

Characterization of Transient Puff Emissions from the Burning of Carpet Waste Charges in a Rotary Kiln Combustor

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Abstract

Transient puff emissions were characterized from burning carpet charges that were fed to a pilot-scale rotary kiln combustor to assess the potential impact on emissions of using post-consumer carpet as an alternative fuel in cement kilns. Carpet with polypropylene, nylon 6, and nylon 6,6 face fiber was cut in one to three inch square pieces and fed as 0.4 kg charges to a 73 kW natural gas fired rotary kiln simulator. Gas emissions monitored included O₂, CO₂, CO, NO, NO_x, N₂O, NH₃, total hydrocarbons, and total polycyclic aromatic hydrocarbons. The charges required about two minutes to burn, and the emission transient exhibited three phases. In the first phase lasting about 30 seconds, fuel-lean combustion of volatiles occurred. In the middle phase lasting about one minute, fuel-rich burning occurred and a CO spike was observed. In the final phase lasting about 30 seconds, fuel-lean burning occurred. For nylon carpets, the fuel-lean combustion periods were characterized by elevated NO emissions. Integrated over the duration of the transient, the NO emission corresponded to a one to two percent conversion of fuel-nitrogen (i.e. nitrogen in the nylon fiber) to NO. These tests demonstrate the feasibility of burning waste carpet as an alternative fuel, that rapid volatilization of batch fed carpet can lead to emission transients, and that NO emissions may result from the burning of nylon carpets.

Introduction

What is carpet?

Carpet is a multilayer mixture of polymers, both thermoplastics and thermosets, and inorganic fillers. The face fiber is composed of high-value polymers, such as nylons and polyethylene terephthalate (PET) that provide the texture color and mechanical wear necessary for the carpet to function as a flooring. These fibers are either tufted through a backing fabric of polypropylene or woven through it in the “level loop” construction. The latex filled in varying amounts with calcium carbonate provides the bulk of the backing and “glues” the face fibers into the backing. The last layer is often another polypropylene backing.

Carpet is designed to be difficult to pull apart and to be resistant to mechanical wear – one reason for the inherent difficulty in recycling it. The average weight of carpet is about 2.1 kg/m^2 (3.88 lbs/yd^2), with about 0.94 kg/m^2 (1.75 lbs/yd^2) of face fiber, and 1.16 kg/m^2 (2.13 lbs/yd^2) of backing. The backing consists of 0.78 kg/m^2 (1.44 lbs/yd^2) of calcium carbonate, 0.2 kg/m^2 (0.38 lbs/yd^2) of polypropylene, and 0.167 kg/m^2 (0.31 lbs/yd^2) of latex. The distribution between different face fibers has nylon 6,6 and nylon 6 comprising about 35 and 20 % of the carpet sold and polypropylene comprising about 30% with the rest PET and wool. In addition to the large stream of broadloom carpet, there is a small percentage of carpet tile, 10% of overall sales, much of which is backed with polyvinyl chloride (PVC), although new non-PVC based backings are now in production.

How much post-consumer waste carpet is generated?

It is estimated that between 1.8 and 2.3 million metric tons (4 to 5 billion pounds) of post-consumer waste carpet is land filled annually in the United States, about 7.7 kg (17 lbs) per person per year, and hundreds of million kilograms of post-industrial manufacturing waste is similarly disposed of. This quantity is expected to grow over the next decade at a rate of 3% per annum leading to approximately 2.3 to 2.7 billion kg (5 to 6 billion pounds) in a decade from now. There is significant value locked up in this stream. The nylon in this stream would be worth about \$300 million, given a price of \$0.44/kg (\$0.20/lb) and the approximate percentage of nylon face fiber carpets (55%) in the overall stream. However, the overall stream contains a significant fraction of low value material, as well as including all of the backing components. The question is how to realize the potential value in the material by building recycling infrastructure that recognizes how to best put the different fractions of the stream to different end uses.

What are the drivers for using carpet as a fuel?

The central issue for carpet recycling is the construction of cost-effective infrastructure that can support the diverse set of production processes that will convert post-consumer carpet into useful products. In order to build robust collection systems and infrastructure for high value uses for recycled carpet we need to establish outlets for carpet that can absorb significant quantities of material in a relatively undifferentiated form. A high volume use, such as a fuel, will enable a

collector to dispose of those fractions of carpet, thus avoiding a high handling cost and disposal fee.

Carpet consists of two basic material types, calcium carbonate and oil-derived polymers. Due to the stringent performance requirements on carpet, the polymer materials are well characterized and free from impurities, and hence represent a clean, oil based, fuel. The calcium carbonate is an inert material that forms an ash. Due to the large percentage of the calcium carbonate in carpet, if used as fuel in traditional power boilers, there would be increased generation of ash. This suggests that finding a use for carpet as a fuel in which the calcium carbonate could be incorporated into a product would be beneficial. Cement kilns are an example of such use, although the quantity of calcium carbonate provided by carpet is very small compared to the feed rates.

In more quantitative terms, carpet has an energy value of approximately 23200 kJ/kg (10,000 Btu/lb), whereas coal typically has a value of between 27900-32500 kJ/kg (12,000-14,000 Btu/lb). Carpet is essentially sulfur-free (0.1 wt%) and has very low halogen content (0.2 wt%), as compared to coal which may have a sulfur content of the order of 1.2% and low halogen content (comparable to carpet). The key element that is higher in carpet is nitrogen, because of the nylon, which can render carpet as high as 6-8% nitrogen, compared to a value of 1.4% for coal. It is not clear how much of this fuel nitrogen will be converted to NO_x emissions, and if nylon carpet is separated for use in higher value applications, what the fuel composition will be. This is an area of active research, being undertaken in conjunction with the EPA and their test kiln at Research Triangle Park.

