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Techniques for Enhancing Durability and Equivalence Ratio Control in a Rich-Lean, Three-Stage Ground Power Gas Turbine Combustor

(NASA-TM-82922) TECHNIQUES FOR ENHANCING
DURABILITY AND EQUIVALENCE RATIO CONTROL IN
A RICH-LEAN, THREE-STAGE GROUND POWER GAS
TURBINE COMBUSTOR (NASA) 14 p HC A02/MP A01

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Work performed for
U.S. DEPARTMENT OF ENERGY
Fossil Energy
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Prepared for
1982 Joint Power Generation Conference sponsored by the
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ABSTRACT

This effort summarizes the work performed under Task IV, Sector Rig tests of the CRT - Critical Research and Support Technology Program, a Department of Energy funded project. The rig tests of a can-type combustor were performed to demonstrate two advanced ground power engine combustor concepts: steam cooled rich-burn combustor primary zones for enhanced durability; and variable combustor geometry for three stage combustion equivalence ratio control. Both concepts proved to be highly successful in achieving their desired objectives. The steam cooling reduced peak liner temperatures to less than 800 K. This offers the potential of both long life and reduced use of strategic materials for liner fabrication. Three degrees of variable geometry were successfully implemented to control airflow distribution within the combustor. One was a variable blade angle axial flow air swirler to control primary airflow while the other two consisted of rotating bands to control secondary and tertiary or dilution air flow.

INTRODUCTION

Sector rig testing, was the last of four combustion tasks performed under the CRT-Critical Research and Support Technology Program funded at the Department of Energy and performed in-house at NASA Lewis Research Center. The CRT program was initiated to analytically and experimentally determine techniques for burning coal-derived synthetic fuels and heavy petroleum fuels in ground based gas turbine engines. These fuels contain chemically bonded fuel nitrogen and lower percent hydrogen than clean light conventional petroleum fuels. Fuel bound nitrogen (FBN) in conventional combustion systems combines with oxygen to form high levels of oxides of nitrogen (NO_x). If stationary gas turbines are to meet EPA emissions limits, it will be necessary to evolve fundamental combustion concepts for minimizing fuel nitrogen to NO_x conversion.

One promising approach to this problem is the rich-lean combustion concept. In this concept the combustion is carried out in four discrete steps (rich burn, quench, lean burn and dilution). First, fuel is burned at an equivalence ratio greater than one, where an equivalence ratio of one is stoichiometric combustion and a value of less than one is lean combustion. This fuel rich condition suppresses NO_x formation by oxygen depletion. After a finite period of time the rich-burn products are "quenched" by rapid mixing of the secondary air at the front end of the secondary combustor section. The secondary zone is operated at a lean equivalence ratio near the lean blowout limit. Thus combustion continues. However, since flame temperatures are relatively low

in the secondary zone, due to lean combustion, little thermal NO_x is formed. Thus total NO_x formation is suppressed. Reference 1 demonstrates this control. And finally the remaining air is added in the tertiary or dilution zone to reduce the exit temperature to its desired value. The CRT combustion program was initiated to define answers to the following questions:

- o What are the typical properties of synthetic fuels derived from coal (liquid and gases), and heavy petroleum fuels?
- o What equivalence ratios are required in the rich and lean burn combustion sections?
- o Can a combustor be configured to operate over the entire load range of the engine and still meet the EPA exhaust emission standards?
- o What viable approaches exist for evolving environmentally acceptable combustors with sufficient durability for meeting ground power mission needs?

To answer these questions, the program was subdivided into four tasks. The first was a literature survey to determine representative fuel properties of coal-derived synthetic fuels, reported in (2, 3). The second task was a NO_x modeling effort which was aimed at predicting NO_x emissions from simulated coal derived fuels.

The flame tube rig, task three, was designed to determine the proper equivalence ratio for operation of the primary and secondary combustion zones, as a function of the percent hydrogen and nitrogen in the fuel, in order to minimize the formation of NO_x emissions. In this premixed system, synthetic fuels were simulated by blending propane, toluene and pyridine. In this way, percent hydrogen could be varied from 9 to 18 percent and percent nitrogen from 0 to 1.5 percent. Two SRC II fuels, naphtha and

middle-heavy blend were tested to compare the simulated fuels to the real ones. The flame tube was maintained at 672 K inlet air temperature and 0.48 MPa inlet total pressure for all testing. Primary and secondary residence times were varied. The results of this task were reported in (0). The flame tube rig results were compared to the second task, NO_x modeling effort of (4).

The last task, sector rig testing, was undertaken to bridge the gap between the flame tube rig and combustor type hardware. This report presents the results of the task four effort. Task four was conducted in two stages. In the initial stage a fixed geometry combustor can was fueled with both #2 and #4 heating oils. In these tests data were obtained with a standard pressure atomizing fuel injector and an air assist fuel injector. Results are compared to show the effects of fuel injector design on NO_x emissions for conventional lean burn combustion of both #2 and #4 heating oils.

These results also served as a data base for the second stage experimental efforts. In the second stage a similar size combustor can featuring rich-lean technology was evaluated with heavy oils and SRC-II middle distillate. This combustor incorporated three degrees of variable geometry to obtain equivalence ratio control in each combustor burning zone, and utilized a steam cooled primary zone. Data were obtained at three simulated engine conditions from simulated 50 percent power to full power. Inlet temperature was varied from 535 K to 665K, inlet total pressure from 0.74 to 1.21 MPa, air flow from 3.9 to 5.3 kg/sec and exhaust gas temperature varied from 1115 to 0355 K.

