

Paper for presentation at the 2005 Conference on Incineration and Thermal Treatment Technologies, Galveston, TX, May 9-13, 2005

Emissions from Combustion of Post-Consumer Carpet in a Cement Kiln

P. Lemieux, R. Hall
U.S. Environmental Protection Agency
Office of Research and Development
Research Triangle Park, NC 27711

M. Realff
GA Institute of Technology
Atlanta, GA 30332-0100

K. Bruce
ARCADIS G&M
Durham, NC 27709

P. Smith
Lehigh Cement Company
Allentown, PA 18195

G. Hinshaw
Environmental Assurance Monitoring, LLC
Overland Park, KS 66215

ABSTRACT

The Portland cement industry is interested in the utilization of post-consumer carpet as a fuel to replace a portion of its traditional fuels. In response to this interest, the Carpet and Rug Institute, US Department of Energy, Georgia Institute of Technology School of Chemical and Biomolecular Engineering, US Environmental Protection Agency, Lehigh Cement Company, and the American Society of Mechanical Engineers Research Committee on Industrial and Municipal Waste are performing a collaborative program to assess the feasibility of using cement kilns for the destruction of post-consumer carpet.

This paper reports on the results from cement kiln source sampling activities during two operating conditions: normal operation (firing coal at nominal load) and substituting shredded carpet for 15% of the total fuel value. The pollutants measured include fixed combustion gases, total filterable particulate matter (PM), PM with an aerodynamic diameter smaller than 10 μm (PM₁₀), particle size distributions, halogens, polychlorinated dibenzo-*p*-dioxins and polychlorinated dibenzofurans, and the RCRA and Clean Air Act metals. The resulting data will be utilized by the collaborating parties to determine the operational, environmental, and economic feasibility of cement kiln co-firing as a strategy for the energy recovery of post-consumer carpet.

INTRODUCTION

Portland cement production is a very energy intensive process, requiring energy inputs ranging from 3200 to 5000 kJ/kg of clinker produced (1). The process for manufacturing Portland Cement involves heating limestone [calcium carbonate (CaCO_3)] to form calcium oxide (CaO) clinker. The cement industry has placed a high priority on energy savings as a primary means of achieving cost reductions. The fuel requirements of cement kilns (usually in the form of coal) represent the main energy cost associated with cement production. Some cement plants have successfully replaced a portion of their coal feed with other high heating value secondary fuels including tires and tire-derived fuel (2) or hazardous waste (3). Post-consumer carpet is another potential auxiliary fuel that could be used in cement kilns.

In the US, approximately 2.2-2.7 billion kg (5–6 billion lbs) of carpet is sold annually, of which 60% is for replacement (4). In spite of considerable effort in the past decade to develop recycling technologies for carpet wastes, most carpet continues to be disposed of in landfills (5). The development of economically viable, environmentally sound, high volume, robust systems for dealing with carpet waste would move the carpet industry closer to its goals of environmental stewardship and protection. Carpet has a heating value similar to that of coal, and carpet contains a significant fraction ($\approx 30\%$ by weight) of CaCO_3 in the backing, which suggests that carpet might be an ideal supplemental fuel for cement kilns because the major inorganic impurity in the carpet would be incorporated into the product rather than being emitted as a pollutant.

The application of carpet as a fuel for cement kilns is potentially attractive, but there are potential environmental and operational issues that need to be addressed in order to promote this as a viable practice for industry. For example, some of the elemental components of carpeting (e.g., nitrogen) could potentially result in the formation of pollutants of concern (e.g., nitrogen oxides [NO_x]). In response to this data gap, in a separate study, the US EPA performed testing on a pilot-scale rotary kiln, which showed only a slight increase in NO_x emissions from co-firing carpeting with natural gas (6). This study also showed only minor increases in organic pollutants and no measurable emissions of mercury (Hg).

As a result of these promising small-scale tests, the Carpet and Rug Institute (CRI), US Department of Energy (DOE), Georgia Institute of Technology School of Chemical and Biomolecular Engineering, US Environmental Protection Agency (US EPA), Lehigh Cement Company, and the American Society of Mechanical Engineers (ASME) Research Committee on Industrial and Municipal Waste, initiated a collaborative full-scale test program on the feasibility of using cement kilns for the energy recovery of post-consumer carpet. The objective of this program is to conduct a feasibility test to determine the impact of carpet burning on kiln fouling, fuel economy, mechanical/feeding equipment operation, and stack emissions.

A field test and data evaluation made up a portion of this program. The complete program involved:

- Delivery of a pre-shredded sample of carpet to the site to establish steady-state feeding conditions and to scope out initial operational feasibility;
- Delivery and installation of advanced shredding/grinding equipment to the site;

- Acquisition of necessary permissions from the Pennsylvania Department of Environmental Protection (PA DEP) to conduct a trial;
- Delivery of 907 tonnes (1,000 tons) of post-consumer carpet to the site for use during the tests;
- Establishing parameters for operating the shredding/grinding equipment with the feeder to assure sufficient material delivery to the kiln; and
- Perform source sampling during cement kiln operation with and without carpet feed for fuel comparison purposes.
- Perform further operational testing using the remainder of the 907 tonnes (1000 tons) of the carpet (still ongoing).

This paper reports on the results from the emissions testing portion of the project.

