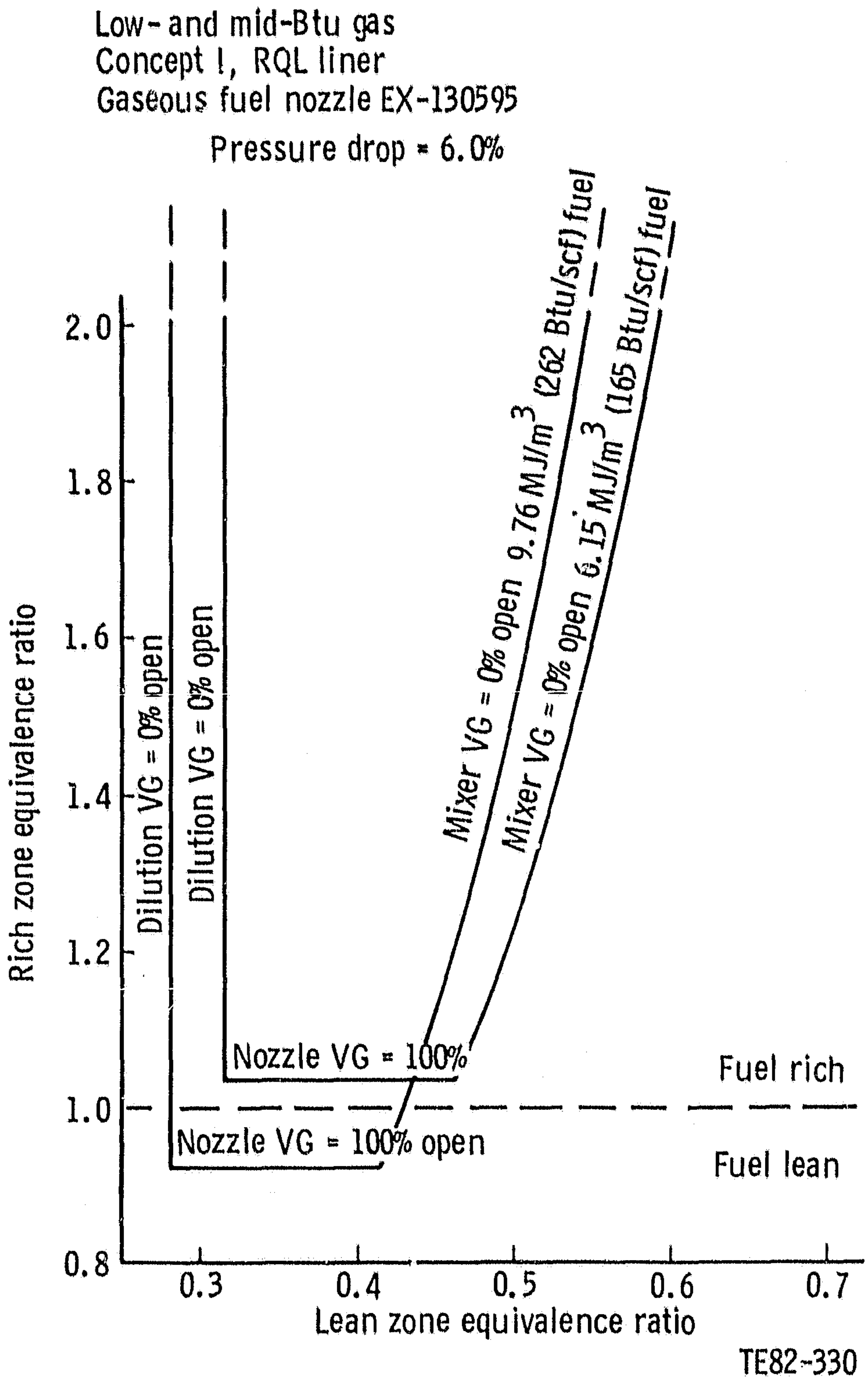


Figure 6. Combustor operational map, 50% power.

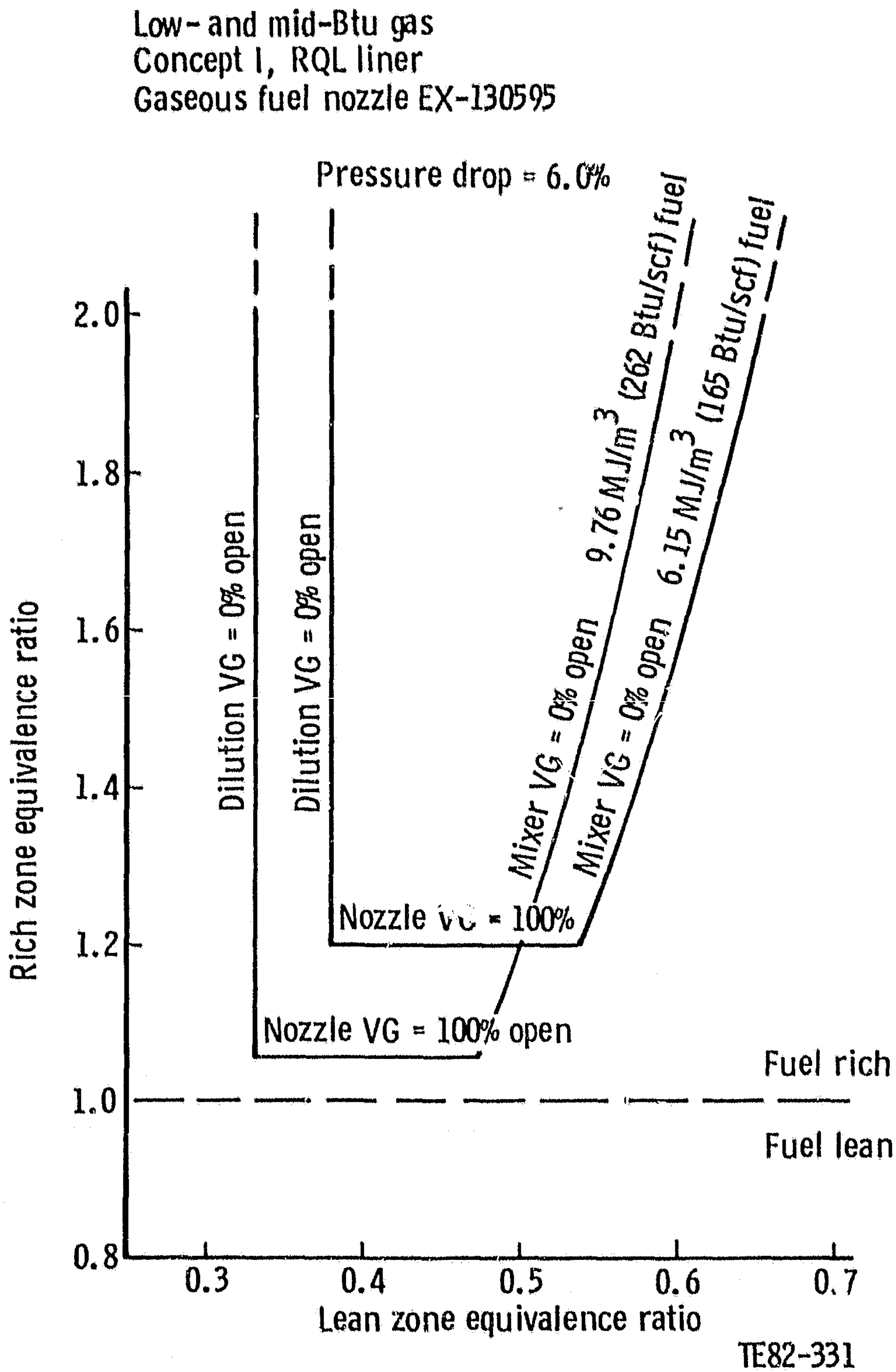


Figure 7. Combustor operational map, 70% power.

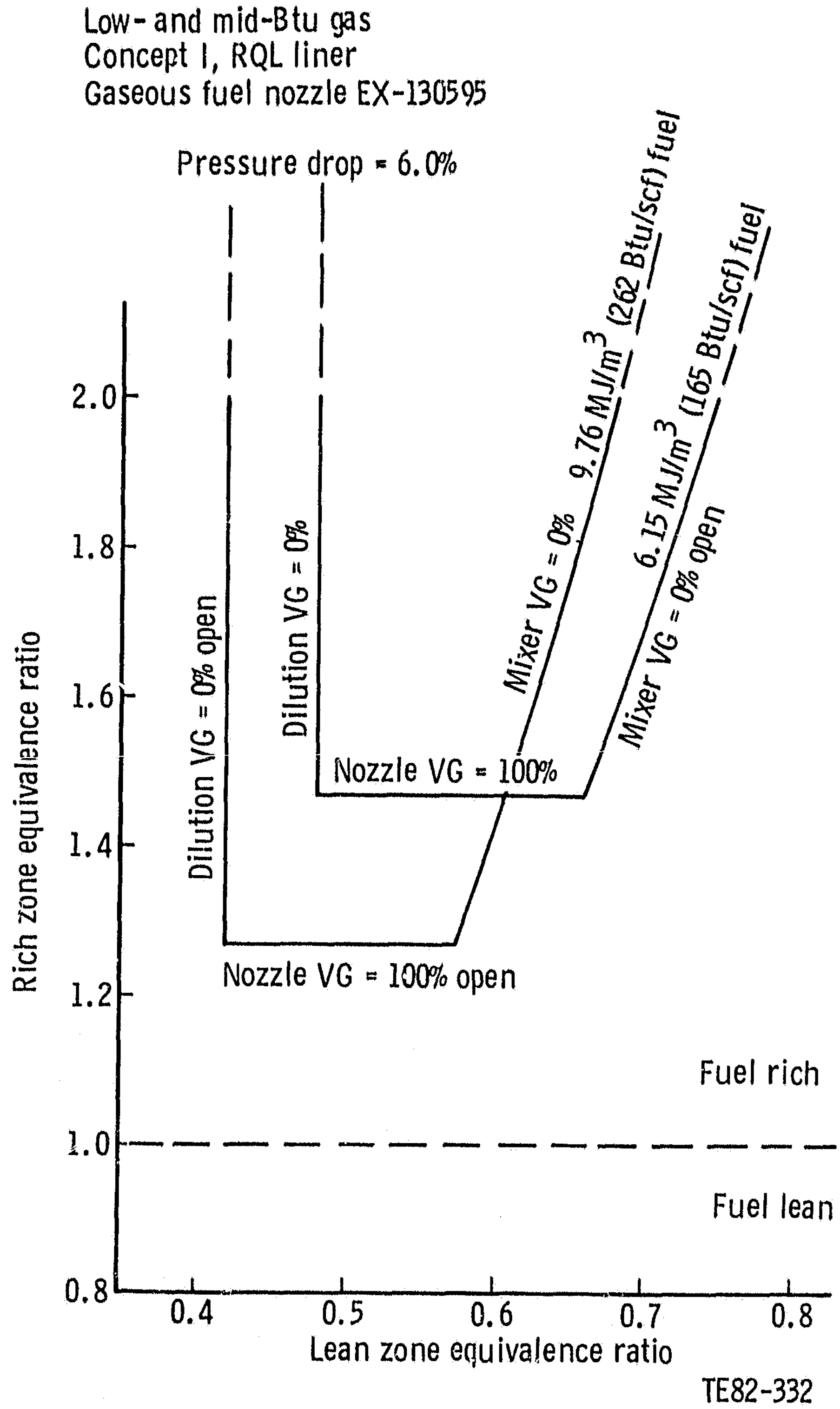


Figure 8. Combustor operational map, maximum continuous power.

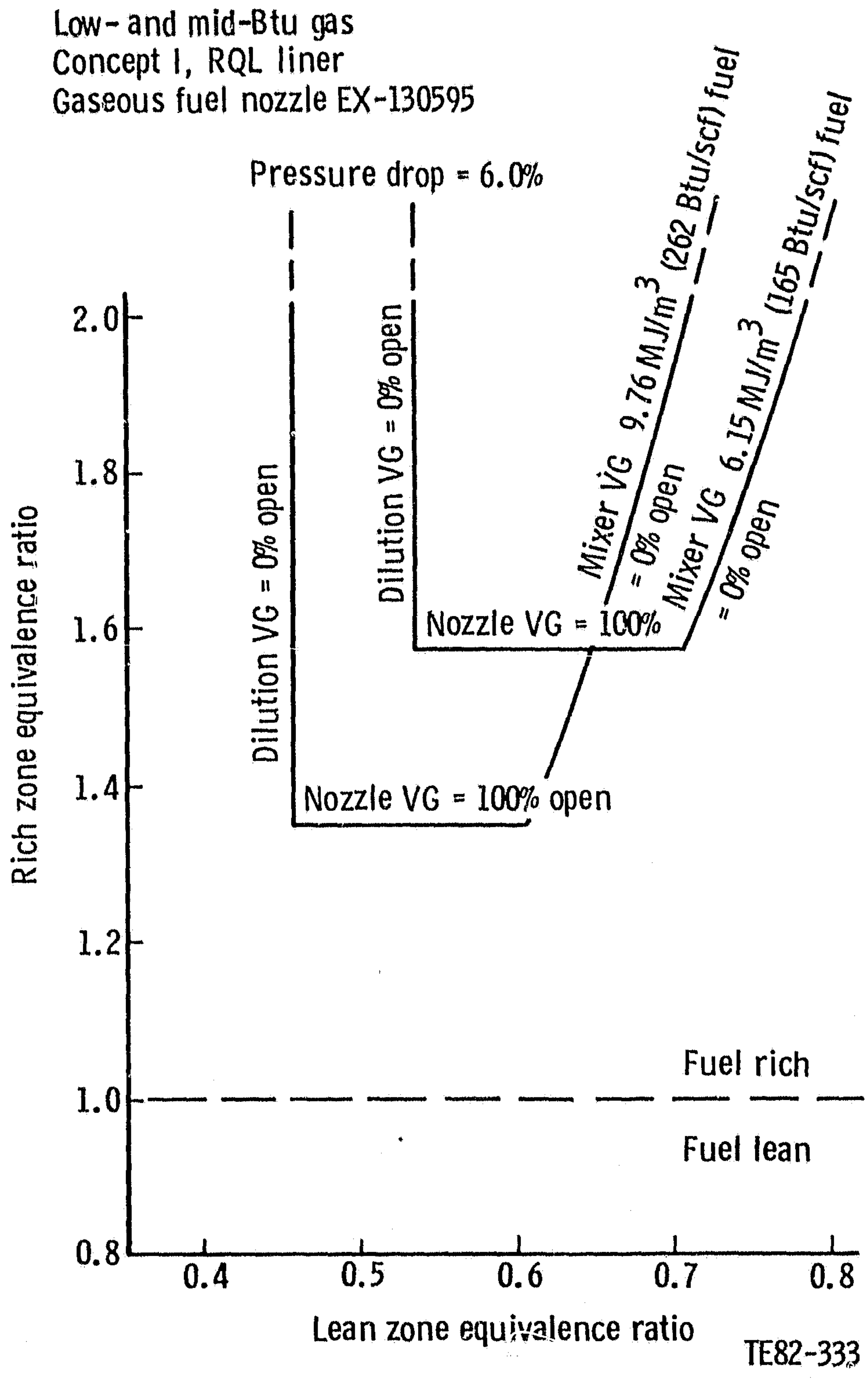


Figure 9. Combustor operational map, maximum rated power.

ORIGINAL PAGE IS
OF POOR QUALITY

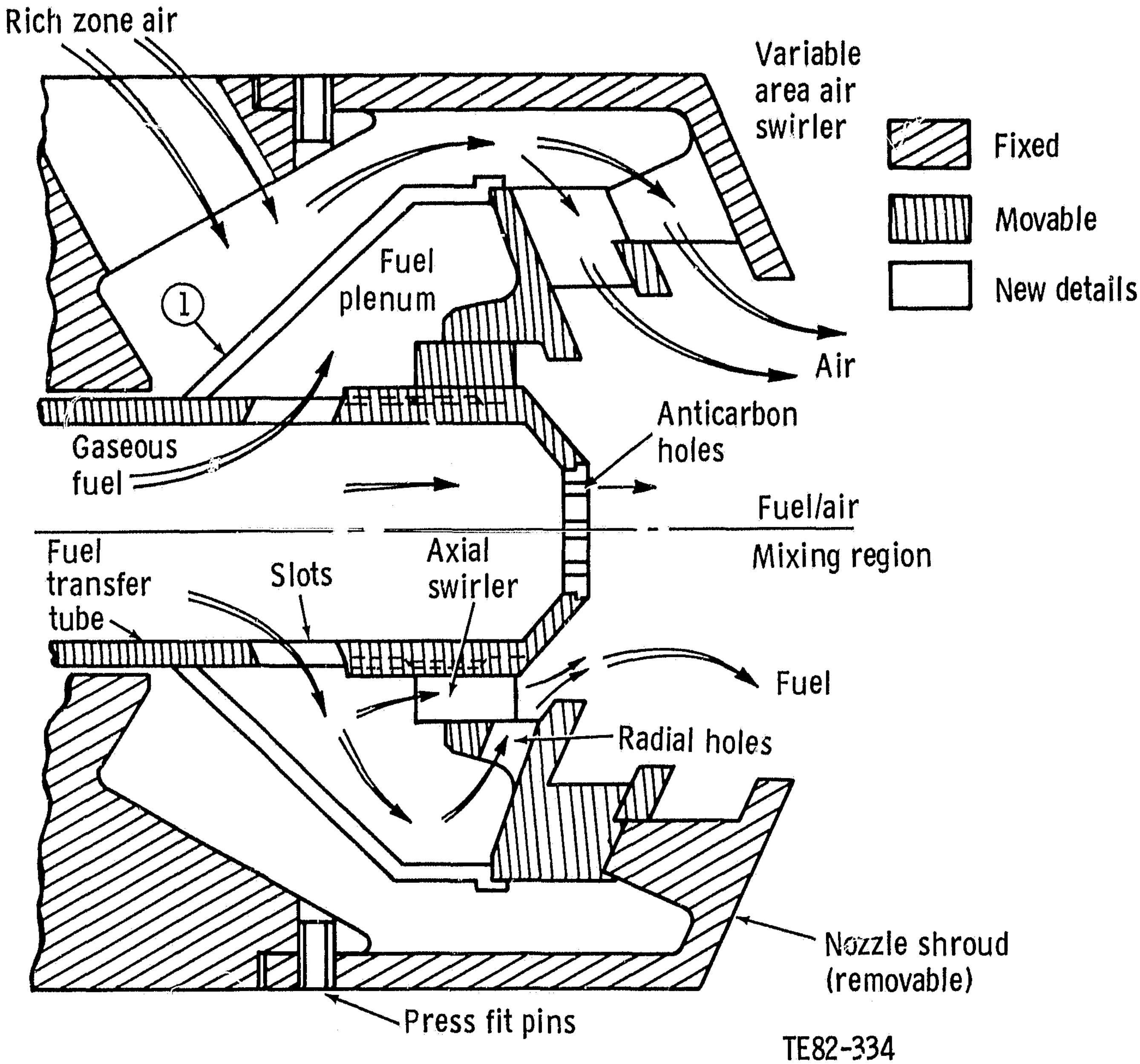


Figure 10. Air-assist nozzle modified for gaseous fuel.

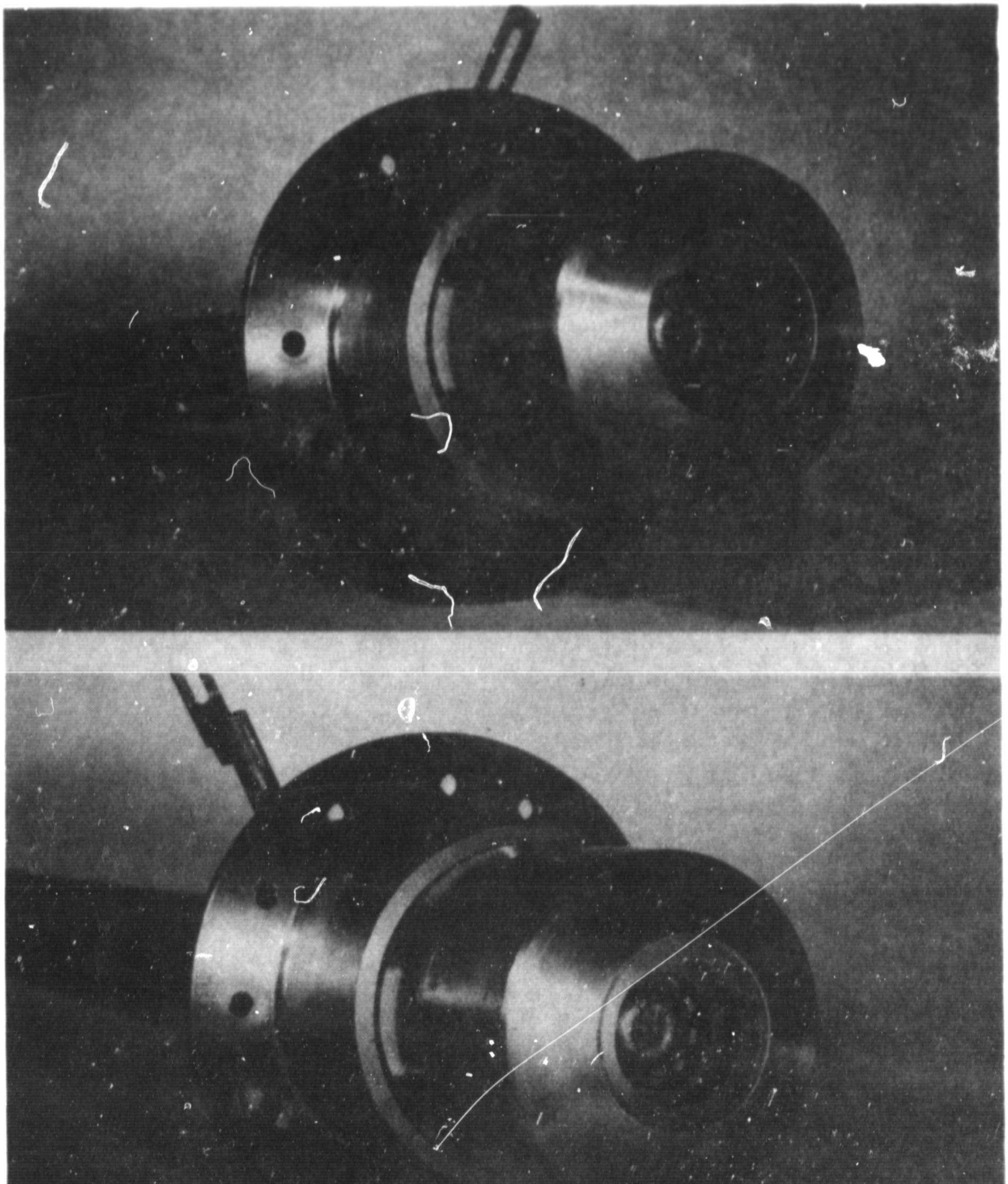


Figure 11. Air-assist liquid fuel nozzle modified for gaseous fuel operation.

PRECEDING PAGE BLANK NOT FILMED

III. FUELS AND FUEL SYSTEM

TEST FUELS

DDA procured two gaseous fuels, mixed specifically for this program, that met the specifications for low heating values (2.98–6.71 MJ/m^3 [80–180 Btu/scf]) and mid heating values (6.71–12.48 MJ/m^3 [180–335 Btu/scf]). The specified chemical composition and principal properties of the test fuels are listed in Table I. The fuels are representative of actual coal-derived gaseous fuels. The gaseous fuels were analyzed for their constituency by the supplier and substantiated by DDA analysis. Measured fuel properties are listed in Table II. Although these test fuels lie outside present DDA industrial engine field experience, the fuels do fall within an envelope of customer-requested fuel application.

