

# Evaluation of Tire-Derived Fuel for Use in Nitrogen Oxide Reduction by Reburning

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## ABSTRACT

Tire-derived fuel (TDF) was tested in a small-scale (44 kW or 150,000 Btu/hr) combustor to determine its feasibility as a fuel for use in reburning for control of nitrogen oxide (NO). TDF was gravity-fed into upward flowing combustion gases from a primary natural gas flame doped with ammonia to simulate a high NO combustion process. Emissions of NO, oxygen, carbon dioxide, carbon monoxide, and particulate matter were measured. The tests varied the nominal primary NO level from 600 to 1,200 ppm and the primary stoichiometry from 1.1 to 1.2, and used both natural gas and TDF as reburn fuels. The reburn injection rate was varied to achieve 8–20% of the total heat input from the reburn fuel. NO emissions reductions ranged between 20 and 63% when using TDF, depending upon the rate of TDF injection, primary NO, and primary stoichiometry. NO emission reductions when using natural gas as the reburn fuel were consistently higher than those when using TDF. While additional work remains to optimize the process and evaluate costs, TDF has been shown to have the potential to be a technically viable reburning fuel.

## IMPLICATIONS

In many urban areas, increasingly stringent nitrogen oxides (NO<sub>x</sub>) controls are being required for both new and existing combustion sources. Many of these same areas are also faced with the difficult solid waste management problems associated with disposal of waste tires. Tire-derived fuel (TDF) has been successfully co-fired as a fuel in solid fuel boilers. An additional incentive to the use of TDF as a fuel can be its ability to reduce both air emissions and solid waste by applying TDF as a reburning fuel for NO<sub>x</sub> reduction. This paper has implications for policy makers evaluating solid waste disposal options, as well as for boiler and furnace operators involved in determining appropriate NO<sub>x</sub> control strategies.

## INTRODUCTION

In 1995, utility fuel combustion in the U.S. emitted 5.65 million tonnes (6.23 million tons) of nitrogen oxides (NO<sub>x</sub>) from the combustion of coal, oil, and natural gas. Of this amount, 5.04 million tonnes (5.56 million tons) were from coal-fired utility units, which represents just over 25% of the total NO<sub>x</sub> emissions in the United States.<sup>1</sup> Emission limits were established by the 1990 Clean Air Act Amendments (CAAAAs) for the purposes of reducing emissions of ozone precursors (under Title I of the CAAAs) and reducing emissions of acid precipitation precursors (under Title IV of the CAAAs).<sup>2</sup> Emissions reduction requirements may be significant in ozone nonattainment areas, in some cases over 75%.

One method of reducing nitrogen oxide (NO) emissions from utility combustion systems is the use of reburning. Reburning is a method in which a portion of the fuel to the burners is diverted to a part of the furnace downstream of the main burners, thereby creating a "reburn zone" in which either the oxygen (O<sub>2</sub>) level is reduced or a fuel-rich condition is achieved. Under these conditions, NO and the available hydrocarbons are converted to nitrogen and carbon monoxide (CO) or hydrocarbons.<sup>3,4</sup> Additional O<sub>2</sub> (in the form of air) is then usually injected into the region following the reburn zone to ensure completion of the combustion process. Reburning can achieve up to a 65% reduction in NO emissions, and the use of additional reagents in either the reburning or burnout zone can provide additional reductions.<sup>5</sup>

Any hydrocarbon-based fuel can be used as the reburning fuel, regardless of the fuel used in the main burners. A fuel that does not contain nitrogen (N) and reacts rapidly in the flue gas stream is a good reburn fuel. Natural gas is an ideal fuel for reburning, but fuel oil or solid fuels can also be used as reburning fuels if the fuel volatility and reactivity are adequate and if

sufficient room is available in the furnace to allow complete burnout of the reburn fuel in the shorter residence times associated with reburning.<sup>6</sup> One solid fuel that meets the volatility and reactivity requirements, is low in both sulfur (S) and N content (on a per-unit-energy basis), and is widely available is tire-derived fuel (TDF). Beyond its good combustion characteristics, TDF is an attractive reburn fuel because of the large mass of waste tires requiring disposal. Approximately 240 million tires are discarded annually in the United States, and with less than 25% of them being reused or reprocessed, a significant potential exists for using waste tires as a large source of reburn fuel while simultaneously reducing the number of tires to be disposed of in landfills.<sup>7</sup>

