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GE Power Systems

Dry Low NO_x Combustion Systems for GE Heavy-Duty Gas Turbines

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Abstract

State-of-the-art emissions control technology for heavy-duty gas turbines is reviewed with emphasis on the operating characteristics and field experience of Dry Low NO_x (DLN) combustors for E and F technology machines. The lean premixed DLN systems for gas fuel have demonstrated their ability to meet the ever-lower emission levels required today. Lean premixed technology has also been demonstrated on oil fuel and is also discussed.

Introduction

The regulatory requirements for low emissions from gas turbine power plants have increased during the past 10 years. Environmental agencies throughout the world are now requiring even lower rates of emissions of NO_x and other pollutants from both new and existing gas turbines. Traditional methods of reducing NO_x emissions from combustion turbines (water and steam injection) are limited in their ability to reach the extremely low levels required in many localities. GE's involvement in the development of both the traditional methods (*References 1 through 6*) and the newer Dry Low NO_x (DLN) technology (*References 7 and 8*) has been well documented. This paper focuses on DLN.

Since the commercial introduction of GE's DLN combustion systems for natural-gas-fired heavy-duty gas turbines in 1991, systems have been installed in more than 222 machines, from the most modern FA+e technology (firing temperature class of 2420 F/1326 C) to field retrofits of older machines. As of May 1999, these machines have operated more than 4.8 million hours with DLN; and more than 1.4 million hours have been in the F technology. To meet marketplace demands, GE has developed DLN products broadly classified as either DLN-1, which was developed for E-technology (2000°F/1093°C firing temperature class) machines, or DLN-2, which was developed specifically for the F technology machines and is also being applied to the EC and H machines.

Development of these products has required an intensive engineering effort involving both GE Power Systems and GE Corporate Research and Development. This collaboration will continue as DLN is applied to the H machines and combustor development for Dry Low NO_x on oil ("dry oil") continues.

This paper presents the current status of DLN-1 technology and experience, including dry oil, and of DLN-2 technology and experience. Background information about gas turbine emissions and emissions control is contained in the Appendix.

Dry Low NO_x Systems

Dry Low NO_x Product Plan

Figure 1 shows GE's Dry Low NO_x product offerings for its new and existing machines in three major groupings. The first group includes the MS3002J, MS5001/2 and MS6001B products. The 6B DLN-1 is the technology flagship product for this group and, as can be noted, is available to meet 9 ppm NO_x requirements. Such low NO_x emissions are generally not attainable on lower firing temperature machines such as the MS3002s and MS5001/2s because carbon monoxide (CO) would be excessive.

The second major group includes the MS7001B/E, MS7001EA and MS9001E machines with the 9 ppm 7EA DLN-1 as the flagship product.

The dry oil program focuses initially on this group.

The third group combines all of the DLN-2 products and includes the FA, EC, and H

	Gas			Distillate		
Turbine Model	NOx (ppmvd)	CO (ppmvd)	Diluent	NOx (ppmvd)	CO (ppmd)	Diluent
MS3002(J)-RC	33	25	Dry	N/A	N/A	N/A
MS3002(J)-SC	42	50	Dry	N/A	N/A	N/A
MS5001P	25	50	Dry	65	20	Water
MS5001R	42	50	Dry	65	20	Water
MS5002C	42	50	Dry	65	20	Water
MS6001B	9	25	Dry	42	30	Water
MS7001B/E Conv.	25	25	Dry	42	30	Water
MS7001EA	9	25	Dry	42	30	Water
MS9001E	15	25	Dry	42	20	Water
	25	25	Dry	90	20	Dry
MS6001FA	25	15	Dry	42/65	20	Water/Steam
MS7001FA	25	15	Dry	42/65	20	Water/Steam
	9	9	Dry	42/65	30	Water/Steam
MS7001FB	25	15	Dry	42	20	Water
MS7001H	9	9	Dry	42/65	30	Water/Steam
MS9001EC	25	15	Dry	42/65	20	Water/Steam
MS9001FA	25	15	Dry	42/65	20	Water
MS9001FB	25	15	Dry	42	20	Water
MS9001H	25	15	Dry	42	20	Water

Figure 1. Dry Low NO_x product plan

machines, with the 7FA product as the flagship.

As shown in *Figures 2 and 3*, most of these products are capable of power augmentation and of peak firing with increased NO_x emissions. With gas fuel, power augmentation with steam is in the premixed mode for both DLN-1 and DLN-2 systems.

Turbine Model	NO_x @15% O_2 (ppmvd)	Operating Mode	Diluent	Maximum Diluent/Fuel	NO_x at Max D/F (ppmvd)	CO Max D/F (ppmvd)
MS6001(B)	9	Premix	Steam	2.5/1	9	25
	25	Premix	Steam	2.5/1	25	15
MS7001(EA)	9	Premix	Steam	2.5/1	9	25
	25	Premix	Steam	2.5/1	25	15
MS7001(FA)	9	Premix	Steam	2.1/1	12	15

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Figure 2. DLN power augmentation summary

	NO_x-Base (ppmvd)	NO_x-Peak (ppmvd)	CO-Base (ppmvd)	CO-Peak (ppmvd)
MS6001(B)	9	18	25	6
	25	50	15	4
MS7001(EA)	9	18	25	6
	25	50	15	4
MS7001(FA)	25	35	15	6
MS9001(E)	25	40	15	6

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Figure 3. DLN peak firing emissions - natural gas fuel

The GE DLN systems integrate a staged premixed combustor, the gas turbine's SPEEDTRONIC™ controls and the fuel and associated systems. There are two principal measures of performance. The first is meeting the emission levels required at baseload on both gas and oil fuel and controlling the variation of these levels across the load range of the gas turbine.

The second measure is system operability, with emphasis placed on the smoothness and reliability of combustor mode changes, ability to load and unload the machine without restriction, capability to switch from one fuel to another and back again, and system response to rapid transients (e.g., generator breaker open events or rapid swings in load). GE's design goal is to make the DLN system operate so the gas turbine operator does not know whether a DLN or conventional combustion system has been installed (i.e., its operation is "transparent to the user"). A significant portion of the DLN design and development effort has focused on system operability. As operational experience has increased, design and development efforts have moved towards hardware durability and extending combustor inspection intervals.

Design of a successful DLN combustor for a heavy-duty gas turbine also requires the designer to develop hardware features and operational methods that simultaneously allow the equivalence ratio and residence time in the flame zone to be low enough to achieve low NO_x, but with acceptable levels of combustion noise (dynamics), stability at part-load operation and sufficient residence time for CO burnout, hence the designation of DLN combustion design as a "four-sided box" (*See Figure 4*).

A scientific and engineering development program by GE's Corporate Research and Development, Power Systems business and Aircraft Engine business has focused on understanding and controlling dynamics in lean premixed flows. The objectives have been to:

- Gather and analyze machine and laboratory data to create a comprehensive dynamics data base
- Create analytical models of gas turbine combustion systems that can be used to understand dynamics behavior
- Use the analytical models and experimental methods to develop methods to control dynamics

These efforts have resulted in a large number of hardware and control features that limit dynamics, plus analytical tools that are used to predict system behavior. The latter are particularly useful in correlating laboratory test data from full scale combustors with actual gas turbine data.

DLN-1 System

DLN-1 development began in the 1970s with the goal of producing a dry oil system to meet the United States Environmental Protection Agency's New Source Performance Standards of 75 ppmvd NO_x at 15% O_2. As noted in *Reference 7*, this system was tested on both oil and gas fuel at Houston Lighting & Power in 1980 and met its emission goals. Subsequent to this, DLN program goals changed in response to stricter environmental regulations and the pace of the program accelerated in the late 1980s.

DLN-1 Combustor

The GE DLN-1 combustor (shown in cross section in *Figure 5* and described in *Reference 8*) is a two-stage premixed combustor designed for use with natural gas fuel and capable of operation on liquid fuel. As shown, the combustion system includes four major components: fuel injection system, liner, venturi and cap/centerbody assembly.

