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Spatial Deposition Pattern of Adsorbed Material in Activated Carbon Respirator Filters

*R.C. Brown, M.J. Bagley, D. Wake, J. Thompson,
M.I. Pengelly, M.D. Wright, N.T. Plant, and R.A. Broughton*

Health and Safety Laboratory, Broad Lane, Sheffield S3 7HQ

Abstract

The spatial deposition pattern of adsorbates in activated carbon filters has been examined experimentally, by use of a technique whereby the filters are opened, the carbon bed accurately sectioned into a number of disc-shaped layers and the adsorbate on each quantitatively analysed. The technique has been validated in the laboratory with adsorbates of iso-propyl acetate, hexane, ethanol and acetone. The spatial distribution pattern of the first three adsorbates had a sigmoid shape which passed through the filter as loading proceeded, in accordance with the established theory. Filters loaded with acetone and left for 48 hours had an almost uniform deposit within them. Cartridges loaded during normal use in industry showed a variety of patterns. In some instances the deposit reached a maximum at a finite depth in the filter. In others the deposit increased with depth. Both of these indicated significant desorption of the adsorbate during the use of the filter. Other cartridges showed a secondary peak at the downstream face of the filter, probably caused by the cartridge being exposed to vapour from this side.

Introduction

Activated carbon filters are used in many industries for personal protection and, on a larger scale, for workplace environment protection. Such filters are very effective when new, but they have a limited adsorption capacity, and eventually vapour will break through. Following breakthrough, the concentration of vapour on the downstream side of the filter increases approximately exponentially with time, causing a respiratory hazard. Monitoring of the concentration of vapour on the downstream side of a filter will identify a filter that is virtually spent, but it will not distinguish between a new filter and one that is partly loaded, as vapour is not detected in either case.

The physical structure of the filter is not significantly affected by breakthrough, and it may be

difficult for the wearer to detect when the filter is spent. Occasionally manufacturers recommend that filters should be discarded when the wearer becomes aware of the smell of the contaminant; however olfactory sensitivity varies considerably amongst wearers, and the maximum exposure limit or occupational exposure standard may be below the odour threshold. In any case the contaminant may be odour free. A measure of surety could be obtained in some circumstances by wearers using the filter for one period of exposure only and then disposing of it, but filters of this sort are expensive, and this option is not practical for most users. Understanding the behaviour of filters needs to be improved, so that recommendations about use can be made and implemented, and possibly so that improvements can be made to filter design.

The purpose of the research described in this paper was to gain a better understanding of the behaviour of filters by studying filters exposed in a controlled manner in the laboratory and filters that had been exposed to vapour in industrial conditions. This was done by measuring and interpreting the spatial deposition patterns of adsorbates within them.

Loading of Filter Cartridges in the Laboratory

In order to validate a test system to measure spatial deposition of adsorbate in partly loaded filters, it is necessary to load filters with known quantities of adsorbate under controlled conditions and to compare the patterns observed with those predicted from theory. The apparatus used to achieve this was of the type frequently used as part of manufacturers' quality control systems for monitoring the breakthrough of a test adsorbate (Breyse *et al.*, 1983). It consisted of an air supply, a syringe injection system and two rotameters for controlling pollutant concentration, an air humidifier and a filter holder. The last of these was specially constructed from stainless steel and PTFE, to ensure that it would not be affected by any of the organic vapours used in the loading experiments. Vapour concentrations were measured by infra-red vapour detection systems (MIRANs) in front of and behind the filter holder. With an atmosphere of constant concentration of contaminant a filter could be loaded to breakthrough, and other filters of the same type could be loaded with the same vapour for shorter periods. In this way standard fractionally-loaded filters could be produced.

Four compounds were used in the laboratory tests to validate the system: iso-propyl acetate,

The work was carried out in conjunction with an ergonomic study of the usage and maintenance of RPE used for protection against vapours (Alton *et al.*, 1996).

hexane, ethanol, and acetone; several cartridges were loaded with each compound, all at a constant flow rate of 20 l/min. The cartridges were preconditioned in a dry air stream from the laboratory piped air supply for at least 12 hours. After preconditioning, each cartridge was placed in a ziplock bag to prevent uptake of moisture, and weighed. It was then fitted into the filter holder and loaded. The challenge concentration for the compounds was 500 ppm, with the exception of acetone for which it was 1800 ppm. Experimental details of the filter loading operations are given in Table 1. When the loading of any cartridge was complete it was removed immediately, placed back in its own ziplock bag, and re-weighed. The system was then blown through with dry air for at least 1 hour before another cartridge was tested. The syringe and capillary were cleaned before a different compound was to be used, to avoid contamination.

The cartridges loaded with iso-propyl acetate, ethanol or hexane were sectioned, using the method to be described below, within 24 hours of the end of loading. Those that were loaded with acetone were not sectioned until several days after loading was completed.

Sectioning of Activated Carbon Respirator Filter Cartridges

In order to obtain useful measurements of the amount of compound adsorbed by a filter bed as a function of depth, it is necessary to divide the bed into a number of layers, the boundaries of which are parallel to the flat ends of the cartridge. Commercially available carbon respirator filter cartridges are usually cylindrical in shape, and range from 8 cm to 11 cm in diameter and from 1.5 cm to 4 cm in depth. The filter cartridges used in our laboratory experiments satisfied standard EN141 A2, they were 9 cm in diameter and 2 cm deep, and they contained, typically, 50 g of carbon.

Some cartridges have caps in the form of plates of plastic or metal. Frequently opening a cartridge is difficult without disturbing the granules. The method we used to overcome this was to mount the cartridge securely in the chuck of a vertically mounted microlathe, and to part the top using a sharp tool.

Devising a method of accurately sectioning the carbon filters without disturbing the carbon proved the most technically difficult part of this project. The carbon beds have considerable rigidity when they are

Table 1. Cartridges loaded in the laboratory: experimental details of the filter loading

Cartridge	Adsorbate	Concentration (ppm)	Loading time (min)
1L	Iso-propyl acetate	500	94
2L	Iso-propyl acetate	500	188
3L**	Iso-propyl acetate	500	282
4L	Hexane	500	75
5L	Hexane	500	215
6L*	Hexane	500	480
7L	Ethanol	500	160
8L	Ethanol	500	320
9L*	Ethanol	500	480
10L	Acetone	1,800	29
11L	Acetone	1,800	58
12L	Acetone	1,800	87
13L	Acetone	1,800	117

* Cartridges made up in the laboratory

** Cartridge not preconditioned

encapsulated, but once the capsule has been opened a carbon bed has similar physical properties to granulated sugar in a bowl. Fixing the bed was not possible because this would have involved the use of materials that cause grains to adhere to one another, hindering the desorption of material from the carbon. Other methods were tried unsuccessfully.

The method eventually chosen for sectioning the filter was the removal of layers of granules piece-meal, using the constant suction apparatus shown in Fig. 1. The capsule to be sectioned is placed on a circular platform (A) which is made to rotate by a synchronous motor operating at a fixed rate of 2 RPM, located in a housing (B). The rotating platform and motor housing rest on another platform (C) which is moved linearly, by a small motor (D) with a lead-screw (E) attached to the underside of the platform. The entire apparatus is mounted on a rigid base.

