Development of the GE Quiet Combustor and Other Design Changes to Benefit Quality

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The attractiveness of gas turbines in cogeneration facilities and combined–cycle (Brayton–Rankine) power plants is linked to high specific work; power per unit mass flow. Manufacturers have, over the years, increased gas turbine firing temperature to increase specific work, hence combined–cycle efficiency. High firing temperatures, insofar as they are related to high adiabatic stoichiometric flame temperatures, have brought higher NOx emissions along with high efficiency. Furthermore, efforts to combat smoke have also driven flame temperatures higher.

As combustors evolved to produce higher firing temperatures, and designs matured so as to lower smoke emissions and.control these NOx emissions, dynamic pressure oscillation activity within the combustor, noise, has increased; increasing wear and necessitating more frequent maintenance.

In response, a multiphase program was conducted in the GE Gas Turbine Development Laboratory from 1974 to 1980 with the goal of reducing the noise in the combustor. Many different designs were built and tested, and the one found to have significant value in reducing noise was the multi–fuel–nozzle combustion system.

Figure 1 shows the MS7001 multi–fuel–nozzle cap arrangement for such a combustion liner. The addition of diluent injection to this design for NOx control did not cause a significant increase in dynamic pressure activity. The benefits of this multiple–fuel–nozzle system are: low noise, low wear, decreased operation cost, increased availability, and a combustor design which can be applied to all MS7001 machine designs without extensive modification.

To prove the performance and reliability of the quiet combustor in the field, a three–year program sponsored in part by the Electric Power Research Institute (EPRI) was initiated in September 1980 to conduct a field endurance test on a water–injected, dual–fuel, multi–nozzle quiet combustion system on an MS7001B combined–cycle unit.

The objective of this program was to improve the wear life of combustion liners, transition pieces, and seals with the primary goal of increasing combustion inspection intervals.

The 12,268–hour endurance test began April 15, 1981, at the Houston Light and Power Company Wharton station and continued until November 27, 1983. In April of 1982, a full set of combustor dynamic pressures was recorded and compared with similar measurements taken at the beginning of the testing in 1981.

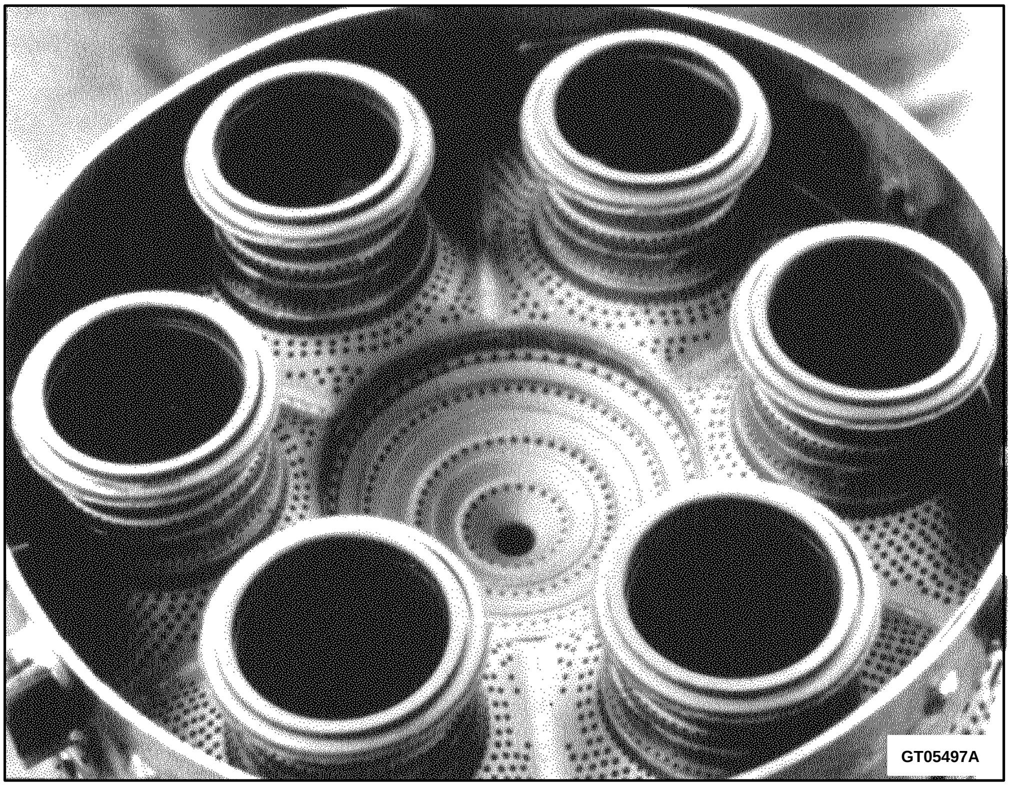

Figure 1. Multi–nozzle MS7001 combustion system (quiet combustor)

For all practical purposes, the dynamic data from 1981 and 1982 were identical, indicating that the system remains quiet. The field endurance program demonstrated the major wear reduction benefits; the quiet multi–nozzle combustion system achieved its inspection interval goals.

In January 1985, GE issued the final report to EPRI on the Quiet Combustor Program. In May 1985, EPRI issued report EPRI AP.3885/project 1801–1 on the High–Reliability Gas Turbine Combustor Project.

