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# Component Testing of a Ground Based Gas Turbine Steam Cooled Rich-Burn Primary Zone Combustor for Emissions Control of Nitrogenous Fuels

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Work performed for
**U.S. DEPARTMENT OF ENERGY**
**Fossil Energy**
**Office of Coal Utilization and Extraction**

Prepared for
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## SUMMARY

This effort summarizes the work performed on a steam cooled, rich-burn primary zone, variable geometry combustor designed for combustion of nitrogenous fuels such as heavy oils or synthetic crude oils. The steam cooling was employed to determine its feasibility and assess its usefulness as part of a ground based gas turbine bottoming cycle. Variable combustor geometry was employed to demonstrate its ability to control primary and secondary zone equivalence ratios and overall pressure drop. 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 low temperature offers the potential of both long life and reduced use of strategic materials for liner fabrication. Three degrees of variable geometry were successfully employed to control air flow distribution within the combustor. A variable blade angle axial flow air swirler was used to control primary zone air flow, while the secondary and tertiary zone air flows were controlled by rotating bands which regulated air flow to the secondary zone quench holes and the dilutions holes respectively.

## INTRODUCTION

Clean combustion of nitrogenous fuels in gas turbine combustors presents some unique design problems (ref. 1). The conventional approach to dealing with oxides of nitrogen ($NO_x$) emissions, lean combustion, does not work well, as demonstrated in reference 2 and others, where fuel bound nitrogen conversion rates of nearly 100 percent have been reported.

However, three stage combustion can significantly reduce emissions of $NO_x$ from nitrogenous fuels (refs. 3 to 5). In this approach, the primary zone is maintained fuel rich throughout the operating cycle of the engine. The secondary zone is operated fuel lean as is the tertiary zone. The operational concept of this principle is that fuel bound nitrogen is converted to N and $N_2$ in the primary zone as the limited amount of oxygen present is taken by the hydrogen and carbon. The secondary zone is then operated as a lean burn combustor to prevent the formation of $NO_x$.

To accomplish the tight equivalence ratio control required to make this rich/lean approach work (ref. 6), a unique three stage variable geometry combustor was employed (note fig. 1). The primary zone equivalence ratio was controlled through the use of a variable vane inlet air swirler. This figure also shows the variable area quench holes used to control secondary equivalence ratio and the variable area tertiary holes used to control overall pressure drop.

Unlike a conventional combustor primary zone, a rich-burn primary zone cannot tolerate film cooling. Film cooling air permits some of the primary zone charge to burn at or near stoichiometric thus negating some of the benefits of rich-burn combustion and tends to increase liner durability problems by creating higher gas temperatures near the wall. To solve this problem, a steam cooled primary zone liner was employed. In a typical ground/ship power application, a boiler would be used in the engine exhaust to extract additional heat energy, which would then be used in a bottoming cycle. We chose to increase the efficiency of that cycle by super heating the boiler steam before it is used elsewhere in the system.

Both number 4 heating oil and SRC-II middle distillate fuels were used in this program. In addition, some limited testing was also done with a similar size fixed geometry combustor for performance comparison.

Another unique feature of this apparatus built but not evaluated, was the installation of a visbreaker in the inlet fuel line to the combustor. The visbreakers function was to use some of the super heated steam generated by the combustor primary zone to break down the heavy oil before injecting it into the combustor. This approach improves fuel atomization by raising the fuel temperature and by breaking down the heavy oil into lighter oils, which are more easily vaporized due to their lower viscosity.

## APPARATUS AND PROCEDURE

### Test Rig

A closed duct, high pressure, nonvitiated 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. In an engine instillation, a turbine would be incorporated between the combustor and condenser. 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 figure 2(a) and pictorially in figure 2(b). 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 diameter by 1.27 cm wall housing while the variable geometry combustor used a 35.6 diameter by 1.51 cm wall 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 five 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.

Variable geometry combustor. - This hardware was specifically designed to address the fuel bound nitrogen FBN conversion problem. It is advanced technology hardware which utilizes a steam cooled rich burn primary zone and variable geometry combustor. An assembled view of this combustor is shown in figure 3 while detailed views of the combustor components are shown in figure 4. 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 1 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 which are shown in figure 4. 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 $ZrO_2$ $8Y\text{-}_2O_3$. 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[1] air assist fuel nozzle Model 188J was used for all the testing with the variable geometry hardware. Figure 1 shows such a nozzle installed.

Other unique features of this hardware are its steam cooled, rich-burn primary zone and the rich-burn related ignitor seal. To cool the primary zone

[1]NASA use does not imply endorsement.

liner 0.79-MPa saturated steam was introduced on the backside of the primary zone 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 consistent 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. Figure 5 is an x-ray view of the steam channels in the vicinity of the ignitor. This sealing was confirmed by the observation of minor oxidation of the stainless steel backside liner from contact with the channel wires.

