



# PAH and soot emissions from burning components of medical waste: examination/surgical gloves and cotton pads

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## Abstract

This is a laboratory investigation on the emissions from batch combustion of representative infectious (“red bag”) medical waste components, such as medical examination latex gloves and sterile cotton pads. Plastics and cloth account for the majority of the red bag wastes by mass and, certainly, by volume. An electrically heated, horizontal muffle furnace was used for batch combustion of small quantities of shredded fuels (0.5–1.5 g) at a gas temperature of  $\approx 1000^\circ\text{C}$ . The residence time of the post-combustion gases in the furnace was  $\approx 1$  s. At the exit of the furnace, the following emissions were measured: CO, CO<sub>2</sub>, NO<sub>x</sub>, particulates and polynuclear aromatic compounds (PACs). The first three gaseous emissions were measured with continuous gas analyzers. Soot and PAC emissions were simultaneously measured by passing the furnace effluent through a filter (to collect condensed-phase PACs) and a bed of XAD-4 adsorbent (to capture gaseous-phase PACs). Analysis involved soxhlet extraction, followed by gas chromatography–mass spectrometry (GC–MS). Results were contrasted with previously measured emissions from batch combustion of pulverized coal and tire-derived fuel (TDF) under similar conditions. Results showed that the particulate (soot) and cumulative PAC emissions from batch combustion of latex gloves were more than an order of magnitude higher than those from cotton pads. The following values are indicative of the relative trends (but not necessarily absolute values) in emission yields: 26% of the mass of the latex was converted to soot, 11% of which was condensed PAC. Only 2% of the mass of cotton pads was converted to soot, and only 3% of the weight of that soot was condensed PAC. The PAC yields from latex were comparable to those from TDF. The PAC yields from cotton were higher than those from coal. A notable exception to this trend was that the three-ring gas-phase PAC yields from cotton were more significant than those from latex.

Emission yields of CO and CO<sub>2</sub> from batch combustion of cotton were, respectively, comparable and higher than those from latex, despite the fact that the carbon content of cotton was half that of latex. This is indicative of the more effective combustion of cotton. Nearly all of the mass of carbon of cotton gasified to CO and CO<sub>2</sub>, while only small fractions of the carbon in latex were converted to CO<sub>2</sub> and CO (20% and 10%, respectively). Yields of NO<sub>x</sub> from batch combustions of latex and cotton accounted for 15% and 12%, respectively, of the mass of fuel nitrogen indicating that more fuel nitrogen was converted to NO<sub>x</sub> in the former case, possibly due to higher flame temperatures. No SO<sub>2</sub> emissions were detected, indicating that during the fuel-rich combustion of latex, its sulfur content was converted to other compounds (such as H<sub>2</sub>S) or remained in the soot. © 2001 Elsevier Science Ltd. All rights reserved.

## 1. Introduction

The treatment and disposal of medical wastes is a subject of concern and controversy, particularly since

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recent locally enforced air pollution standards have forced the closure of many on-site hospital incinerators. As is stated in a recent US-DOE newsletter “infectious waste disposal has reached crisis proportions in many of the nation’s hospitals”. Approximately 465,000 tons of biohazardous waste are generated in the US each year by 377,000 healthcare facilities (Green, 1992). Hospitals, which comprise only 2% of the total number of generators, produce the greatest amount ( $\approx 77$  wt%, or 4 t per month per hospital) of the total biohazardous waste (Green, 1992). Over the last decade, the amount of waste generated by hospitals has increased, due to the wide acceptance of single-use disposable items. It is important here to distinguish how the categories of “hospital wastes”, “medical wastes” and “infection wastes” are defined, because such terms are often mistakenly interchanged (Rutala et al., 1989; MacNight, 1993; Burke, 1994). “Hospital waste” is the most general term and refers to all waste from hospitals, biological and non-biological, that is discarded and not intended for further use. It consists of infectious and non-infectious solid waste, hazardous waste and low-level radioactive waste (Cross et al., 1990; Etter et al., 1992; Rutala and Weber, 1991; Burke, 1994; Klangsin and Harding, 1998). “Medical waste” is a subset of hospital waste, and in turn, infectious waste is a subset of medical waste. Medical waste is defined in Section 3 of the Medical Waste Tracking Act of 1988 “as any solid waste that is generated in the diagnosis, treatment, or immunization of human beings or animals in research pertaining thereto, or in the production or testing of biologicals” (US Department of Health report, 1990). The portion of medical waste capable of producing an infectious disease is considered to be “infectious waste” or “red bag waste”. In order for waste to be infectious, the four conditions necessary for infection to occur must be present, i.e., a virulent pathogen, a sufficiently high dose, a portal of entry, and a host resistance (US Department of Health report, 1990; Burke, 1994; Klangsin and Harding, 1998).