Why is waste carpet proposed as an alternative fuel for use in cement kilns?

Cement kilns consume 5.31 gigajoules per metric ton (5.04 million Btu per ton) product (1999 figures) with 74% of this energy being provided by coal and coke combinations. 75,600,000 metric tons of finished cement was produced in 1999 and the industry has been on an upward trend since these figures were released [1].

There are several specific reasons for cement kilns being a good outlet for carpet as a fuel.

1. Calcium carbonate is a raw material for cement production. The disadvantage of carpet containing calcium carbonate and generating high ash loads if burned in boilers is thus converted into an advantage in cement kilns.
2. Cement kilns are experienced at handling waste fuels. There are plants that have solid waste feed systems that could handle carpet, if it were processed into the right form. 45 of 122 cement kilns report using wastes as fuels and 10 of these report that waste is their primary fuel [1].
3. Cement kilns are energy-intensive furnaces and can utilize a large volume of waste fuels and alternate materials sources, thus providing a good outlet for non-recyclable waste carpet materials.

To establish whether carpet could be an effective fuel for cement kilns, several experiments have been performed at a pilot scale facility in EPA's Research Triangle Park facility. These experiments enable a more precise quantification of the emissions from carpet than are possible in a field trial where the background emissions and variability of operation are greater. The specific issue that is addressed in this work is the effect on emissions of nitrogen species from burning different types of carpet and, secondarily, different sized pieces of carpet.

Experimental

Rotary Kiln Simulator

Experiments were performed in EPA's 73 kW (250,000 Btu/h) Rotary Kiln Incinerator Simulator (RKIS). A schematic is shown in Figure 1. The primary fuel is natural gas. A ram feeder is used to inject small charges of waste (0.4 kg, nominal). The kiln rotates at a slow speed, typically 0.5 rpm. A secondary combustion chamber is available, but was not fired in this study. Exhaust gases pass through a flue gas cleaning system consisting of an afterburner, spray quench, baghouse, and wet scrubber. Emissions are monitored both at the exit of the primary combustion chamber and the exit of the secondary combustion chamber, before the flue gas cleaning system. This facility has been used to study transient puff emissions from combustion of charges of several different types of wastes [2-4].

Figure 1

The RKIS is equipped with continuous emission monitors (CEMs) for oxygen (O₂), carbon dioxide (CO₂), carbon monoxide (CO), nitric oxide (NO), NO_x (NO and nitrogen dioxide), and total hydrocarbons (THCs). In addition to these conventional CEMs, CEMs for ammonia (NH₃), nitrous oxide (N₂O), and polycyclic aromatic hydrocarbons (PAH) were used. The NH₃ monitor is a Perkin-Elmer MCS 100. N₂O was monitored by on-line gas chromatography with an electron capture detector. The PAH monitor was an Ecochem model PAS 2000.

Previous carpet burn study and a priori hypothesis

In fall 2002 we began carpet burn studies to support two initiatives. One is an initiative supported by the carpet industry, the state of Georgia, and DOE to explore the feasibility of burning post-consumer carpet in cement kilns. The second is a homeland security initiative at EPA to study the disposal of contaminated carpet by incineration [5].

In a previous study conducted in August-October 2002 at the RKIS facility, we studied emissions from the semi-continuous feeding of shredded carpet fiber and finely ground carpet backing to the RKIS at rates of up to 30 percent of the total energy input [6]. In these experiments, there was almost no increase in CO emissions when carpet was co-fired, but carpet nitrogen conversion to NO ranged from three to eight percent.

As a follow-up to this work, experiments were designed to address emissions when carpet is co-fired in 0.4 kg charges. The *a priori* hypothesis for the current study was that batch-fed carpet would result in decreased NO emissions, but increased CO emissions.

Tests performed in this study

Sixty-two tests were performed at the RKIS facility between November, 2003, and February, 2004. Three types of carpet were tested: polypropylene, nylon 6, and nylon 6,6. An ultimate analysis was performed on each type of carpet, with results summarized in Table 1. The major difference in the elemental composition of the carpets is that the nylon carpets contained significant amounts of nitrogen. The results are consistent with the fact that nylon contains 12 percent nitrogen and the fiber is approximately one-third of the total carpet weight. The polypropylene carpet tested had a higher carbon content than the nylon carpet tested, and its heat of combustion was significantly higher. For comparison, the composition of a typical bituminous coal is shown [7]. The ash content of carpet is higher due to the calcium in carpet backing. The volatile content of carpet is significantly higher than that of coal. The sulfur content of carpet is significantly less than that of coal.

Table 1

The carpet was provided in three different size squares: 1 inch, 2 inch, and 3 inch. Carpet squares were banded together using polypropylene straps and batch fed in 0.4 kg (nominal) charges every ten minutes. Because emission transients can vary between charges, depending on how the material is released from the canister, at least five charges are necessary to provide sufficient data to characterize this variability. We found that the size of the carpet squares in each charge did not significantly influence emission transients. Therefore, results presented here address differences in the emission transients from the three types of carpet tested. The kiln temperature at the exit of the primary combustion chamber was 1000°C (nominal) for these experiments.

