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DRY LOW NO_x COMBUSTION SYSTEM FOR UTILITY GAS TURBINE

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ABSTRACT

A Dry Low NO_x combustion system has been developed for a 80 MW gas turbine operating on natural gas and on distillate oil. The system, employing two-stage combustion and multimode operation, meets the New Source Performance Standards (NSPS) for NO_x emissions across much of the load range for both fuels. Mid-load smoke, NO_x, and carbon monoxide emissions on distillate oil require further development. This paper outlines the emissions performance of the system for Dry Low NO_x applications, specifically in terms of NSPS NO_x requirements. Machine data, in addition to test stand data, support the conclusions.

INTRODUCTION

The U.S. Environmental Protection Agency's implementation of the New Source Performance Standards (NSPS) has led to the development of emissions control techniques for utility gas turbines. In the case of the General Electric MS7001E power generation gas turbine, these regulations translate into (with a heat rate correction) maximum allowable oxides of nitrogen (NO_x) of approximately ninety-four parts per million by volume measured dry (ppmvd) at fifteen percent oxygen. A MS7001E Dry Low NO_x combustion system that complies with the NSPS NO_x regulation over much of the load range is described here.

Oxides of nitrogen emissions from gas turbine combustion are the result of the thermal dissociation of diatomic nitrogen (N_2) and the ensuing recombination with oxygen (O), and also the result of fuel bound nitrogen and ammonia reactions. The levels for these latter sources are negligible for the present application.

Zeldovich (Ref. 1) postulated that the rate limiting step in the post flame formation of NO is

$$O + N_2 \rightarrow NO + N$$

with the resulting formation rate being given by

$$dX_{NO}/dt = 1.65 \times 10^{17} \, (X_{O_2}{}^{1/2} \, X_{N_2} P^{1/2}/RT) \exp([-135.5 \; kcal/mole]/RT).$$

Where

X_{NO} : Mole fraction of NO

X_{O_2} : Mole fraction of O_2

X_{N_2} : Mole fraction of N_2

dX_{NO}/dt : Time rate of change of the mole fraction of NO

P : Absolute pressure in atmospheres

R : Universal gas constant

T : Absolute temperature in degrees Kelvin

While only limited success has been obtained while using the above theory to correlate NO_x emissions, the exponential NO_x dependence on the peak flame temperature is generally accepted (for example, References 2, 3, and 4). Therefore, any method that reduces the peak temperature of a combustion system usually reduces the NO_x emissions. Also, differences in the peak flame temperatures account for the tendency of some fuels to produce less NO_x than other fuels. For example, natural gas has lower peak flame temperatures than distillate oil, and, correspondingly, tends to produce less NO_x.

The gas turbine combustor generally has a physically constricted recirculating airflow pattern into which fuel is introduced, typically resulting in an efficient, stable diffusion flame. Unfortunately, since diffusion flame combustion occurs at near maximum temperatures, NO_x emissions tend to be near maximum. The conventional (and effective) method for reducing diffusion flame NO_x is to lower the flame temperature by either spraying water or injecting steam into the combustor's primary zone. There are two major drawbacks to this approach: (1) to prevent deposition on downstream hot gas path parts, a source of fairly pure water is required and (2) water injection and steam injection decreases the cycle thermal efficiency.

To avoid these drawbacks, dry (without water/steam injection) NO_x reduction has been investigated. The Dry Low NO_x approaches that have shown some merit over the past decade can be classified into 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.

The General Electric Dry Low NO_x system uses a combination of the latter three approaches. As the name implies, a lean diffusion flame retains the diffusion flame structure but, due to greater flame zone aeration than most diffusion flames, a substantial fraction of the fuel burns in lean conditions. Staged combustion may either decrease flame temperatures (and therefore NO_x) by separating combustor flame zones so that the products of one flame zone vitate downstream flame zones or reduce flame resistance time (and therefore NO_x) by using smaller individual primary combustion zones. Lean premixed combustion occurs when the fuel and the air are combined into a lean mixture before combustion and then introduced to an ignition source.