TDF is composed of tires that have been shredded, chopped, or otherwise prepared to allow existing fuel feed and combustion systems to utilize their high heat content. TDF typically has roughly 39,500 kJ/kg (17,000 Btu/lb) heat content, relatively low N and S, high volatile carbon, and relatively low ash content compared to a typical U.S. bituminous coal.<sup>8</sup> These properties make TDF a potentially good fuel for reburning NO control; however, to our knowledge, no information is currently available on the effectiveness of TDF in such applications. In order to more fully explore the abilities of TDF to perform as a reburn fuel, the Air Pollution Prevention and Control

Division of the U.S. Environmental Protection Agency's (EPA) National Risk Management Research Laboratory conducted a series of tests using a vertically fired combustor (VFC) at EPA's Environmental Research Center in Research Triangle Park, NC.

## FACILITY AND EQUIPMENT

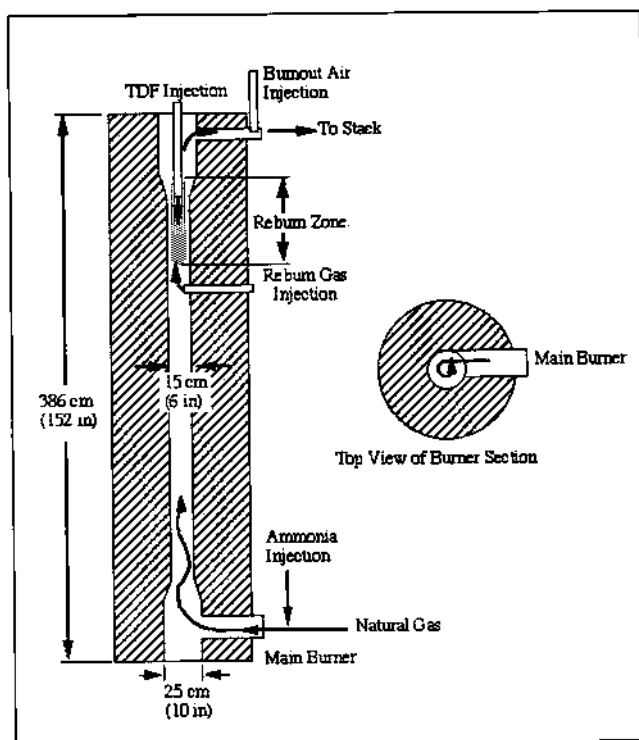
The tests were conducted on the VFC, which can be configured as either a down- or up-fired combustor, depending on the location of the main burner and the flue gas ducting. The VFC is capable of burning either natural gas or pulverized coal in its main burner (coal is used only when the VFC is in the down-fired configuration). When burning natural gas as the main fuel, the main burner can be located either at the top or the bottom of the combustor. The VFC is refractory-lined and has an inner diameter of 15.2 cm (6 in.). The VFC is rated at 44kW (150,000 Btu/hr), with a design flue gas flow of 85 m<sup>3</sup>/hr (50 cfm) at 232 °C (450 °F), and is equipped with a number of access ports for insertion of measurement probes or reagent injectors. The gases from the VFC pass through a small heat exchanger to reduce the flue gas temperature, then to a pilot-scale spray dryer for control of acid gases, followed by a fabric filter for removal of particulates. Figure 1 is a schematic of the VFC as configured for this series of tests.

The main natural gas burner was located at the bottom of the VFC, oriented tangentially to the combustor centerline. This system provided a generally upward flow of combustion gases, with a slight swirling component, as shown in Figure 1. The reburn fuels were injected near the top of the combustor. Natural gas was injected from the side using a nozzle designed for reburn injection. The nozzle had four jets oriented at 90° intervals, 45° from the injector axis. TDF was injected using a calibrated screw feeder feeding tire crumbs with a nominal diameter of 0.63 cm (0.25 in.) into a cooled gravity feed tube, injecting along the combustor centerline directly downward into the upwardly flowing combustion gases. Primary NO levels were varied by mixing different amounts of ammonia into the main fuel gas prior to combustion.