Development of the new MS7001F gas turbine was important to the continued progress in quiet, multi–nozzle combustors. After the development of the 1981 vintage multi–nozzle combustor, combustion development moved rapidly to support the 7F gas turbine.

The new machine features a firing temperature of 2300°F as compared to the 2020°F of the current MS7001EA or 1850°F of the MS7001B. To realize the increase in firing temperature, a multi–nozzle combustor was designed, utilizing facts learned during the EPRI work and concepts proven on GE aircraft engine combustors.

In November of 1984, GE responded to Gilroy Foods/Bechtel’s expressed need for low NOx production and high reliability by proposing a steam–injected, multi–nozzle quiet combustion system to meet the 25 ppmvd NOx requirement for their project in Gilroy, California. In December of 1984, technical presentations were made at the request of Gilroy Foods/Bechtel to the BAAQMD and to Region IX of the EPA in San Francisco. A new quiet combustor, one based on the 7F developments, was the centerpiece of that presentation.

The Houston Light and Power machine was an early production model. The combustor used in those tests had to be upgraded to be suitable for application by Gilroy Foods/Bechtel in an MS7001EA, the current production model. Advances made while developing the 7F combustor supplied proven technology to meet the MS7001EA needs with abundant margin. The Model B water–injected, multi–nozzle quiet combustor was optimized to demonstrate a low noise level and therefore reduced combustor wear resulting in longer combustion inspection intervals.

The Gilroy Foods/Bechtel Model EA steam–injected, multi–nozzle quiet combustor has the same low noise characteristics of the Model B at high steam flows, but is optimized for NOx and CO control. Prior to the installation of the quiet combustors in the Gilroy Foods/Bechtel machine, GE completed over a dozen laboratory full–scale, high–pressure combustor development tests at Model EA cycle conditions (Fig. 2). GE combustors are tested at full flow, full pressure and full temperature simultaneously in the Gas Turbine Development Laboratory in Schenectady, New York. These tests demonstrated the ability to meet 25 ppmvd NOx on natural gas fuel and 55 ppmvd NOx on No. 2 fuel oil with CO emissions at low levels.

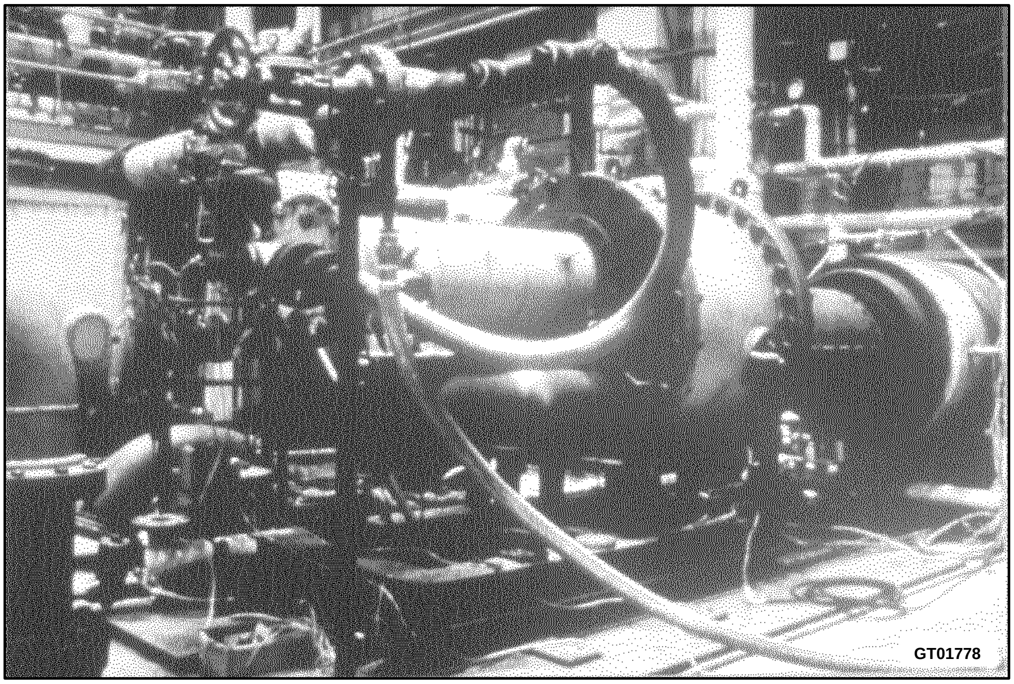

Figure 2. Typical combustion single–burner test stand

On March 14, 1985, an experimental quiet combustor was run steam injected at MS7001EA cycle conditions on both oil and gas. The test ran for eight hours and demonstrated NOx levels of 25 ppmvd on gas and 55 ppmvd on oil. On June 25, 1985, a similar test was run with and without steam injection. Final confirmation tests were run on actual Gilroy Foods/Bechtel combustion systems prior to delivery to the turbine.

In November 1987 the Gilroy Foods/Bechtel unit was run on natural gas at base load, which is 88 MW with the steam injection level at 1.54 times the fuel flow, with NOx emissions slightly below 25 ppmvd and CO below 20 ppmvd. These emission levels were maintained to 75 percent load. The unit has passed acceptance tests and state compliance tests.

We are satisfied that this combustion system can provide NOx control to 25 ppmvd with low noise levels. Mechanical performance of the multi–nozzle quiet combustors as installed on the Gilroy Foods/Bechtel units is expected to equal that of standard combustors without NOx control.

