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Evaluation of Advanced Combustion Concepts for Dry NO\textsubscript{x} Suppression with Coal-Derived, Gaseous Fuels

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National Aeronautics and Space Administration
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Work performed for
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Fossil Energy
Office of Coal Utilization and Extraction

Prepared for
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EVALUATION OF ADVANCED COMBUSTOR CONCEPTS
FOR DRY NO, SUPPRESSION WITH COAL-DERIVED, GASEOUS FUELS

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NOMENCLATURE

CO = carbon monoxide emissions
EI = emissions index, g/kg fuel
f/a = fuel-air mass ratio
(f/a), = stoichiometric fuel-air mass ratio
IGCC = Integrated Gasification Combined Cycle
ISO = International Standards Organization reference humidity condition, 0.0063 lb H,O/lb dry air
M.W. = molecular weight
MW = power, megawatts electrical output
NCM = normal cubic meter, at 273K
NO, = oxides of nitrogen emissions
P3 = combustor inlet pressure
ppmv = parts per million by volume
T3 = combustor inlet temperature
T4 = average combustor exhaust temperature
T5 = stoichiometric temperature
UHC = unburned hydrocarbon emissions
0 = 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.

NO, performance of the rich-lean combustor did not meet program goals with the 244 Btu/scf gas because of high thermal NO, similar to levels expected from conventional lean-burning combustors. The NO, 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, yield from ammonia injected into the fuel gas decreased rapidly with increasing ammonia level, and is projected to be less than 10% at NH, levels of 0.5% or higher. NO, generation from NH, is significant at ammonia concentrations significantly less than 0.5%. These levels may occur depending on fuel gas cleanup 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, emissions were low (1.4g NO,/kg fuel). CO emissions and combustion efficiency were satisfactory. Airflow split instabilities occurred which eventually led to test termination.

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, 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, 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, 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, Combustor Program will emphasize dry low-NO, combustion technology development for low and intermediate Btu heating value coal gases (LBtu and IBtu gases). Under NASA sponsorship, General Electric has completed the Phase IA program to develop combustion technology for LBtu and IBtu gases.

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The Phase IA program provides a bridge between the low NOx, liquid fuel technology of Phase I and the anticipated emphasis on low NOx, 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 (NH₃) was injected at several rates up to 0.5 weight percent for the 244 Btu/scf gas fuel to determine organic NOₓ 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 ASME orifice 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 and test ducts.

The process air system can deliver nonvitiated air to the test stands with:
- Mass flow rate min 1 to 50 lb/s (45 to 23 kg/s)
- Pressure from slightly beyond 1 atm to greater than 10 atm (101 to 1014 kPa)
- Temperature from slightly beyond ambient temperature to greater than 700 K (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 trailer-type 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. 

**Instrumentation**

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

Total inlet air 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...
impressions 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 ganged 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 NOₓ 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 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)](image_url)