Flue gas components were measured using a series of continuous emission monitors (CEMs) for O<sub>2</sub>, carbon dioxide (CO<sub>2</sub>), CO, NO, sulfur dioxide (SO<sub>2</sub>), and total hydrocarbons. The different temperatures along the length of the combustor were also measured using a number of thermocouples. Both CEM and thermocouple measurements were recorded at approximately 5-second intervals throughout the tests using a computerized data acquisition system.

## EXPERIMENTAL APPROACH

The experimental test matrix was designed to determine



**Figure 1.** Schematic of Vertically Fired Combustor. The top view of the burner section shows the tangential arrangement of the natural gas-fired burner. TDF reburn fuel was injected using a gravity feeder.

**Table 1.** Proximate and ultimate analyses of TDF.

Ultimate Analysis	Mass % (as received) <sup>1</sup>	Mass % (dry) <sup>1</sup>	Proximate Analysis	Mass % (as received)
Carbon	75.4	76.0	Volatile Matter	65.5
Hydrogen	7.2	7.2	Fixed Carbon	26.4
Nitrogen	0.3	0.3	Ash	7.2
Sulfur	1.7	1.8	Moisture	0.8
Oxygen	7.1	7.2		
Halogens (as Chlorine)	0.3	0.3	Heating Value, Btu/lb (kJ/kg)	17,831 (37,272)
Moisture	0.8			
Ash	7.1	7.2		

<sup>1</sup>Totals may not add to 100% due to round-off error.

whether TDF can be an effective reburn fuel and to determine the rates of TDF injection that would result in different NO reductions without excessive CO or particulate emissions. Natural gas reburning was used as the basis for comparison of NO reduction performance, and the tests were designed to provide direct comparison between the performance of TDF and natural gas reburning. The most important parameters measured were the NO emissions, the feed rate of reburn fuel, and O<sub>2</sub>, CO, and particulate matter (PM) levels in the stack. These parameters provided the information necessary to determine whether TDF can be effectively used as a reburn fuel. Other parameters, including combustor temperatures, CO<sub>2</sub> emissions, and stack

**Table 2.** Trace metal content of TDF.

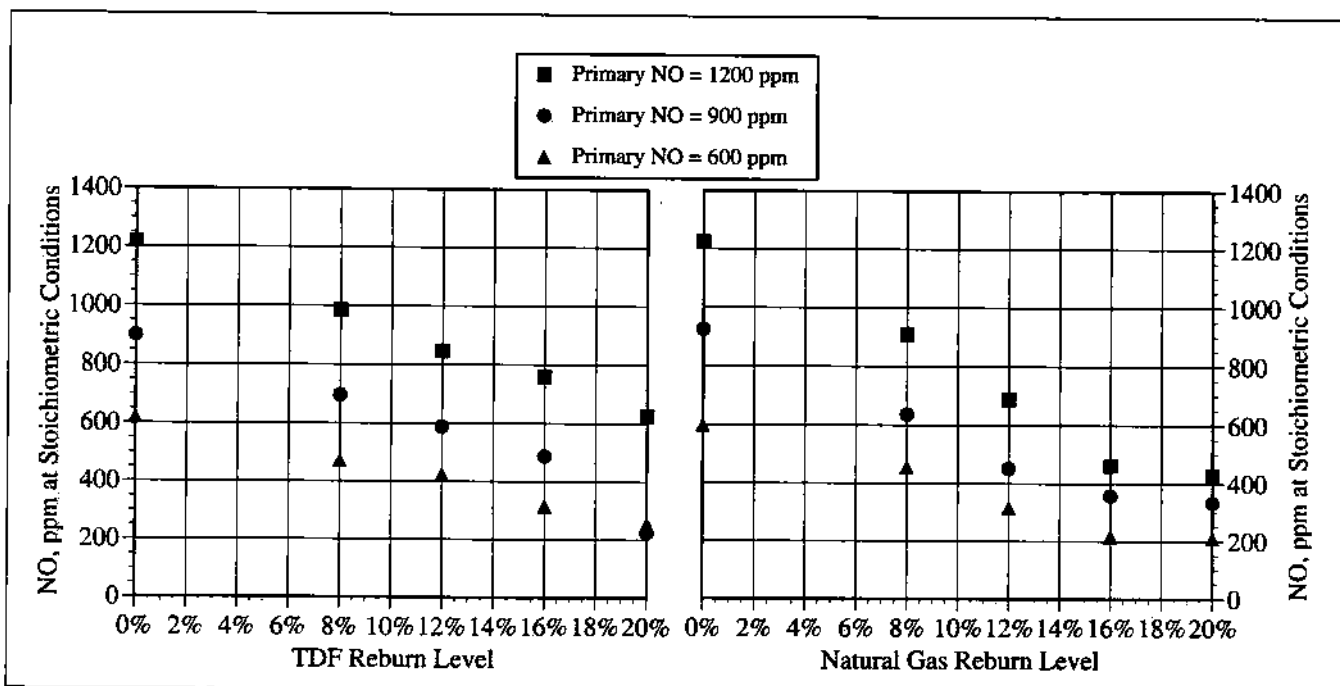
	Mass Concentration in ppm (zinc in %)
Cadmium	<5
Chromium	<5
Iron	295
Lead	51
Zinc	2.14%