APPARATUS AND PROCEDURE

Test Rig

A closed duct, high pressure, non-vitiated test facility was utilized for this effort. Simulated ground power test conditions ranging from idle to full power could be obtained at full pressure, temperature and flows. Special facility equipment included connections to the Research Center's central steam heating system to provide steam cooling of the rich burn combustor primary zones, and special storage and handling facilities for the SRC-II, solvent refined coal fuel. Water cooled condensers were installed downstream of the combustor in the steam system to provide steam flow for cooling the combustor primary zone. The condensate then passed through steam traps to the central steam condensate return system. A simple petroleum visbreaker was also installed but not tested. This was a counterflow heat exchanger consisting of two concentric tubes. The inner tube was to supply heavy oil to the combustor while the outer pipe carried the superheated combustor cooling steam to the condensers. The visbreaker was intended to aid combustion of very heavy oils by reducing their viscosity, thus increasing atomization, before combustion.

The combustion sector rig is shown schematically in Fig. 1. In operation, air is metered and then enters an indirect fired preheater where it is heated to the desired temperature, which in these tests did not exceed 665 K at the test section. Upon heating the air entered an inlet plenum where the combustor inlet temperature and pressure were measured. Fuel, air assist nozzle air, and the aforementioned combustor steam cooling lines all share this plenum downstream of the inlet instrumentation station. The fixed geometry hardware used a 27.3 by 1.27 cm housing while the variable geometry combustor used a 35.6

by 1.51 cm housing. The larger size pipe was necessitated by the variable geometry actuation mechanism and the steam cooling line plumbing. An exhaust instrumentation section followed the test section. Exhaust instrumentation included 40 platinum-platinum-13-percent-rhodium thermocouples mounted 5 to a rake on centers of equal area, static pressure taps, and a 10 point centers of equal area gas sample probe. Remote control valves were used upstream and downstream of the rig to provide flow and pressure control.

Test Hardware

Fixed geometry combustor. A production type burner can was used for the fixed geometry can evaluation. This can is about 45-cm long and 17-cm in diameter and is supplied with a thermal barrier coating on the inside surface. The crossfire tube port was plugged for this test series. Twenty Chromel-Alumel thermocouples were installed to monitor liner temperatures.

Two fuel nozzles were compared: a pressure atomizing dual orifice fuel nozzle and a NASA modified air assist fuel nozzle. The fuel nozzle modification consisted of drilling six 2.53-mm holes to supplement the existing nozzle holes in the face of the nozzle. This was done to provide a greater number of small fuel particles. The pressure atomizing dual orifice fuel nozzle was used as an "air assist" nozzle by supplying air to the primary orifice instead of fuel. This improved atomization of the secondary orifice.

Variable geometry combustor. This hardware was specifically designed to address the FBN conversion problem. It is advanced technology hardware which utilizes a steam cooled rich burn primary zone and variable geometry combustor. A drawing of this combustor is shown in Fig. 2. It features three degrees of variable geometry to control primary and secondary stoichiometries and overall pressure loss. The primary zone stoichiometry was controlled by varying the vane angle of a variable pitch vane, axial flow air swirler located at the inlet to the primary zone. The secondary stoichiometry was controlled by circumferentially rotating a band which would expose or close-off the quench holes located at the inlet to the secondary zone, while the overall pressure loss was controlled by circumferentially rotating a band which would expose or close off the dilution holes located at the inlet to the tertiary zone. Figure 2 also highlights the locations of the combustion zones and the variable geometry provisions. This figure also shows that this combustor is a composite of components. The primary, secondary and tertiary or dilution zone are discrete pieces of hardware. This hardware also features a shroud around the secondary and tertiary zones to increase the backside convective cooling by increasing the backside air velocity. The combustor was constructed of Hastelloy-X for all the flame contact surfaces. The secondary and tertiary zones were coated on the hot gas side with a thermal barrier coating consisting of an undercoat of 0.127-mm NiAlY and an over coat of 0.381 mm ZrO₂ 8Y₂O₃. Type 304 stainless steel was used for the secondary and tertiary shrouds and the exterior of the steam cooling jacket for the primary zone.

A Sonic Development Corporation Sonicore air assist fuel nozzle Model 188J was used for all the testing with the variable geometry hardware. Figure 2 shows such a nozzle installed.

Two other unique features of this hardware are its steam cooled, rich-burn primary zone and the

rich-burn related ignitor seal. The rich-burn liner concept for exhaust emission control requires that no film cooling air be permitted to enter the rich-burn combustion zone. Steam cooling of the combustor rich-burn primary zone was employed. The 0.79-MPa saturated steam was introduced on the backside of the combustor liner at its downstream end where it was manifolded into a narrow 0.38-cm annular channel. This channel extended along the backside of the liner at constant height until it reached the front end of the primary zone where the steam was collected for delivery out of the combustor casing. Twenty 0.32-cm wires divided the steam into 20 spiral flow passages within this annular channel. During hot operation, thermal expansion of the Hastelloy-X inner liner would cause the gap between the wires (which were attached to the Hastelloy) and the outer cooler stainless steel shell to go to zero clearance, effectively dividing the steam flow into 20 spiral passages. These 0.32-cm wires spiraled one-half revolution around the surface of the Hastelloy-X liner.

The second unique feature of this hardware is the ignitor seal. This seal consisted of a 1.59 by 0.68 cm copper tube which was threaded at both ends and was about 6.5 cm long. One end screwed into the steam cooled liner. The ignitor was inserted down the center of the tube, which was chamfered at the housing end to provide volume for packing. A packing nut was then used to provide the seal. The primary zone was anchored to the housing in the same axial plane as the ignitor to minimize axial thermal expansion affects, the packing permitting radial thermal expansion. The copper provided conductive cooling for both the liner at that location and the ignitor to the inlet air. Nickel was plated onto the outer surface of the copper to provide oxidation resistance.