A short metal pipe (F) of internal diameter 4 mm is held vertically at a fixed point relative to the rigid base. Its height can be adjusted with a vernier micrometer which forms part of its support (G). The carbon from the capsule is removed by suction: air is sucked at a rate of 41/min through the metal pipe by a Casella Type HSF800T pump with automatic flow control. The pipe is constructed with its outer diameter tapered to a knife edge so that the air flow into it is as smooth as possible, ensuring that the surrounding material is not disturbed. The carbon removed from the bed is collected in a Dreschel bottle (H) which is situated between the pipe (F) and the pump unit. An in-line filter (J) is located downstream of the Dreschel bottle to prevent fine carbon granules from being carried over into the pump unit. After collection in the Dreschel bottle the carbon is transferred to and sealed in a preweighed glass vial. The loaded glass vial is then reweighed to obtain the weight of carbon.

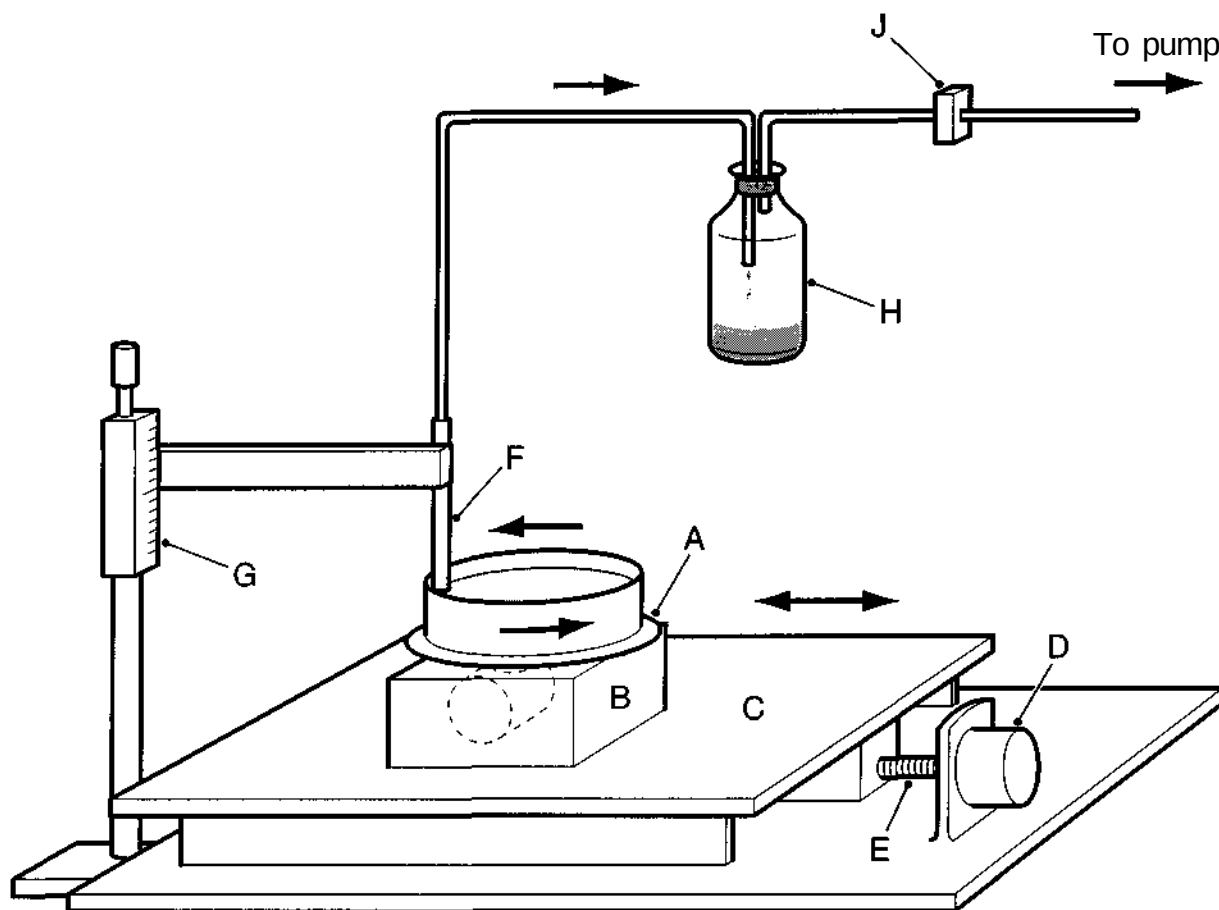


Figure 1. Apparatus used for sectioning granular filter beds.

The metal pipe inlet is initially held 2 mm above the normally uneven top layer of the carbon bed and the removal of a single layer takes about 1 minute. When a layer of granules has been removed, the resulting surface is much more even, and by the time two or three layers have been removed, fluctuations from uniformity of the surface are less than 0.4 mm peak to trough. (The evenness of the surface depends upon the nature of the granulated carbon; the surface obtained with cylindrical formed granules is less perfect than that obtained with isometric granules).

The height of the pipe is reduced between the removal of layers in sequence. A little practice

enables the operator to adjust the height of the inlet so as to remove a layer with approximately the thickness required. It is not possible to prescribe the thickness exactly, but measurements using the vernier micrometer enabled the exact thickness to be determined. The thickness of the layer removed is independent of the rate of motion of the pipe relative to the bed, and a second scan with the metal pipe at the same height removes no further granules. No carbon granules are observed to move during the process, except for those actually removed by the suction. Careful use of the equipment enables a normal-sized filter to be split into approximately eight layers.

Analysis of Filter Cartridges Loaded in the Laboratory

Typically the sections of the carbon beds loaded in the laboratory contained 4-6 g of activated carbon plus adsorbate, and these samples were analysed individually. In order to remove the adsorbates,

17-20 ml of eluting solvent containing an internal standard were accurately weighed into each of the glass vials containing the carbon sections. Volumes of solvent were calculated to $\pm 0.1\%$ from the results

of a density measurement on the solvent in calibrated glassware. The vials were left for 3–4 hours, with occasional shaking, to allow complete equilibration before analysis. 1 µl aliquots were then injected into a gas chromatograph equipped with a flame ionisation detector. Calibration standards for each adsorbate were prepared by gravimetry.

The weight gain of each cartridge and the weight of recovered adsorbate are given in Table 2. In some instances the weight of recovered adsorbate exceeded the weight gain of the cartridge; this may result from prior adsorption of atmospheric water by the carbon. All the cartridges showed slight signs of desorption during the sectioning procedure as indicated by a MIRAN vapour detection system positioned near to the apparatus. The results for cartridges loaded with iso-propyl acetate are illustrated in Fig. 2 (Thompson *et al.*, 1996); all the cartridges show a distinct sigmoid spatial profile of adsorbed material. The mass of adsorbate collected by each layer of carbon decreases monotonically with distance from the leading edge of the cartridge except in one instance, probably as a result of experimental error.