A further 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 air flow 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 I describes these conditions, which range from idle to full power.

## Fuel System and Test Fuels

Due to special handling required of most of the fuels tested, which included heating oil and SRC-II mid-distillate, separate fuel systems were used for each. The number 4 heating oil used in this testing was a blend of number 2 heating oil, a distillate, and number 6 heating oil, a residual fuel oil, rather than number 4 distillate heating oil. It therefore contained considerable particulate matter.

## RESULTS AND DISCUSSION

### 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 (ref. 2). Computer modelling, confirmed by experimentation, indicated that rich-burn nonfilm-cooled combustion followed by a rapid transition to lean burn film cooled liner technology would provide very low conversions of fuel bound nitrogen to $NO_x$ (ref. 7). 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. This 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 reference 6.

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 flow rate of $0.169 \pm 0.003$ kg/sec was controlled by the steam condenser apparatus and was found to be virtually independent of test condition. Figure 6 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 7 shows liner temperatures as a function of primary equivalence ratio at the full power condition burning number 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. 1). Figure 7 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. 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 figure 8. 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 9 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 which was used 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 a fixed geometry production type can and the rich-burn variable geometry combustor is shown in figure 10. 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 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 hot (residence time determined by gas conditions in the primary zone as opposed to cold residence times which are based on combustor inlet conditions). 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. 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 (refs. 4 to 6).

## Pattern Factor

Figure 11 shows pattern factor to be only a function of power condition. Pattern factor is plotted as a function of power level for a typical 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 test 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 distillage number 4 heating oil was used in these tests. The test used two types of hardware. One was a fixed geometry combustor can, and the other was an advanced design rich-burn three segment combustor using variable geometry to control the equivalence ratio in each sector. 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 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 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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7. Bittker, D.A.: An Analytical Study of Nitrogen Oxides and Carbon Monoxide Emissions in Hydrocarbon Combustion with Added Nitrogen-Preliminary Results. ASME Paper 80-GT-60, Mar. 1981.

TABLE I. - NOMINAL TEST CONDITIONS

| Power level | Idle | 30 percent | 50 percent | 70 percent | 80 percent | 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 |