Incineration has been the traditional method used by hospitals to dispose medical waste. In recent years, many hospitals stopped operating their incinerators because the units were old and had no emission control systems. In the US, regulations vary from state to state. For example, in Washington State, 60% of the on-site hospital incinerators have closed in recent years because of the passing of stringent state regulations that prohibit, among other restrictions, the existence of any visible combustibles in incineration ash (Washington Department of Ecology, 1993). In contrast, 35% of hospitals in Oregon and 31% in Idaho have discontinued the use of on-site incinerators (Klangsin and Harding, 1998). A recent article reported that 2400 on-site medical incinerators (corresponding roughly to one-third of the hospitals in the US) were operational in 1996 (Fisher, 1996).

Other technologies considered or used for the treatment of medical wastes involve, in descending order of importance, the usage of private waste haulers to transport the medical waste to regional municipal solid waste (MSW) incinerators, pouring liquids into municipal sewage waste, landfilling, steam sterilization, macrowaving (EDT), microwaving, hydropulping, etc. (Klangsin and Harding, 1998). The most frequent practice, if the on-site incinerators are closed, is off-site incineration in MSW incinerators. Incineration has the important advantages of drastically reducing the volume of waste, and of sterilizing and detoxifying the residue. As added benefits, heat or electricity are produced in waste-to-energy incinerator facilities.

Emissions from uncontrolled incineration include products of incomplete combustion such as CO, polynuclear aromatic hydrocarbons (PAH), polychlorinated dibenzo-dioxins (PCDD) and polychlorinated dibenzofurans (PCDF),<sup>1</sup> polychlorinated biphenyls (PCBs), chlorobenzenes, chlorophenols, hydrogen chloride, particulate matter, mercury, lead, cadmium emissions, etc. Modern medical waste incinerators with properly designed and well-maintained air pollution control equipment can minimize some of the above emissions.

The work presented herein is part of a broader investigation aimed at the combustion characteristics and emissions of organic wastes. The emissions of CO, CO<sub>2</sub>, polynuclear aromatic compounds (PAC), soot and NO<sub>x</sub> from batch combustion of latex examination/surgical gloves and cotton pads are examined. These materials were selected for this work because they are very common in the infectious waste. Generally, plastics and rubber (gloves, containers, tubes, bags, packaging) typically account for more than 1/3 by weight of the infectious red bag waste (Wong et al., 1994),<sup>2</sup> and cotton (pads, bandages, cotton balls, clothes, bedding) account for another 1/3 by weight of the red bag waste (Wong et al., 1994). In this laboratory study, small amounts of shredded latex gloves and cotton pads were burned in fixed beds in a laminar-flow, horizontal electric (muffle) furnace. The emissions of particulates (mostly soot containing both soluble compounds (PAH, sulfates) and insoluble compounds (carbon)), PACs, NO<sub>x</sub>, CO and CO<sub>2</sub> were monitored. The emission yields from the two fuels were contrasted and compared to emission yields from other fuels such as plastics, waste tire chunks and pulverized coal, burning under the same conditions as in previous work in this laboratory.

<sup>1</sup> Accounts for 25% of the total combined PCDD and PCDF flux that enters the US environment (Klangsin and Harding, 1998).

<sup>2</sup> Plastics and rubber account for 20–60 wt% of the red bag waste, according to US EPA, 1996.

## 2. Experimental

### 2.1. Fuel characteristics

The two fuels (latex gloves and cotton pads) were cut into small pieces  $\approx 5 \times 5 \text{ mm}^2$ , see Fig. 1, and were placed in porcelain boats. The elemental composition of the two fuels is shown in Table 1, as determined at Galbraith Laboratories. Cotton pads, being a cellulose material, are rich in oxygen. Both fuels have a high volatile content (especially the latex) and a small inorganic content, generating little ash. A small amount of sulfur (0.73 wt%) was detected in the latex gloves. The energy content (heating value) of latex gloves is comparable to that of premium hydrocarbon fuels (gasoline, diesel oil). The heating value of cotton pads is much lower because of their high oxygen content; it is comparable to that of the alternative fuel methanol.