Although not shown graphically, the general sigmoid shape of the deposition profile is implicit in the data of Tables 3 and 4 for ethanol and hexane. Simplified theory, reported by Brown (1995), suggests that the mass of adsorbate per unit volume of bed, $M(x, t)$ is described by

$$M(x, t) = \frac{M_o \exp\left(-\frac{kx}{U}\right) \left[\exp\left(\frac{kC_i t}{M_o}\right) - 1 \right]}{\left\{ 1 + \exp\left(-\frac{kx}{U}\right) \left[\exp\left(\frac{kC_i t}{M_o}\right) - 1 \right] \right\}} \quad (1)$$

The equation above describes a sigmoid profile of relatively constant shape passing through an activated carbon filter cartridge. M_o is the saturation concentration of the carbon bed and can be estimated from the y-axis intercept of the experimental graphs. The shape of the curves is critically dependent on the value of k , the rate constant of adsorption, which can be estimated from the gradient of the curves at their point of inflection. U is the velocity of air through the system and C_i is the concentration of the compound at the inlet of the filter. The intercepts, which are related to M_o , and gradients at the points of

Table 2. Cartridges loaded in the laboratory: correlation between weight gain of cartridge and recovered adsorbate.

Cartridge	Total weight of carbon (g)	Weight gain (g)	Total adsorbate recovered (g)	Breakthrough time (min)
1L	54.53	7.45	3.23	N/A
2L	55.70	6.05	5.36	156
3L	56.88	5.76	7.71	212
4L	51.30	2.70	2.21	N/A
5L	56.12	6.47	5.68	162
6L	55.26	3.91	8.40	N/A
7L	52.15	1.76	2.34	N/A
8L	52.99	6.13	4.62	N/A
9L	49.79	3.89	3.75	N/A
10L	47.91	0.17	0.29	N/A
11L	48.03	1.09	1.67	N/A
12L	48.68	3.27	2.35	N/A
13L	51.18	4.43	3.04	117

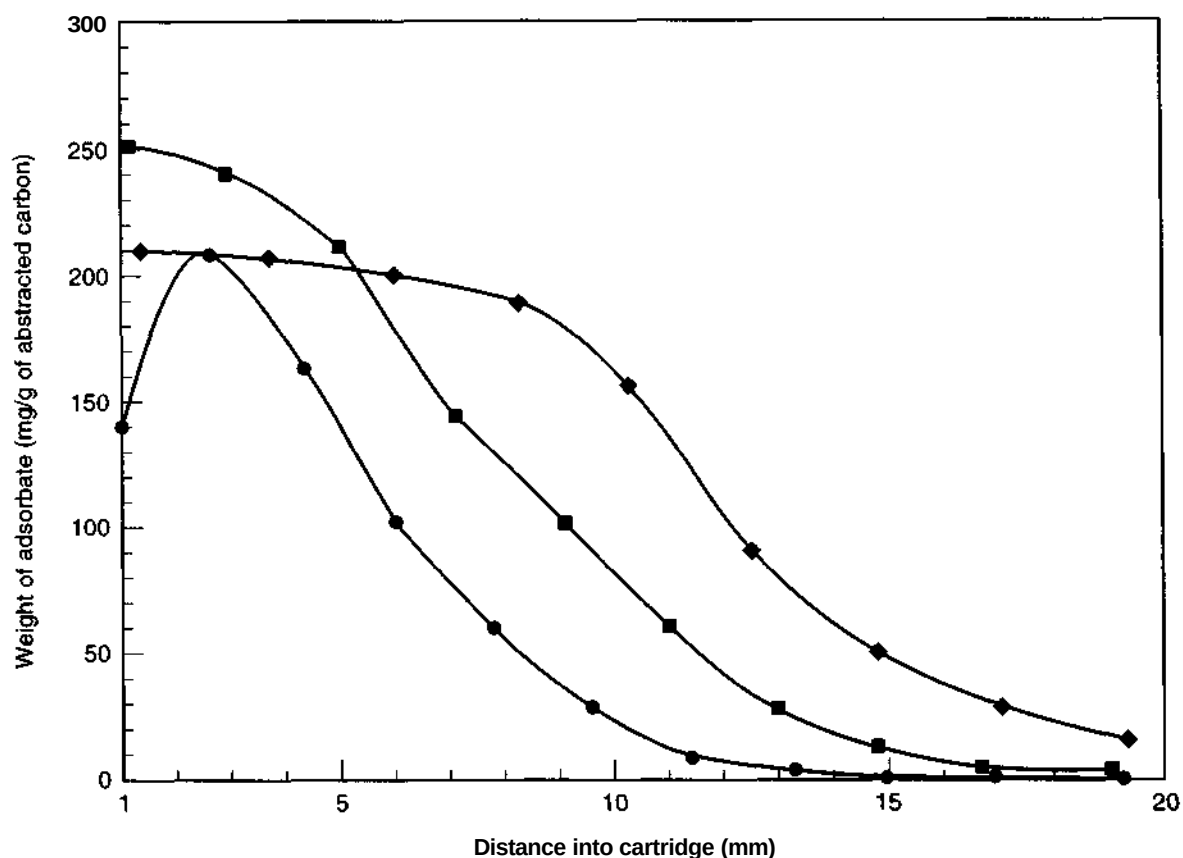


Figure 2. Deposition profiles of filters loaded in the laboratory with iso-propyl acetate. Cartridges were loaded for: ●—94 min; ■—188 min; ◆—282 min.

Table 3. Analytical results for cartridges loaded with ethanol in the laboratory.

Loaded for 160 min		Loaded for 320 min		Loaded for 480 min	
Distance (mm)	Ethanol	Distance (mm)	Ethanol	Distance (mm)	Ethanol
0.94	115.00	1.23	119.00	1.01	123.50
2.87	106.00	3.20	118.00	2.77	119.30
4.68	89.00	4.68	116.00	4.93	112.10
6.68	71.00	6.34	109.00	7.23	99.70
8.69	49.00	8.11	99.00	9.13	89.0
10.67	30.00	9.97	88.00	11.13	72.70
12.83	11.00	11.99	75.00	13.13	54.60
14.82	5.0	14.05	62.00	15.03	30.60
16.95	3.0	16.07	50.00	16.83	17.80
18.80	1.0	18.23	46.00	19.13	18.10

Table 4. Analytical results for cartridges loaded with n-hexane in the laboratory.

Loaded for 75 min		Loaded for 215 min		Loaded for 480 min	
Distance (mm)	n-Hexane	Distance (mm)	n-Hexane	Distance (mm)	n-Hexane
0.96	154.00	0.91	147.00	1.25	182.0
2.90	134.00	2.88	146.00	3.50	181.10
5.17	89.00	4.86	148.00	5.75	179.10
7.42	50.00	6.59	146.00	8.25	176.40
9.36	24.00	8.43	138.00	10.50	171.20
11.13	8.60	10.26	117.00	12.75	164.10
12.85	6.60	12.04	81.00	15.25	151.20
14.76	1.0	13.97	47.00	17.75	113.50
16.66	0.30	15.92	31.00	19.50	42.0
18.11	0.30	17.77	14.00	20.00	49.50

inflection, which are related to k , are similar for the three filters exposed to each compound, but different amongst the compounds.

Table 5 shows the values of M_0 and k calculated from the data. Values of M_0 were published by Nelson and Harder (1974) and the values of k' , a parameter related to k , were given by Yoon and Nelson (1992). The differences between the values calculated and those previously published can be attributed to the effects of flow rate, humidity, lower challenge concentration and different type of activated carbon used in our system. The values shown in Table 5 serve, however, to show that the values calculated from the presented data follow the same trend as the previously published values. The values for M_0 decrease from iso-propyl acetate through hexane to ethanol.