Three additional quiet combustor equipped units are now being assembled for Midway Sunset. These units are of the Model E configuration and are to be water injected for NOx compliance. These units will deliver 25 ppmvd NOx emission on gas and 42 (140 lb/hr) on oil. The units ship in the second quarter of 1988, with commercial operation planned for the December–January time frame.

Description of the Quiet Combustor

Like all combustor arrangements used in GE power generation gas turbines, MS 7001 machines feature a can–annular combustor. Both the standard and multi–nozzle quiet combustor are so arranged.

As learned early in the development of aircraft engines, such arrangements offer the advantages of control and optimization of combustor discharge temperature profile, high component natural frequencies, low surface area and manageable component size.

Figure 3 shows the arrangement of combustion covers. Each cover has a connection for gas fuel, atomizing air, diluent steam (or water), and six connections for liquid fuel. The fuel nozzle and end cover arrangement differ significantly from those of the standard combustor.

Figure 4, showing the standard fuel nozzle and end cover, reveals the fuel nozzle as a self–contained unit bolted to the center of the end cover. The end cover is simply a pressure boundary enclosing the combustion system.

Figure 5 shows the end cover of the multi–nozzle quiet combustor to be multifunctional. It not only encloses the combustion system, but contains manifolds delivering gas fuel and atomizing air to the six fuel nozzles. It further functions as the body of the fuel nozzle. Each fuel nozzle is brazed into the end cover. The diluent steam is introduced through the central connection.

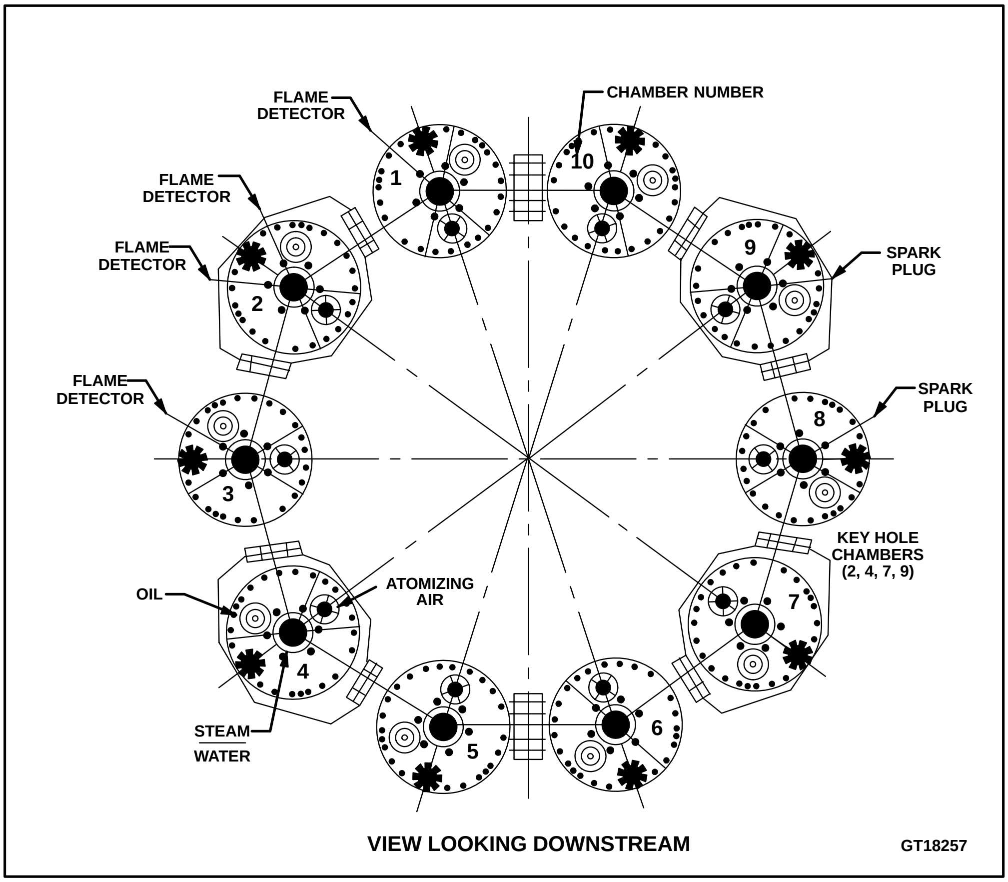

Figure 3. Multi–nozzle combustion system

Once inside the cavity between the combustion liner head end and the end cover, it is forced radially outward toward each of the nozzles. The end cover assembly is made of 300 series stainless steel to prevent scale from forming in the passages. It is necessarily heavier than the covers of the standard system, and is installed with the aid of guide pins rather than hinges. There are six fuel nozzles spaced around the circumference of the cover. The six fuel nozzle bodies are an integral part of the cover and are connected by manifolds within the cover assembly.

To ensure uniform distribution of liquid fuel among the six fuel nozzles in each combustor, each cover is provided with an external oil distribution valve. This valve overcomes the pressure head effect which would work to deliver more fuel to the nozzles on the low side of the cover. As with the standard combustor, uniform division of oil among the combustors is accomplished via a geared flow divider located on the accessory base.

The cap and cowl of the liner shown in Fig. 6 accommodate the six fuel nozzles. The standard liner has an air–metering cowl plate with a large central hole where the fuel nozzle swirler tip fits. The standard cap is a louver–cooled conical configuration. The entrance side of the quiet combustor head end is the structural portion of the cap/cowl assembly.