Results

Transient puff duration

In Figure 2, typical emission transients for a nylon carpet charge are shown. During burning of the charge, emissions of CO, THC and PAH peak at approximately two orders of magnitude above the baseline. The NO/NO_x profile is more complex. In all tests, the NO_x and NO profiles were identical, indicating that NO₂ levels are negligible. When nylon carpet is co-fired in the kiln, NO emissions increase during initial burning, decrease during peak burning when the incomplete combustion byproduct emissions peak, and increase again in the final stages of carpet burning. In Figure 3, a series of five CO and NO transients are shown to demonstrate the repeatability of these puffs.

Figure 2 and Figure 3

The duration of an emission transient was defined as the time for NO concentration to return to within 25% of the baseline value. The average duration and standard deviation of durations for carpets of different types and cut sizes are shown in Figure 4. As shown, there is no significant difference in the burn duration of these charges which have the same mass but are cut in different sizes and are composed of different types of face fiber.

Figure 4

Carbon emissions

Since the CO, THC and PAH transients all had similar shapes, only the CO results are presented. These results are shown in Figure 5. The average CO concentration was obtained by integrating over the emission transient duration, as defined above. For all three carpet types, peak CO concentrations were two to three orders of magnitude above the baseline value of 10-15 ppm.

Figure 5

Nitrogen emissions

Peak NO_x concentration and a concentration averaged over the transient duration are shown in Figure 6. As previously mentioned, differences between NO_x and NO emissions were negligible. As expected because of its low nitrogen content, NO_x emissions from polypropylene carpet were small, with a slight increase observed that is likely due to a slight increase in flame temperature and, therefore, thermal NO. Nylon carpet burning, on the other hand, resulted in a significant increase in NO emissions above the 35-45 ppm baseline concentration. The total increase in NO emissions was calculated by integrating over the transient. This value was then compared to the total nitrogen input in each charge of nylon carpet. The conversion of the nylon nitrogen to NO was found to range from one to two percent for these tests. This level of fuel nitrogen conversion to NO is less than the three to eight percent found previously with the semi-continuous feeding of shredded fiber and ground fines, which is consistent with a portion of the carpet combustion occurring under oxygen-limited conditions in these batch-fed tests.

Figure 6

Emissions of other measured nitrogen species were small. NO₂ emissions (see NO/NO_x curves in Figures 2 and 3), N₂O emissions (Figure 7), and NH₃ emissions (Figure 8) were not significant in these tests.

Figure 7 and Figure 8

Conclusions

Transient puff emissions were characterized from burning carpet charges fed to a 73 kW pilot-scale rotary kiln test combustor. The 0.4 kg charges required about two minutes to burn. CO spikes of up to one percent were observed. Effects of carpet burning on thermal NO emissions

were negligible, based on the polypropylene carpet tests. For nylon carpets, increased NO emissions corresponded to a one to two percent conversion of fuel-nitrogen (i.e. nitrogen in the nylon fiber) to NO. These tests demonstrate the feasibility of burning batch fed waste carpet as a supplemental fuel, that rapid volatilization of batch fed carpet can lead to emission transients, and that increased NO emissions may result from the burning of nylon carpets.

References

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- [6] Lemieux, P., E. Stewart, M. Realff, J. A. Mulholland (2004), Emissions Study of co-firing waste carpet in a rotary kiln, *Journal of Environmental Management*, 70, 27-33.
- [7] Bartok, W., Sarofim, A.F. (eds), *Fossil Fuel Combustion*, Table p.1, p. 835, Wiley, 1991.

Table 1. Ultimate and proximate analysis results for three carpet types tested and a typical medium-volatile bituminous Pennsylvania coal [7]. 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

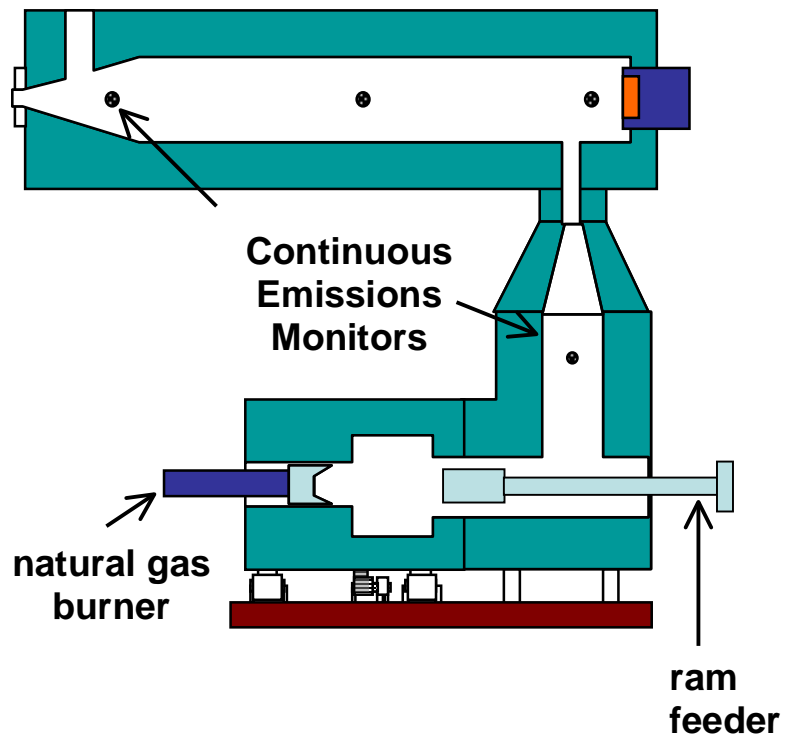


Figure 1. RKIS facility.