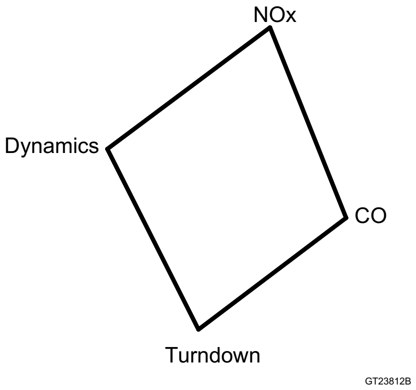


Figure 4. DLN technology - a four sided box

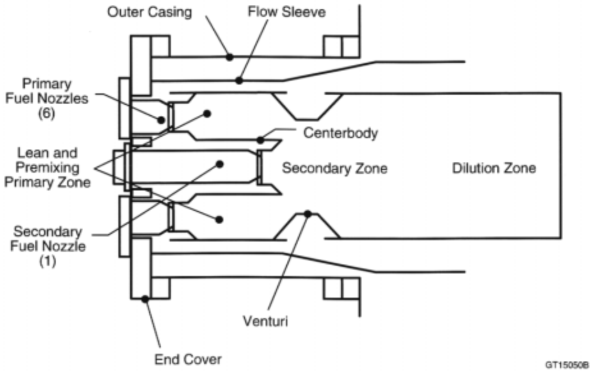


Figure 5. Dry Low NO_x combustor

The GE DLN-1 combustion system operates in four distinct modes, illustrated in *Figure 6*, during premixed natural gas or oil fuel operation:

These components form two stages in the combustor. In the premixed mode, the first stage thoroughly mixes the fuel and air and delivers a uniform, lean, unburned fuel-air mixture to the second stage.

Mode/Operating Range

- *Primary* – Fuel to the primary nozzles only. Flame is in the primary stage only. This mode of operation is used to ignite, accelerate and operate the machine over low- to mid-loads, up to a pre-selected combustion reference temperature.
- *Lean-Lean* – Fuel to both the primary and secondary nozzles. Flame is in both the primary and secondary stages. This mode of operation is used for intermediate loads between two pre-selected combustion reference temperatures.
- *Secondary* – Fuel to the secondary nozzle only. Flame is in the secondary zone only. This mode is a transition state between lean-lean and premix modes. This mode is necessary to extinguish the flame in the primary zone, before fuel is reintroduced into what becomes the primary premixing zone.
- *Premix* – Fuel to both primary and secondary nozzles. Flame is in the secondary stage only. This mode of operation is achieved at and near the combustion reference temperature design point. Optimum emissions are generated in premix mode.

The load range associated with these modes varies with the degree of inlet guide vane modulation and, to a smaller extent, with the ambient temperature. At ISO ambient, the premix operating range is 50% to 100% load with IGV modulation down to 42°, and 75% to 100% load with IGV modulation down to 57°. The 42° IGV minimum requires an inlet bleed heat system.

If required, both the primary and secondary fuel nozzles can be dual-fuel nozzles, thus allowing automatic transfer from gas to oil throughout the load range. When burning either natural gas or distillate oil, the system can operate to full load in the lean-lean mode (*Figure 6*). This allows wet abatement of NO_x on oil fuel and power augmentation with water on gas.

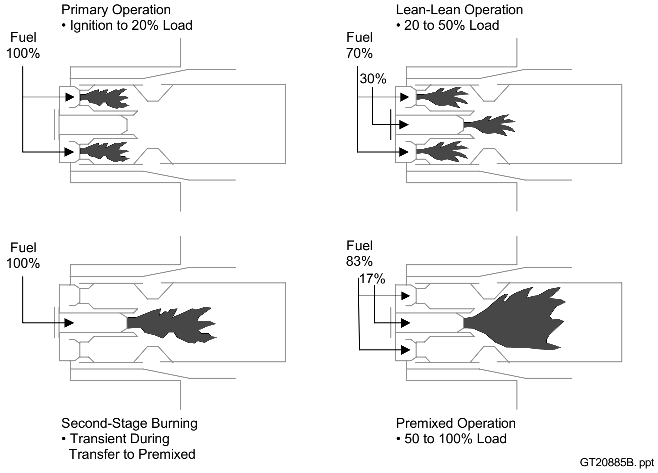


Figure 6. Fuel-staged Dry Low NO_x operating modes

The spark plug and flame detector arrangements in a DLN-1 combustor are different from those used in a conventional combustor. Since the first stage must be re-ignited at high load in order to transfer from the premixed mode back to lean-lean operation, the spark plugs do not retract. One plug is mounted near a primary zone cup in each of two combustors. The system uses flame detectors to view the primary stage of selected chambers (similar to conventional systems), and secondary flame detectors that look through the centerbody and into the second stage.

The primary fuel injection system is used during ignition and part load operation. The system also injects most of the fuel during premixed operation and must be capable of stabilizing the flame. For this reason, the DLN-1 primary fuel nozzle is similar to GE's MS7001EA multi-nozzle combustor with multiple swirl-stabilized fuel injectors. The GE DLN-1 system uses five primary fuel nozzles for the MS6001B and smaller machines and six primary fuel nozzles for the larger machines. This design is capable of providing a well-stabilized diffusion flame that burns efficiently at ignition and during part load operation.

In addition, the multi-nozzle fuel injection system provides a satisfactory spatial distribution of fuel flow entering the first-stage mixer. The primary fuel-air mixing section is bound by the combustor first-stage wall, the cap/centerbody and the forward cone of the venturi. This volume serves as a combustion zone when the combustor operates in the primary and lean-lean modes. Since ignition occurs in this stage, crossfire tubes are installed to propagate flame and to balance pressures between adjacent chambers. Film slots on the liner walls provide cooling, as they do in a standard combustor.

In order to achieve good emissions performance in premixed operation, the fuel-air equivalence ratio of the mixture exiting the first-stage mixer must be very lean. Efficient and stable burning in the second stage is achieved by providing continuous ignition sources at both the inner and outer surfaces of this flow. The three elements of this stage comprise a piloting flame, an associated aerodynamic device to force interaction between the pilot flame and the inner surface of the main stage flow, and an aerodynamic device to create a stable flame zone on the outer surface of the main stage flow exiting the first stage.

The piloting flame is generated by the secondary fuel nozzle, which premixes a portion of the natural gas fuel and air (nominally, 17% at full-load operation) and injects the mixture through a swirler into a cup where it is burned. Burning an even smaller amount of fuel (less than 2% of the total fuel flow) stabilizes this flame as a diffusion flame in the cup. The secondary nozzle, which is mounted in the cap centerbody, is simple and highly effective for creating a stable flame.

A swirler mounted on the downstream end of the cap/centerbody surrounds the secondary nozzle. This creates a swirling flow that stirs the interface region between the piloting flame and the main-stage flow and ensures that the flame is continuously propagated from the pilot to the inner surface of the fuel-air mixture exiting the first stage. Operation on oil fuel is similar except that all of the secondary oil is burned in a diffusion flame in the current dry oil design.

The sudden expansion at the throat of the venturi creates a toroidal re-circulation zone over the downstream conical surface of the venturi. This zone, which entrains a portion of the venturi cooling air, is a stable burning zone that acts as an ignition source for the main stage fuel-air mixture. The cone angle and axial location of the venturi cooling air dump have significant effects on the efficacy of this ignition source. Finally, the dilution zone (the region of the combustor immediately downstream from the flame zone in the secondary) provides a region for CO burnout and for shaping the gas temperature profile exiting the combustion system.

DLN-1 Controls and Accessories

The gas turbine accessories and control systems are configured so that operation on a DLN-equipped turbine is essentially identical to that of a turbine equipped with a conventional combustor. This is accomplished by controlling the turbines in identical fashions, with the exhaust temperature, speed and compressor discharge pressure establishing the fuel flow and compressor inlet-guide-vane position.

A turbine with a conventional diffusion combustor that uses diluent injection for NO_x control will use an underlying algorithm to control steam or water injection. This algorithm will use top level control variables (exhaust temperature, speed, etc.) to establish a steam-to-fuel or water-to-fuel ratio to control NO_x.

In a similar fashion, the same variables are used to divide the total turbine fuel flow between the primary and secondary stages of a DLN combustor. The fuel division is accomplished by commanding a calibrated splitter valve to move to a set position based on the calculated combustion reference temperature (*Figure 7*). *Figure 8* shows a schematic of the gas fuel system for a DLN-equipped turbine.