flue gas temperatures, were also measured to provide additional information.

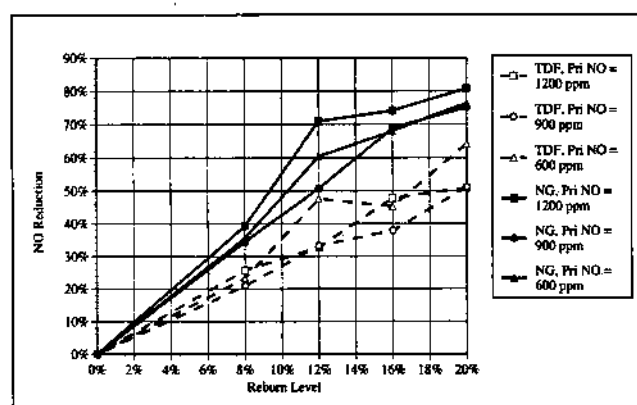
The TDF was purchased with a size range of 0.63 cm (0.25 in.) diameter or smaller and with the metal belt material removed. No other fuel preparation was done. The proximate and ultimate analyses of the TDF are given in Table 1, and trace metal content is given in Table 2.

### Operating Conditions

Temperatures in the VFC ranged from approximately 1,260 °C (2,300 °F) near the natural gas burner at the bottom of the combustor to approximately 590 °C (1,100 °F) at the combustor exit. The temperature gradient along the combustor length was roughly linear from 1,260 °C (2,300 °F) at the natural gas burner to 820 °C (1,500 °F) at a point 51 cm (20 in.) below the combustor exit. The temperature profile was essentially constant for all TDF injection



**Figure 2.** NO emissions (corrected to stoichiometric conditions) for TDF and natural gas reburning vs. percent reburn fuel injected at different primary NO levels. Tests were conducted at a primary zone stoichiometry of 1.20.



**Figure 3.** Percent NO reductions as a function of percent reburn for TDF and natural gas for different primary NO levels. Primary stoichiometry is 1.15.

rates. At the TDF injection location, the temperature was approximately 840 °C (1,550 °F). Since the TDF injection was gravity-fed, the TDF had very low initial velocity into the combustion gas stream. However, since the TDF was fed downward into the upward flowing combustion gases and with the small combustor cross section, the mixing of the reburn fuel and the combustion gases was not considered to be a problem for this unit.

The combustion gases were estimated to have an average velocity of approximately 3 m/sec (10 ft/sec), based on the temperature and load of the combustor. It is relatively straightforward to calculate the gas residence time in the combustor. However, it is much more difficult to determine the average particle residence time, due to the counterflow injection, the range of particle sizes, and the thermal degradation of the particles in the hot gases.