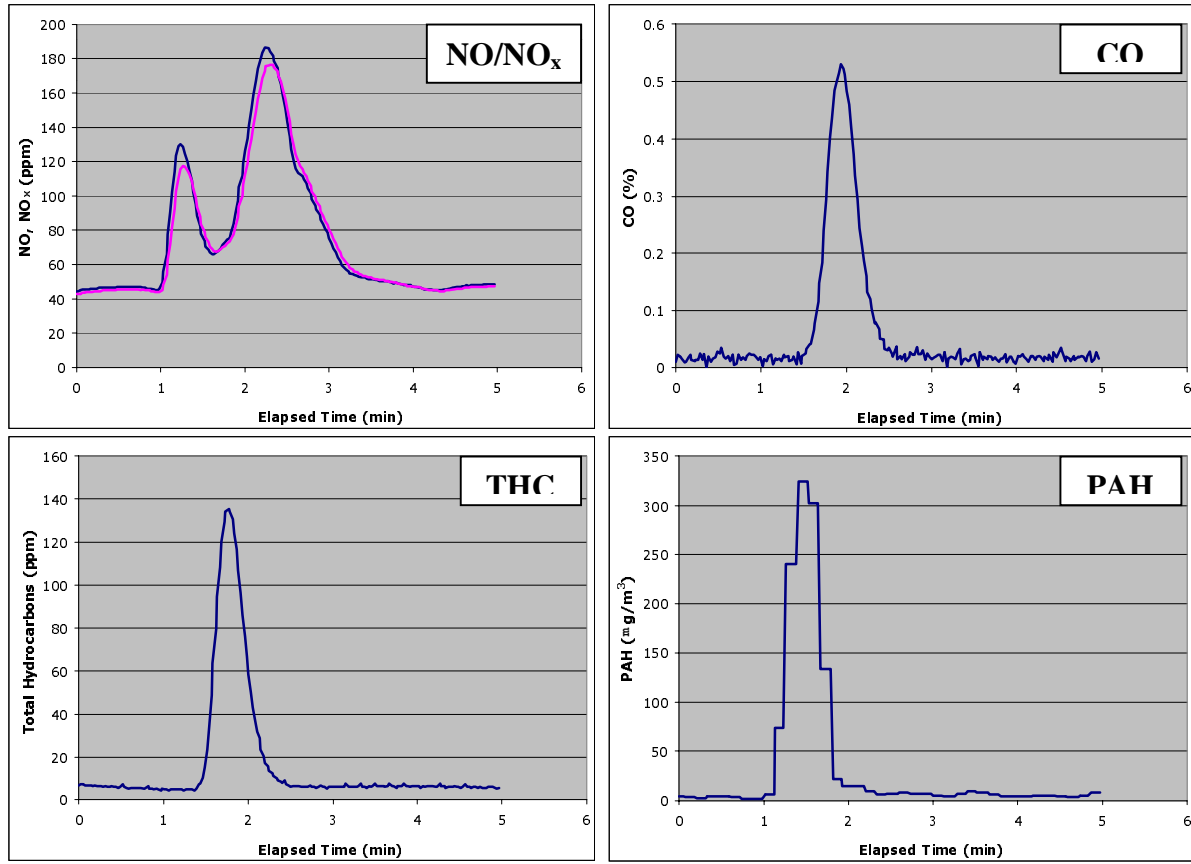


Figure 2. Typical emission profiles for a nylon carpet transient puff.

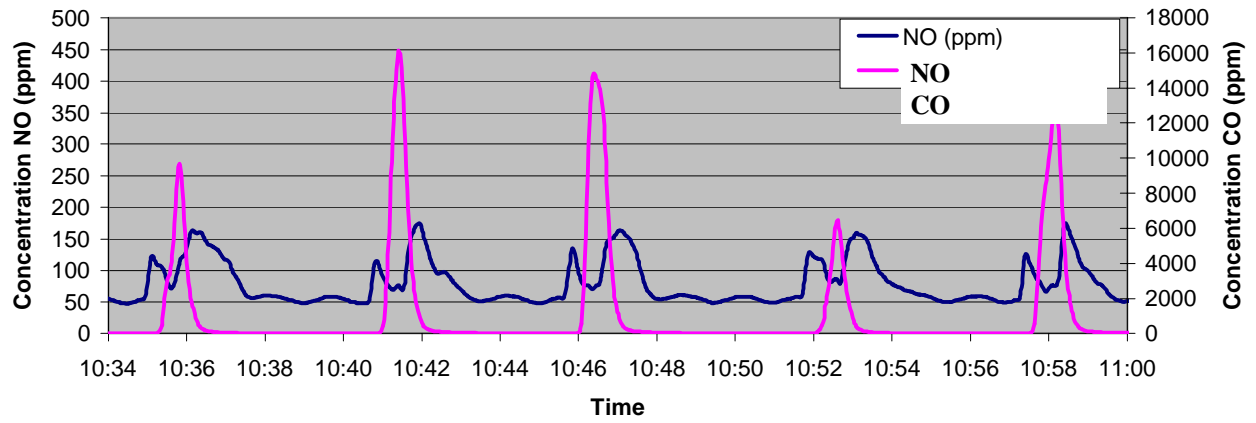


Figure 3. NO and CO transients from a series of five nylon carpet charges.