Liner Instrumentation

Twenty-one Chromel-Alumel thermocouples were installed to monitor liner temperatures, eight on both the primary and secondary zone and five on the tertiary zone. A static pressure tap was also located in each combustor zone to provide pressure drop information for calculating airflow into each combustor zone.

Test Conditions

As ground power gas turbine engines generally have compression ratios of about 12:1, operating conditions representative of a 12:1 pressure ratio engine were chosen. Table 1 describes these conditions, which range from idle to full power.

TABLE 1. NOMINAL TEST CONDITIONS

Power level	Idle	30%	50%	70%	80%	Full
Total air flow, kg/sec	1.9	3.2	3.9	4.5	4.9	5.3
Inlet temperature, K	400	480	535	585	610	665
Inlet total pressure, MPa	0.28	0.55	0.74	0.93	1.02	1.21
Exit average temperature, K	795	990	1115	1235	1240	1355

Fuel System and Test Fuels

Due to special handling required of most of the fuels tested, which included #2 and #4 heating oil and SRC-II mid-distillate, separate fuel systems were used for each. The #4 heating oil used in this testing was a blend of #2 heating oil, a distillate,

and #6 heating oil, a residual fuel oil, rather than #4 distillate heating oil. It therefore contained considerable particulate matter.

RESULTS AND DISCUSSION

Fixed Geometry Combustor

The production type combustor can was fueled with two petroleum derived fuels, #2 and #4 heating oils, and operated with two different fuel nozzles. One was a dual orifice pressure atomizing nozzle with air assist substituted for fuel in the primary orifice, and the other an air assist nozzle. The #2 heating oil was run only with the dual orifice nozzle, while the #4 heating oil was run with both types of nozzles. The #2 heating oil burned cleanly leaving little or no deposits in the combustor can. The #4 heating oil, on the other hand, left a thin black deposit which was densely speckled with white crystallized deposits when either nozzle was used. The white deposit is likely mineral ash resulting from combustion of minerals in the fuel.

Liner temperatures. Peak liner temperature proved to be a function of both fuel and fuel nozzle type. As illustrated in Fig. 3, burning #4 heating oil increased liner temperatures above that obtained burning #2 heating oil while using the pressure atomizing fuel nozzle. This effect can be explained by the lower percent hydrogen in the #4 heating oil compared to the #2 fuel. There is more carbon present in #4 heating oil which increases the flame emissivity resulting in greater radiation to the liner. It can also be seen that with the air assist nozzle, still higher liner temperatures were obtained at most operating conditions while burning #4 heating oil, compared to burning #4 heating oil with the pressure atomizing nozzle. It is less obvious why this occurred. One explanation is poorer atomization with the air assist nozzle which generated hot streaks, or the air assist nozzle may have had a wider spray angle which could also produce the higher liner temperatures. In any case, this nozzle was abandoned in favor of a Sonicore air assist nozzle for the variable geometry testing.

Exhaust emissions Exhaust emissions of NO_x (oxides of nitrogen), CO (Carbon monoxide), HC (unburned hydrocarbons), and CO₂ (carbon dioxide) were measured directly. Percent remaining oxygen was determined by computing the oxygen balance based on the fuel properties including sulfur content; fuel/air ratio and the measured exhaust products.

Figure 4 compares the NO_x emissions as a function of power condition. It also shows curves comparing the combustion of #2 to #4 heating oil, and #4 heating oil burned with two different styles of fuel nozzles. Figure 4 shows that, with the dual orifice fuel nozzle, #4 heating oil produced higher NO_x than that nozzle did with #2 heating oil. This is as expected since finer atomization is obtained with the less viscous #2 heating oil. This figure also shows that the NASA modified air assist nozzle produced less NO_x burning #4 heating oil than the dual orifice nozzle did burning #2 heating oil at the higher power conditions.

The NASA modified air assist nozzle also produced the lowest CO and HC emissions at all operating points except idle. Carbon monoxide emissions ranged from 200 to 300 ppm at the 30 percent power point and decreased to less than 20 ppm at the full power point when comparing both nozzles regardless of fuel type, with the NASA modified air assist nozzle being the lowest in this power range. Similarly, HC emissions remained below 16 ppm for both nozzles over the 30

30 percent to full power range, regardless of fuel. Therefore, from an emissions standpoint the NASA modified air assist nozzle performed reasonably well. However, even this nozzle produced NO_x levels considerably greater than the 85 ppm goal for this program while burning the #4 heating oil.

New Combustor Technology

In an effort to minimize exhaust emissions from burning nitrogen rich fuels such as heavy petroleum and synthetic fuels, it was found that new technology needed to be developed. Conventional lean burn combustion with film cooled combustor liners was found to provide very high conversions of fuel bound nitrogen to NO_x . Conversion rates up to 100 percent have been reported (5). Computer modeling, confirmed by experimentation, indicated that rich burn non-film-cooled combustion followed by a rapid transition to lean burn film cooled liner technology would provide very low conversions of fuel bound nitrogen to NO_x (4). Rich burn combustion, however, presents two significant challenges. The first is that very high liner heat loadings are generated in the rich-burn primary zone due in part to the prohibition on film cooling. The second challenge is the relatively narrow range of equivalence ratio at which low nitrogen conversion occurs. This narrow range probably necessitates some means of controlling primary and secondary equivalence ratios. The sector rig testing was directed at addressing the rich-burn primary zone liner cooling and equivalence ratio control problems, as opposed to emphasizing the emissions benefits of rich-lean combustion which was demonstrated previously in the flame tube experiments.