EXPERIMENTAL APPROACH

The goal of the source-sampling task was to determine the emission rates and concentrations of the target stack gas constituents from the exhaust stack of Cement Kiln #1 owned by Lehigh Cement in Evansville, Pennsylvania. Kiln #1 (see Fig. 1) is equipped with an auxiliary fuel line that has been used successfully to feed wood chips into the burner end of the kiln. Note that during these tests no tire-derived fuel was being burned. Fig. 2 shows a photograph of the auxiliary fuel line and its location relative to the main fuel line. Post-consumer carpet, from Carpet Cycle LLC, New Jersey, was collected from various locations in the region and sent to a site adjacent to the cement plant. A shredder (Republic Machines 250 HP, 2" single shaft, 15 inch rotor, 6 cutter rows) was also installed at that same site. Trucks transported the shredded carpet, where it was dumped into a hopper that was connected to the auxiliary fuel line. This system was capable of delivering 2.2 tonnes/hr (2.4 tons/hr) of finely shredded carpet to the kiln, providing up to 15% of the total fuel energy requirements. Fig. 3 shows the shredded carpet material as fed to the kiln.

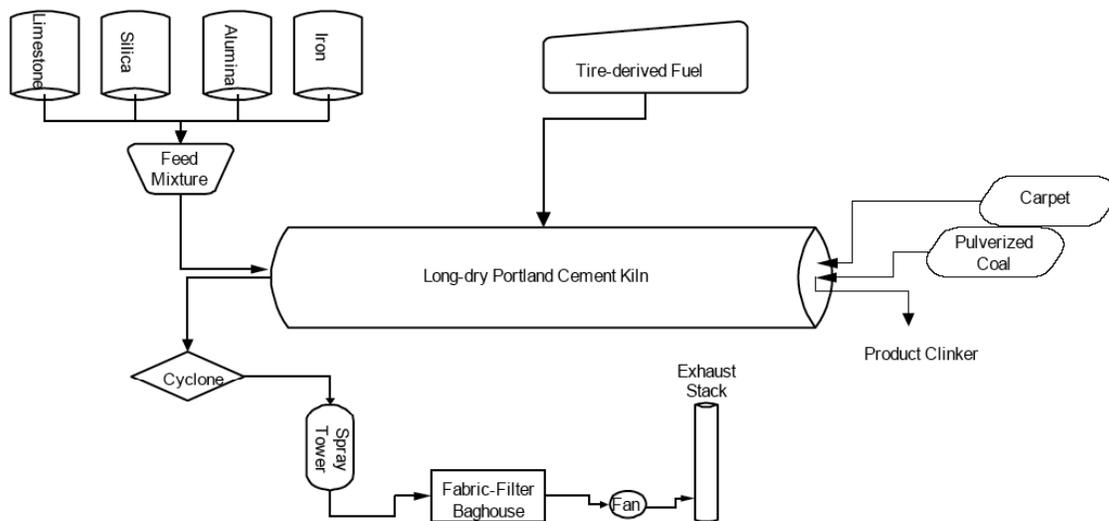


Fig. 1. Lehigh Cement Kiln #1, Evansville, PA.

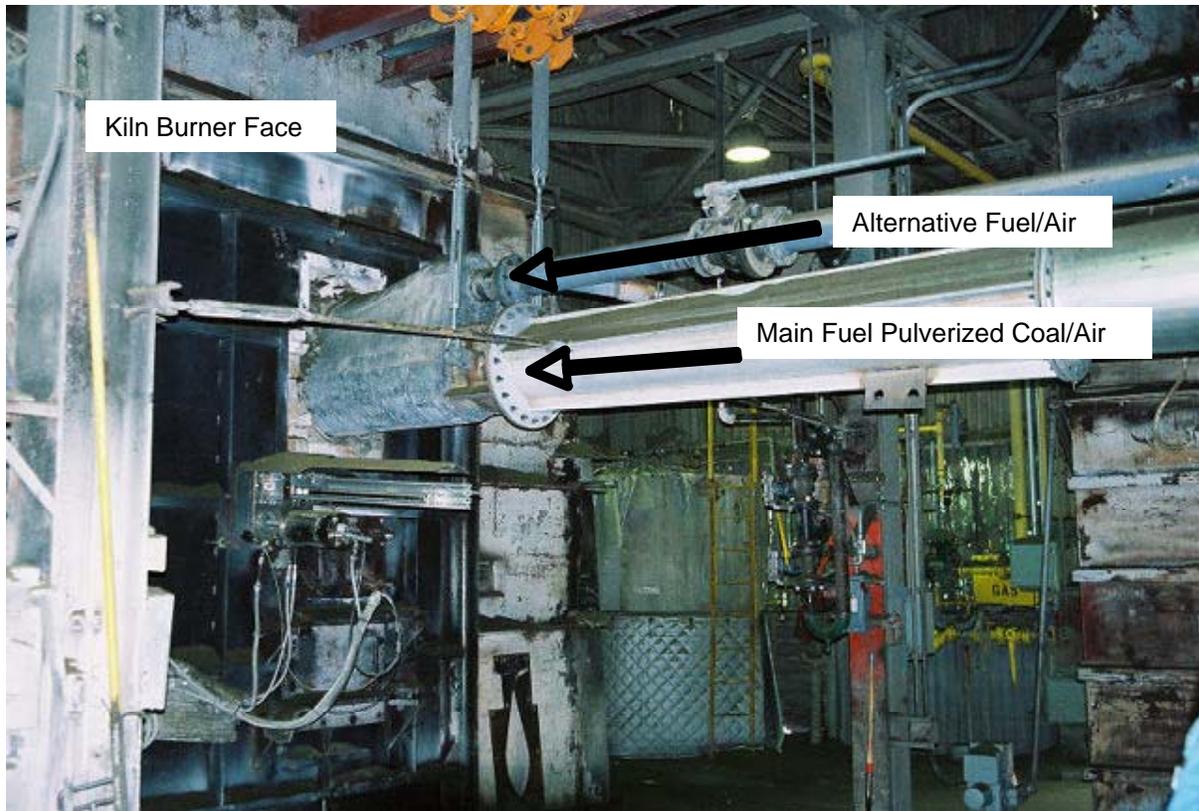


Fig. 2 Auxiliary Fuel Line.