Table I.
Specified gaseous fuel properties.

Fuel No. 1 (mid heating value)

Constituent	Molecular weight	Volume--%	Weight--%
Nitrogen	28.01	1.0	1.3
Hydrogen	2.01	37.0	3.6
Carbon monoxide	28.01	50.0	68.9
Carbon dioxide	44.01	12.0	25.9

Average molecular weight = 20.31
Net heat of combustion = 11.38 MJ/kg (4892.8 Btu/lb)
9.78 MJ/m^3 (262.4 Btu/scf)
Stoichiometric fuel/air ratio = 0.338
Stoichiometric air/fuel ratio = 2.96
Specific gravity = 0.701

Fuel No. 2 (low heating value)

Constituent	Molecular weight	Volume--%	Weight--%
Nitrogen	28.00	47.2	55.2
Hydrogen	2.01	17.0	1.4
Carbon monoxide	28.01	28.3	33.0
Carbon dioxide	44.01	4.5	8.2
Methane	16.04	3.0	2.0

Average molecular weight = 23.95
Net heat of combustion = 6.07 MJ/kg (2609.4 Btu/lb)
= 6.15 MJ/m^3 (165.0 Btu/scf)
Stoichiometric fuel/air ratio = 0.605
Stoichiometric air/fuel ratio = 1.65
Specific gravity = 0.827

Table II.
Measured gaseous fuel properties.

Fuel No. 1

Components	Reported concentration --% volume
Hydrogen	36.4%
Nitrogen	1.8%
Carbon monoxide	50.2%
Carbon dioxide	11.6%

Physical data*

Compressibility factor (STP) Z = 0.9992
Specific gravity (air = 1) at 20°C = 0.7047
Heat of combustion = 10.19 MJ/m^3 (273.5 Btu/ft^3)

Fuel No. 2

Components	Reported concentration --% volume
Hydrogen	17.4%
Nitrogen	45.6%
Carbon monoxide	29.7%
Carbon dioxide	4.6%
Methane	2.7%

Physical data*

Compressibility factor (STP) Z = 1.003
Specific gravity (air = 1) at 20°C = 0.8252
Heat of combustion = 6.56 MJ/m^3 (176.0 Btu/ft^3)

*As determined from theoretical calculations

Technical grade ammonia (~99% purity by analysis) was obtained by DDA to simulate FBN in the test program.

FUEL SYSTEM

The fuel system supplies filtered and remotely controllable gas flow at 2413 kPa (350 lb/$in.^2$) delivery pressure. Flow is measured by an ASME orifice.

The gaseous fuel system for this program is shown schematically in Figure 12. The system's essential components include a vented high-pressure trailer, a high-pressure volume reducing station, filters, safety controls, and a flow control and measuring station. The reduced operating pressure of the system was 2413 kPa (350 lb/$in.^2$ gage), which provides a usable gas volume of 1982 m^3 (70,000 ft^3). Ammonia was added to gas fuel No. 1 to simulate FBN as required by the test program.

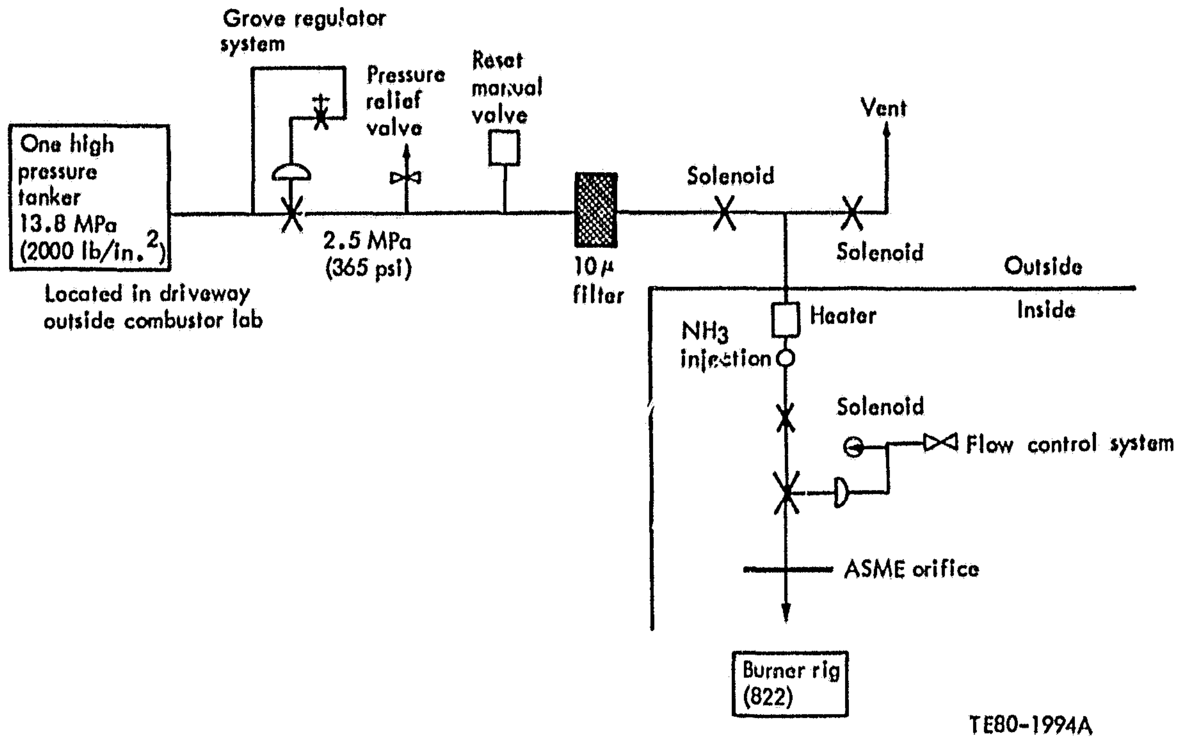


Figure 12. Low Btu gas fuel delivery system.

PRECEDING PAGE BLANK NOT FILMED

IV. EXPERIMENTAL SYSTEMS

RIG TEST FACILITY

The Low/Mid Heating Value Gaseous Fuel Combustion Program was conducted at the Research and Engineering Center (Plant 8) of DDA, located at 2001 S. Tibbs Avenue, Indianapolis, Indiana. The main effort at DDA Plant 8 is directed toward research and development of gas turbine engines and their components. Many major engine development programs have been conducted at the center, including the Low NO_x Heavy Fuel Combustor Concept Program.

The company-owned combustion facility has the following major systems, as shown in the Figure 13 block diagram:

- o Airflow system
- o Fuel system
- o Ignition system
- o Data acquisition and computation system

These systems are briefly discussed in the following paragraphs.

Airflow System

Figure 14 is a schematic of the air supply system, which includes air heaters, airflow control, and pressure and temperature control. Nonvitiated high-pressure air is supplied to the test section by facility compressors through indirect oil-fired heaters, which are used to elevate inlet temperatures to simulate engine compressor discharge characteristics. The exhaust piping is equipped with a water spray bar system for reducing exhaust temperatures of up to 2255 K (3600°F) without detriment to the exhaust system.

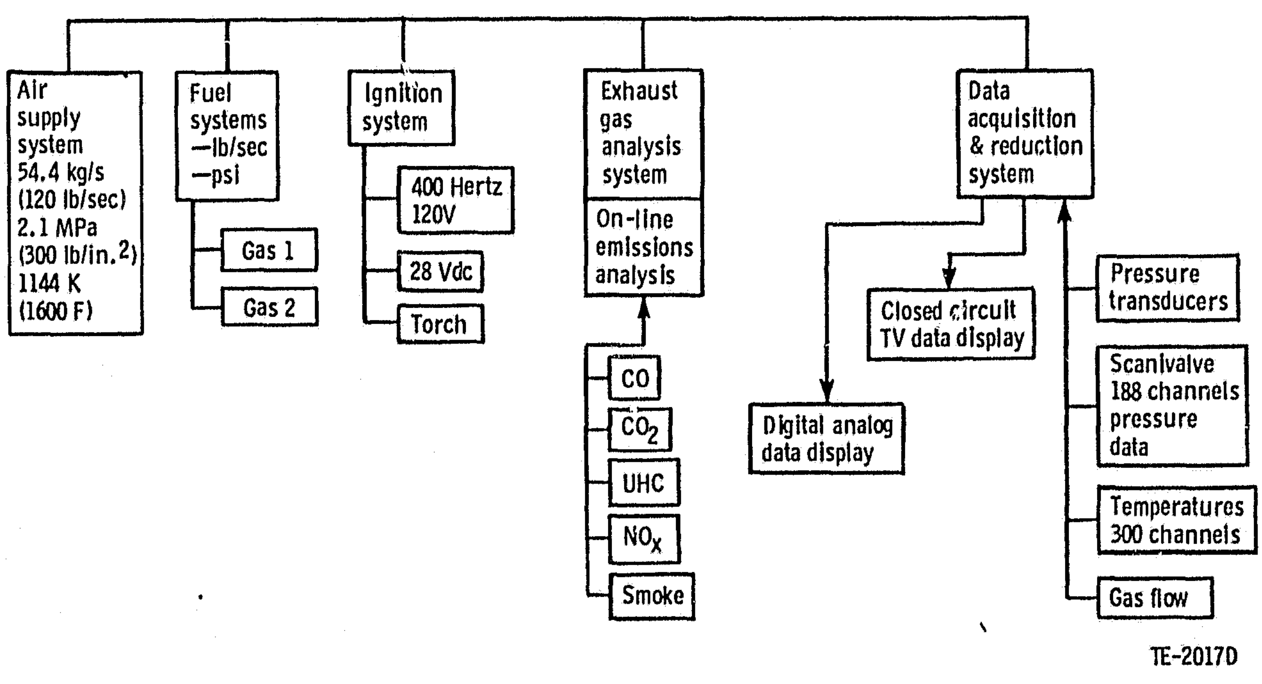


Figure 13. Combustion test facility block diagram.

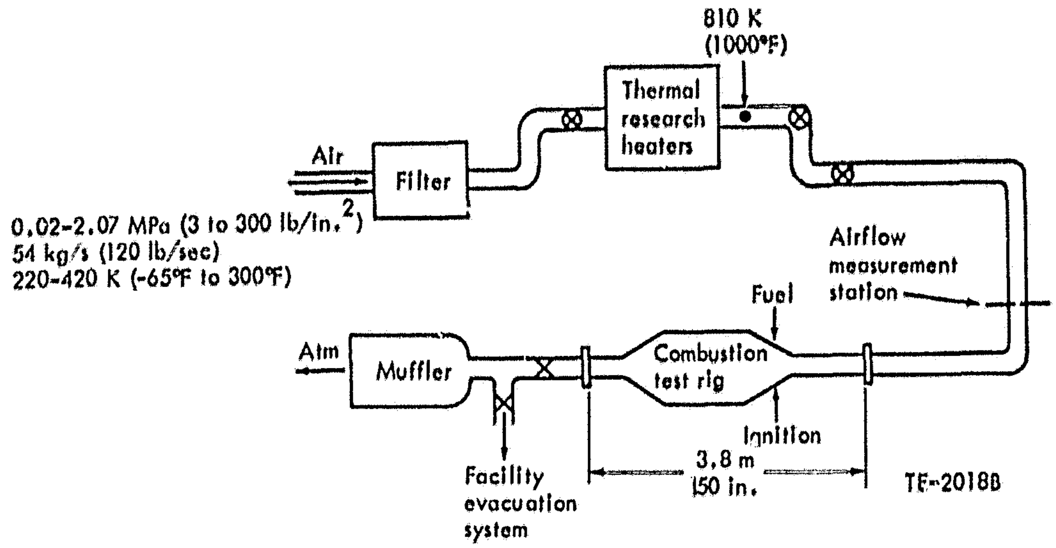


Figure 14. Combustor test facility schematic.

Ignition System

A portable methane/oxygen torch igniter, initiated by an air gap spark source, was employed for all testing in this program.

Data Acquisition and Computation System

Combustor development testing requires extensive pressure and temperature instrumentation for effective performance analysis. These requirements have been met by the following:

- o direct-display pressure gages, manometers, and temperature readout equipment
- o computerized static data acquisition system
- o digital-to-analog data output
- o quick-look (Silvertone) data display of test data including various routines for calculations of flows, temperature rise, etc.

The central digital data acquisition system is built around the SEL 840 MP computer. The SEL 840 system processes incoming data in real time and transmits the answers to the test cell site for visual display so that test stand personnel can observe the current or past configuration operating conditions. The SEL 840 system is linked with an IBM 370/168 computer, which is used for data storage and processing. The digital data acquisition system eliminated most of the hand recording of data and provided a fast, efficient, and accurate means of obtaining final test results.

A 48-port, 4-channel pressure scanning system for recording burner pressures was used. This unit is a differential pressure measuring system using four 0- to 34.7-kPa (0- to 50-lb/in.^{2}) pressure transducers, sensing pressures on 47 ports of the scanning valve. A reference pressure is connected to both sides of the pressure transducer via the forty-eighth port.

Digital data acquired by the SEL data acquisition system are transferred to an IBM Model 370/168 computer where they are stored on disk. These data are converted to engineering units, numerous calculations are performed, and the results are displayed on an IBM Model 2260 scope in the SEL data acquisition center and the combustion facility via closed circuit television for quick-look analysis of the rig operation by the test engineer. Such calculations as airflow, fuel/air ratio, average burner inlet and outlet pressures, inlet flow factor, and emissions are displayed at the test site approximately 1 minute after the data are acquired.

TEST SECTION

The combustor test section, shown in Figure 15, adapts to an existing DDA facility supply and exhaust system with conventional rig hardware sections. The combustor housing is equipped with three variable geometry actuator systems, as well as instrumentation, ignition, fuel, and rig control systems. The independent, remotely actuated variable geometry controls of the air staging to each combustor section allowed testing of numerous combustor configurations (airflow splits) without removing the combustor from the rig. Fuel flow rate and variable geometry movement were remotely controlled from the test cell control room.

Instrumentation

Instrumentation for this program included the items shown in Table III.

Table III.
Test instrumentation.

Parameter	Number	Comments
Airflow	1	ASME standard orifice
Fuel flow	2	Flotron and metering pump
Skin temperature	8	C-A thermocouples
Gas analysis	25	5 rakes, 5 depths* commonly manifolded
Combustor outlet temperature	26**	Pt-Pt 13% Rh thermocouples 4 at 5 depths 1 at 6 depths
Inlet temperature	2	I-C thermocouples
Inlet total pressure	2	1 depth each
Liner static pressures	2	

*Gas analysis probes could alternately provide outlet total pressure.
**Actual number of functional thermocouple elements was considerably less.

ORIGINAL PAGE IS
OF POOR QUALITY

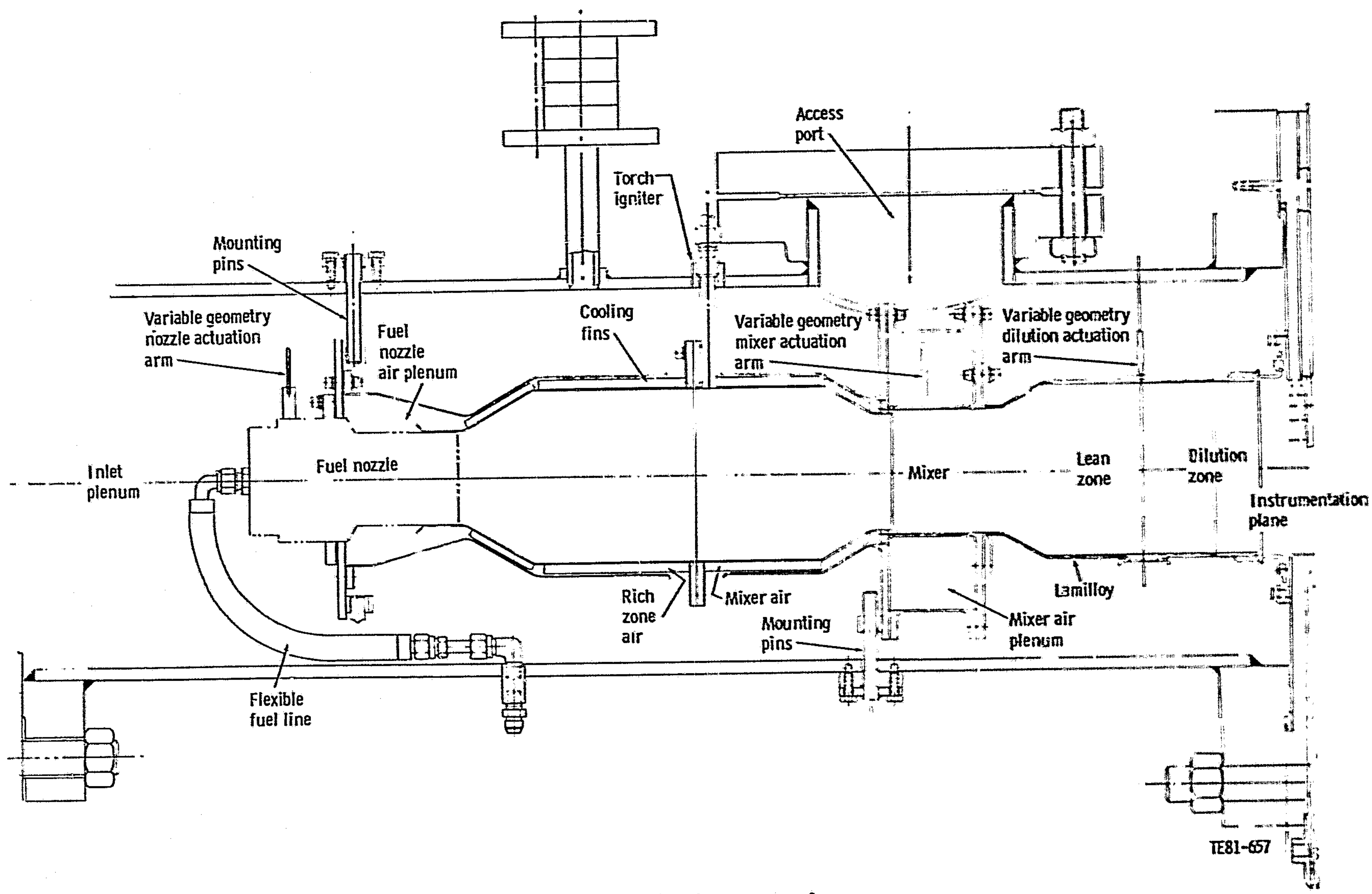


Figure 15. Rig installation.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

Inlet instrumentation for total pressure and temperature included standard DDA probes at two circumferential locations each as shown in Figure 15. Combustor outlet temperatures were measured using five probes (four having five elements and a fifth having six elements) located in the combustor exit instrumentation plane as shown in Figure 16. These probes used a platinum/platinum-rhodium thermocouple junction. The actual number of functional thermocouple elements for this test program was considerably fewer than 26 because no thermocouple refurbishment was included in this contract.

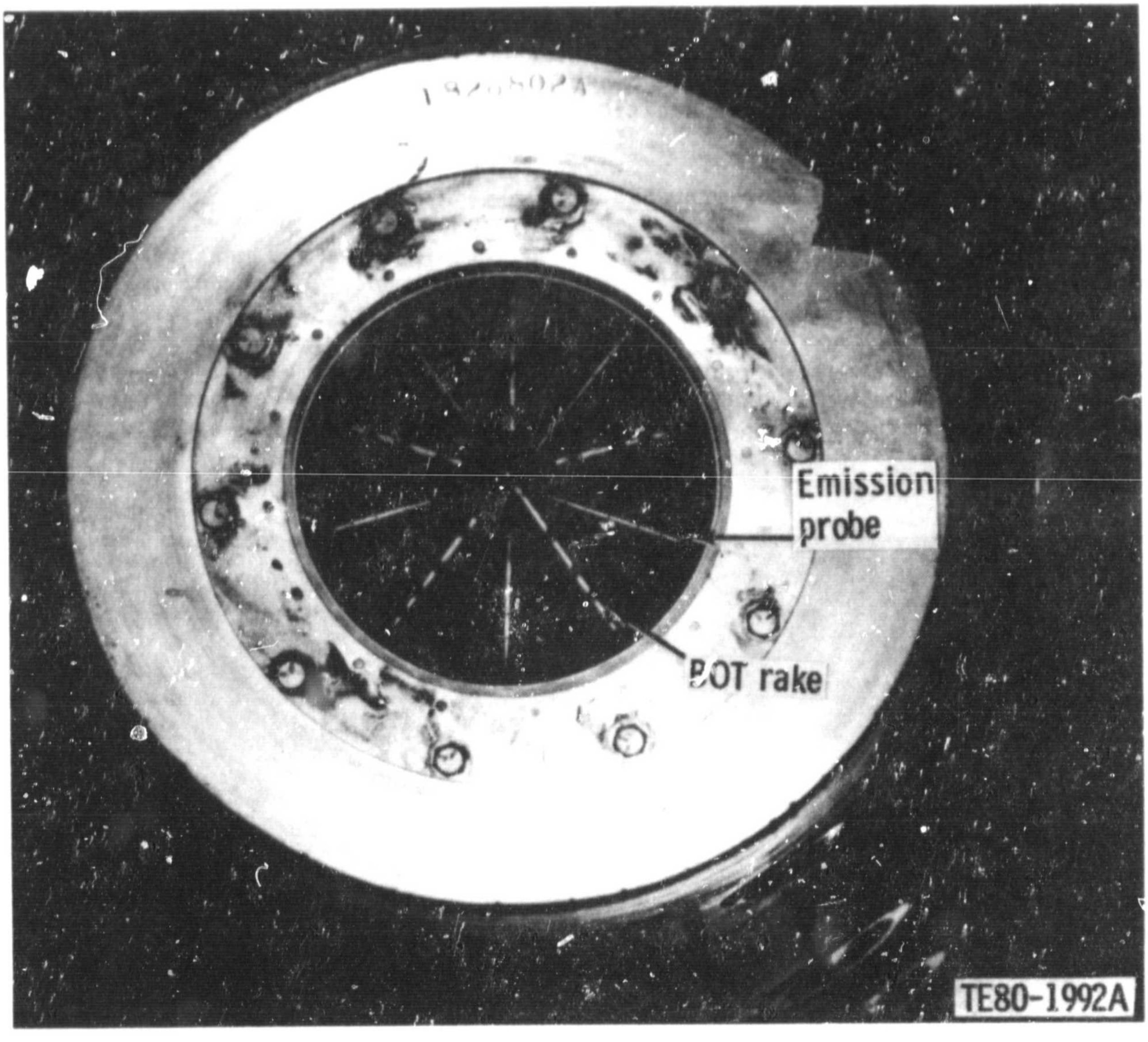


Figure 16. Outlet temperature and emissions probes installed in test rig.

The gaseous emission probes shown in Figure 17 sample five depths at equal areas and are water cooled. These probes are manifolded to a common heated line, which transfers the exhaust sample to the DDA-supplied gas sampling and measuring equipment described below. The probes also can be used for combustor outlet total pressure measurement.

The variable geometry control mechanisms are shown in the rig installation drawing. Position readout of this control system in concert with combustor calibrations provided the necessary data to specify geometric definition and airflow splits of each combustor test configuration.

Eight skin thermocouples were located in the rich zone to monitor the integrity of the hardware during testing. The regenerated inlet air temperature to the rich and quench zones was also measured. The hot gas static pressure at the liner exit was recorded in addition to the nozzle and quench mixer cavity pressures.

Exhaust Gas and Smoke Measurement System

For this combustor development program an on-line exhaust gas measurement system was utilized, which included the exhaust gas composition measurement instruments listed in Table IV.