Figure 3 illustrates the effect of leaving cartridges loaded with acetone for more than 24 hours before sectioning them. These cartridges were loaded at the same vapour concentration for different periods of time, and each has adsorbed different quantities of compound. The sigmoid distribution, observed with the other challenge compounds, is not observed with these cartridges. The acetone would appear to have diffused throughout each of the cartridges. This behaviour, which the sectioning method reveals, is not unexpected since as reported earlier, the cartridges used in the experiments satisfied standard EN141A2. This means that they are only approved for use against certain organic gases and vapours with a boiling point higher than 65°C as specified by the manufacturer. Acetone boils at 59°C.

Analysis of Filter Cartridges Loaded in Industry

The results obtained from loading filters in the laboratory, in spite of their shortcomings, do indicate that the sectioning method is basically sound. The deposition profiles are of the form that would be expected. However the ultimate aim of the work is to obtain a better understanding of the behaviour of filters used in industry and how this is affected by patterns of work. We therefore approached a number of commercial firms with the objective of obtain-

ing filters that had been used in normal workplace practice. Three firms agreed to cooperate as described below.

Firm 1

This firm had a medium sized glass-fibre moulding plant mainly making items for the caravan industry and bathroom fittings. There was an

Table 5. Cartridges loaded in the laboratory: comparison between experimental results and previously published data.

Compound	Mo (g/g)	Rate constant k (sec^{-1})	Mo(g/g) (published)	k' (min^{-1}) (published)
Iso-propyl acetate	0.25	83.00	0.507*	0.101
Hexane	0.155	71.00	0.334	0.101
Ethanol	0.12	54.00	0.168	0.0796
Acetone	0.068		0.135	0.213

* Value shown for n-propyl acetate.

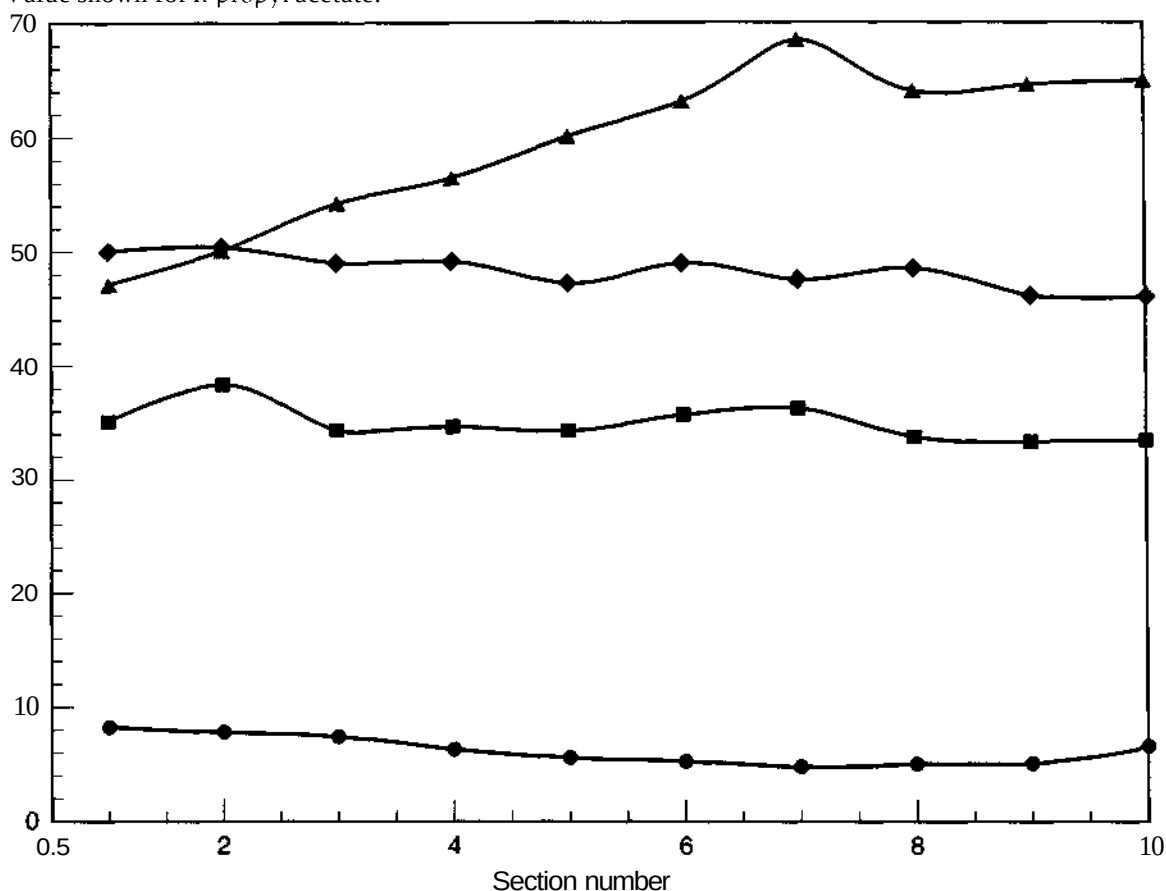


Figure 3. Deposition profiles of filters loaded in the laboratory with acetone, and left 48 hours before sectioning. Cartridges were loaded for: ●—29 min; ■—58 min; ◆—87 min; ▲—117 min.

exhaust ventilation system but respirators containing activated carbon filter cartridges were used intermittently by two employees to protect against styrene.

Firm 2

This firm was a small business that carried out vehicle paint spraying. Activated carbon filter cartridges of a different type from those used in

Firm 1 were used intermittently by two people, who frequently worked together, to protect them against a range of organic solvents including xylene, toluene, methyl ethyl ketone and propanol.

Firm 3

Firm 3 was a very large organization that used activated carbon filter cartridges of the same type as those employed by Firm 2 to protect against a range

of solvents, including xylene, toluene, methyl ethyl ketone and iso-propanol released during the spraying of both primer and epoxy paint. Approximately 90% of the spraying involved primer, and most spraying was carried out in ventilated booths. When large parts were sprayed substantial back draught occurred. Other spraying operations were carried out in places with difficult access. In both of these situations respirators were necessary.

Filter cartridges sent to us by the companies were opened and sectioned as described previously. Following desorption in 95/5 dichloromethane/

methanol, the solvents adsorbed on each filter section were analysed by gas chromatography using a flame ionisation detector. For some solvents, identification was confirmed with a gas chromatograph equipped with a mass selective detector (MSD). The solvents for which analyses were carried out were styrene, toluene, xylene, ethyl benzene, n-butyl acetate, n-butanol, 1-methoxypropanol, 2-butanone (MEK), 4-methyl 2-pentanone (MIBK), ethyl 3-ethoxy propionate, 2-ethoxy ethyl acetate, methoxy propyl acetate and 1,1,1-trichloroethane.