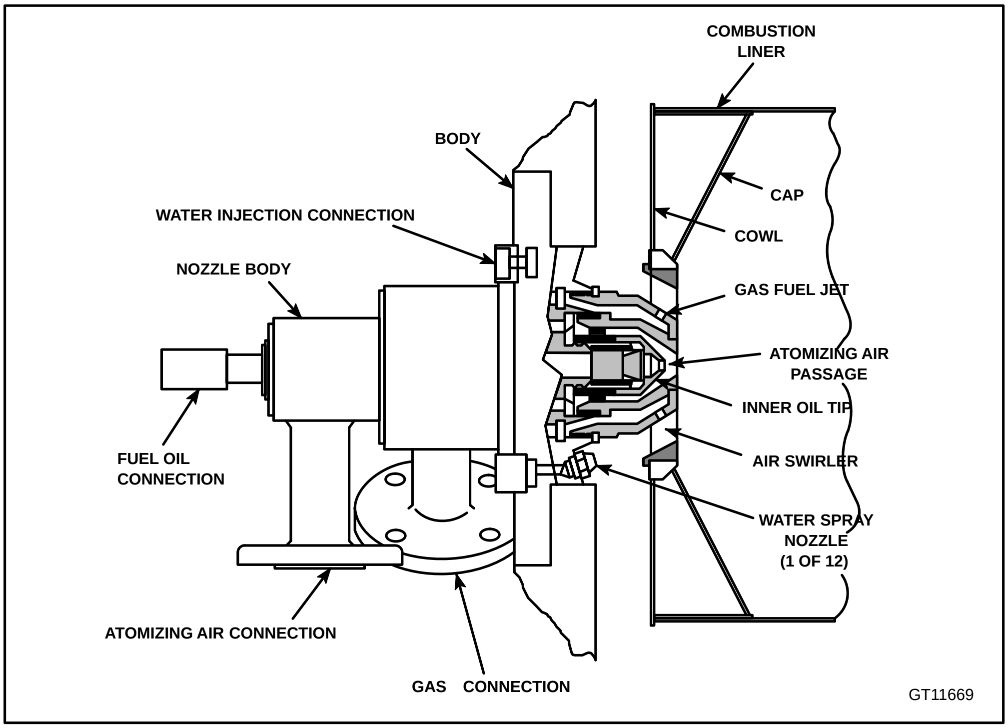

Figure 4. Typical fuel nozzle (dual fuel–H2O injection)

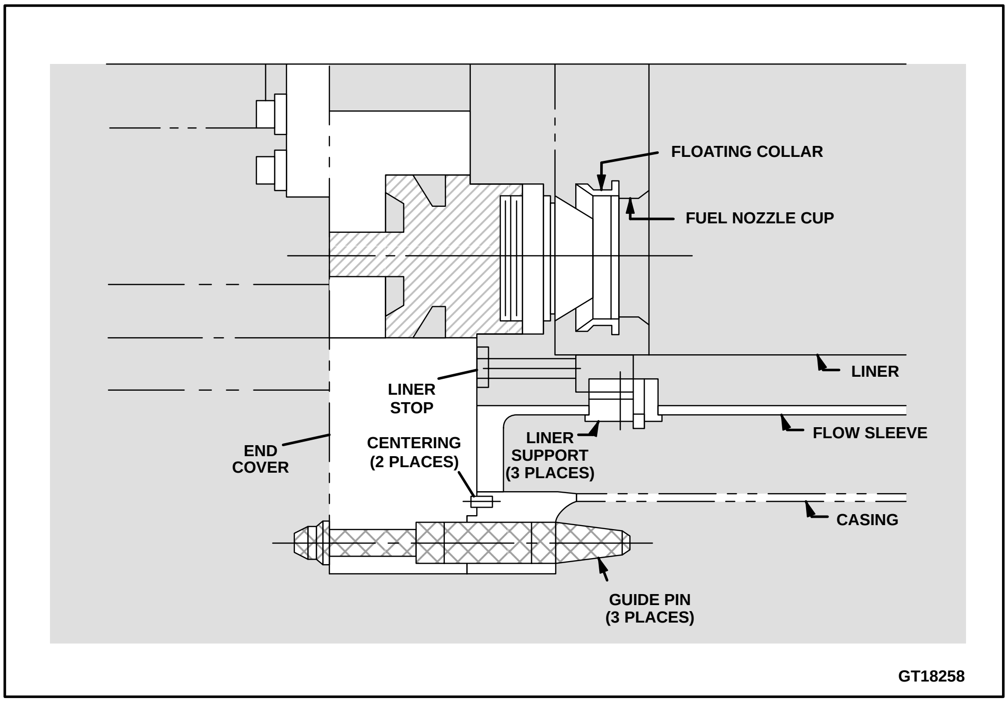

Figure 5. Multi–nozzle combustion arrangement

The array of small holes is the impingement cooling system which cools six splash plates on the gas side of the head end of the combustor.