The SEL acquisition system converted the on-line emissions signals to appropriate units and calculated a fuel-air weight ratio from the exhaust gas composition measurements. This allows an on-site check of the gas sampling validity.

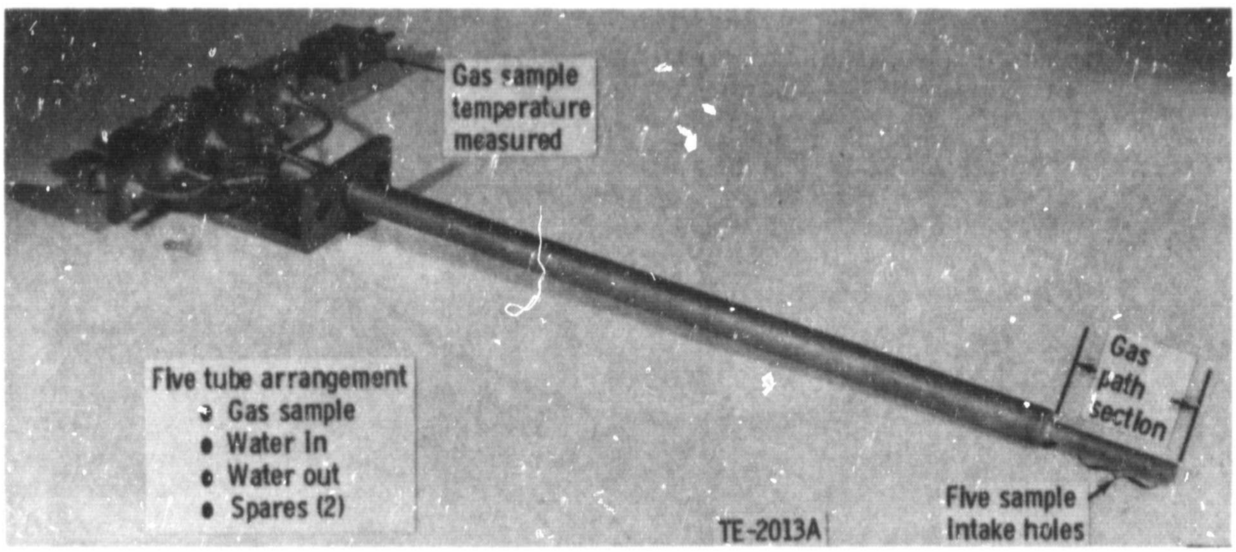


Figure 17. Gas sampling probe.

Table IV.
Exhaust gas sampling instruments.

Ranges--ppm	Accuracies--%
Carbon monoxide (NDIR-Beckman Model 865)	
0 to 100	±2 (full scale)
0 to 500	±1 (full scale)
0 to 2500	±1 (full scale)
Oxides of nitrogen (CL-TECO Model 10A)	
0 to 2.5	±1 (full scale)
0 to 10	±1 (full scale)
0 to 25	±1 (full scale)
0 to 100	±1 (full scale)
0 to 500	±1 (full scale)
0 to 1000	±1 (full scale)
Unburned hydrocarbons (heated FID-Beckman Model 402)	
0 to 10	±1 (full scale)
0 to 50	±1 (full scale)
0 to 100	±1 (full scale)
0 to 500	±1 (full scale)
0 to 1000	±1 (full scale)
Carbon dioxide (NDIR-Beckman Model 864)	
0 to 2	±1 (full scale)
0 to 5	±1 (full scale)
0 to 15	±1 (full scale)

Figure 18 shows a schematic of the smoke measurement system used in this program. This smoke measurement method is in agreement with the SAE recommended practice (ARP 1179).

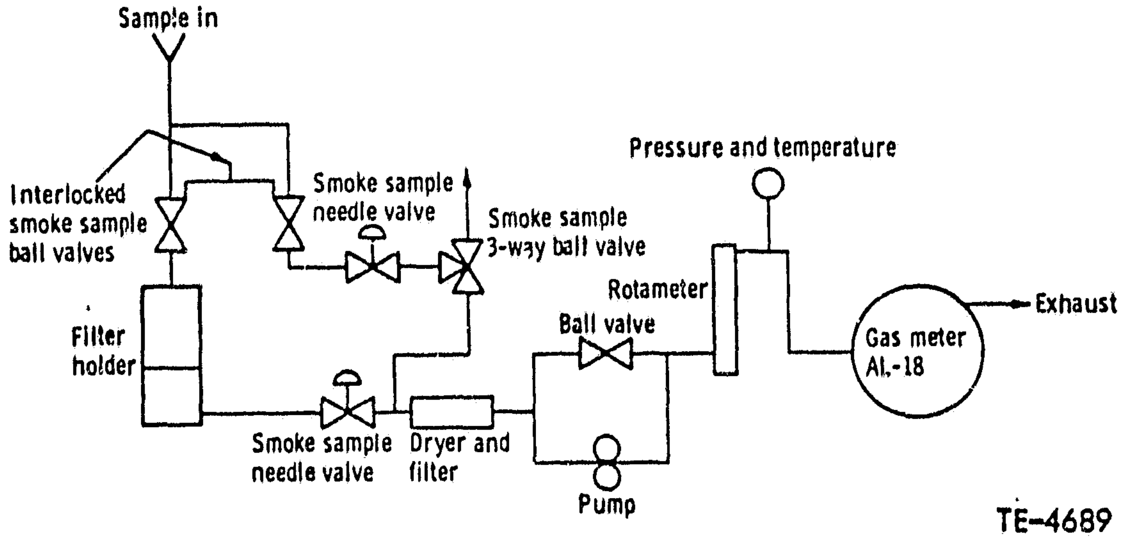


Figure 18. Smoke sampling system schematic.

V. TEST RESULTS

This technology program is an addendum to the "Low No_x Heavy Fuel Combustor Concept Program" and has as its specific purpose the evaluation of the RQL gas turbine combustor burning low- and mid-heating-value gaseous fuels. The program was designed with this goal in mind, and hence limited but pertinent data were recorded. The major development and test effort was spent on the modified concept I RQL combustor because it had proved highly successful in the heavy liquid fuels program. This section presents the significant test data obtained on the RQL combustor modified to burn gaseous fuels. Table V summarizes the number of test points obtained for the major divisions of the testing effort.

Table V.
Summary of test data points recorded.

Combustor	Test type	Fuels*	Data points	Total data points
RQL modified	Performance Parametric	A, B B	27 12	39

*A - Low-heating-value gas
B - Mid-heating-value gas

Development Testing

Major development testing was performed under the heavy liquids program described in Ref. 3. Modifications to the combustor to burn gases were minimal, involving only changes in the fuel injection system. All operational problems involving the original combustor that were encountered and subsequently solved are discussed in Ref. 3. Initial experiments performed using the modified combustor to burn both low- and mid-heating-value range gases revealed no significant problems. As a consequence no additional development testing was required, and the gas phase combustor test program was initiated.

Final Results

Testing of the modified RQL combustor design encompassed two test series: performance testing and parametric testing. In the performance testing both of the gaseous fuels were used. For the parametric testing only the mid-heating-value gas was used. The purpose of the performance tests was to assess the fuel characteristics and operating sensitivity of the modified RQL combustor. The parametric testing involved the addition of 1% to 2.8% (by weight) NH_3 to the mid-heating-value gas to determine possible effects of both NH_3 and FBN as pollutant sources.

All test points correspond closely to the combustor operating conditions of the DDA Model 570-K industrial gas turbine. These operating conditions are summarized in Tables VI and VII.

Table VI.
Engine/combustor operating conditions for low-heating-value gas.

Engine mode	Airflow kg/s (lbm/sec)	Inlet temp. K (°F)	Pressure MPa (psi)	Flow factor $W_a\sqrt{T}/P$	Fuel flow kg/h (lbm/hr)	F/A	Outlet temp. K (°F)
50% load	1.313 (2.895)	559 (546)	0.801 (116)	38.73	598.5 (1319)	0.127	1150 (1610)
70% load	1.461 (3.221)	584 (591)	0.934 (135)	37.78	790.5 (1743)	0.150	1256 (1801)
Max continuous (base load)	1.680 (3.704)	623 (661)	1.142 (166)	36.69	1149.4 (2533)	0.190	1416 (2089)
Max rated (peak load	1.756 (3.871)	638 (688)	1.220 (177)	36.28	1303.2 (2873)	0.206	1478 (2200)

Table VII.
Engine/combustor operating conditions for mid-heating-value gas.

Engine mode	Airflow kg/s (lbm/sec)	Inlet temp. K (°F)	Pressure MPa (psi)	Flow factor $W_a\sqrt{T}/P$	Fuel flow kg/h (lbm/hr)	F/A	Outlet temp. K (°F)
50% load	1.313 (2.895)	559 (546)	0.801 (116)	38.73	298.5 (658)	0.063	1150 (1610)
70% load	1.461 (3.221)	584 (591)	0.934 (135)	37.78	389.6 (859)	0.074	1256 (1801)
Max continuous (base load)	1.680 (3.704)	623 (661)	1.142 (166)	36.69	553.4 (1220)	0.092	1416 (2089)
Max rated (peak load)	1.756 (3.8718)	638 (688)	1.220 (177)	36.28	622.8 (1373)	0.099	1478 (2200)

Inlet temperature, pressure, and airflow were matched as presented in Tables VI and VII. Though the gaseous fuels had considerably different heating values than the liquid fuels used in the basic program the same burner outlet temperature was maintained in this addendum. This is an important parameter affecting pollutant emissions, and determination of these emissions is the primary goal of this addendum. Thus the fuel flow rates for the gases differ from those of the liquids. Stoichiometric fuel/air ratios were computed for both gases from their constituent composition as presented in Tables I and II. Consequently rich and lean zone equivalence ratios reflect this characteristic.

Performance Testing

The modified RQL combustor was tested at four steady-state Model 570-K engine operating conditions. 50% load power, 70% load power, maximum continuous power, and maximum rated power. Idle conditions were not considered. Both the low- and mid-heating-value gases were tested under the conditions listed in Table VIII.

Table VIII.
Performance test operating conditions.

Power setting	$\phi_{rich\ zone}$	$\phi_{lean\ zone}$	Data points
Low-heating-value gas			
50% load	1.25 - 1.50	0.50	3
	1.35	0.45	1
	1.35	0.40	1
70% load	1.35	0.55	1
Maximum continuous	1.47 - 1.8	0.60	3
Maximum rated	1.50	0.60	1
			10 points total
Mid-heating-value gas			
50% load	1.50 - 2.20	0.50	3
70% load	1.50 - 2.20	0.50	3
Max continuous	1.50 - 2.40	0.60	6
	1.50 - 2.20	0.50	3
Max rated	1.80 - 2.20	0.60	2
			17 points total

Figures 19 to 40 present data plots of the adjusted CO, combustion efficiency, corrected NO_x, and maximum combustor liner metal temperatures when both the low- and mid-heating-value gases are utilized in the combustor. All data points are shown on each graph as a function of either the rich zone equivalence ratio or the percent of shaft output power.

For the power levels considered the modified RQL combustor performance was excellent. CO emissions were high (up to 342 ppmv) for the 50% load setting when burning low-heating-value gas but dropped to fewer than 30 ppmv at maximum continuous and maximum rated power, as shown in Figures 19 and 20. High CO emissions for this gas at low-power operation reflect its initial high CO composition and low combustor outlet temperature. Mid-heating-value gas CO emissions (Figures 21 and 22) were fewer than 40 ppmv at 50% power load ($\phi_{rich\ zone} < 1.6$) and decreased to 12-15 ppmv at maximum rated power.

The low CO emission of the mid-heating-value gas reflects both a higher overall flame temperature, Figure 23, compared with the low-heating-value gas and optimization of CO emission as a function of rich zone equivalence ratio. Unburned hydrocarbons were fewer than 6 ppmv for both fuels at all operating power levels, and thus data are not presented. Exhaust smoke was below a 5-10 smoke number, so no data are presented. Combustion efficiencies were above 99.5% for the low-heating-value fuel and 99.8% for the mid-heating value fuel, as illustrated in Figures 24 to 27. Combustion efficiency increased with increasing power level as expected.

Corrected NO_x emissions (Figures 28, 29, and 30) illustrate very low levels (<20 ppmv) for the low-heating-value gaseous fuel at all operating conditions. These low-heating-value gas NO_x emissions appear to slightly decrease with increasing power level, a result not usually expected and contrary to both the data measured using liquid fuels (Figure 31) and mid-heating-value gaseous fuels in this addendum. This apparent discrepancy is due to nonoptimization of the rich zone equivalence ratio at the lower power settings. At higher power settings, operation at rich zone equivalence ratios above 1.5 had no effect on NO_x emission data.

Results of the NO_x emissions from mid-heating-value gas fuel are presented in Figures 32 to 36. Both performance and parametric (NH_3 addition) data points are presented; however, only the former will be discussed in this section. The NO_x values generally increase with increasing power conditions, as shown in Figure 37. Minimum NO_x levels apparently occur at a rich zone equivalence ratio in the region of 2.2. Combustor lean zone equivalent ratio variations between 0.5 and 0.6 had no significant effect on NO_x emission measurements. Comparison of the mid-heating-value gas NO_x emission minimum values to those obtained in the liquids program (Figure 31) reveals some significant changes in operating conditions when burning the two fuels. The minimum NO_x emissions resulting from combustion of the mid-heating-value gas are slightly higher than the minimum values obtained when liquid fuels are burned. Further, the rich zone equivalence ratio for which minimum NO_x emissions are obtained shifts from approximately 1.3 for the liquids to approximately 2.2 for the mid-heating-value gas. These phenomena were initially anticipated; as both of the gases used in this program contain few if any hydrocarbons (the low-heating-value gas has less than 3% methane by volume), the primary mechanism for NO_x production is thermal.

The principal reactions governing the formation of NO from molecular nitrogen during the combustion of fuel/air mixtures are fairly well understood and have been described by Zeldovich and others. The amount of NO formed is dependent upon temperature, as well as oxygen and nitrogen concentrations. These generalizations regarding thermal NO also apply to combustion of clean liquid fuels, i.e., low FBNs burning at rich equivalence ratios. Thus the NO emissions resulting from combustion of ERBS fuel below $\phi \approx 1.35$, (Figure 31), primarily reflects thermal NO production. If adequate mixing for both the liquid and gaseous fuels is assumed, a thermochemical equilibrium computation of combustor temperature profiles indicates that a typical hydrocarbon liquid fuel has a combustion temperature between that of the low- and mid-heating-value gases (Figures 23 and 38). An example from these computations is illustrated in Table IX.

Table IX.
Combustion temperatures at $\phi = 1.35$.

Low-heating-value gas	Liquid	Mid-heating-value gas
2075 K (3275°F)	2300 K (3680°F)	2445 K (3941°F)
This result predicts the observed trend of measured NO_x emissions:		
$NO_{\text{low-heating-value gas}} < NO_{\text{Liq fuel}} \leq NO_{\text{mid-heating-value gas}}$		

The level of NO emissions from the combustion of gaseous fuels, simulating those obtained from coal gasification processes, is a direct function of both gas composition and heating value. Higher-heating-value gases (those with more hydrogen) will require increased rich zone equivalence ratios to minimize the NO_x emission. Thus, a variable geometry RQL combustion system can conceptually meet emission standards when operating with a wide range of gaseous fuels.

The maximum liner metal temperatures utilizing the low- and mid-heating-value gases are presented in Figures 39 and 40. The RQL regenerative/convective cooled combustion system permits operation at equivalence ratios in the rich zone which minimizes pollutant emissions. This has the effect of appreciably reducing the liner maximum metal temperature for mid-heating-value gaseous fuels as is clearly evident in Figure 40.

Parametric Testing

After performance testing the RQL modified combustor over a wide range of rich zone equivalence ratios (with some limited variation in lean zone), a series of parametric tests was defined to evaluate the NO_x emission sensitivity of the combustor to gaseous FBN. This effect was simulated by the addition of 1% to 2.8% NH_3 (by weight) to the mid-heating-value gaseous fuel. The choice of NH_3 as the additive was dictated by the knowledge that this compound may be contained in some of the sulfur clean-up processes being considered in the production of gaseous fuels from coal. Further, NH_3/air mixtures undergoing combustion are known to produce unusually large amounts of NO through the formation of hydrogen - nitrogen - oxygen intermediate species. It is also quite probable that NH_3 combustion in the presence of carbon (contained in CO and CO_2 of the mid-heating-value gas) and air yields the typical C-H-N intermediate species found in FBN liquid fuel combustion that can produce significant amounts of NO. As such, this compound was considered an excellent simulant additive to the mid-heating-value gas to determine the ability of the RQL combustor to minimize any potential increased NO_x emissions due to different chemistry than that involved when the gas alone was used as a fuel.

Parametric tests were performed at the operating conditions described below:

Table X.
Parametric test operating conditions.

Power setting mid-heating-value gas	$\phi_{rich\ zone}$	$\phi_{lean\ zone}$	% NH_3 added	Data points
50% load	1.8	0.5	1.0-2.8	2
	2.2	0.5	1.0	1
70% load	1.8	0.5	1.0	1
	2.2	0.5	1.0-2.5	2
Max continuous	1.5	0.5	1.0	2 (Identical check tests)
	2.0	0.6	1.0	1
	2.2	0.6	1.0	1
	2.4	0.6	1.0	1
Max rated	2.2	0.6	1.0	1
			Total points	12

The corrected NO_x emission data in ppmv as a function of rich zone equivalence ratio are presented in Figures 32 to 36. Results of the NH_3 additive combustion tests indicate that at the lower load (50 and 70%) settings NO_x emission increased slightly with measured addition of NH_3 up to one percent. This occurred when the combustor was operated at rich zone equivalence ratios less than 2.2. Operation at $\phi_{rich\ zone}$ = 2.2 or addition of NH_3 above 1% produced no measurable effects with regard to NO_x emissions. At the higher power settings 1% NH_3 addition at lower rich zone equivalence ratios produced no significant change in NO_x emission levels. At these same power settings this amount of NH_3 addition at higher rich zone equivalence ratios either produced no change or slightly lower NO_x emission levels. (See Figures 34 and 35.) Summaries of the effects of NH_3 addition at the lower power settings on NO_x emission levels are presented in Figures 41 and 42. These figures depict the results described above as functions of the FBN level present in the NH_3. As previously indicated, significant addition of NH_3 to mid-heating-value gaseous fuels operating at rich zone equivalance ratio above 2.0 to 2.2 have little or no effect on measured NO_x emission levels. Thus, a variable geometry RQL combustion system can conceptually meet emission standards when operating with a wide range of gaseous fuels even should they contain appreciable amounts of FBN.

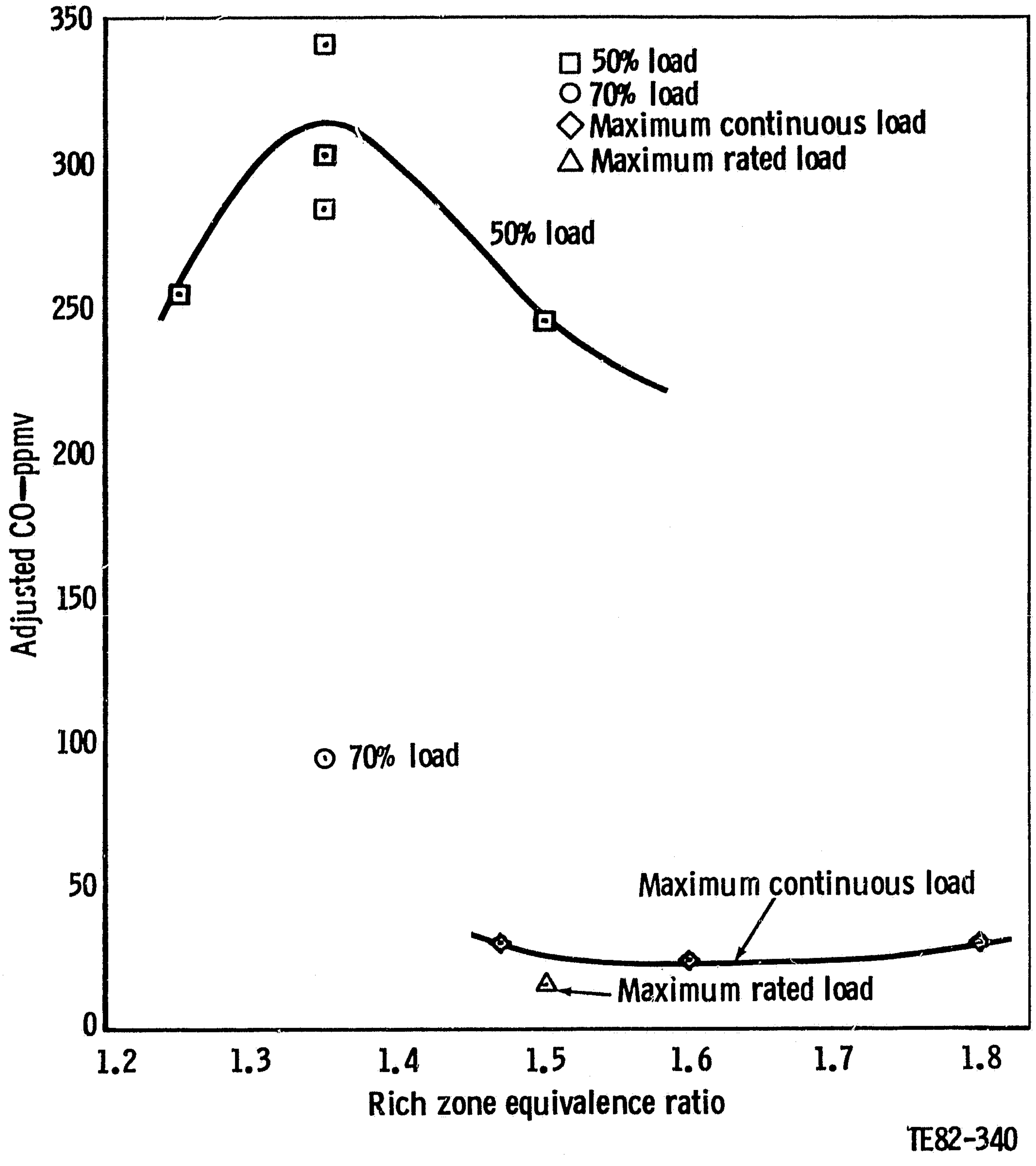


Figure 19. Adjusted CO emissions for low-heating-value gas fuel versus rich zone equivalence ratio.