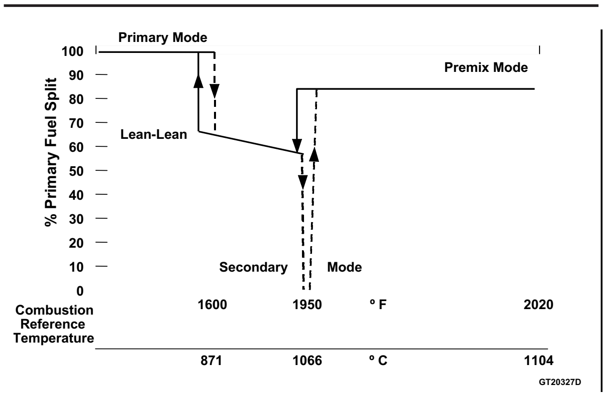


Figure 7. Typical DLN-1 fuel gas split schedule

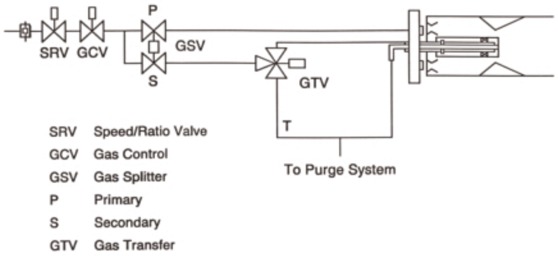


Figure 8. Dry Low NO_x gas fuel system

The only special control sequences required are for protection of the turbine during a generator breaker open trip, or for a Primary Zone Ignition or Primary Re-Ignition (PRI) (i.e., flame is established in first stage during premixed operation). When either the breaker opens at load or a PRI is sensed by ultraviolet flame detectors looking into the first stage, the splitter valve is commanded to move to a predetermined position. For the breaker open event the combustor returns to normal operation in primary mode at full speed no load (FSNL). In the case of a PRI there is no hardware damage and the combustor maintains load but operates in extended lean-lean mode with high emissions.

DLN-1 Emissions

The emissions performance of the GE DLN system can be illustrated as a function of load for a given ambient temperature and turbine configuration. *Figures 9 and 10* show the NO_x and CO emissions from typical MS7001EA and MS6001B DLN systems designed for 9 ppmvd NO_x and 25 ppm CO when operated on natural gas fuel. Note that in premixed operation, NO_x is generally highest at higher loads and CO only approaches 25 ppm at lower premixed loads. The MS9001E DLN system has very similar behavior but with somewhat higher NO_x emissions (*See Figure 1*). *Figures 11 and 12* show NO_x and CO emissions for the same systems operated on oil fuel with water injection for NO_x control, rather than premixed oil. These figures are for units equipped with inlet bleed heat and extended IGV modulation.

At loads less than 20% of baseload, NO_x and CO emissions from the DLN are similar to those from standard combustion systems. This result is expected because both systems are operating as diffusion flame combustors in this range. Between 20% and 50% load, the DLN system is operated in the lean-lean mode. On gas fuel the flow split between the primary fuel nozzles and secondary nozzle may be varied to optimize emissions, while on oil fuel the flow split is fixed.

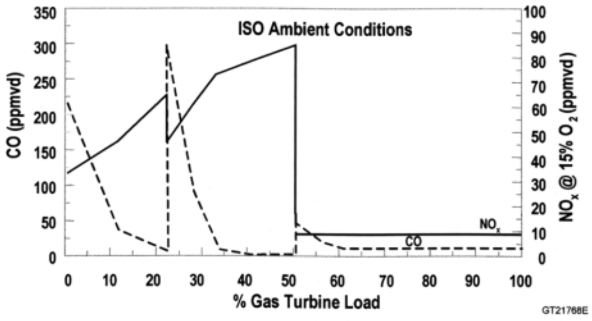


Figure 9. MS7001EA/MS9001E emissions - natural gas fuel

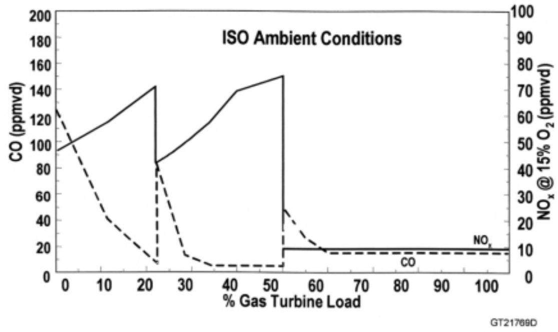


Figure 10. MS6001B emissions - natural gas

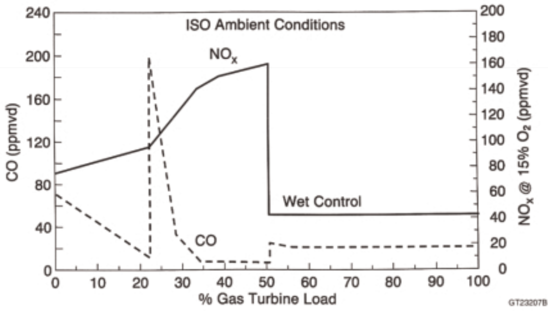


Figure 11. MS7001EA Dry Low NO_x combustion system performance on distillate oil

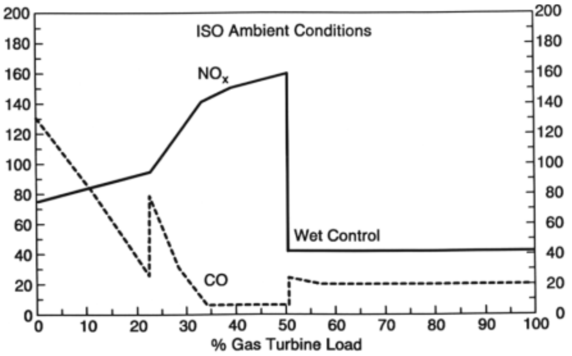


Figure 12. MS6001B emissions distillate oil fuel

From 50% to 100% load, the DLN system operates as a lean premixed combustor when operated on gas fuel, and as a diffusion flame combustor with water injection when operated on oil fuel. As shown in *Figures 9–12*, NO_x emissions are significantly reduced, while CO emissions are comparable to those from the standard system.

DLN-1 Experience

GE's first DLN-1 system was tested at Houston Lighting and Power in 1980 (*Reference 7*). A prototype DLN system using the combustor design discussed above was tested on an MS9001E at the Electricity Supply Board's (ESB) Northwall Station in Dublin, Ireland, between October

1989 and July 1990. A comprehensive engineering test of the prototype DLN combustor, controls and associated systems was conducted with NO_x levels of 32 ppmvd (at 15% O_2) obtained at baseload. The results were incorporated into the design of prototype systems for the MS7001E and MS6001B.

The 7E DLN-1 prototype was tested at Anchorage Municipal Light and Power (AMLP) in early 1991 and entered commercial service shortly afterward. Since then, development of advanced combustor configurations have been carried out at AMLP. These results have been incorporated into production hardware.

The MS6001B prototype system was first operated at Jersey Central Power & Light's Forked River Station in early 1991. A series of additional tests culminated in the demonstration of a 9 ppm combustor at Jersey Central in November 1993.

As of May 1999, 44 MS6001B machines are equipped with DLN-1 systems. In total, they have accumulated more than 1.4 million hours of operation. There are, in addition, 4 MS7001E, 8 MS7001B/E, 39 MS7001EA, 27 MS9001E, 2 MS5001P and 4 MS3002J DLN-1 machines that have collectively operated for more than 2 million hours. Excellent emission results have been obtained in all cases, with single-digit NO_x and CO achieved on many MS7001EAs. Several MS7001E/EA machines have the capability to power augment with steam injection in premixed mode.

Starting in early 1992, eight MS7001F machines equipped with GE DLN systems were placed in service at Korea Electric Power Company's Seoinchon site. These F technology machines have achieved better than 55% (gross) efficiency in combined-cycle operation, and the DLN systems are currently operating between 30 and 40 ppmvd NO_x on gas fuel (the guarantee level is 50 ppmvd). These units have operated for more than 250,000 hours. Four additional F technology DLN-1 systems were commissioned at Scottish Hydro's Keadby site and at National Power's Little Barford site. These 9F machines have operated more than 80,000 hours at less than 60 ppm NO_x.

The combustion laboratory's testing and field operation have shown that the DLN-1 system can achieve single digit NO_x and CO levels on E technology machines operating on gas fuel. Current DLN-1 development activity focuses on:

- Application of single-digit technology to the MS6001B and MS7001EA uprates.
- Application of DLN-1 technology for retrofitting existing field machines (including MS3002s and MS5000s, some of which will require upgrade before DLN retrofit)
- Completing the development of steam power augmentation as needed by the market
- Completing the development of lean premixed oil fuel DLN-1 products.
- Increasing combustion inspection intervals.
- Improving overall system reliability and operability for operation on oil fuel.

