



## Project Summary

# Pilot-Scale Evaluation of the Potential for Emissions of Hazardous Air Pollutants from Combustion of Tire-Derived Fuel

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Experiments were conducted in a 73-kW (250,000-Btu/hr) rotary kiln incinerator simulator to examine and characterize emissions from incineration of scrap tire material. The purposes of the project are to (1) generate a profile of target analytes for full-scale stack sampling, not statistically defensible emissions factors for the controlled combustion of scrap tire material and (2) where possible, give insight into the technical issues and fundamental phenomena related to controlled combustion of scrap tires. Wire-free crumb rubber, sized to < 0.64 cm (< 1/4 in.), was combusted at two feed rates, two temperatures, and three kiln oxygen concentrations. Along with continuous emissions monitoring for oxygen (O<sub>2</sub>), carbon dioxide, carbon monoxide (CO), nitric oxide, sulfur dioxide, and total hydrocarbons (THCs), samples were taken to examine volatile and semi-volatile organics, polychlorinated p-dibenzodioxins and dibenzofurans (PCDD/PCDF), and metal aerosols. In addition, a continuous polycyclic aromatic hydrocarbon (PAH) analyzer was used in all the tests. Samples were analyzed with emphasis on the 189 hazardous air pollutants listed in the 1990 Clean Air Act Amendments, but other compounds were also identified where possible.

Results indicate that, if burned in a steady-state mode, tire-derived fuel (TDF) combustion will result in very low emissions of CO, THCs, volatile and semi-volatile organics, and PCDD/PCDF. Metal emissions were also very low, except for arsenic (As), lead (Pb),

and zinc (Zn). Uncontrolled stack concentrations of As and Pb were 37.16 and 65.96 µg/Nm<sup>3</sup>, respectively. Uncontrolled Zn emissions were considerably higher, 35,465 µg/Nm<sup>3</sup>. Results also indicate that organic emissions can increase significantly when TDF is fired in a non-steady mode. The continuous PAH analyzer appeared to track transient operation well and gave concentration results in the same range as those using EPA standard semi-volatile organic sampling methodologies.

*This Project Summary was developed by EPA's Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).*

### Introduction

Approximately 240 million vehicle tires are discarded annually in the U.S. Viable methods for reclamation exist. One attractive option for use of scrap tires is burning, either alone or with another fuel (such as coal) in a variety of energy-intensive processes, such as cement kilns and utility boilers. Another potentially attractive option is the use of ground tire material as a supplement to asphalt paving materials. Congress has passed a law, the *Intermodal Surface Transportation Efficiency Act of 1991*, which mandates that up to 20% of all federally funded roads in the U.S. include as much as 9 kg (20 lb) of rubber derived from scrap tires per 907 kg (1 ton) of asphalt by 1997. In spite of these efforts, less than 25% of the total amount of



discarded tires are reused or reprocessed, and the remaining 175 million scrap tires are discarded in landfills, above-ground stockpiles, or illegal dumps. Disposal in above-ground dumps increases the potential for uncontrolled tire fires, which produce large quantities of air pollutants, many of which are known or suspected carcinogens. In addition, these reclamation efforts do little to affect the estimated 2 billion tires already stockpiled.

Tires can be burned whole or can be shredded or chipped before burning. Tires that have been processed into smaller pieces are called tire-derived fuel (TDF). Three main industries use either whole tires or TDF either as a sole fuel or a fuel supplement. These industries are

- Electric utilities that use TDF and whole tires as supplemental fuel in power generation. One company is using whole tires as its sole source of fuel in power generation.
- Cement manufacturing companies using tires and TDF to supplement their primary fuel (usually coal) for firing cement kilns. Some of the companies are using tires or TDF directly in the kiln, and some are using tires or TDF in the precalciner (prior to the kiln).
- Pulp and paper companies using tires or TDF as supplemental fuel in their waste-wood products boilers.

TDF can be processed to remove steel belts and the metal bead that surrounds the wheel rim. TDF with the metals removed is termed wire-free, and TDF with the wire remaining is termed wire-in. TDF can be purchased in a variety of sizes, some as small as < 0.7 cm (< 0.25 in.). TDF that is very small is termed crumb rubber. TDF has a higher heating value than coal and contains about as much sulfur as medium sulfur coal.