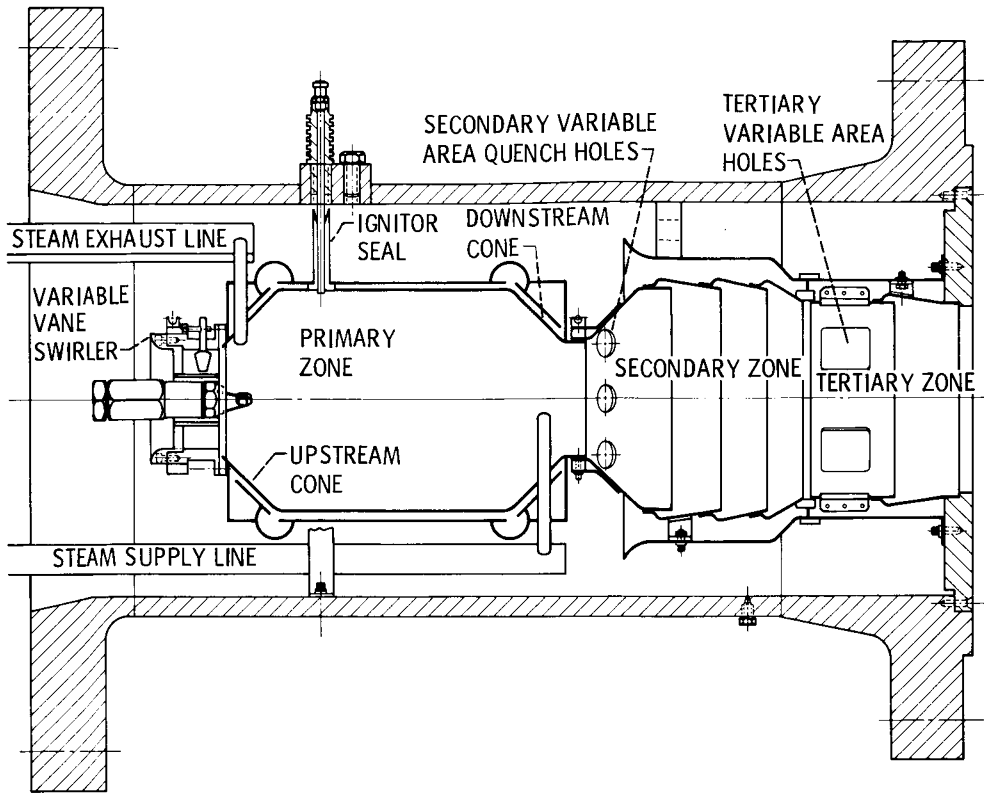
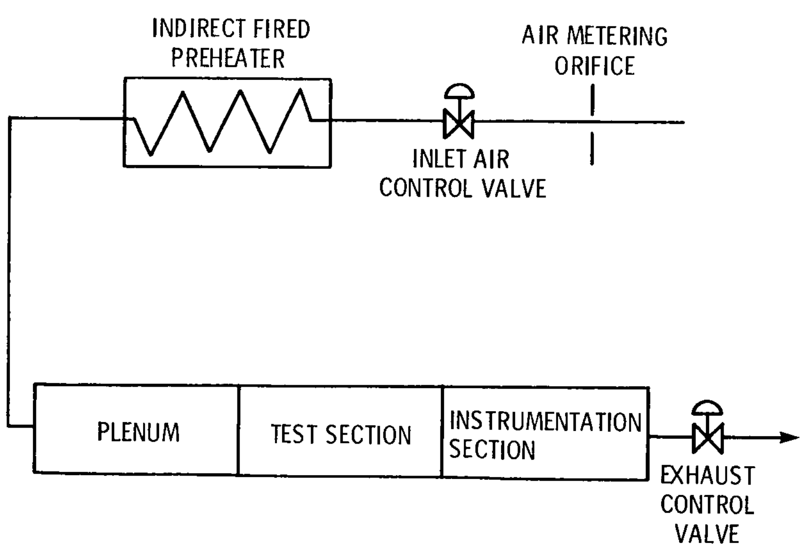
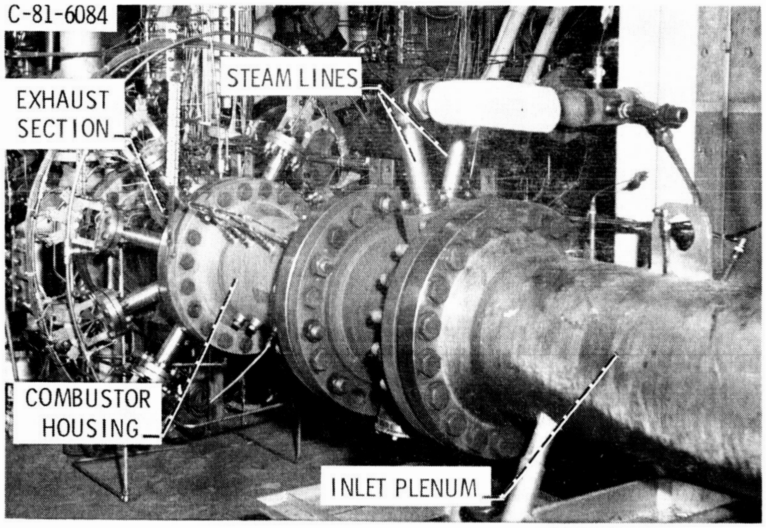



Figure 1. - Cross section of NASA variable geometry combustor.




(a) Schematic of test rig.

Figure 2. - Test rig.




(b) Installation photo of combustor rig.

Figure 2. - Continued.