Results

Firm 1

The deposition profiles for the two cartridges loaded with styrene in a resin-glass fibre moulding plant, are shown in Fig. 4, and they illustrate different patterns of deposition. Cartridge 1 shows a well-advanced deposition pattern with the sigmoid profile given by standard theory. The styrene has, in fact, broken through, indicating that the filter has been exposed to vapour contaminant for too long. Within experimental error cartridge 2 has a fairly normal sigmoid-type deposition pattern on the upstream edge of the filter to be expected from dynamic adsorption theory and expressed mathematically in equation 1. There is little deposition in the middle of the filter and no indication of breakthrough, but there is an increase in deposition on the downstream edge of the filter. The reason for this increase is not known for certain. One possible explanation is diffusion of vapour from the workplace air to the inside of a respirator that has been left unprotected. That respirators are frequently stored where they may be exposed to workplace vapours is commented on by Alton *et al.* (1996), though it is not known for certain whether it applies to Firm 1. A second possibility is that the downstream face of the filter has been exposed to vapour during inward leakage into the respirator. Both of these processes would be hindered by action of the inhalation valve of the respirator, though this component is often among the first to deteriorate as a result of imperfect maintenance (private communication, N.P. Vaughan). A third possibility is transport of the vapour through the air during storage of the filter in a bag prior to sectioning and analysis.

Firm 2

Figure 5 shows the results obtained from one of two cartridges loaded over an extended period of time during paint spraying in a small firm. The adsorbates analysed were xylene, toluene, MEK and propanol, believed to be the principal, but not the only, contaminants. The results shown in the figure come from the more heavily loaded cartridge. Each layer of carbon has collected some of each adsorbate. Three orders of magnitude more toluene and xylene have been adsorbed than methyl ethyl ketone and propanol, an effect that may be partly due to differences in the concentrations of the contaminants in the paint spray and partly to differences in their volatility. A further possibility is enhanced desorption of a more volatile compound in a mixture by a less volatile compound (Yoon *et al.*, 1991). The maximum concentration of the adsorbed aromatic compounds on this filter is considerably lower than that of the styrene shown in Fig. 4. This may be the result of competition between compounds or it may be the effect of concentration.

Figure 5 shows toluene to be very close to breakthrough whereas the cartridge has a considerable residual capacity for xylene. The spatial distribution of propanol and methyl ethyl ketone show that both of these chemicals have broken through and that the cartridge would not have been effective against either of them for some time. None of the deposition profiles has any close resemblance to the sigmoid profile observed in laboratory loading at constant concentration. The concentration of all adsorbates increases initially with depth, and that of

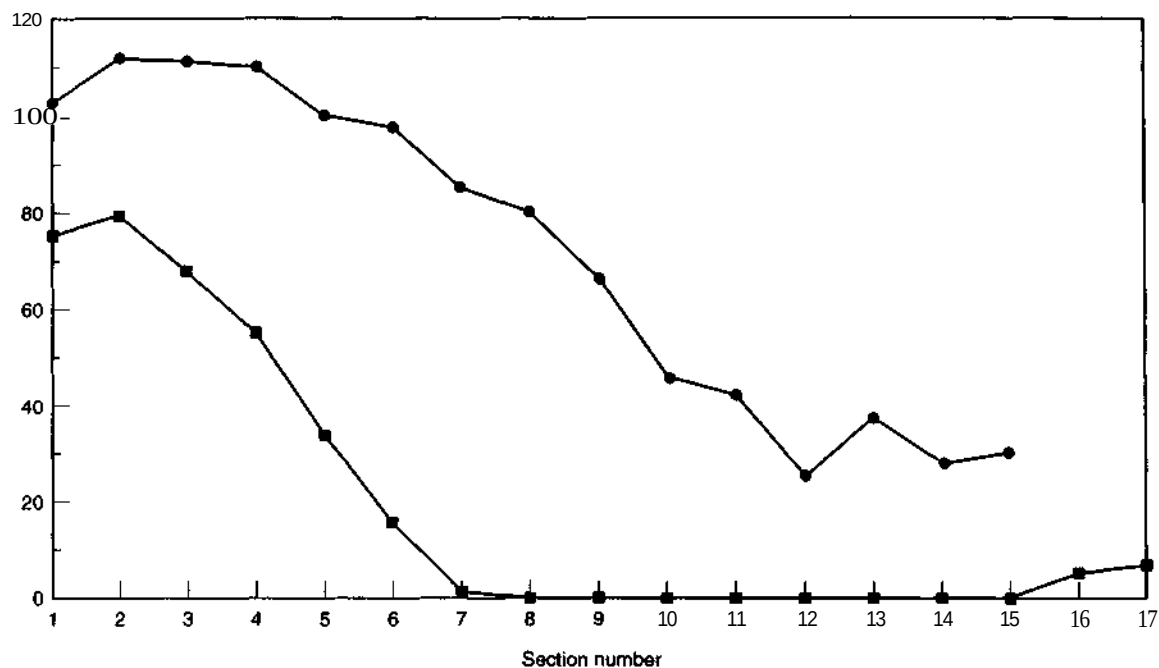


Figure 4. Deposition profiles of filters loaded with styrene vapour at a glass fibre manufacturing plant. ●—Cartridge 1; ■—Cartridge 2.

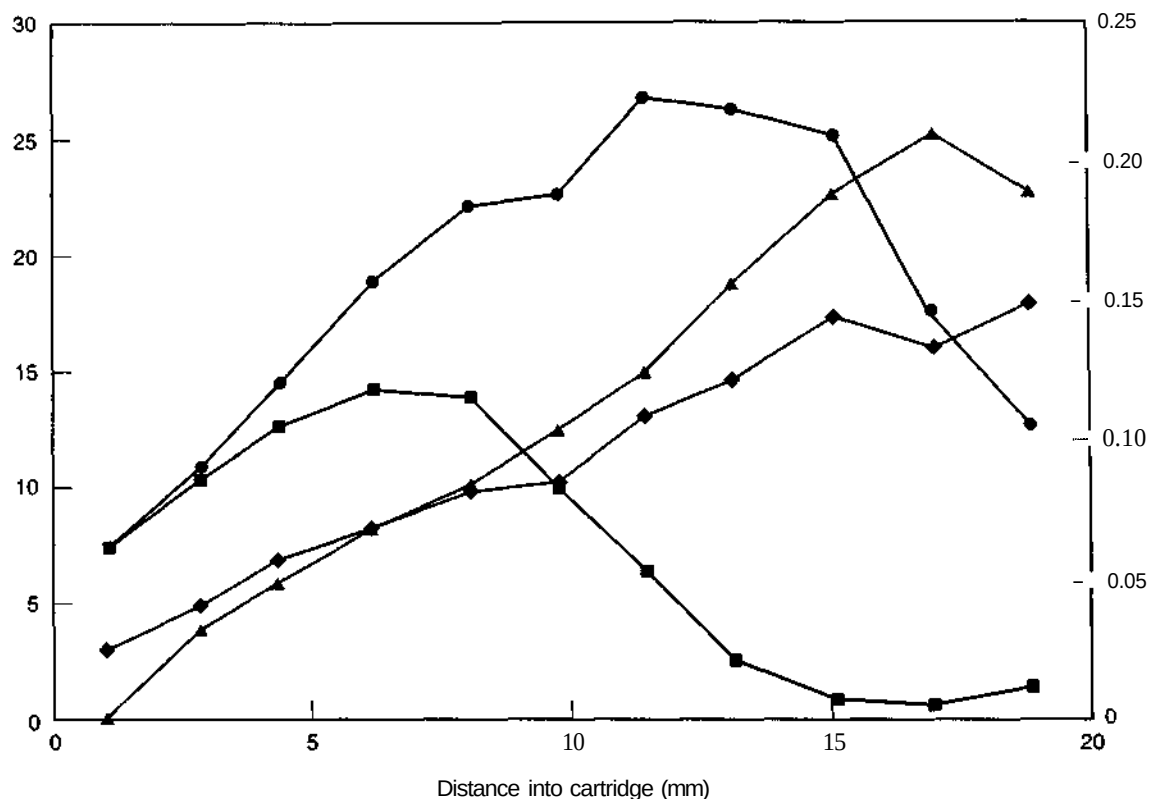


Figure 5. Deposition profiles of a filter loaded during paint spraying:
Left ordinate: ●—toluene; ■—xylene;
Right ordinate: ◆—propanol; ▲—MEK.

