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ENVIRONMENTAL STUDY OF FIREFIGHTERS

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Abstract—A study of firefighter exposures was undertaken at the request of the U.S Fire Administration. This work was part of a larger study which included field evaluation of the performance of the self-contained breathing apparatus (SCBA) worn by firefighters during structural firefighting. Measurements were made for a variety of contaminants including CO, CO_2, benzene, HCN, HCl, H_2SO_4, HF, acrolein, CH_4, formaldehyde and PNAs. Many of the analyses were performed by collection of bag samples followed by Fourier transform infrared spectroscopy using a field mobile spectrometer. Measurements were also made using solid sorbent tubes and direct-reading meters. Sampling was done both during the knockdown and during overhaul phases of structural firefighting. Also, in order to estimate exposures including those when the SCBAs were worn, measurements were made both inside and outside the SCBA facepiece.

Carbon monoxide was the most common contaminant found during knockdown, and about 10% of the samples were greater than 1500 ppm. Formaldehyde, acrolein, hydrogen chloride, hydrogen cyanide, sulphuric acid and hydrogen fluoride all exceeded their respective short-term exposure limits (STEL) on some occasions. Approximately 50% of the knockdown samples for acrolein exceeded the STEL. During overhaul, when masks were usually not worn, many of the contaminants found during knockdown were detected, but typically at much lower concentrations. Inside-mask sampling data suggest that exposure to low concentrations of a variety of compounds is occuring but this is believed to be principally the result of early mask removal or of non-use during knockdown rather than of leakage. The three basic sampling approaches (bag sampling, sorbent tubes and direct-reading meters) proved in this study to be complementary and served to maximize our ability to detect and quantify a wide range of combustion products.

INTRODUCTION

FIREFIGHTING is among the most difficult and hazardous occupations. Apart from exposure to a variety of combustion products, firefighters must also contend with heat, noise, and the extreme difficulty of doing precise and physically demanding tasks (rescue, ventilation, forcible entry, etc.) while wearing heavy and restrictive protective equipment.

Although the self-contained breathing apparatus (SCBA) has been demonstrated to be effective in protecting firefighters from toxic gases and particulate under laboratory conditions, there is some question as to how well the SCBAs perform under actual firefighting conditions. This issue prompted the U.S. Fire Administration to request the National Institute for Occupational Safety and Health to conduct tests to determine their effectiveness during structural firefighting. To complement the SCBA testing it was also recommended that an environmental survey of firefighters' exposure be conducted.

While there are numerous studies of combustion products resulting from controlled fires under laboratory conditions, there are fewer of the combustion products encountered by firefighters during actual structural firefighting (BURGESS *et al.*, 1979; TREITMAN *et al.*, 1980; IVES *et al.*, 1972; TERRILL *et al.*, 1978; BRANDT-RAUF *et al.*, 1988). There are two basic phases of firefighting: knockdown, where the main body of fire is

brought under control, and overhaul, which involves searching for and extinguishing hidden fire. SCBAs are normally not worn during overhaul activities. Of the studies known to us, only BURGESS *et al.* (1979) considered overhauling, and this only to a limited extent. Also, in none of the studies were there attempts made to estimate 'true' exposures, estimates which take into account the portion of time that the SCBAs are worn. Thus, we focused our attention on these areas where there were gaps in the literature. Coincidentally, the concept of estimating 'true' exposure fits well with the respirator testing portion of the study. Current trends in respirator testing are turning to field measurement of ambient concentration divided by inside-mask concentration to produce what is termed a workplace protection factor. Therefore, the measurement of contaminants both inside and outside the mask served simultaneously to characterize the ambient environment, to measure firefighter exposure and to provide a means for assessing the performance of the SCBA. Note that we measured *exposure* and not *dose*. Dose is a function of many other variables which were not measured in this study.

The purpose of this paper is to report on the methods and results of the environmental portion of the study. The results of the SCBA evaluation will be reported separately.

METHODS

Because of the unusual and difficult conditions found in firefighting activities, the equipment had to be light, compact, mobile, ready to operate with minimal delay, and able to withstand an environment involving extremes of temperature and moisture, poor visibility and difficult access. A sampling and analysis system with broad capability and sufficient sensitivity, which would perform satisfactorily for short sampling times at low flow rates for compounds in different physical states, had to be found.

No single approach could satisfy all requirements, so a variety of techniques evolved. For measurements both inside and outside the firefighters mask, it was decided to limit sampling to gases collected in an airbag and analysed using Fourier transform infrared spectroscopy (FTIR). This technique was chosen because of the compactness of the sampling system, the variety of gases which absorb in the i.r. region and the availability of a system which could operate from a mobile laboratory, thus making possible rapid analysis of the samples. Recognizing that even with quick analysis reactive gases might be lost, and that components in other phases would not be detectable with the FTIR system, we also used a variety of solid sorbent tubes, filters, impactors and direct-reading meters (Table 1).

The sample from inside the mask was collected by means of a sample probe mounted inside the facepiece (Fig. 1). A probe was also located outside, to collect simultaneously an ambient (breathing zone) sample. Both samplers operated continuously whether or not the mask was removed during firefighting.

The gas samples were collected in two 3-l. Tedlar bags—one for the ambient sample and one connected to the probe in the SCBA facepiece. Interferograms for each gas sample were produced as rapidly as possible, usually within 30 min of collection, using a Nicolet 20 SXC FTIR spectrometer equipped with a liquid-nitrogen-cooled mercury–cadmium–telluride (MCT) sandwich detector (Nicolet Instrument Corp.,

TABLE 1. SAMPLING/ANALYSIS METHODS

Contaminant	Sampling system	Analytical method	Approx. detection limit*
Various gases	Tedlar bags	On-site FTIR	variable†
Hydrochloric acid	Silica gel tube	Chloride by ion chromatography	0.5 mg m^{-3}
Hydrofluoric acid	Silica gel tube	Fluoride by ion chromatography	0.1 mg m^{-3}
Nitric acid	Silica gel tube	Nitrate by ion chromatography	1.3 mg m^{-3}
Sulphuric acid	Silica gel tube	Sulphate by ion chromatography	0.4 mg m^{-3}
Hydrogen cyanide	Soda lime tube	Cyanide by modified Konig Reaction	0.1 ppm
Acetaldehyde	Treated porous Polymer tube	Gas chromatography/FID	0.1 ppm
Formaldehyde	Polymer tube	Gas chromatography/FID	0.1 ppm
Acrolein	Polymer tube	Gas chromatography/FID	0.1 ppm
Volatile organic compounds	Charcoal tube	Gas Chromatography/FID/ Spectrometry	0.3 ppm‡
Fibres	Cellulose ester filter	Phase contrast microscopy	0.4 f ml^{-1}
Bulk materials	Hand collected	Polarized light microscopy	<1%
Particle size distribution	Cascade impactor	Gravimetric	—
PNAs	Teflon filter	Gas chromatography/FID	5 $\mu g\ m^{-3}$§
CO	Direct-reading meter	Electrochemical cell	1.0 ppm

*Detection limits calculated based on a 0.5 l. min^{-1} flow rate and 15-min sample time unless otherwise noted. These are only approximate since actual sample time and flow rate varied for individual field samples.
†Varies as the signal to noise ratio for each sample.
‡Total hydrocarbons calculated in terms of *n*-nonane.
§Determined for an LOD of 100 ng in a 15-min sample at 1.5 l. min^{-1}.