## RESULTS

### NO Emissions

The results of the tests were based on the CEM data collected by the data acquisition system, along with data on particulate emissions from extractive sampling. The NO emissions data collected by the CEMs were relatively steady for the baseline and natural gas reburning tests but showed significantly greater fluctuations during the TDF reburning tests. These fluctuations were due to the fact that the solid feed process for the tire crumbs was not steady, since there was variability in the size of the fuel crumbs. As the average injection rate was no more than about 225 mg/sec (1.8 lb/hr), it was impossible to maintain steady instantaneous feed rates given the presence of large (0.25 in.) tire crumbs. Although the TDF pieces are quite small, the fact that they are still rather large in comparison to the small diameter of the combustor also contributed to the fluctuations. Nevertheless, the average rate was maintained quite steadily, and the resulting average NO emissions compared well with the corresponding NO emissions measured during natural gas reburning.

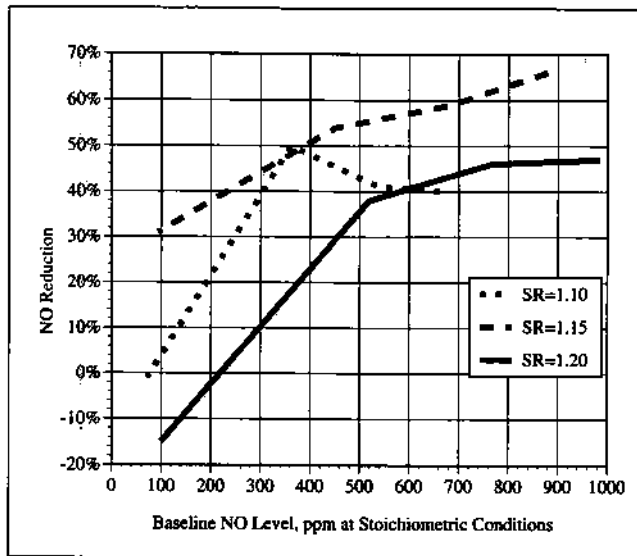
**Table 3.** Relation between primary zone stoichiometric ratio, reburn injection rate, and reburn zone stoichiometric ratio.

Primary Zone SR	Percent Reburn Fuel	Reburn Zone SR (TDF)	Reburn Zone SR (NG)
1.20	8	1.11	1.11
1.20	12	1.06	1.06
1.20	16	1.01	1.01
1.20	20	0.96	0.96
1.15	8	1.06	1.06
1.15	12	1.02	1.01
1.15	16	0.97	0.97
1.15	20	0.93	0.92
1.10	8	1.02	1.01
1.10	12	0.98	0.97
1.10	16	0.94	0.92
1.10	20	0.90	0.88

Figure 2 shows NO emissions for TDF and natural gas reburning for three primary NO values (600, 900, and 1,200 ppm) and at five different reburn rates (0, 8, 12, 16, and 20%). The reburn rate is the percentage of total energy input to the combustor from the reburn fuel. The data in Figure 2 are for a primary zone stoichiometry of 1.20 and are corrected to stoichiometric conditions. In each case, the minimum controlled NO emissions are approximately 200 ppm for both TDF and natural gas. The plot of NO emissions for a primary stoichiometry of 1.15 and 1.10 showed very similar results and are not shown here due to the similarity of the data in all three tests.

Figure 3 shows the percent NO reductions for both TDF and natural gas reburning, again at primary NO levels of 600, 900, and 1,200 ppm and at reburn fuel injection levels of 0, 8, 12, 16, and 20%. In this case, the primary stoichiometry is 1.15. The percent NO reduction is consistently higher for the natural gas tests than for the TDF tests, with the difference increasing at higher reburn levels. For all four reburn levels, the average NO reduction for TDF reburn varied between 28 and 38% lower than the average NO reduction for natural gas reburn for the three primary NO levels tested, for a primary stoichiometry of 1.15. For a primary stoichiometry of 1.20, the average NO reduction for TDF reburn ranged from 5 to 32% lower than the average NO reduction for natural gas reburn for the three primary NO levels tested. In both cases, the percentage reductions were roughly linear with respect to percentage reburn, as seen in Figure 3.