**Table 1**

<table>
<thead>
<tr>
<th>Test Points</th>
<th>3A, 3B, 3C, 4</th>
<th>5A, 18C</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>18A</th>
<th>18B</th>
<th>7.7A, 8.9</th>
<th>11, 12, 13</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂ (vol %)</td>
<td>38.4</td>
<td>37.1</td>
<td>37.9</td>
<td>37.3</td>
<td>37.4</td>
<td>37.8</td>
<td>32.83</td>
<td>26.56</td>
<td></td>
</tr>
<tr>
<td>O₂ (vol %)</td>
<td>0</td>
<td>0.17</td>
<td>0.14</td>
<td>0.18</td>
<td>0.11</td>
<td>0.13</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>N₂ (vol %)</td>
<td>0.65</td>
<td>0.59</td>
<td>0.61</td>
<td>0.58</td>
<td>0.62</td>
<td>0.57</td>
<td>15.06</td>
<td>31.28</td>
<td></td>
</tr>
<tr>
<td>CO (vol %)</td>
<td>44.53</td>
<td>44.5</td>
<td>44.3</td>
<td>44.7</td>
<td>44.1</td>
<td>44.9</td>
<td>38.07</td>
<td>30.8</td>
<td></td>
</tr>
<tr>
<td>CH₄ (vol %)</td>
<td>0</td>
<td>0.18</td>
<td>0.17</td>
<td>0.18</td>
<td>0.17</td>
<td>0.18</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>CO₂ (vol %)</td>
<td>16.43</td>
<td>16.50</td>
<td>16.50</td>
<td>16.70</td>
<td>16.60</td>
<td>16.8</td>
<td>14.05</td>
<td>11.36</td>
<td></td>
</tr>
<tr>
<td>NH₃ (vol %)</td>
<td>0</td>
<td>0.45</td>
<td>0.30</td>
<td>0.32</td>
<td>0.11</td>
<td>0.07</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Mol. wt.</td>
<td>20.65</td>
<td>20.74</td>
<td>20.75</td>
<td>20.91</td>
<td>20.62</td>
<td>20.94</td>
<td>21.76</td>
<td>23.37</td>
<td></td>
</tr>
<tr>
<td>LHV Btu/scf</td>
<td>244</td>
<td>242.7</td>
<td>243.8</td>
<td>243.6</td>
<td>241.9</td>
<td>245.6</td>
<td>209.0</td>
<td>169.0</td>
<td></td>
</tr>
<tr>
<td>(MJ/NCM)</td>
<td>(10.3)</td>
<td>(10.2)</td>
<td>(10.2)</td>
<td>(10.2)</td>
<td>(10.2)</td>
<td>(10.3)</td>
<td>(8.8)</td>
<td>(7.1)</td>
<td></td>
</tr>
<tr>
<td>Fuel Temp °F</td>
<td>418</td>
<td>405</td>
<td>407</td>
<td>409</td>
<td>409</td>
<td>410</td>
<td>421</td>
<td>423</td>
<td></td>
</tr>
<tr>
<td>(K)</td>
<td>(488)</td>
<td>(481)</td>
<td>(482)</td>
<td>(483)</td>
<td>(483)</td>
<td>(483)</td>
<td>(489)</td>
<td>(491)</td>
<td></td>
</tr>
</tbody>
</table>
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\textsubscript{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.

![Diagram](image)

**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\textsubscript{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\textsubscript{x} is produced while fuel nitrogen is released with minimal conversion to NO\textsubscript{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\textsubscript{x}, the original combustor was used as a basis for the rich-lean combustor design.

**Table 2**

<table>
<thead>
<tr>
<th>Fuel Lower Heating Value (Btu/scf)</th>
<th>MS7001E Load (%)</th>
<th>T\textsubscript{in} Inlet Temp. (°F)</th>
<th>P\textsubscript{in} Inlet Press. (psia)</th>
<th>T\textsubscript{out} Outlet Temp. (°F)</th>
<th>P\textsubscript{out} Outlet Press. (psia)</th>
<th>W\textsubscript{com} Compressor Compressor Flow (lb/s)</th>
<th>W\textsubscript{fl} Fuel-Air Ratio</th>
<th>(\phi)</th>
<th>Overall (\phi)</th>
<th>(\Delta P/P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>244</td>
<td>100 (peak)</td>
<td>636</td>
<td>169</td>
<td>2190</td>
<td>15122</td>
<td>0.110</td>
<td>0.309</td>
<td>16.8</td>
<td>5.87</td>
<td></td>
</tr>
<tr>
<td>244</td>
<td>92 (base)</td>
<td>631</td>
<td>166</td>
<td>2082</td>
<td>15217</td>
<td>0.104</td>
<td>0.289</td>
<td>16.8</td>
<td>6.15</td>
<td></td>
</tr>
<tr>
<td>244</td>
<td>50</td>
<td>598</td>
<td>149</td>
<td>1460</td>
<td>15974</td>
<td>0.058</td>
<td>0.161</td>
<td>16.9</td>
<td>7.98</td>
<td></td>
</tr>
<tr>
<td>209</td>
<td>100 (peak)</td>
<td>636</td>
<td>169</td>
<td>2190</td>
<td>14724</td>
<td>0.141</td>
<td>0.320</td>
<td>16.8</td>
<td>5.59</td>
<td></td>
</tr>
<tr>
<td>209</td>
<td>92 (base)</td>
<td>631</td>
<td>166</td>
<td>2082</td>
<td>14841</td>
<td>0.132</td>
<td>0.300</td>
<td>16.8</td>
<td>5.88</td>
<td></td>
</tr>
<tr>
<td>209</td>
<td>50</td>
<td>598</td>
<td>149</td>
<td>1460</td>
<td>15634</td>
<td>0.081</td>
<td>0.184</td>
<td>16.9</td>
<td>7.91</td>
<td></td>
</tr>
<tr>
<td>172</td>
<td>100 (peak)</td>
<td>635</td>
<td>169</td>
<td>2190</td>
<td>14177</td>
<td>0.185</td>
<td>0.330</td>
<td>16.8</td>
<td>5.19</td>
<td></td>
</tr>
<tr>
<td>172</td>
<td>92 (base)</td>
<td>631</td>
<td>166</td>
<td>2082</td>
<td>13184</td>
<td>0.168</td>
<td>0.300</td>
<td>16.8</td>
<td>5.51</td>
<td></td>
</tr>
<tr>
<td>172</td>
<td>50</td>
<td>598</td>
<td>149</td>
<td>1460</td>
<td>15266</td>
<td>0.107</td>
<td>0.191</td>
<td>16.9</td>
<td>7.65</td>
<td></td>
</tr>
</tbody>
</table>