### 2.2. Batch combustion in the horizontal muffle furnace.

Batch combustion experiments involving fixed beds of shredded fuel were conducted in a horizontal, split-cell electric furnace (1 kW max.) fitted with a quartz tube, 4 cm in diameter and 87-cm long, see Fig. 2. The wall temperature was 1000°C. The gas temperature profile was measured by a suction pyrometer (Wheatley et al., 1993). The gas temperature was found to increase in the first half length of the furnace, but was fairly constant in the second half of the furnace, at  $\approx 1000^\circ\text{C}$ . Hence, the first half length of the furnace acted as an air pre-heater. Upon reaching the pre-determined wall temperature, a porcelain boat loaded with 0.5–1.6 g of sample was inserted from the tube's entrance and it was positioned in the middle of the quartz tube. All experiments were conducted in air. The air flow rate was 4 lpm, and the gas residence time in the second half of the tube (downstream of the sample) was calculated to be 1 s. Sampling was conducted at the exit of the furnace. While visible diffusion flame durations over the boat were in the order of 1 min, sampling lasted for several minutes to provide sufficient time for complete carbon



Fig. 1. A photographic depiction of the two fuels: (a) medical examination latex gloves, and (b) sterile cotton pads (gauze), which are abundantly found in “red-bag” medical wastes.

Table 1

Fuel composition and energy content

Property	Latex gloves	Cotton pads
Fixed carbon (%)	$\approx 0$	12.59
Volatiles (%)	97.80	85.57
Ash (%)	2.20	1.84
Carbon (%)	82.61	42.44
Hydrogen (%)	11.47	6.89
Sulfur (%)	0.73	0
Nitrogen (%)	0.21	0.20
Oxygen (%)	2.78	48.67
(by difference)		
High heat.val. (estimated) (MJ/kg)	44	24

oxidation. This was determined by continuously monitoring the  $\text{CO}_2$  emissions.

### 2.2.1. Combustion emissions monitoring

Unburned PAC emissions, as well as  $\text{NO}_x$ ,  $\text{CO}$ ,  $\text{CO}_2$ , and particulates (mostly soot and, possibly, traces of minerals) from the combustion of examination/surgical gloves and cotton pads were measured. The PAHs were sampled at the exit of the furnace by passing the entire effluent through a sampling stage consisting of a Grassby sampling head with a filter stage and a glass cartridge containing XAD-4. The sampling stage was placed adjacent to the furnace, see Fig. 2, to minimize losses. The particulate emissions were trapped on the upper portion of the sampling stage on a 90-mm diameter by 1-mm thick Whatman glass fiber filter with a nominal pore size of 0.45  $\mu\text{m}$ . Gas-phase aromatic hydrocarbon emissions were adsorbed on the bed of Supelco XAD-4 resin. After this, the effluent passed through a mildly-heated Permapure dryer, where the moisture was removed, and the effluent was then monitored for  $\text{NO}_x$  using a Beckman 951A chemiluminescent  $\text{NO}/\text{NO}_x$  analyzer, for  $\text{SO}_2$  using a Rosemount Analytical 590 UV analyzer, and for  $\text{CO}$  and  $\text{CO}_2$  with Horiba infrared analyzers. The output of the analyzers was recorded using an Omega analog-to-digital converter interfaced with a microcomputer running Omega data acquisition software and Microsoft Excel. The signals from the analyzers were recorded for the duration of the experiment and subsequently were converted to partial pressures.

### 2.3. Extraction and concentration of PAC emissions

The XAD-4 and the filters were pre-cleaned prior to use. Pre-cleaning was performed by extracting unused XAD-4 resin in a soxhlet apparatus for two 12-h periods with methylene chloride prior to use. The methylene chloride was changed before the second 12-h extraction. The resulting solutions were concentrated and checked