The primary zone stoichiometric ratio is important because, in combination with the rate of reburn fuel injection, it determines the reburn zone stoichiometry. In most cases, NO reductions increase as reburn zone stoichiometry decreases. Table 3 shows the relationship



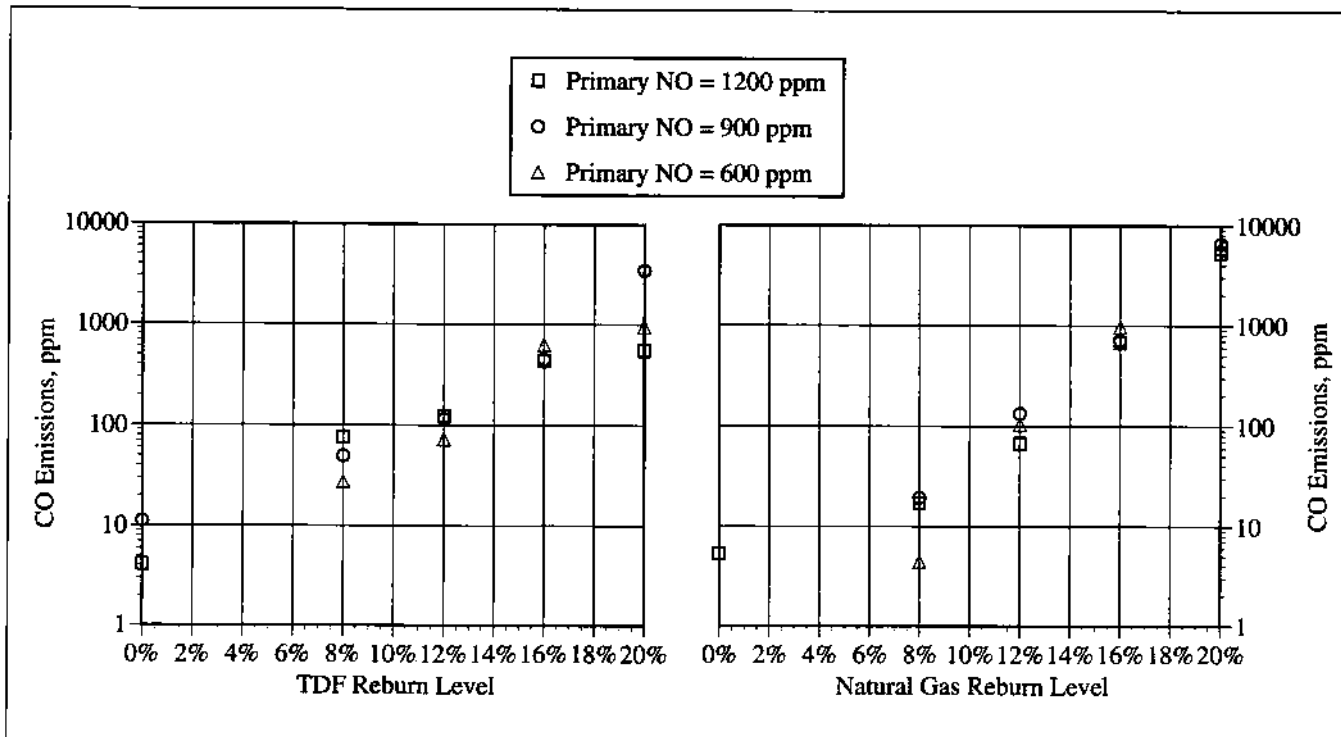
**Figure 4.** Percent NO reduction for TDF as a function of baseline NO levels for three different primary stoichiometries, at 16% reburn. NO measurements are corrected to stoichiometric conditions.

between primary zone stoichiometry and reburn zone stoichiometry for the fuels used in these tests. The effect of primary zone stoichiometry on percentage NO reduction as a function of baseline NO level is shown in Figure 4 for 16% reburn fuel injection. For this case, there is a substantial increase in NO reduction for a primary stoichiometry of 1.15 compared to a primary stoichiometry of 1.20, and this behavior was consistent for the other

reburn injection levels. There is, however, a decrease in NO reduction when the primary stoichiometry is decreased from 1.15 to 1.10.