Fig. 3. Photograph of Shredded Carpet.

For the baseline (coal only) test series, the kiln was operating at a clinker production rate of approximately 1727 tonnes/day (1900 tons/day) from 2182 tonnes/hr (2400 tons/hr) of raw material. The stack gas flow rate was approximately 2662 scm/min (94,000 scfm) at a gas temperature of about 204 °C (400°F) while operating on coal. Similar conditions were observed during carpet co-firing operation. The use of stainless steel probes, quartz probe liners, and graphite ferrules during the test program minimized potential problems sampling at this temperature. All operational parameters were monitored and recorded by plant instrumentation.

Prior to detailed sampling, the kiln was operated under a variety of fuel input combinations of carpet and coal over a period of four days. After these four days of scoping tests, two kiln test conditions were evaluated in detail, with two sampling days per test condition. Condition 1 was considered normal baseline operation, with the kiln firing its normal coal fuel at a rate of approximately 9.1 tonnes/hr (10 tons/hr). Condition 2 substituted shredded carpet for 15% of the total kiln fuel energy input. Table I lists the operating conditions for the test matrix.

Table I. Test Matrix.

Condition	Raw Meal Feed Rate (tonnes/hr)	Coal Feed Rate (tonnes/hr)	Carpet Feed Rate (tonnes/hr)	% Fuel as Carpet
Condition 1 (Baseline – Coal only)	90.9	9.1	0	0
Condition 2 (Coal/Carpet)	90.9	7.7	2.0	15

Sampling for various combustion-related air pollutants was performed over the duration of the tests. Continuous emission monitors (CEMs) were used for fixed combustion gases during the entire test duration. Extractive samples, using standard sampling/analytical methods were performed at discrete times, based on minimum sample volumes required by PA DEP. The target analytes, sampling/analytical methods, and sample times/volumes are described in Table II.

The sampling location was a series of four evenly spaced 15.2 cm (6 in) test ports located at the 69.5 m (228 ft) level. The stack inner diameter at that location is 304 cm (10 ft). The four test ports were utilized to accommodate either two or three sampling trains simultaneously. Each port was traversed by each train by rotating the sampling trains between the four ports sequentially.

The samples were collected over a period of several days during which the cement kiln was operating under stable and steady conditions. The carpet feed was started and time equal to the solid phase kiln residence time (approximately 3 hrs) was allowed to elapse prior to initiation of extractive sampling methods. Table III shows a timeline of the sample events within the various days. Runs where samples were taking simultaneously are noted; otherwise, duplicate sample trains were taken sequentially.

Table II. Target Analytes and Sampling/Analytical Methods Used.

Target Analyte	Method Used	Sampling Duration
O ₂	Paramagnetic CEM	Continuous
CO ₂	NDIR CEM	Continuous
CO	NDIR CEM	Continuous
NO _x	Chemiluminescent CEM	Continuous
SO ₂	UV CEM	Continuous
RCRA/CAA Metals (Sb, As, Ba, Be, Cd, Cr, Co, Pb, Mn, Hg, Ni, Se, Ag, Tl)	Extractive sample/ICAP (EPA Method 29)	90 min
Halogens (HCl, chlorides, HBr, bromides ⁻)	Extractive sample/IC (EPA Method 26A)	90 min
PCDD/F	Extractive sample/HRGC/HRMS (EPA Method 23)	240 min
Total filterable particulate	Extractive sample (EPA Methods 1,2, 4, and 5)	90 min
PM10/PSD	Cyclone/cascade impactor (CARB Method 501)	240 min – 480 min
Condensables	EPA Method 202	240 min – 480 min

Table III. Timeline of sampling events.

Day	Condition	Samples
1 (11-5-04)	2	CEMs, M23 x 3 (2 simultaneous), M501 x1
2 (11-8-04)	2	CEMs, M26 x 3, M29 x 3
3 (11-9-04)	1	CEMs, M23 x 3 (2 simultaneous, 1 bad run)
4 (11-10-04)	1	CEMs, M23 x 1 (repeat of bad run), M501 x 2 (simultaneous)
5 (11-11-04)	1	CEMs, M26 x 3, M29 x 3
6 (11-12-04)	2	CEMs, M501 x 2 (simultaneous)

Oxygen (O₂) was measured using a paramagnetic continuous emission monitor (CEM), carbon dioxide (CO₂) and carbon monoxide (CO) were measured using non-dispersive infrared (NDIR) CEMs, NO_x was measured using chemiluminescent CEM, and sulfur oxides (SO_x) were measured using ultraviolet (UV) CEM.

Metals emissions were determined by the use of EPA Method 29 (7). A metered flue gas sample was withdrawn from the stack isokinetically through a heated probe and glass fiber filter into an impinger/condenser train. The filter and impinger solutions were digested and analyzed for the target metals by ICAP. Three simultaneous Method 29 trains were operated in the available ports in the stack. This was not precisely compliant with the definition of co-located trains; however, information about the precision of the sampling trains can still be derived from sampling this way.

Halogen emissions were determined by EPA Method 26A (8). Gaseous and particulate pollutants were withdrawn isokinetically from the source through a heated, glass-lined probe and

heated filter into an impinger/condenser train. The impinger solutions were analyzed by ion chromatography (IC) to determine halogen concentration.

PCDD/F emissions were determined by the use of EPA Method 23 (9). A metered flue gas sample was withdrawn from the stack isokinetically through a heated probe and Teflon coated, glass fiber filter onto a condenser/XAD-2 packed resin trap. The filtered, dried gas was measured with a calibrated dry gas meter. The XAD resin trap and filter were extracted and analyzed for PCDDs/Fs by high-resolution gas chromatography/high-resolution mass spectrometry (HRGC/HRMS).