Madison, Wisconsin). The spectrometer was in a mobile trailer kept at the fire station. A total of 32 interferograms were collected and averaged for each sample at a spectral resolution of 0.5 cm^{-1}. All sample spectra were collected at a total pressure of 740 Torr. Sample spectra were ratioed against a background of high purity nitrogen. Gas concentrations for a variety of pre-determined compounds were calculated by computer, using a least-squares fit (LSF) algorithm modified by the manufacturer for our application (HAALAND and EASTERLING, 1982).

Since the spectrum of the sample collected is a permanent record, the analyst can search it for additional components not in the LSF program, and can also confirm the presence of compounds found by the program. The latter is done by displaying the wavelength region of interest, comparing the sample spectrum with reference spectra and finally subtracting each reference spectrum from the sample spectrum. A flat baseline confirms the identification. Other methods, such as the addition of known quantities of reference compounds, may be used to confirm both the presence of a compound and the quantitative estimate of concentration obtained from the LSF program.

As mentioned previously, FTIR analysis of gases would not alone be sufficient to characterize the fire environment; two industrial hygienists, therefore, carried a variety of samplers into each fire knockdown and overhaul. A complete listing of the types of

samplers, collected media, analytical methods and their approximate detection limits is contained in Table 1. Since speed and mobility were required the various sampling devices were prepared in advance and placed in wire baskets (Fig. 2) stored in the fire response vehicle.

For each fire, personal samples (inside and outside mask) were typically collected on two engine company and two truck company firefighters. The two industrial hygienists were also fitted with the modified respirators. In addition to serving as two additional test subjects for the respirator evaluation, the hygienists also carried in the area samplers for both knockdown and overhaul, made direct-reading measurements of CO and temperature, collected bulk samples, and made general observations on environmental conditions, SCBA use, etc. All measurements and observations were recorded on audio tape using a small microphone mounted inside the respirator facemask.

RESULTS

During the course of this study we were able to collect and analyse samples from a total of 22 fires: six training fires, 15 residential fires and one automobile fire. Table 2 provides summary information on location, materials involved, and general conditions for each of the fires.

Figures 3–14 summarize the data from all fires in the form of cumulative log probability plots. This form of data expression was selected since it made possible direct comparison of knockdown values indicated by (K) with levels measured during overhaul (O) and with those measured inside the facemask (M). It also allowed for comparison with levels measured previously by BURGESS *et al.*, (1979), which are indicated by asterisks. Included on many of the figures are the Short-Term Exposure Limit (STEL), the Immediately Dangerous to Life and Health level (IDLH), and the Short-Term Lethal Concentration (STLC) (TREITMAN *et al.*, 1980). Although the various time-weighted average exposure limits for these compounds would typically be well below these values, they are not included here since most fires are brought under control within a few minutes. Note that these figures contain measurements made both with the FTIR and with solid sorbent techniques. The range of values for knockdown, overhaul, and inside-mask samples are also summarized in Table 3.

The most common contaminants found in ppm quantities during knockdown, ranked in decreasing order of occurrence, were carbon dioxide, carbon monoxide, ethylene, methanol, methane, acetaldehyde, acrolein, benzene, hydrogen cyanide and hydrochloric acid. Carbon monoxide was the only gas measured that exceeded its IDLH value. This occurred in approximately 10% of the knockdown samples (see Fig. 3). This figure also demonstrates the agreement between the knockdown values collected in this study and those of BURGESS *et al.* (1979). This agreement was also found for carbon dioxide (Fig. 4), benzene (Fig. 5) and acrolein (Fig. 8), but did not hold for hydrogen cyanide (Fig. 10) or for hydrogen chloride (Fig. 11). These differences may be real or the results of differing collection efficiencies for the sampling methods used. Ninety-nine per cent of the hydrogen chloride collected on our silica gel tubes was found on the upstream fibreglass plug suggesting that the HCl may have been present predominantly as an aerosol and not detectable in our filtered air bag samples. This would explain the lower frequency of occurrence in our study. In all cases, except

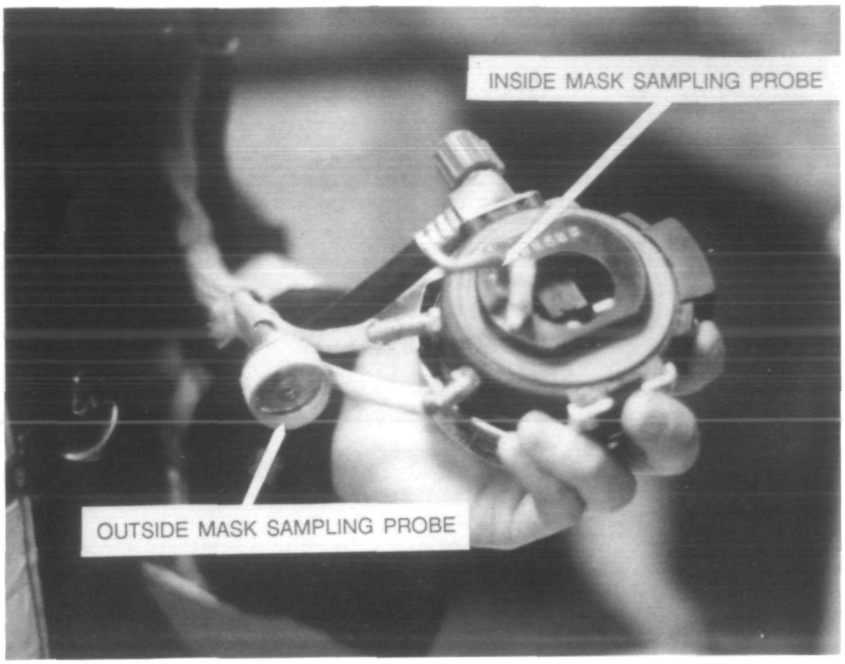


FIG. 1. Mask sampling probe locations.

FIG. 2. Hand carried sampling devices.

