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Evaluation of Advanced Combustion Concepts for Dry NO_x Suppression with Coal-Derived, Gaseous Fuels

K. W. Beebe and R. A. Symonds
General Electric Company

and

J. Notardonato
National Aeronautics and Space Administration
Lewis Research Center



Work performed for
U.S. DEPARTMENT OF ENERGY
Fossil Energy
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Prepared for
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K. W. Beebe and R. A. Symonds
General Electric Company
Schenectady, New York 12345

and

J. Notardonato
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

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EVALUATION OF ADVANCED COMBUSTOR CONCEPTS FOR DRY NO_x SUPPRESSION WITH COAL-DERIVED, GASEOUS FUELS

by

K.W. Beebe
Engineer
Member ASME

R.A. Symonds
Engineer
Member ASME
General Electric Company
Schenectady, N.Y. 12345

J. Notardonato

NASA/Lewis Research Center
Cleveland, Ohio 44135

NO_x performance of the rich-lean combustor did not meet program goals with the 244 Btu/scf gas because of high thermal NO_x, similar to levels expected from conventional lean-burning combustors. The NO_x emissions are attributed to inadequate fuel-air mixing in the rich stage resulting from the design of the large central fuel nozzle delivering 71% of the total gas flow. NO_x yield from ammonia injected into the fuel gas decreased rapidly with increasing ammonia level, and is projected to be less than 10% at NH₃ levels of 0.5% or higher. NO_x generation from NH₃ is significant at ammonia concentrations significantly less than 0.5%. These levels may occur depending on fuel gas clean-up system design.

CO emissions, combustion efficiency, smoke and other operational performance parameters were satisfactory.

A test was completed with a catalytic combustor concept with petroleum distillate fuel. Reactor stage NO_x emissions were low (1.4g NO_x/kg fuel). CO emissions and combustion efficiency were satisfactory. Airflow split instabilities occurred which eventually led to test termination.

NOMENCLATURE

- CO - carbon monoxide emissions
- EI - emissions index, g/kg fuel
- f/a - fuel-air mass ratio
- (f/a)_s - stoichiometric fuel-air mass ratio
- IGCC - Integrated Gasification Combined Cycle
- ISO - International Standards Organization reference humidity condition, 0.0063 lb H₂O/lb dry air
- M.W. - molecular weight
- MW - power, megawatts electrical output
- NCM - normal cubic meter, at 273K
- NO_x - oxides of nitrogen emissions
- P₃ - combustor inlet pressure
- ppmv - parts per million by volume
- T₃ - combustor inlet temperature
- T₄ - average combustor exhaust temperature
- T_s - stoichiometric temperature
- UHC - unburned hydrocarbon emissions
- φ - mass equivalence ratio

ABSTRACT

A test program has been completed to determine the emissions performance of a rich-lean combustor (developed for liquid fuels in Phase I of the DOE/LeRC Advanced Conversion Technology Project) for combustion of simulated coal gases ranging in heating value from 167 to 244 Btu/scf (7.0 to 10.3 MJ/NCM). The 244 Btu/scf gas is typical of the product gas from an oxygen-blown gasifier, while the 167 Btu/scf gas is similar to that from an air-blown gasifier.

INTRODUCTION

The projected decline in the availability of petroleum fuels for electricity generation or industrial applications, and the projected increase in an uncertainty of fuel costs throughout the next decade have been driving forces towards the utilization of the nation's coal resources.

Significant effort has been expended and progress achieved in the development of processes to produce coal-derived liquid (CDL) and gaseous (CDG) fuels. Earlier projections were that CDL's could be expected to be available in quantities suitable for market penetration by the late 1980's. On this basis, development of dry low NO_x combustion technology to meet NSPS emissions standards with high nitrogen content CDL's was the focal point of the Phase I effort in the NASA-sponsored Low NO_x Heavy Fuel Combustor Concept Program. General Electric completed its Phase I development tests and reported the results in October 1981. It was demonstrated that the two stage, rich-lean combustor concept would meet all program objectives for emissions with satisfactory operational performance. Combustor development addressed two key CDL properties which impact on performance, i.e., low hydrogen content which can promote smoke formation and leads to high radiant heat loadings to liner walls, and high fuel-bound nitrogen content (FBN) which promotes organic NO_x formation in conventional lean-burning combustors. Rich-lean Concepts 2 and 3 of that program addressed these fuel properties, successfully meeting emissions criteria.

More recent trends in national energy policy and fuel economics could lead to deferment of CDL availability to the 1990's. Utilization of coal-derived gaseous fuels is now considered the more likely candidate for market introduction in Utility applications. General Electric is strongly involved in the application of coal-derived gases through its integrated gasification combined cycle (IGCC) plant studies.

It is now anticipated that a Phase II of the NASA-sponsored Low NO_x Combustor Program will emphasize dry low-NO_x combustion technology development for low and intermediate Btu heating value coal gases (LBtu, IBtu gases). Under NASA sponsorship, General Electric has completed the Phase IA program to develop combustion technology for LBtu and IBtu gases.

The Phase IA program provides a bridge between the low NO_x liquid fuel technology of Phase I and the anticipated emphasis on low NO_x coal-derived gas fuel technology to be developed in Phase II. Phase IA objectives were to provide an initial assessment of the emissions and operational performance of the successful rich-lean and lean-lean combustor concepts developed for liquid fuels in Phase I, and to identify problem areas and development needs to be studied in Phase II. A test of the catalytic combustor hardware developed in Phase I was also planned.

Program resources were minimal, considering the cost of simulated LBtu/IBtu gas fuels, and only minor modifications to the existing Phase I hardware and limited testing were possible. Tests were conducted using rich-lean combustor Concept 2 (a multinozzle, two-stage, rich-lean design) with a range of gas heating values from 167 to 244 Btu/scf (7.0 to 10.3 MJ/NCM) at MS7001E turbine load conditions. Tests were run largely at reduced pressure conditions to reduce fuel costs. A full-pressure, full-flow test was also completed to provide a correlation of all data to full MS7001E cycle conditions. Ammonia (NH_3) was injected at several rates up to 0.5 weight percent for the 244 Btu/scf fuel gas to determine organic NO_x generation from potential organic nitrogen contaminants in cleaned fuel gases. The catalytic combustor was tested with petroleum distillate fuel. A lean-lean combustor hardware configuration was developed and fabricated, but it was not tested because of limited program resources. This combustor hardware is available for early testing in the anticipated Phase II program.

This report presents the results of the Phase IA program.

TEST FACILITIES

Combustor tests with liquid fuels in the Phase I program were conducted in a 10-inch diameter (.25m) test rig, in the A5 facility of General Electric's Aircraft Engine Group (AEG) facility in Evendale, Ohio. For the Phase IA gas tests discussed in this report, combustor tests with simulated coal-derived LBtu/IBtu gases were conducted with that 10-inch diameter test rig installed in the combustor test area of the General Electric Gas Turbine Development Laboratory (GTDL) facilities in Schenectady, New York. This facility has a unique capability for on-line blending and delivery of simulated coal-derived gases, can provide blending with nitrogen and steam to adjust gas heating values, and also has gas preheat for large-scale combustor testing.

Test Facilities and Fuel Systems

The combustor test area is a large bay which currently contains five test stands or test ducts.

The process air system can deliver nonvitiated air to the test stands with:

- Mass flow rate from 1 to 50 lb/s (.45 to 23 kg/s)
- Pressure from slightly beyond 1 atm to greater than 10 atm (101 to 1014 kF)
- Temperature from slightly beyond ambient temperature to greater than 700 °F (640K)

For the combustor tests with coal-derived gases described in this report, test stand 4 was removed and replaced by the 10-inch (.25m) diameter test rig used for the Phase I liquid fuel tests. The test rig was connected directly to the blast gate and exhaust section of the test stand using an adapter section. Air supply from the facility was similarly adapted to the entrance of the test rig.