The main environmental concern of using whole tires or TDF as supplementary fuel is the potential for increased air emissions. Pollutants of concern include criteria pollutants—carbon monoxide (CO), sulfur dioxide (SO<sub>2</sub>), nitrogen oxides (NO<sub>x</sub>), and particulates—metals, and unburned organics. Title III of the 1990 Clean Air Act Amendments (CAAA) lists 189 hazardous air pollutants (HAPs) of concern. These include volatile organic species such as benzene, polycyclic aromatic hydrocarbons (PAHs) such as benzo(a)pyrene, metal species such as lead, and several individual compounds such as polychlorinated p-dibenzodioxins and polychlorinated dibenzofurans (PCDD/PCDF).

Past field data have shown that, for the most part, emissions of most criteria pol-

lutants from coal-fired boilers and cement kilns are reduced when a fraction of the fuel input is replaced with tires or TDF. This includes SO<sub>x</sub> (which drops if the primary fuel is a high sulfur eastern coal), and NO<sub>x</sub> (since tires have very little fuel nitrogen). Particulates have generally increased slightly. Emissions data for other pollutants, however, are either very limited or nonexistent.

A significant data gap exists in the database of HAPs that can be formed from combustion of tires or TDF. This makes it difficult for state and local air pollution agencies to grant air quality permits allowing a facility to supplement its fuel with tires or TDF, since stack sampling is quite expensive, especially when a list of target analytes does not exist. It was for this reason that EPA's Control Technology Center (CTC) funded this project. The purposes of this project are to (1) generate a profile of target analytes for full-scale stack sampling, not statistically defensible emissions factors for the controlled combustion of scrap tire material and (2) where possible, give insight into the technical issues and fundamental phenomena related to controlled combustion of scrap tires.

Several issues are of concern with the use of TDF in combustion devices:

- The effect on products of incomplete combustion (PICs) of the mode of tire feeding (e.g., whole tires vs. shredded tires).
- The potential for the formation of classes of air toxics not normally found in the stacks of combustion devices burning conventional fuels.
- The impact of TDF-generated particulate on operation of existing particulate control devices.
- Potential operational problems due to differences in feed characteristics.
- Potential operational problems due to differences in the residues that are generated.

This project addresses the first two issues listed above. As much as possible, the last three issues are eliminated from the scope of the project by 1) utilizing a very uniform feed so as to enable as close to steady-state operation as possible and 2) using a grade of TDF that will not generate significant residue.

### Experimental Equipment

A single laboratory-scale combustor was used to perform all the tests, and the tests were performed in as wide a range of operating conditions as possible, to simulate the process conditions in a variety of

combustion units. In addition, it was decided that the scrap tire material be co-fired with natural gas (rather than coal or wood waste) as the primary fuel. By using natural gas as the primary fuel, it was hoped that the effect of the TDF could be isolated, rather than adding the additional experimental complications inherent with burning an additional heterogeneous fuel like coal or wood.

The tests were performed in EPA's rotary kiln incinerator simulator (RKIS) at Research Triangle Park, NC. Figure 1 shows the simulator schematically. A small afterburner (43.8 kW, 150,000 Btu/hr) mounted at the base of the secondary combustion chamber established near-isothermal operating conditions throughout the unit. Sample ports are at various locations.

Measurements made on the RKIS are not intended to be extrapolated *directly* to full-scale units. It is, for example, very difficult to scale up some of the important gas-phase mixing phenomena from the simulator, where, for instance, stratification is not significant, to a full-scale unit, where stratification is significant. In addition, there are significant differences between kilns and other combustion devices, and this study does not address those issues, although some of the information from this study can be applied to other types of combustors. The purpose of the simulator is to individually examine the fundamental phenomena that occur in full-scale units and to gain an understanding of the qualitative trends that would be found in a full-scale rotary kiln. In no way should it be inferred that the concentrations of pollutants from this apparatus would be the same as those from full-scale units.

TDF, consisting of wire-free crumb rubber, sized < 0.64 cm (< 0.25 in.), was introduced into the kiln via a vibrating feeder. The feeder enabled TDF to be fed into the RKIS continuously at rates from 0 to 2 kg/hr.