Total filterable particulate matter (PM) sampling was performed according to EPA Method 5. A flue gas sample is withdrawn from the stack isokinetically through a heated probe and pre-weighed, heated, glass fiber filter into an impinger/condenser train. The filtered, dried gas is measured with a calibrated dry gas meter, and the PM captured in the probe and filter are desiccated and weighed. The filters used in the three Method 26A trains were used for the Method 5 total filterable particulate measurement.

PM with an aerodynamic diameter less than 10 μm (PM_{10}) and particle size distributions (PSDs) were measured using Method 501 (10), which utilizes a cyclone with a 10 μm cutoff and an Andersen Cascade Impactor with multiple stages to determine the PSD.

Condensables were measured using EPA Method 202 (11), using the back half of the same trains that were being used for PM_{10} .

RESULTS

Operationally, the substitution of carpet for part of the coal resulted in an overall shorter flame length in the kiln. This is due to the carpet being completely combusted at a shorter axial distance from the burner face. This slightly altered the thermal distribution in the kiln, which caused some concern to the plant for jeopardizing the refractory lining of the kiln (which was nearly due for its annual recasting).

The proximate and ultimate analysis of various types of carpeting as well as a typical coal is shown in Table IV.

In all of the presentation of results, the raw concentrations are shown (i.e., no correction to a fixed O_2 or CO_2 concentration was performed). The results from continuous combustion gas measurements for the two test conditions are shown in Figs. 4-6. Emissions of CO (Fig. 4) were essentially unchanged between the conditions with and without the carpet feed. This suggests that the carpet was being effectively combusted in the burner zone without significantly impacting the emissions of organic pollutants and products of incomplete combustion (PICs). Emissions of NO_x (Fig. 5) were also not impacted either positively or negatively by the substitution of carpet. Although nylon carpeting contains significant amounts of nitrogen, which could form fuel NO_x , the temperatures in the burning zone of the cement kiln are very high ($\approx 1500^\circ\text{C}$) and mechanisms of thermal NO_x formation dominate, so it is not unexpected that significantly increasing fuel nitrogen content would have little effect on NO_x emissions.

Although the carpet being fed contained little to no sulfur, SO₂ emissions (Fig. 6) were increased somewhat during the first carpet run possibly due to instability in the process.

Table IV. Ultimate and proximate analysis results for various carpet types tested and a typical medium-volatile bituminous Pennsylvania coal (12). All values are as received.

	polypropylene	nylon 6	nylon 6,6	coal
Carbon (% mass)	56.93	42.25	45.59	81.6
Hydrogen (% mass)	8.47	5.47	6.13	5.0
Nitrogen (% mass)	< 0.05	4.46	4.74	1.4
Sulfur (% mass)	0.07	0.11	0.11	1.0
Ash (% mass)	21.17	25.42	23.96	6.1
Oxygen (% mass, by difference)	13.36	22.28	19.46	4.9
Chlorine (ppm mass)	77	64	52	NA
Moisture (% mass)	0.21	0.85	0.58	2.1
Volatile matter (% mass)	69.11	61.90	65.57	24.4
Ash (% mass)	21.17	25.42	23.96	6.1
Fixed carbon (% mass, by difference)	9.51	11.83	9.89	67.4
Heat of combustion (MJ/kg)	28.10	17.17	18.81	33.26

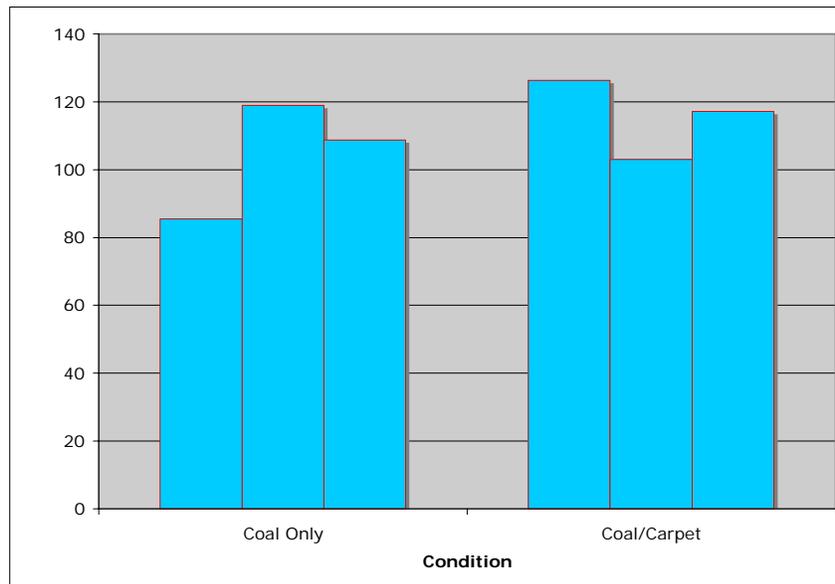


Fig. 4. CO Emissions Results Averaged Over Each Run.

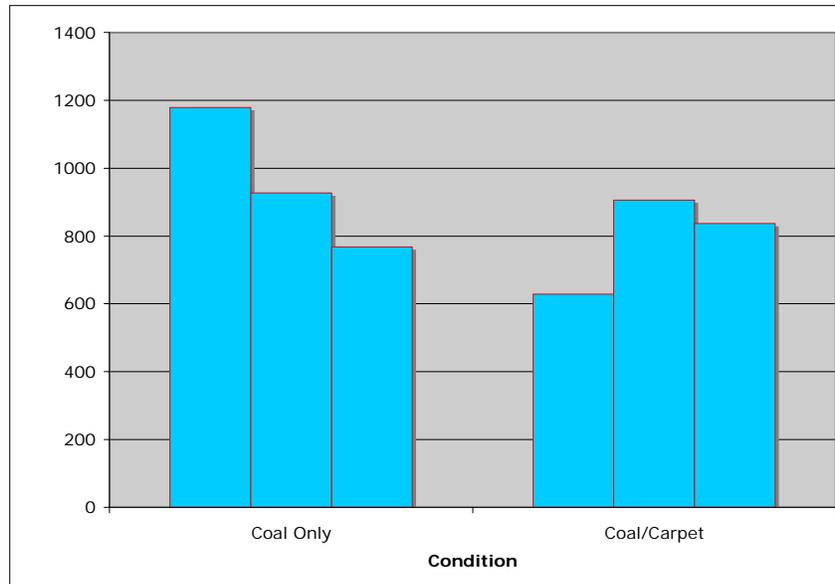


Fig. 5. NO_x Emissions Results Averaged Over Each Run.