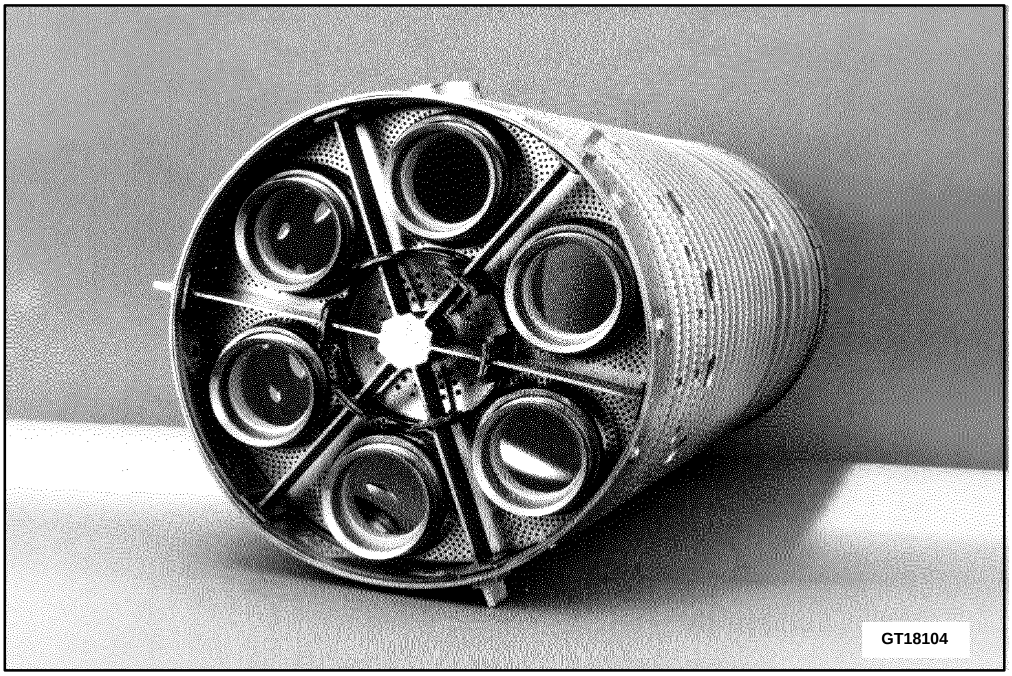

Figure 6. Combustion liner cap and cowl

The six large holes accommodate the fuel nozzles. Sliding locating ferrules within each of the holes close the fuel nozzles and seal the space between the outer diameter of each nozzle and the cap/cowl. This cap design is patterned after the GE Model CF6 aircraft engine combustor dome. The systems utilize GE's standard 14.3 inch diameter heavy–duty, brazed–ring construction, slot–cooled liner. The spacing and location of the combustion zone reaction holes and dilution holes differ slightly since the multi–nozzle quiet combustor has a shorter flame length (see Fig. 7).

Both the standard and quiet combustor utilize the same aerodynamic body shape and flow sleeve; minor differences exist on the location of the access holes for the common spark plugs and flame detectors.

Other NOx Control Technologies

Most of the world's experience in gas turbine NOx control is based on water and steam injection. The GE experience in heavy–duty machines appears in Fig. 8. Although gas turbine output increases with the injection of diluent, cycle efficiency suffers due to the less than optimum utilization of the steam. At the emissions levels allowed by the national NSPS regulation, 75 ppmvd with efficiency correction, the MS7001EA complies with the injection of slightly in excess of 20,000 pph of steam. This is significantly less steam than required by gas turbines which do not employ can–annular combustors, and penalizes the combined–cycle heat rate only 90 Btu/kWh.

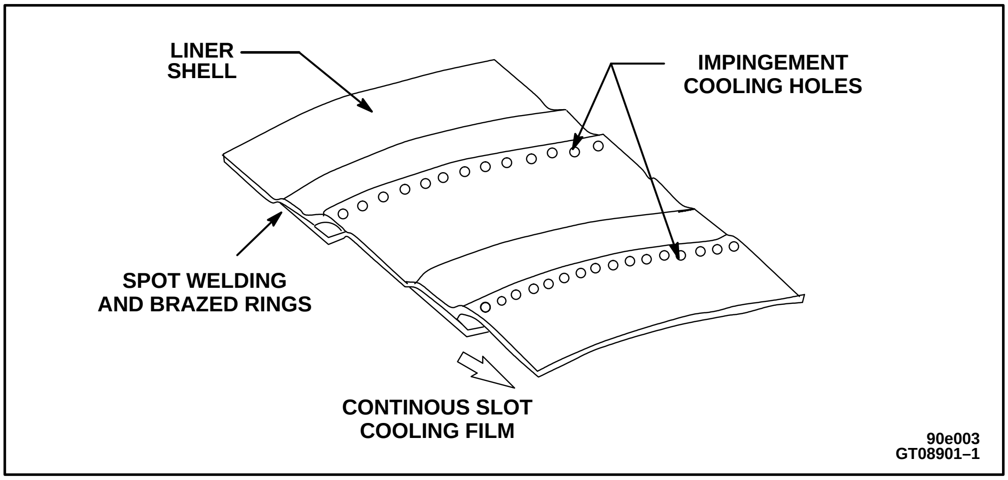

Figure 7. MS76001B/7001E/9001E slot–cooled liner, cutaway view

NSPS (75 ppm)	– 59 UNITS
40–50 ppm	– 32 UNITS
25 ppm	– 1 UNITS

GT18259

Figure 8. GE NOx control experience

In cases of inherently more polluting combustion geometries, in the case of very strict emission codes, and in cases of high premiums placed on steam generation, there is substantial incentive for manufacturers and users to explore alternative control technologies. At 25 ppmvd with no efficiency correction, the heat rate impact on an MS7001EA combined–cycle plant is 230 Btu/kWh (Fig. 9). At $3 per million Btu fuel prices, the fuel cost of compliance is $497,000 per year per gas turbine. An increased cost of equipment of $6 million could be offset if this fuel would be saved.