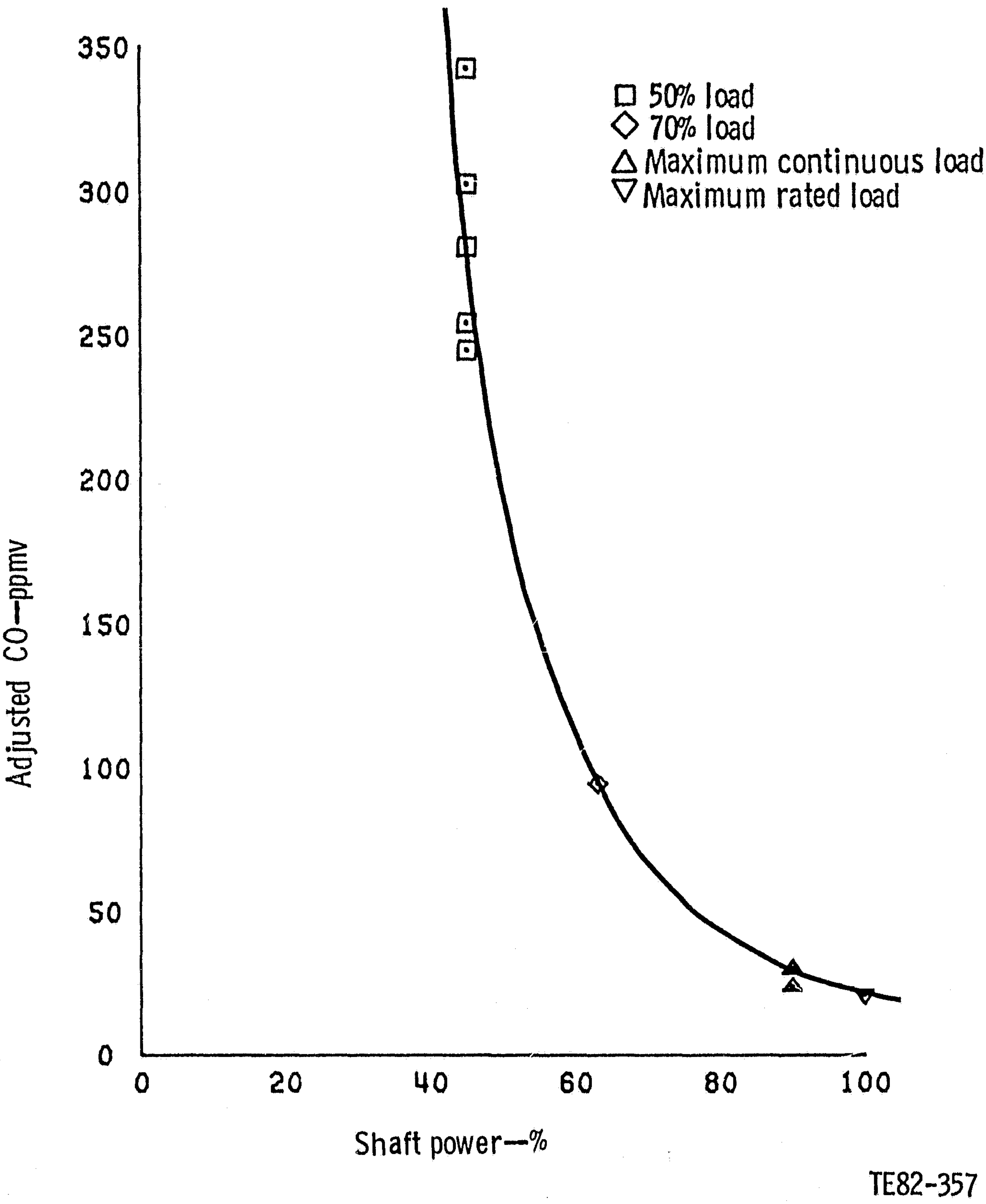


Figure 20. Adjusted CO emissions for low-heating-value gas fuel versus output shaft power level.

ORIGINAL PAGE IS
OF POOR QUALITY

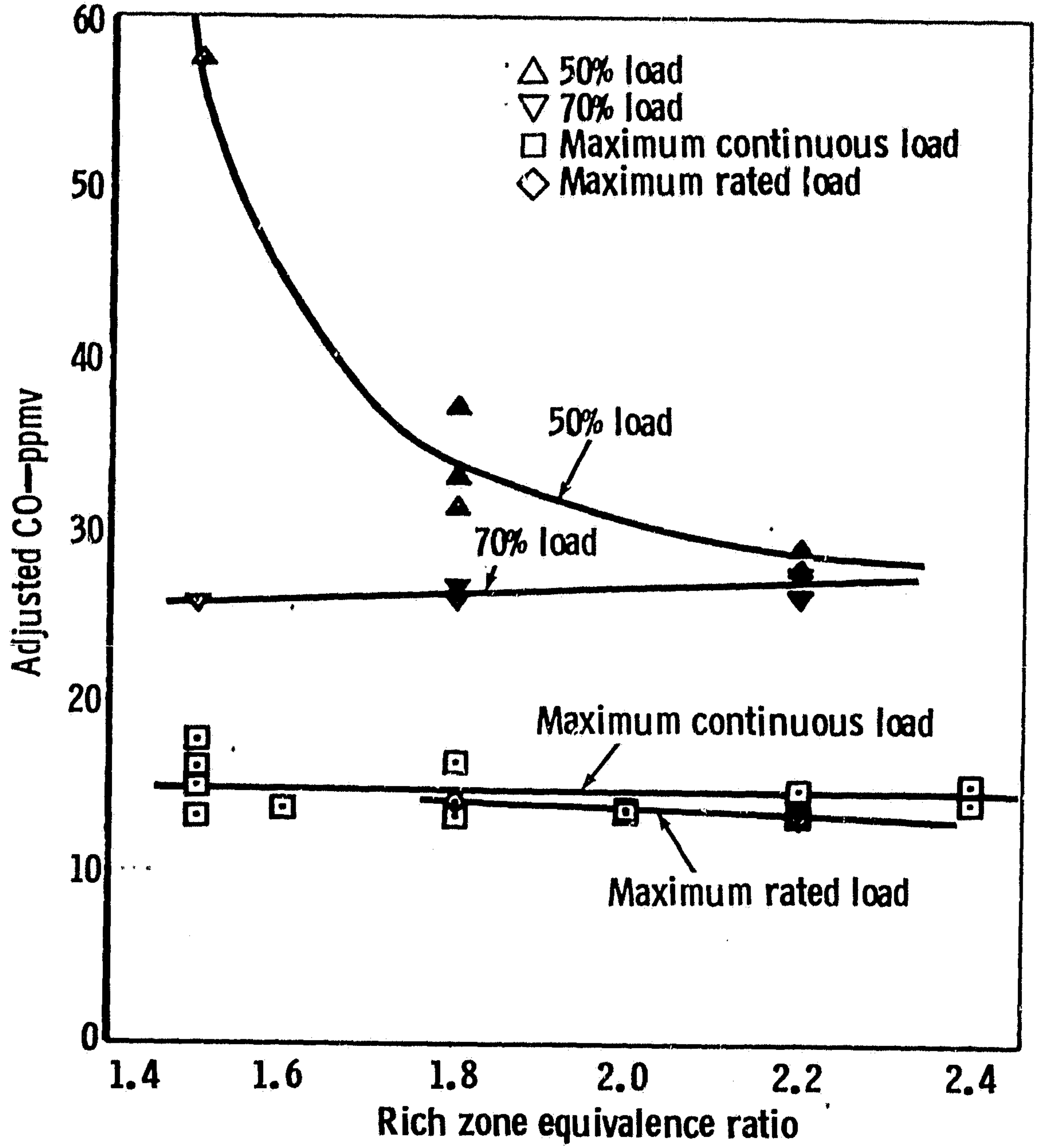


Figure 21. Adjusted CO emissions for mid-heating-value gas fuel versus rich zone equivalence ratio.

ORIGINAL PAGE IS
OF POOR QUALITY

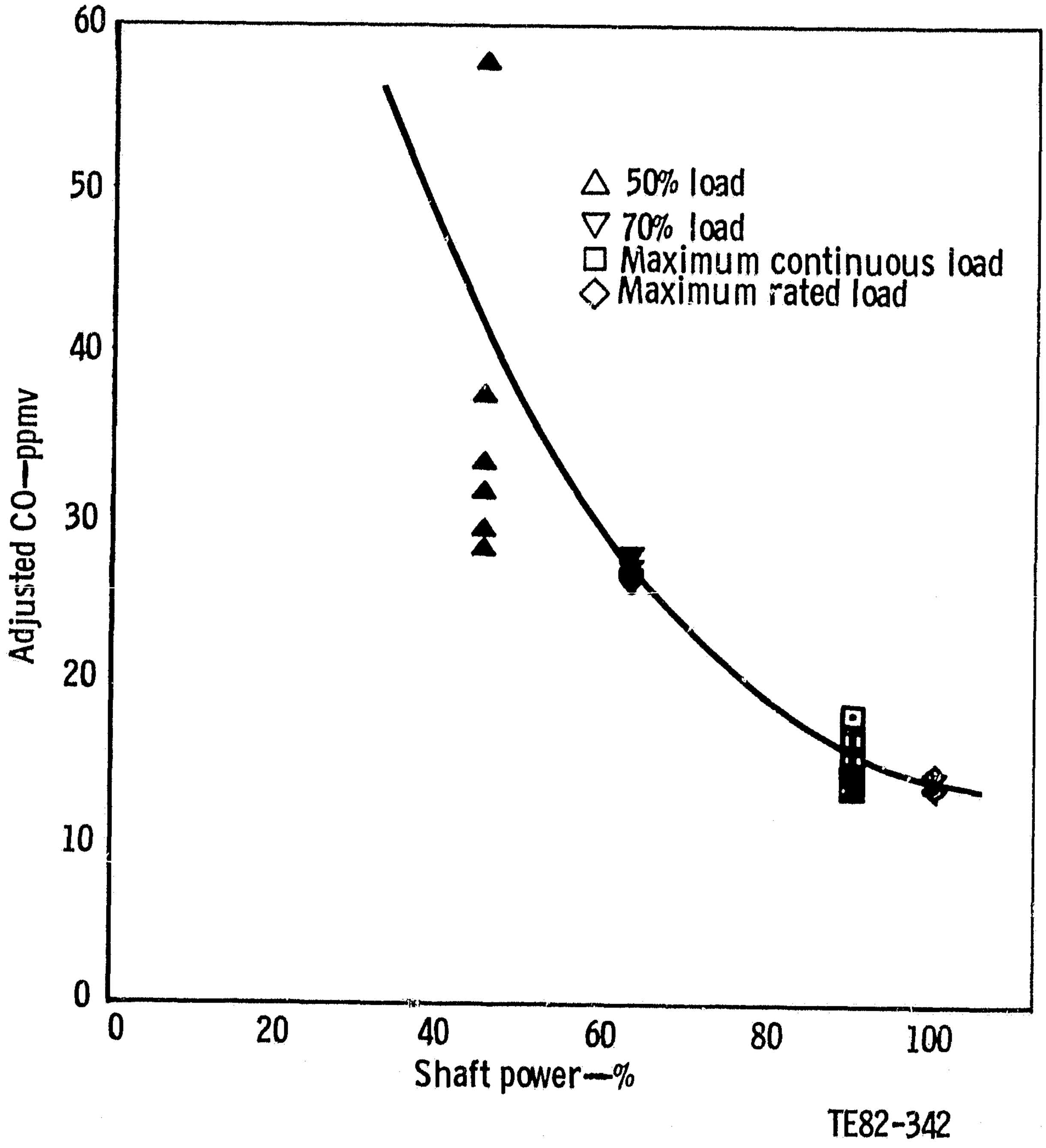


Figure 22. Adjusted CO emissions for mid-heating-value gas fuel versus output shaft power level.

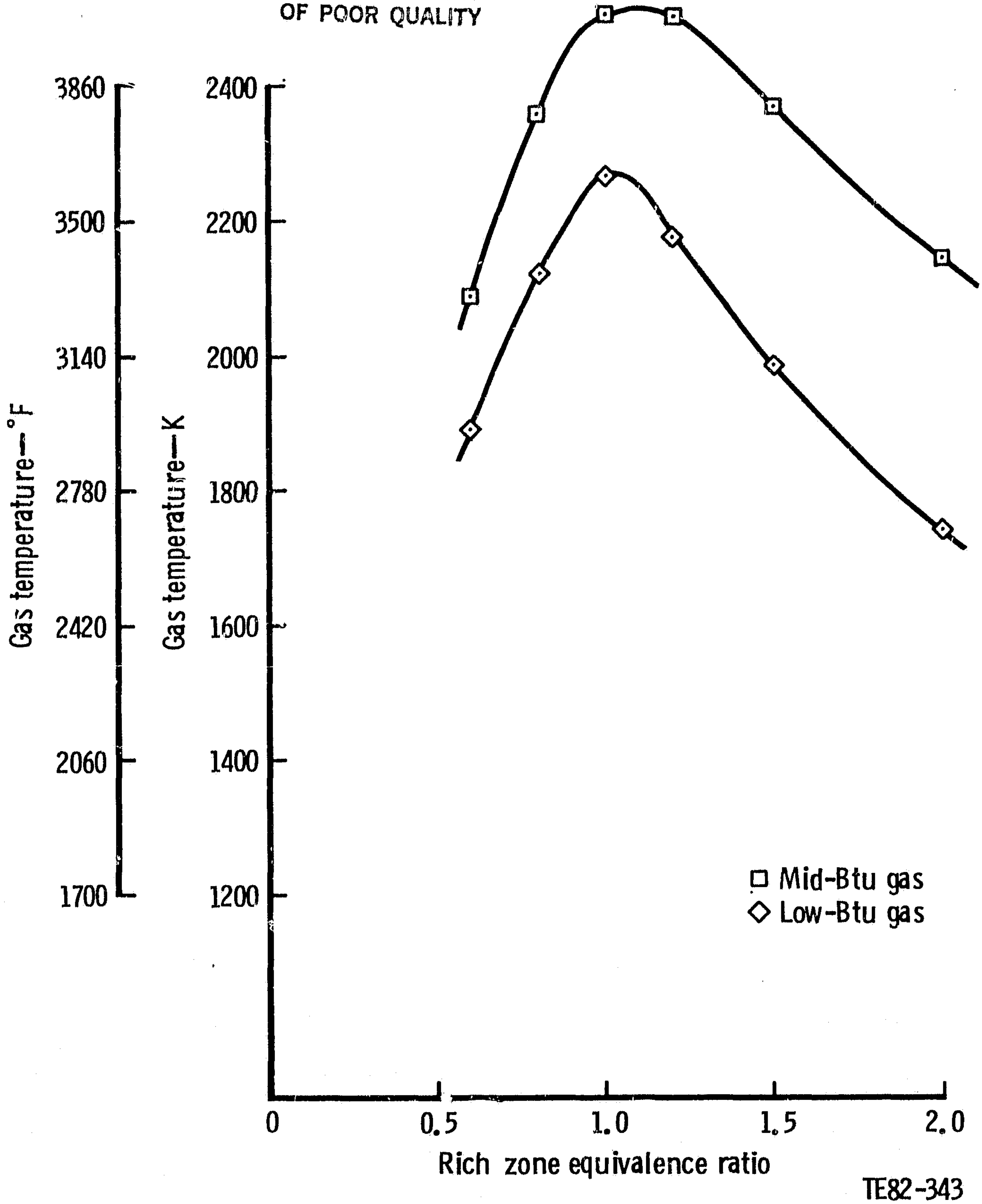


Figure 23. Theoretical gas temperatures for low- and mid-heating-value gaseous fuels versus rich zone equivalence ratio.

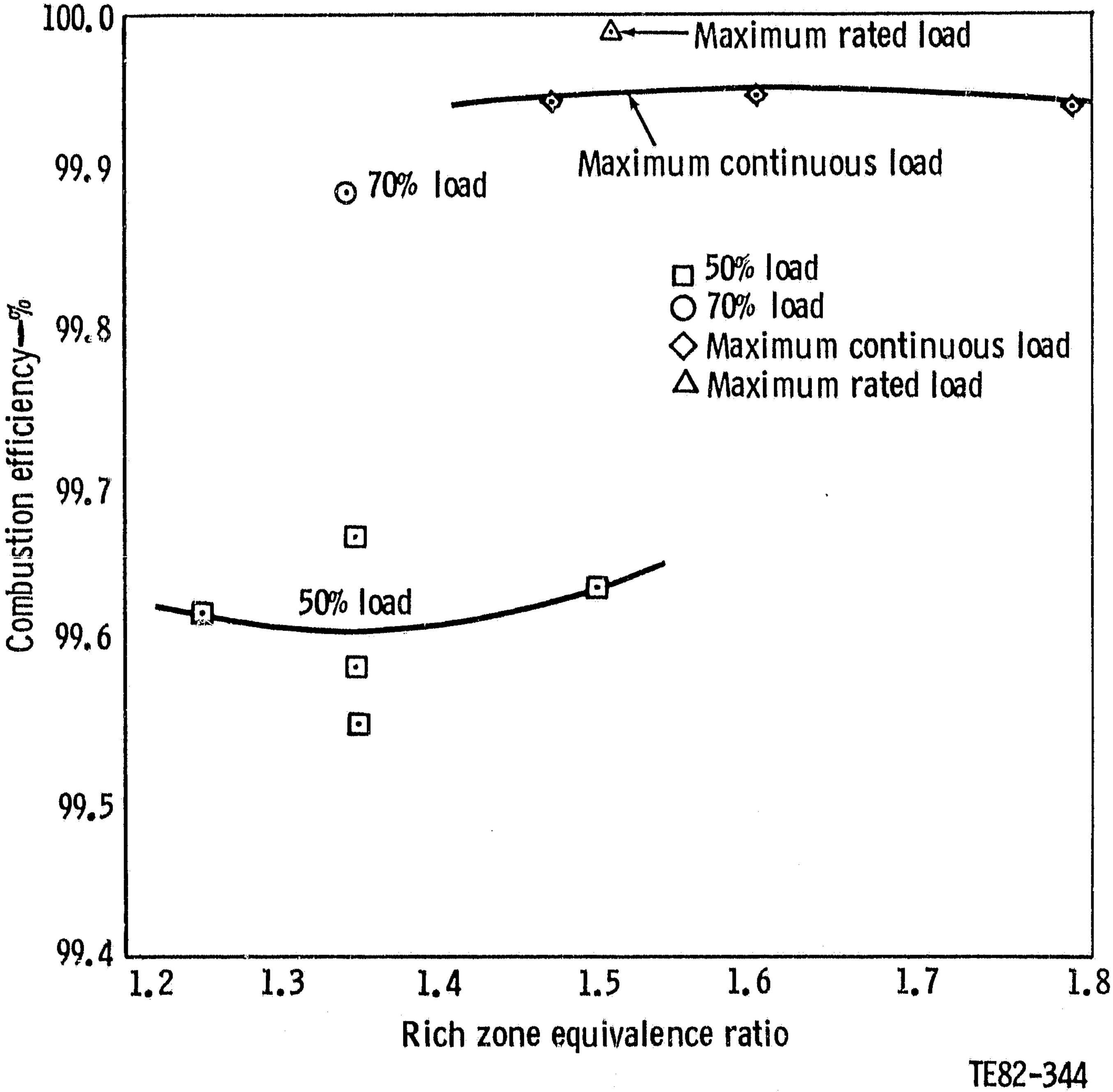


Figure 24. Combustion efficiency for low-heating-value gas fuel versus rich zone equivalence ratio.

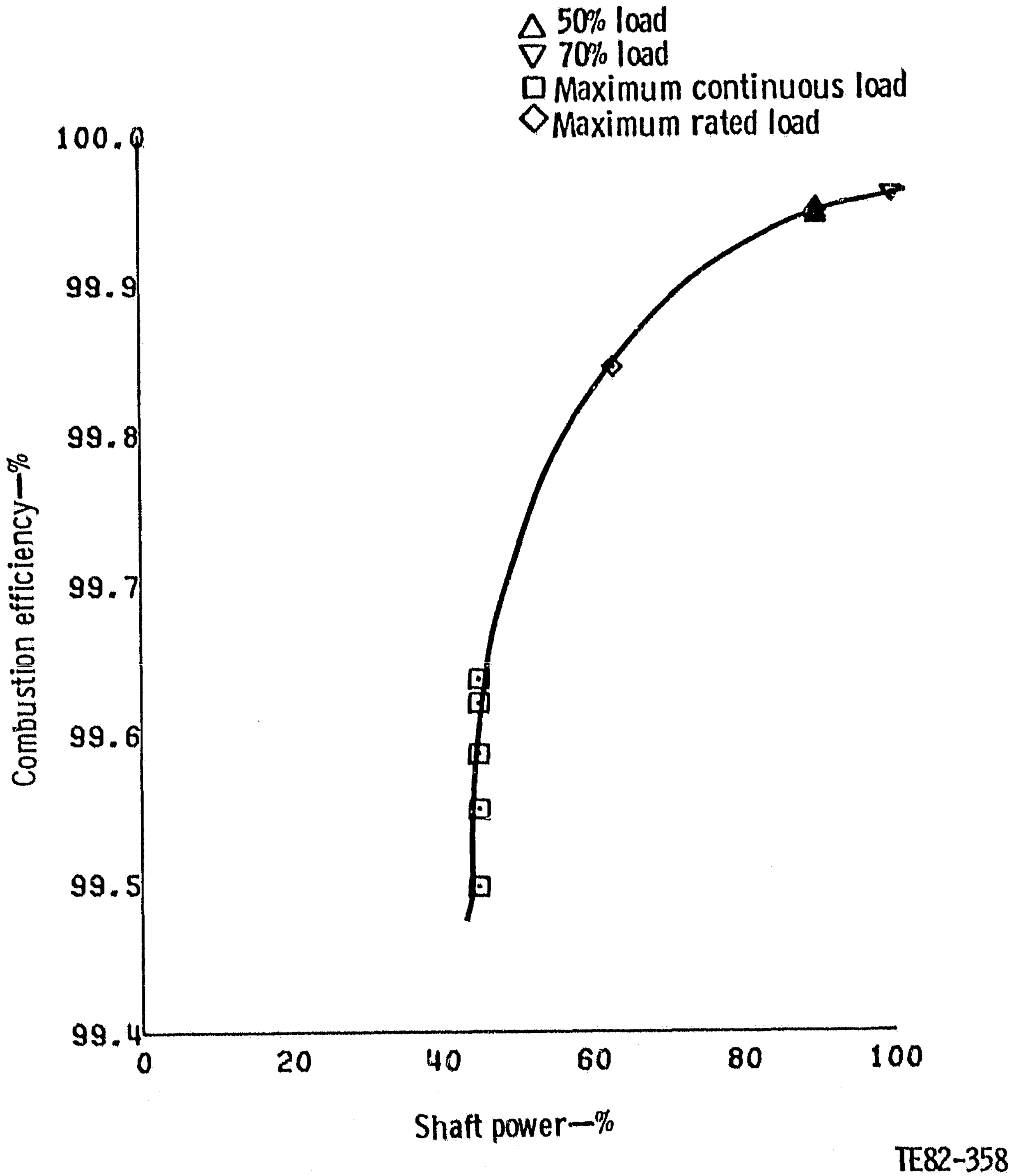


Figure 25. Combustion efficiency for low-heating-value gas fuel versus output shaft power level.