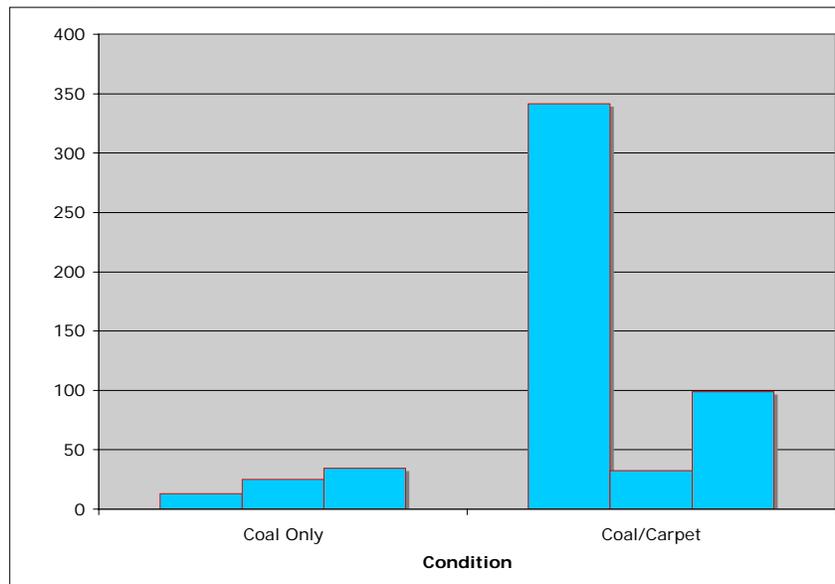


Fig. 6. SO₂ Emissions Results Averaged Over Each Run.

The results of the airborne metals measurements are shown in Fig. 7, as an average of 3 runs (error bars reflect the spread of the measurements). Only the target analytes that were present at levels above the detection limits are shown. Emission levels were quite low, and there appeared to be no discernable effect of the fuel substitution, as the ranges bounded by the error bars clearly overlap between the two conditions. It is estimated that there is approximately 15% variability inherent in the Method 29 measurements – some of the metals emissions measurements are showing higher variability than that. The wide variability that some metals are showing could be due to non-homogeneities in the raw materials.

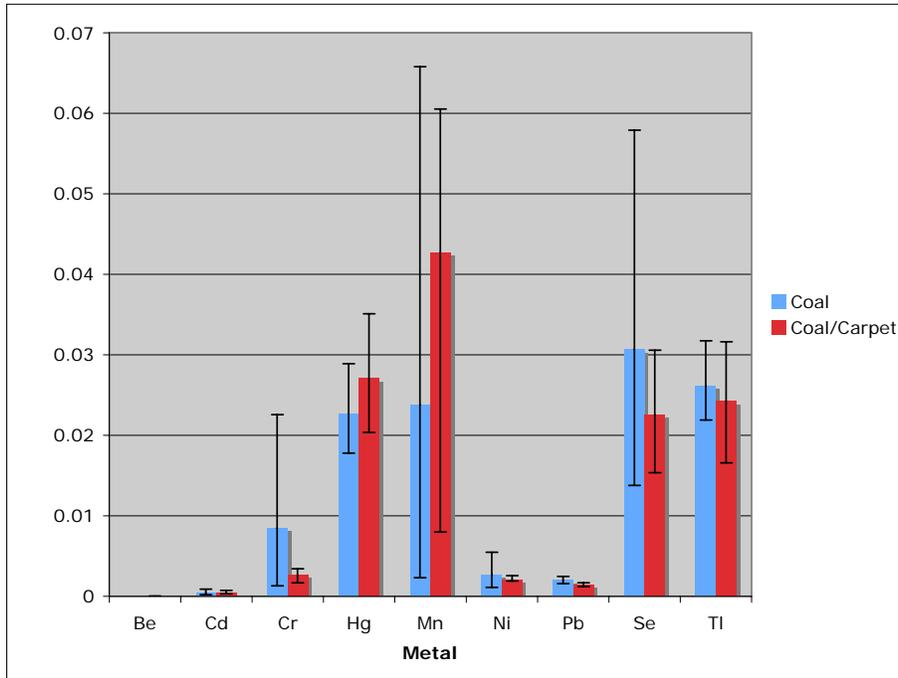


Fig. 7. Metals Results (Averages of 3 Runs).

The results from the halogen measurements are shown in Fig. 8 (as an average of 3 runs). Brominated species were not detected in any of the samples. There appears to be a slight reduction in the HCl and chlorides resulting from the fuel substitution. As shown in Table IV, carpet does have a lower chlorine content than coal, so this is not inconsistent.