MEK and propanol continue to increase throughout the depth of the filter. If the adsorptive properties of the carbon are homogeneous, it would be impossible for such profiles to arise from loading at constant concentration. The only reasonable explanation for this behaviour is desorption. It is likely that the filters have been exposed to a high concentration of contaminants followed by lower concentrations or even clean air. The low concentration of vapour, or clean air, has caused adsorption and desorption to act in the same sort of way that they do in a chromatography column. The profile of xylene and that of toluene, each has a maximum in the concentration passing through the filter. That of toluene is further downstream, as would be expected for a compound that is less tightly bound. In the case of MEK and propanol it is likely that we are seeing the residue after the peak has passed through the filter, since both of these compounds are more weakly adsorbed than the aromatics. It is likely, therefore, that the cartridge will not have been effectively protecting against any of them, but for differing periods of time in each case. The local minimum in the profile for toluene at about 8mm distance into cartridge is also apparent in the profile of the other cartridge, loaded at the same time, and may indicate a period of no

loading or low loading between two loading periods.

Firm 3 (Tables 6 to 10)

Five cartridges loaded at the large paint spraying firm were sectioned and analysed. The deposition profiles for cartridges K3, K2, and K1 are given in Figs. 6a, b, and c respectively and they show significant variations in the patterns of deposition of the adsorbates, but certain similarities with the results from the cartridges loaded in the resin-glass fibre moulding plant. The absolute levels of loading are rather similar to those shown in Fig. 5, taken from the small paint-spraying plant. In all instances there is a maximum in the profile for toluene, though in this case the operatives wearing the respirators were not working together. Breakthrough of toluene has clearly occurred in the filter of Fig. 6b. No breakthrough has occurred in the case of the other two filters, but in both instances there is an increase in toluene concentration at the downstream surface of the filter. In the case of the filter in Fig. 6c, this increase is considerable.

Some adsorbates, like n-butyl alcohol, show an almost uniform profile in the case of Fig. 6b. Xylene

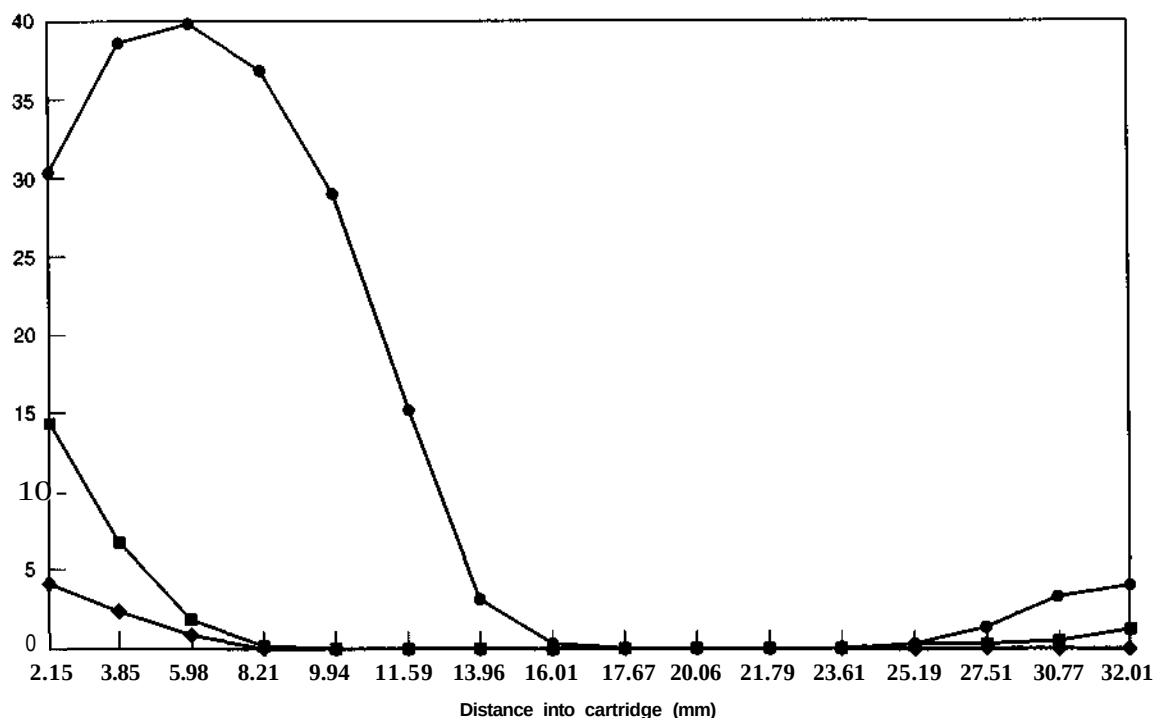


Figure 6a. Deposition profiles of filter K3 loaded with various organic compounds during paint spraying, at a large firm: ●—toluene; ■—xylene; ◆—ethyl benzene.