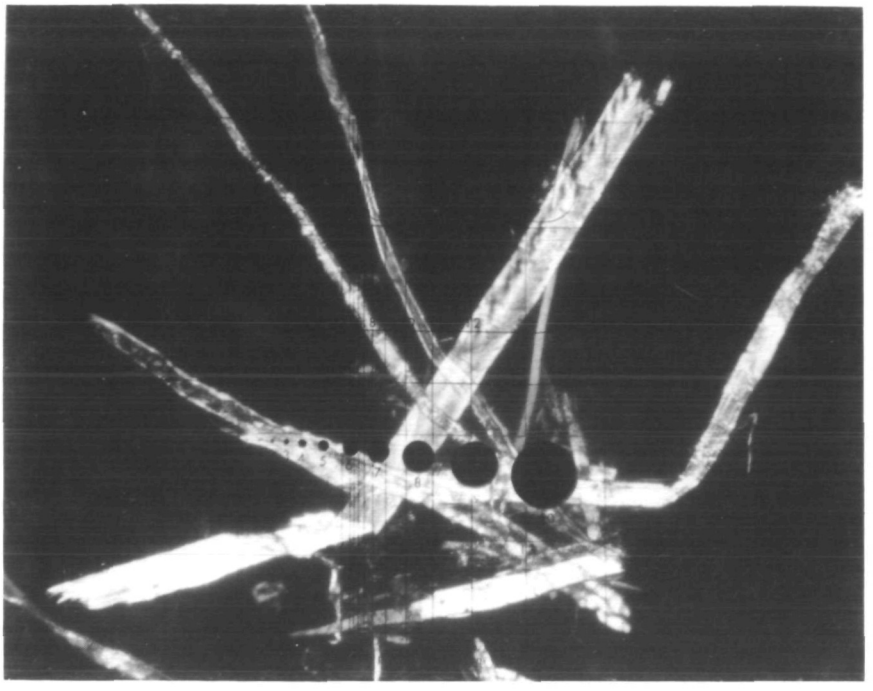


FIG. 18. Photomicrograph of cellulose fibres detected in bulk sample from fire No. 20. Crossed polars, circle No. 4 = 10 μm.

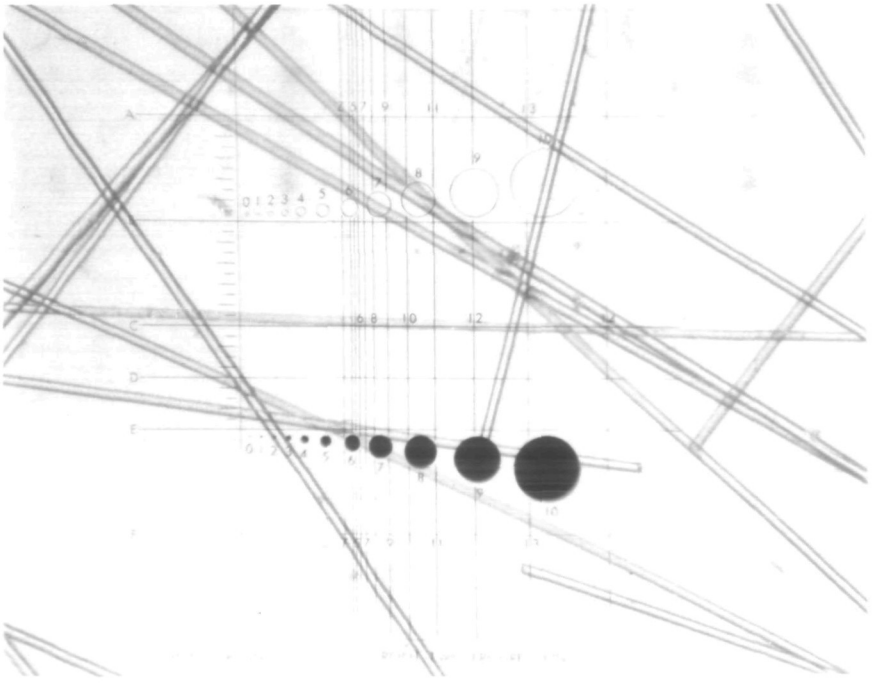


FIG. 19. Photomicrograph of glass fibres detected in bulk sample from fire No. 13. Plane polarized light, circle No. 4 = 10 μm.

TABLE 2. DESCRIPTION OF FIRES

Fire No.	Location	Materials/structure	Conditions at area sampling locations Smoke	Temp. (°F)
1	Fire training centre obstacle course	Wood/kerosene and PVC plastic	Dense	< 100
2	Fire training centre obstacle course	Wood/kerosene and PVC plastic	Dense	< 100
3	Fire training centre obstacle course	Wood/kerosene and PVC plastic	Dense	< 100
4	Training fire	Wood/kerosene and PVC plastic and stuffed furniture	Variable	> 100
5	Training fire	Wood/kerosene and PVC plastic and stuffed furniture	Variable	> 100
6	Training fire	Wood/kerosene and PVC plastic and stuffed furniture	Variable	> 100
7	Urban Fire Department	Duplex/furnished	Dense	> 100
8	Urban Fire Department	Tenement/furnished	Dense	< 100
9	Urban Fire Department	Trash fire in concrete stairwell/styrofoam and cardboard	Light	< 100
10	Urban Fire Department	Tenement/mattress and woodwork	Light	< 100
11	Urban Fire Department	Vacant tenement fought from outside	Variable	< 100
12	Urban Fire Department	High-rise apartment/ furnished	Light	< 100
13	Urban Fire Department	Automobile fire	Light	< 100
14	Urban Fire Department	Apartment/furnished	None	< 100
15	Urban Fire Department	Basement/wood and paper	Dense	< 100
16	Urban Fire Department	Tenement/rubbish	Light	< 100
17	Urban Fire Department	Vacant tenement fought from outside	Variable	< 100
18	Urban Fire Department	Single family residence/ unoccupied	Light	< 100
19	Urban Fire Department	Single family residence/ unoccupied	Light	< 100
20	Urban Fire Department	Double wide trailer/ furnished as school	Dense	> 100
21	Urban Fire Department	Apartment/furnished	Light	< 100
22	Urban Fire Department	Condominium/carpeted but unfurnished	Moderate	< 100

for hydrogen cyanide, BURGESS *et al.* (1979) also found higher concentrations in a few per cent of their samples. This may be explained by the fact that 17% of the Burgess samples came from large fires (three-alarm or greater), whereas all of ours were from smaller fires (one- or two-alarm). For hydrogen cyanide, both the FTIR analysis and the solid sorbent determinations in our study yielded concentrations higher than those reported by BURGESS *et al.* (1979). This could be an artefact of sampling. In a study of cyanide in fires BECKER (1986) reported dramatically different cyanide concentrations in the same fire from samplers placed as little as 15 cm apart.

Carbon monoxide (Fig. 3), acrolein (Fig. 8), formaldehyde (Fig. 9), hydrogen cyanide (Fig. 10) hydrogen chloride (Fig. 11), sulphuric acid (Fig. 12) and hydrogen fluoride (Fig. 13) all had values which exceeded the STEL or ceiling values. Of the four,

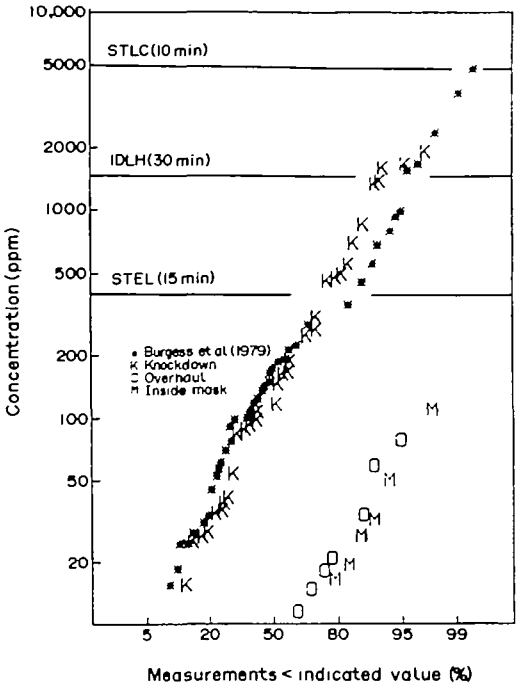


FIG. 3. Distribution of carbon monoxide measurements.