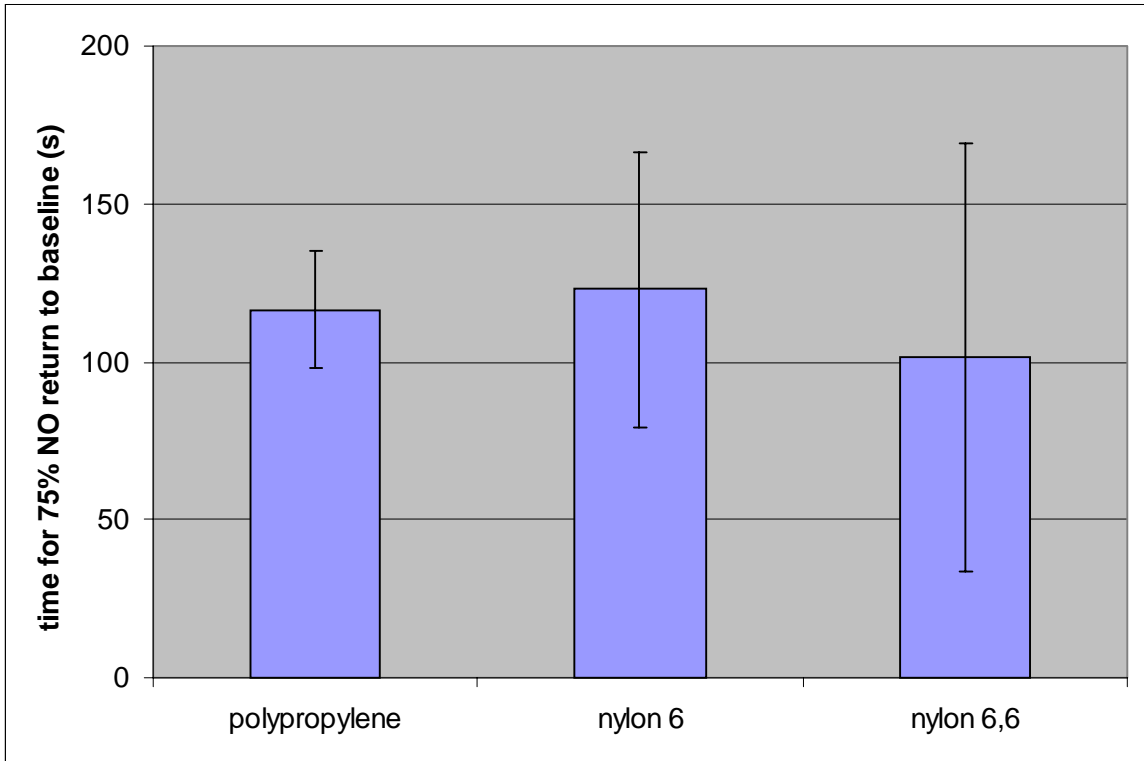
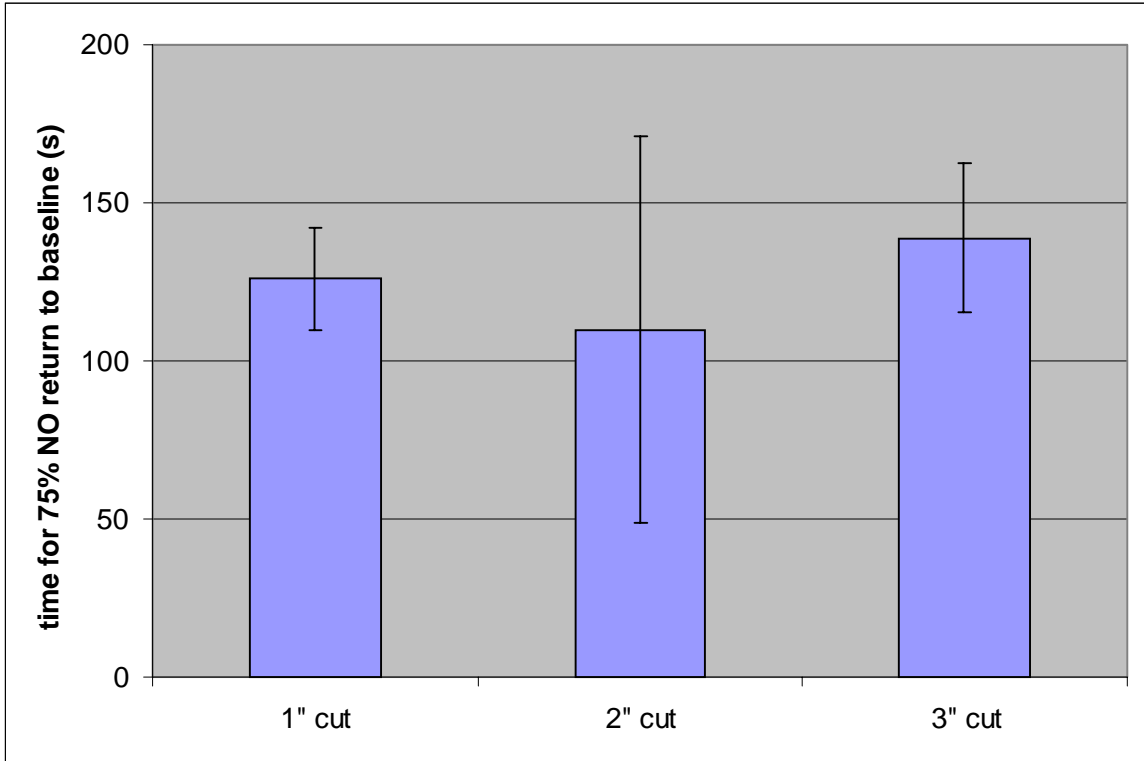


Figure 4. Transient puff duration for three different cut sizes and carpet types. The columns represent the average of 5 to 20 charges, and the bars represent the standard deviation.