HARDWARE

The General Electric Dry Low NO_x combustion system is designed to operate in the 80 megawatt MS7001E gas turbine. The MS7001E is an axial flow, constant speed gas turbine. Each machine has ten sets of combustion hardware with an individual set comprised of a casting, an endcover, a set of fuel nozzles, a flowsleeve, a combustion liner, and a transition piece. The casing and the endcover are the pressure vessel around the combustion liner; in addition, the endcover is the mount for the fuel nozzles. The conventional MS7001E combustion system has one fuel nozzle per combustor while more advanced systems (such as Dry Low NO_x) may have multiple fuel nozzles per combustor. The flowsleeve is an axisymmetric cylinder/cone that surrounds much of the combustion liner to aid in distributing compressor airflow (to reduce liner-to-liner variations) and in increasing liner backside air velocities (to reduce liner metal temperatures). The combustion liner encloses the combustion process. Finally the transition piece is the duct between the liner and the turbine first stage nozzle.

The control system, the endcover, the flowsleeve, and the combustor of the Dry Low NO_x system are different than the standard MS7001E system. As mentioned before, this is a *staged*, multimode combustion system, considerably different than a conventional single mode, single fuel control combustion system. Therefore, the control scheme must be altered to dictate a suitable pattern of fuel flowrate with load, and fuel splitting between stages with mode. The endcover and the flowsleeve required redesign to accommodate a combustor that is physically dissimilar to the conventional system. This combustor will be discussed in detail below.

Figure 1 is a picture and Figure 2 is a schematic of the combustor. The liner shell, the venturi, the cap, the centerbody, and the fuel nozzles are the components of the combustor. The liner shell is a film cooled cylinder. The venturi is a film cooled section that fits inside of the liner shell. The cap fits into the upstream end of the liner shell and contains six impingement cooled fuel cups equally spaced around an annulus. The centerbody is a film cooled cylinder that is attached to the cap; the centerbody's downstream end contains a fuel cup. The six identical axial swirl fuel nozzles that fit into the cap and the single larger axial swirl fuel nozzle that fits into the centerbody fuel cup have inner passages that contain the air-atomized oil fuel system. The outer passages are for the injection of gaseous fuel (see Figure 3).

OPERATIONAL MODES

In terms of internal flow, the Dry Low NO_x combustor can be divided into three zones: the first stage, the second stage, and the dilution zone. The first stage extends from the cap fuel cups to the end of the centerbody, the second stage includes the volume from the centerbody fuel cup to the plane of the dilution holes, and the dilution zone is immediately downstream of the dilution holes.

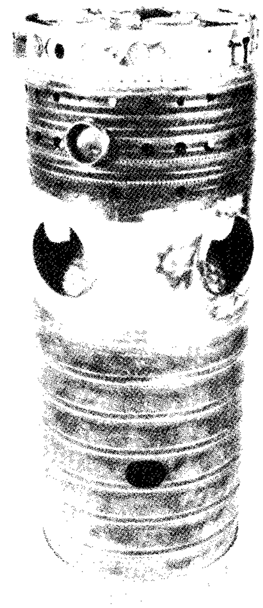

Figure 1. GE MS7001 multinozzle Dry Low NO_x combustion liner.

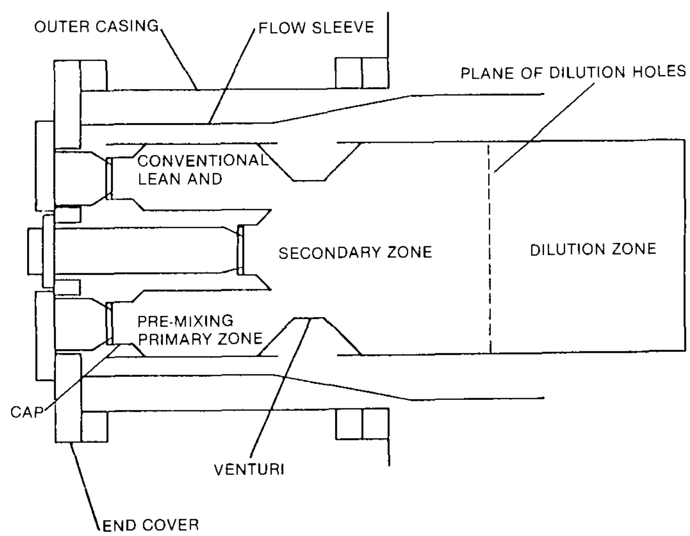

Figure 2. Two-stage premixing combustion system.