TABLE 3. SUMMARY OF MEASUREMENTS FROM 22 FIRES

Analyte	Knockdown	Overhaul	Inside-mask
Carbon monoxide	BG–1900 ppm	BG 82 ppm	<1 105 ppm
Carbon dioxide	350–5410 ppm	130–1420 ppm	460 21 300 ppm
Benzene	ND–22 ppm	ND–0.3 ppm	ND 21 ppm
Hydrogen cyanide	ND–23 ppm	ND–0.4 ppm	ND
Hydrogen chloride	ND–8.5 ppm	ND	NA
Sulphuric acid	ND–8.5 mg m^{-3}	ND–0.9 mg m^{-3}	NA
Hydrogen fluoride	ND–6.4 mg m^{-3}	ND	NA
Nitric acid	ND 1.8 mg m^{-3}	ND	NA
Acrolein	ND–3.2 ppm	ND–0.2 ppm	ND 0.9 ppm
Formaldehyde	ND 8 ppm	ND–0.4 ppm	ND 0.3 ppm
Acetaldehyde	ND–8.1 ppm	ND–1.6 ppm	ND 0.9 ppm
PNAs	ND–0.5 mg m^{-3}	ND 0.02 mg m^{-3}	NA
Simple asphyxiant (as methane)	ND–289 ppm	ND 27 ppm	ND 33 ppm
Fibre counts	BG–0.21 f ml^{-1}	BG–0.36 f ml^{-1}	NA
Total particulate	ND 560 mg m^{-3}	ND 45 mg m^{-3}	NA

ND = not detected.
BG = background.
NA = not analysed.

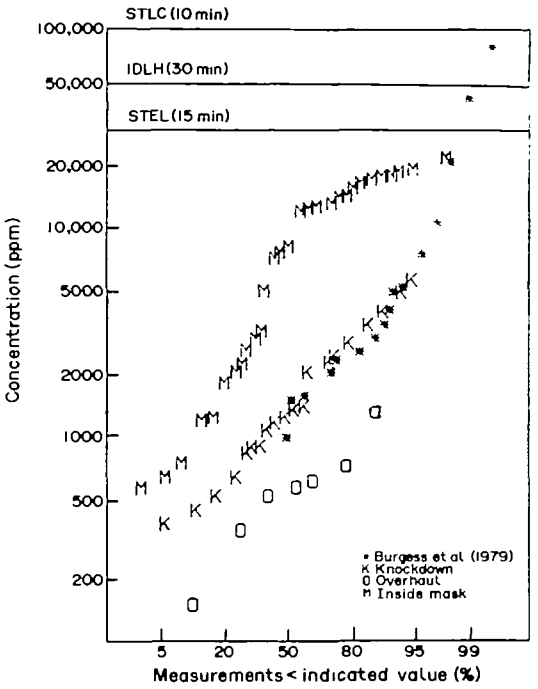


FIG. 4. Distribution of carbon dioxide measurements.

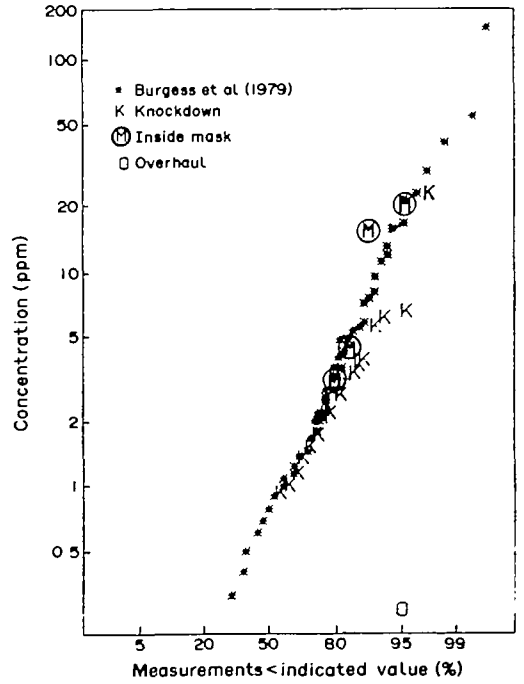


FIG. 5. Distribution of benzene measurements.

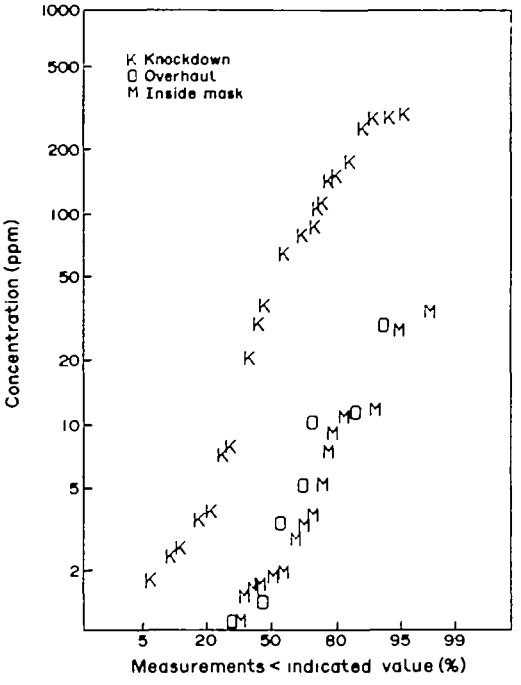


FIG. 6. Distribution of propylene, ethylene, acetylene and methane measurements as PPM equivalents of methane

acrolein was the most significant in that approximately 50% of the knockdown samples exceeded the STEL.

Note that some of the smaller fires did not involve overhaul which accounts for fewer measurements during this phase. The contrasts between knockdown and overhaul measurements are also evident in Figs 3–14. Intuitively, one would expect knockdown values to be higher than overhaul, and this is supported by our measurements. As an alternative comparison between knockdown and overhaul, Fig. 15 presents the i.r. spectra for samples taken in fire No. 22 during both activities. One can easily see the increased absorbance characteristic of carbon monoxide, carbon dioxide, methane and several other hydrocarbons. Figure 16 presents the same sort of comparison with GC–MS analysis of charcoal tubes collected from the same fire. As with the i.r. data, there is a dramatic reduction in combustion products in the overhaul phase.