It would be expected that the NO reduction would decrease further with this change in primary stoichiometry rather than the increase noted, but the reburning process is likely to have been affected by factors other than stoichiometry alone. A key factor is the degree to which the TDF particles devolatilize in a compact reburn zone. Because it is a solid fuel, TDF must first devolatilize to generate the hydrocarbon radicals required for the reburn chemistry to work. If the particles are too large or the temperature is too low, the devolatilization may occur throughout a large volume relative to the overall combustion process. In some cases, the devolatilization and subsequent combustion may actually be stretched into the primary combustion zone, resulting in fewer reactions in the reburn zone and more in the primary combustion zone, and hence lower NO reductions. Fluctuations in the devolatilization rate of individual TDF particles, as well as the greater ability of the natural gas to effectively mix with the primary zone combustion gases (in this small combustor), are the primary reasons for the greater variability in NO reductions for TDF reburning illustrated in Figure 3.

Of all three primary zone SRs tested (1.10, 1.15, and 1.20), the resulting reburn zone stoichiometry was less than 1.0 only for 20% reburn. Even at the higher reburn



**Figure 5.** Uncorrected CO emissions for TDF and natural gas reburning vs. percent reburn fuel injected at different primary NO levels. Data were taken at a primary zone stoichiometry of 1.20.

zone stoichiometries, substantial NO reductions were noted, showing that a fuel-rich reburn zone is not required to achieve reductions in NO emissions.

### CO Emissions

Emissions of CO were also measured during the reburn testing using CEMs. For the highest levels of reburn fuel injection, CO emissions were measured at levels of several thousand ppm (uncorrected) for both natural gas and TDF. As seen in Figure 5, CO emissions during TDF reburning were higher than those during natural gas reburning at the lowest reburn levels of 8% and roughly the same at the 12% reburn level. At the higher reburn rates, CO emissions were higher for the natural gas reburning compared to TDF reburning. Both fuels showed excessive CO emissions at the higher reburn rates, indicative of inadequate burnout time downstream of the reburn zone. The available burnout air injection locations in the vertically fired furnace did not allow adequate burnout time for either fuel.

However, this does not indicate that TDF will not adequately burn out when injected under more optimum conditions. While the TDF was injected at a location slightly farther upstream than the natural gas reburn fuel, the CO emissions were within the range of CO emissions measured for the natural gas reburn cases, indicating that (given adequate burnout time) TDF would not generate CO emissions that are significantly higher than those seen using natural gas as a reburn fuel.

### Particulate Matter and SO<sub>2</sub> Emissions

PM concentrations were measured using EPA Method 5 extractive sampling. Table 4 shows the PM emissions as a function of the percent reburn (using TDF as the reburn fuel). PM emissions are presented in three ways. First, the mass concentration is given in mg/dscm. Second, emissions are presented in the form of mass per unit energy input. Finally, emissions are presented as mass per unit energy of reburn fuel. Figure 6 presents the PM emissions in lb/10<sup>6</sup> Btu of total fuel input. Note that the values in

Table 4 and Figure 6 represent the incremental amount of PM emissions due to the TDF injection, since natural gas is used as the primary fuel.

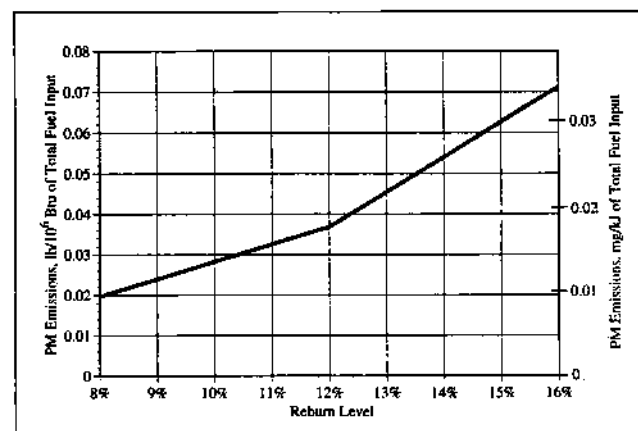
It is interesting that the PM emissions increase at a greater rate than the reburn fuel, as seen in the emissions per unit reburn fuel input. It is not clear what is causing this increase, although the two most likely reasons are that the increased reburning rate and the associated lower reburn zone stoichiometry do not allow for complete burnout of the TDF and that a greater rate of fines is fed into the combustor at the higher feed rates and subsequently carried out of the combustion zone by the flue gases before the fines can thermally decompose and burn. However, it would be expected that the carryover hypothesized in the second scenario would follow the reburn fuel feed rate in a linear manner, thus making the first possibility the most likely one.