ORIGINAL PAGE IS
OF POOR QUALITY

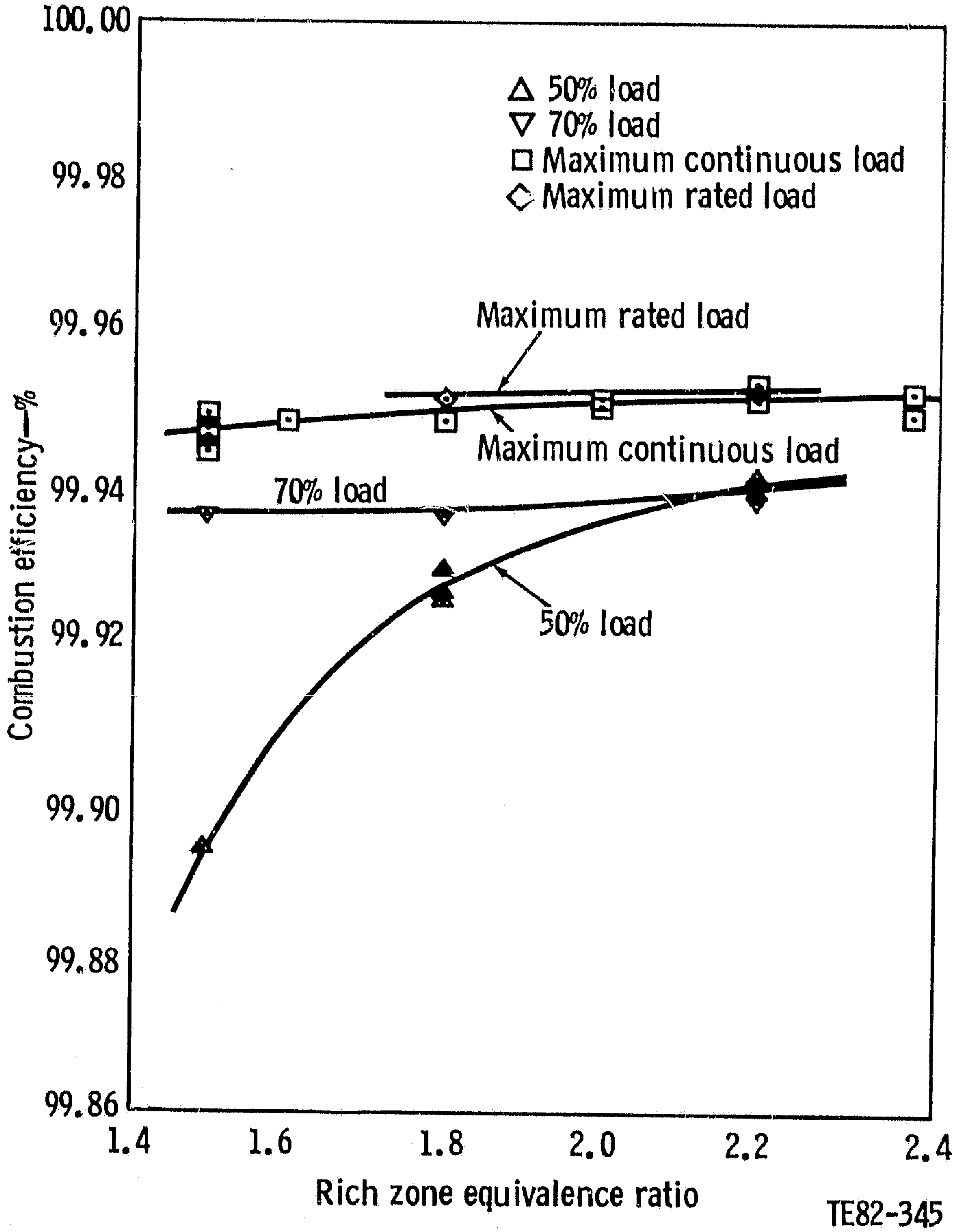


Figure 26. Combustion efficiency for mid-heating-value gas fuel versus rich zone equivalence ratio.

ORIGINAL PAGE IS
OF POOR QUALITY

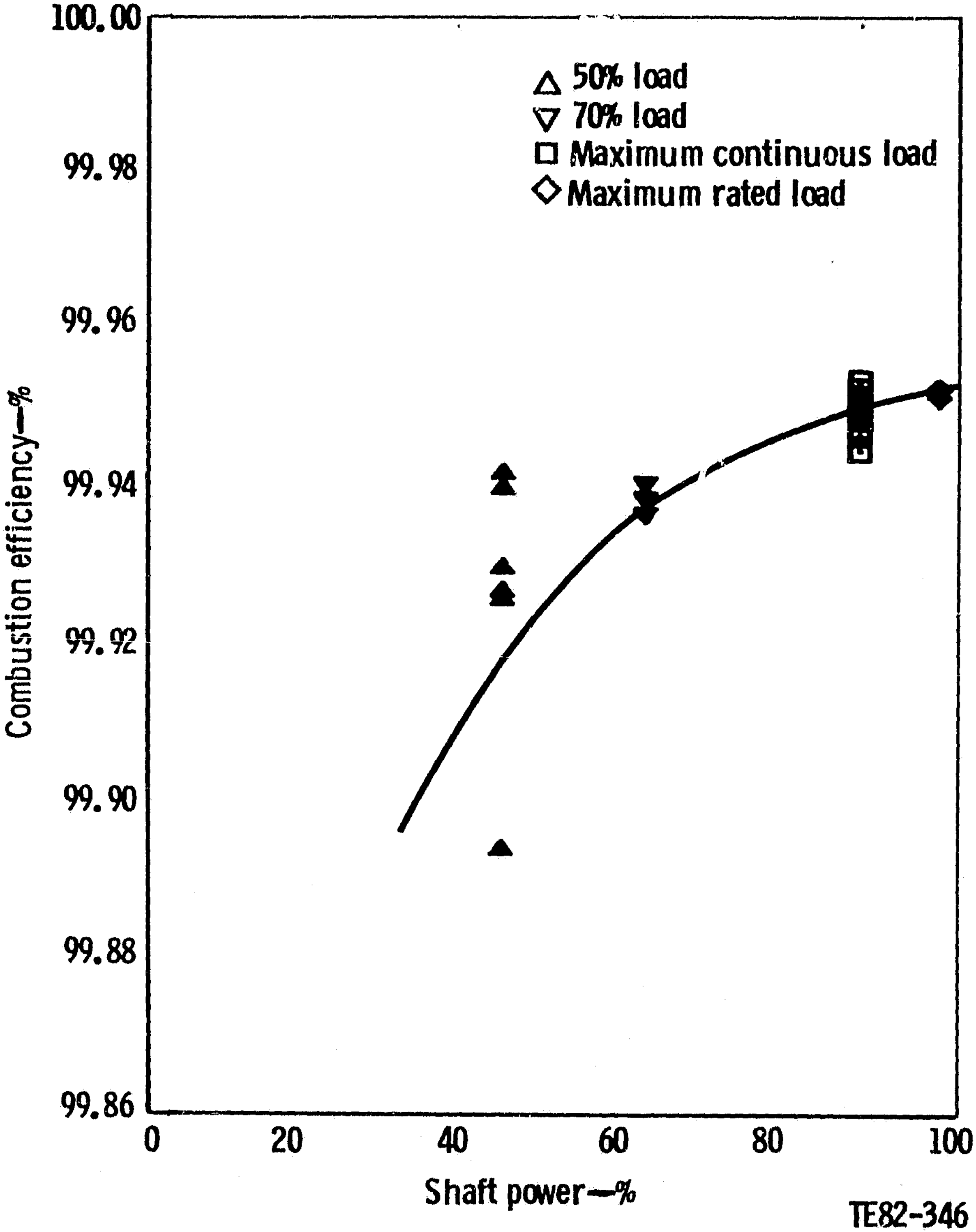


Figure 27. Combustion efficiency for mid-heating-value gas fuel versus output shaft power level.

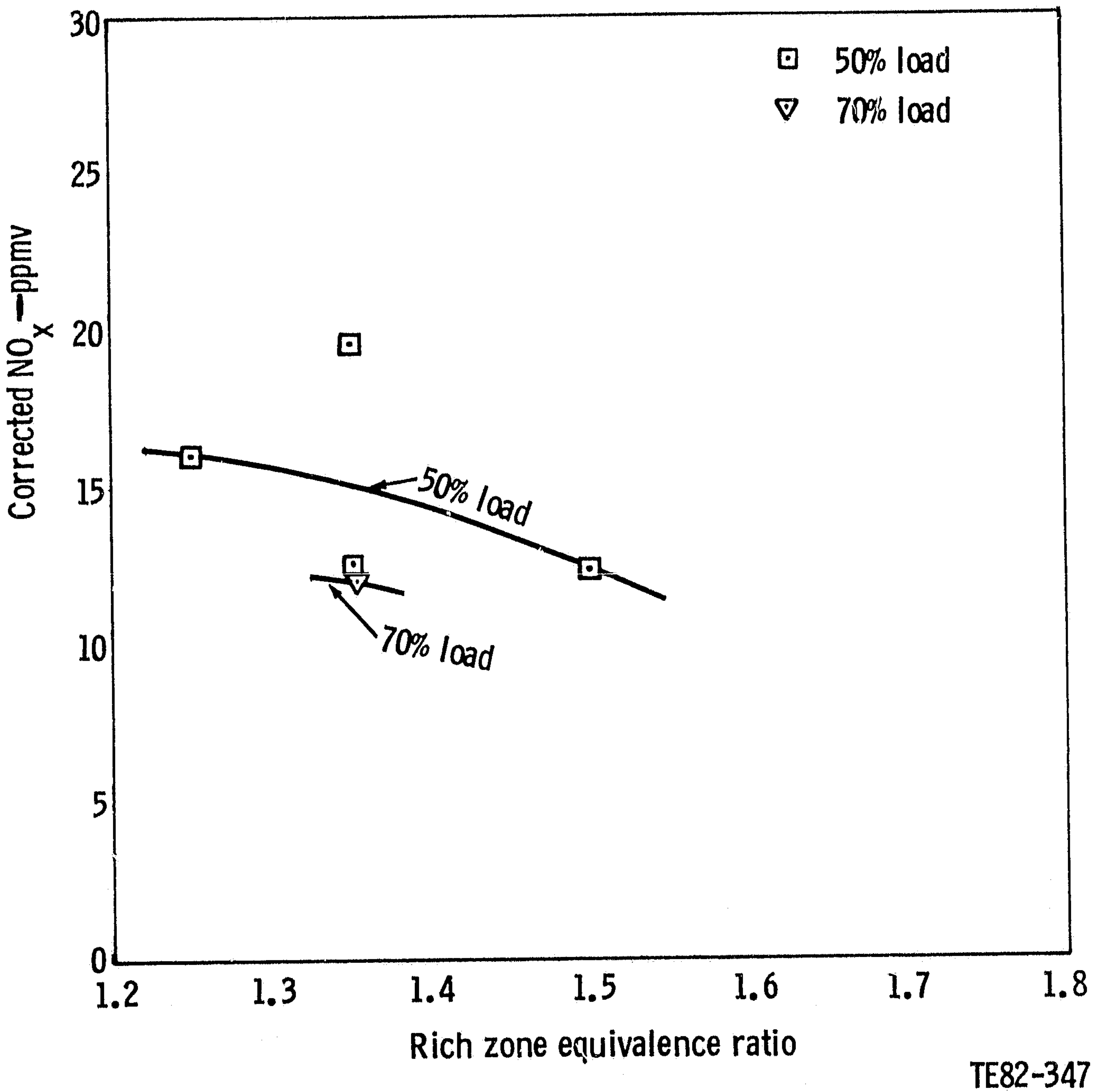


Figure 28. Corrected NO_x emissions for low-heating-value gas fuel versus rich zone equivalence ratio (low power).

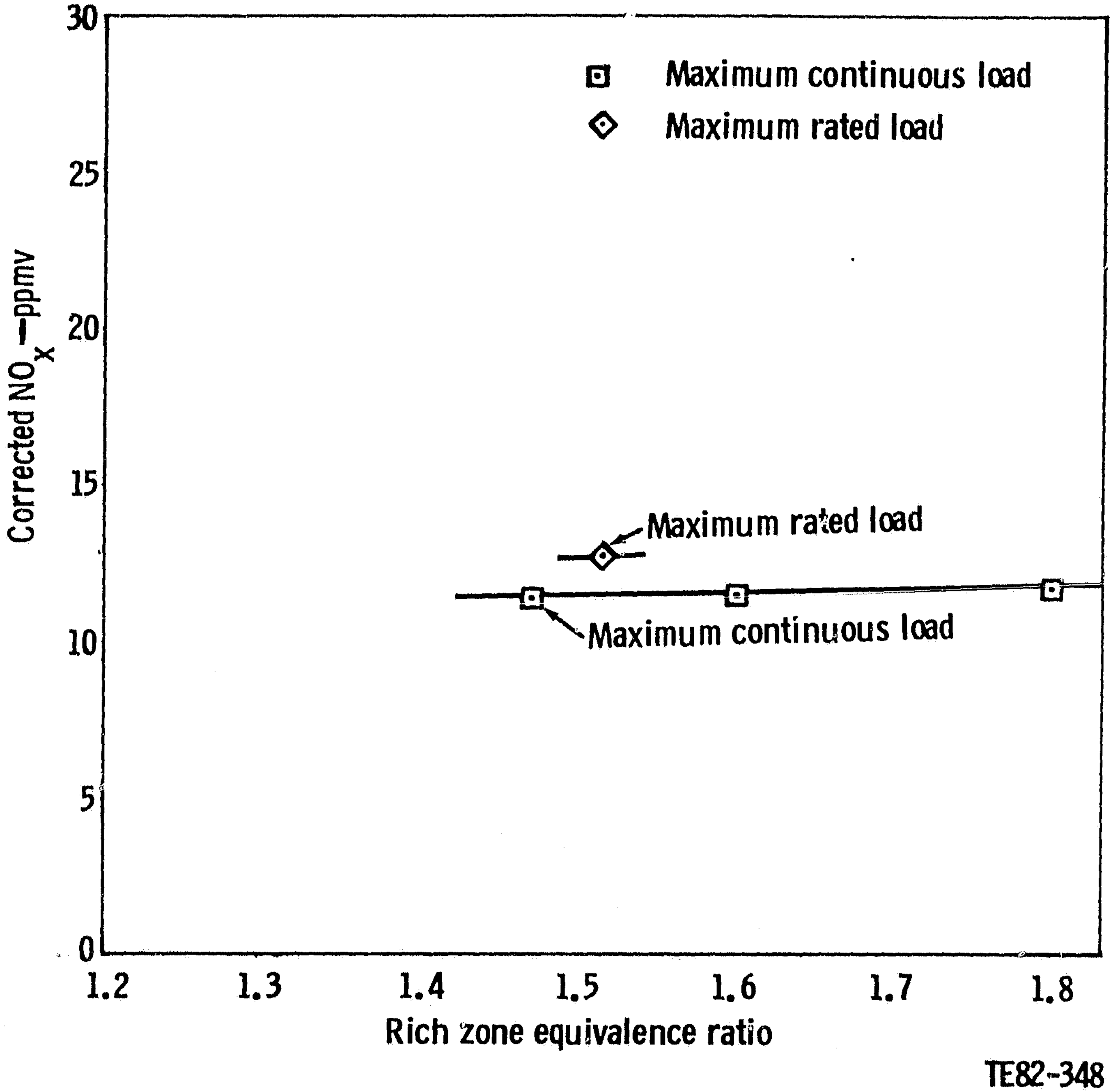


Figure 29. Corrected NO_x emissions for low-heating-value gas fuel versus rich zone equivalence ratio (high power).

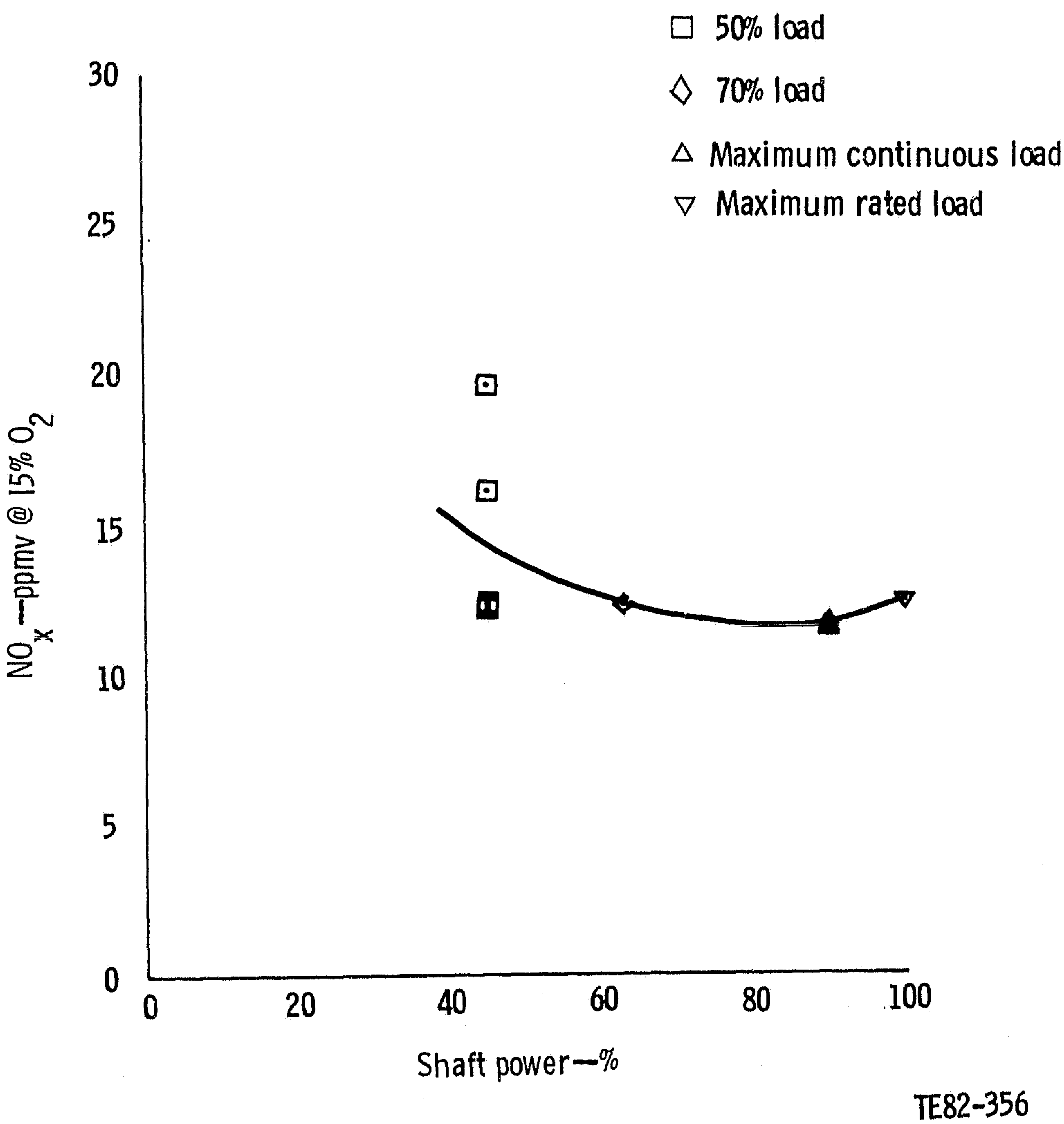


Figure 30. Corrected NO_x emissions for low-heating-value gas fuel versus output shaft power level.

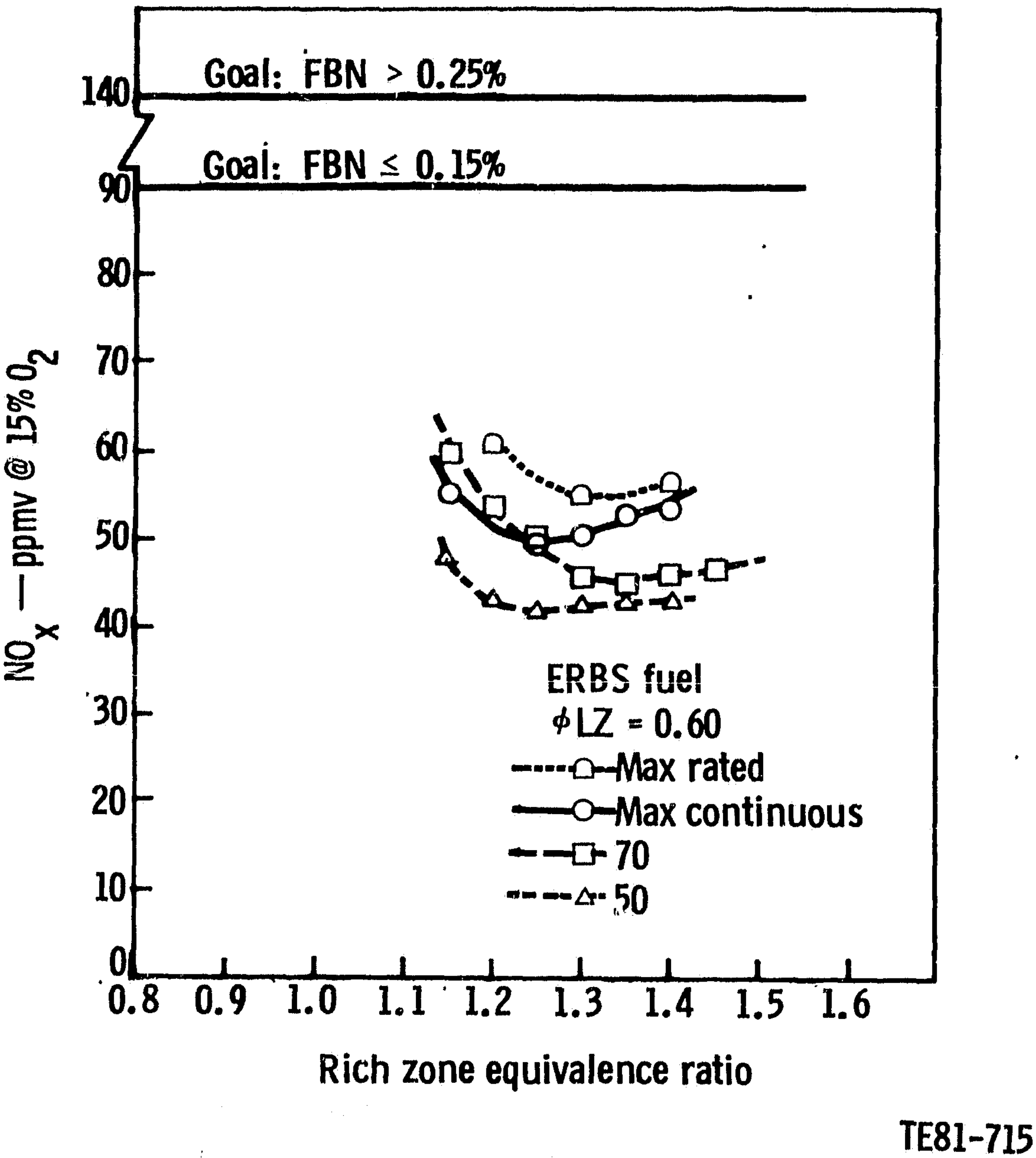


Figure 31. NO_x response to power level.