Ambient particulate ranged from non-detectable to 560 mg m^{-3} during knockdown and from non-detectable to 45 mg m^{-3} in overhaul (Table 3). Figure 17 shows the particle size distribution data for the knockdown and overhaul phases of fire No. 8. The mass median diameters are approximately 10 and 1 μm for overhaul and knockdown, respectively. The difference is probably due to the different natures of the two operations. The particulate in knockdown consists primarily of smoke while particulate generated during overhaul can be a variety of aerosolized building materials typically much larger than smoke particles. Some of these building materials are fibrous, and fibre counts recorded in this study were highest from samples collected

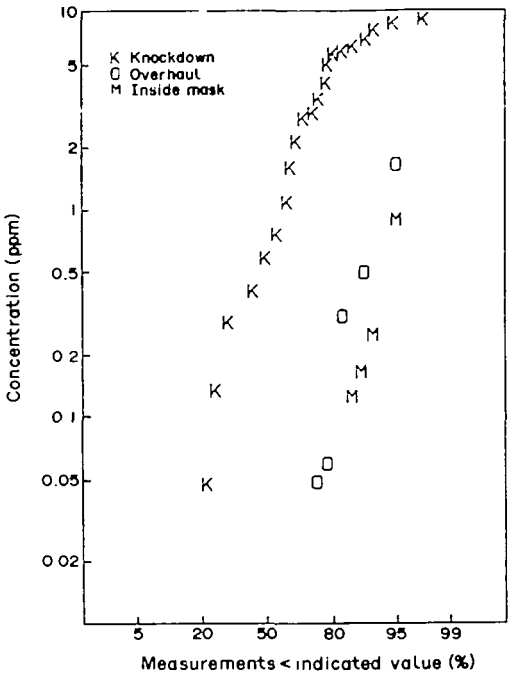


FIG. 7. Distribution of acetaldehyde measurements.

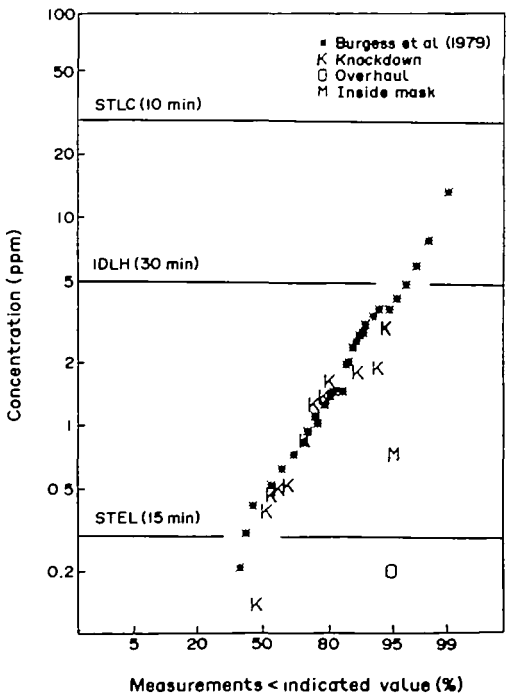


FIG. 8 Distribution of acrolein measurements.

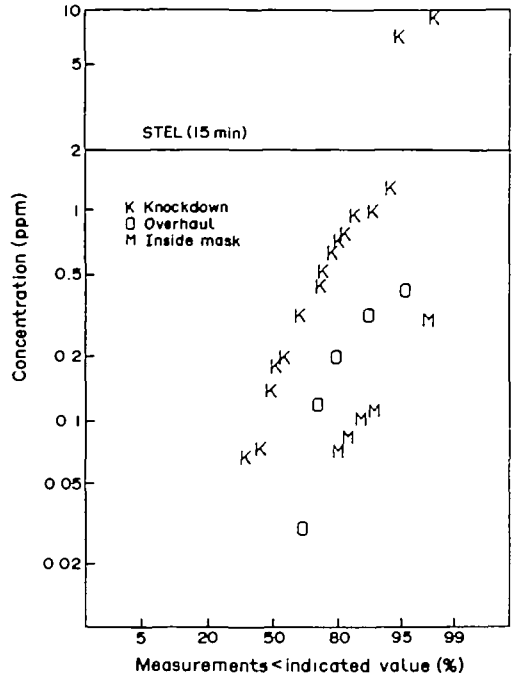


FIG. 9. Distribution of formaldehyde measurements.

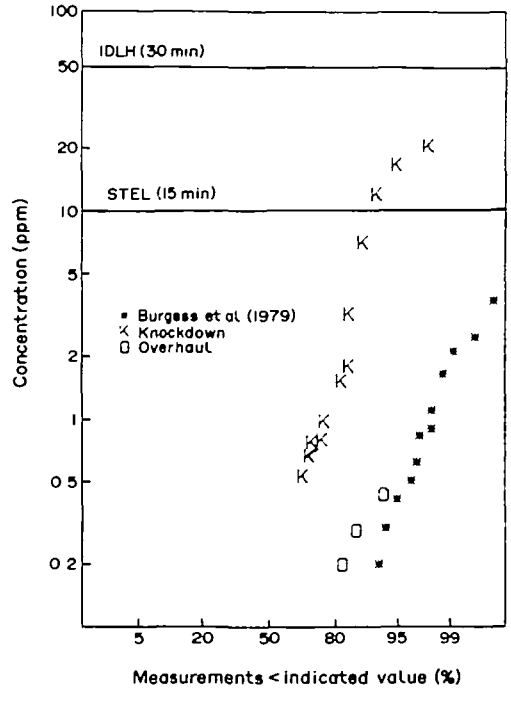


FIG. 10. Distribution of hydrogen cyanide measurements.

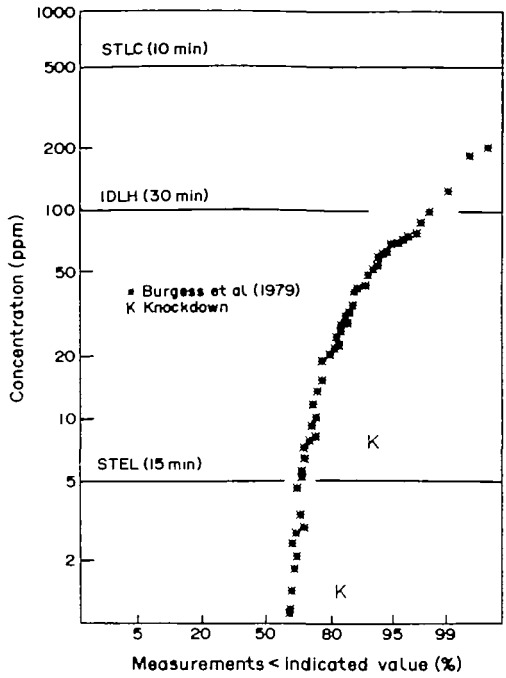


FIG. 11. Distribution of hydrogen chloride measurements

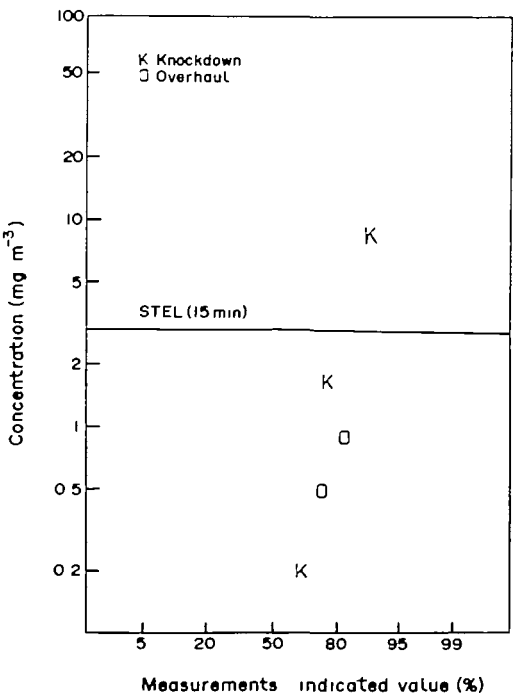


FIG. 12. Distribution of sulphuric acid measurements.