ELECTRICALLY-HEATED  
HORIZONTAL MUFFLE FURNACE

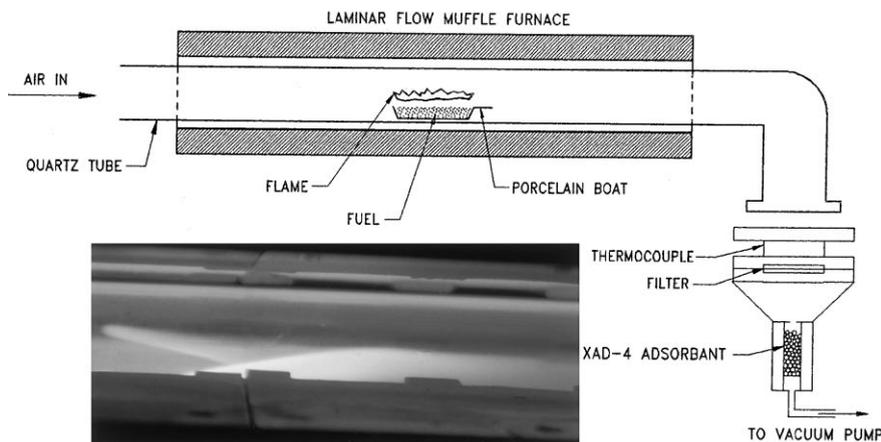


Fig. 2. General schematic of the experimental setup showing features of the laminar-flow, horizontal muffle furnace and a photograph of a combustion run showing the diffusion flame that formed over the sample bed.

for the presence of PAHs. The XAD-4 resin and filters were air-dried prior to use. All glassware was pre-cleaned using a similar procedure. Following the combustion experiments, the filters and resins were removed and stored in separate teflon-lined jars at 4°C. The filters and XAD resins were extracted separately by soxhlet extraction for a 24-h period with methylene chloride. Prior to extraction with methylene chloride, an internal standard containing 50 µg each of naphthalene-*d*<sub>8</sub>, acenaphthene-*d*<sub>10</sub>, anthracene-*d*<sub>10</sub>, chrysene-*d*<sub>12</sub> and perylene-*d*<sub>12</sub> was applied to each of the glass jars. In addition, the furnace was operated in the absence of fuel to provide a combustion blank. The filter and XAD resin from the combustion blank were also extracted with methylene chloride. After extraction, the samples were concentrated to a final volume of 10 ml using a Büchi Rotavapor. The final extracts were stored in glass vials with teflon caps at 4°C before being analyzed by GC-MS. The holding times between collection of the samples and soxhlet extraction never exceeded 14 days.

#### 2.4. GC-MS analysis

The GC-MS system consisted of a Hewlett-Packard (HP) Model 5890 GC equipped with a HP Model 5971 mass selective detector. The GC-MS conditions and data reduction were described by Panagiotou et al. (1996), Atal et al. (1997, 1998). The instrument was tuned in accordance with EPA semivolatile criteria prior to the GC-MS analysis of each set of samples. The instrument passed initial and continuing calibration criteria and no data

were qualified as a result of calibrations. Relative response factors were calculated and all criteria were met. This was to be expected due to the well-controlled experimental conditions and the lack of environmental interferences or matrix effects. Each of the target compounds as well as the tentatively identified compounds was quantified using the appropriate deuterated internal standard. The use of surrogates was not required for this analytical methodology because of the well-controlled experimental conditions and experience has indicated that no matrix interactions occur between the target compounds and the components used in these experiments.

In a departure from the EPA method, the GC-MS system was run in the full scan mode and not in a single ion monitoring mode. This was done to ensure the identification, quantification and reporting of tentatively identified compounds. The use of the full scan mode does not significantly modify the method except to raise the lower reporting limit to about 1 µg of component per gram of fuel combusted. Values shown in Table 2 that are less than 1 µg/g are technically non-detects. Analysis of the combustion system blanks indicated the presence of xylenes, bis(2-ethylhexyl) phthalate, and siloxanes in quantities sufficient to reject all positive results for these compounds in the combustion extracts.

The standard solutions containing 50 µg each of the five standards were diluted to 10 ml and analyzed as an instrument blank, to provide an indication of extraction efficiency for each of the internal standards. Samples with an extraction efficiency of less than 30% for any of the internal standards were repeated.

Table 2

A list of yields of predominant PAC compounds (detected as fuel combustion byproducts from XAD-4 (gas-phase) and filters (condensed phase)), soot, CO, CO<sub>2</sub> and NO<sub>x</sub>.  $T_g = 1000^\circ\text{C}$ ,  $t_{\text{res}} = 1 \text{ s}$

Compound (in $\mu\text{g/g}$ of fuel)	Latex (solid)	Latex (gas)	Latex (total)	Cotton (solid)	Cotton (gas)	Cotton (total)	Tire (total)	Coal (total)
Napthalene (128)	137	14307	14444	0	260	260	4485–8260	184
Acenaphthylene (152)	2600	645	3245	3	365	368	2046–4555	54
Fluorene (166)	980	22	980	2	45	47	492–1508	12
Phenanthrene (178)	4024	15	4039	40	50	90	4443	5246
Anthracene (178)	1182	0	1182	2	21	23	882–1401	20
Fluoranthene (202)	1732	0	1782	64	5	69	1385–1319	49
Pyrene (202)	3109	0	3109	113	2	115	1146–1420	29
Cyclopenta[ <i>cd</i> ]pyrene (226)	719	0	719	86	0	86	202–426	11
Benzo[ <i>a</i> ]pyrene (128)	331	0	331	20	0	20	494–591	8
Cumulative (in mg/g)	28.2	18	46.2	0.6	1.5	2.1	22–40	0.6
Soot (in mg/g of fuel)	264			18				
CO (in mg/g of fuel)		181			183		18–27	1.5
CO <sub>2</sub> (in mg/g of fuel)		525			828		920–1450	1420
NO <sub>x</sub> (in mg/g of fuel)		0.75			0.66		1	3.3