A schematic of the low Btu/intermediate Btu (LBtu/IBtu) gas system used for the Phase IA tests is shown in Figure 1. Gas is supplied in tube trailers (up to four trailers at 100,000 scf (2500 NCM) per trailer) and can be blended on-line with nitrogen and steam to obtain the desired low Btu gas composition and heating value. N_2 and H_2O control is achieved via ratio control stations that maintain the desired proportions of N_2 and/or H_2O to trailer gas. The blending capability has the advantage of reducing the amount of gas that must be supplied in trailers when studying air-blown gases. This capability also permits parametric studies of effects of N_2 or H_2O dilution on the combustion characteristics of coal-derived gases.

Currently, a gas heating system is provided for fuel gas preheat that is capable of achieving gas temperatures up to approximately 600°F (590K). Additional heaters are to be installed that will extend this capability. Ammonia (NH_3) was injected into the fuel gas during tests of the rich-lean combustor with 244 Btu/scf (10.3 MJ/NCM) heating value gas.

Instrumentation

The combustor test rig assembly was instrumented to measure the performance and durability of the combustor.

Total inlet air flow measurements were made using standard ASME orifices which are an integral part of the Gas Turbine Development Laboratory (GTDL) facilities. Inlet total air pressure and temperature were measured with four rakes having two

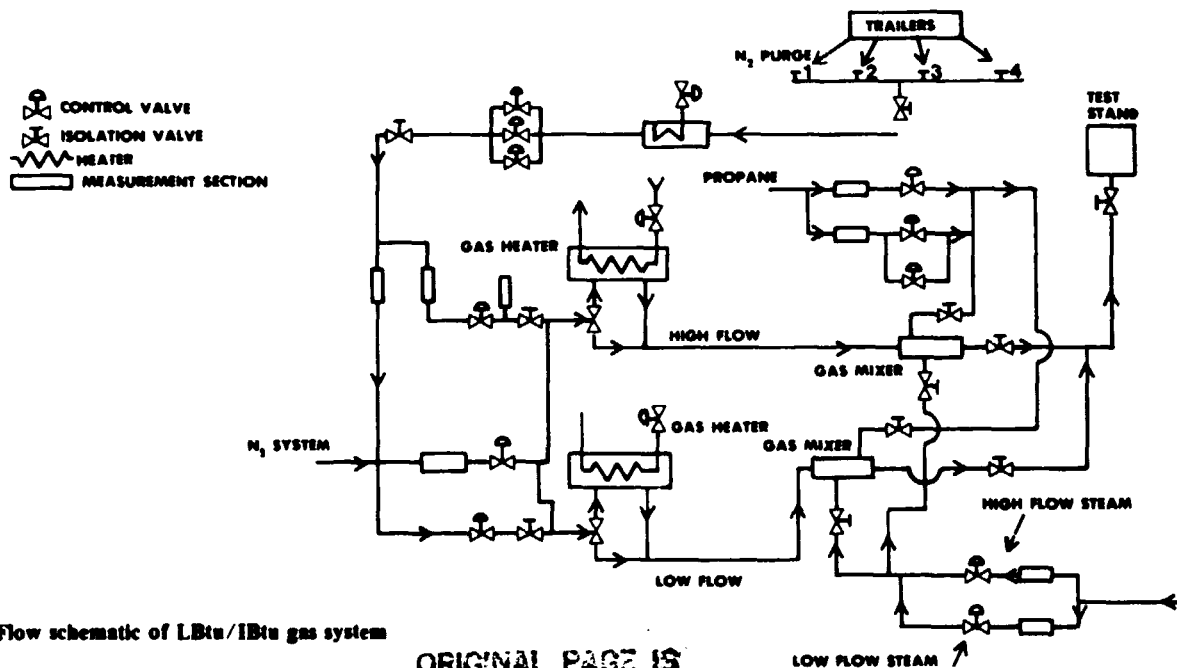


Fig. 1 Flow schematic of LBtu/IBtu gas system

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immersions each. These rakes are an integral part of GTDL test stand No. 4. Test rig and combustor static pressures were measured using three wall static taps. These pressures were referenced to the inlet air total pressure to determine the pressure drops to the rig and across the liner.

Fuel nitrogen and ammonia flows were measured using standard ASME orifices. The combustor liner was instrumented with an array of 16 metal surface thermocouples.

The exhaust gas instrumentation consisted of four three-element gas sampling rakes and four three-element thermocouple rakes. The gas sampling rakes were also utilized for measuring combustor exit total pressures. The three elements on each rake were mounted on centers of equal area in the combustor centerline. The gas sample probes were ganged together for all test points in this program. This was done to reduce the time required at each test point, and so conserve the available fuel gas supply. The gang samples are presumed to be representative of bulk gas properties at the combustor exit. Gas sample probes were water-cooled for durability.

TEST FUELS

The rich-lean combustor was tested using gas fuel blends ranging in lower heating value (LHV) from 167 to 244 Btu/scf (7.0 - 10.3 MJ/NCM). The test fuel compositions are presented in Table 1. The baseline fuel contained 38.4% H₂, 0.65% N₂, 44.53% CO and 16.43% CO₂ by volume. Four tube trailers containing this gas were supplied by the Union Carbide Corporation. The baseline fuel composition was obtained by averaging the analyses supplied by Union Carbide for each trailer. The trailers were manifolded in parallel to supply the test stand fuel requirements. Variations in fuel composition and heating value were obtained by adding nitrogen as a diluent to the baseline fuel. Five data points were taken, with ammonia (NH₃) injected into the baseline fuel to determine the NO_x yield as the rich-lean combustor operated with various levels of fuel-bound nitrogen. In order to make an accurate determination of the ammonia content in the fuel gas during these tests, bottled fuel gas samples were taken at each data point and later analyzed for composition. The fuel ammonia level ranged from 0.07% to 0.5% by weight. The actual level of ammonia encountered in coal gas fuels in an Integrated Gasification Combined Cycle (IGCC) application would be a function of the specific fuel gas cleanup system design. The range of ammonia injection was selected to be representative of potential IGCC plant conditions. Equilibrium

flame temperature and products of combustion were calculated for all three of the nominal gas fuel compositions (heating values) used for the test program. These calculations were performed using the NASA Chemical Equilibrium Code (3). Results of these analyses are presented in Figures 2, 3 and 4.

(The catalytic combustor was tested with #2 distillate oil only.)

TEST CONDITIONS

The operating conditions used in evaluation testing of the rich-lean combustor are representative of the General Electric MS7001E utility turbine. The MS7001E gas turbine has a baseload rating of 72.9 MW at a turbine inlet temperature of 1985°F (1358K), pressure ratio of 11.7 and airflow of 590 lb/s

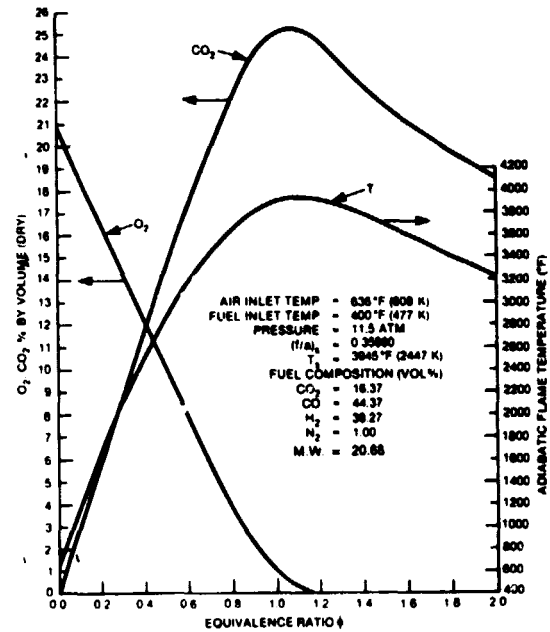


Fig. 2 NASA equilibrium data for 244 Btu/scf gas (10.3 MJ/NCM)
 Conversion factors: (°F + 460) × 5/9 = K; (atm.) × 101.35 = kPa