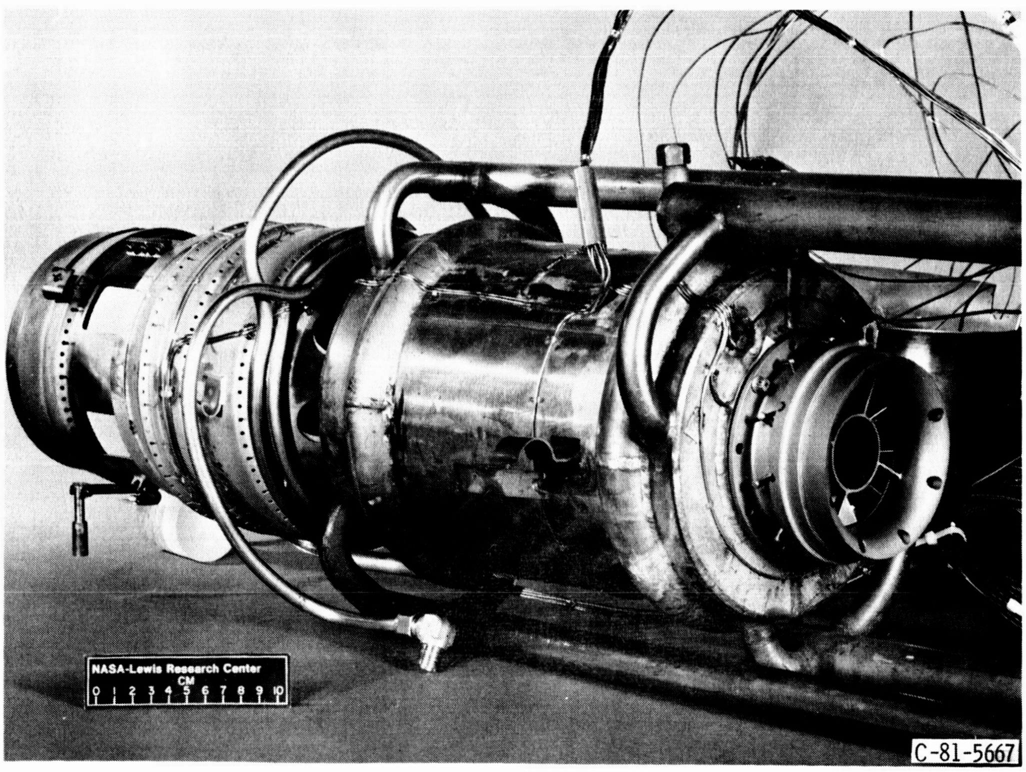
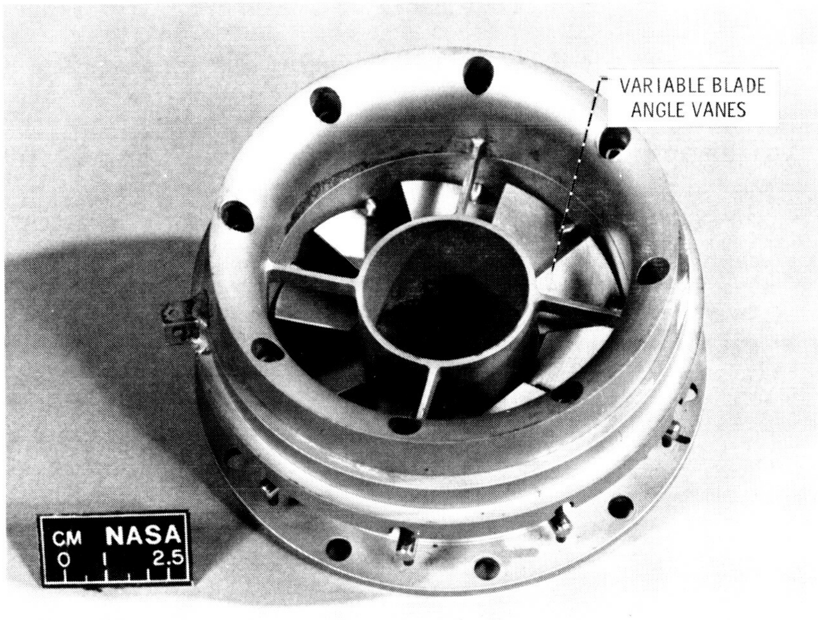


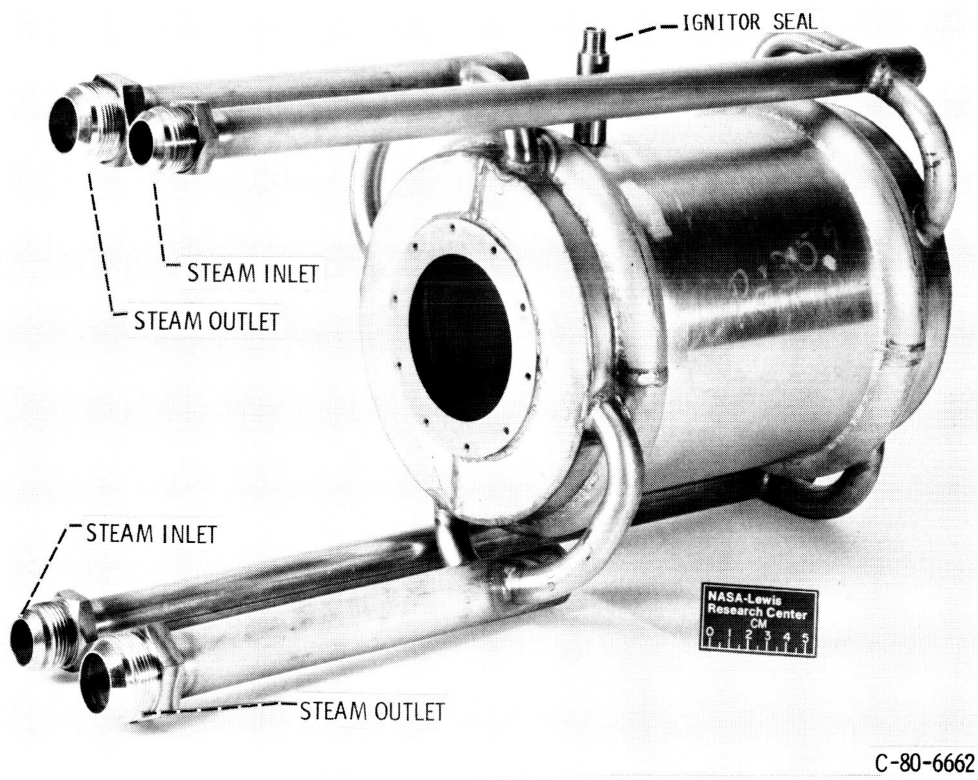

Figure 3. - Assembled steam cooled primary zone, variable geometry combustor.