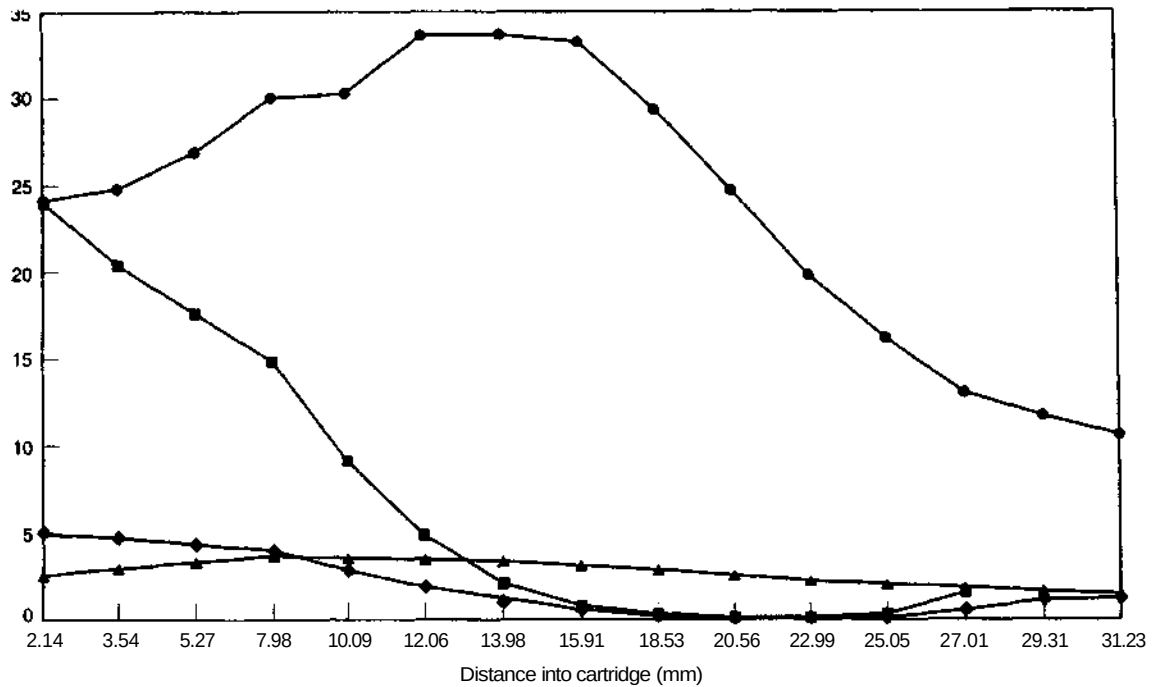


Figure 6b. Deposition profiles of filter K2 loaded with various organic compounds during paint spraying, at a large firm: ●—toluene; ■—xylene; ◆—ethyl benzene; ▲—n-butanol.

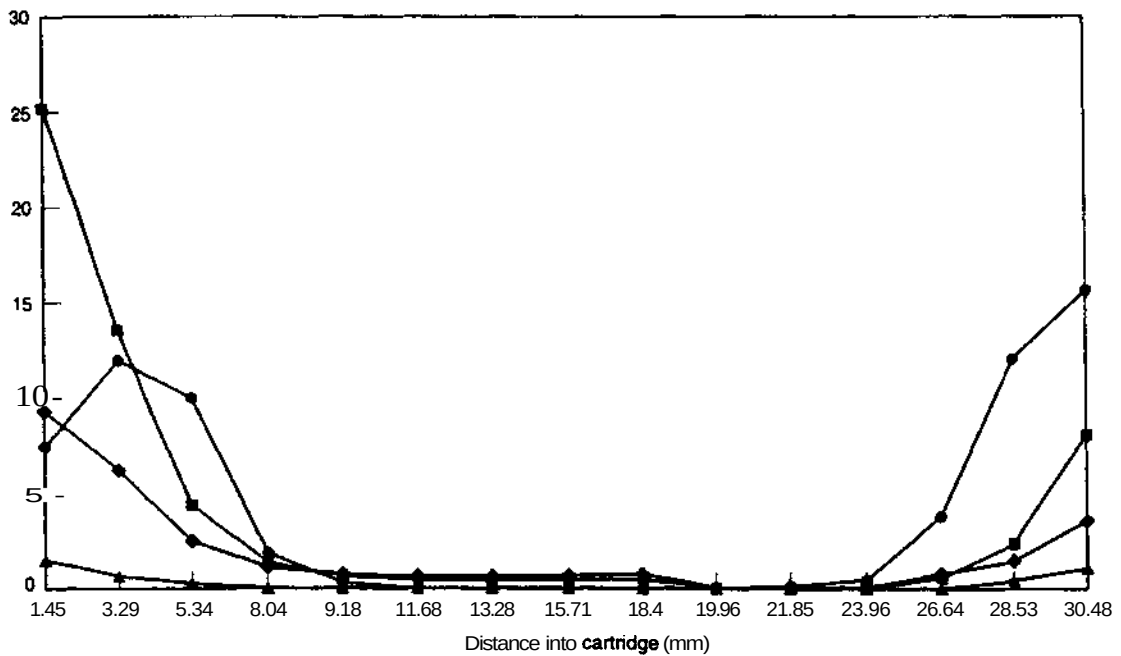


Figure 6c. Deposition profiles of filter K1 loaded with various organic compounds during paint spraying, at a large firm: ●—toluene; ■—xylene; ◆—ethyl benzene; ▲—MPA.

Table 6. Analytical results for Cartridge K3 loaded at large paint spraying firm.

Distance (mm)	o,m,p- Xylene	Ethyl Benzene	Toluene	MIBK	MEK	n-Butyl Acetate	1-Methoxy Propanol	n-Butyl Alcohol	111- TCE	MPA	EEP
2.15	14.50	4.11	30.40	1.50	0.13	0.75	0.27	1.75	0.02	0.23	1.10
3.85	6.80	2.31	38.70	1.25	0.15	0.52	0.31	2.13	0.02	<0.01	0.08
5.98	1.83	0.71	39.9	0.71	0.18	0.12	0.30	2.33	0.02	<0.01	0.04
8.21	0.53	0.18	36.8	0.32	0.19	0.05	0.23	2.10	0.02	<0.01	<0.01
9.94	0.20	0.05	28.90	0.14	0.20	0.02	0.15	1.52	0.02	<0.01	<0.01
11.59	0.13	0.01	15.20	0.08	0.25	<0.01	0.04	0.96	0.02	<0.01	<0.01
13.96	<0.01	<0.01	2.85	<0.01	0.29	<0.01	<0.01	0.56	<0.01	<0.01	<0.01
16.01	0.01	<0.01	0.18	<0.01	0.17	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
17.67	<0.01	<0.01	0.14	<0.01	0.08	<0.01	<0.01	0.08	0.01	<0.01	<0.01
20.06	<0.01	<0.01	<0.01	<0.01	0.02	<0.01	<0.01	0.05	0.02	<0.01	<0.01
21.79	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	0.04	0.02	<0.01	<0.01
23.61	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	0.05	0.02	<0.01	<0.01
25.19	<0.01	<0.01	0.17	<0.01	0.02	<0.01	<0.01	0.05	0.02	<0.01	<0.01
27.51	0.18	0.02	0.96	0.02	0.02	0.02	0.01	0.11	<0.01	<0.01	<0.01
30.77	0.76	0.18	3.23	0.12	0.01	0.17	0.02	0.14	<0.01	0.04	0.12
32.01	1.02	0.26	3.97	0.22	0.02	0.17	0.02	0.16	<0.01	<0.01	0.10

and ethyl benzene, show a less advanced pattern than that of toluene, and in no instance has a maximum been reached. Not all of the compounds adsorbed are shown in these figures, and in fact not all compounds adsorbed were analysed. In the case of the cartridge illustrated in Fig. 6c, there is almost as much deposition on the downstream side of the filter as on the upstream side, though it must be

commented on that the deposition in this instance is light.

Again, an explanation for this effect cannot be given for certain, but it is difficult to understand how it could happen unless the downstream side of the filters were exposed to the adsorbate.

Conclusions

It has been shown that a method of accurate sectioning of carbon filter beds can be put into practice, and that the increments of material can be analysed for adsorbates by standard chemical techniques. The laboratory tests validate the system, and have shown that it has considerable potential for use in fundamental studies of the behaviour of activated carbon in respirator filters.

The results obtained from the glass-fibre industry have shown, in one instance, indication of straight forward vapour breakthrough. In the other case significant residual lifetime has been demonstrated but this has been complicated by an increase in concentration at the downstream face of the filter. Similar behaviour has been observed in filters exposed to paint spraying vapour at a large paint

Table 7. Analytical results for Cartridge K2 loaded at large paint spraying firm.