Table 1
 RICH-LEAN COMBUSTOR TESTS LBTU/18TU FUEL GAS COMPOSITIONS

Test Points	3A,3B,3C,4 5,6A,18C	16	17	18	18A	18B	7,7A,8,9	11,12,13
H ₂ (vol %)	38.4	37.2	37.9	37.3	37.4	37.8	32.83	26.56
O ₂ (vol %)	0	0.17	0.14	0.18	0.11	0.13	0	0
N ₂ (vol %)	0.65	0.59	0.61	0.58	0.62	0.57	15.06	31.28
CO (vol %)	44.53	44.5	44.3	44.7	44.1	44.9	38.07	30.8
CH ₄ (vol %)	0	0.18	0.17	0.18	0.17	0.18	0	0
CO ₂ (vol %)	16.43	16.50	16.50	16.70	16.60	16.8	14.05	11.36
NH ₃ (vol %)	0	0.45	0.50	0.32	0.11	0.07	0	0
Mol. wt.	20.65	20.79	20.75	20.91	20.65	20.96	21.76	23.37
LHV Btu/scf	244	242.7	243.8	243.6	241.9	245.6	209.0	169.0
(MJ/NCM)	(10.3)	(10.2)	(10.2)	(10.2)	(10.2)	(10.3)	(8.8)	(7.1)
Fuel Temp °F	418	405	407	409	409	410	421	423
(K)	(488)	(481)	(482)	(483)	(483)	(483)	(489)	(491)

The operating conditions used in evaluation testing of the rich-lean combustor are representative of the General Electric MS7001E utility turbine. The MS7001E gas turbine has a baseload rating of 72.9 MW at a turbine inlet temperature of 1985°F (1358K), pressure ratio of 11.7 and airflow of 590 lb/s (268 kg/s). The matrix of test conditions is shown in Table 2. In order to conserve fuel and obtain the maximum number of data points with the limited quantity of fuel available, most of the data were taken at half pressure/half flow conditions. The standard procedure was to operate the combustor at three load points for the MS7001E (50% power, base, and peak load) for each fuel blend and to conduct additional tests as appropriate. Fuel-air ratios above and below design levels were tested with the baseline fuel to determine the effect on NO_x emission levels. The baseline fuel test conditions were also used with ammonia injection.

Operating conditions for the catalytic combustor are described elsewhere in this paper.

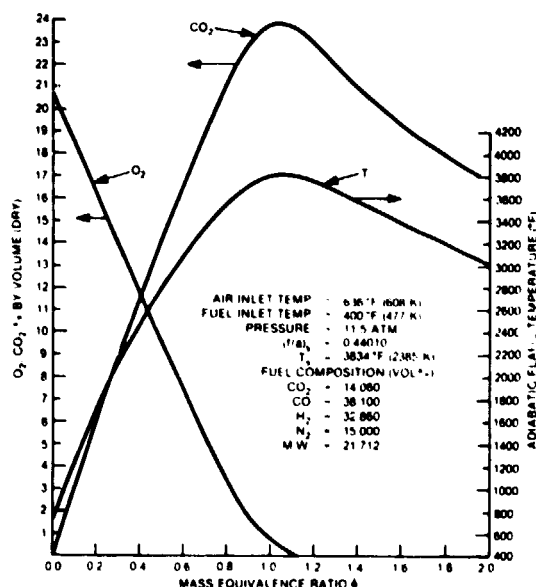


Fig. 3 NASA equilibrium data for 209 Btu/scf gas (8.78 MJ/NCM)

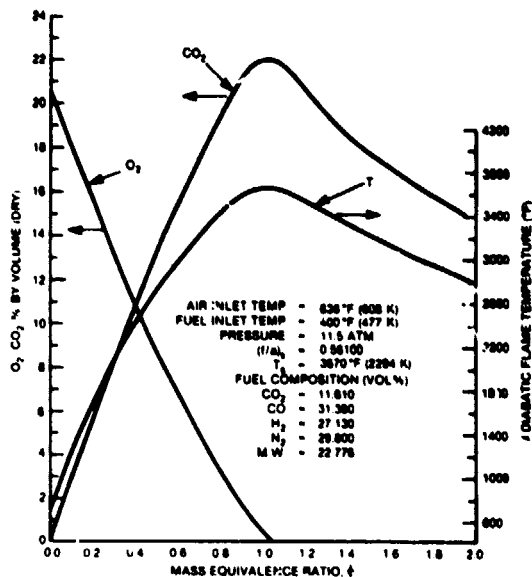


Fig. 4 NASA equilibrium data for 172 Btu/scf gas (7.23 MJ/NCM)

DESCRIPTION OF TEST COMBUSTORS

Gas Fueled Rich-Lean Combustor

Previous work has shown the potential of two-stage rich-lean combustion for producing low NO_x emissions with high nitrogen fuels. The work described here is aimed at development of this concept for use in heavy duty stationary gas turbines operating on gas fuels derived from coal. In the rich-lean combustion mode, a rich mixture of fuel and air ($\phi = 1.7$) is burned in the first stage, producing incomplete combustion at low temperatures in an oxygen-deficient environment. Under these conditions, little thermal NO_x is produced while fuel nitrogen is released with minimal conversion to NO_x. This incompletely combusted mixture is then mixed with additional combustion air in a low residence time quench zone to produce a lean mixture ($\phi = 0.5$), with combustion completed in the lean second stage.

The test combustor used for this effort was obtained by converting a liquid fueled design to gas fuel. Because the original combustor was shown to be quite successful in reducing NO_x,

Table 2

RICH-LEAN COMBUSTOR TEST CONDITIONS

Fuel Lower Heating Value (LHV) (Btu/scf)	MS7001E Load Condition (% Load)	T ₁ , Inlet Total Temp. (°F)	P ₁ , Inlet Total Press. (psia)	T ₂ , Outlet Total Temp. (°F)	W ₁ , Compressor Airflow (lb/s)	f/a Overall Fuel-Air Ratio	ϕ_{sto}	W ₂ , Total Flow (lb/s)	$\Delta P/P_{11}$ (%)
244	100 (peak)	636	169	2190	15.122	0.110	0.309	16.8	5.87
244	92 (base)	631	166	2082	15.217	0.1040	0.289	16.8	6.15
244	50	598	149	1460	15.974	0.0580	0.161	16.9	7.98
209	100 (peak)	636	169	2190	14.724	0.1410	0.320	16.8	5.59
209	92 (base)	631	166	2082	14.841	0.1320	0.300	16.8	5.88
209	50	598	149	1460	15.634	0.0810	0.184	16.9	7.91
172	100 (peak)	636	169	2190	14.177	0.1850	0.330	16.8	5.19
172	92 (base)	631	166	2082	14.384	0.1680	0.300	16.8	5.51
172	50	598	149	1460	15.266	0.1070	0.191	16.9	7.65

(1) Overall combustor equivalence ratio
(2) $\Delta P/P_{11}$ = (liner total pressure drop)/P₁₁

Conversion Factors (Btu/scf) \times 42.03 = MJ/NCM, (°F + 460) \times 5/9 = K, (psia) \times 6.895 = Pa, (lb/s) \times 4.54 = kg/s

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emissions when burning liquid fuels (2), most of its geometry was preserved for the gas fuel test. Nine gas fuel nozzles were installed in the head end of the rich stage replacing the eight liquid fuel nozzles used in prior testing. To handle the large volume flow required with low Btu gas fuel, a large central fuel nozzle designed to pass 71 percent of total fuel flow was added, with the balance of the fuel flow distributed equally among the eight outer nozzles. Figure 5 presents a schematic of the combustor showing the airflow splits for the rich, quench and lean combustion zones, and Table 3 shows the equivalence ratios for the various fuels and load points tested. Figure 6 shows the large center fuel nozzle.

Downstream of the rich stage is the necked down quench zone followed by the lean stage. Rich-stage liner cooling is accomplished by convection cooling of the outside surface. This convective cooling proved inadequate during prior testing of this concept with liquid fuels. Therefore a boundary layer trip wire was installed to enhance the heat transfer coefficient on the outside diameter of the rich stage liner. This trip wire is shown in Figure 7. To help maintain metal temperatures at acceptable levels a thermal barrier coating was applied to the inside surface of the rich-stage liner as was done for the liquid fueled design. The test combustor has a diameter of 8 inches (.2m) and an overall length of 49 inches (1.25m). Figure 8 shows the entire combustor assembly, although the boundary layer trip wire is obscured by the flow sleeve in this photograph.