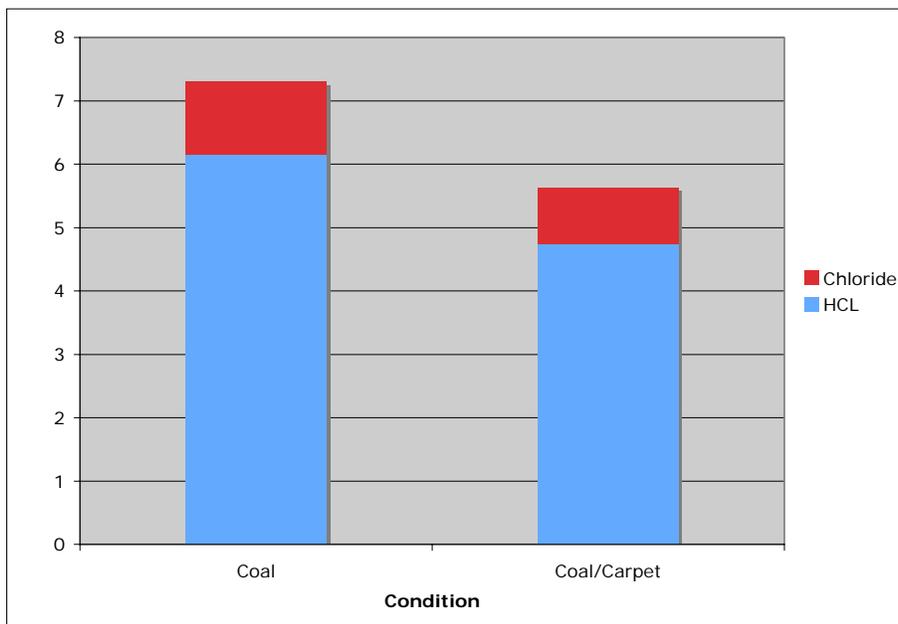


Fig. 8. Halogen Results (Averages of 3 runs).

The results from the total filterable PM measurements are shown in Fig. 9 and PM₁₀ results are shown in Fig. 10. Only 2 runs were captured for PM₁₀ with coal only, due to extended sampling

times resulting from very low particulate loading. It appears that for these tests, PM_{10} constitutes approximately 50% of the total filterable PM. It appears that the fuel substitution did not measurably affect the emissions of filterable PM or PM_{10} . This is not a surprising observation given that entrained feed material at various stages of calcination is probably the main contributor to the PM in the stack.

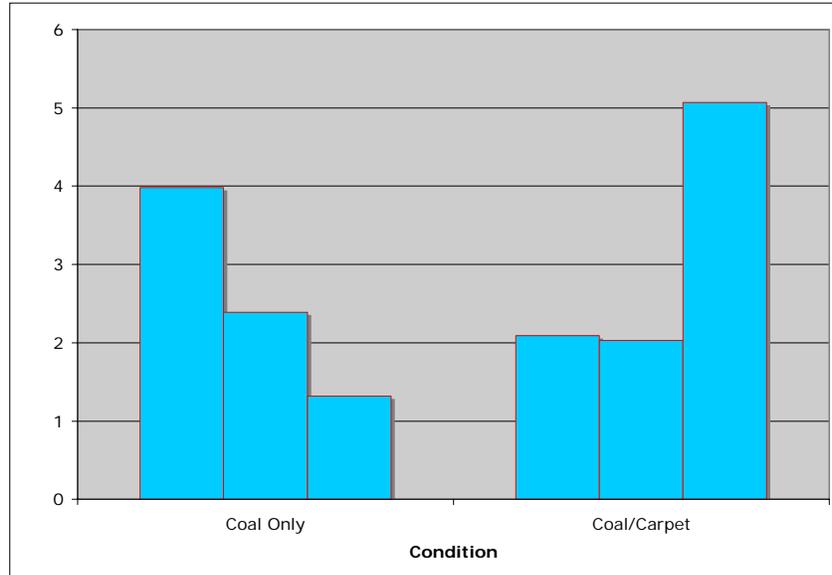


Fig. 9. Total Filterable PM Results.

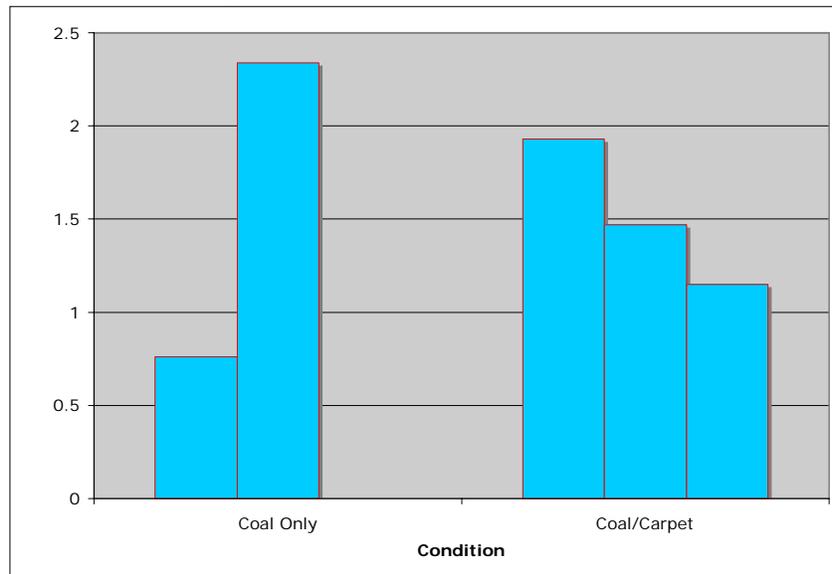


Fig. 10. PM_{10} Results.