Distance (mm)	o,m,p-Xylene	Ethyl Benzene	Toluene	MIBK	MEK	n-Butyl Acetate	1-Methoxy Propanol	n-Butyl Alcohol	111-TCE	MPA	EEP
2.14	24.10	5.08	24.4	1.51	0.09	5.20	0.67	2.49	0.24	4.47	4.40
3.54	20.4	4.61	24.9	1.37	0.10	5.56	0.73	2.95	0.23	3.96	2.11
5.27	17.6	4.23	27.0	1.18	0.11	5.81	0.81	3.25	0.25	3.13	0.80
7.98	14.8	3.82	30.1	0.97	0.13	5.89	0.88	3.55	0.28	2.26	0.33
10.09	9.0	2.73	30.3	0.67	0.13	5.18	0.07	3.33	0.29	1.17	0.14
12.06	4.74	1.80	33.6	0.44	0.15	4.28	0.07	3.37	0.34	0.56	0.11
13.98	1.94	0.95	33.7	0.29	0.16	3.06	0.73	3.21	0.40	0.35	<0.01
15.91	0.72	0.42	33.2	0.19	0.17	1.88	0.64	2.98	0.48	<0.01	<0.01
18.53	0.25	0.13	29.3	0.12	0.17	1.06	0.49	2.71	0.51	<0.01	<0.01
20.56	0.12	0.02	24.70	0.08	0.17	0.58	0.43	2.41	0.58	<0.01	<0.01
22.99	0.11	0.02	19.8	0.07	0.17	0.47	0.29	2.12	0.69	<0.01	<0.01
25.05	0.31	0.08	16.1	0.11	0.17	0.87	0.22	1.93	0.82	0.03	<0.01
27.01	1.48	0.41	13.0	0.18	0.11	1.81	0.18	1.73	0.88	0.03	0.08
29.31	3.86	0.93	11.7	0.27	0.15	2.56	0.17	1.51	0.84	1.09	0.68
31.23	4.90	1.05	10.6	0.30	0.13	2.37	0.18	1.37	0.78	1.23	1.10

spraying factory. In one instance the concentrations observed on the downstream face of the filter were very close to those observed on the upstream side, but there was a region in between where relatively little deposition had taken place. It is hard to explain this effect other than by assuming that the downstream side of the filter had been exposed to the vapour.

The results from cartridges used during paint spraying over long periods in small premises showed a spatial distribution of adsorbed xylene, toluene, propanol and methyl ethyl ketone that would be expected for a situation where significant desorption had taken place. The results for the latter two chemicals suggest breakthrough occurred some time before the analysis. However further work under controlled conditions would be needed before the explanation for this and the other observed behaviour could be confirmed.

An important conclusion is that the technique will produce good information on what occurs in industrial cartridges. This work is continuing, and further cartridges will be analysed in the same way. The project has led to an increase in understanding of the behaviour of granular carbon filters used in industry. It is significant that in none of these cartridges analysed have the downstream layers of filter been completely free of adsorbate. Although plausible explanations can be put forward for what is observed, firm conclusions cannot yet be drawn. Further work is needed to target other industries with different problems. It will also be necessary to explain exactly what is taking place and to link the pattern of deposition with quantitative estimates of wearer exposure.

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Table 8. Analytical results for Cartridge **K1** loaded at large paint spraying firm.

Distance (mm)	MPA	EEA	EEP	Toluene	Ethyl Benzene	m,p-Xylene
1.45	1.45	12.32	2.35	7.34	9.23	25.28
3.29	0.68	5.79	0.91	11.90	6.16	13.53
5.34	0.24	1.68	0.41	9.92	2.46	4.30
8.04	0.06	0.48	0.26	1.79	1.05	1.27
9.18	<0.01	0.24	0.21	0.31	0.75	0.59
11.68	<0.01	0.19	<0.01	0.17	0.64	0.42
13.28	<0.01	<0.01	<0.01	0.12	0.63	0.39
15.71	<0.01	<0.01	<0.01	0.13	0.70	0.43
18.40	<0.01	<0.01	<0.01	0.14	0.73	0.45
19.96	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
21.85	<0.01	<0.01	<0.01	0.12	<0.01	<0.01
23.96	<0.01	<0.01	<0.01	0.38	<0.01	<0.01
26.64	<0.01	0.22	<0.01	3.76	0.77	0.52
28.53	0.37	0.95	0.42	11.97	1.39	2.30
30.48	1.05	3.65	1.26	15.64	3.57	8.96

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Table 9. Analytical results for Cartridge **B1** loaded at large paint spraying firm.

Sample Number	MEK	111-TCE	n-Butanol	1-Methoxy Propanol	MIBK	Toluene	m,p-Xylene	Ethyl Benzene
1.00	<0.01	0.75	3.26	0.44	3.28	1.77	48.33	16.31
2.00	0.01	1.73	11.17	1.76	5.22	3.75	25.91	12.12
3.00	0.17	1.99	6.94	0.33	0.17	0.12	0.27	0.06
4.00	0.15	4.51	30.02	3.19	2.15	1.37	2.90	1.61
5.00	0.15	0.54	0.51	<0.01	0.19	0.18	0.29	<0.01
6.00	<0.01	<0.01	<0.01	<0.01	0.03	<0.01	0.06	<0.01
7.00	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
8.00	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
9.00	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
10.00	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
11.00	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	<0.01	<0.01
12.00	<0.01	0.50	0.24	<0.01	0.54	1.17	0.41	0.07
13.00	<0.01	0.71	0.31	<0.01	0.38	4.20	1.13	0.45

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Table 10. Analytical results for Cartridge B2 loaded at large paint spraying firm.

Distance (mm)	m,p- Xylene	Toluene	MIBK	MEK	n-Butyl Acetate	1-Methoxy Propanol	n-Butyl Alcohol	111- TCE	EEP	EEA
1.05	46.80	0.86	2.15	<0.01	0.12	0.74	4.37	0.62	0.18	23.6
3.41	23.20	1.79	2.89	0.05	0.30	2.23	14.7	1.56	0.14	9.20
5.64	3.95	0.71	1.09	0.11	0.26	2.55	22.6	3.17	<0.01	1.30
8.40	0.92	0.15	0.25	0.19	<0.01	0.82	10.1	2.40	<0.01	0.38
10.77	0.34	0.07	0.10	0.10	<0.01	0.13	1.50	0.59	<0.01	0.21
12.88	0.13	<0.01	<0.01	<0.01	<0.01	<0.01	0.23	0.02	<0.01	<0.01
15.67	0.15	<0.01	<0.01	<0.01	<0.01	<0.01	0.20	0.01	<0.01	<0.01
18.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
20.32	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
22.46	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
24.36	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
26.97	0.15	1.42	<0.01	<0.01	<0.01	<0.01	0.19	0.04	<0.01	<0.01
29.42	0.49	0.24	0.12	<0.01	0.40	<0.01	0.33	0.46	0.02	0.30

Appendix

Tables of Results

Notes on tables: analytical results are expressed in mg/g of carb<

Distance = Distance into cartridge

MEK = 2-butanone

III-TCE=1,1,1-Trichloroethane

MIBK = 4-Methyl 2-Pentanone

EEP = Ethyl 3-Ethoxy Propionate

EEA = 2-Ethoxy Ethyl Acetate

MPA = Methoxy Propyl Acetate