Table 3

RICH-LEAN COMBUSTOR EQUIVALENCE RATIOS

Fuel LHV	Load Condition	50%	92% (Base)	100% (Peak)
244 Btu/scf (10.3 MJ/NCM)	Fuel/Air Overall ⁽¹⁾	0.0580	0.1040	0.1110
	ϕ Overall ⁽²⁾	0.161	0.289	0.309
209 Btu/scf (8.8 MJ/NCM)	Fuel/Air Overall	0.0810	0.1320	0.1410
	ϕ Overall	0.184	0.300	0.320
172 Btu/scf (7.2 MJ/NCM)	Fuel/Air Overall	0.1070	0.1680	0.1850
	ϕ Overall	0.191	0.300	0.330
Equivalence Ratios				
244 Btu/scf (10.3 MJ/NCM)	Rich Stage	0.856	1.537	1.644
	Quench Stage	0.256	0.459	0.491
209 Btu/scf (8.8 MJ/NCM)	Rich Stage	0.979	1.596	1.702
	Quench Stage	0.293	0.477	0.509
172 Btu/scf (7.2 MJ/NCM)	Rich Stage	1.015	1.596	1.755
	Quench Stage	0.304	0.477	0.525

- (1) Overall fuel/air mass ratio
(2) Equivalence ratio, overall

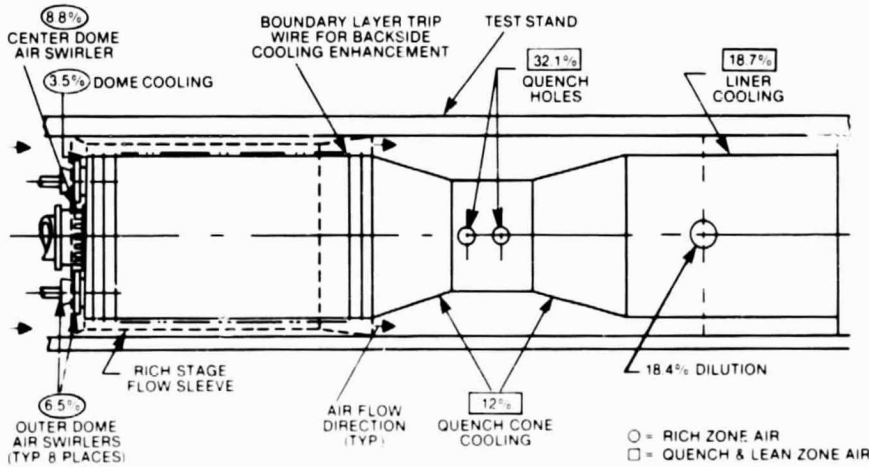


Fig. 5 Rich-lean combustor airflow splits for gas fuel testing



Fig. 6 Center fuel nozzle for rich-lean combustor

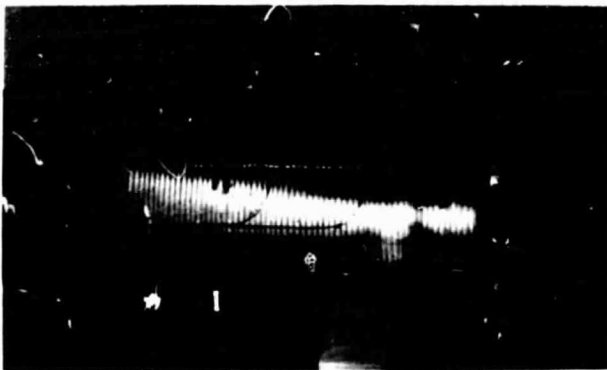


Fig. 7 Rich stage boundary layer trip wire

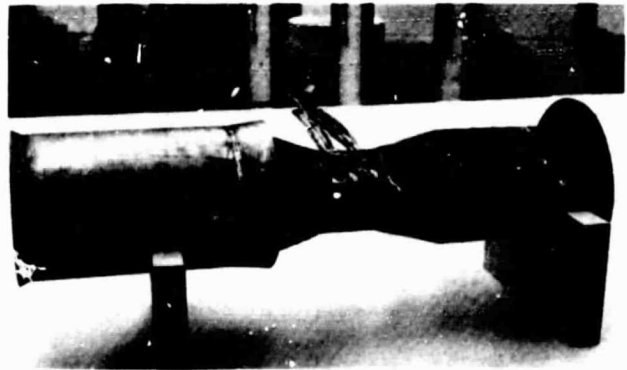


Fig. 8 Rich-lean combustor with flow sleeve

Gas Fueled Lean-Lean Combustor

Lean-lean combustors burn lean in both stages to avoid high combustion gas temperature and thus avoid generation of thermal NO_x . In order to avoid poor combustion and generation of CO associated with too lean a mixture, two stages of combustion are employed. At low engine power conditions when the total fuel flow rate is low, only the primary or pilot stage of the combustor is fueled. At higher power conditions when the engine fuel flow rate is adequate to fuel both stages of the combustor, fuel is introduced into the main stage dome and the pilot fuel flow is reduced. As the engine power and fuel flow rates are increased, the equivalence ratio increases in both stages, but it is always maintained lean enough at all locations to reduce thermal NO_x .

Figure 9 is a schematic of the lean-lean test combustor showing the design airflow splits. Table 4 presents the equivalence ratios for each load point in the test plan. A single gas fuel nozzle was designed for the pilot stage, and eight smaller gas fuel nozzles were designed for the main stage. The pilot fuel nozzle is a strong swirl design of the type utilized for low Btu gas fuel testing of the High Temperature Turbine Technology (HTTT) sectoral combustor development sponsored by the U.S. Department of Energy (DOE). Using this concept, rapid fuel/air mixing and wide turndown ratio are achieved by contra-swirling annular fuel and air streams which produce a strong vortex in the reaction zone. The eight main-stage gas fuel nozzles are identical to the outer fuel nozzles of the rich-lean combustor except that the fuel gas metering holes are larger for the lean-lean combustor. The design intent is to split the fuel so that 35 percent goes to the pilot fuel nozzle and 65 percent to the main stage in all two-stage operations.

The overall length of this combustor is 25.5 in. (.65m), the pilot dome diameter being 6 in. (.15m), and the aft liner diameter 8 in. (.2m). Approximately 31.8% of the combustor air is used for liner cooling. Figure 10 shows the lean-lean combustor assembly prepared for test. Program resources were exhausted before any gas fuel testing of the lean-lean combustor was performed, but the test combustor remains available for future investigation of this concept.

Catalytic Combustor

The catalytic combustor concept, identified in an earlier paper (1) and described in greater detail elsewhere (2), consists of three major stages — fuel preparation, a catalytic reactor stage, and a pilot stage. The combustor itself is shown in Figure 11.

Table 4

LEAN-LEAN COMBUSTOR EQUIVALENCE RATIOS
Pilot/Main Fuel Split = 35/65
244 Btu/scf (10.3 MJ/NCM) Fuel

Load Condition	50% Pilot Only	50% Both Stages	92% (Base) Both Stages	100% (Peak) Both Stages
Overall Fuel/Air Ratio	0.0580	0.0580	0.1041	0.1110
Percent Pilot Fuel	100	35	35	35
Overall Equivalence Ratio	0.161	0.161	0.289	0.309
φ Pilot Swirl Cup	1.134	0.397	0.712	0.762
+ Dome Cooling	0.953	0.333	0.599	0.640
+ Pilot Liner Cooling	0.503	0.176	0.316	0.338
φ Main Dome	0	0.303	0.544	0.582
+ Main Stage Cooling	0	0.255	0.458	0.490
φ Total Combustion	0.22	0.22	0.40	0.42