The operational modes (each with its own distinctive emissions characteristics) are shown below.

Operational Mode	Fuel Distribution	Flame Distribution
primary	first stage	first stage
secondary	second stage	second stage
lean/lean	first and second stage	first and second stage
premixed	first and second stage	second stage

In the primary mode, confined diffusion flames anchor in the first stage cups' recirculation zones. These flames are quite stable and yield emissions typical of conventional combustors.

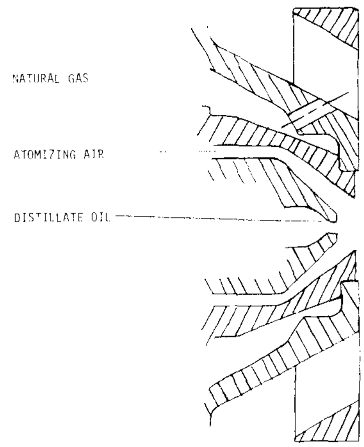

Figure 3. Dual-Fuel Nozzle.

In the secondary mode, a largely unconfined, lean diffusion flame stabilizes in the centerbody recirculation zone. Since this flame is quite aerated by the surrounding throughflow, secondary mode NO_x emissions are lower and CO and UHC emissions are higher than the analogous primary mode levels.

In the lean/lean mode, NO_x 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. CO and UHC emissions are reduced from secondary mode levels by diverting fuel to the stable first stage flames and by providing increased second stage air temperatures to aid pilot flame combustion.

The premixed mode offers the toughest CO and UHC problems and the greatest low NO_x 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. The quality of premixed combustion, and therefore the CO and UHC levels, is primarily dependent on the mixture's stoichiometry and the second stage bulk temperature. Since the NO_x formation from the premixed flow is relatively low, the NO_x emissions level strongly depends on the pilot flame's fuel-to-air ratio and only weakly depends on the premixed flow's stoichiometry.

EMISSIONS PERFORMANCE

Primary Mode

Primary mode (100-0, first stage-second stage percent fuel split) NO_x, CO, and UHC emissions for natural gas and for distillate oil are comparable to the analogous emissions from the conventional MS7001E combustion system. For example, primary mode operation demonstrates emissions characteristics of increasing NO_x and decreasing CO and UHC with increasing firing temperature and the absolute emissions levels that are typical of conventional diffusion flame combustors. In addition, no visible smoke plumes are produced.

Secondary Mode

Secondary mode (0-100 percent fuel split) emissions differ from the analogous primary mode emissions in the following way:

1) During natural gas operation and during distillate oil operation, secondary mode NO_x is lower than primary mode NO_x.
2) During natural gas operation, secondary mode CO and UHC are higher than for the primary mode. In fact, secondary mode CO from natural gas displays (see Figure 4) an unusual mid-load "hump."
3) During distillate oil operation, the secondary mode yields considerable smoke.

Secondary mode NO_x is lower than primary mode NO_x possibly because of increased flame aeration. Likewise, the higher natural gas secondary mode CO may be due to increased flame aeration although distillate oil operation does not demonstrate the pronounced effect that natural gas operation does. Finally, the relatively high secondary mode smoke production may be due to low airflow in the second stage cup.