C-81-4309

(a) Variable blade angle primary zone inlet air swirler.

Figure 4. - Detail view of steam cooled primary zone, variable geometry combustor hardware.

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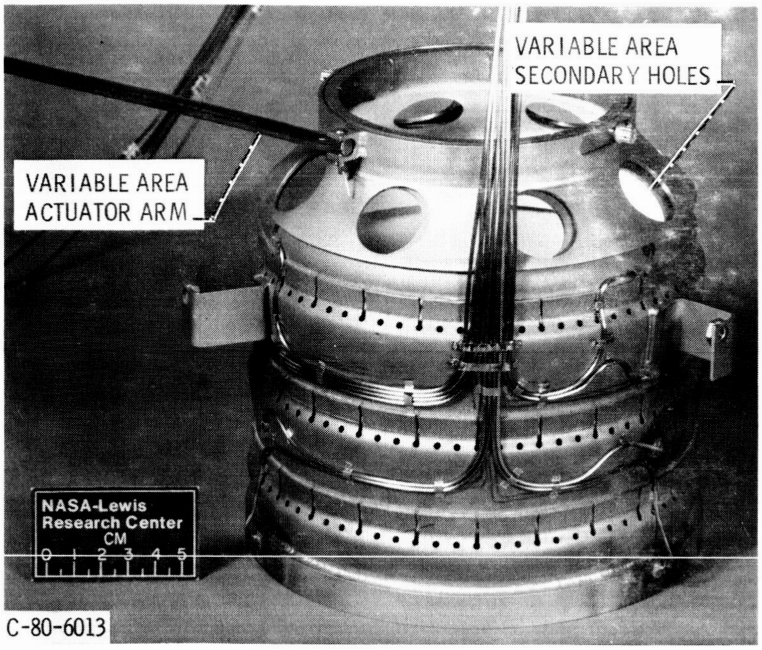
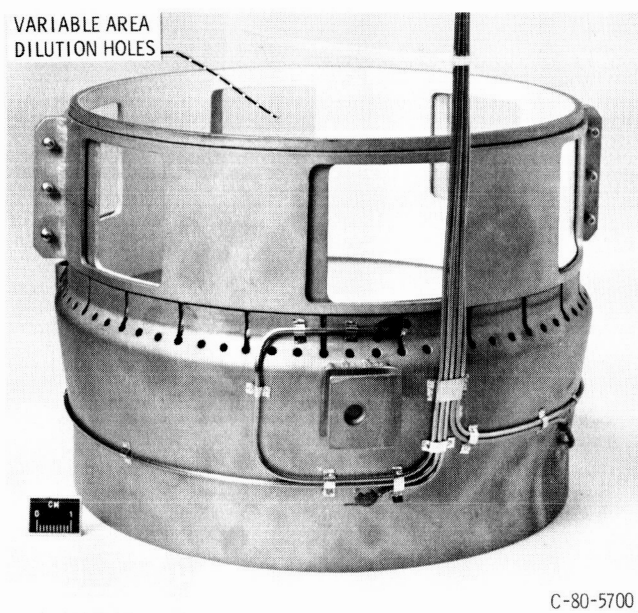
(b) Steam cooled rich-burn combustor primary, zone section showing ignitor seal.

Figure 4. - Continued.




(c) Variable area quench hole, secondary combustion zone section of rich-lean variable geometry combustor.

Figure 4. -Continued.




(d) Variable area dilution hole, tertiary zone section of rich-lean variable geometry combustor.

Figure 4. - Concluded.