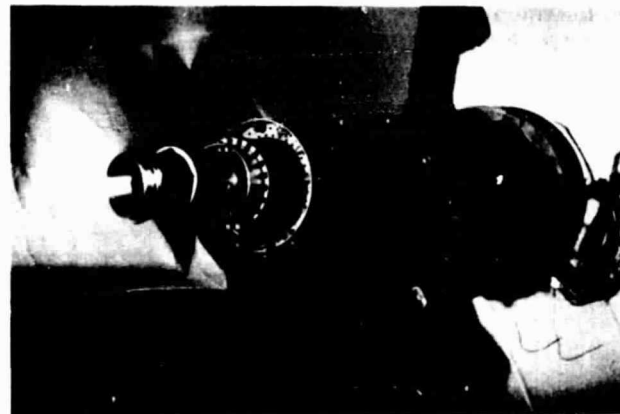


Fig. 10 Gas fuel configuration: lean-lean combustor

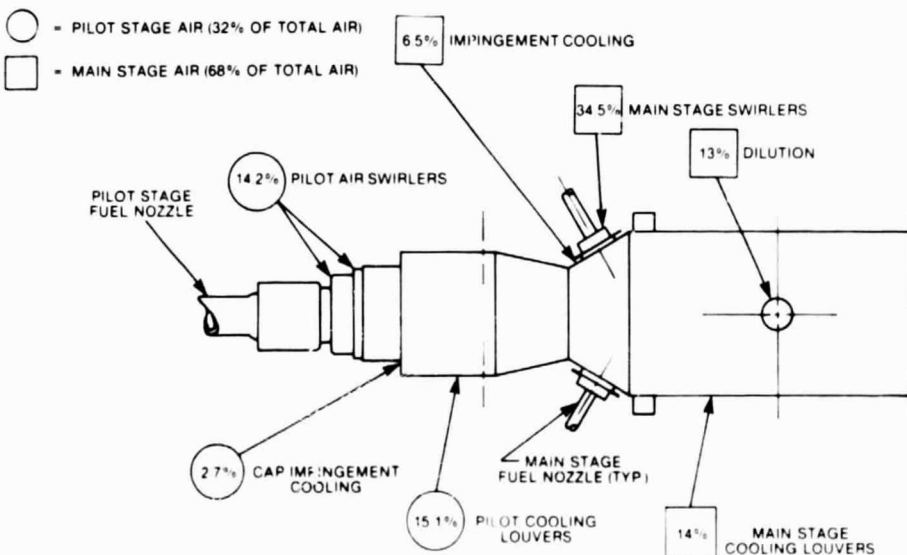


Fig. 9 Lean-lean combustor airflow split: for gas fuel testing

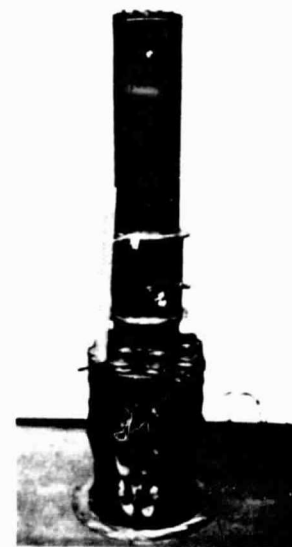


Fig. 11 Catalytic combustor

A multiple nozzle fuel preparation section precedes the catalytic reactor stage. This section, with seven fuel nozzles, provides premixing of the fuel-air mixture and revaporization of liquid fuel. A 15 in. (.38m) long section is provided for thorough premix of liquid and LBtu/lBtu gas fuels. This is followed by a 5 in. (.13m) long section holding the main stage catalytic reactor, which consists of MCB-12 zirconia spinel substrate coated with a proprietary UOP noble metal catalyst. The reactor was designed and manufactured by the Energy and Environmental Division of Acurex Corporation. The reactor stage is followed by the downstream pilot stage section which is used for ignition, acceleration, and part-load to 50% load operation (at which point, reactor lightoff occurs for further load increase to full power).

Figure 12 presents the fuel scheduling necessary for this parallel-staged design to meet the load requirements of an MS7001E gas turbine. In this design, a transfer point between pilot and catalyst was determined by the operational range of the catalyst, i.e., its turn-down ratio, physical dimensions and maximum face velocity. Ignition, acceleration, and loading to about 50% load are accomplished with the pilot stage only. At the transfer point, fuel flow to the combustor is sufficiently high to ignite the reactor stage at a fuel-air ratio of approximately 0.020. The pilot stage fuel flow is then lowered to a flow sufficient to retain pilot operation for cleanup of exhaust gas from the reactor section and to eliminate any need to reignite the pilots. Further increase in load to approximately 80% is achieved by increasing reactor stage fuel flow to a fuel-air ratio of approximately 0.030 in the reactor. This limit provides reactor temperatures meeting those required for reactor durability. Further increases in load are accomplished by increasing pilot stage fuel flow.

Design air flow splits at the baseload (72%) point were as follows:

Catalyst - Main Stage	60%
Pilots	
Dome Cooling	5%
Swirlers	12%
	17%
Liner Cooling	15%
Dilution	8%
	100%

Cold flow testing established, however, that the catalyst received only 42% airflow at cold conditions. Although this figure was significantly less than the 60% design level anticipated, it was

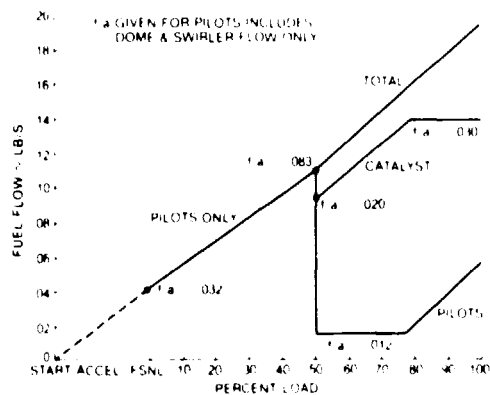


Fig. 12 Fuel schedule—catalytic combustor;
MS7001E cycle, 60/40 airflow split
Conversion factors: (lb/s) × .454 = kg/s

decided to proceed with combustor tests by reducing fuel flow to the reactor section to achieve a fuel-air ratio (and, therefore, reactor temperature) corresponding to the 92% load condition.

As indicated in Figure 13, combustor instrumentation consisted of thermocouples located as follows:

- four thermocouples embedded in the catalytic reactor to monitor catalyst performance and to prevent excessive temperatures in the reactor
- four thermocouples on the outer surface of the premix tube to monitor flashback
- three thermocouples on the converging cone at the reactor exit to monitor temperatures on this uncooled section
- four thermocouples on the pilot stage primary zone to monitor primary zone stability and metal temperature
- two thermocouples on the dilution zone to monitor combustor cooling.

RESULTS AND DISCUSSION

Gas Fueled Rich-Lean Combustor

Figure 14 presents the NO_x emissions data corrected to ISO humidity (0.0063lb H₂O/lb dry air) and 15% oxygen versus engine load and corresponding combustor exit temperature for the reference engine cycle. Data are presented for three levels of fuel heating value tested. All Figure 14 data are for fuel with no fuel-bound nitrogen (i.e., no ammonia injection). The NO_x emissions for the highest heating value fuel (244) were well above the program goals, and emissions for the intermediate heating fuel (209) would also exceed the program goals over most of the load range if corrected to full pressure conditions. The program goals were met only with the lowest heating Btu value fuel (172) tested. In general, the NO_x emissions data for the rich-lean combustor are comparable with data obtained for a more conventional lean burning combustor operating under similar conditions with a similar fuel. All the available data indicate that the rich-lean combustor did not achieve a significant reduction in thermal NO_x production. This unexpected result shows that the full potential of the rich-lean combustion concept was not realized by the test combustor. The reason for this failure to achieve the desired NO_x reduction is believed to be inadequate fuel-air mixing in the rich stage with a resulting rich core flow through the quench zone and into the lean burning zone. This hypothesis is based on the observations that the central fuel nozzle carrying most of the flow was a low swirl design

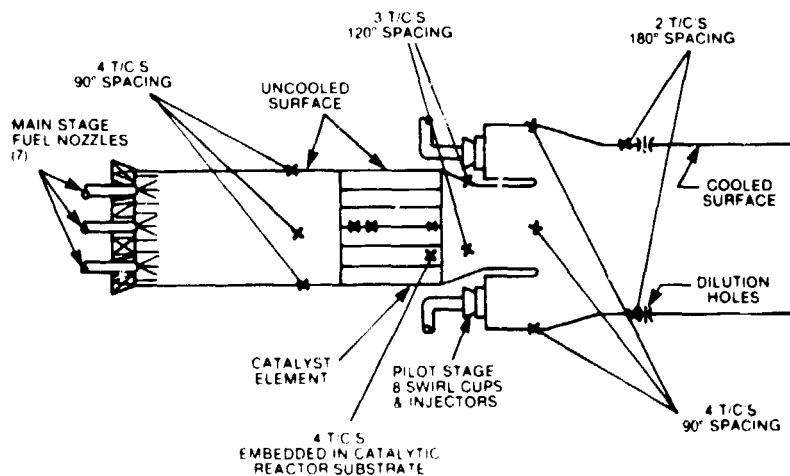


Fig. 13 Catalytic combustor schematic indicating thermocouple locations

producing a strong central fuel jet with no central recirculation zone, and the gas temperature profiles measured at the combustor exit were peaked toward the center at all operating conditions. However, this hypothesis is unproven and other possible explanations exist, including non-optimal dwell times in the rich, quench, or lean stages.