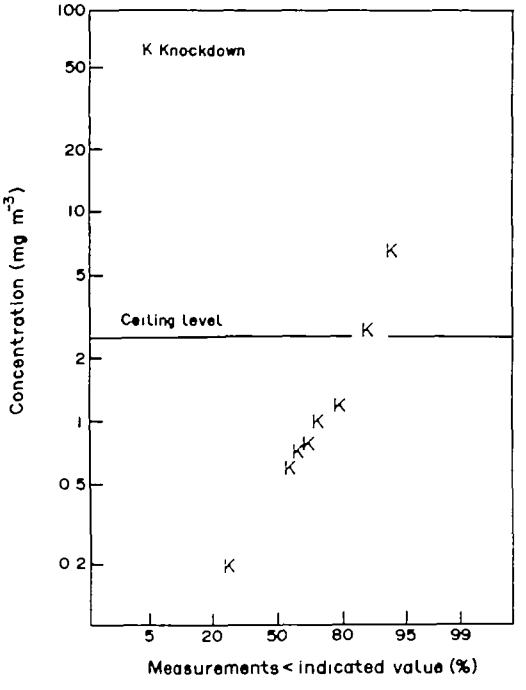


FIG 13. Distribution of hydrogen fluoride measurements.

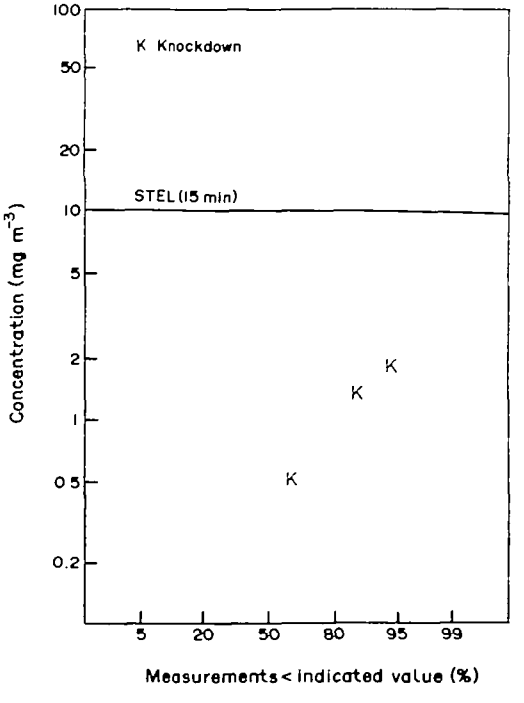
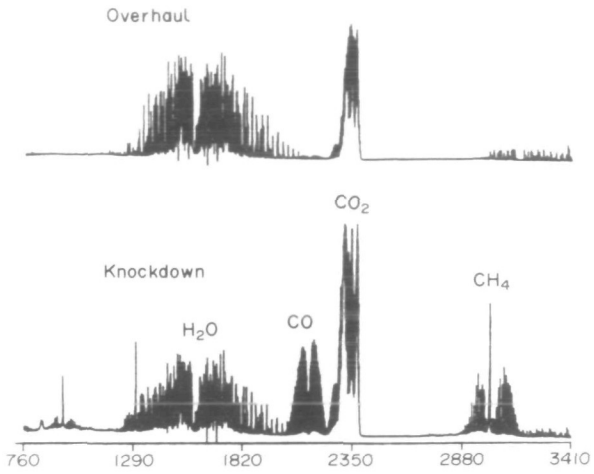


FIG. 14. Distribution of nitric acid measurements.



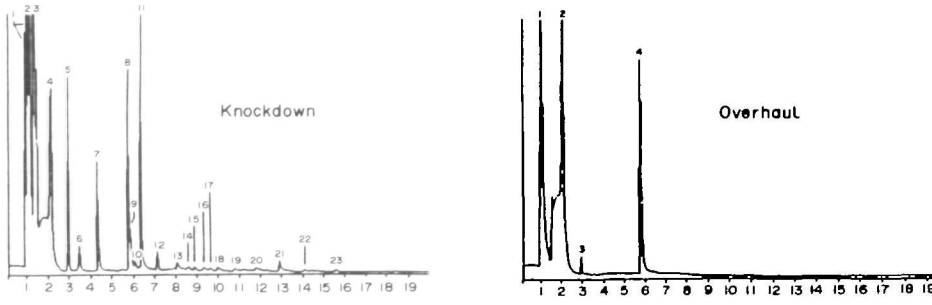
Analyte	Knockdown	Overhaul
C_2H_4	46 ppm	–
C_6H_6	2 ppm	–
C_3H_6	8 ppm	–
CH_3OH	4 ppm	0.2 ppm
CO_2	2506 ppm	376 ppm
CO	480 ppm	14 ppm
CH_4	142 ppm	1 ppm
HCN	1 ppm	–
C_2H_2	11 ppm	–
HCHO	1 ppm	–
CH_3CHO	8 ppm	–
CH_2CHCHO	2 ppm	–

FIG. 15. Comparison of FTIR spectra for knockdown and overhaul.

during overhaul (Table 3). None of the building materials examined contained any asbestos, but some contained non-asbestos fibres such as cellulose and glass fibre (Figs 18 and 19, see p. 586). Therefore, the fibre counts do not represent exposures to asbestos fibres, but do demonstrate the potential for exposure during overhaul when building materials contain asbestos.

Table 4 presents the results of PNA analysis for fires 18, 21 and 22. PNAs were collected on porous polymer tubes preceded by Teflon filters, thus allowing us to estimate the fractions present as vapour and as particulate. Of the compounds analysed, only acenaphthene was found to predominate in the vapour phase. The higher molecular weight compounds were found primarily as particulate or adsorbed onto particulate. The variety and concentrations of PNAs in knockdown were considerably greater than in overhaul. PNAs are known to be contained in the coal tar pitch volatiles produced from the destructive distillation of bituminous coal and are suspected of being the agents responsible for excesses in cancer of the lungs, skin, bladder and kidneys found among coke oven workers (NIOSH, 1981). Many of the same PNAs found in coke oven emissions were also present in the fires. While PNA concentrations were high in knockdown, overhaul concentrations fell to background levels typical of ambient air.