The results from the condensable organic measurements are shown in Fig. 11. The results from the condensable inorganic fraction are shown in Fig. 12. Like for the PM_{10} , only two samples were acquired for the coal only runs. It is hard to determine the effect of the fuel substitution on the condensable organic fraction because the first run showed a significant difference from the other two runs. Since a certain amount of the condensable organic fraction is due to organics being driven off the raw material, it is possible that the outlier result in the first run could be due

to something in the raw material that was released into the gas phase. The condensable inorganic fraction, however, showed significantly lower emissions in the samples with the coal/carpet fuel. Since a significant fraction of the condensable inorganic material may be SO_3 , this observation is the reverse of that observed in the SO_2 emissions. It is possible that whatever shift in the sulfur-calcium-oxygen-carbon equilibrium that may have occurred in the burning zone resulted in a shift from SO_3 to SO_2 when the carpet was being co-fired with the coal. We are further analyzing the condensable inorganic fraction to verify this hypothesis.

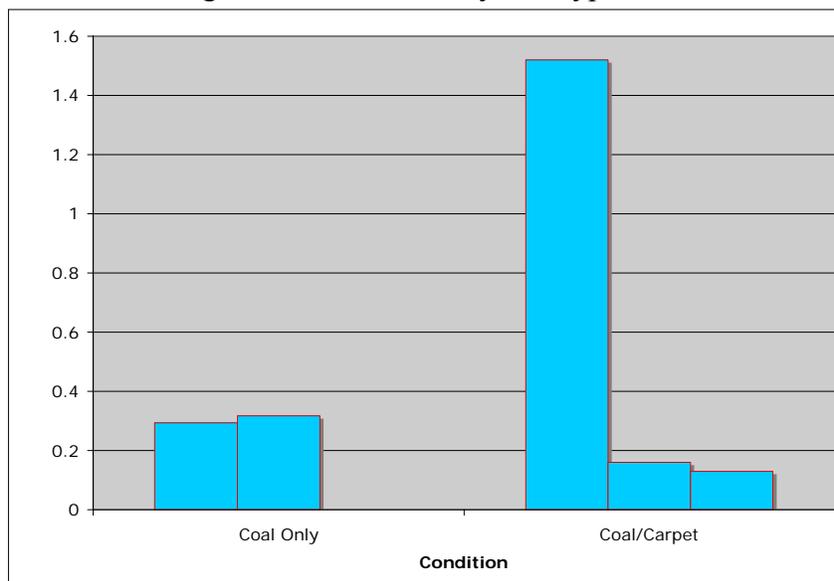


Fig. 11. Condensable Organic Results

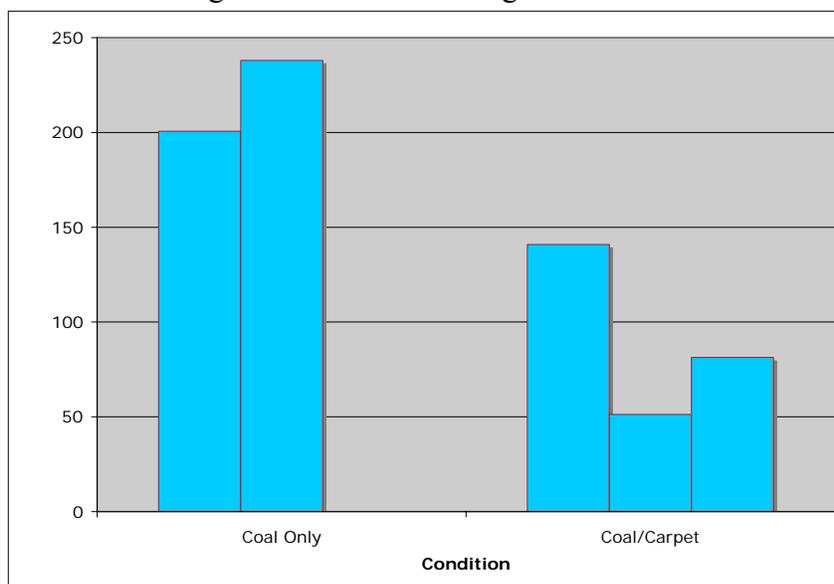


Fig. 12. Condensable Inorganic Results

The results from the total PCDD/F measurements are shown in Fig. 13 and the PCDD/F results converted to International Toxicity Equivalent (I-TEQ) measurements (average of 3 runs) are shown in Fig. 14. Both the total PCDD/F and TEQ emissions were very low. The runs with the carpet co-firing however, showed significantly lower emissions of total PCDD/F and TEQ.

Given that current knowledge of the PCDD/F formation mechanism suggests that the PCDDs/Fs are being formed in the cooler parts of the combustion system, such as in the baghouse, and the fact that there were no indications of neither more nor less effective combustion with the carpet co-firing (as indicated by CO measurements), it suggests that some other gas-phase species indirectly related to the fuel composition may be responsible for this significant difference in emissions. The main differences between the coal only runs, and the coal/carpet runs were seen in the SO₂, halogens, and the inorganic condensable results. Therefore it is likely that one of these three measurements may give an indication of why the PCDD/F emissions were significantly reduced.

The halogens were only slightly lower in the case where carpet was being co-fired with coal. Past work on waste combustion systems (13) showed little to no effect of chlorine species on PCDD/F emissions. It is unlikely that a slight reduction in the chlorine species could result in a significant reduction in PCDD/F emissions for other types of combustion systems. Rather, it is more likely that the change in sulfur species is what resulted in the dramatically lower emissions of PCDD/F. Further examination of the process data to examine this and other potentially important variables (e.g., baghouse temperature) will be performed.

The presence of sulfur has been implicated as an inhibitor of PCDD/F formation rates. Previous research (14) showed that addition of high-sulfur coal to a refuse-derived fuel combustor resulted in significantly lower emissions of PCDD/F. If the reduction in PCDD/F that were seen in these tests is a result of sulfur inhibition of the PCDD/F formation reactions, then it appears that it would be SO₂ and not SO₃ that seems to be the species that inhibits the PCDD/F formation reactions. Further analyses will be performed to check this hypothesis.