Data for combustion of the highest heating value fuel, 244 Btu/scf (10.3 MJ/NCM), with ammonia injection up to 0.4 percent by weight are presented in Figures 15 and 16. These data show that substantial increases in NO_x emissions occur when fuel-bound nitrogen is present. At 0.06 percent ammonia injection by weight, approximately 78 percent of the fuel-bound nitrogen was converted to NO_x. However, as the ammonia injection rate was increased, the percentage of fuel-bound nitrogen

converted to NO_x was found to decrease. At 0.4 weight percent ammonia injection, the NO_x yield was approximately 24 percent. This trend of decreasing NO_x yield with increasing fuel-bound nitrogen has been observed in prior experimental investigations (4).

Aside from the failure to achieve the desired NO_x emissions reduction, the performance of the rich-lean combustor was generally satisfactory for all fuels tested. Figure 17 presents the carbon monoxide (CO) emissions data versus engine load and corresponding combustor exit temperature for the reference engine cycle. The performance of the rich-lean combustor for several important combustion performance parameters is summarized as follows:

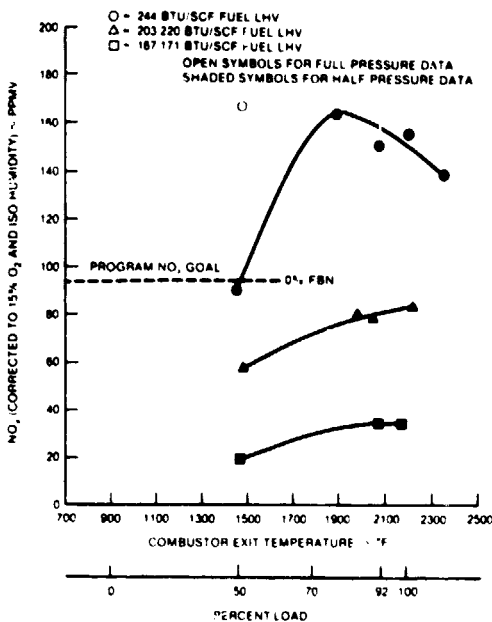


Fig. 14 Rich-lean combustor NO_x emissions vs. load

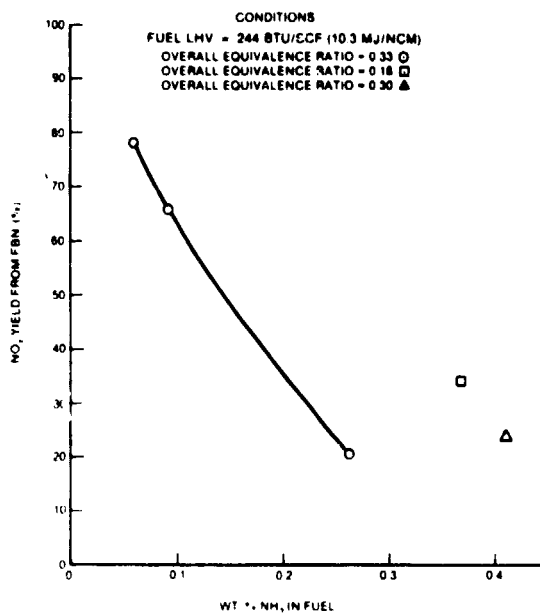


Fig. 16 Rich-lean combustor: NO_x yield—gas fuel with ammonia

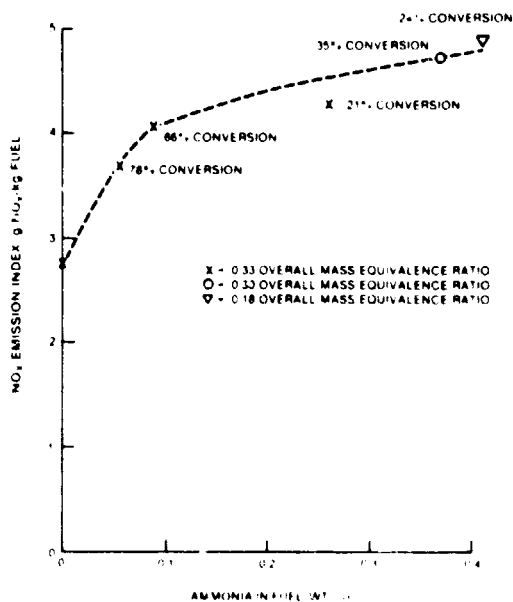


Fig. 15 Rich-lean combustor: NO_x vs. fuel ammonia content

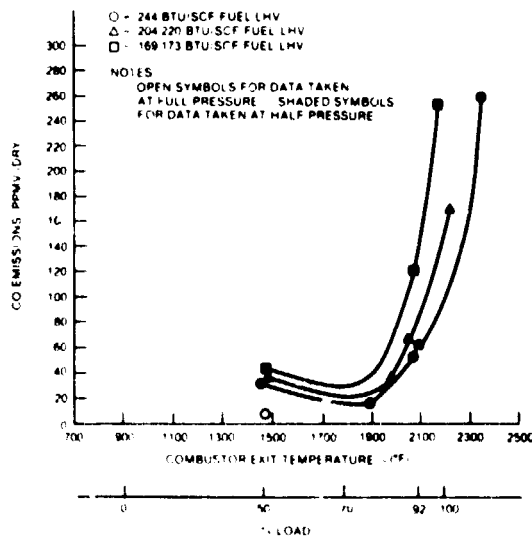


Fig. 17 Rich-lean combustor: CO emissions vs. load
 Conversion factors: (Btu/scf) × 42.03 = MJ/NCM;
 (°F + 460) × 5/9 = K

Rich-Lean Combustor Performance Summary

- NO_x Emissions — Aside from the lowest heating value fuel, program goals were not met due to thermal NO_x production.
- Combustion Efficiency (99.77% - 99.99%) — Satisfactory.
- Smoke — No smoke was observed for any fuel.
- Pattern Factor/Temperature Profile (.127 - .220) — Program goals were met, but there was an indication of rich central core in the rich stage.
- Pressure Drop (7% - 8%) — Approaches the design objective.
- Liner Metal Temperature (1400°F - 1470°F); (1030 - 1070K) — Higher than desired for liner durability, but satisfactory for test purposes.
- Ignition — Satisfactory.
- Turndown — Satisfactory.
- Post Test Condition — Satisfactory.

Catalytic Combustor Test Results

Approximately two hours of reactor operating time were accumulated at design cycle conditions during the test program. Data were taken at five steady state test points for reactor-only and pilot-only operation, as well as for numerous transient conditions. The first three steady state test points were established with only the reactor stage fueled, while the next two steady

state points were taken with only the pilot-stage fueled. Rather than start directly into the test program with both stages operating in the parallel-staged mode of intended operation, first reactor-only and then pilot-only operation were selected for the initial test operations. Pilot stage liner damage occurred during pilot-only operation which precluded testing in the intended dual, parallel-staged operating mode.

Test points 1, 2 and 3 were for reactor-only operation. During these test points, stable air flow, emissions and reactor temperatures were all achieved. Ignition of the reactor stage was accomplished by raising the preheat temperature (i.e., combustor inlet air temperature) to 700°F (640K) followed by a controlled opening of the fuel valve to the reactor stage nozzles. Points 2 and 3 are for catalyst fuel-air ratios of approximately 0.031 which corresponds to the 92% (baseload operation) load condition for the MS7001E cycle application of this combustor; the reactor fuel-air ratio during test point 1 corresponds to the 70% load point. After 1-1/2 hours of reactor operation, the reactor failed due to substrate overtemperature. The first two axial reactor segments (2 inches of coarse cell substrate) remained intact so that a little change in liner pressure drop and efficiency were immediately apparent. But the loss of catalyst temperature indication (loss of reactor thermocouple readings) used for test control caused a termination of the reactor-only portion of the test.