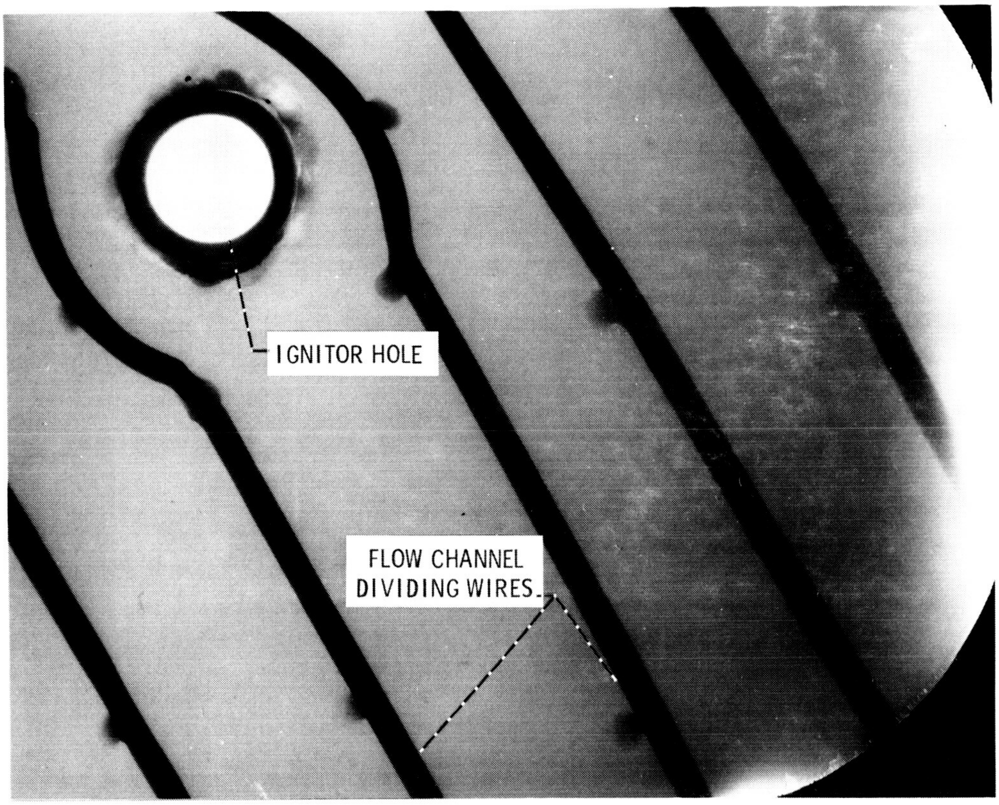



Figure 5. - X-ray of rich-burn steam cooled combustor liner showing internal steam flow passages.

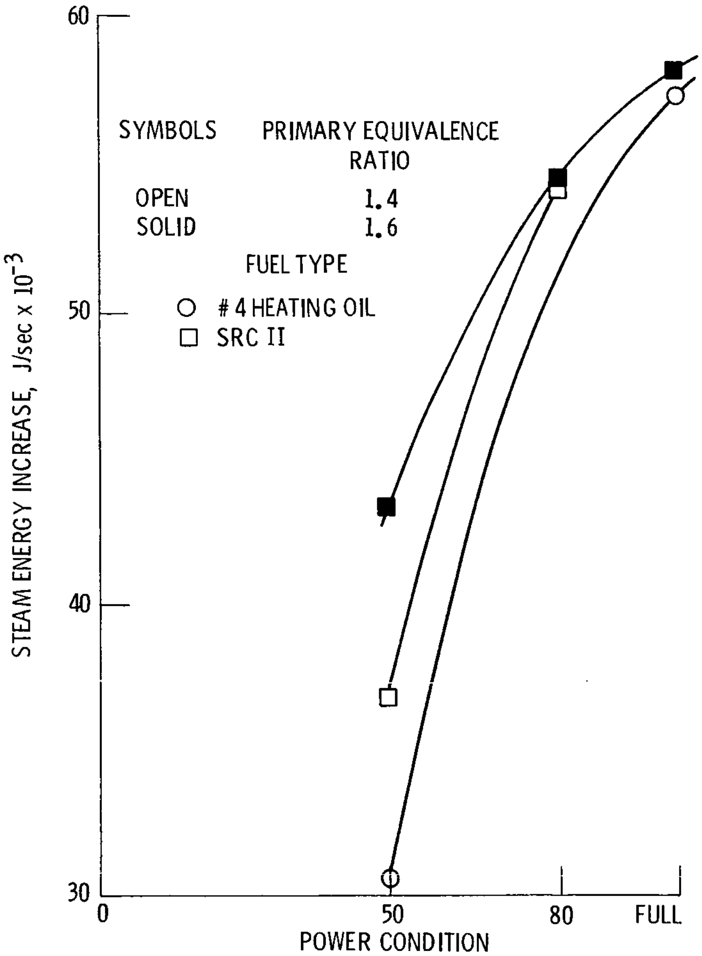



Figure 6. - Steam cooled rich-burn combustor steam energy increase as a function of power level and fuel type at primary equivalence ratios of 1.4 and 1.6.