Table 5 provides qualitative results of the GC–MS analysis. Benzene was the most common compound identified, being found in all samples collected.



Knockdown

Entry	mg m^{-3}	ppm	Identity
1	-	-	Carbon dioxide
2		2.7	Mixture of *n*-butane, butadiene, and 1 or 2 butene
3		2.9	Trichlorofluoro methane (Freon 11)
4	-	-	Solvent (carbon disulphide)
5		0.9	Benzene
6		0.2	Methy methacrylate
7		0.7	Toluene
8	5		Internal standard (DIO-ethyl benzene)
9	0.7		Ethyl benzene
10		0.06	Xylene
11		1.5	Styrene
12	0.4		Alpha pinene
13	0.3		(1-Methylethenyl) benzene
14	0.2		Octahydro-1,3,4-methano-1H-Cyclobutha[c,d] pentalene or 3a,4,7,7a-tetrahydro-4,7-methano-indane-1H-limonene
15	0.2		
16	0.1		Indane
17	0.1		Unknown*
18	0.2		Unknown*
19	0.1		Unknown*
20		0.03	Naphthalene
21	0.6		Unknown*
22	0.2		Methyl naphthalene
23	0.1		t-Butyl anisole

Unknown* appear to bridged cyclic olefins, possibly pyrolysed terpenes

Overhaul

Entry	mg m^{-3}	ppm	Identity
1	-	-	Carbon dioxide
2	-	-	Solvent (carbon disulphide)
3		0.09	Benzene
4	5	-	Internal standard (DIO-ethyl benzene)

FIG. 16 GC–MS results (fire No. 22).

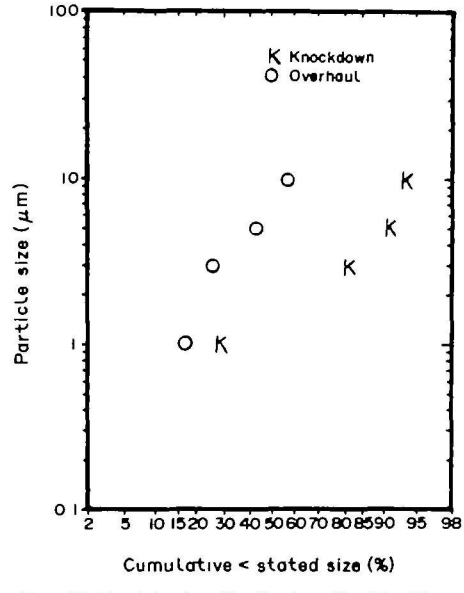


FIG. 17. Particle size distribution (fire No. 8)

TABLE 4. CONCENTRATION OF PNAs MEASURED DURING KNOCKDOWN AND OVERHAUL

Analyte	Knockdown $\bar{x}$ concentration ($\mu g\ m^{-3}$)	Max.	% on filter	Overhaul $\bar{x}$ concentration ($\mu g\ m^{-3}$)	Max.	% on filter
Acenaphthene	63	100	29	ND	—	—
Phenanthrene	54	100	87	ND	—	—
Anthracene	15	30	96	ND	—	—
Fluoranthene	32	60	100	2	6	100
Pyrene	36	70	100	2	6	100
Benz(a)anthracene	15	30	100	1	3	100
Chrysene	10	20	100	1	3	100
Benzo(b)fluoranthene	6	12	100	ND	—	—
Benzo(k)fluoranthene	3	6	100	ND	—	—
Benzo(e)pyrene	22	40	100	1	4	100
Benzo(a)pyrene	10	20	100	ND	—	—
Indeno(1,2,3-cd)pyrene	10	20	100	—	—	—
Dibenz(a,h)anthracene	3	5	100	ND	—	—
Benzo(ghi)perylene	5	10	100	ND	—	—

TABLE 5. QUALITATIVE RESULTS OF GC–MS ANALYSIS

Compound	Fire No. and Phase 7(K)	7(O)	8(K)	18(O)	19(O)	21(K)	22(K)	22(O)
Benzo furan			X					
Furan	X			X				
C_4H_8 isomers	X		X					
Methyl furan	X		X					
Benzene	X	X	X	X	X	X	X	X
Perchloroethylene	X							
Dimethyl furan	X		X					
Methyl methacrylate	X						X	
Toluene	X	X	X				X	
Furfural	X		X					
Xylene	X		X			X		
Phyenl acetylene	X							
Styrene	X		X				X	
Pinenes	X		X				X	
Limonene	X						X	
Indane	X		X			X	X	
Methyl cyclopentane	X					X		
2,4-Dimethyl-1-pentene						X		
Ethyl benzene						X	X	
C_3-Alkyl benzene						X		
C_4-Alkyl benzene						X	X	
Dimethyl indane						X	X	
n-Butane							X	
Freon. II							X	
t-Butyl anisole						X	X	
Methyl naphthalene						X	X	
Naphthalene							X	
2 Fural methyl ketone		X						
Heptane isomers			X					

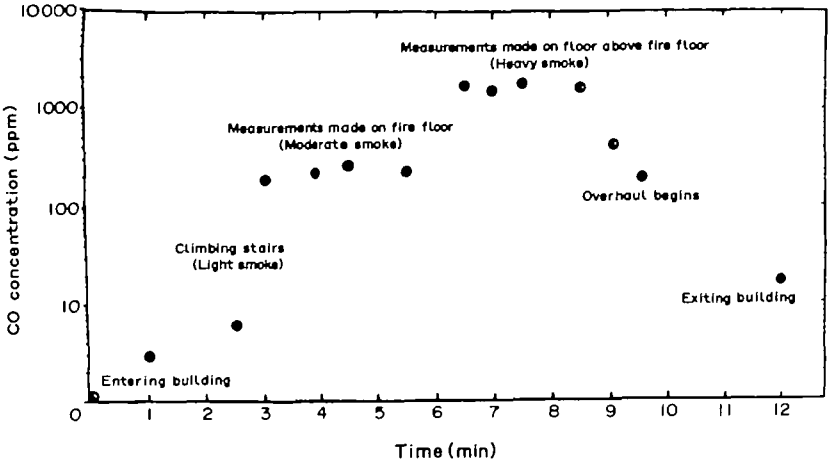


FIG. 20. Direct-reading measurements of CO (fire No. 8).

As mentioned, CO concentrations were recorded and notes taken by the industrial hygienists during the fires. Figure 20 provides the data recorded for one of the larger fires (fire No. 8). Note that concentrations of CO correlated well with our estimates of smoke level. The figure also illustrates how quickly the fire was brought under control (approximately 10 min). Note also that the transition from knockdown to overhaul is not always abrupt but rather is characterized by a gradual decline in concentration.