Steam cooled rich burn primary zone. In a ground power application where a steam bottoming cycle would typically be used, a steam cooled, rich burn primary zone which doubles as a steam superheater is a unique feature which could benefit both cycles. In this application, no power was actually extracted from the steam but its energy level was monitored. The steam flowrate of 0.169 ± 0.003 kg/sec was controlled by the steam condenser apparatus and was found to be virtually independent of test condition. Figure 5 shows that steam energy increase varied from about 30,000 to 58,000 J/sec as a function of fuel type, power condition, and equivalence ratio. High power levels, increasing equivalence ratios and lower percent hydrogen fuels all produced steam energy increases. This is as expected as heat transfer rates generally increase with increasing pressure, and increasing flame emissivity. Flame emissivity tends to increase with increasing pressure, increasing equivalence ratio, and increasing percent carbon in the fuel.

As expected, steam pressure loss in the combustor shell was found to be relatively high (8.3 percent) due to the low pressure 0.79 MPa steam available. It would be desirable to use steam of about 1.6 MPa for a combustor operating at 1.21 MPa. This would reduce the steam pressure loss to a more acceptable 4 percent. It was not the intent of this program to minimize the steam pressure loss, but to demonstrate its feasibility. Obviously some additional reduction can be made without affecting liner integrity.

Since the steam is being superheated in the process of cooling the primary zone, the effect on overall cyclic efficiency should be quite minimal. Even the total installation cost may not be greatly affected by the steam cooling system, as a smaller superheated would be required on the boiler-steam turbine system as a result of the direct heat input from the combustor primary zone.

Related to steam pressure loss and energy increase, is steam cooled liner temperatures. Figure 6 shows liner temperatures as a function of primary equivalence ratio at the full power condition burning #4 heating oil. Temperatures from two thermocouple locations are plotted, one on the upstream cone and one on the downstream cone (locations shown in Fig. 2). Figure 6 indicates upstream cone liner temperature was independent of overall primary equivalence ratio as it remained steady at 595 K. At this same condition the downstream cone temperature peaked at a 1.45 overall primary zone equivalence ratio with a value of 794 K. This relatively low liner temperature would permit the use of less exotic materials than the superalloys to be employed as rich burn combustor primary liner materials thus reducing the consumption of strategic materials. The flatness of the upstream cone temperature probably resulted from disintegration of the Sonicore fuel nozzle which lost its sonic cup. This nozzle was not intended to be operated at high ambient pressures, but has been used successfully by others. The loss of the sonic cup permitted fuel to jet down the center of the primary. It is thought that a lean local equivalence ratio thus existed in the forward one-third of the primary zone and rich combustion occurred in the last two-thirds. This is evidenced by the presence of a thin film of soot on the downstream two-thirds of the primary zone. This dusting of soot, was also present in the secondary and tertiary zones. It is thought that the nozzle failure was fortuitous in that it provided a real "acid test" for the rich-burn primary zone. Due to the nozzle failure the liner encountered a wider range of heat fluxes including higher than anticipated values as the flame transitioned from lean to rich equivalence ratios, as opposed to only operating at rich equivalence ratios.

Liner temperatures as a function of power level and fuel type are shown in Fig. 7. This figure, as expected, indicates that liner temperatures increase with increasing power level and with increasing percent carbon in the fuel.

Variable geometry. As mentioned earlier, this combustor had three degrees of variable geometry to provide independent equivalence ratio control to each combustion zone. All the variable geometry components performed well. Possible binding of variable geometry components due to oxidation or warpage did not materialize.

Total pressure loss. Figure 8 is a typical plot of hot flow total pressure loss as a function of axial length for the variable geometry combustor. Most of the pressure drop was taken across the variable geometry air swirler to promote rapid mixing in the rich-burn primary. It was intended that the next largest pressure drop should occur at the quench plane. It is obvious that did not occur. Secondary liner film cooling air was found excessive. This reduced the amount of air available for quenching, while maintaining a particular secondary zone equivalence ratio. Secondary film cooled liner temperatures at the full power condition ranged from 790 to 1045 K, as opposed to the design temperature of 1200 K.

A comparison of percent total pressure loss as a function of power level comparing the fixed geometry and the rich-burn variable geometry combustors is shown in Fig. 9. Only the percent total pressure loss that was used for most of the variable geometry data is presented in this figure. Total pressure loss at the full power condition was actually varied from 2.0 to 3.6 percent. The total pressure loss at the 50 percent power condition was varied from 2.25

to 4.6 percent. The variable geometry proved to be a very flexible tool.

Exhaust emissions. Exhaust emissions were a secondary measurement in this task due to the emphasis on primary zone durability and variable geometry integrity. Exhaust emissions of NO_x were relatively high, about comparable to that of the lowest fixed geometry combustor emissions. The high NO_x emissions are attributed to several factors. First was the disintegration of the nozzle tip on the Sonicore fuel nozzle which permitted fuel to jet down the center of the combustor. This fuel jetting permitted lean combustion to occur in the front third of the rich-burn primary zone thus negating the benefits of rich-burn combustion. The second factor was a relatively ineffective quench zone located in the beginning of the secondary zone due to excessive secondary film cooling air. The third and most significant factor was the relatively short primary zone residence times of only 9 to 18 msec. This low-primary zone residence time resulted from a design constraint that dictated the variable geometry combustor could not be significantly larger in length or diameter than a typical lean burn combustor. This was an unreasonable constraint, as others have suggested significantly larger combustors be used to address the FBN problem. Concurrent work performed at several engine manufacturers under the ACT, Advanced Conversion Technology Program, a DOE funded-NASA managed effort showed how significantly larger combustors could be utilized on existing engines (6-8).

Pattern Factor

Figure 10 shows pattern factor to be only a function of power condition. Pattern factor is plotted as a function of power level for the fixed geometry combustor and the variable geometry combustor. The variable geometry combustor data are also broken down by fuel type. It can be seen that a single curve can be plotted through all the data. Considering the numerous differences, it would appear that this is primarily coincidence although the two combustors have the same exit plane and approximate volume.