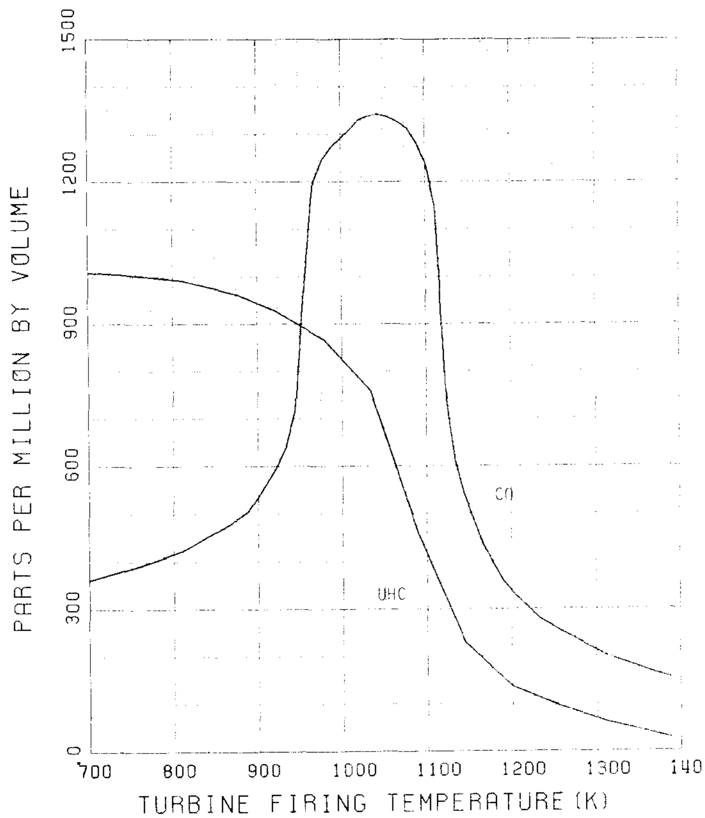

Figure 4. Secondary mode CO and UHC — natural gas.

Lean/Lean Mode

Lean/lean operation is a tradeoff between NO_x emissions and CO and UHC emissions. At a given combustor fuel-to-air ratio, NO_x emissions are highest for one hundred percent primary fuel flow and lowest for one hundred percent secondary fuel flow and vary roughly linearly for fuel splits. Conversely, for CO and UHC, emissions are lowest for one hundred percent primary fuel flow and highest for one hundred percent secondary fuel flow, and nonlinear (due to primary zone heat addition to the secondary flame) for fuel splits. Fortunately, the nonlinearity of emissions is favorable in the sense that relatively low percents of first stage fuel flow, which keeps NO_x at near-minimum levels, are disproportionally effective (with fuel split) at reducing CO and UHC from secondary mode levels. Referring to Table 1, notice that base load lean/lean operation natural gas meets NSPS while distillate oil operation does not.

Premixed Mode

Since lean/lean natural gas operation satisfies NSPS, only distillate oil results will be discussed for the premixed mode. Equivalent machine exhaust NO_x emissions and CO emissions are

Table 1

RANGE OF BASE LOAD LEAN-LEAN NO_x

Fuel Type	Fuel Split	NO_x* at ISO-Hum 15% O_2, PPMVD
Distillate	100-0	194
Distillate	0-100	158
Natural Gas	100-0	114
Natural Gas	0-100	76

*Note: These values represent an expected mean of base load conditions and machine-to-machine variations. Also, moderate-to-high CO and UHC levels may be obtained during 0-100 fuel split operation.

shown in Figure 5 and in Figure 6, respectively. Notice that the emissions are plotted versus percent premixed fuel for a number of firing temperatures.

Figure 5 demonstrates the potential of premixed operation to reduce distillate oil NO_x emissions below NSPS. Figure 6 shows that premixed operation often results in high CO emissions. But, base load operation (T_{fire} = 1340 → 1390°K) results in NO_x emissions less than NSPS and in moderate CO emissions. Also, at the higher firing temperatures, notice that increasing the premixed ratio results in simultaneous reductions in NO_x (due to decreased diffusion flame burning) and in CO (due to the increased flammability of the premixed flow).

MACHINE OPERATION

The previous section showed the potential of the Dry Low NO_x system to operate at NO_x levels below the NSPS standard. Since