DLN-2 System

As F-technology gas turbines became available in the late 1980s, studies were conducted to establish what type of DLN combustor would be needed for these new higher firing temperature machines. Studies concluded that that air usage in the combustor (e.g., for cooling) other than for mixing with fuel would have to be strictly limited. A team of engineers from GE Power Systems, GE Corporate Research and Development and GE Aircraft Engines proposed a design that repackaged DLN-1 premixing technology but eliminated the venturi and centerbody assemblies that require cooling air.

The resulting combustor is called DLN-2, which is the standard system for the 6FA, 7FA, and 9FA machines. Fourteen combustors are installed in the 7FA, 18 in the 9FA, and six in the 6FA. Two additional variants of the DLN-2 system have been developed to meet the additional design requirements imposed by either new machine cycles or reduced emissions levels. These combustors, the DLN-2.6 and the DLN-2+, will be described briefly in later sections.

DLN-2 Combustion System

The DLN-2 combustion system shown in *Figure 13* is a single-stage dual-mode combustor that can operate on both gaseous and liquid fuel. On gas, the combustor operates in a diffusion mode at low loads (< 50% load), and a premixed mode at high loads (> 50% load). While the combustor can operate in the diffusion mode across the load range, diluent injection would be required for NO_x abatement. Oil operation on this combustor is in the diffusion mode across the entire load range, with diluent injection used for NO_x control.

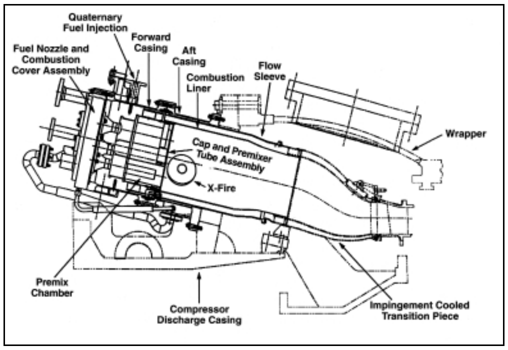


Figure 13. DLN-2 combustion system

Each DLN-2 combustor system has a single burning zone formed by the combustor liner and the face of the cap. In low emissions operation, 90% of the gas fuel is injected through radial gas injection spokes in the premixer, and combustion air is mixed with the fuel in tubes surrounding each of the five fuel nozzles. The premixer tubes are part of the cap assembly. The fuel and air are thoroughly mixed, flow out of the five tubes at high velocity and enter the burning zone where lean, low-NO_x combustion occurs. The vortex breakdown from the swirling flow exiting the premixers, along with the sudden expansion in the liner, are mechanisms for flame stabilization. The DLN-2 fuel nozzle/premixer tube arrangement is similar in design and technology to the secondary nozzle/centerbody of a DLN-1. Five nozzle/premixer tube assemblies are located on the head end of the combustor. A quaternary fuel manifold is located on the circumference of the combustion casing to bring the remaining fuel flow to casing injection pegs located radially around the casing.

Figure 14 shows a cross-section of a DLN-2 fuel nozzle. As noted, the nozzle has passages for diffusion gas, premixed gas, oil and water. When mounted on the end cover, as shown in *Figure 15*, the diffusion passages of four of the fuel nozzles are fed from a common manifold, called the primary, that is built into the end cover. The premixed passages of the same four nozzles are fed from another internal manifold called the secondary. The pre-mixed passages of the remaining nozzle are supplied by the tertiary fuel system; the diffusion passage of that nozzle is always purged with compressor discharge air and passes no fuel.

Figure 15 shows the fuel nozzles installed on the combustion chamber end cover and the connections for the primary, secondary and tertiary fuel systems. DLN-2 fuel streams are:

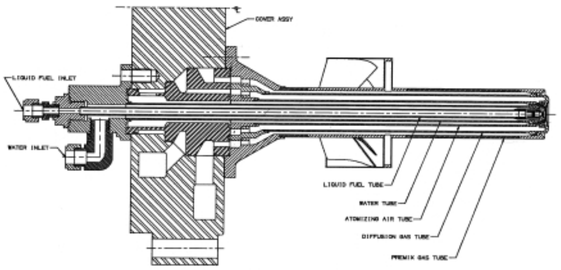


Figure 14. Cross-section of a DLN-2 fuel nozzle

- *Primary fuel* – fuel gas entering through the diffusion gas holes in the swirler assembly of each of the outboard four fuel nozzles
- *Secondary fuel* – premix fuel gas entering through the gas metering holes in the fuel gas injector spokes of each of the outboard four fuel nozzles
- *Tertiary fuel* – premix fuel gas delivered by the metering holes in the fuel gas injector spokes of the inboard fuel nozzle
- *The quaternary system* – injects a small amount of fuel into the airstream just up-stream from the fuel nozzle swirlers

The DLN-2 combustion system can operate in several different modes.

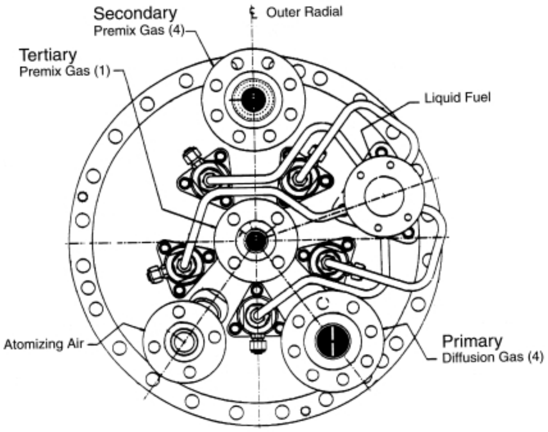


Figure 15. External view of DLN-2 fuel nozzles mounted

Primary

Fuel only to the primary side of the four fuel nozzles; diffusion flame. Primary mode is used from ignition to 81% corrected speed.

Lean-Lean

Fuel to the primary (diffusion) fuel nozzles and single tertiary (premixing) fuel nozzle. This mode is used from 81% corrected speed to a pre-selected combustion reference temperature. The percentage of primary fuel flow is modulated throughout the range of operation as a function of combustion reference temperature. If necessary, lean-lean mode can be operated throughout the entire load range of the turbine. Selecting "lean-lean base on" locks out premix operation and enables the machine to be taken to base load in lean-lean.

Premix Transfer

Transition state between lean-lean and premix modes. Throughout this mode, the primary and secondary gas control valves modulate to their final position for the next mode. The premix splitter valve is also modulated to hold a constant tertiary flow split.

Piloted Premix

Fuel is directed to the primary, secondary and tertiary fuel nozzles. This mode exists while operating with temperature control off as an intermediate mode between lean-lean and premix mode. This mode also exists as a default mode out of premix mode and, in the event that premix operating is not desired, piloted premix can be selected and operated to base-load. Primary, secondary and tertiary fuel split are constant during this mode of operation.

Premix

Fuel is directed to the secondary, tertiary and quaternary fuel passages and premixed flame exists in the combustor. The minimum load for premixed operation is set by the combustion reference temperature and IGV position. It typically ranges from 50% with inlet bleed heat on to 65% with inlet bleed heat off. Mode transition from premix to piloted premix or piloted premix to premix, can occur whenever the combustion reference temperature is greater than 2200 F/1204 C. Optimum emissions are generated in premix mode.

Tertiary Full Speed No Load (FSNL)

Initiated upon a breaker open event from any load > 12.5%. Fuel is directed to the tertiary nozzle only and the unit operates in secondary FSNL mode for a minimum of 20 seconds, then transfers to lean-lean mode.

Figure 16 illustrates the fuel flow scheduling associated with DLN-2 operation. Fuel staging depends on combustion reference temperature and IGV temperature control operation mode.

DLN-2 Controls and Accessories

The DLN-2 control system regulates the fuel distribution to the primary, secondary, tertiary and quaternary fuel system. The fuel flow distribution to each combustion fuel system is a function of combustion reference temperature and IGV temperature control mode. Diffusion, piloted premix and premix flame are established by changing the distribution of fuel flow in the combustor. The gas fuel system (*Figure 17*) consists of the gas fuel stop-ratio valve, primary gas control valve, secondary gas control valve premix splitter valve and quaternary gas control valve. The stop-ratio valve is designed to maintain a predetermined pressure at the control-valve inlet.