Emissions performance of the reactor stage was excellent. At 92% load conditions, measured emissions indices were 1.4 g NO_x/kg fuel (see Table 5) which corresponds to approximately 10 ppmv NO_x. Figure 18 presents measured reactor-only NO_x emissions index as a function of reactor stage equivalence ratio.

Table 5
CATALYTIC COMBUSTOR TEST DATA

Test Point Number	Cycle Load Condition	Inlet Temperature (°F)	Inlet Pressure (psia)	Reactor Fuel Flow W _{FUEL-C} (lb/s)	Reactor Air Flow W _{AIR-C} (lb/s)	Reactor Fuel-Air Ratio (f/a) _c	Reactor Equivalence Ratio Φ _c	Pilot Fuel Flow W _{FUEL-P} (lb/s)	Pilot Air Flow W _{AIR-P} (lb/s)	Pilot Fuel Air Ratio (f/a) _p	Pilot Equivalence Ratio Φ _p	Reactor Reference Velocity (ft/s)
1	70%	706	145.2	0.094	3.43	0.0274	0.397	—	4.69	—	—	66.5
2	92%	705	148.4	0.109	3.42	0.0319	0.461	—	4.68	—	—	64.9
3	92%	706	165.5	0.106	3.49	0.0304	0.440	—	4.77	—	—	59.4
4	~85%	642	162.2	—	3.32	—	—	0.058	4.55	0.0127	0.1845	54.6
5	~100%	642	170.3	—	3.26	—	—	0.090	4.47	0.0201	0.2914	54.0

Conversion Factors

(psia) × 6.895 = kPa (ft/s) × 3048 = m/s
(lb/s) × 454 = kg/s (°F + 460) × 5/9 = K

Test Point Number	Overall Pressure Drop AP/P ₃	Exhaust ⁽¹⁾ Temperature (°F)	Reactor Exit Temperature ⁽²⁾ (°F)	CO (ppm)	CO ₂ (%)	NO _x Uncorrected ⁽⁴⁾ (ppmv)	NO _x Corrected (ppmv)	NO _x Corrected @ 15% O ₂ (ppmv)	EI NO _x (g NO _x /kg fuel)	Mass Flow Function	Combustion Efficiency η _c
1	5.22	1271	1764	86.8	3.91	9.6	9.1	11.5	1.32	3.65	>99%
2	5.56	1388	2637	4.2	3.74	12.2	11.6	14.2	1.46	3.4	>99%
3	4.53	1365	2459	1.0	3.71	11.3	10.7	13.2	1.41	2.90	>99%
4	3.01	1073	642 ⁽³⁾	497	2.05	41.5	39.3	93	9.0	2.59	98.5%
5	4.27	1343	642 ⁽³⁾	1.73	3.51	121.9	115.5	155	17.0	2.27	>99%

- (1) Exhaust gas temperature measured at combustor exit plane; reactor and pilot flows mixed
(2) Reactor exit temperature, average of thermocouples embedded in outlet of reactor substrate
(3) Inlet air temperature for pilot-only operation of test points 4 & 5
(4) NO_x uncorrected, as measured
NO_x adjusted to ISO humidity
NO_x corrected to 15% O₂ adjusted for humidity, corrected to 15% O₂

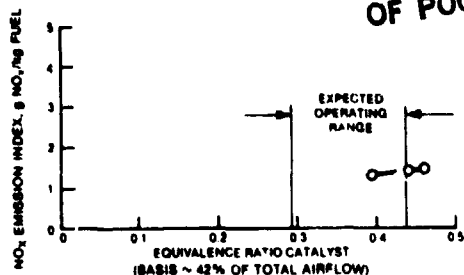


Fig. 18 Catalytic combustor: reactor stage NO_x emissions index

CO emissions were approximately 1-4 ppm at the 92% base load condition, and 87 ppm at 70% load. Combustion efficiencies exceeded 99% at all test points. Combustor pressure drop was approximately 5 percent during the reactor-only tests.

Although combustor exhaust temperature (measured at the exit plane with reactor and pilot stage flows mixed) was approximately 1400°F (1030K), reactor stage exit temperature estimated from reactor bed thermocouple readings was approximately 2550°F (1670K). Figure 19 presents the measured temperature distribution at the exit plane for reactor-only operation. The exhaust flow shows a hot central core associated with the reactor exit flow, and temperature approaching inlet air (700°F; 640K) at the outer periphery, reflecting the cool, pilot air flow. Von Brand smoke numbers for reactor operation were greater than 99, i.e., essentially an SAE smoke number of 0.

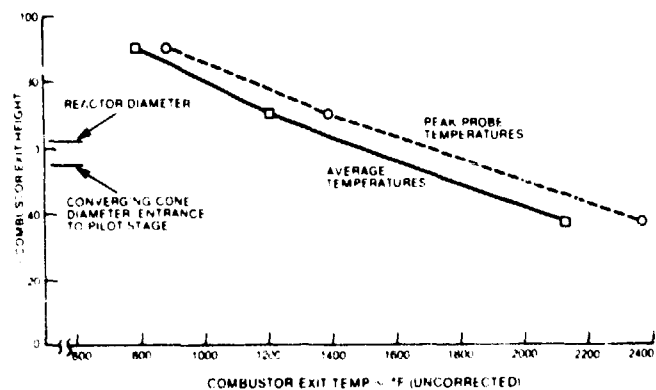


Fig. 19 Exit temperature distribution—test point 3 (92% load)—reactor only Conversion factor: $(^{\circ}\text{F} + 460) \times 5/9 = \text{K}$

To check ignition, cooling, and emissions performance of the pilot stage, pilot-only operation was initiated after completion of the reactor testing. Test points 4 and 5 of Table 5 were completed with the pilot fuel stage fired. Difficulty was encountered in maintaining pilot ignition around the annular pilot stage, in part due to the core flow of relatively cool reactor stage air (700°F; 640K). Test point 4 represented the first combination of fuel and air which led to stable temperatures and emissions. Point 5 was completed with fuel flow limited by the high metal temperatures experienced in the dilution zone (1700°F; 1200K).

NO_x emissions were 93 ppm at approximately 80-85% load (test point 4) and 155 ppm at 100% load (peak load). Figure 20 presents pilot-only NO_x emissions index data as a function of pilot equivalence ratio. The pilot NO_x emissions compare very well with levels measured for conventional lean-burning combustors. MS7001E combustor test data show an emissions index of approximately 9.6 at an overall equivalence ratio of 0.2, which is in good agreement with the present results. CO emissions were relatively high for pilot operation (200-500 ppm),

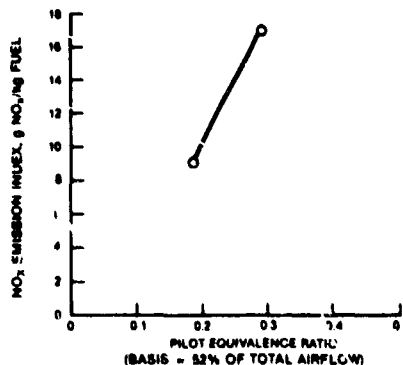


Fig. 20 Catalytic combustor: pilot stage NO_x emissions index

caused in part by the low overall temperature rise which accompanied pilot-only operation (dilution by cool reactor flow), and by relatively unstable operation. Due to the unstable combustion and high metal temperatures, smoke measurements were not taken.

Combustion efficiency was 98.5% at 80-85% load and exceeded 99% at 100% load. Exhaust temperature measured at the combustor exit plane was 1343°F (1000K) at 100% load (test point 5), with a pressure drop of 3-4%. Figure 21 presents the radial temperature distribution at the exhaust plane for pilot-only operation. Low central temperatures (at 40% of combustor exit height) reflect the inlet air exiting the reactor.