ORIGINAL PAGE IS
OF POOR QUALITY

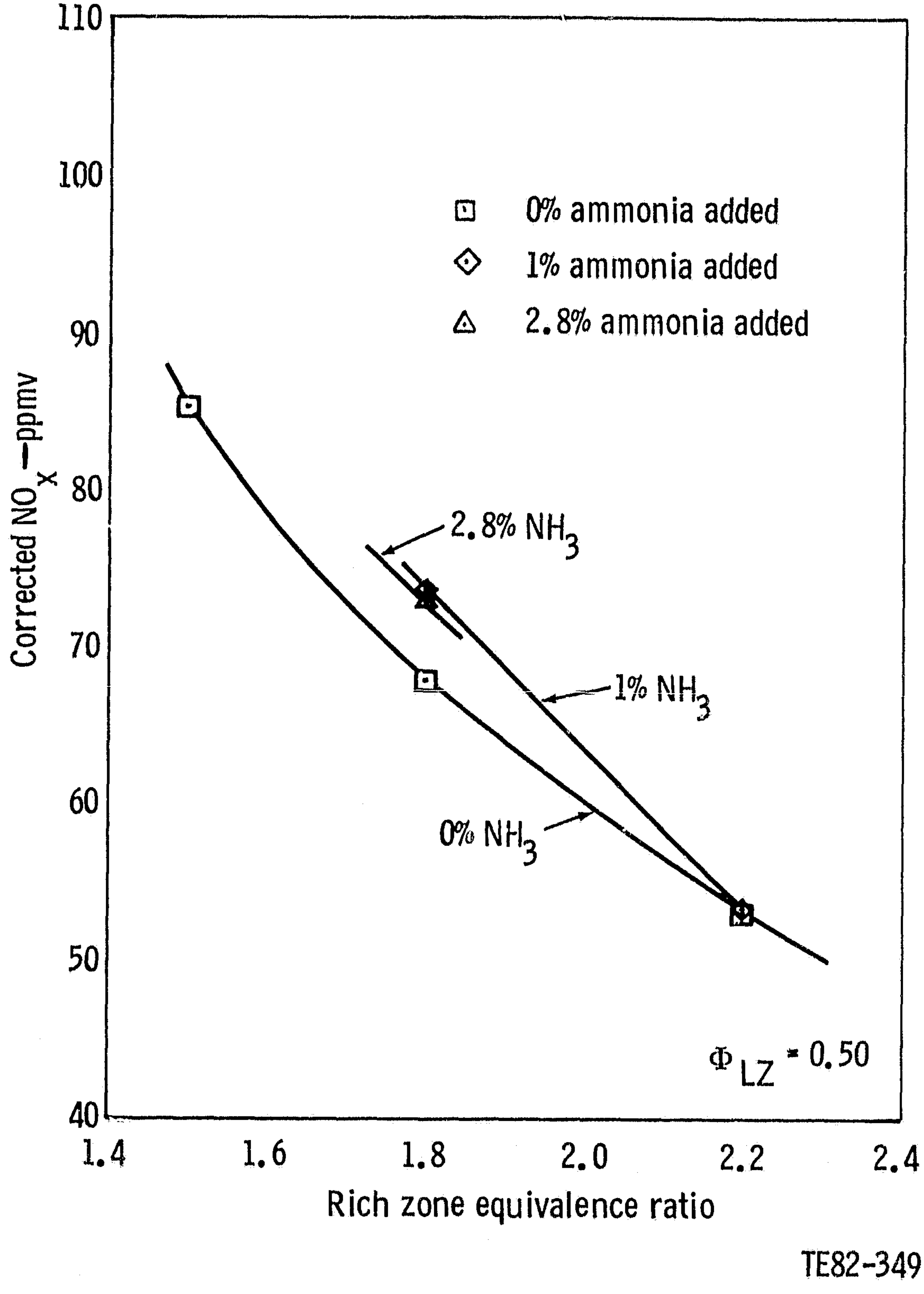


Figure 32. Corrected NO_x emissions for mid-heating-value gas fuel versus rich zone equivalence ratio (50% load).

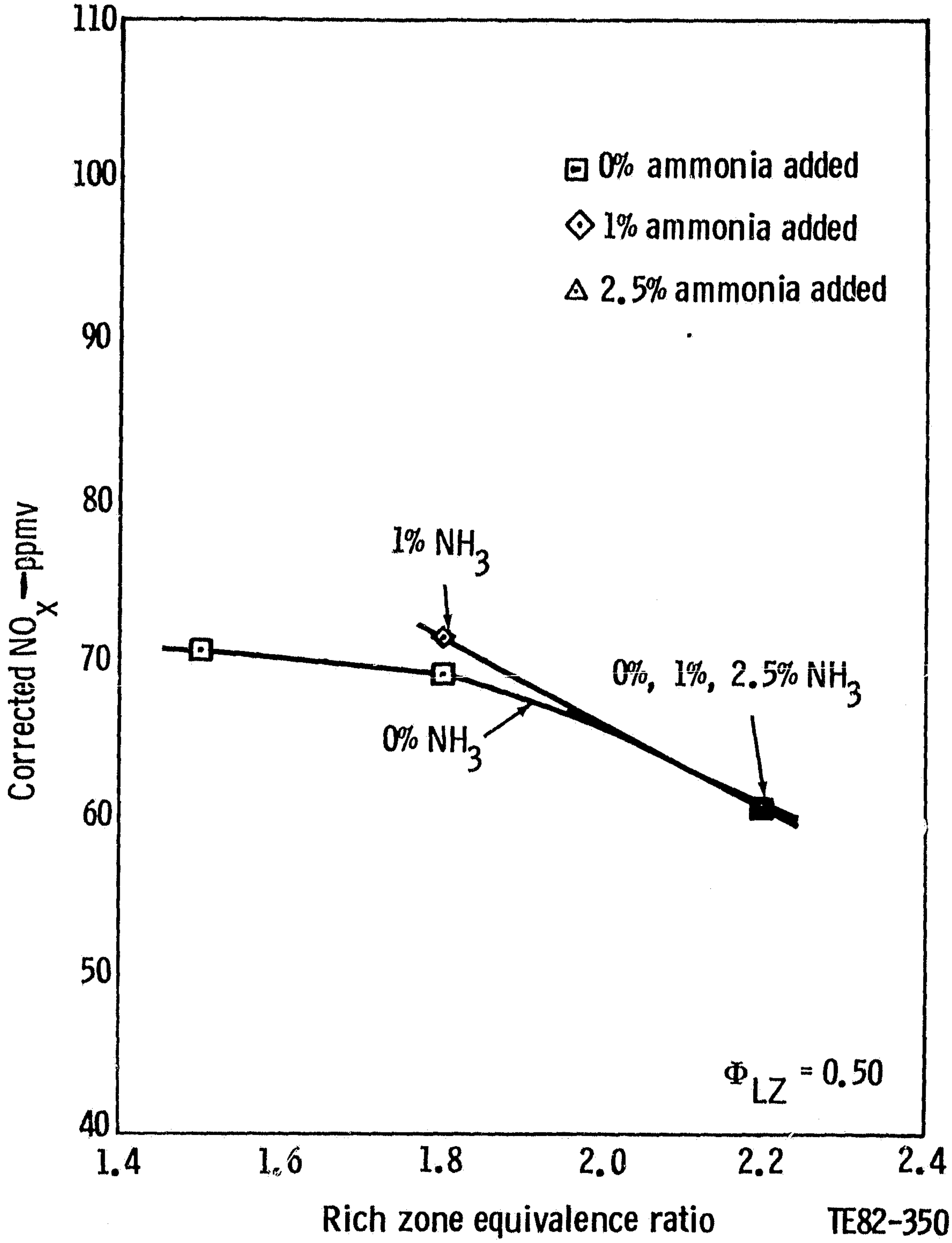


Figure 33. Corrected NO_x emissions for mid-heating-value gas fuel versus rich zone equivalence ratio (70% load).

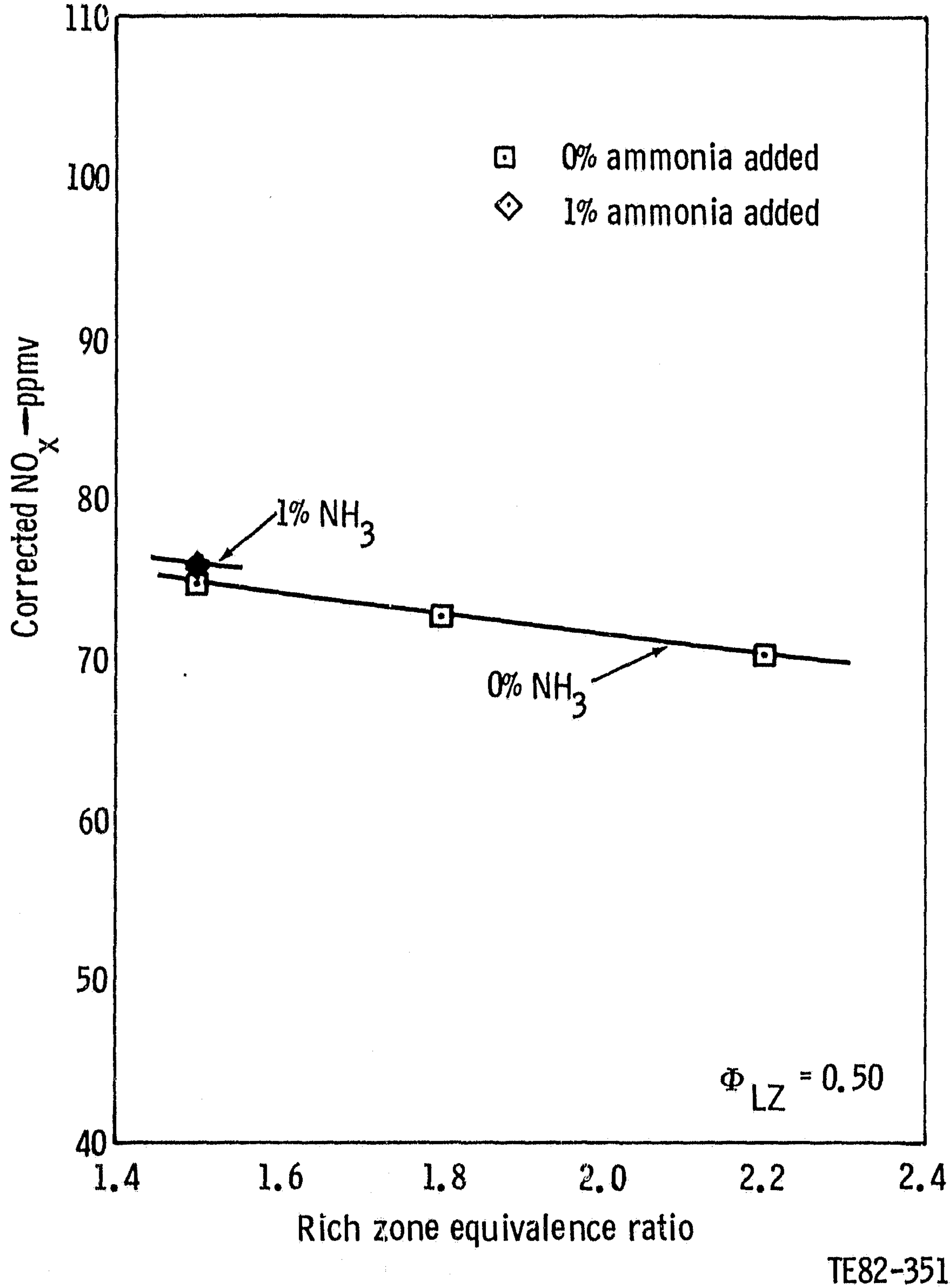


Figure 34. Corrected NO_x emissions for mid-heating-value gas fuel versus rich zone equivalence ratio (maximum continuous power) at 0.50 lean zone equivalence ratio.

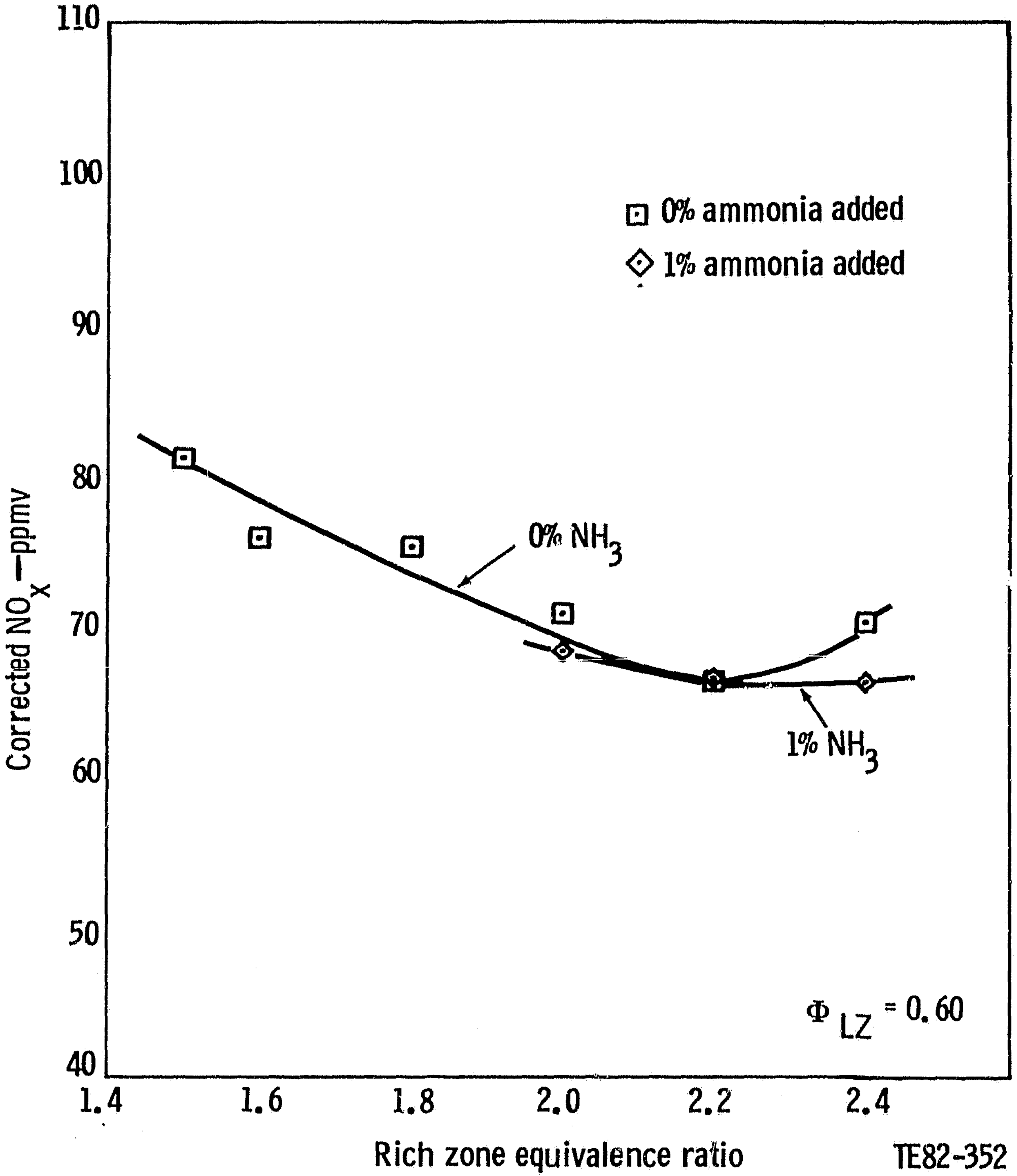


Figure 35. Corrected NO_x emissions for mid-heating-value gas fuel versus rich zone equivalence ratio (maximum continuous power) at 0.60 lean zone equivalence ratio.

ORIGINAL PAGE IS
OF POOR QUALITY

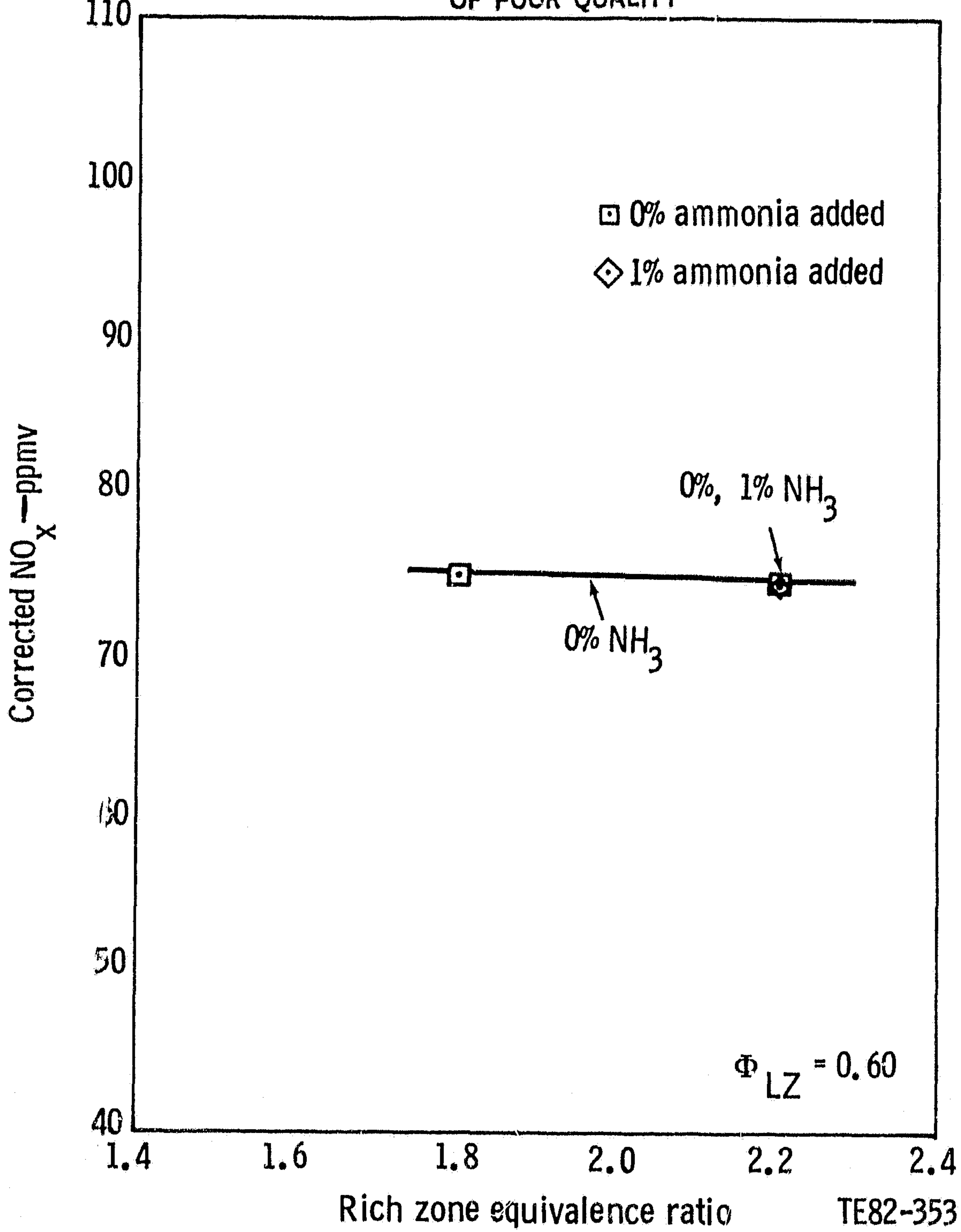


Figure 36. Corrected NO_x emissions for mid-heating-value gas fuel versus rich zone equivalence ratio (maximum rated power).

ORIGINAL PAGE IS
OF POOR QUALITY

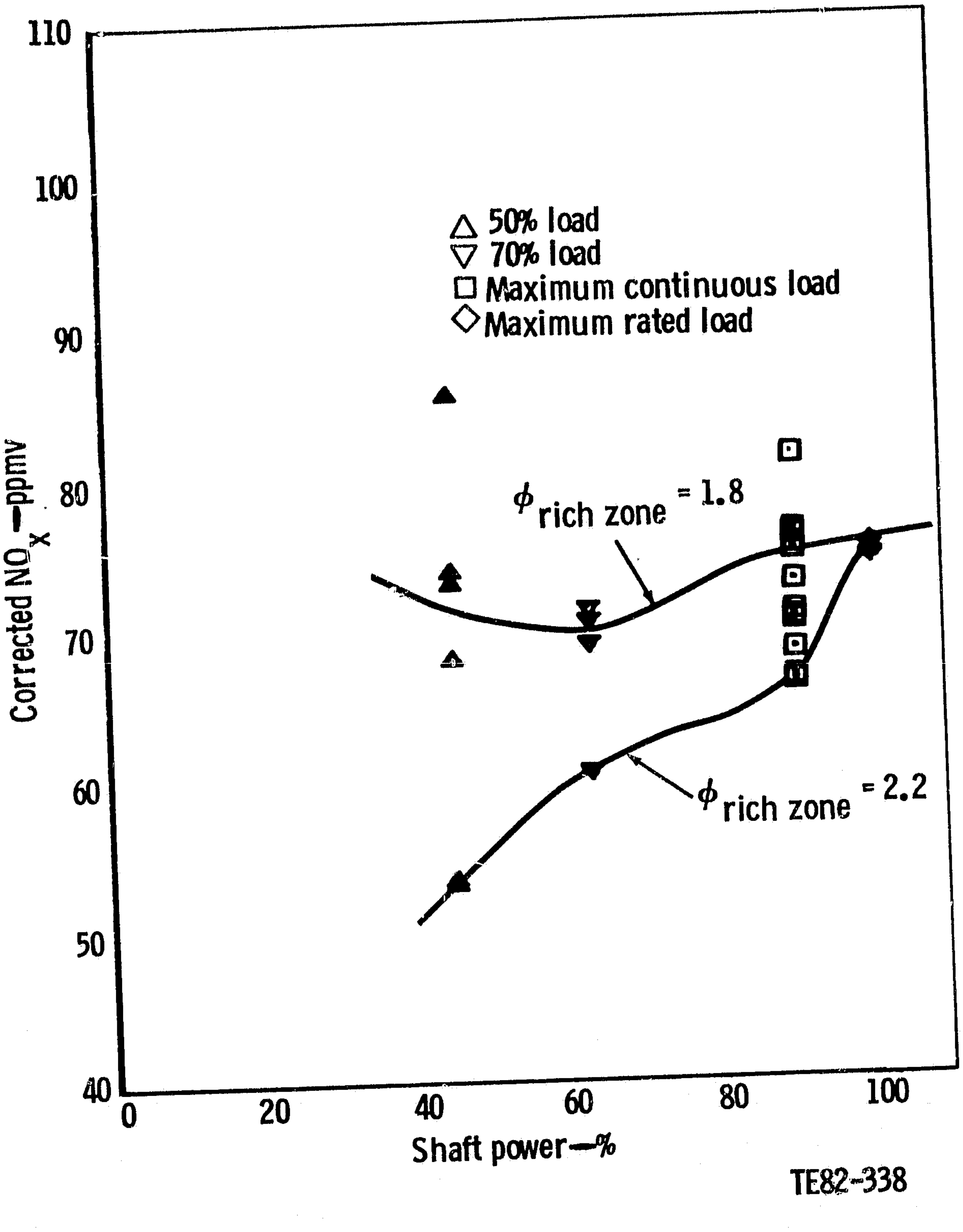


Figure 37. Corrected NO_x emissions for mid-heating-value gas fuel versus output shaft power level.