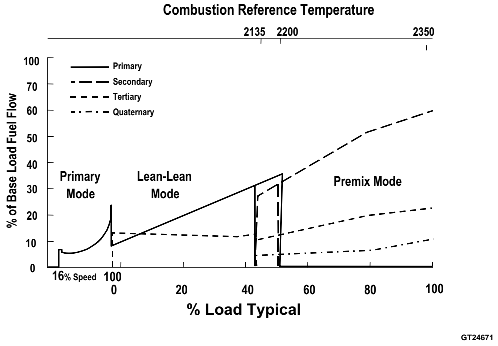
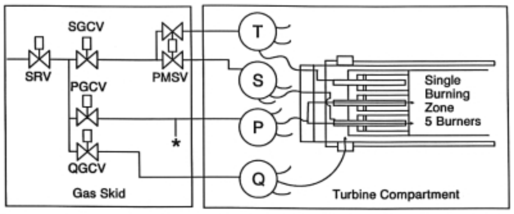


Figure 16. Typical DLN-2 gas fuel split schedule

The primary, secondary and quaternary gas control valves regulate the desired gas fuel flow delivered to the turbine in response to the fuel command from the SPEEDTRONIC™ controls.



SRV	Speed/Ratio Valve	T	Tertiary Manifold, 1 Noz. Premix Only
PGCV	Gas Control, Primary	S	Secondary Manifold, 4 Noz. Premix Inj.
SGCV	Gas Control, Secondary	P	Primary Manifold, 4 Noz. Diffusion Inj.
QGCV	Gas Control, Quaternary	Q	Quat Manifold, Casing, Premix Only
PMSV	Premix Splitter Valve	*	Purge Air (PCD Air Supply)

Figure 17. DLN-2 gas fuel system

The premix splitter valve controls the fuel flow split between the secondary and tertiary fuel system.

DLN-2 Emissions Performance

Figures 18 and 19 show the emissions performance for a DLN-2-equipped 7FA/9FA for gas fuel and for oil fuel with water injection.

DLN-2 Experience

The first DLN-2 systems were placed in service at Florida Power and Light's Martin Station with commissioning beginning in September 1993, and the first two (of four) 7FA units entered commercial service in February 1994. During commissioning, quaternary fuel was added and other combustor modifications were made to control dynamic pressure oscillations in the combustor.

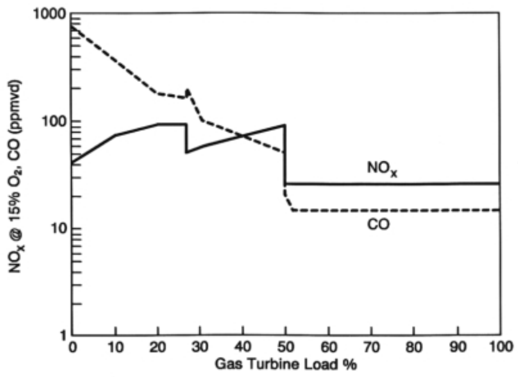


Figure 18. Gas fuel emissions in diffusion and premixed

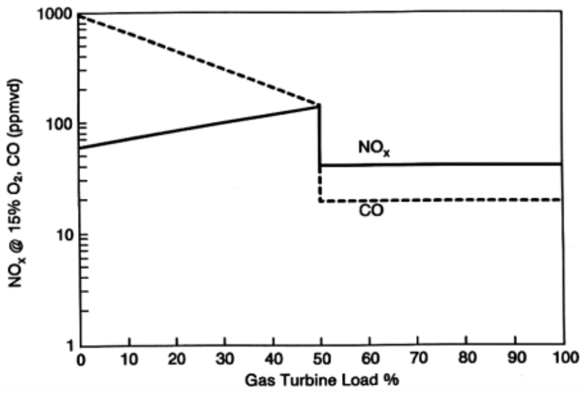


Figure 19. Distillate oil emissions with water injection above 50% load

After the 7FA DLN-2 entered commercial service the 9FA DLN-2 was introduced. Subsequent fleet experience indicated that to achieve adequate operational robustness against the entire range of site specific events, an improvement in premixer flashback resistance was needed. Under certain transient conditions flashback can occur where flame "holds" or is supported in the recirculation zone downstream of the premixed gas pegs. This region is not designed to withstand the abnormally high temperatures resulting from the presence of a flame. In the event of a flashback, the metal temperatures increase to unacceptable levels and hardware damage occurs. In some cases, these events have caused forced outages and adversely impacted availability. The solution chosen was to install full "fairings" on the downstream side of the cylindrical fuel injection pegs. Laboratory testing and subsequent fleet experience has demonstrated that full fairings are highly effective in reducing the probability of fuel nozzle flash-back. The fairings improve the peg aerodynamics in order to reduce the size of the recirculation zone downstream of the pegs. The result is to significantly reduce the probability of flame holding or attachment to the premixed pegs. *Figure 20* shows the original DLN-2 fuel nozzle while *Figure 21* illustrates the same nozzle with the addition of the fuel-peg fairings.

As of May 1999 there were 8 6FA, 26 7FA and 38 9FA units equipped with DLN-2 in commercial service. They have accumulated more than 1.1 million hours of operation.

DLN-2.6 Evolution

Regulatory pressures in the U.S. market in the early 1990s led to the need to develop a 9 ppm combustion system for the Frame 7FA. The result of this development is the DLN-2.6, which was first placed into service in March 1996 at Public Service of Colorado.

Reduction of NO_x levels from the DLN-2 at 25 ppm to 9 ppm required that approximately 6%

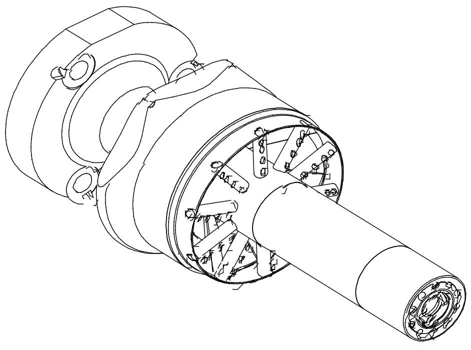


Figure 20. Un-faired DLN-2 fuel nozzle

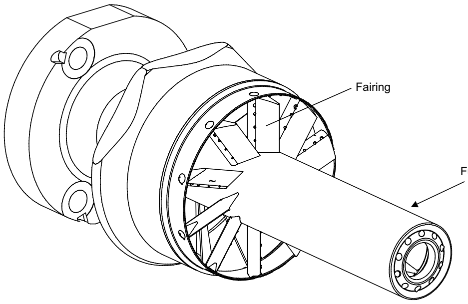


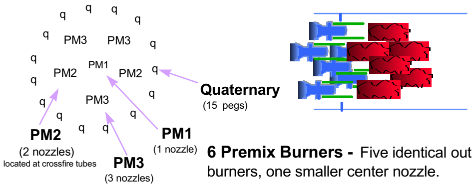
Figure 21. Fully faired (flashback resistant) fuel nozzle

additional air was needed to pass through the premixers in the combustor (see Appendix for description of the NO_x and temperature relationship). This change in air splits was accomplished through reductions in cap and liner cooling air flows, requiring increased cooling effectiveness. However, without changes in the operation of the DLN-2 system, certain penalties would have been incurred for achieving 9 ppm baseload performance. The turndown of a DLN-2 combustor tuned to 9/9 operation was estimated to be about 70% load, compared to 40% load for the 25/15 system. A new combustor configuration was conceived based on the DLN-2 burner, but overcoming these difficulties. The DLN-2 burner was carried forward as the basis of the new combustor because of its excellent flame stabilization characteristics and the large database of knowledge, which had been accumulated on the parameters affecting combustion dynamics.

The key feature of the new configuration is the addition of a sixth burner located in the center of the five existing DLN-2 burners. The presence of the center nozzle enables the DLN-2.6 to extend its 9/9 turndown well beyond the five nozzle DLN-2. By fueling the center nozzle separately from the outer nozzles, the fuel-air ratio can be modulated relative to the outer nozzles leading to approximately 200°F of turndown from baseload with 9 ppm NO_x. Turning the fuel down in the center burner does not result in any additional CO generation.

Absent any other changes in the DLN-2 other than the addition of the center nozzle, the DLN-2.6 combustor would have required five fuel manifolds, compared to four on the DLN-2. An alternative scheme was proposed to operate the machine at startup and low load, which eliminated diffusion mode. The result was a premixed-only combustor with 4 manifolds: 3 premixed manifolds staging fuel to the six burners, and a fourth premixed manifold for injecting quaternary fuel for dynamics abatement, (*See Figure 22*). The first three premixed manifolds, designated PM1, PM2, and PM3, are configured such that any number (1 to 6) of burners can be operated at any time. The PM1 manifold fuels the center nozzle, the PM2 manifold fuels the two outer nozzles located at the cross-fire tubes, and the PM3 manifold fuels the remaining three outer nozzles. The five outer nozzles are identical to those used for the DLN-2, while the center nozzle is similar but with simplified geometry to fit within the available space.