In order to assess the reproducibility of the PAH analysis, duplicate analyses were performed and a standard deviation of less than 10% was observed. The source of the experimental error results from a combination of sampling, extraction, concentration and analysis techniques. The experimental procedure was kept consistent in all tests to ensure the validity of relative trends.

### 3. Results and discussion

As mentioned earlier, batch combustion of fixed beds of fuel occurred in the horizontal laminar-flow furnace at a gas temperature of  $1000^\circ\text{C}$ . Upon introduction of the fuel, placed in porcelain boats, to the pre-heated furnace, the fuel bed heated up and ignited. A flame formed over the fuel bed, see Fig. 2, and a plume of smoke was visible moving to the exit of the furnace. The luminous and sooty volatile flame burn-times were in the order of 1 min. The temporal evolution and burning of the pyrolyzates is illustrated by the CO<sub>2</sub> partial pressure vs. time profiles, shown in Fig. 3. The flames from the latex fuel were much brighter and sootier than those from the cotton. During the combustion period, the oxygen concentration in the post-flame zone plunged to a minimum as low as 8% (from a baseline of 21%). CO<sub>2</sub> and CO partial pressures were as high as 9% and 7%, respectively, for latex (0.6-g fuel sample). For cotton, the CO<sub>2</sub> and CO partial pressures reached maxima as high as 25% and 15%, respectively (1.4-g fuel sample).

#### 3.1. Emissions of soot and PAC

The emission yields (expressed as mass/mass of fuel burned) of prominent PAC, soot, CO, CO<sub>2</sub> and NO<sub>x</sub> are listed in Table 2. The experiments were repeated three times and average values are given herein. *The emissions of soot* from latex gloves were found to be more than an order of magnitude higher than those from cotton, compare 246 mg/g ( $\pm 15\%$ ) for latex with 18 mg/g ( $\pm 20\%$ ) for cotton. These numbers also mean that, under the conditions of the experiments, almost 25% of the mass of the latex gloves was converted to soot, contrasted to less than 2% of the mass of cotton pads. Of course, it should be kept in mind that these absolute values depend on the combustion conditions. If the mass of the fixed bed, or the gas temperature, or the air flow rate were to change, the emissions would vary.

The emissions of some components of the PAC are shown in Table 2, where also shown are the total amounts of the detected PAC, both in the condensed phase (soot) and in the gas phase (XAD-4) as well as the combined amounts in both phases. For comparison, the combined amounts of PAC components detected in the combustion effluent of waste tire-derived fuel (TDF) (both tire crumb and tire chips, in 0.8-g fuel samples) are also listed. More than 120 semivolatile organic compounds were recorded, ranging from indene (MW = 116) to anthanthrene (MW = 276).<sup>3</sup> As expected, the lighter,

<sup>3</sup> Please note that the detection efficiency of GC-MS may be low for the largest and least volatile compounds in this work.

low molecular weight hydrocarbons (such as naphthalene and other two-ring PACs) were found in the gaseous phase. The heavier multi-ring compounds were found in the condensed (solid) phase, i.e., in the collected soot. Often, many different isomers existed in the extracts with the same condensed chemical formula, which only increased in complexity as the number of carbon atoms within the PAC increased. This was even further complicated by the detection of partially substituted PACs observed in the combustion product extracts of soot. These substituted PACs were generally single carbons or short unsaturated carbon chains that existed in a myriad of isomeric positions on the larger PAHs.

In an overall comparison, the cumulative PAC yields from the combustion of latex were more than an order of magnitude higher than those from the combustion of cotton pads.<sup>4</sup> This is in line with the copious emissions of soot emitted from the combustion of latex (264 mg/g), which accounted for 26% ( $\pm 2\%$ ) of the mass of the fuel. Approximately 10% of the soot was found to be made of extractables in the form of PAC (28.2 mg/g). On the contrary, the soot emitted from the combustion of cotton (18 mg/g) accounted for 1.8% ( $\pm 0.3\%$ ) of the mass of the fuel. Only 3% of the soot was found to be consisting of extractables in the form of PAC (0.56 mg/g). Thus, the combustion of cotton pads not only emits much less soot than that of shredded latex gloves but it also contains a much smaller fraction of condensed PAC.