(1) Overall combustor equivalence ratio
(2) \(\Delta P/P = \frac{\text{liner total pressure drop}}{P}\)
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

<table>
<thead>
<tr>
<th>Fuel LHV</th>
<th>Load Condition</th>
<th>50%</th>
<th>92% (Base)</th>
<th>100% (Peak)</th>
</tr>
</thead>
<tbody>
<tr>
<td>244 Btu/scf</td>
<td>Fuel/Air Overall&lt;sup&gt;(1)&lt;/sup&gt;</td>
<td>0.0580</td>
<td>0.1040</td>
<td>0.1110</td>
</tr>
<tr>
<td>(10.3 MJ/NCM)</td>
<td>φ Overall&lt;sup&gt;(2)&lt;/sup&gt;</td>
<td>0.161</td>
<td>0.289</td>
<td>0.309</td>
</tr>
<tr>
<td>209 Btu/scf</td>
<td>Fuel/Air Overall</td>
<td>0.0810</td>
<td>0.1320</td>
<td>0.1410</td>
</tr>
<tr>
<td>(8.8 MJ/NCM)</td>
<td>φ Overall</td>
<td>0.184</td>
<td>0.300</td>
<td>0.320</td>
</tr>
<tr>
<td>172 Btu/scf</td>
<td>Fuel/Air Overall</td>
<td>0.1070</td>
<td>0.1680</td>
<td>0.1850</td>
</tr>
<tr>
<td>(7.2 MJ/NCM)</td>
<td>φ Overall</td>
<td>0.191</td>
<td>0.300</td>
<td>0.330</td>
</tr>
</tbody>
</table>

Equivalence Ratios

- 244 Btu/scf Rich Stage Quench Stage 0.856 1.537 1.644
- 209 Btu/scf Rich Stage Quench Stage 0.979 1.596 1.702
- 172 Btu/scf Rich Stage Quench Stage 1.015 1.596 1.755

<sup>(1)</sup> Overall fuel/air mass ratio  
<sup>(2)</sup> 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 Fuel Lean-Lean Combustor

Lean-lean combustors burn lean in both stages to avoid high combustion gas temperature and thus avoid generation of thermal NO. 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.

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. (65 cm), the pilot dome diameter being 6 in. (15 cm), and the aft liner diameter 8 in. (20 cm). 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.
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 revaporation of liquid fuel. A 15 in. (.38m) long section is provided for thorough premix of liquid and LBtu/IBtu 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 Aucurex 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 increases 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 baseline (87%) point were as follows:

- Catalyst — Main Stage: 60%
- Pilots: 5%
- Swirlers: 12%
- Liner Cooling: 15%
- Dilution: 8%
- Core Flow: 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 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 NOx emissions data, converted to ISO humidity (0.0063 lb 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 NOx emissions for the highest heating value fuel were well above the program goals, and emissions for the intermediate heating fuel were 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 tested. In general, the NOx 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 NOx 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 NOx 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.
producing a strong antral 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 NOx 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 NOx. However, as the ammonia injection rate was increased, the percentage of fuel-bound nitrogen converted to NOx was found to decrease. At 0.4 weight percent ammonia injection, the NOx yield was approximately 24 percent. This trend of decreasing NOx yield with increasing fuel-bound nitrogen has been observed in prior experimental investigations (4).