At the lower levels of allowable NOx emissions, more capital–intensive control technologies become viable. In anticipation of regulatory development and increased heat recovery applications, GE has maintained development activity on dry NOx control.

The first dry low–NOx control development at GE was also the first development of multi–nozzle quiet combustors. From 1973 on, dry low–NOx combustors were tested in the laboratory in Schenectady. In March and April of 1980, Houston Light and Power hosted a field test of a dry low–NOx combustor capable of meeting U.S. EPA NSPS, nominally 75 ppmvd. Since that time, the design has evolved to meet today’s clean air requirements.

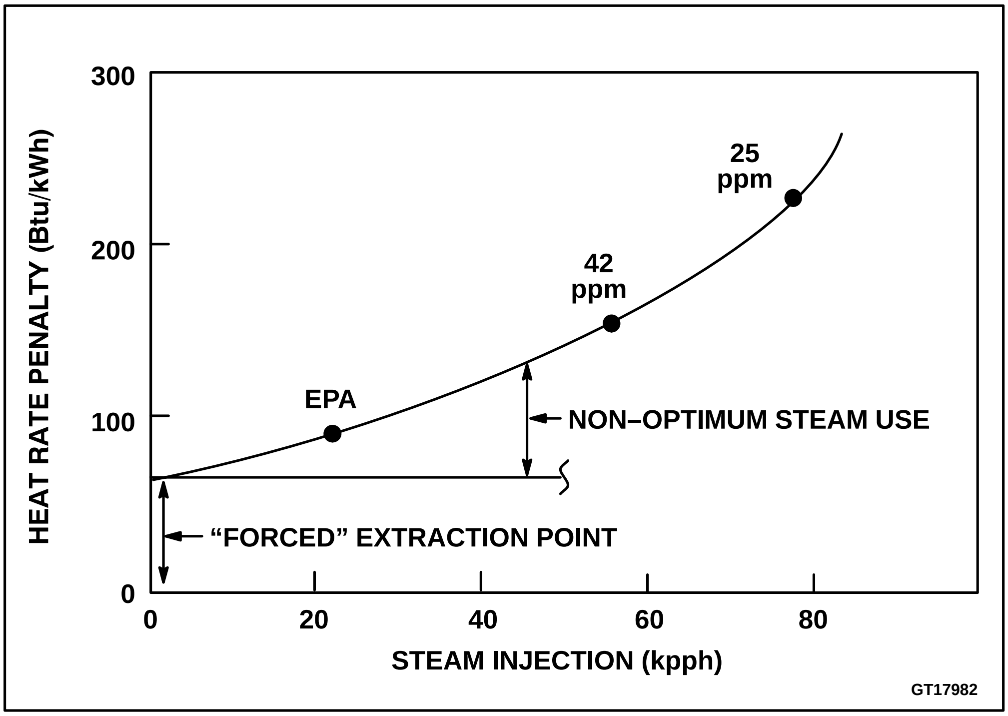

Figure 9. Effect of steam injection on MS7001EA–based combined–cycle plant

The current version of the dry low–NOx combustor appears in Fig. 10. Since NOx generation increases exponentially with the flame temperature, the objective of NOx control is to reduce peak flame temperature while maintaining high combustor discharge temperature. The dry low–NOx approaches which have shown merit over the past decade can be classified in five categories: (1) catalytic combustion, (2) rich combustion, (3) lean diffusion flames, (4) staged combustion, and (5) lean premixed combustion.

Each approach encourages burning at less than the normally occurring stoichiometric temperatures, which in turn results in lower flame temperatures. The GE dry low–NOx system uses a combination of the last three approaches. How these approaches combine can be explained by following the combustor operation during a typical turbine start–up.

Figure 11 is a cross section of the GE dry low–NOx combustor. The operating modes are noted in Fig. 12. At low load, the combustor operates in the primary mode. In the primary mode, confined diffusion flames anchor in the first–stage cups' reaction zones. These flames are quite stable and yield emissions typical of conventional combustors.

In the secondary mode, a largely unconfined, lean diffusion flame stabilizes in the centerbody recirculation zone. Since this flame is highly aerated by the surrounding throughflow, secondary mode NOx emissions are lower than in the primary mode. In the lean/lean mode, NOx emissions are reduced from primary mode values by diverting fuel to the lean centerbody pilot flame and by vitiating the pilot flame with first–stage combustion products.