SUMMARY OF RESULTS

A sector rig using prototype combustor hardware, was operated over a range of conditions simulating a 12:1 pressure ratio engine with operating points ranging from idle to full power. SRC-II middle distillate and #2 and #4 heating oils were used in these tests. The sector rig used two types of hardware. One was a fixed geometry combustor can used to evaluate minor changes to existing technology, and the other was an advanced design rich-burn three segment combustor using variable geometry to control the equivalence ratio in each sector. The fixed geometry can used two fuel nozzles. One was a dual orifice pressure atomizing nozzle with air assist supplied to the primary orifice instead of fuel, and the other was a NASA modified air assist nozzle. The variable geometry combustor utilized steam cooling to maintain rich burn primary combustor liner integrity. The rich burn primary zone was followed by a lean-burn secondary zone and a tertiary or dilution zone. The sector rig results are presented in two elements the fixed geometry and the rich-burn three segment variable geometry combustor. The fixed geometry combustor results are:

1. The #4 heating oil increased liner temperatures about 15 K above that observed with #2 heating oil.

2. The NASA modified air assist fuel nozzle marginally reduce NO_x emissions, over that obtained with a pressure atomized nozzle with air assist.
3. The NASA modified air assist nozzle increased liner temperatures about 100 K above that observed with the conventional fixed geometry combustor when burning #4 heating oil.

The three-stage variable geometry rich burn combustor results are:

1. Variable geometry provided a satisfactory means of maintaining equivalence ratio control in multizone combustors.
2. Steam cooling provides a satisfactory technique for providing liner durability in rich burn combustion systems. Steam cooled primary zones provide potential for using less strategic materials for combustor liners due to their lower operating temperatures.

ACKNOWLEDGMENTS

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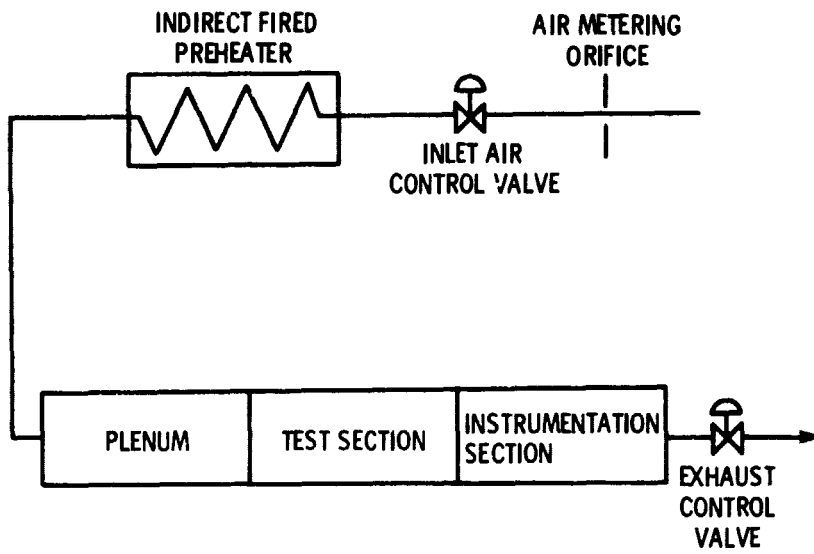
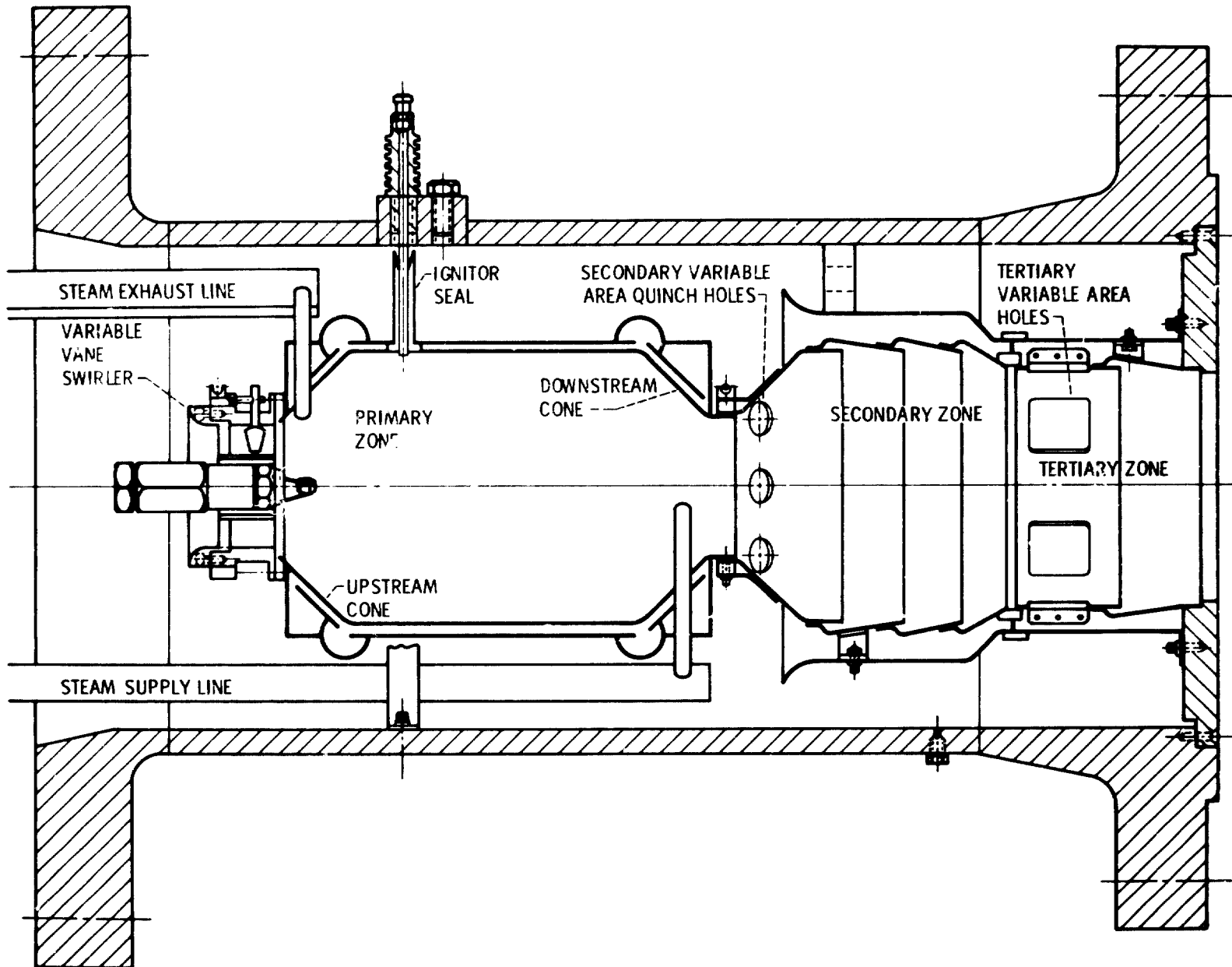