Regarding the gas-phase PAC emissions from the combustion of the two fuels, the situation is somewhat different. Unlike latex, the combustion of cotton resulted in higher relative yields of PAC in the gas phase of mid-size PACs with molecular weights of 150–180 amu, including three-ring PACs. The fact that compounds such as gas-phase fluorene (166) and gas-phase phenanthrene (178) are higher not only in relative but also absolute amounts than those from the combustion of latex merits further attention. The reason is that gaseous PACs may be more difficult to capture by pollution control devices (electrostatic precipitators, venturi scrubbers, baghouses-

<sup>4</sup> Actually, the cumulative PAC yields from latex were 22 times higher than the corresponding emissions from cotton; however, the exact magnitude depends on the mass loading and to a lesser extent, on the geometry of the sample. In these experiments, the mass loading of the shredded cotton pads was more than two times that of the latex gloves. This was done to equalize the calculated global equivalence ratios,  $\phi$ , of the two fuels in the flame zone of the tubular furnace. The global equivalence ratio was calculated as:

$$\phi = \left( \frac{m_{\text{fuel}}}{m_{\text{air}}} \right)_{\text{actual}} / \left( \frac{m_{\text{fuel}}}{m_{\text{air}}} \right)_{\text{stoichiometric}} \quad (1)$$

The equivalence ratio is equal to the inverse of the excess air ratio,  $\lambda$ , based on the chemical composition of the two fuels listed in Table 1.

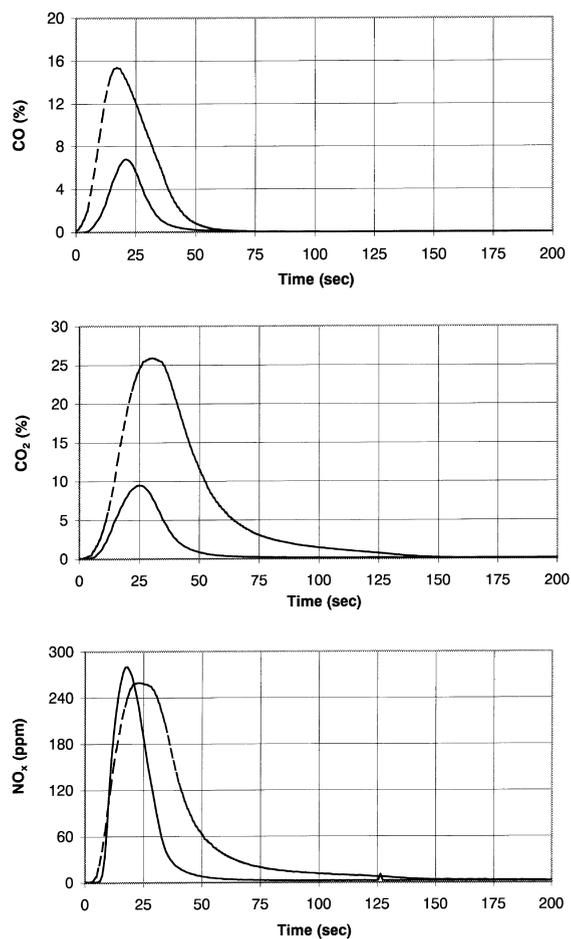


Fig. 3. CO, CO<sub>2</sub> and NO<sub>x</sub> emissions vs. time profiles for batch combustion of shredded latex gloves (solid lines) and cotton pads (dashed lines), at  $T_g = 1000^\circ\text{C}$ .

es, etc.). This result was quite consistent in all experiments conducted in this study, and it should not be an artifact since the sampling stages were kept at similar conditions during combustion of both latex and cotton.