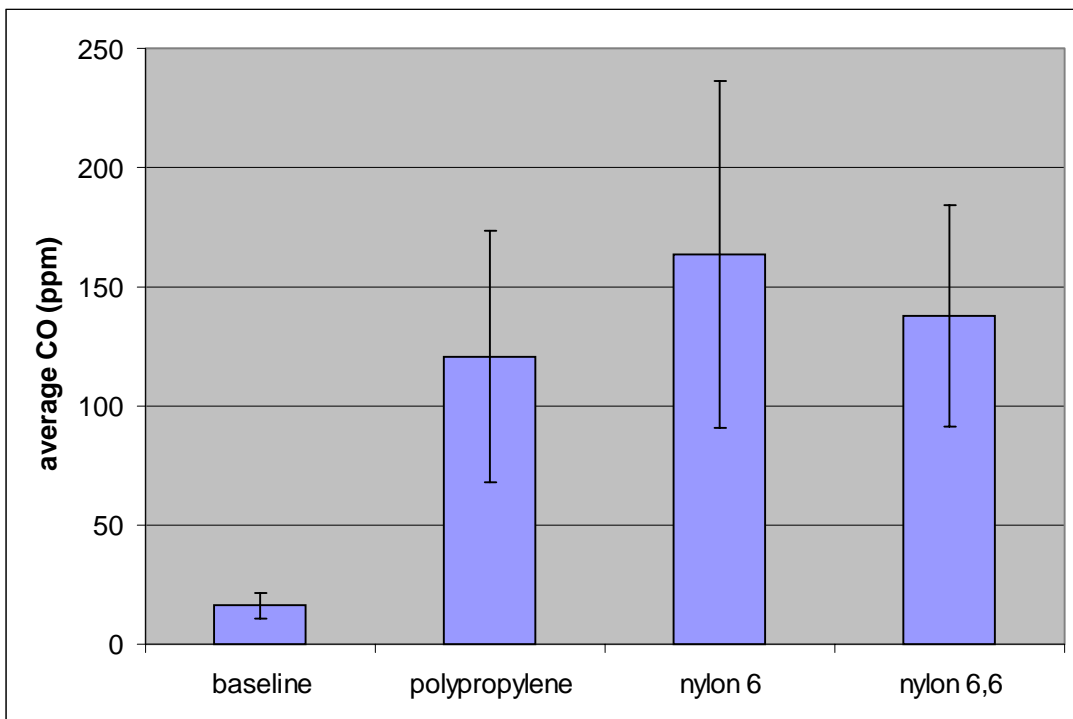
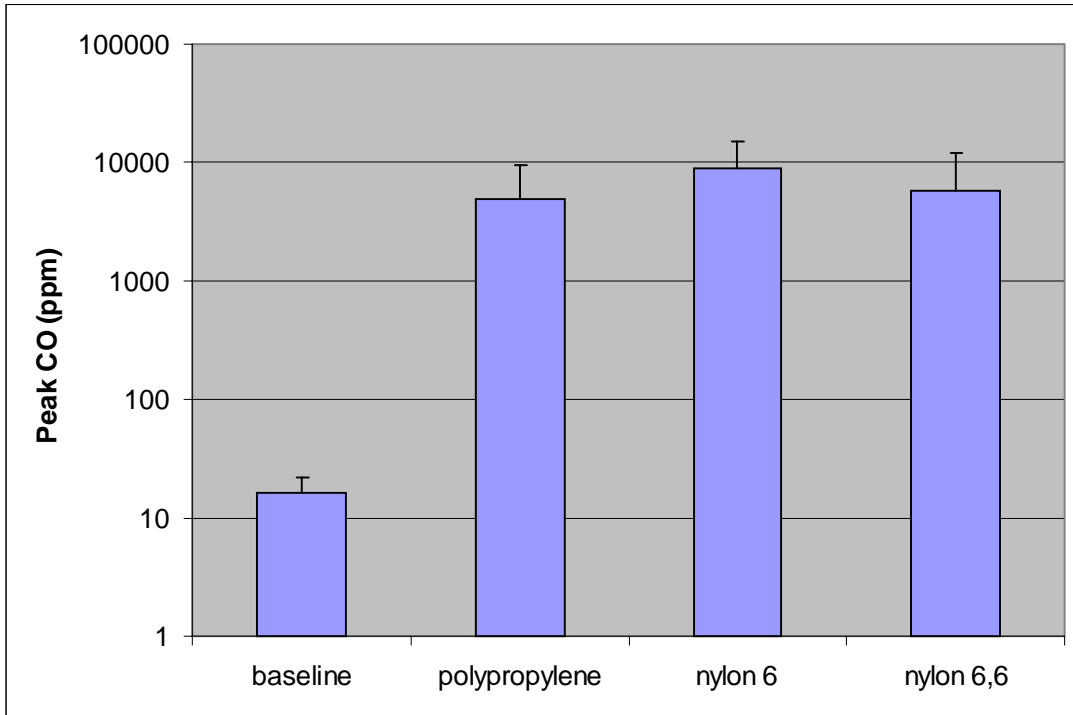


Figure 5. Peak and averaged CO emissions during carpet burning.