Figure 1. - Schematic of sector test rig.



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Figure 2. - Cross section of variable geometry combustor.

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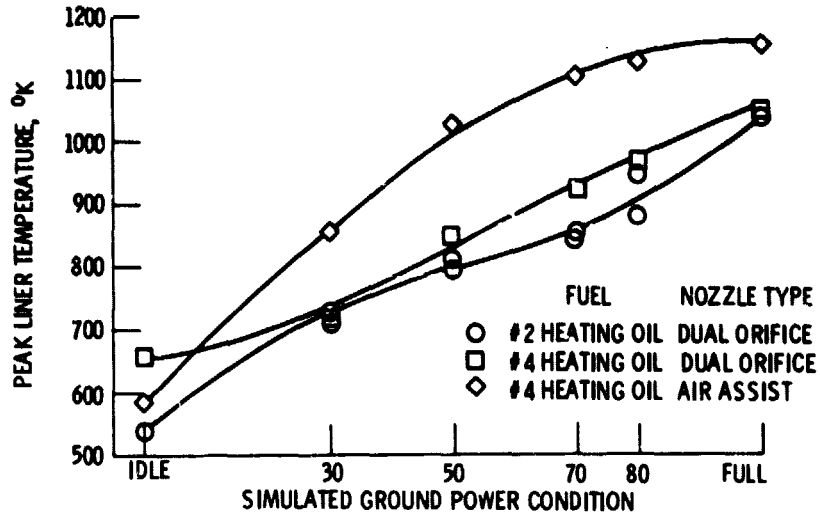
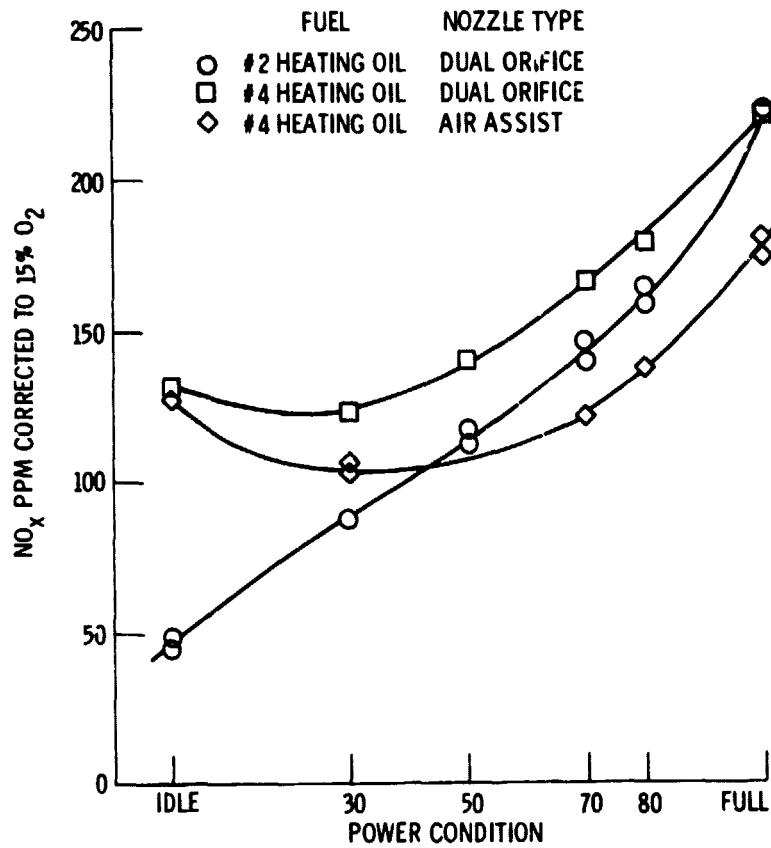


Figure 3. - Peak production type combustor liner temperature as a function of power condition, fuel type and fuel nozzle type.



(a) NO_x emissions.

Figure 4. - NO_x exhaust emissions as a function of power condition for the production type combustor can with dual orifice and air assist fuel nozzles.