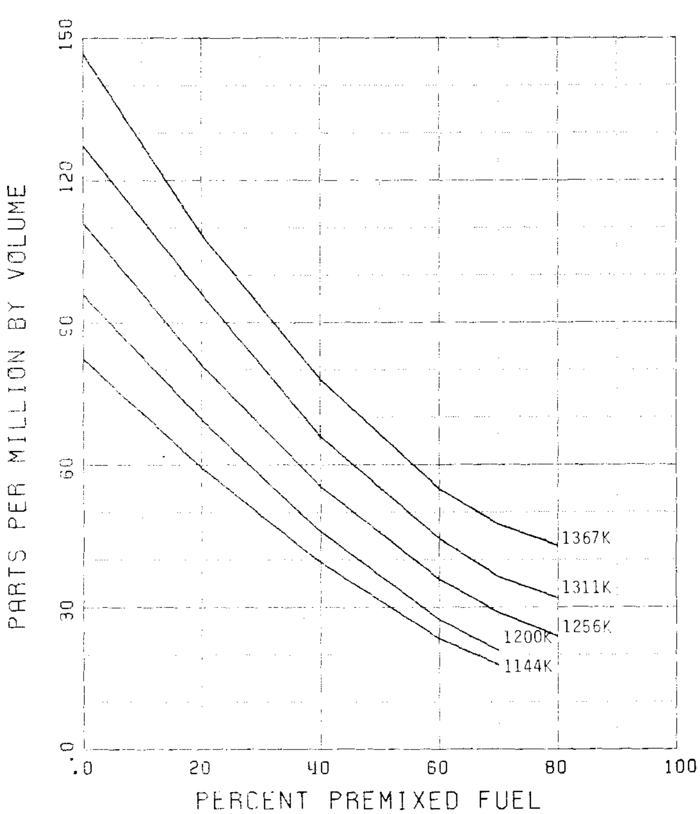

Figure 5. Premixed mode NO_x – distillate oil.

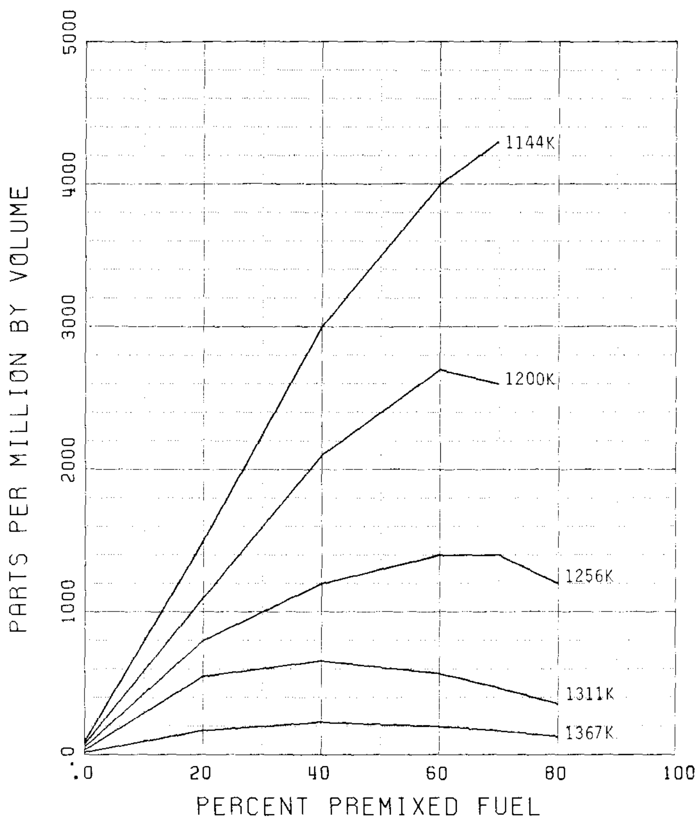

Figure 6. Premixed mode CO – distillate oil.

CO, UHC, and smoke emissions are also concerns, system operation is optimized to minimize the above emissions while attempting to maintain an acceptable NO_x level. For natural gas, this means operating in the primary and the lean/lean modes; for distillate oil, this means operating in the primary, the secondary, the lean/lean, and the premixed modes.

Figure 7 is a plot of fuel flow split versus firing temperature for a possible natural gas machine operation scheme. Figure 8 shows the corresponding NO_x emissions (as machine exhaust measured values and as oxygen adjusted values) and Figure 9 shows the resulting CO and UHC emissions (as machine exhaust values).

Figures 10, 11, and 12 for distillate oil are analogous to Figures 7, 8, and 9 for natural gas. Notice that Figure 10 shows the four modes of operation. Figure 13 is a plot of exhaust smoke versus firing temperature.

CONCLUSIONS

Compared to conventional gas turbine combustion systems, the General Electric Dry Low NO_x system is more mechanically, aerodynamically, and operationally involved. On the other hand, the Dry Low NO_x system is capable of maintaining relatively low NO_x levels across the operating range. On natural gas, NSPS NO_x levels are achieved while maintaining relatively low CO and UHC emissions. On distillate oil, the NSPS levels are achieved at all conditions, except in the mid-load mode transfer range, with a penalty of high mid-load CO and smoke emissions. At firing temperatures typical of base operation, low NO_x and smoke emissions are obtained with substantially reduced (from mid-load) C0 emissions.