With the elimination of the diffusion mode the DLN-2.6 loads and unloads very differently than the DLN-2. The loading and unloading strategies are shown in *Figures 23 and 24*. The additional mode changes are necessary to maintain the premixed flames within their burnable zones and so prevent combustor blowout. The



6 Premix Burners - Five identical outer burners, one smaller center nozzle.

During different machine cycle conditions, PM1, PM2, PM3 are flowed in varying combinations to give low F/A.

Quaternary Pegs are located circumferentially around the combustion casing.

Figure 22. DLN-2.6 fuel nozzle arrangement

gas fuel control system is also changed relative to the DLN-2. Control is accomplished with one stop ratio valve and four individual gas control valves, (*See Figure 25*). The splitter valve utilized in both the DLN-1 and DLN-2 combustion systems is eliminated.

Emissions performance of the DLN-2.6 depends on the operational mode (*See Figures 26 and 27*). As can be seen, the emissions goal of 9 ppm NO_x and CO over a 50% load range was met. Since its introduction in 1996 the DLN-2.6 has been installed on 8 machines and accumulated approximately 17,000 hours of operation.

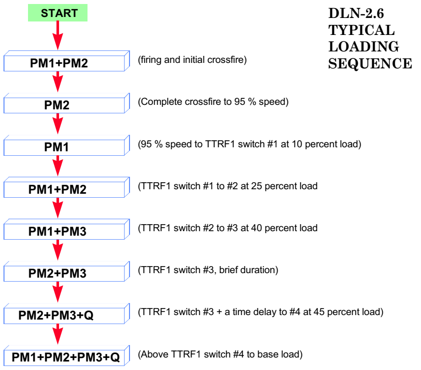


Figure 23. DLN-2.6 ignition, crossfire, acceleration, and loading strategy

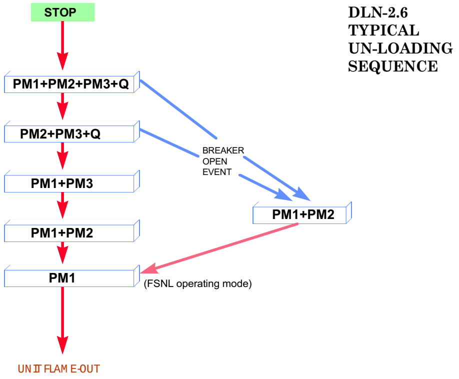


Figure 24. DLN-2.6 unloading and fired shutdown sequence

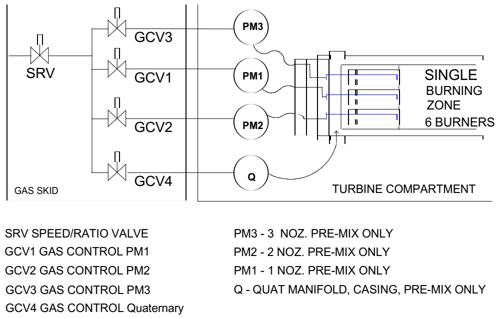


Figure 25. DLN-2.6 fuel distribution and controls system

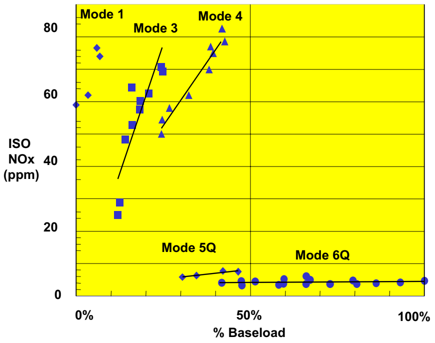


Figure 26. NO_x at 15% O_2 vs. percent load

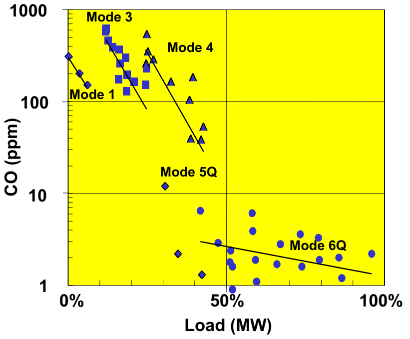


Figure 27. CO level vs. percent load

DLN-2+ Evolution

In late 1996 an uprated version of the Frame 9FA was introduced. Called the 9FA+e, the cycle for this machine increased the air and fuel flow to the combustion system by approximately 10%. In addition, the machine was intended for use with gas fuels ranging in heat content from approximately 70–100% of natural gas while still maintaining low emissions.

To meet these requirements an updated version of the DLN-2, called the DLN-2+, was developed. The DLN-2+ retains the basic architecture of the DLN-2 with adaptations for both the new requirements and to improve the operability and robustness of the existing system. In comparison to the DLN-2, the major changes are concentrated in the fuel nozzle and endcover arrangement (*See Figure 28*). Both the endcover and fuel nozzle have substantially enlarged fuel passages for the increased volumetric flow of fuel. In addition the fuel nozzle (*See Figure 29*), was redesigned for further improvements in flame holding margin, reduced pressure drop, and improved diffusion-flame stability.

The additional gains in flame-holding velocity margin result from cleaner aerodynamics in the premixers. This is achieved via a new swirler design, which incorporates fuel injection directly from the swirler surface. Each swirler vane comprises a turning vane and an upstream straight section. The straight section is hollow and houses the fuel manifolds plus the discrete injection holes. Upstream of the swirler an inlet flow conditioner improves the character of the flow entering the premixer, while downstream an integral outer shroud eliminates any potential flow disturbances after the point of fuel injection. The improvement in aerodynamics also reduces the overall system pressure drop to the level required by the new cycle.

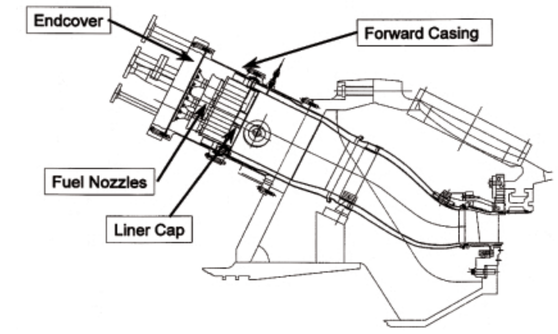


Figure 28. Parts highly modified for DLN-2+ as compared to DLN-2

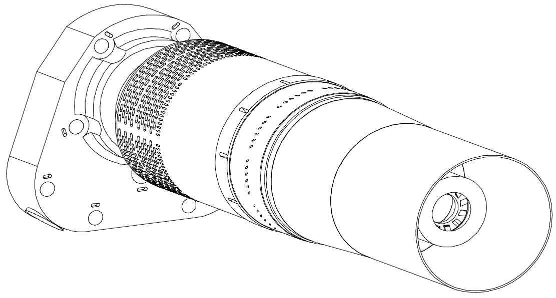


Figure 29. DLN-2+ fuel nozzle

The nozzle-tip geometry and the improvements in diffusion flame stability allow the use of a diffusion flame on every nozzle. This eliminates the lean-lean mode of the DLN-2 and results in the simplified staging methodology shown in *Figure 30*.

A further simplification illustrated in *Figure 30* is the elimination of the DLN-2 Quaternary fuel system. This is achieved through the use of bi-radial fuel staging in each swirler vane. In this design the radial fuel injection balance can be adjusted via fixed orifices on the endcover as part of the system setup procedure.

Overall, the fuel nozzle and endcover arrangement of the DLN-2+ can accept fuels with Wobbe Index ranging from 28 to 52. The fuel

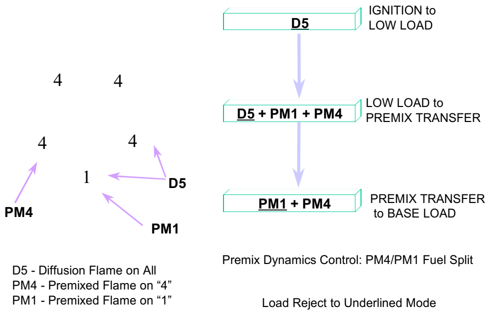


Figure 30. DLN-2+ staging methodology

delivery system is very similar to the one used for the DLN-2.6, with a stop ratio valve and independent gas control valves for each of the three gas fuel circuits.