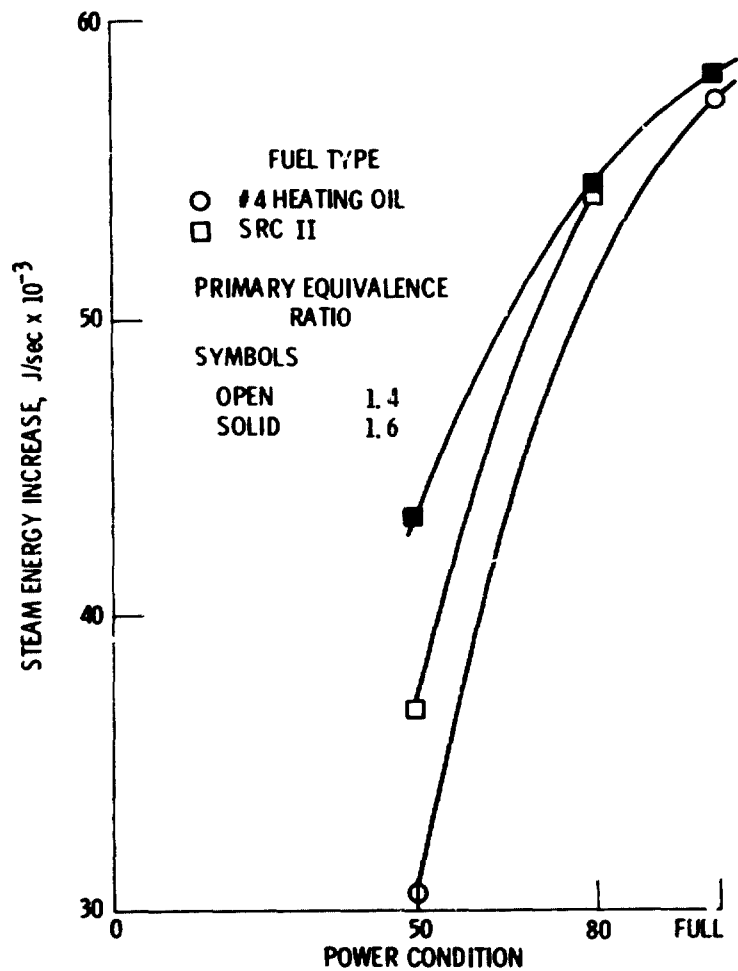


Figure 5. - Steam cooled rich-burn combustor steam energy increase as a function of power level and fuel type at primary equivalence ratios of 1.4 and 1.6.

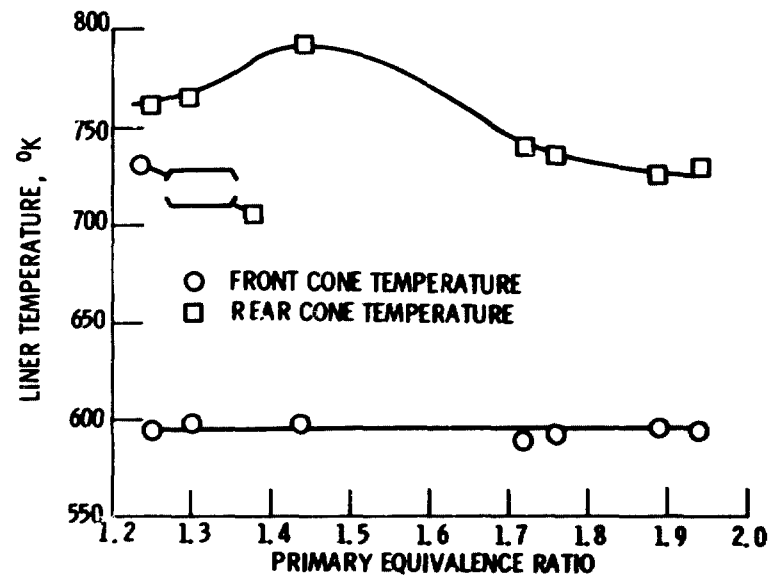


Figure 6. - Steam cooled rich-burn combustor liner temperature as a function of primary equivalence ratio at a simulated full power condition burning #4 heating oil.

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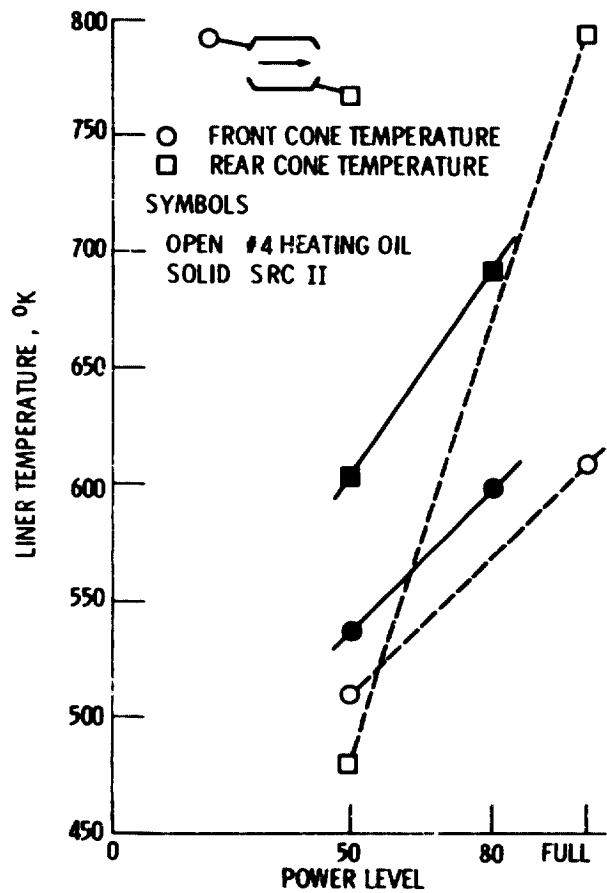


Figure 7. - Steam cooled rich-burn combustor liner temperature as a function of power level and fuel type at a primary equivalence ratio of 1.4.