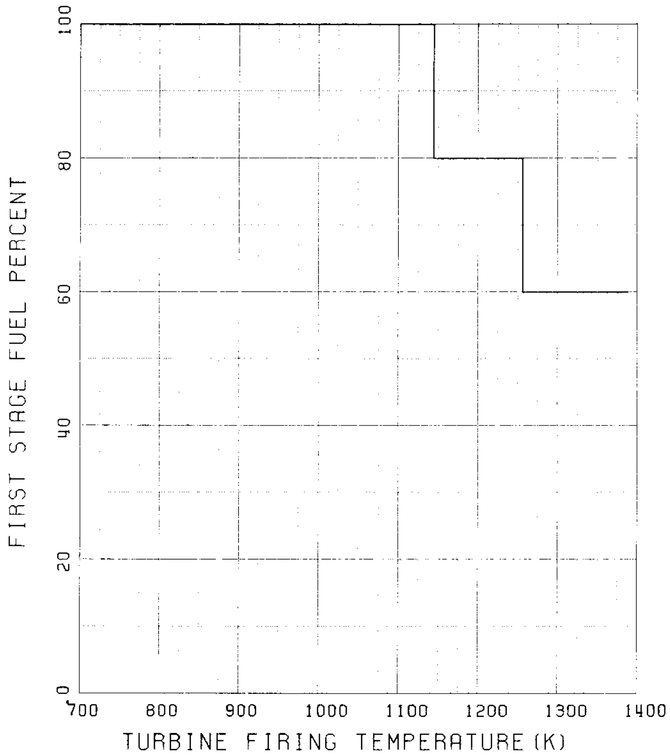

Figure 7. Operational fuel split of natural gas.

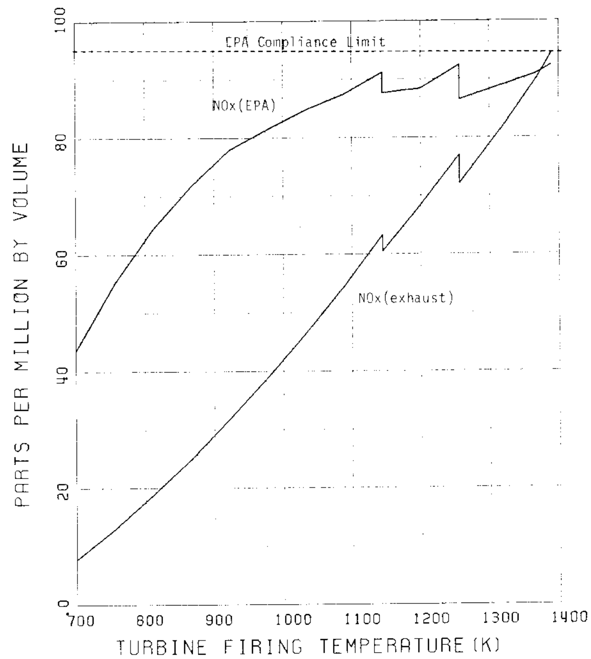

Figure 8. NO_x (exhaust and EPA) — natural gas.