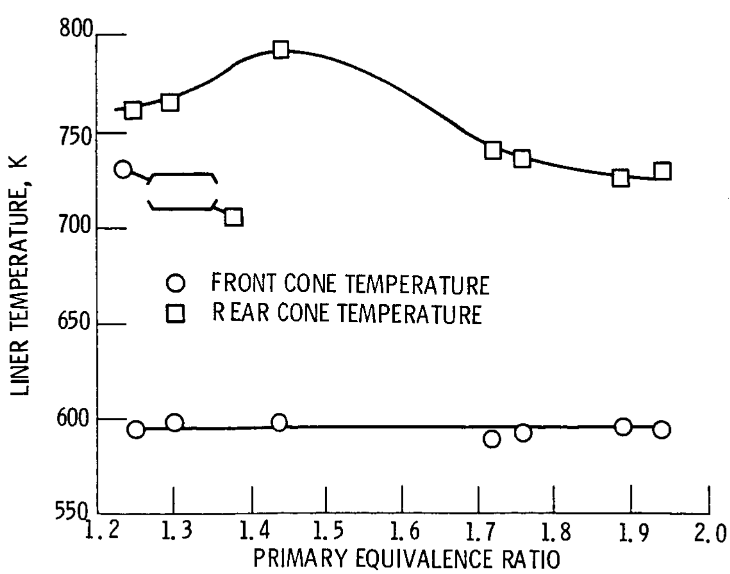



Figure 7. - Steam cooled rich-burn combustor liner temperature as a function of primary equivalence ratio at a simulated full power condition burning #4 heating oil.

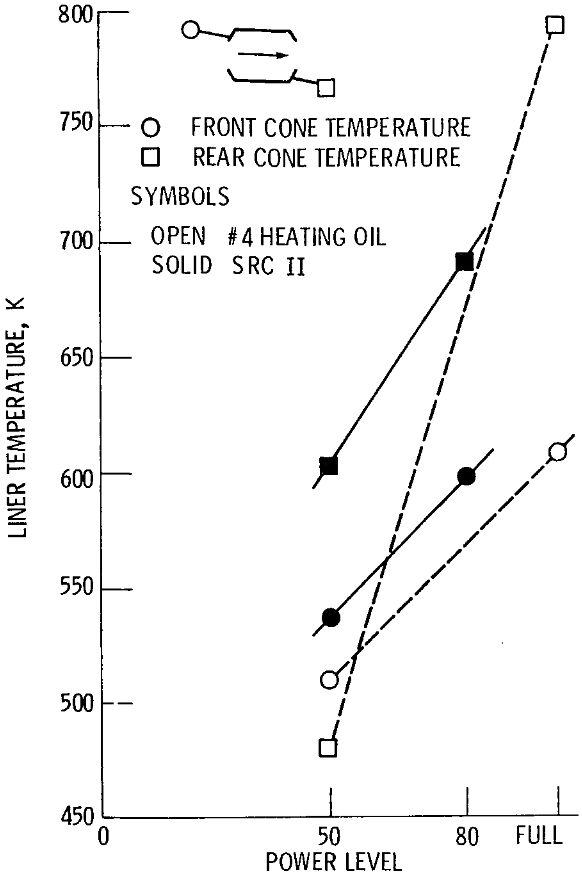



Figure 8. - Steam cooled rich-burn combustor liner temperature as a function of power level and fuel type at a primary equivalence ratio of 1.4.

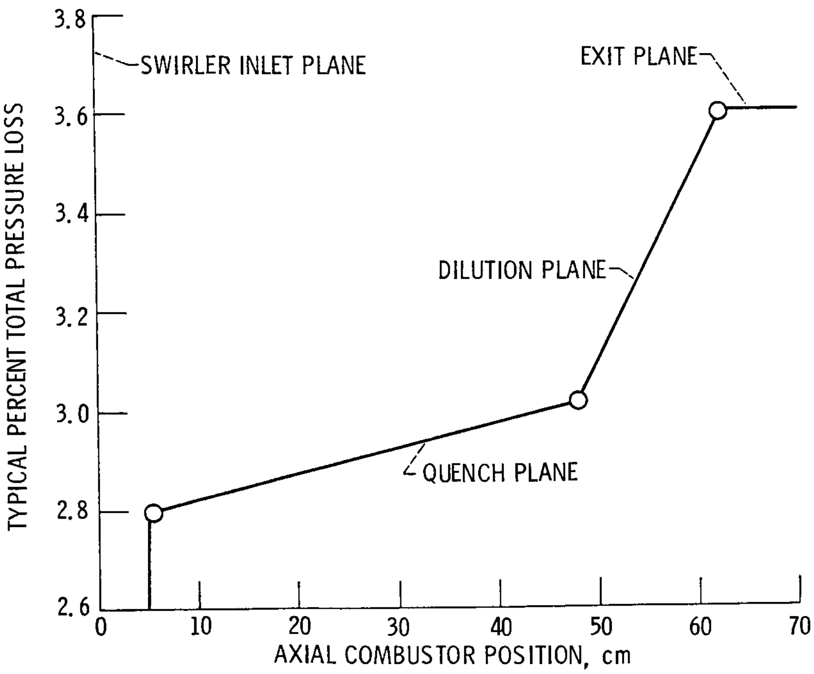



Figure 9. - Typical variable geometry combustor total pressure loss as a function of axial length.