Continuous emission monitors (CEMs) measured oxygen (O<sub>2</sub>), carbon dioxide (CO<sub>2</sub>), CO, nitric oxide (NO), and total hydrocarbons (THC) both before and after the secondary combustion chamber (SCC), as well as SO<sub>2</sub> at the SCC exit. In addition, a continuous photoelectric PAH analyzer sampled the gases at the stack exit. VOCs were collected by a Volatile Organic Sampling Train (VOST) system. Semi-volatile organics and bulk particulate were collected by isokinetic sampling protocols with a Modified Method 5 (MM5) train. Metal aerosols were collected by a Multiple Metals Train (MMT), except that the potassium permanganate (KMnO<sub>4</sub>) so-

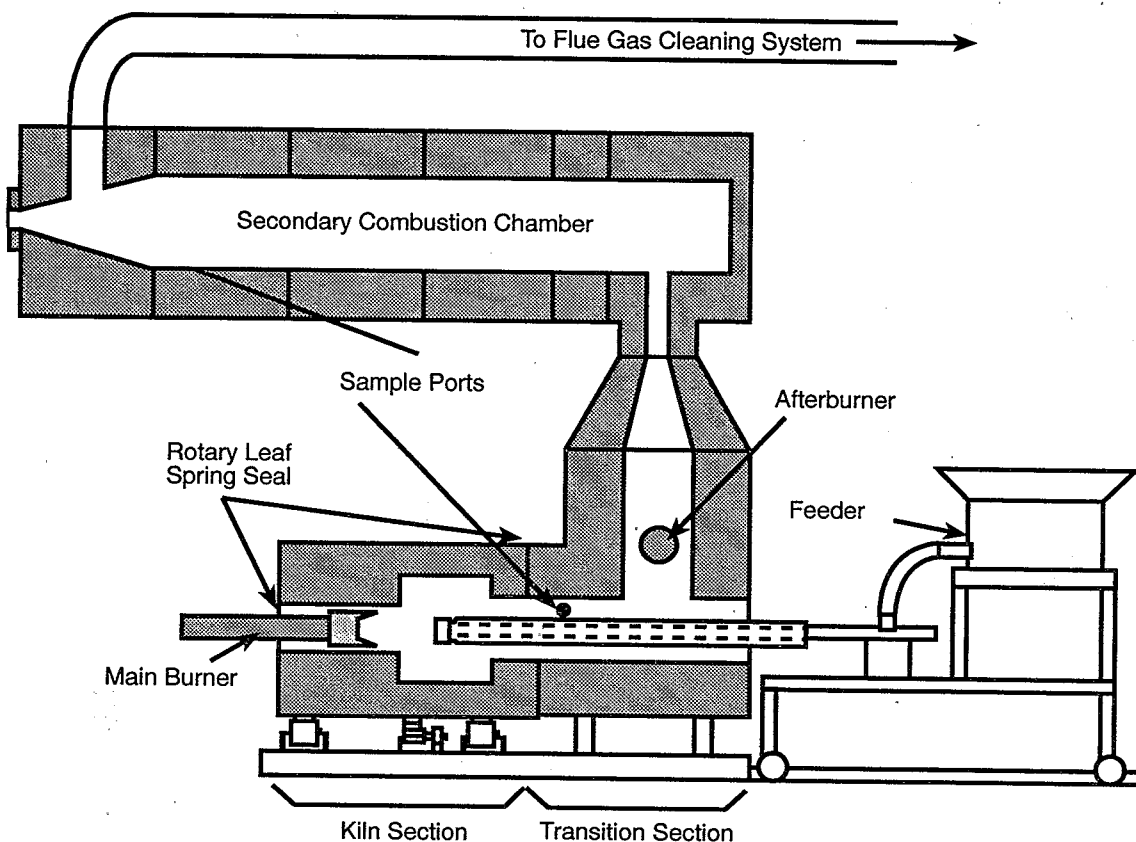


Figure 1. Rotary kiln incinerator simulator.

lution was omitted. The TDF samples were analyzed for metals before the experiments, and the absence of mercury (Hg) in the analysis made it unnecessary to configure the sampling train for Hg sampling. PCDD and PCDF were sampled using the MM5 train with the protocols laid out in EPA Method 23 and analyzed by high resolution gas chromatography/low resolution mass spectrometry (HRGC/LRMS), using a Hewlett-Packard 5890/5970 Gas Chromatography/Mass Selective Detector (GC/MSD) system and methods adapted from EPA Method 23 and RCRA Method 8280.

## Results

### Continuous Emission Monitor Samples

All CEM data were averaged over the course of the run to yield a single number. Tables 1 and 2 list average values from the CEMs: Table 1 taken at the kiln exit sample port, and Table 2 taken at the exit of the secondary combustion chamber.