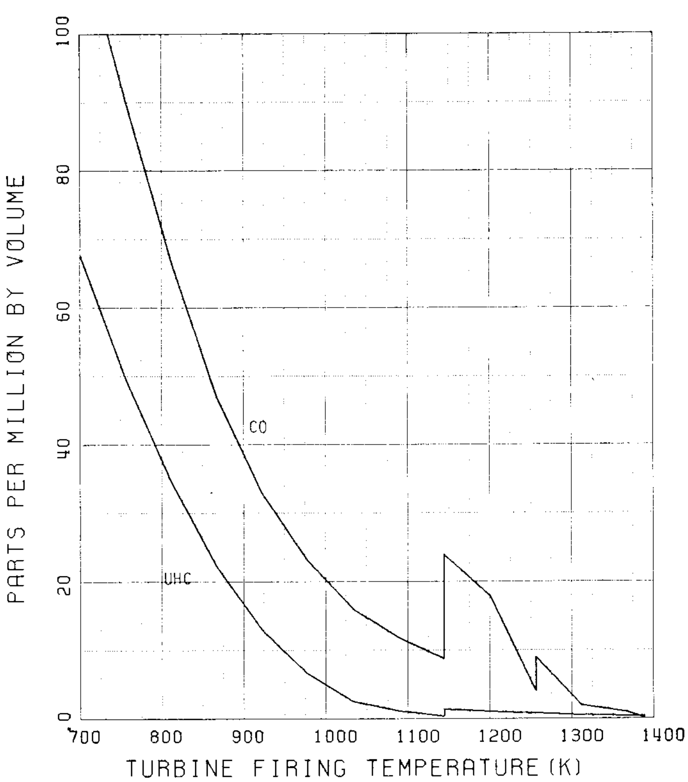

Figure 9. CO and UHC — natural gas.

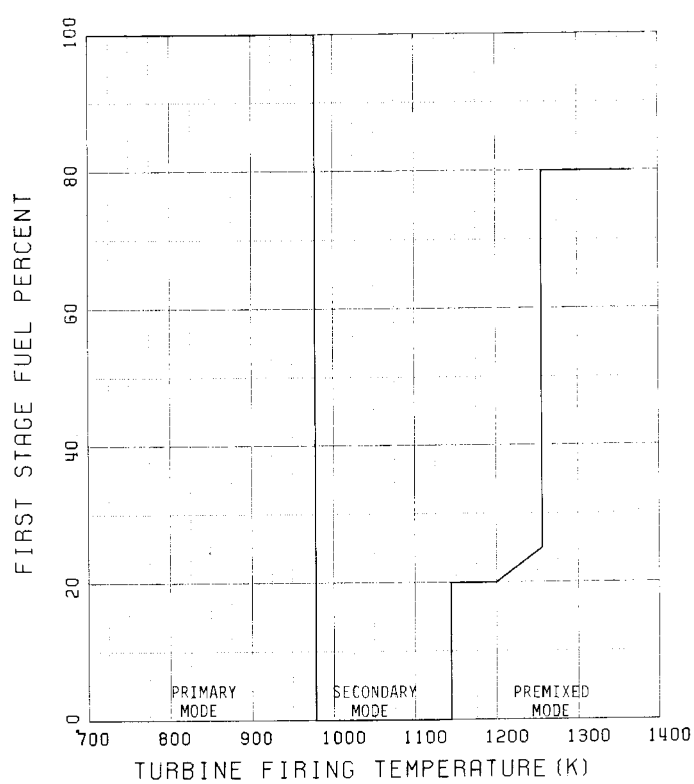

Figure 10. Operating fuel split of distillate oil.

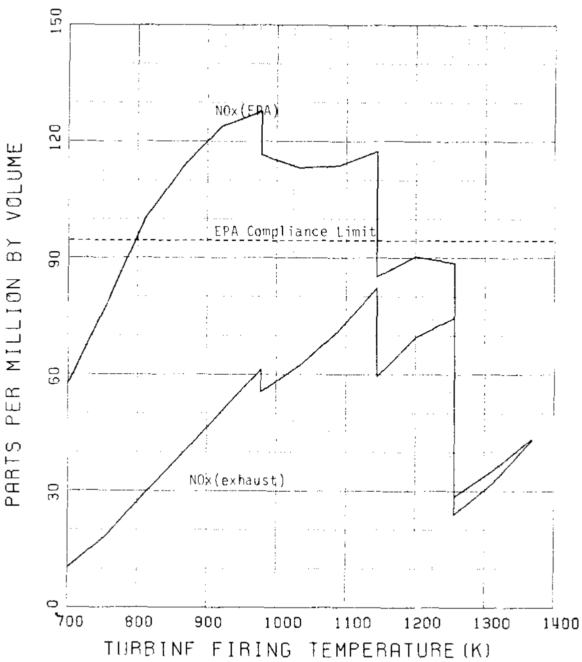

Figure 11. NO_x (exhaust and EPA) — distillate oil.