A comparison of the cumulative PAC emissions from the combustion of the two fuels of this study with those from a pulverized HVA bituminous coal and waste TDF, burned in the same apparatus at similar conditions (Levendis et al., 1998), is also given in Table 2. Since the experiments were performed at different time periods and the sampling train conditions may have been slightly different and, hence the separation between gas and condensed phase might have been affected, only the comparison of the total gaseous + condensed PAC is given herein. The PAC emissions from the combustion of cotton pads were higher than those from fixed beds of pulverized coal by factors of 1.5–8. At the high end, the emissions of shredded latex gloves were similar to those

of TDF. The range of values for the PAC yields from the combustion of TDF given in Table 2 correspond to: (a) the lower values to emissions from tire crumb (200  $\mu\text{m}$ ), and (b) the higher values to emissions from small (a few mm) chips of waste tire. Both tire crumb and tire chip samples were burned in fixed beds of 0.8 grams each. The pulverized coal (80–100  $\mu\text{m}$ ) was also burnt in fixed sample beds of 0.8 g. The PAC yields from burning latex appear to be in the range of those of TDF.

Regarding the individual PAC species on from the combustion of the fuels, a few additional comments may be made. Benzo[*a*]pyrene, cyclopenta[*cd*]pyrene, fluoranthene and phenanthrene, among others, are known to exhibit high mutagenic activities (Howard et al., 1995). Within the same sample:

(a) The yields of naphthalene and acenaphthylene were comparable for cotton, but naphthalene was much higher from the rest of the fuels, in agreement with results reported by Longwell for premixed flames (Longwell, 1982).

(b) The yields of phenanthrene, fluoranthene and pyrene, were comparable to each other, and were all less than naphthalene. The striking analogy of the yields of the isomers of pyrene and fluoranthene ( $\text{C}_{16}\text{H}_{10}$ ) has also been reported by Longwell (1982) for toluene and acetylene flat flames as well as diesel engines and gasoline engines; however, absolute values varied widely among the different fuels.

(c) The yield of cyclopenta[*cd*]pyrene was lower, by factors of 2–4, than that of pyrene.

(d) The yield of benzo[*a*]pyrene was comparable or typically lower than cyclopenta[*cd*]pyrene.

Given the completely different nature of the fuels herein, as well as those discussed by Longwell (1982), such similarities are notable and may indicate PAH growth by a similar mechanism. Current work in our laboratory is targeting the minimization of PACs and soot, exploring the effects of mixing with air, as well as changing temperature and residence times of the combustion products in the furnace.

### 3.2. Emissions of $\text{CO}$ , $\text{CO}_2$ , $\text{NO}_x$ and $\text{SO}_2$

Sampling for the gaseous emissions of  $\text{CO}$ ,  $\text{CO}_2$ ,  $\text{NO}_x$  and  $\text{SO}_2$  was conducted simultaneously with PACs. As explained earlier, the entire effluent was passed through the PAC sampling stage (filter and XAD-4 adsorbent), then through a Permapure drier and, subsequently to the analyzers. To verify that the presence of XAD-4 in the sampling train did not interfere with the  $\text{CO}$ ,  $\text{CO}_2$  and  $\text{NO}_x$  gases in the sampling lines, blank runs were conducted. In each of those runs, the aforementioned gases, supplied from laboratory tanks at known concentrations, passed through the furnace fitted with or without the XAD-4 bed stage. No difference was recorded by the analyzers.

Typical profiles of the evolution of  $\text{CO}$ ,  $\text{CO}_2$  and  $\text{NO}_x$  during combustion of shredded latex gloves and cotton pads are shown in Fig. 3. Each plot depicts the change in the partial pressures of  $\text{CO}$ ,  $\text{CO}_2$  and  $\text{NO}_x$  (all three superimposed) vs. burnout time.

Emission yields of  $\text{CO}$  from batch combustion of cotton and latex were similar ( $183 \pm 50$  vs.  $181 \pm 100$  mg/g). However, the  $\text{CO}_2$  yields from cotton were higher than those from latex ( $828 \pm 20$  vs.  $525 \pm 60$  mg/g), despite the fact that the carbon content of cotton was half that of latex, see Table 2.<sup>5</sup> This is indicative of the more effective combustion of cotton, half the mass of which is oxygen, see Table 1. Calculations showed that nearly all of the mass of carbon in cotton gasified to  $\text{CO}$  and  $\text{CO}_2$ , while only fractions of the carbon in latex were converted to  $\text{CO}_2$  and  $\text{CO}$  (20% and 10%, respectively). Overall, the  $\text{CO}_2$  emissions from cotton were a little lower than those from fixed beds of coal and TDF, but those from latex were less than half. However, the  $\text{CO}$  emissions were the highest from cotton, and latex followed by TDF and then coal, a distant fourth. The much lower  $\text{CO}$  emissions from TDF and coal are partly due to the respectively much lower volatile content of the char-forming coal (35% volatiles) and the TDF (55% volatiles). A major portion of the last two fuels burns slowly as char with plenty of air, eventually forming mostly  $\text{CO}_2$ .