Note that the  $\text{SO}_2$  analyzers exhibited unreliable and erratic operation. The  $\text{SO}_2$  data did not meet quality control specifications, although they are reported in Table 2, except where data were not available.

### Volatile Organic Samples

In general, the volatile organic compounds (VOCs) detected were fairly close to practical quantitation levels. A number of compounds identified in combustion samples were not present in the field (combustion) blanks. However, several of the compounds found in combustion samples were also present in the field blanks at similar levels; primarily chloromethane, acetone, methylene chloride, and benzene. Benzene is a common PIC from combustion in general and could be attributed to PICs from the natural gas flame found in the field blanks. However, benzene is also a breakdown product of Tenax, and acetone and methylene chloride are ubiquitous in laboratory environments. In addition, some samples contained trichloro-

fluoromethane, which is a chlorofluorocarbon commonly used in air conditioners. Table 3 summarizes the results from the volatile organic samples, by averaging the emission values from all compounds that were present in concentrations greater than the quantitation level on at least one VOST tube. On compounds where one or more VOST tubes had concentrations below the quantitation level, the quantitation level was used for averaging. The results from the trichlorofluoromethane, acetone, and methylene chloride are considered suspect and are not reported in Table 3.

### Semi-Volatile Organic Samples

The results from the semi-volatile organic compound (SVOC) analyses do not seem to indicate the presence of SVOCs in detectable concentrations. The PAH analyzer gave readings on all steady-state tests ranging up to  $3289 \text{ ng/Nm}^3$ , which converts into  $3.3 \text{ } \mu\text{g/Nm}^3$ . This concentration is below the method detection level for individual PAH compounds in the SVOC analysis. Considering that other

past experiences with the PAH analyzer gave good agreement with conventional SVOC analyses, it can be surmised that the results reported from the PAH analyzer compare favorably with the PAH concentrations that were actually present in the stack. Overall, it appears that, when combusted in an efficiently operated facility, emissions of SVOCs from TDF combustion are not significantly different than from natural gas.

The results of the PCDD/PCDF analyses indicate that insignificant amounts of PCDDs and PCDFs were emitted during these tests. The results from the TB6 - 17% TDF test reveal that hexachlorodibenzofuran was present at a concentration essentially equal to the method detection limit. Similarly, the results from the combustion background test (TB7 - 0 % TDF) revealed that tetrachlorodibenzodioxin was present at a concentration also essentially equal to the method detection limit. The method blank did not detect either of these target analytes.

Table 1. CEM Data Taken at Kiln Exit

Run No. (TB)	O <sub>2</sub> (%)	CO <sub>2</sub> (%)	CO (ppm)	NO (ppm)	THC (ppm)
1*	8.28	7.33	33	52	3
2*	7.17	7.45	36	73	3
3*	7.35	7.70	16	58	0
4*	8.51	7.14	31	54	1
5*	9.23	6.31	44	39	0
6	7.64	7.77	20	55	1
7	9.82	5.85	17	32	2
8*	6.45	8.38	30	60	1
9*	8.38	7.32	700	53	43
10	7.66	7.09	30	39	-1
11	3.68	9.34	38	53	0
12	5.71	8.22	36	47	1
13	7.62	7.15	35	40	0
14	7.85	7.25	35	46	1
15	3.10	9.97	42	62	2
16	5.07	8.86	40	57	1
17	7.53	7.43	35	50	1
18	5.40	8.92	44	62	1
19	3.55	10.00	48	64	1
20	8.32	7.35	41	54	1
21	4.24	9.59	47	64	1
22	6.06	8.71	43	62	1
23	5.33	8.08	28	56	0
24	4.91	9.03	50	66	1
25	7.59	7.55	45	64	1
26	3.70	9.71	51	65	2
27	3.18	10.24	59	68	1
28	6.39	8.54	54	66	2
29	8.23	7.39	54	58	1
30	5.49	8.94	53	68	1

\* Electrical noise problems on the CEMs.  
 † Non-continuous feed tests.