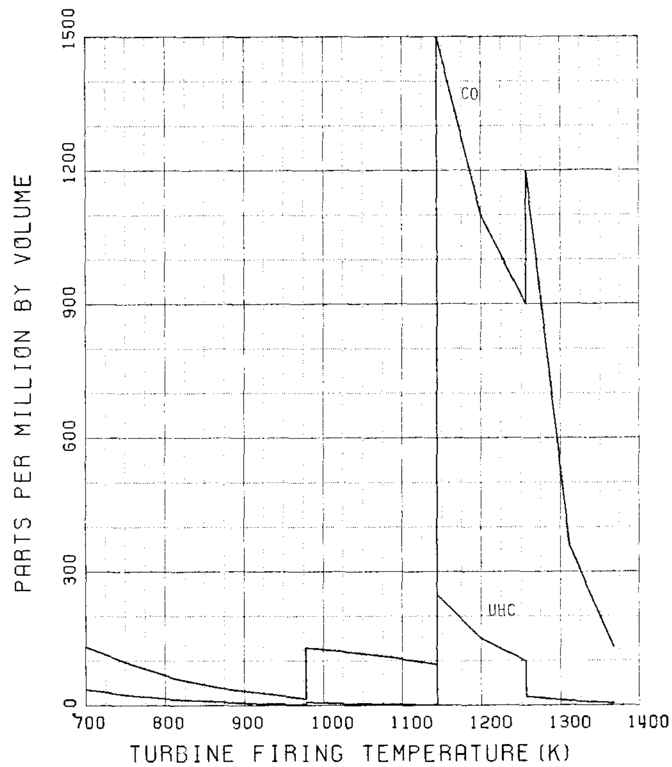

Figure 12. CO and UHC — distillate oil.

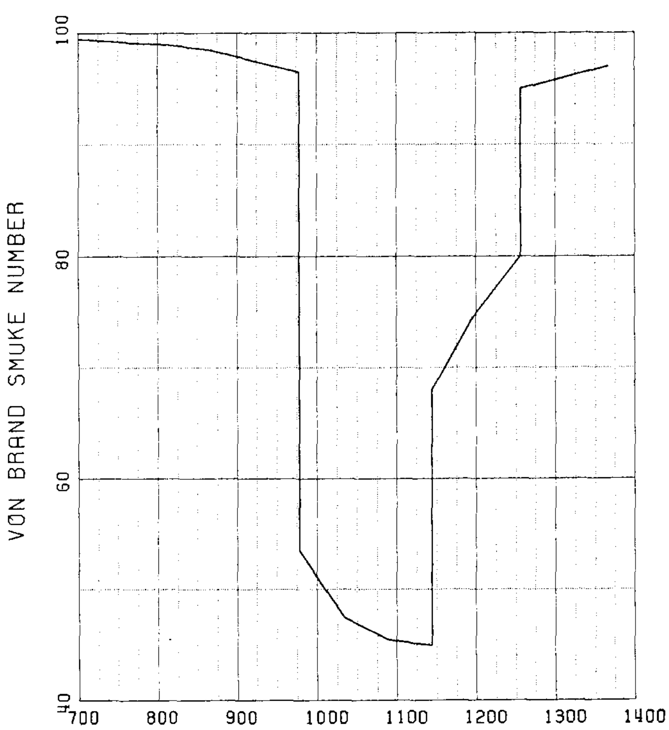

Figure 13. Smoke emissions — distillate oil.

In summary, General Electric's Dry Low NO_x combustion has been shown field operative in a MS7000 series machine. While the NSPS NO_x code is generally met, some mid-load and transfer condition emissions problems persist. Development work is continuing in selected areas.

REFERENCES

1. Zeldovich, J., "The Oxidation of Nitrogen in Combustion and Explosions," *Acta Physicochimica U.R.S.S.*, Vol. 21, No. 4, 1946, pp 577-628.
2. Lipfert, F.W., *Correlation of Gas Turbine Emissions Data,* ASME Paper 72-GT-60, 1972.
3. Lewis, G.D., *Prediction of NO_x Emissions*, ASME Paper 81-GT-119, 1982.
4. Fenimore, C.P., "Formation of Nitric Oxide in Premixed Hydrocarbon Flames," *13th Symposium (International) on Combustion,* Combustion Institute, Pittsburgh, PA., 1971, pp 373-380.