The first installation and startup of a 9FA+e was in early 1999 at the Sutton Bridge Power Station in the UK. Emissions measured during the startup were well within design goals (*See Figures 30 and 31*). Additional machines will be commissioned throughout 1999.

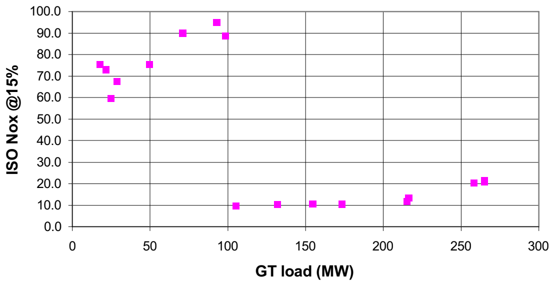


Figure 31. DLN-2+ combustion system NO_x emissions

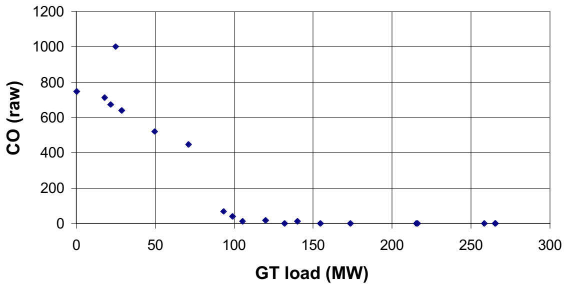


Figure 32. DLN-2+ combustion system NO_x emissions

Conclusion

GE's Dry Low NO_x Program continues to focus on the development of systems capable of the extremely low NO_x levels required to meet today's regulations and to prepare for more stringent requirements in the future. New unit production needs and the requirements of existing machines are being addressed. GE DLN systems are operating on more than 222 machines and have accumulated more than 4.8 million service hours. GE is the only manufacturer with F technology machines operating below 15 ppmvd.

Appendix

Gas Turbine Combustion Systems

A gas turbine combustor mixes large quantities of fuel and air and burns the resulting mixture. In concept the combustor is comprised of a fuel injector and a wall to contain the flame. There are three fundamental factors and practical concerns that complicate the design of the combustor: equivalence ratio, flame stability, and ability to operate from ignition through full load.

Equivalence Ratio

A flame burns best when there is just enough fuel to react with the available oxygen. With this stoichiometric mixture (equivalence ratio of 1.0) the flame temperature is the highest and the chemical reactions are the fastest, compared to cases where there is either more oxygen ("fuel lean," < 1.0) or less oxygen ("fuel rich," > 1.0) for the amount of fuel present.

In a gas turbine, the maximum temperature of the hot gases exiting the combustor is limited by the tolerance of the turbine nozzles and buckets. This temperature corresponds to an equivalence ratio of 0.4 to 0.5 (40% to 50% of the stoichiometric fuel flow). In the combustors used on modern gas turbines, this fuel-air mixture would be too lean for stable and efficient burning. Therefore, only a portion of the compressor discharge air is introduced directly into the combustor reaction zone (flame zone) to be mixed with the fuel and burned. The balance of the airflow either quenches the flame prior to the combustor discharge entering the turbine or cools the wall of the combustor.

Flame Stability

Even with only part of the air being introduced into the reaction zone, flow velocities in the zone are higher than the turbulent flame speed at which a flame propagates through the fuel-air mixture. Special mechanical or aerodynamic devices must be used to stabilize the flame by providing a low velocity region. Modern combustors employ a combination of swirlers and jets to achieve a good mix and to stabilize the flame.

Operational Stability

The combustor must be able to ignite and to support acceleration and operation of the gas turbine over the entire load range of the machine. For a single-shaft generator-drive machine, speed is constant under load and, therefore, so is the airflow for a fixed ambient temperature. There will be a five-to-one or six-to-one turndown in fuel flow over the load range. A combustor whose reaction zone equivalence ratio is optimized for full-load operation will be very lean at the lower loads. Nevertheless, the flame must be stable and the combustion process must be efficient at all loads.

GE uses multiple-combustion chamber assemblies in its heavy-duty gas turbines to achieve reli-able and efficient turbine operation. As shown in *Figure A-1*, each combustion chamber assembly comprises a cylindrical combustor, a fuel-injection system and a transition piece that guides the flow of the hot gas from the combustor to the inlet of the turbine. *Figure A-2* illustrates the multiple-combustor concept.

There are several reasons for using the multiple-chamber arrangement instead of large silo-type combustors:

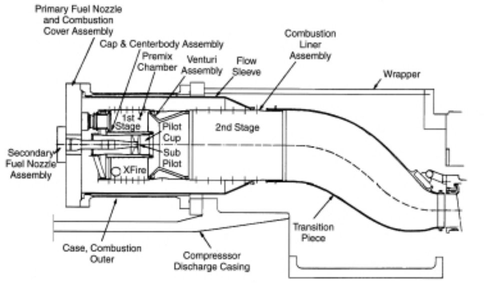


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Figure A-1. MS7001E Dry Low NO_x combustion system

- The configuration permits the entire turbine to be factory assembled, tested and shipped without interim disassembly
- The turbine inlet temperature can be better controlled, thus providing for longer turbine life with reduced turbine cooling air requirements
- Smaller parts can be handled more easily during routine maintenance
- Smaller transition pieces are less susceptible to damage from dynamic forces generated in the combustor; furthermore, the shorter combustion system length ensures that acoustic natural frequencies are higher and less likely to couple with the pressure oscillations in the flame

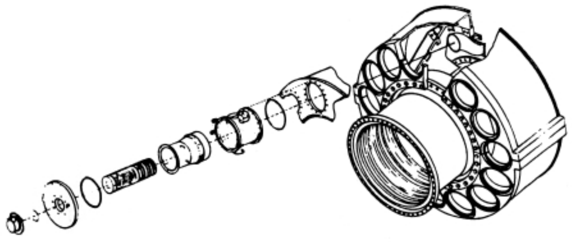

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Figure A-2. Exploded view of combustion chamber

- Smaller combustors generate less NO_x because of much better mixing and shorter residence time
- As turbine inlet temperatures have increased to improve efficiency, the size of the combustors has decreased to minimize cooling requirements, as in aircraft gas turbine combustors
- Small can-type combustors can be completely developed in the laboratory through a combination of both atmospheric and full-pressure, full-flow tests. Therefore, there is a higher degree of confidence that a combustor will perform as designed across all load ranges before it is installed and tested in a machine.

Gas Turbine Emissions

The significant products of combustion in gas turbine emissions are:

- Oxides of nitrogen (NO and NO_2, collectively called NO_x)
- Carbon monoxide (CO)
- Unburned hydrocarbons or UHCs (usually expressed as equivalent methane [CH_4] parti-cles and arise from incomplete combustion)
- Oxides of sulfur (SO_2 and SO_3) particulates.

Unburned hydrocarbons include both volatile organic compounds (VOCs), which contribute to the formation of atmospheric ozone, and compounds, such as methane, that do not.

There are two sources of NO_x emissions in the exhaust of a gas turbine. Most of the NO_x is generated by the fixation of atmospheric nitrogen in the flame, which is called thermal NO_x. Nitrogen oxides are also generated by the conversion of a fraction of any nitrogen chemically bound in the fuel (called fuel-bound nitrogen or FBN). Lower-quality distillates and low-Btu coal gases from gasifiers with hot gas cleanup carry various amounts of fuel-bound nitrogen that must be taken into account when emissions calculations are made. The methods described below to control thermal NO_x emissions are ineffective in controlling the conversion of FBN to NO_x.

Thermal NO_x is generated by a chemical reaction sequence called the Zeldovich Mechanism (*Reference 6*). This set of well-verified chemical reactions postulates that the generation of thermal NO_x is an exponential function of the temperature of the flame and a linear function of the time which the hot gases are at flame temperature. Thus, temperature and residence time determine thermal NO_x emissions levels and are the principal variables that a gas turbine designer can adjust to control emission levels.

For a given fuel, since the flame temperature is a unique function of the equivalence ratio, the rate of NO_x generation can be cast as a function of the equivalence ratio. *Figure A-3* shows that the highest rate of NO_x production occurs at an equivalence ratio of 1.0, when the temperature is equal to the stoichiometric, adiabatic flame temperature.