Table 2. CEM Data Taken at SCC Exit

Run No. (TB)	O <sub>2</sub> (%)	CO <sub>2</sub> (%)	CO (ppm)	NO (ppm)	THC (ppm)	SO <sub>2</sub> (ppm)	PAH (ng/m <sup>3</sup> )
1*	7.59	8.62	16	49	-2	12	1437
2*	5.43	9.44	14	64	-1	81	2278
3*	5.62	9.62	12	48	-2	59	2284
4*	6.78	9.07	20	62	2	67	3289
5*	7.50	8.44	16	52	1	14	1941
6	6.06	9.45	15	60	1	51	982
7	8.10	7.80	9	42	2	35	429
8*	5.20	10.07	18	58	1	76	1957
9*	8.85	8.11	70	46	6	26	214000
10	6.23	8.86	13	28	0	†	410
11	2.82	10.77	17	36	0	†	630
12	4.49	9.94	16	35	-1	†	404
13	6.17	9.01	16	30	0	†	426
14	6.60	8.99	16	35	0	42	767
15	2.48	11.18	20	46	0	†	1553
16	4.07	10.35	19	44	0	103	1313
17	6.28	9.15	17	41	0	106	702
18	4.30	10.46	19	50	0	†	1939
19	2.61	11.33	20	50	0	96	2364
20	7.12	9.00	18	45	0	82	1474
21	3.20	11.01	20	50	0	74	1937
22	5.01	10.18	20	50	0	78	1734
23	4.11	9.94	13	32	-1	7	925
24	4.40	10.30	19	36	-1	26	1581
25	6.85	9.02	18	37	-1	22	618
26	3.68	10.60	20	36	0	42	1550
27	3.47	10.83	20	37	0	108	1787
28	5.97	9.68	20	39	0	106	1632
29	7.36	8.88	20	36	0	100	1130
30	5.39	9.93	19	37	0	84	1551

\* Electrical noise problems on the CEMs.  
 † Non-continuous feed tests.  
 ‡ Analyzer not working.

### Metals Samples

Table 4 lists the concentrations of metals for the two tests where sampling occurred. Conversion of metal species concentrations to emission factor units and comparing the resulting estimated emissions to emission factor data from combustion of coal and oil in utility boilers suggest that, except for zinc, uncontrolled metal emissions from TDF combustion are similar in magnitude to those for coal and oil.

### Conclusions

Experiments were performed on a bench-scale RKIS to examine HAPs from combustion of TDF. Both steady-state and transient testing were performed so that continuous vs. incremental TDF feeding could be evaluated. Samples were analyzed continuously by CEM for O<sub>2</sub>, CO, CO<sub>2</sub>, NO, THCs, SO<sub>2</sub>, and PAHs. VOST, MM5, Method 23, and MMT samples were collected to analyze for VOCs, SVOCs, PCDD/PCDF, and metal aerosols, respectively. X-ray diffraction and X-ray fluorescence techniques were used to identify species in the fly ash. A regression analy-

sis of the CEM data helped determine pollutant emission trends.

Several VOCs were identified, particularly chloromethane, benzene, and styrene. The concentrations of those VOCs were affected by the amount and mode of TDF feeding. Emissions of benzene, in particular, are particularly sensitive to transient upsets of the combustion process. Comparison of calculated emission factors to those found in the literature for conventional fossil fuel combustion indicates that VOC emissions from TDF combustion are comparable to those from coal and oil combustion.

No significant amounts of SVOCs were identified. The PAH analyzer indicated PAH concentrations on the same order as the detection level of the SVOC analytical methods, except for the test where TDF was batch fed to the RKIS. The PAH analyzer indicated considerably higher concentrations of PAHs during batch feeding; however, these elevated PAH levels were not detected with the MM5 samples. It is possible that the short duration of the transients, coupled with the mandatory isokinetic sampling protocols, prevented

**Table 3. Summary of VOC Concentrations (ng/L)**

Compound	TB5 0% TDF (blank)	TB1 7% TDF (steady-state)	TB3 17% TDF (steady-state)	TB8 19% TDF (ramp)	TB9 15% TDF (batch)
1,1,1, trichloroethane	0.55	0.88	1.00	0.52	0.47
2-methyl propene	2.36	5.40	4.38	1.70	0.50
2-methyl-2-propanol	0.52	0.51	4.10	0.52	0.50
Benzene	1.65	2.93	2.83	17.00	47.31
Bromomethane	0.49	0.51	0.58	2.82	0.83
Carbon disulfide	0.52	0.81	0.52	0.52	2.04
Chlorobenzene	0.52	0.51	0.52	0.52	0.48
Chloromethane	0.59	1.68	8.81	55.03	11.17
Ethyl benzene	0.52	0.51	0.61	0.52	1.07
Heptane	0.52	0.67	0.56	0.52	0.50
Hexane	0.49	0.58	0.55	0.52	0.51
Iodomethane	0.52	0.51	0.52	0.54	0.50
m,p-xylene	1.52	0.98	2.40	0.61	3.85
Nonane	0.68	1.72	0.96	0.52	0.59
o-xylene	0.45	0.51	0.72	0.52	1.13
Styrene	0.65	1.85	1.62	1.62	1.69
Toluene	0.97	1.18	1.05	0.80	2.78

sufficient amounts of pollutants from being sampled.