Yields of  $\text{NO}_x$  from batch combustion of latex ( $0.75 \pm 0.2$  mg/g) and cotton ( $0.66 \pm 0.2$  mg/g) accounted for 15% and 12%, respectively, of the fuel nitrogen,<sup>6</sup> indicating that more fuel nitrogen was converted to  $\text{NO}_x$  in the former case. This may be surprising, given the high oxygen content of cotton. It could be due to the higher heating value of latex, which could have induced higher flame temperatures (not measured here) and thus produced more “fuel- $\text{NO}_x$ ” as well as “thermal- $\text{NO}_x$ ”. As expected, the  $\text{NO}_x$  yields from batch combustion of TDF and coal were higher (1.0 and 3.3 mg/g), in line with their higher fuel nitrogen content (0.28 and 1.36 wt%, respectively, see Levendis et al., 1998).

No  $\text{SO}_2$  emissions were detected, indicating that during the fuel-rich combustion of latex, its sulfur content (0.73 wt%) was converted to other compounds, possibly  $\text{H}_2\text{S}$ , or remained in the soot as sulfates.

<sup>5</sup> The margins indicate standard deviation among various runs. For PAC compounds, the variation was within 10–20%.

<sup>6</sup> Assuming all  $\text{NO}$ , and after some approximate corrections were applied to account for “thermal- $\text{NO}$ ” (assumed 25% of the total).

#### 4. Summary

Laboratory experiments were conducted in a horizontal muffle furnace to explore the emissions from batch combustion of predominant components of 'red bag' medical wastes. Since plastics and cotton account for most of the weight (and certainly the volume) of the infectious medical wastes, their combustion was exemplified herein by burning medical examination latex gloves and cotton pads. The emissions of soot, PACs, CO, CO<sub>2</sub> and NO<sub>x</sub> were examined. For comparison purposes, the results were contrasted with the emissions from the combustion of pulverized coal and TDF in the same apparatus and similar conditions, obtained in a recent study, see Levendis et al. (1998). Emissions were measured at the exit of an electrically heated muffle furnace with a post-flame residence time of  $\approx 1$  s at a gas temperature of 1000°C. This work is part of a bigger investigation on the combustion emissions from medical wastes and on methods for their minimization. Some of the main results of this study are summarized as follows:

- Batch combustion of shredded latex gloves in fixed beds resulted in yields of PAC and soot that were more than an order of magnitude higher than those from batch combustion of cotton pads.
- At the high end of emissions, shredded latex gloves generated PAC emission yields that were comparable to those emitted from batch combustion of TDF.
- At the low end of emissions, shredded cotton pads generated PAC emission yields that were a little higher than those emitted from batch combustion of fixed beds of a pulverized, bituminous coal.
- Under the conditions of these experiments, particulate yields from batch combustion of latex accounted for one quarter of the original mass of latex, while the particulate emissions from cotton accounted for one tenth of its original mass. Moreover, while a little over one tenth of the particulate mass from latex was condensed-phase PAC, only a few percent of the particulate mass from cotton was condensed-phase PAC.
- The gas-phase PAC yields from the combustion of cotton were high relative to those in the condensed phase, with the three-membered ring PACs (such as phenanthrene and anthracene) reaching values even higher than those from latex.
- Batch combustion of cotton resulted in CO yields that were comparable to those from latex gloves ( $183 \pm 50$  vs.  $181 \pm 20$  mg/g), 10 times as much as those from TDF ( $18\text{--}27$  mg/g) and more than 100 times as those from fixed beds of pulverized coal ( $1.5$  mg/g).
- Batch combustion of cotton resulted in CO<sub>2</sub> yields that were a higher than those from latex gloves ( $828 \pm 100$  mg/g vs.  $525 \pm 25$  mg/g) but lower than

those from TDF and coal and ( $920\text{--}1450$  and  $1420$  mg/g, respectively).

- Batch combustion of cotton resulted in the lowest NO<sub>x</sub> yield ( $0.66 \pm 0.2$  mg/g), followed by that from cotton ( $0.75 \pm 0.2$  mg/g), then followed by TDF ( $1$  mg/g) and coal ( $3.3$  mg/g) in ascending order.
- No SO<sub>2</sub> emissions were detected, indicating that during the fuel-rich combustion of latex, its sulfur content ( $0.73$  wt%) was converted to other compounds, possibly H<sub>2</sub>S, or sulfates in the soot.

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