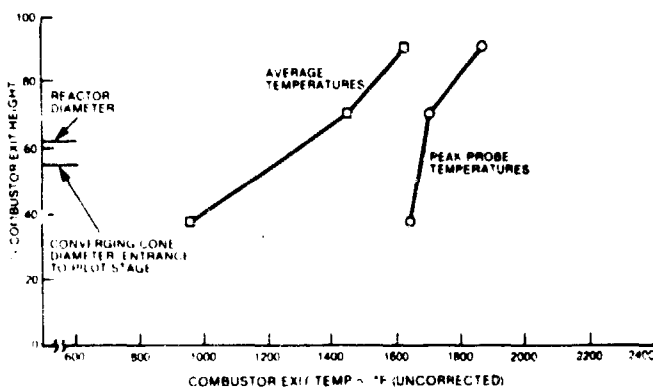


Fig. 21 Exit temperature distribution—test point 5 (100% load)—pilots only Conversion factor: $(^{\circ}\text{F} + 460) \times 5/9 = \text{K}$

Two types of instability occurred during the reactor-only portion of the test. The first had to do with the parallel flow path design, in which any increase in pressure drop in the catalyst tends to reduce the catalyst airflow and increase airflow to the pilot stage of the combustor. Although expected to occur to some degree, the magnitude of the effect was much larger than anticipated during operation. As the catalyst exit temperature increases with increased catalytic efficiency, the airflow is reduced, which in turn increases the catalyst fuel-air ratio. This relative increase in fuel flow causes the catalyst pressure drop to increase even further until a stable point is reached or until the catalyst fails, due to overtemperature in the substrate. As a result, it was impossible to maintain the catalyst temperature in the range of 1800-2400°F (1260-1590K). Any slight increase in fuel flow resulted in a catalyst temperature above the recommended limit (2400°F), while any attempt to control the excessive temperature brought the catalyst temperature back down below 1800°F. This characteristic of catalyst operation may present a strong obstacle to the development of parallel stage combustors without variable geometry capabilities.

The second difficulty was that the catalytic reactor itself exhibited unstable characteristics. During the early portion of this test while attempting to reach a stable catalyst temperature in the range of 1800-2400°F (1260-1590K), it was observed that the highest temperatures in the reactor would be located in one instance near the reactor exit and in another near the reactor entrance. For example, Figure 22 presents the data noted for test points 2 and 3 of Table 5 and a transient point, each point nominally at the same reactor fuel-air ratio. Inlet velocities are the same for point 2 and the transient, while point 3 differs only slightly, having a higher inlet pressure. There were occasions noted during other transients between test points when the central thermocouple (#3 in Figure 22), was lowest in temperature of the four thermocouples. Two possible explanations for the observed transient nature of this axial temperature distribution are:

- (1) A non-uniform fuel distribution at the entrance of the reactor causes the combustion reactions to occur at different points and with varying efficiencies and heat releases along the reactor. The difference in temperatures 3 and 4 supports this hypothesis.
- (2) Test point 2 and the transient point presumably have the same fuel-air ratio but exhibit different average temperatures and axial distributions. Carbon monoxide at the transient point was about 80 ppm, while it was only 42 ppm at test point 2. The difference in the average temperature and the axial reactor temperature distribution (see Figure 22) may be attributed to the instability in the airflow split between reactor and pilot stages discussed earlier. [Note, however, that reactor operation can occur in only a narrow fuel-air ratio band. Furthermore, measured NO_x data are relatively flat with fuel-air ratio changes. Therefore, predictions of overall combustor NO_x (pilot and reactor operating in parallel mode) are expected to be reasonably accurate.]

Post-test examination of the reactor catalyst showed the central area of the last three axial reactor segments had broken loose and gone downstream. There was no evidence of melting nor deposits or plugging.

In pilot-only operation, ignition was accomplished with some difficulty. Misalignment of fuel nozzles in the cups, plus the in-

creased core airflow through the damaged catalyst, made pilot operation unstable. Metal temperatures in the pilot primary zone showed that some portions of the pilot section had flame only intermittently. The difficulties in controlling backside cooling with a flow sleeve with a small gap and the eventual combustion of fuel which passed beyond the primary zone are the suspected contributors to pilot stage liner burnout.

CONCLUSIONS

Gas Fueled Rich-Lean Combustor

The rich-lean combustor, in the single configuration tested, was not successful in significantly reducing thermal NO_x emissions for the baseline gas fuel having a lower heating value of 244 Btu/scf (10.3 MJ/NCM). This unexpected result is believed to be due to inadequate fuel-air mixing in the rich stage with the result that fuel-rich central core flow persisted through the rich and quench stages with burning similar to a conventional combustor in the lean stage. However, this hypothesis is unproven, and there are other possible explanations, such as non-optimal dwell times in the rich, quench, and lean stages. Aside from NO_x emissions, the combustor provided generally satisfactory performance for all other important combustion parameters including CO emissions (efficiency), smoke, pattern factor, pressure drop, metal temperatures, ignition, turndown, and post-test condition. For the lowest heating value fuel tested, 172 Btu/scf (7.3 MJ/NCM), program NO_x emissions goals were met.

Data collected to date indicate that the lean-lean combustor concept has the potential to achieve ultra-low NO_x emissions for liquid and gas fuels having no fuel-bound nitrogen (FBN). It is recommended that this concept be tested on gas fuels with and without bound nitrogen. A baseline test on a conventional combustor with gas fuel having fuel-bound nitrogen should also be run to provide data for comparison with new concepts designed to reduce NO_x emissions with fuel-bound nitrogen. Mixing effectiveness tests should be run on the fuel nozzles used for the rich-lean combustor and on all new fuel nozzle designs proposed for low NO_x combustors so that this critical aspect of fuel nozzle performance can be evaluated. Future test rigs for NO_x emissions reduction testing should be designed to allow variation in internal airflow splits at constant overall equivalence ratio during the test so that stoichiometry and dwell times in the various reaction zones can be optimized for minimum emissions regardless of test fuel.

Catalytic Combustor

The catalytic combustor concept has demonstrated the potential for very low NO_x emissions burning distillate fuel. The catalytic reactor can be ignited with ease at the compressor discharge temperatures available in present-day industrial gas turbines. Premix section length and the fuel injection method appeared satisfactory, although no instrumentation was available to monitor the performance of this section.

Parallel staging of the catalyst with a conventional design requires careful control of airflow splits and catalyst pressure drop. Use of variable-geometry devices to control airflow distribution to the reactor and pilot stages are necessary for the parallel-design approach. General Electric has completed the preliminary design of a series-staged combustor which will avoid flow-split instabilities which occurred during the Phase IA catalytic combustor testing.

Test data at test points 3 and 5 for reactor-only and pilot-only operation, respectively, can be combined to predict the NO_x production to be expected for this parallel-staged combustor with both stages operating at the 92% load design point. Assuming that NO_x production of the two stages is independent, overall combustor NO_x is predicted to be 3.4g NO_x/kg fuel, which is substantially lower than the 7.0g/kg program goal for low nitrogen content fuel.

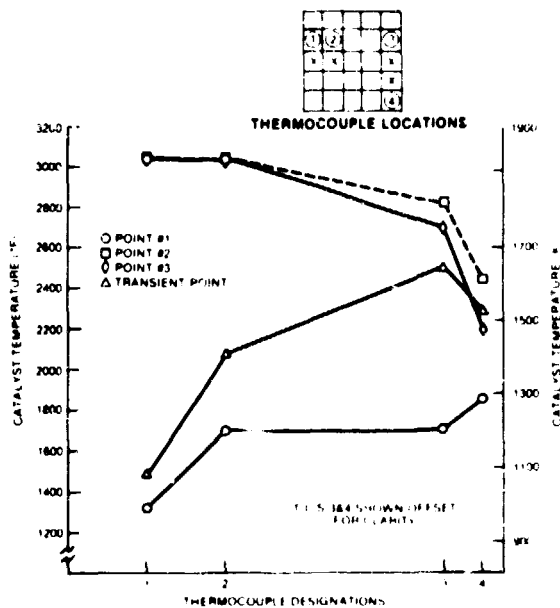


Fig 22 Catalytic reactor temperatures
Conversion factor: $(^{\circ}\text{F} + 460) \times 5/9 = \text{K}$

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