To the left of the maximum temperature point (*Figure A-3*), more oxygen is available (the equivalence ratio is < 1.0) and the resulting flame temperature is lower. This is a fuel-lean operation. Since the rate of NO_x formation is a function of temperature and time, it follows that some difference in NO_x emissions can be expected when different fuels are burned in a given combustion system. Since distillate oil and natural gas have approximately a 100°F/38°C flame temperature difference, a significant difference in NO_x emissions can be expected if reaction zone equivalence ratio, water injection rate are equal.

As shown in *Figure A-3*, the rate of NO_x production dramatically decreases as flame temperature decreases (i.e., the flame becomes fuel lean). This is because of the exponential effect of temperature in the Zeldovich Mechanism and is the reason why diluent injection (usually water or steam) into a gas turbine combustor flame zone reduces NO_x emissions. For the same reason, very lean dry combustors can be used to control emissions. Lean, dry control is desirable for reaching the lower NO_x levels now required in many applications, and also to avoid the turbine efficiency penalty associated with diluent injection.

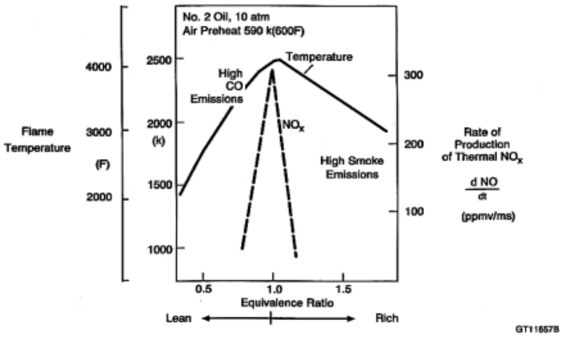

Figure A-3. NO_x production rate

There are two design challenges associated with very lean combustors. First, care must be taken to ensure that the flame is stable at the design operating point. Second, a turndown capability is necessary since a gas turbine must ignite, accelerate, and operate over the load range. Both of these challenges are driven by the need to operate the combustor at low flame temperatures to achieve very low emissions. Therefore the combustor operating point at full load is just above the flame blowout point, which is the point at which a premixed fuel and air mixture is unable to self sustain. At lower loads, as fuel flow to the combustors decreases, the flame temperature will approach the blowout point and at some point the flame will either become unstable or blow out. This behavior is in direct contrast to that of a diffusion flame combustor. In that type of combustor the fuel is injected unmixed and burns at maximum flame temperature using only a portion of the available air. This results in high NO_x emissions, but has the benefit of very good stability because the flame burns at the same temperature independent of fuel flow.

In response to these challenges, combustion system designers use staged combustors so a portion of the flame zone air can mix with the fuel at lower loads or during startup. The two types of staged combustors are fuel-staged and air-staged (*Figure A-4*). In its simplest and most common configuration, a fuel-staged combustor has two flame zones; each receives a constant fraction of the combustor airflow. Fuel flow is divided between the two zones so that at each machine operating condition, the amount of fuel fed to a stage matches the amount of air available. An air-staged combustor uses a mechanism for diverting a fraction of the airflow from the flame zone to the dilution zone at low

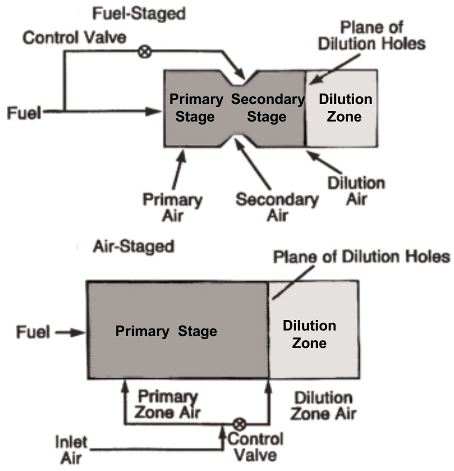

Figure A-4. Staged combustors

load to increase turndown. These methods can be combined, but both work to achieve the same objective, to maintain a stable flame temperature just above the blowout point.

Emissions Control Methods

There are three principal methods for controlling gas turbine emissions:

- Injection of a diluent such as water or steam into the burning zone of a conventional (diffusion flame) combustor
- Catalytic clean-up of NO_x and CO from the gas turbine exhaust (usually used in conjunction with the other two methods)
- Design of the combustor to limit the formation of pollutants in the burning zone by utilizing “lean-premixed” combustion technology

The last method includes both DLN combustors and catalytic combustors. GE has considerable experience with each of these three methods.

Since September 1979, when regulations required that NO_x emissions be limited to 75 ppmvd (parts per million by volume, dry), more than 300 GE heavy-duty gas turbines have accumulated more than 2.5 million operating hours using either steam or water-injection to meet required NO_x emissions levels, sometimes producing levels even lower than required. The amount of water required to accomplish this is approximately one-half of the fuel flow. However, there is a 1.8% heat rate penalty associated with using water to control NO_x emissions for oil-fired simple-cycle gas turbines. Output increases by approximately 3%, making water (or steam) injection for power augmentation economically attractive in some circumstances (such as peaking applications).

Single-nozzle combustors that use water or steam injection are limited in their ability to reduce NO_x levels below 42 ppmvd on gas fuel and 65 ppmvd on oil fuel. GE developed multi-nozzle quiet combustors (MNQC) for the MS7001EA and MS7001FA capable of achieving 25 ppmvd on gas fuel and 42 ppmvd on oil, using either water or steam injection. Since October 1987, more than 26 MNQC-equipped MS7001s that use water or steam injection have been placed in service. One unit that uses steam injection has operated nearly 50,000 hours at 25 ppmvd NO_x (at 15% O_2).

Frequent combustion inspections and decreased hardware life are undesirable side effects that can result from the use of diluent injection to reduce NO_x emissions from combustion turbines. For applications that require NOx emissions below 42 ppmvd (or 25 ppmvd in the case of the MS7001EA or MS7001FA MNQC), or to avoid the significant cycle efficiency penalties incurred when water or steam injection is used for NO_x control, one of the other two principal methods of NO_x control mentioned above must be used.

Selective catalytic reduction (SCR) converts NO and NO_2 in the gas turbine exhaust stream to molecular nitrogen and oxygen by reacting the NO_x with ammonia in the presence of a catalyst. Conventional SCR technology requires that the temperature of the exhaust stream remain in a narrow range (550°F to 750°F or 288°C to 399°C) and is restricted to applications with a heat recovery system installed in the exhaust. The SCR is installed at a location in the boiler where the exhaust gas temperature has decreased to the above temperature range. New high-temperature SCR technology is being developed that may allow SCRs to be used for applications without heat recovery boilers.

For an MS7001EA gas turbine, an SCR designed to remove 90% of the NOx from the gas turbine exhaust stream has a volume of approximately 175 cubic meters and weighs 111 tons. It is comprised of segments stacked in the exhaust duct. Each segment has a honeycomb pattern with passages that are aligned in the direction of the exhaust gas flow. A catalyst, such as vanadium pentoxide, is deposited on the surface of the honeycomb.

SCR systems are sensitive to fuels containing more than 1,000 ppm of sulfur (light distillate oils may have up to 0.8% sulfur). There are two reasons for this sensitivity.

First, sulfur poisons the catalyst being used in SCRs. Second, the ammonia will react with sulfur in the presence of the catalyst to form ammonium bisulfate, which is extremely corrosive, particularly near the discharge of a heat recovery boiler. Special catalyst materials that are less sensitive to sulfur have been identified, and there are some theories as to how to inhibit the formation of ammonium bisulfate. This, however, remains an open issue with SCRs.

More than 100 GE units have accumulated more than 100,000 operating hours with SCRs installed. Twenty of the units are in Japan; others are located in California, New Jersey, New York and several other eastern U.S. states. Units operating with SCRs include MS9000s, MS7000s, MS6000s, LM2500s and LM5000s.

Lean premixed combustion is the basis for achieving low emissions from Dry Low NO_x and catalytic combustors. GE has participated in the development of catalytic combustors for many years. These systems use a catalytic reactor bed mounted within the combustor to burn a very lean fuel-air mixture. They have the potential to achieve extremely low emissions levels without resorting to exhaust gas cleanup. Technical challenges in the combustor and in the catalyst and reactor bed materials must be overcome in order to develop an operational catalytic combustor. GE has development programs in place with both ceramic and catalyst manufacturers to address these challenges.

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