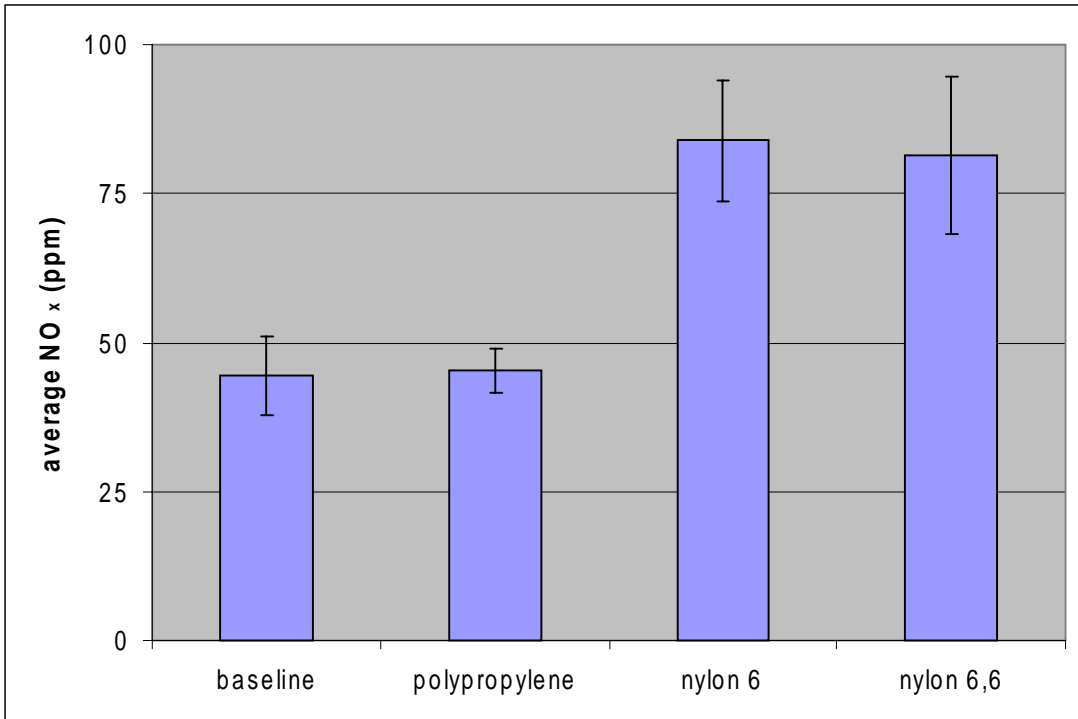
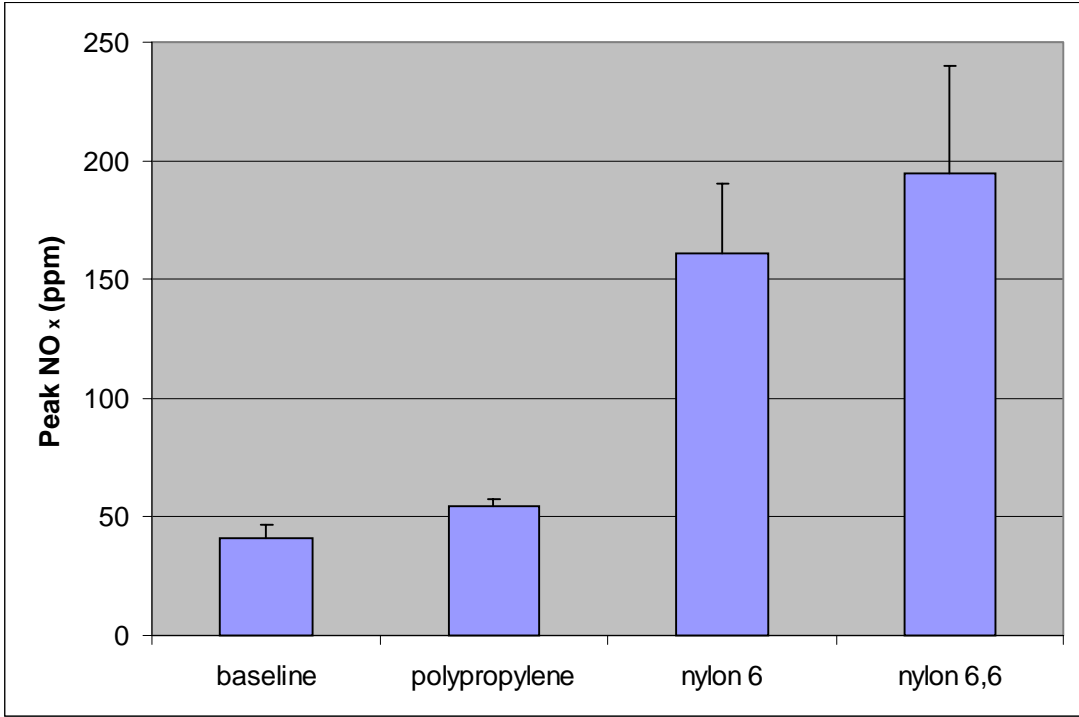


Figure 6. Peak and averaged NO_x concentrations during carpet burning.