It was expected that emissions of SO<sub>2</sub> would linearly follow the rate of TDF injection, since the only source of S was the TDF. Unfortunately, CEM malfunctions prevented reliable SO<sub>2</sub> emissions data from being collected, and this expectation could not be verified. However, based on the S concentration in the TDF, the emissions of SO<sub>2</sub> should vary linearly between 0.04 mg/kJ (0.09 lb/10<sup>6</sup> Btu) at 5% reburn and 0.17 mg/kJ (0.36 lb/10<sup>6</sup> Btu) at 20% reburn. These levels correspond to concentrations of 44 and 180 ppm, respectively, corrected to 3% O<sub>2</sub> (at a final excess air level of 20%).

The measured PM and calculated SO<sub>2</sub> emissions are uncontrolled emissions due only to the use of TDF and represent increases over uncontrolled emissions from the combustion of the natural gas primary fuel. However, for systems not using reburning or using coal as a reburn fuel, replacing coal with TDF may decrease emissions of both of these pollutants, depending primarily on the S contents of the coal and the TDF. For example, comparing the current TDF to a coal with 1.8% S and 6.5% ash, at a

**Table 4.** Measured PM emissions for different levels of TDF reburning.

Reburn Level	PM Emissions		
	mg/dscm	lb/10 <sup>6</sup> Btu (mg/kJ) of Total Fuel	lb/10 <sup>6</sup> Btu (mg/kJ) of Reburn Fuel
8%	42	0.0196 (0.0094)	0.2456 (0.1175)
12%	75	0.0368 (0.0176)	0.3070 (0.1469)
16%	145	0.0712 (0.0341)	0.4451 (0.2129)



**Figure 6.** PM emissions in lb/10<sup>6</sup> Btu (mg/kJ) of total fuel input as a function of reburn percent for TDF reburning.

reburn rate of 15%, reductions of 6.2% in uncontrolled SO<sub>2</sub> emissions and 4.0% in uncontrolled PM emissions can be realized due strictly to the lower S and ash contents (on a per unit energy basis) of the TDF compared to those of the coal.

## CONCLUSIONS

Given the limited scope of these tests, TDF appears to be a viable reburning fuel. In these tests, we have demonstrated the ability of TDF reburning to achieve NO reductions of greater than 60%. Where TDF replaces coal (specifically coal with higher S and ash contents), reductions of PM and SO<sub>2</sub> emissions may also be realized. The use of TDF as a reburning fuel can provide substantial reductions in NO emissions while also reducing the volume of scrap tires in the nation's solid waste stream.

However, a number of questions remain to be answered before TDF can be successfully applied as a reburn fuel in commercial facilities. Additional work is needed to optimize the use of TDF in reburning applications, as highlighted by the excessive CO emissions and the increase in PM emissions per unit of reburn fuel noted at high reburn injection rates. Changes in parameters, such as TDF particle size, burnout residence time, and furnace temperature, can result in substantial variation in reburning effectiveness and will play a significant role in determining the appropriateness of TDF in reburning applications. Emissions of other pollutants, such as metals and organic hazardous air pollutants, also need to be quantified. Further engineering studies to examine TDF preparation, means of injecting TDF into large boilers, and costs associated with the use of TDF as a reburn fuel must also be conducted before TDF can be accepted as a commercial alternative. Nevertheless, these tests have shown that TDF has the potential to be successfully applied as a reburn fuel for the control of NO in combustion systems.

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