ORIGINAL PAGE IS
OF POOR QUALITY

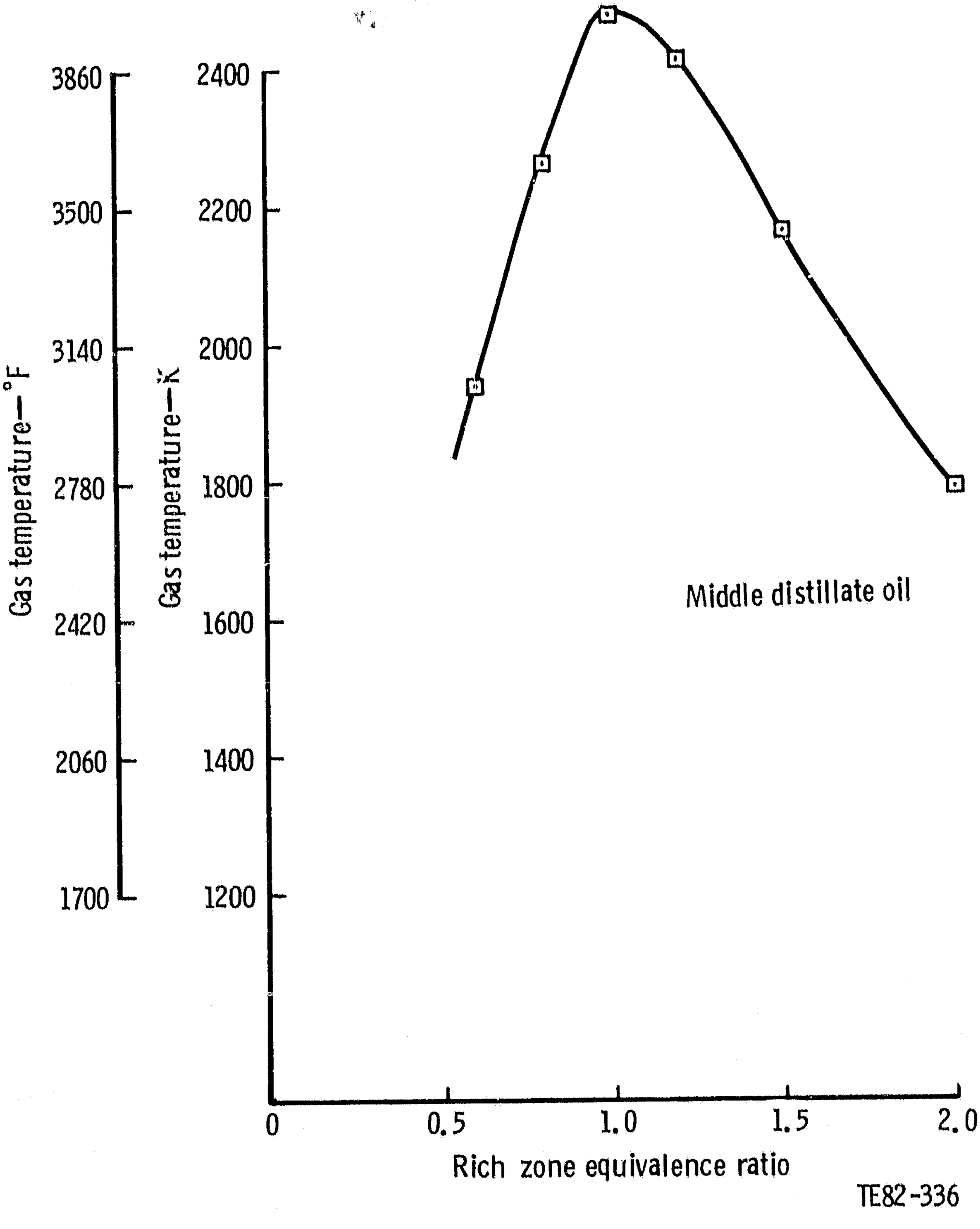


Figure 38. Middle distillate oil equilibrium combustion gas temperature versus equivalence ratio.

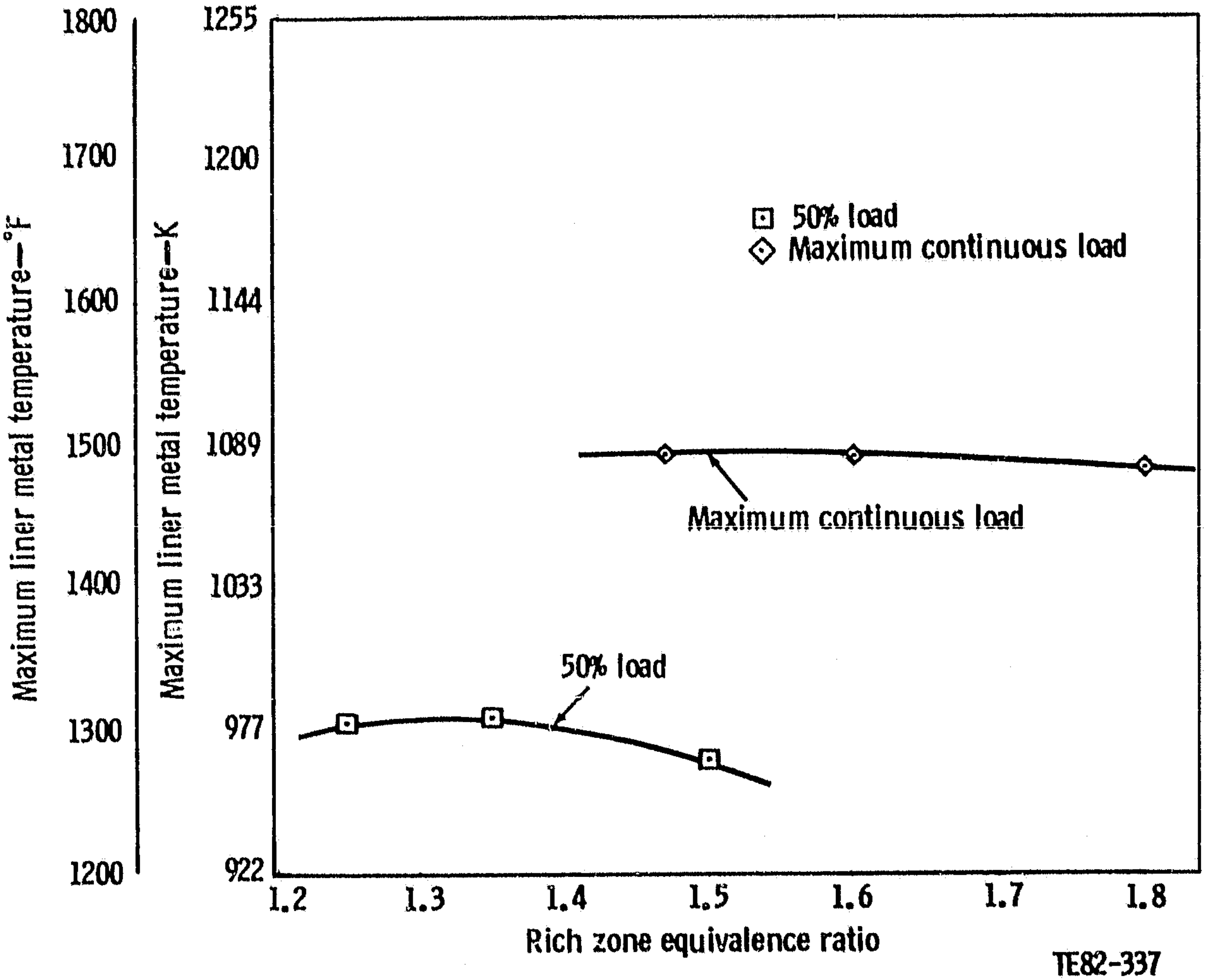


Figure 39. Maximum metal temperature for low-heating-value gas fuel versus rich zone equivalence ratio.

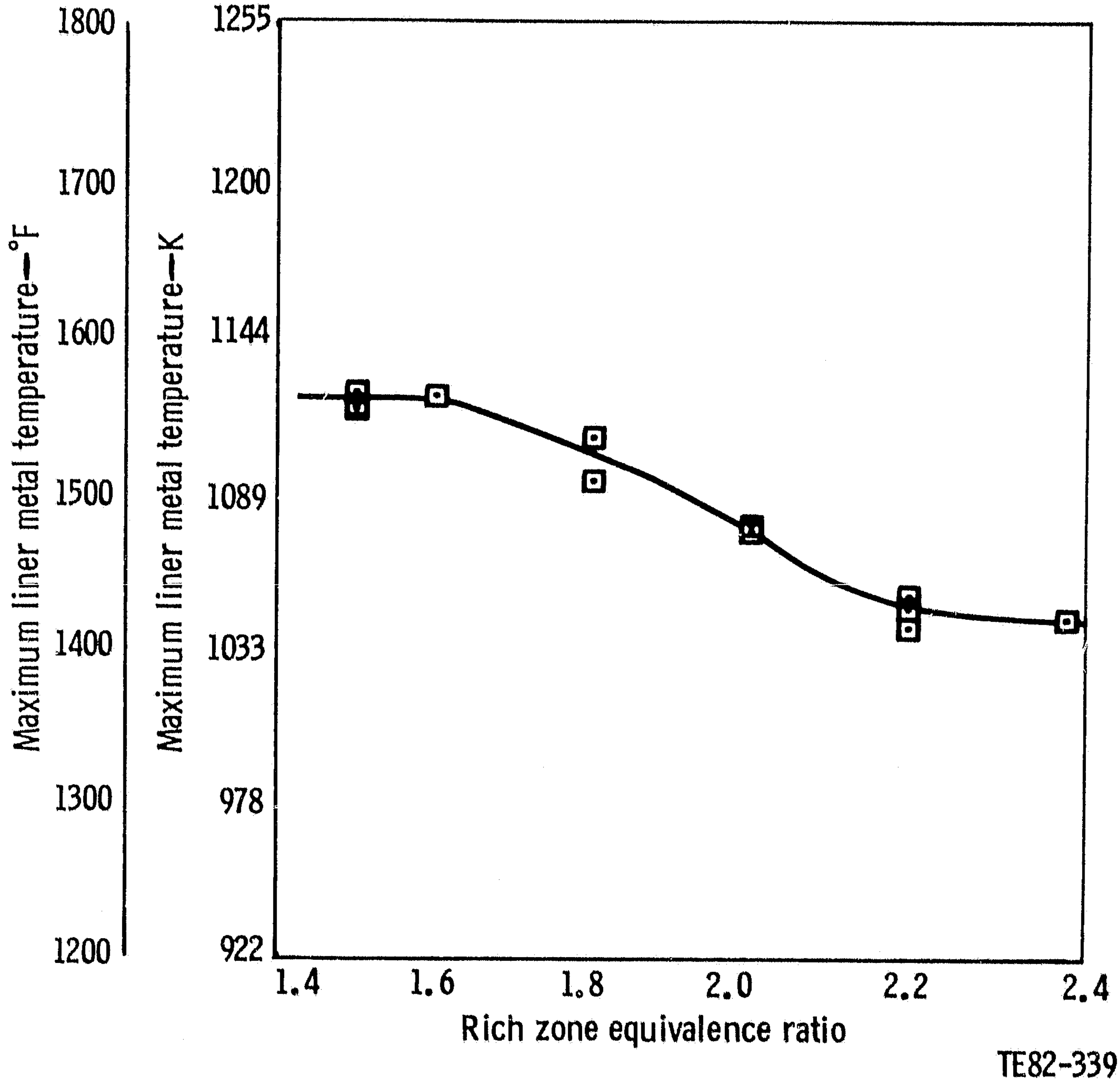


Figure 40. Maximum metal temperature for mid-heating-value gas fuel versus rich zone equivalence ratio at maximum continuous load.

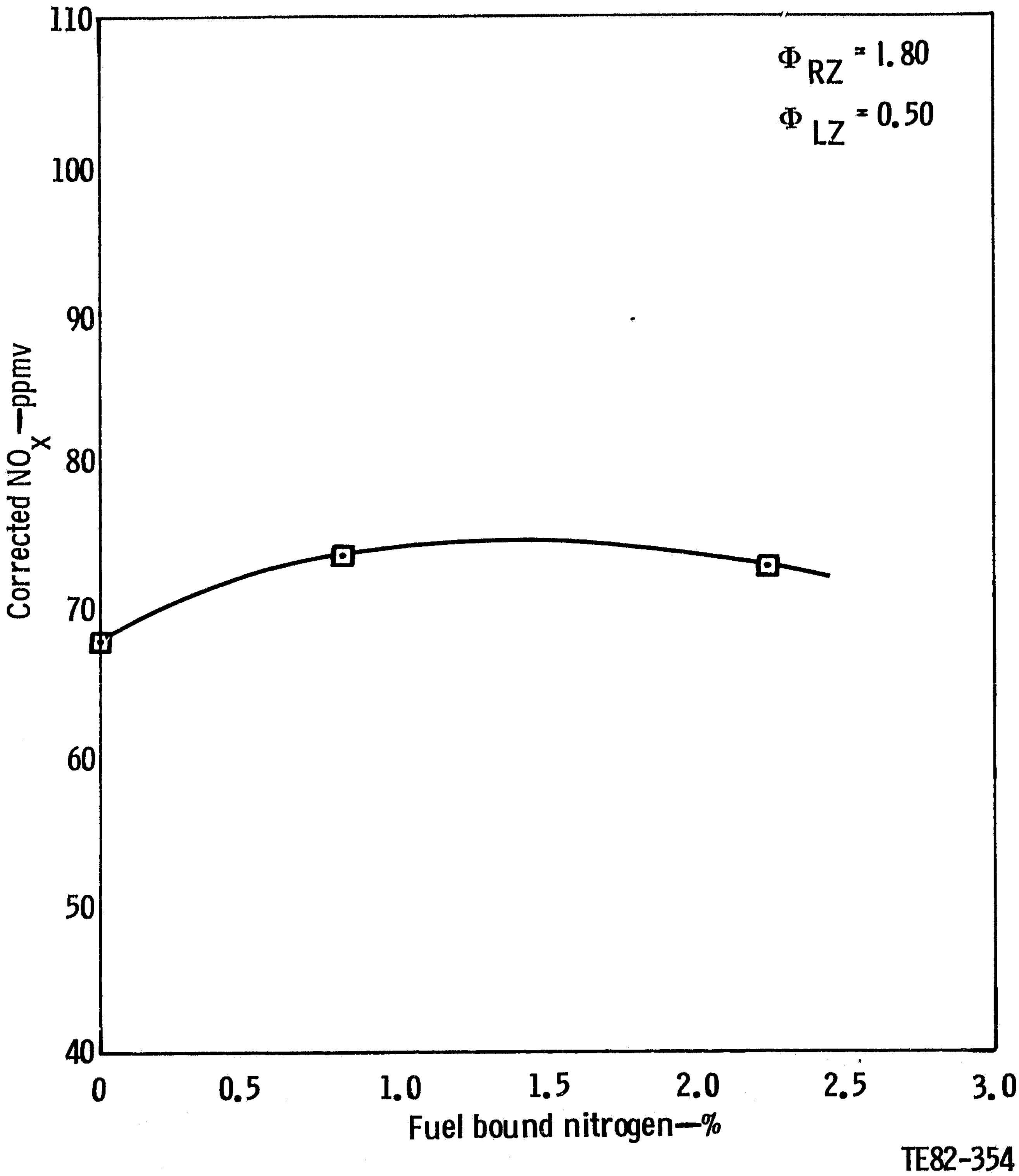


Figure 41. Corrected NO_x emissions for mid-heating-value gas fuel versus FBN content at 50% load conditions.

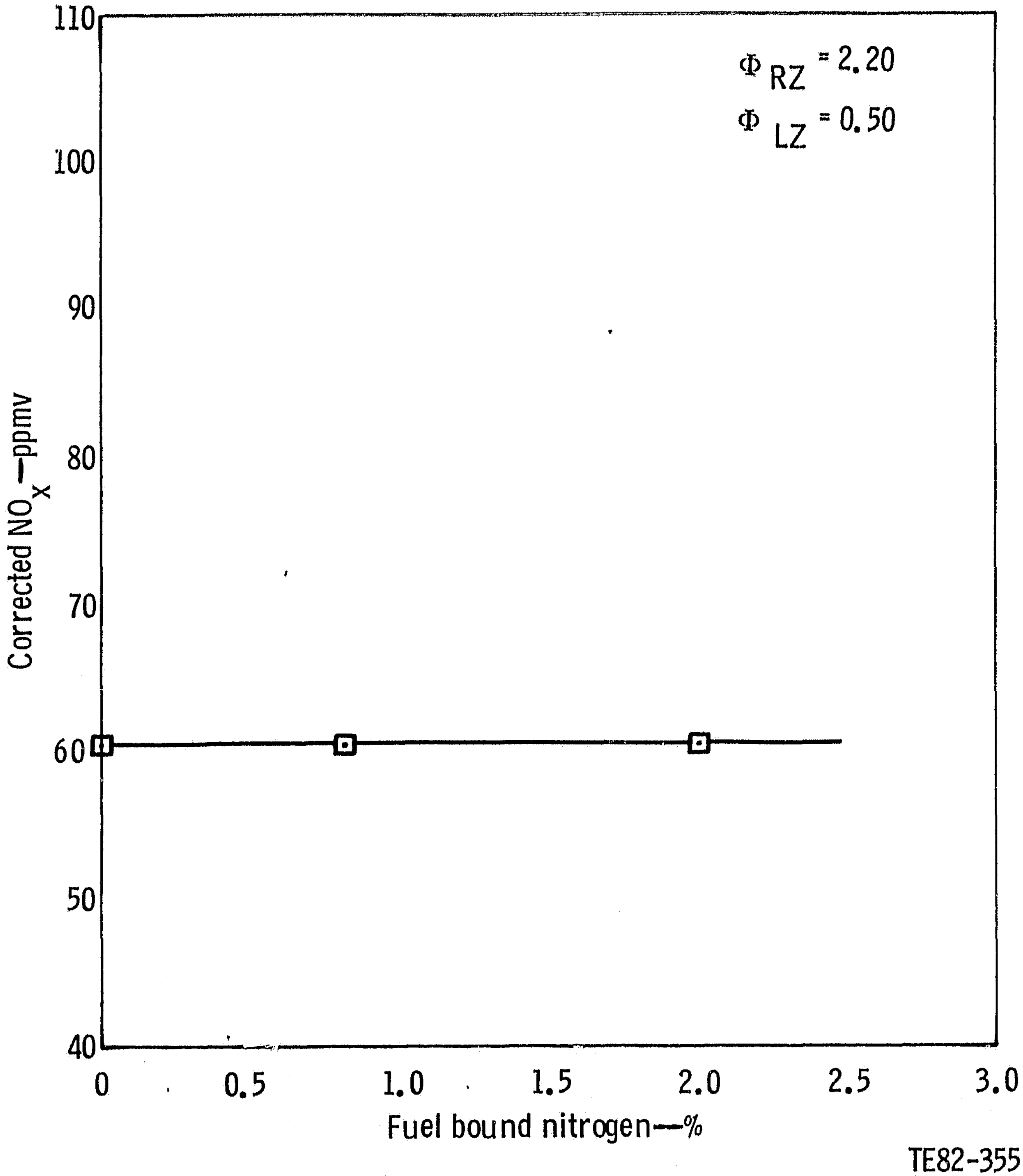


Figure 42. Corrected NO_x emissions for mid-heating-value gas fuel versus FBN content at 70% load conditions.

VI. CONCLUSIONS

A multifuel-flexible, variable geometry, air-staged regenerative/convection and transpiration-cooled combustor was previously designed and successfully tested using various types of liquid fuels (Ref. 1). This unique combustor was denoted as an RQL combustor. The purpose of this addendum program to the previous contract, DEN3-148, is to provide an initial data base characterizing the combustion of low- to mid-heating-value gaseous fuels. Some of these gaseous fuels may be derived from coal gasification processes and contain significant levels of FBN. One of the prime concerns of this program is to determine if such fuels can meet environmental standards and perform satisfactorily in a gas turbine combustor.

Modifications to the original liquid-fueled combustor were minor, involving only changes to the fuel injector. The modified combustor exhaust emissions results are summarized in Table XI. The combustor produced emission levels well below both maximum EPA limits and program goals when operating on each of the three fuels tested: low-heating-value gas, mid-heating-value gas, and mid-heating-value gas with NH_3 added (up to 2.8% by weight). Smoke levels were well below a smoke number of 5-10 (one-half the program goal) at all operating conditions. Carbon monoxide levels were high only at the lower power levels for the low-heating-value gas. This reflected the gas's initial high CO composition, its low combustor outlet temperature, and nonoptimization of CO emission levels with equivalence ratio in the rich zone. Carbon monoxide levels were less than 30 ppmv at the higher power conditions for both the low- and mid-heating-value gases and did not exceed 40 ppmv at all operating conditions for the mid-heating-value gas ($\phi_{RZ} > 1.6$). Unburned hydrocarbon emissions were fewer than 6 ppmv for both fuels at all operating power levels.

Nitrogen oxide emissions were extremely low with the low-heating-value gas fuel. The emission levels never exceeded 20 ppmv for all operating conditions. At the optimum conditions for minimizing NO_x using the mid-heating-value gas (equivalence ratios in the region of 2.2 in the rich zone), NO_x emission levels did not exceed 75 ppmv. The combustor NO_x emission levels are also essentially insensitive to the quantity of FBN from the added ammonia.

A variable geometry RQL combustion system can therefore meet emission standards when operating with a wide range of gaseous fuels even should they contain appreciable amounts of FBN.

Table XI.
Program summary.

Conditions: Modified RQL combustor
6% pressure drop
0.5 to 0.6 lean zone equivalence ratio
Gaseous fuels with NH_3 addition
Fifty percent and maximum continuous power conditions

	Gaseous fuel		
	Low-heating-value	Mid-heating-value	Mid-heating-value + NH_3
FBN content, wt %	0	0	1.0-2.8
Maximum EPA NO_x, ppmv at 15% O_2	180	180	230
Program NO_x goal, ppmv at 15% O_2	90	90	---
Minimum NO_x measured, ppmv at 15% O_2			
50% load	12	52	52
Max cont load	12	70	66
Program smoke goal, SAE smoke number (SN)	20	20	20
Measured smoke, SAE SN			
50% load	(5-10)	(5-10)	(5-10)
Max cont load	(5-10)	(5-10)	(5-10)
Program combustion efficiency goal, %	99.0	99.0	99.0
Demonstrated combustion efficiency, %			
50% load	99.6	99.9	99.9
Max cont load	99.9	99.9	99.9
Rich-zone equivalent ratio at minimum measured NO_x			
50% load	1.5	2.2	2.2
Max cont load	1.5-1.8	2.2	1.8-2.4
Measured CO, ppmv at 15% O_2			
50% load	~300	~40	~40
Max cont load	30	15	15
Measured unburned hydrocarbons ppmv at 15% O_2			
50% load	6	6	6
Max cont load	6	6	6
Rich zone maximum metal temperature			
50% load K	963	1117	1117
(°F)	(1275)	(1530)	(1550)
Max cont load K	1089	1047	1047
(°F)	(1500)	(1425)	(1425)

APPENDIX

Summarized in this appendix are the performance and parametric test data from the RQL combustor testing. Each data point requires three lines of description. The second line in each table is designated "A" table; the third line, "B" table. Each line for a data point begins with its reading number on the left. The comments below describe the parameters in the following tables.