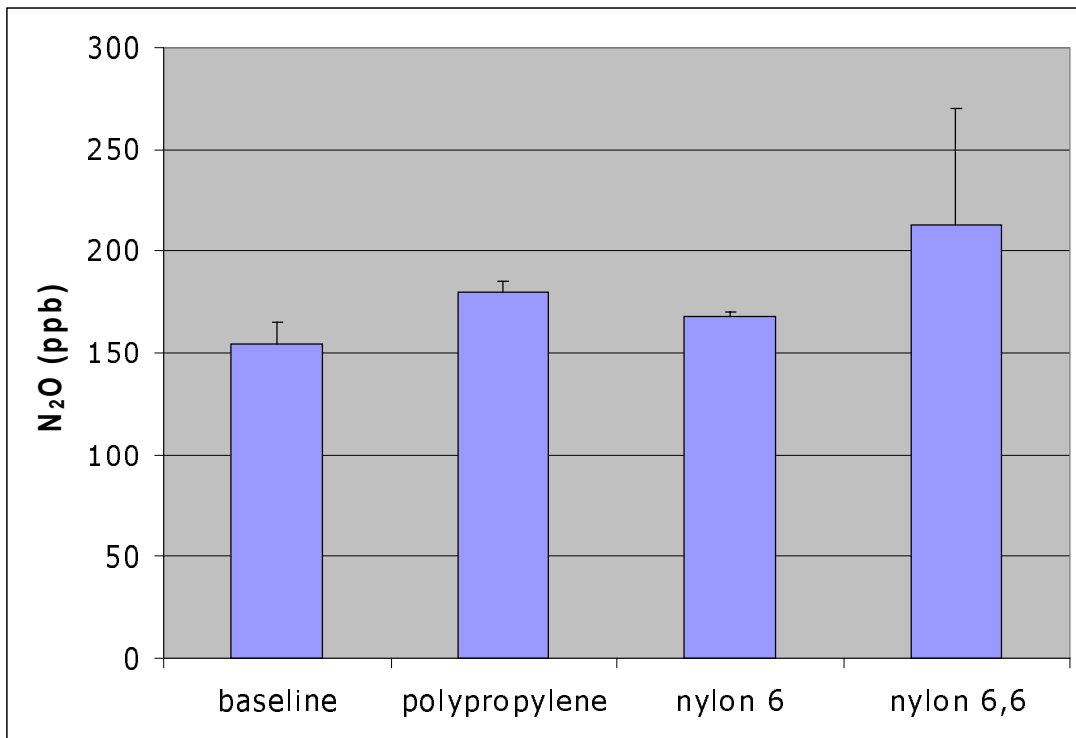


Figure 7. Averaged N_2O emissions during carpet burning.

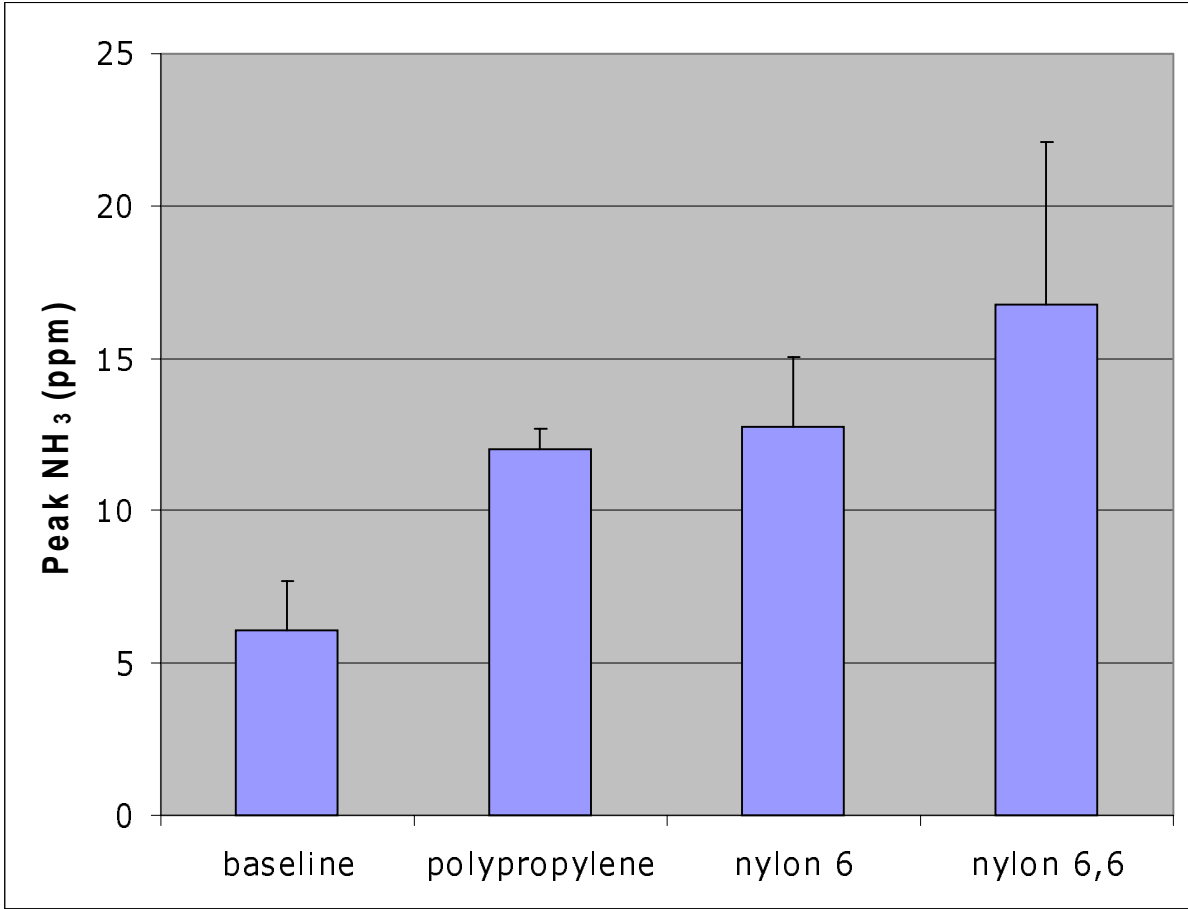


Figure 8. Peak NH₃ concentrations during carpet burning.