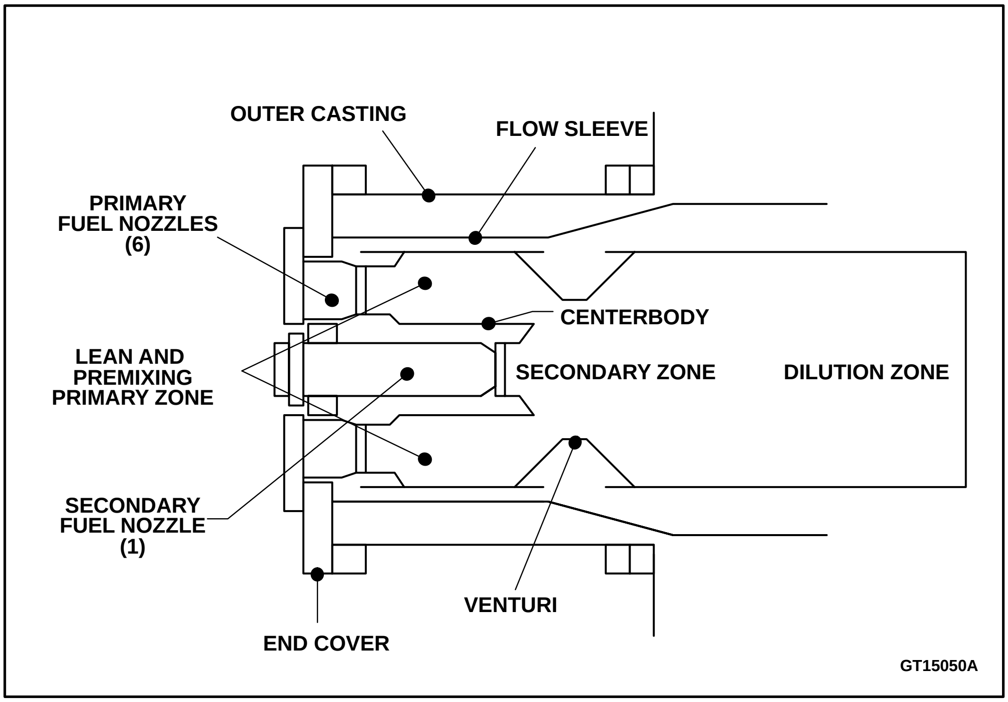

Figure 10. Dry low–NOx combustor

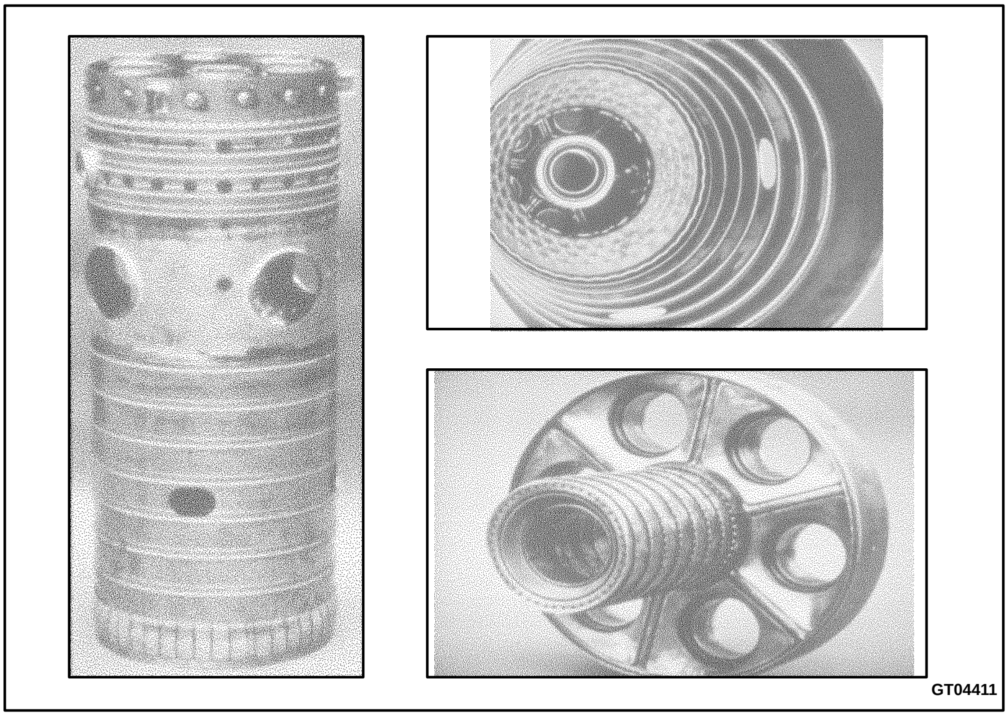

Figure 11. MS7001 dry low–NOx combustor

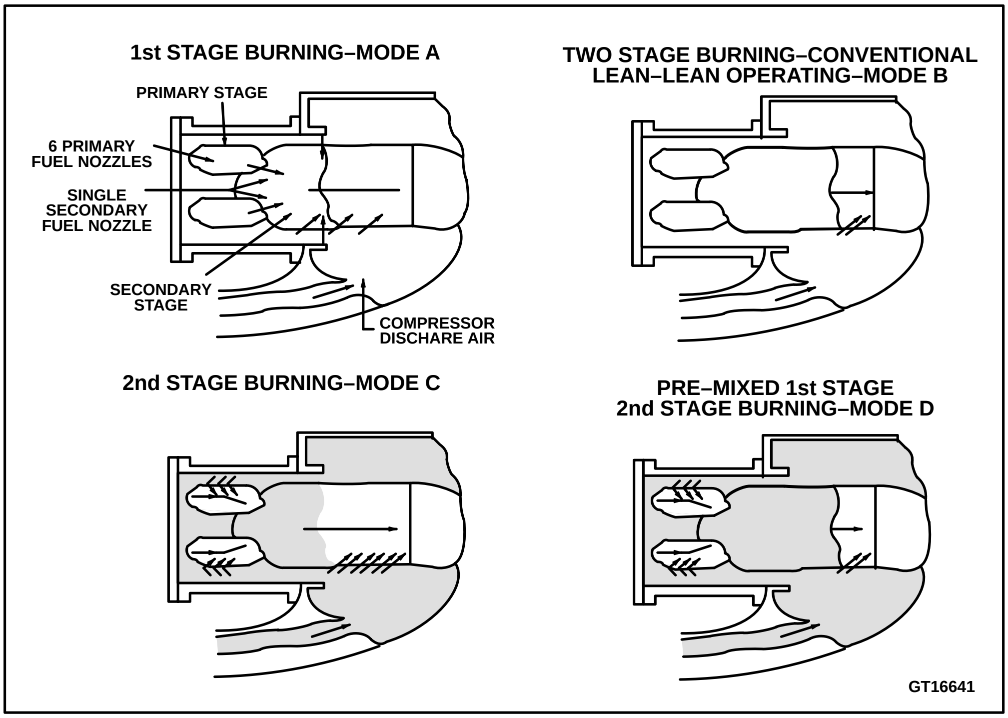

Figure 12. Dry low–NOx combustor operating modes

The premixed mode offers the lowest NOx potential. In the first stage, the fuel mixes with air to yield a stoichiometrically lean flow. When this flow reaches the vicinity of the pilot flame, the mixture begins to burn. Since the NOx formation from the premixed flow is relatively low, the NOx emissions level strongly depends on the pilot flame's fuel–to–air ratio and only weakly depends on the premixed flow's stoichiometry.

The current version of the dry low–NOx combustor is undergoing final laboratory testing now. NOx levels of 25 ppmv are being met in the laboratory, at turbine operating conditions. Mechanical design calculations and life prediction are being completed. After field testing, anticipated to commence in 1989, production versions of this combustor will be manufactured for the MS7001EA, MS9001E, and MS6001B machines.

Both the dry low–NOx and quiet combustor with steam injection share limits acknowledged in the industry as to part load emissions and some increase in CO when pursuing the lowest levels of NOx. For flat emission control from below 50 percent to full load at levels below 25 ppmvd, catalytic combustion offers one attractive alternative. A catalytic combustor operates in the very lean regime and uses a combustion enhancing catalyst to maintain flame stability.