Aside from the failure to achieve the desired NOx 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 NOx emissions vs. load

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

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

**Fig. 17** Rich-lean combustor: CO emissions vs. load
Rich-Low Combustor Performance Summary

- NOx Emissions — Aside from the lowest heating value fuel, program goals were not met due to thermal NOx 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 (460K) 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; the 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 emission indices were 1.4 g NOx/kg fuel (see Table 5) which corresponds to approximately 10 ppmv NOx. Figure 18 presents measured reactor-only NOx emissions index as a function of reactor stage equivalence ratio.

Table 5

<table>
<thead>
<tr>
<th>CATALYTIC COMBUSTOR TEST DATA</th>
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<tr>
<td>---------------------</td>
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<td>3</td>
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<tr>
<td>4</td>
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</table>

Conversion Factors:
- (psia) × 6 895 = kPa
- (ft/s) × 3048 = m/s
- (lb/s) × 454 = kg/s
- 5°F × 460 × 5/9 = K

<table>
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<tr>
<th>Test Point Number</th>
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<th>Exhaust Temperature</th>
<th>Reactor Exit Temperature(1)</th>
<th>CO (ppm)</th>
<th>CO2 (%)</th>
<th>NOx Uncorrected(4)</th>
<th>NOx Corrected at 15% O2 (ppm)</th>
<th>NOx Corrected (g NOx/kg fuel)</th>
<th>SI NOx (g NOx/kg fuel)</th>
<th>Mass Flow</th>
<th>Combustion Efficiency</th>
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<td>115.5</td>
<td>15.0</td>
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</table>

(1) Exhaust gas temperature measured at combustor exit plane and reactor and pilot flows mixed
(2) Reactor exit temperature, average of thermocouples e-jected in outlet of reactor substrate
(3) Inlet air temperature for pilot-only operation of test points 4 & 5
(4) NOx, uncorrected as measured

NOx adjusted to 150 humidity
NOx corrected to 15% O2 adjusted for humidity, corrected to 15% O2
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 distribution at the exit plane for reactor-only operation. 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.

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Combustion efficiency was 98.5% at 80-85% load and exceeded 99% at 100% load. Exhaust temperature measured at the combustor exit plane was 1342°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. 18 Catalytic combustor: reactor stage NOx 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 distribution at the exit plane for reactor-only operation. 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. 20 Catalytic combustor: pilot stage NOx 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 1342°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. 19 Exit temperature distribution—test point 3 (92% load)—reactor only Conversion factor: (°F + 460) x 5/9 = 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, 460K). 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, 12000K).

NOx 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 NOx emissions index data as a function of pilot equivalence ratio. The pilot NOx 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. 21 Exit temperature distribution—test point 5 (100% load)—pilot only Conversion factor: (°F + 460) x 5/9 = 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 (1260-1390K). 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 release 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 NOx data are relatively flat with fuel-air ratio changes. Therefore, predictions of overall combustor NOx (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 increased 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 Fired Rich-Lean Combustor**

The rich-lean combustor, in the single configuration tested, was not successful in significantly reducing thermal NOx 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 NOx emissions, the combustor provided generally satisfactory performance for all important combustion parameters including CO emissions (efficiency), smoke, pattern factor, pressure drop, metal temperatures, ignition, turndown, and post-test conditions. For the lowest heating value fuel tested, 172 Btu/scf (7.3 MJ/NCM), program NOx emissions goals were met.

Data collected to date indicate that the lean-lean combustor concept has the potential to achieve ultra-low NOx 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 NOx 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 NOx combustors so that this critical aspect of fuel nozzle performance can be evaluated. Future testing for NOx 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 NOx 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 catalytic reactor 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 NOx production to be expected for this parallel-staged combustor with both stages operating at the 92% load design point. Assuming that NOx production of the two stages is independent, overall combustor NOx is predicted to be 34.4 lb NOx/kg fuel, which is substantially lower than the 70 lb NOx/kg program goal for low nitrogen content fuel.
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