Emission levels of PCDD and PCDF were found to be similar in magnitude to the combustion blank that consisted of a natural gas flame. Those congeners of PCDD and PCDF identified in all samples were on the same order of magnitude as the method detection level.

Elevated levels of arsenic, lead, and zinc were found in the stack gas. Zinc was present in significant concentrations. Analysis of the fly ash residue indicates that most of the particulate matter was SiO<sub>2</sub>, Al<sub>2</sub>Si<sub>2</sub>O<sub>13</sub>, and Zn<sub>2</sub>SiO<sub>4</sub>. Comparison of calculated emission factors from TDF combustion to those found in the literature for conventional fossil fuel combustion suggests that, except for zinc, the magnitudes of metal emissions are similar to those from coal and oil, although the distributions are significantly different, especially with respect to emissions of mercury and selenium, which are significantly higher from coal combustion.

The PAH analyzer tracked transient kiln operation during periods of good combustion more effectively than the CO analyzer, and with faster response. It may be significantly more effective for process control applications due to its sensitivity. Regression analysis of PAH analyzer measurements indicated that an approximately fivefold increase (over natural gas emissions) in PAH emissions occurs while increasing the TDF fuel input fraction from 0 to 20%.

Regression analysis of CO emissions from the steady-state tests did not significantly correlate with kiln operating condi-

tions. A slight increase in CO emissions with increasing TDF feed rate was found.

The results suggest that burning TDF in batches, such as during the feeding of whole tires, has the potential to form significant transient emissions. This phenomenon could be exacerbated in a system that exhibits significant vertical gas-phase stratification or operates at low excess air levels, such as cement kilns. The size of the facility, however, will certainly impact the intensity of transient emissions resulting from batch charging of tires or TDF since, for an extremely large facility, a steady stream of whole tires may roughly approximate steady-state operation. Even so, the potential for generation of large transients should not be ignored, especially in smaller facilities.

Data gaps still exist, since this limited study was performed on a small combus-

tor, under controlled conditions. The following issues might be addressed in future research:

- The effect of TDF particle size and feeding mode on HAP emissions. This study was done using a single TDF particle size and included only limited testing on different feeding modes.
- Emissions of HAPs from combustion of wire-in TDF. It would be logical to assume that emissions of metals from combustion of wire-in TDF may be significantly different than from TDF that has had the wire removed. Combustion temperature would likely affect metals emissions significantly, since the partitioning of metals between the bottom ash residue and the fly ash would change.
- Characteristics of other TDF-generated residues, such as bottom ash, especially in regard to leachability of metals, and slag composition and quality.
- Emissions of HAPs from co-firing of TDF with other solid fuels, such as coal, biomass-derived fuels, municipal solid waste, or refuse-derived fuel.
- The characteristics of TDF-generated fly ash, including the particle size distributions and speciation of the metals, especially as a function of halogens or sulfur that might be present due to co-firing of other fuels.
- Some basic research, on a very small scale, to examine the chemistry of TDF pyrolysis and combustion.
- Tests on other types of facilities (such as a vertically fired unit), including studies examining TDF combustion in suspension vs. bed-burning phases.

Overall, it appears that, except for zinc, potential emissions from TDF combustion are not significantly different from emissions from combustion of conventional fossil fuels, when burned in a well-designed and well-operated combustion device. If particulate loading is unacceptable because of zinc emissions, the emissions would have to be controlled by an appropriate particulate control device.

**Table 4. Stack Concentration (µg/m<sup>3</sup>) of Metals from TDF Combustion**

Metal	TB7 0% TDF (blank)	TB6 17% TDF (steady-state)
Antimony	0.18	2.11
Arsenic	1.12	37.16
Beryllium	nd*	0.05
Cadmium	0.41	1.06
Chromium	0.65	3.88
Lead	8.05	65.96
Manganese	2.82	5.79
Nickel	0.71	3.51
Selenium	0.83	4.50
Zinc	286.94	35465

\*None detected.