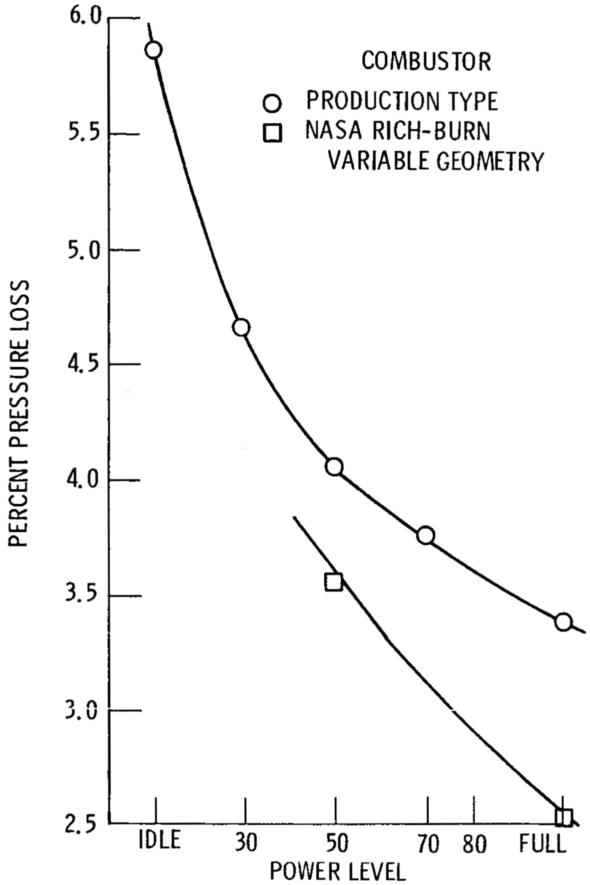



Figure 10. - Percent total pressure loss as a function of power level and combustor type.

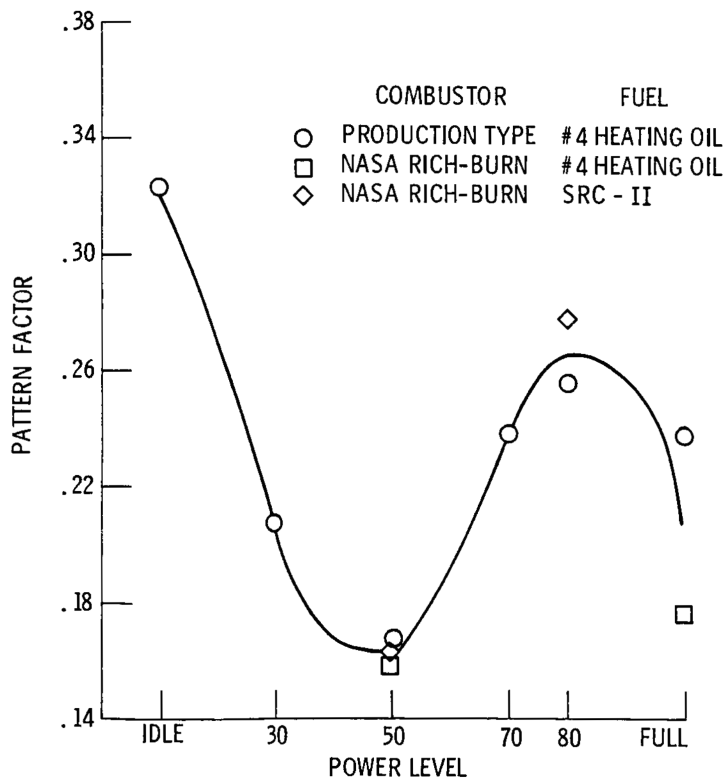



Figure 11. - Pattern factor as a function of power level, fuel type and combustor type.

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16. Abstract

This effort summarizes the work performed on a steam cooled, rich-burn primary zone, variable geometry combustor designed for combustion of nitrogenous fuels such as heavy oils or synthetic crude oils. The steam cooling was employed to determine its feasibility and assess its usefulness as part of a ground based gas turbine bottoming cycle. Variable combustor geometry was employed to demonstrate its ability to control primary and secondary zone equivalence ratios and overall pressure drop. 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 low temperature offers the potential of both long life and reduced use of strategic materials for liner fabrication. Three degrees of variable geometry were successfully employed to control air flow distribution within the combustor. A variable blade angle axial flow air swirler was used to control primary zone air flow, while the secondary and tertiary zone air flows were controlled by rotating bands which regulated air flow to the secondary zone quench holes and the dilutions holes respectively.

| 17. Key Words (Suggested by Author(s)) | 18. Distribution Statement |
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