GE has designed a suitable unit, under a program sponsored in part by Tokyo Electric Power Company (TEPCO) and Southern California Edison Company. The design shown in Fig. 13 is in fact the second design concept tested by GE. The significant components of the system include the preburner, which performs the combustion at loads too low for catalytic reaction, the fuel–air preparation system which is required to present a uniform mixture of fuel, air, or products of preburner combustion to the catalyst, and the catalytic reactor.

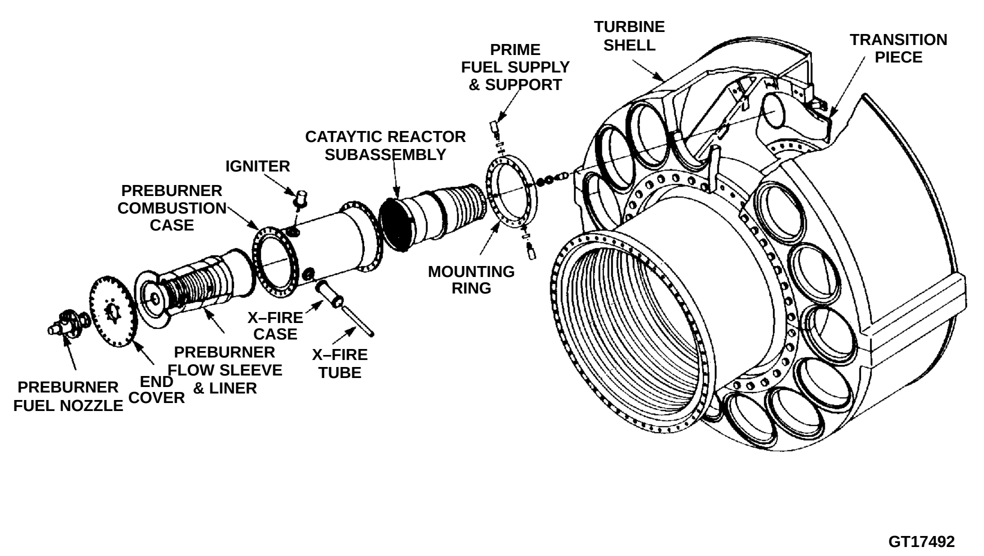

Figure 13. Catalytic combustion system (natural gas)

Testing of this combustor continues in the GE Combustion Laboratory and has been run on the design preburner, fuel preparation system and catalytic reactor of currently available materials. Full temperature, flow, and pressure tests show the design goal of 10 ppmvd NOx, CO, and UHC can be met. Currently, a catalyst structural substrate of sufficient integrity for long combustor life does not exist. Research in this area continues.

Development of catalytic combustors is still at an early stage, but, provided the problems of cost and high–temperature performance for the catalyst can be overcome, offers great promise for ultra–low NOx combustors in the next decade. Meanwhile, the staged combustor operating in the lean/lean and premixed modes and the multi–nozzle quiet combustor operating with diluent injection offer more immediate prospects for achieving the NOx levels demanded today with natural gas and distillate oils.

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