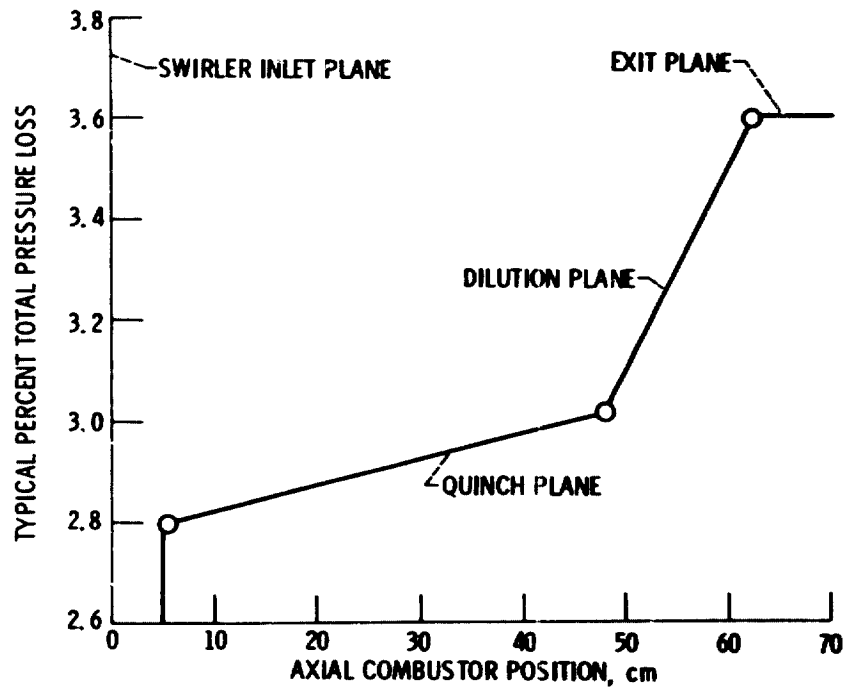


Figure 8. - Typical variable geometry combustor total pressure loss as a function of axial length.

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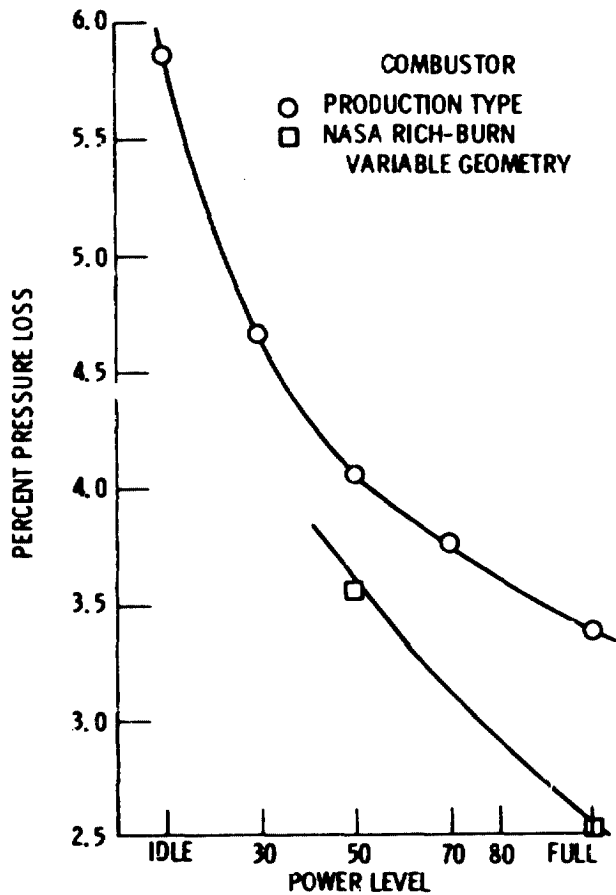


Figure 9. - Percent total pressure loss as a function of power level and combustor type.

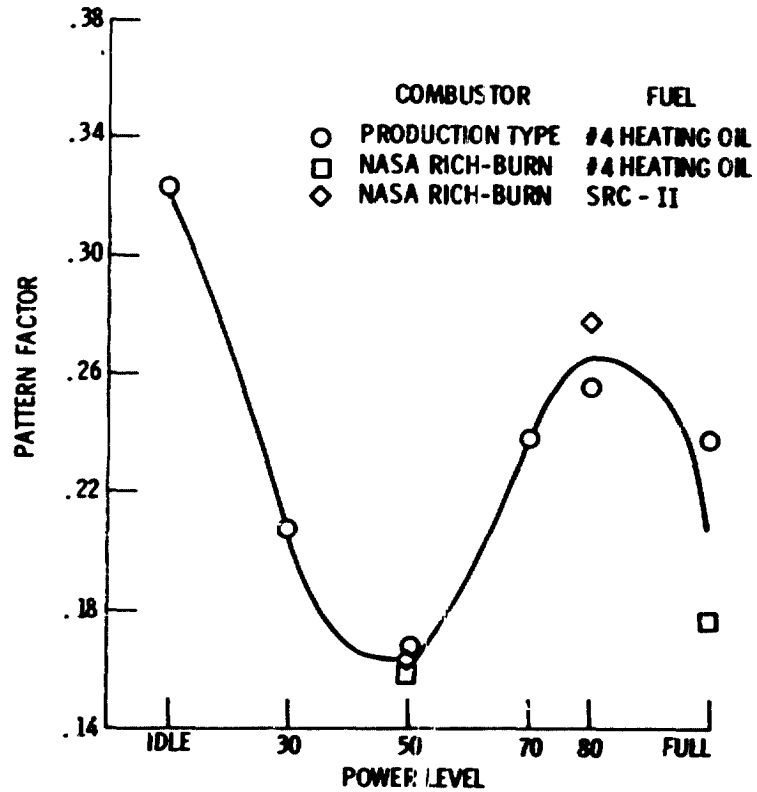


Figure 10. - Pattern factor as a function of power level, fuel type and combustor type.

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