<u>Line 1</u>

Reading number	A six-digit year/month/day number followed by a three-digit initial record number
Hardware identification	All data are for Liner Concept I, the rich/quench/lean (RQL) combustor. The fuel nozzle is a premixing gas nozzle and is unchanged
Fuel type	Fuels were used either singly or in combination: L--low-Btu gas M--mid-Btu gas A--ammonia for FBN simulation
Fuel, % H	Percent hydrogen content in fuel or fuel blend
Fuel, % N	Percent nitrogen content in fuel or fuel blend
Fuel, LHV	Lower heating value of fuel or fuel blend (computed by mass averaging)
Fuel temp, °F	Fuel temperature measured at the fuel inlet fitting to the test rig
Simulated engine power condition	Model 570 steady-state conditions
W NOZ, lb/sec (if air assist)	Fuel nozzle assist air flow (if air assist nozzle)
TINLET, °F	Combustor inlet total temperature
PINLET, psia	Combustor inlet total pressure
W fuel P, lb/sec	Fuel mass flow entering rich (primary) zone through fuel nozzle
W air P, lb/sec	Air mass flow entering rich (primary) zone through fuel nozzle
W fuel S, lb/sec	Fuel mass flow entering lean (secondary) zone (not used in RQL combustor)
W air S, lb/sec	Air mass flow entering lean (secondary) zone through rich zone plus mixer

Line 2 (A tables)

Reading number	Same as in line 1
Primary equivalence ratio	Equivalence ratio in rich (primary) zone $(f/a)_{rz} \div (f/a)_{st}$. Back calculated from measured data.
Secondary equivalence ratio	Equivalence ratio in lean (secondary) zone $(f/a)_{lz} \div (f/a)_{st}$. Back calculated from measured data.
Overall equivalence ratio	Equivalence ratio for entire combustor $(f/a)_o \div (f/a)_{st}$

Primary res. time, ms — Rich (primary) zone residence time based on combustor inlet conditions, rich zone reference velocity, and rich zone volume and area

$$t_p\ (\text{ms}) = \frac{Vol_p}{A_p \cdot Vel_p}$$

Vol_p and A_p are volume and area of rich (primary) zone determined from hardware

Secondary res. time, ms — Lean (secondary) zone residence time based on combustor inlet conditions, lean zone reference velocity, and lean zone volume and area

$$t_s\ (\text{ms}) = \frac{Vol_s}{A_s \cdot Vel_s}$$

Primary ref. velocity (ft/sec) — Rich (primary) zone velocity based on rich zone air mass flow, inlet temperature and pressure, and average rich zone cross-sectional area

$$Vel_p\ (\text{ft/sec}) = \frac{M_{air_p} \cdot R_{air} \cdot T_{in}}{P_{in} \cdot A_p}$$

Secondary ref. velocity (ft/sec) — Lean (secondary) zone velocity based on lean zone air mass flow, inlet temperature and pressure, and average lean zone cross-sectional area

$$Vel_s\ (\text{ft/sec}) = \frac{M_{air_s} \cdot R_{air} \cdot T_{in}}{P_{in} \cdot A_s}$$

Exit temperature, °F	Average reading of 26 combustor outlet temperature thermocouples. Note: Many thermocouples were not functioning so the average indicated temperature is not valid.
Exit pressure	Average of two static pressures in combustor lean zone
Specific humidity	Ratio of grams of water in inlet air per gram of dry air, computed from $$S = \frac{pv}{\frac{M_{air}}{M_{H_2O}}(B - pv)}$$ pv = vapor pressure of water in inlet air B = barometric pressure
Combustor delta P, psi	Measured pressure drop across combustor in psi
Liner temperature, °F	Maximum measured metal temperature of 8 combustor liner thermocouples in the forward portion of the rich zone
CO, ppm	Measured carbon monoxide in exhaust
CO_2, ppm	Measured carbon dioxide in exhaust
HC, ppm	Measured unburned hydrocarbons in exhaust (C_1 base as CH_4)
NO_x, ppm	Measured total nitrogen oxides in exhaust (NO_x as NO_2)
NO_x, ppmc	Total nitrogen oxides in exhaust corrected to 15% O_2 and for inlet temperature, pressure, and humidity per EPA Reference Method 20

Line 3 (B tables)

Reading number	Same as in line 1

% N conversion	Ratio of corrected NO_x divided by NO_x equivalent of nitrogen in the fuel (not computed for % FBN less than 0.01%)

$$\% \text{ N conversion} = \frac{NO_x \text{ (ppmc)}}{\left[\frac{(f/a)_o}{1 + (f/a)_o}\right] \cdot \% N_F \cdot \frac{M_{exh}}{M_{NO_2}} \times 100}$$

where

NO_x (ppmc) = corrected NO_x as NO_2

$(f/a)_o$ = overall fuel-air ratio

$\% N_F$ = percent nitrogen in fuel by weight

M_{exh} = molecular weight of exhaust gas, = f (f/a_o, H/C of fuel)

M_{NO_2} = 46.008, molecular weight of NO_x as NO_2

Combustion efficiency, %	Percent combustion efficiency, computed from corrected exhaust gas emissions (NO_x, CO, CH_x), CO_2, heat release rate of fuel (Btu/lb-mole) based on C_1 fuel molecule
Smoke number	Smoke number per ARP 1179
Pattern factor	Circumferential pattern factor of exhaust

$$PF_c = \frac{T_{max} - T_{avg}}{T_{avg} - T_{in}}$$

Note: Erroneous due to nonfunctional exit temperature instrumentation.

FARR	Ratio of overall fuel-air ratio computed from exhaust gas analysis to overall fuel-air ratio determined from airflow and fuel flow measurements
Desired primary zone equivalence ratio	Rich (primary) zone equivalence ratio desired when test point was recorded
Desired lean zone equivalence ratio	Lean (secondary) zone equivalence ratio desired when test point was recorded

ORIGINAL PAGE IS
OF POOR QUALITY

Table XII.
RQL combustor performance data--
low-heating-value gaseous fuel.

READING NUMBER	HARDWARE CONFIGURATION	FUEL TYPE	FUEL %H	FUEL %N	FUEL LHV	FUEL TEMP (F)	SIMULATED ENGINE POWER CONDITION	W NOZ (LB/S) (IF AIR ASSIST)	TINLET (F)	PINLET (PSIA)	W FUEL P (LB/S)	W AIR P (LB/S)	W FUEL S (LB/S)	W AIR S (LB/S)
810904119	LINER RQL, NOZ GAS	LG	1.92	53.45	168.	412.	70% LOAD	0.0	552.	134.8	0.481	0.595	0.0	1.695
810904128	LINER RQL, NOZ GAS	LG	1.92	53.45	166.	386.	MAX CONTINUOUS	0.0	638.	168.9	0.691	0.808	0.0	2.403
810904137	LINER RQL, NOZ GAS	LG	1.92	53.45	168.	419.	MAX CONTINUOUS	0.0	637.	162.4	0.681	0.707	0.0	2.298
810904146	LINER RQL, NOZ GAS	LG	1.92	53.45	166.	425.	MAX CONTINUOUS	0.0	638.	170.2	0.716	0.674	0.0	2.367
810904155	LINER RQL, NOZ GAS	LG	1.92	53.45	168.	355.	MAX RATED	0.0	681.	175.9	0.779	0.835	0.0	2.359
810904165	LINER RQL, NOZ GAS	LG	1.92	53.45	166.	353.	50% LOAD	0.0	540.	117.5	0.358	0.480	0.0	1.790
810904174	LINER RQL, NOZ GAS	LG	1.92	53.45	168.	380.	50% LOAD	0.0	545.	117.7	0.357	0.474	0.0	1.560
810904183	LINER RQL, NOZ GAS	LG	1.92	53.45	166.	369.	50% LOAD	0.0	536.	117.0	0.370	0.392	0.0	1.552
810904196	LINER RQL, NOZ GAS	LG	1.92	53.45	169.	396.	50% LOAD	0.0	529.	116.7	0.369	0.447	0.0	1.699
810904205	LINER RQL, NOZ GAS	LG	1.92	53.45	168.	399.	50% LOAD	0.0	527.	116.8	0.368	0.443	0.0	1.844

Table XII-A.
RQL combustor performance data--
low-heating-value gaseous fuel.

READING NUMBER	PRIMARY (RICH ZONE) EQUIVALENCE RATIO	SECONDARY (LEAN ZONE) EQUIVALENCE RATIO	OVERALL EQUIVALENCE RATIO	PRIMARY RES. TIME (MSEC.)	SECONDARY RES. TIME (MSEC.)	PRIMARY REF. VELOCITY (FT/S)	SECONDARY REF. VELOCITY (FT/S)	EXIT TEMPERATURE (F)	EXIT PRESSURE (PSIA)	SPECIFIC HUMIDITY	COMBUSTOR DELTA P (PSI)	LINER TEMPERATURE (F)	CO (PPM)	CO2 (PPM)	HC (PPM)	NOX (PPM)	NOX (PPMC)
810904119	1.35	0.42	0.25	122.	16.	8.	29.	1351.	127.	0.00125	7.95	1532.	120.	62000.	8.	18.	12.
810904128	1.43	0.43	0.30	104.	14.	10.	32.	1499.	159.	0.00167	9.93	1493.	50.	81800.	4.	22.	11.
810904137	1.61	0.50	0.31	116.	15.	9.	32.	1515.	154.	0.00146	9.41	1492.	40.	81800.	8.	22.	12.
810904146	1.78	0.51	0.32	129.	15.	8.	31.	1433.	160.	0.00146	10.46	1433.	53.	86000.	7.	24.	12.
810904155	1.56	0.55	0.34	102.	15.	10.	31.	1534.	166.	0.00167	10.52	1344.	36.	89000.	3.	25.	12.
810904165	1.25	0.33	0.20	132.	14.	8.	32.	1283.	110.	0.00052	8.00	1309.	316.	51200.	4.	23.	20.
810904174	1.26	0.33	0.20	134.	17.	8.	28.	1315.	111.	0.00042	6.70	1306.	254.	49900.	3.	18.	16.
810904183	1.58	0.40	0.21	165.	17.	6.	27.	1319.	110.	0.00042	6.67	1280.	268.	53700.	3.	16.	12.
810904196	1.38	0.37	0.21	144.	15.	7.	30.	1280.	110.	0.00042	6.95	1279.	330.	57600.	3.	17.	12.
810904205	1.39	0.33	0.21	146.	14.	7.	33.	1269.	110.	0.00042	6.79	1280.	404.	57800.	3.	17.	12.

Table XII-B.
RQL combustor performance data--
low-heating-value gaseous fuel.

READING NUMBER	% N CONVERSION	COMBUSTION EFFICIENCY (%)	SMOKE NUMBER	PATTERN FACTOR	FARK	DESIRED PRIMARY ZONE EQUIVALENCE RATIO	DESIRED LEAN ZONE EQUIVALENCE RATIO
810904119	0.03	99.84	0.	0.61	0.947	1.35	0.55
810904128	0.02	99.95	0.	0.81	1.033	1.47	0.60
810904137	0.02	99.95	0.	0.77	1.006	1.60	0.60
810904146	0.02	99.94	0.	0.77	1.028	1.80	0.60
810904155	0.02	99.96	0.	0.74	1.000	1.58	0.60
810904165	0.05	99.55	0.	0.82	0.979	1.35	0.50
810904174	0.04	99.62	0.	0.84	0.950	1.25	0.50
810904183	0.03	99.64	0.	0.87	0.979	1.50	0.50
810904196	0.03	99.59	0.	0.85	1.042	1.35	0.45
810904205	0.03	99.50	0.	1.13	1.046	1.35	0.40

Table XIII.
RQL combustor performance data--
mid-heating-value gaseous fuel.

READING NUMBER	HARDWARE CONFIGURATION	FUEL TYPE	FUEL %H	FUEL %N	FUEL LHV	FUEL TEMP (F)	SIMULATED ENGINE POWER CONDITION	W NOZ (LB/S) (IF AIR ASSIST)	TINLET (F)	PINLET (PSIA)	W FUEL P (LB/S)	W AIR P (LB/S)	W FUEL S (LB/S)	W AIR S (LB/S)
811102110	LINER RQL, NOZ GAS	MG	3.60	2.47	261.	379.	MAX CONTINUOUS	0.0	665.	168.3	0.342	0.608	0.0	2.476
811102119	LINER RQL, NOZ GAS	MG	3.60	2.47	261.	402.	MAX CONTINUOUS	0.0	667.	168.7	0.336	0.567	0.0	2.453
811102128	LINER RQL, NOZ GAS	MG	3.60	2.47	261.	404.	MAX CONTINUOUS	0.0	666.	169.7	0.342	0.503	0.0	2.452
811102137	LINER RQL, NOZ GAS	MG	3.60	2.47	261.	388.	MAX CONTINUOUS	0.0	667.	167.2	0.339	0.454	0.0	2.537
811102146	LINER RQL, NOZ GAS	MGA	3.74	3.27	263.	391.	MAX CONTINUOUS	0.0	667.	167.7	0.339	0.452	0.0	2.493
811102155	LINER RQL, NOZ GAS	MGA	3.74	3.27	263.	389.	MAX CONTINUOUS	0.0	665.	165.4	0.340	0.406	0.0	2.512
811102164	LINER RQL, NOZ GAS	MG	3.60	2.47	261.	387.	MAX CONTINUOUS	0.0	667.	169.4	0.342	0.402	0.0	2.497
811102173	LINER RQL, NOZ GAS	MG	3.60	2.47	261.	388.	MAX CONTINUOUS	0.0	667.	169.6	0.338	0.376	0.0	2.413
811102183	LINER RQL, NOZ GAS	MGA	3.74	3.27	263.	386.	MAX CONTINUOUS	0.0	666.	170.2	0.339	0.374	0.0	2.470
811102192	LINER RQL, NOZ GAS	MGA	3.74	3.27	263.	388.	MAX CONTINUOUS	0.0	665.	169.9	0.342	0.626	0.0	2.405
811102201	LINER RQL, NOZ GAS	MGA	3.74	3.27	263.	388.	MAX CONTINUOUS	0.0	665.	169.1	0.342	0.592	0.0	2.494
811102211	LINER RQL, NOZ GAS	MG	3.60	2.47	261.	390.	MAX CONTINUOUS	0.0	663.	166.0	0.344	0.615	0.0	2.549
811102220	LINER RQL, NOZ GAS	MG	3.60	2.47	261.	394.	MAX CONTINUOUS	0.0	663.	168.2	0.343	0.504	0.0	2.525
811102229	LINER RQL, NOZ GAS	MC	3.60	2.47	261.	399.	MAX CONTINUOUS	0.0	664.	165.4	0.342	0.413	0.0	2.495
811102238	LINER RQL, NOZ GAS	MG	3.60	2.47	261.	390.	MAX RATED	0.0	684.	177.9	0.370	0.594	0.0	2.620
811102247	LINER RQL, NOZ GAS	MC	3.60	2.47	261.	406.	MAX RATED	0.0	685.	177.5	0.369	0.449	0.0	2.596
811102256	LINER RQL, NOZ GAS	MGA	3.74	3.27	263.	400.	MAX RATED	0.0	688.	176.9	0.372	0.461	0.0	2.502
811102265	LINER RQL, NOZ GAS	MC	3.60	2.47	261.	300.	50% LOAD	0.0	538.	117.6	0.173	0.324	0.0	1.704
811102274	LINER RQL, NOZ GAS	MG	3.60	2.47	261.	369.	50% LOAD	0.0	544.	118.7	0.181	0.263	0.0	1.631
811102283	LINER RQL, NOZ GAS	MGA	3.74	3.27	263.	385.	50% LOAD	0.0	543.	118.1	0.183	0.261	0.0	1.636
811102292	LINER RQL, NOZ GAS	MGA	3.99	4.71	265.	382.	50% LOAD	0.0	554.	117.8	0.183	0.275	0.0	1.637
811102301	LINER RQL, NOZ GAS	MGA	3.74	3.27	263.	377.	50% LOAD	0.0	555.	116.0	0.182	0.220	0.0	1.672
811102310	LINER RQL, NOZ GAS	MG	3.60	2.47	261.	376.	50% LOAD	0.0	556.	116.7	0.183	0.215	0.0	1.657
811102319	LINER RQL, NOZ GAS	MC	3.60	2.47	261.	378.	70% LOAD	0.0	576.	136.0	0.238	0.441	0.0	2.166
811102328	LINER RQL, NOZ GAS	MG	3.60	2.47	261.	379.	70% LOAD	0.0	581.	135.0	0.237	0.355	0.0	2.125
811102337	LINER RQL, NOZ GAS	MGA	3.74	3.27	263.	383.	70% LOAD	0.0	583.	134.7	0.236	0.353	0.0	2.126
811102346	LINER RQL, NOZ GAS	MGA	3.74	3.27	263.	388.	70% LOAD	0.0	588.	136.3	0.237	0.292	0.0	2.155
811102355	LINER RQL, NOZ GAS	MC	3.60	2.47	261.	392.	70% LOAD	0.0	589.	136.8	0.233	0.295	0.0	2.162
811102363	LINER RQL, NOZ GAS	MGA	3.95	4.47	264.	396.	70% LOAD	0.0	595.	136.0	0.232	0.292	0.0	2.109

Table XIII-A.
RQL combustor performance data--
mid-heating-value gaseous fuel.

READING NUMBER	PRIMARY (RICH ZONE) EQUIVALENCE RATIO	SECONDARY (LEAN ZONE) EQUIVALENCE RATIO	OVERALL EQUIVALENCE RATIO	PRIMARY RES. TIME (MSEC.)	SECONDARY RES. TIME (MSEC.)	PRIMARY REF. VELOCITY (FT/S)	SECONDARY REF. VELOCITY (FT/S)	EXIT TEMPERATURE (F)	EXIT PRESSURE (PSIA)	SPECIFIC HUMIDITY	COMBUSTOR DELTA P (PSI)	LINER TEMPERATURE (F)	CO (PPM)	CO_2 (PPM)	HC (PPM)	NOX (PPM)	NOX (PPMC)
811102110	1.65	0.41	0.27	131.	13.	8.	35.	1628.	160.	0.00042	8.36	1553.	17.	85000.	4.	116.	81.
811102119	1.75	0.40	0.27	141.	13.	7.	35.	1635.	160.	0.00031	8.24	1561.	17.	82300.	4.	105.	75.
811102128	1.99	0.41	0.27	163.	13.	6.	35.	1635.	162.	0.00050	8.11	1534.	17.	85200.	4.	103.	75.
811102137	2.19	0.39	0.26	179.	13.	6.	36.	1599.	159.	0.00073	8.39	1476.	18.	86500.	4.	102.	71.
811102146	2.25	0.41	0.27	178.	13.	6.	36.	1575.	159.	0.00073	8.26	1474.	17.	83400.	4.	95.	68.
811102155	2.51	0.41	0.27	202.	13.	5.	36.	1599.	160.	0.00046	8.06	1432.	17.	84000.	3.	94.	67.
811102164	2.49	0.40	0.27	208.	13.	5.	35.	1593.	162.	0.00052	7.88	1424.	17.	84300.	3.	94.	66.
811102173	2.64	0.40	0.26	224.	13.	5.	35.	1591.	162.	0.00052	8.23	1417.	19.	83000.	3.	98.	70.
811102183	2.71	0.41	0.27	222.	13.	5.	35.	1595.	162.	0.00027	8.16	1417.	18.	84700.	3.	95.	66.
811102192	1.63	0.43	0.28	127.	14.	8.	34.	1436.	161.	0.0	8.80	1564.	24.	90000.	3.	116.	76.
811102201	1.73	0.41	0.28	134.	13.	8.	35.	1541.	161.	0.0	7.88	1555.	22.	90500.	2.	117.	76.
811102211	1.64	0.40	0.27	129.	13.	8.	36.	1549.	159.	0.0	8.57	1563.	20.	88200.	2.	112.	75.
811102220	2.00	0.40	0.27	161.	13.	6.	36.	1560.	160.	0.0	8.21	1507.	22.	89000.	2.	110.	73.
811102229	2.43	0.40	0.27	201.	13.	5.	35.	1617.	160.	0.0	8.34	1412.	19.	85300.	2.	102.	70.
811102238	1.83	0.41	0.28	141.	13.	7.	36.	1565.	169.	0.0	8.59	1473.	20.	93500.	1.	120.	75.
811102247	2.41	0.42	0.28	191.	13.	5.	35.	1585.	169.	0.0	8.37	1434.	19.	95500.	1.	121.	75.
811102256	2.41	0.43	0.29	182.	13.	6.	36.	1587.	168.	0.0	8.86	1436.	19.	95500.	1.	120.	74.
811102265	1.56	0.30	0.17	193.	15.	5.	31.	1195.	112.	0.00146	5.71	1443.	46.	53000.	3.	76.	[illegible]
811102274	2.02	0.32	0.18	245.	15.	4.	30.	1252.	113.	0.00125	5.50	1448.	31.	55300.	2.	63.	[illegible]
811102283	2.09	0.33	0.19	241.	15.	4.	30.	1260.	113.	0.00115	5.51	1457.	28.	56200.	3.	69.	79.
811102292	2.07	0.35	0.20	221.	15.	5.	30.	1279.	112.	0.00104	6.12	1463.	27.	57300.	3.	69.	73.
811102301	2.48	0.33	0.19	284.	15.	4.	31.	1237.	110.	0.00094	5.92	1527.	25.	57200.	3.	50.	53.
811102310	2.49	0.32	0.19	296.	15.	3.	31.	1269.	111.	0.00094	5.70	1533.	24.	57400.	3.	50.	53.
811102319	1.59	0.32	0.21	158.	13.	7.	35.	1327.	129.	0.00052	7.15	1415.	27.	69500.	3.	64.	70.
811102328	1.96	0.33	0.22	198.	13.	5.	35.	1362.	128.	0.00052	6.82	1413.	28.	69300.	3.	81.	59.
811102337	2.00	0.33	0.22	196.	13.	5.	35.	1389.	128.	0.00052	6.80	1419.	27.	69000.	3.	63.	71.
811102346	2.43	0.33	0.22	242.	13.	4.	36.	1373.	129.	0.00042	6.93	1456.	27.	68500.	3.	70.	[illegible]
811102355	2.32	0.32	0.21	244.	13.	4.	36.	1381.	130.	0.00042	7.03	1468.	23.	67500.	3.	69.	60.
811102363	2.45	0.34	0.22	235.	13.	4.	35.	1378.	129.	0.00042	7.00	1473.	27.	68200.	3.	69.	61.

ORIGINAL PAGE IS
OF POOR QUALITY

Table XIII-B.
RQL combustor performance data--
mid-heating-value gaseous fuel.

READING NUMBER	% N CONVERSION	COMBUSTION EFFICIENCY (%)	SMOKE NUMBER	PATTERN FACTOR	FARR	DESIRED PRIMARY ZONE EQUIVALENCE RATIO	DESIRED LEAN ZONE EQUIVALENCE RATIO
811102110	6.05	99.95	1.	0.49	1.089	1.50	0.60
811102119	5.68	99.95	1.	0.45	1.059	1.50	0.60
811102128	5.57	99.95	1.	0.49	1.084	1.80	0.60
811102137	5.40	99.95	1.	0.52	1.136	2.00	0.60
811102146	3.87	99.95	1.	0.57	1.070	2.00	0.60
811102155	3.75	99.95	1.	0.56	1.076	2.20	0.60
811102164	4.94	99.95	1.	0.58	1.080	2.20	0.60
811102173	5.30	99.95	1.	0.57	1.077	2.40	0.60
811102183	3.73	99.95	1.	0.55	1.082	2.40	0.60
811102192	4.18	99.95	1.	0.86	1.127	1.50	0.50
811102201	4.20	99.95	1.	0.75	1.133	1.50	0.50
811102211	5.60	99.95	1.	0.68	1.136	1.50	0.50
811102220	5.39	99.95	1.	0.71	1.136	1.80	0.50
811102229	5.20	99.95	1.	0.61	1.083	2.20	0.50
811102238	5.38	99.95	1.	0.66	1.156	1.80	0.60
811102247	5.29	99.95	1.	0.63	1.165	2.20	0.60
811102256	3.98	99.95	1.	0.63	1.159	2.20	0.60
811102265	9.72	99.89	1.	0.70	1.050	1.50	0.50
811102274	7.32	99.93	1.	0.75	1.035	1.80	0.50
811102283	5.81	99.93	1.	0.74	1.015	1.80	0.50
811102292	3.93	99.93	1.	0.67	1.026	1.80	0.50
811102301	4.29	99.94	1.	0.75	1.053	2.20	0.50
811102310	5.62	99.94	1.	0.68	1.055	2.20	0.50
811102319	6.50	99.94	1.	1.01	1.111	1.50	0.50
811102328	6.26	97.13	1.	0.83	1.090	1.80	0.50
811102337	4.87	99.94	1.	0.80	1.078	1.80	0.50
811102346	4.20	99.94	1.	0.86	1.086	2.20	0.50
811102355	5.69	99.94	1.	0.82	1.099	2.20	0.50
811102363	3.05	99.94	1.	0.82	1.067	2.20	0.50

REFERENCES

1. E. Lister, R. W. Niedzwiecki, and L. Nichols, "Low NO_x Heavy Fuel Combustor Program," ASME Paper 80-GT-69, 1980, Gas Turbine Conference, New Orleans.

2. A. S. Novick, D. L. Troth, and H. G. Yacobucci, "Design and Preliminary Results of a Fuel Flexible Industrial Gas Turbine Combustor," ASME Paper 81-GT-108, 1981, Gas Turbine Conference, Houston.

3. A. S. Novick and D. L. Troth, "Low NO_x Heavy Fuel Combustor Concept Program," NASA CR-165367, final report for Contract DEN3-148, October 1981.