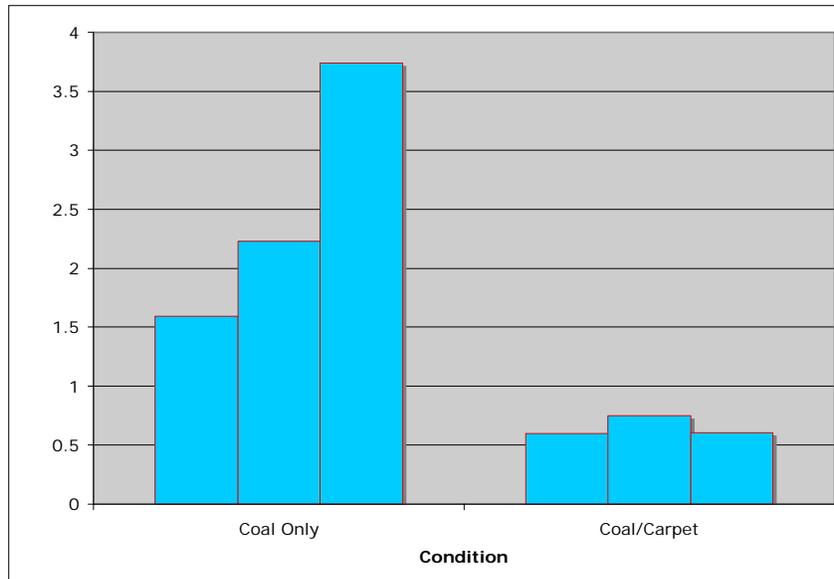


Fig. 13. Total PCDD/F Results.

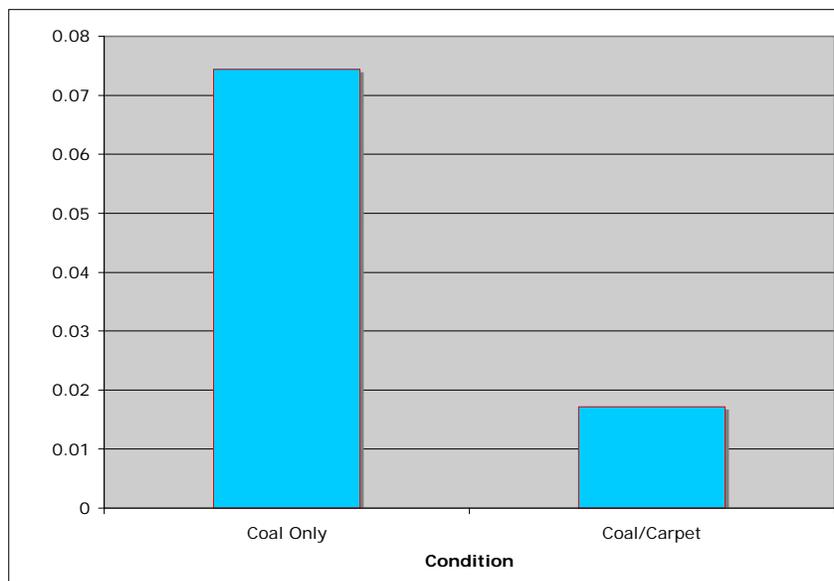


Fig. 14. PCDD/F I-TEQ Results (Averages of 3 Runs).

CONCLUSIONS

A series of emissions tests was performed at a full-scale Portland Cement kiln where a portion of the coal fuel was substituted with shredded carpet, and compared with normal operation on coal only. This paper reports on the results from cement kiln source sampling activities during two operating conditions: normal operation (firing coal at nominal load), and substituting shredded carpet for a 15% of the total fuel value. The pollutants measured include fixed combustion gases, total filterable particulate matter (PM), PM₁₀, particle size distributions, halogens, polychlorinated dibenzo-*p*-dioxins and polychlorinated dibenzofurans, and the RCRA and Clean Air Act metals.

The following conclusions were made based on the testing:

- The program successfully demonstrated the process of shredding the carpet, transporting it to the facility, and feeding it into the cement kiln with a replacement of 15% of the coal fuel (on a heating value basis) with carpet.
- The carpet burned out quicker than the coal, resulting in a thermal profile with the higher temperatures slightly shifted closer to the burner face.
- The emissions of CO and NO_x did not appreciably change by substituting the carpet for a portion of the fuel
- The emissions of total filterable PM and PM₁₀ did not appreciably change by substituting the carpet for a portion of the fuel.
- The emissions of halogens were slightly lower when the carpet was being co-fired.
- The emissions of SO₂ appear to be slightly higher, although one test showed similar emissions, and the emissions of condensable inorganics (presumably SO₃) were lower when the carpet was being co-fired. It is believed that the slightly different thermal profile in the burning zone resulted in this shift from SO₃ to SO₂. Additional analyses are being performed to investigate this phenomenon, and additional testing for longer periods

to further investigate this phenomenon will be required to make more substantive conclusions.

- The emissions of total PCDD/F and PCDD/F I-TEQs were notably lower when the carpet was being co-fired. It is believed that the increase in SO₂ emissions may be inhibiting formation of PCDD/F. It also suggests that SO₂ and not SO₃ appears to be the species that inhibits PCDD/F formation.

ACKNOWLEDGMENTS

The authors would like to acknowledge Charles Bortz of Lehigh Cement Company, Sean Ragiell of Carpet Cycle LLC, George Sotsky of Republic Machines, David Zwicky of Zwicky and Sons, Gene Stephenson, Matt Hamilton, John Martin, Mike Bowling, and Ronnie Mills from ARCADIS, the ASME research committee on Industrial and Municipal Waste, Frank Hurd of CRI, Robert Small of PA DEP, and Ron Myers of EPA/OAQPS.

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