DISCUSSION

Examining the results from the i.r. analysis of air bag samples with the GC–MS assay from charcoal tube samples it is evident that many of the compounds observed by GC–MS, which are known to absorb in the i.r. region, do not appear in the i.r. analysis. This demonstrates the increased sensitivity gained by concentrating the sample on a solid sorbent allowing for the determination of compounds present in too low a concentration to be observed unconcentrated in a bag sample. On the other hand, solid sorbents vary in their efficiency in capturing different classes of compounds, while the collection efficiency for bag sampling is essentially 100% for all gases. Thus we were able to detect low-boiling-point hydrocarbons in the i.r. spectra while these compounds were not detected on the GC–MS spectra owing to inefficient collection on charcoal tubes. The two approaches are, therefore, complementary and when used together can maximize the ability to detect combustion products.

Measurements made inside the masks were typically well below knockdown values, and in many cases, below the overhaul values. There are three possible explanations why any measurable concentrations of contaminants were detected in the inside-mask samples: (1) the mask leaked; (2) the mask was not worn or was removed for a period of time; or (3) the contaminant was previously present in the firefighters' expired air. To control for the third possibility, we conducted pre- and post-fire alveolar air analysis for each person wearing a probed SCBA. Figure 6 shows inside-mask values for simple asphyxiants about equal with overhaul. This was undoubtedly due to the methane that was frequently found in expired breath. The second possibility was dealt with in two

ways. First, the industrial hygienists entering each fire made general notes of SCBA use. Also, continuous inside-mask pressure recordings provided specific data on the proportion of time the masks were worn (see Fig. 21). Note that most (70%) of the

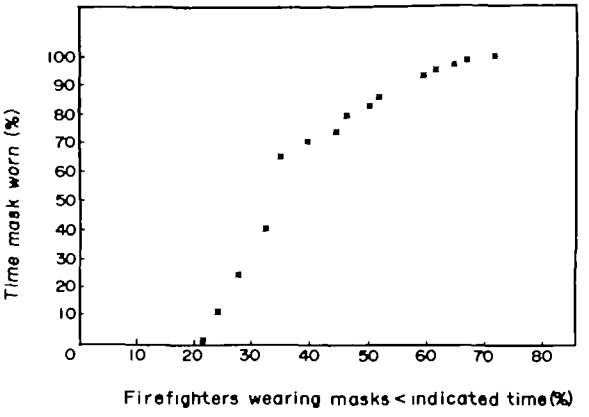


FIG. 21. Distribution of mask use in knockdown.

firefighters had removed their SCBAs for at least some portion of knockdown. This data combined with our own observations of SCBA use leads us to believe that exposure from early mask removal or non-use dwarfs the effect of exposure that may result from leaks when the SCBA is worn. Also, from our limited experience, it appears that certain fire fighting jobs are more conducive to SCBA use than others. The job of the engine crew, for instance, appeared somewhat more predictable and could be accomplished more easily while wearing a SCBA, while some of the jobs of the ladder crew (rescue, roof ventilation and forcible entry) are, in our opinion, more difficult to accomplish while wearing a SCBA. New respirator designs should be encouraged. Training and tradition among the different departments seemed also to be an important factor in SCBA use.

As another method of judging the overall performance of the SCBAs, we measured pre- and post-fire alveolar CO on participating firefighters (see Fig. 22). Note that the inside-mask values are also presented and that comparisons are made between those who wore the SCBA 100% of the time and those who did not. The bars indicate the 95% confidence interval for the mean. The differences between full- and part-time SCBA users were not statistically significant, but several features in the figure are noteworthy. The average inside-mask carbon monoxide concentrations for those who wore the respirator for the full time were lower than the pre- and post-fire alveolar concentrations, demonstrating the dilution effect produced by the CO-free air entering the mask from the SCBA bottle. The decreasing trend in CO concentration from pre- and post-alveolar to inside-mask level was reversed for those wearing the SCBA respirator less than 100% of the time, which lends support to the supposition that it is predominantly SCBA non-use rather than mask leakage which produces elevated inside-mask concentrations.

Carbon dioxide is interesting in that it was the only inside-mask contaminant

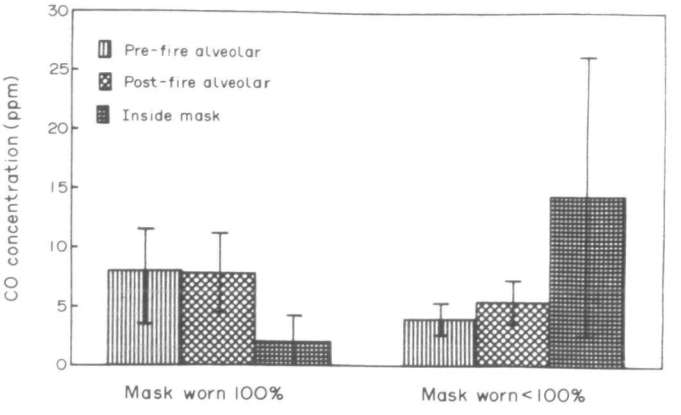


FIG. 22. Alveolar and inside mask measurements of CO.

measured which was consistently higher than the ambient values in knockdown. Carbon dioxide exceeded the 8-h standard and approached the STEL in a few per cent of the samples. This may in part be due to the fact that nose cups were typically not worn by firefighters in the study. Expired air high in carbon dioxide fills the facepiece instead of being directly venting to the atmosphere through the nosecup. One other interesting feature of the inside-mask sampling relates to benzene (Fig. 5). (Note that in this figure the inside-mask values are circled to distinguish them more easily from knockdown measurements since both distributions were similar.) We believe this to be the direct result of premature mask removal. There are only two ways that mask values could equal ambient values: either the mask was never worn and thus the inside-mask sampler sampled the ambient environment simultaneously with the ambient probe, or benzene was present only during the time that the firefighters had their masks off. We know from our observations and mask pressure data that the masks were worn during the initial phase of knockdown but typically removed shortly after the flames were extinguished. This suggests that benzene was present only in the later stages of knockdown. It has been suggested that benzene is produced by rearrangements of free radicals, the free radicals themselves resulting from earlier thermal pyrolysis and degradation (LOWRY *et al.*, 1985a,b).

Oxgen dificiency is another concern for firefighters; however, past data (GOLD *et al.*, 1978) suggests that this is not a common hazard in actual fires and it was not measured in our study.

CONCLUSIONS

Knockdown measurements

— Carbon monoxide was the most persistent contaminant with about 10% of values greater than 1500 ppm.

— Levels of acrolein, formaldehyde, HCL, HCN and sulphuric acid were all on occasion greater than their respective short-term exposure limits. About 50% of the acrolein samples exceeded the STEL.

— For those contaminants which had been previously measured in past studies of firefighters there was generally good agreement with our results.

Overhaul measurements

— Many of the same contaminants found in knockdown were also detected during overhaul activities.
— Concentrations were low relative to ambient knockdown values and generally of the order of concentrations measured inside the masks during knockdown. The exception was fibre counts which were higher in overhaul than in knockdown.

Inside-mask measurements

— In most cases the SCBAs (as used by the firefighters) were effective in reducing knockdown exposure well below current short-term exposure criteria.
— There were measurable levels of several contaminants within the SCBA masks but these concentrations are thought to be due principally to patterns of use rather than to leakage.
— Levels of CO_2 were higher inside the mask than outside, with concentrations up to around 20000 ppm.

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