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Distribution of lead inside the home: case studies in the North of England

A.S. Al-Radady, B.E. Davies*, M.J. French

Department of Environmental Science, University of Bradford, Bradford, West Yorkshire, BD7 1DP, England

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Abstract

Air lead concentrations, deposition on moss bags and window velocity decreased rapidly through an open window in a university room. The indoor/outdoor air lead ratio was 0.82. Other experiments took place in houses in Bradford and Manchester. Lead deposition was studied using irrigated moss bags, by cleaning surfaces with moistened tissues, by washing curtains and by vacuum cleaning floors. Within a home, air lead concentrations were approximately the same upstairs and downstairs, but there was less lead in settled floor dusts upstairs compared with downstairs. Lead and dust loading on a hall floor decreased away from the front door and a front room downstairs had more lead in floor dust than a back room. Lead loadings on other surfaces were in the order window sills > furniture > walls > ceilings. Net curtains on windows effectively trapped lead aerosols. Garden soil contained more lead near the house. More lead was tracked into a hallway in wet weather and more lead entered through windows in summer months when windows were left open more often. Overall, lead loadings were higher for houses on busy streets near city centres.

Key words: Dust; Paint; Air; Moss bags; Furnishings; Soil pollution

1. Introduction

Human exposure to lead continues to be a matter for concern, particularly in the case of small children. Recently (1991), the (USA) Centers for Disease Control lowered their advisory limit for blood lead to 10 μg/dl whole blood from the earlier 25 μg/dl. Children derive most of their lead either through inhalation of suspended dusts and aerosols or by accidental or purposeful ingestion (*pica*) of dusts and other materials while they play. They may play out of doors or in their homes. Over recent years increasing importance has been attached to lead in the home environment.

Lead in the home environment may be derived from a variety of internal sources, e.g. flaking lead-based paints, transportion of soil or dirt from outside (Davies et al., 1985) and movement of lead-rich aerosols or suspended dust into the house.

Outdoor and indoor air exchange occurs continuously through draughts around doors and

* Corresponding author.

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windows or intermittently when doors and windows are opened. A number of studies have shown that indoor air lead concentrations are less than those immediately outside the house (Daines et al., 1972; Roberts et al., 1974; Diemel et al., 1981; Davies et al., 1987). Concentrations of lead in settled house dust correlate with contents in street dusts or garden soils but, as with airborne levels, they may be lower than those outside (Yocom et al., 1971; Schaefer et al., 1972; Lefcoe and Inculet, 1975; Alzona et al., 1979; Rowe et al., 1985). Redistribution within the home can occur as airborne dusts sediment, as aerosols adhere to surfaces through impaction or electrostatic attraction and settled dusts can temporarily be resuspended during normal household activity.

The reported studies show that the interior environment is complex. But there is a general lack of studies concerning the distribution of lead within homes. This paper provides new information on lead in home environments through surveys and experiments in selected houses in Bradford and Manchester, England.

1.1. Study locations

It was not practicable to carry out all the studies in a single home since this would have trespassed too much on the goodwill of the resident family. The work was therefore carried out in several houses in Bradford and Manchester where the householders were prepared to accept some invasion of their privacy. One study involved placing a long plank of wood through an open window and leaving it there for several months. This could be done only in an institutional building and an instrument room in the Department of Environmental Science was used. The house locations were:

A: Little Lane, Bradford 9. A terrace house on a busy street approximately 2.5 km north-west of the city centre.

B: Glenbrook Drive, Bradford 7. A semi-detached house in a post-War residential development. A quiet suburban street 2.5 km west of the city centre.

C: Glenrose Drive, Bradford 7. Similar to House B and approximately 180 m south of it.

D: Park View Road, Bradford 9. An Edwardian terrace house on a busy street approximately 2.5 km north-west of the city centre.

E: Botany Avenue, Bradford 2. A semi-detached house approximately 2.5 km north of the city centre.

F: Cringle Road, Manchester 19. A semi-detached house in a suburban area.

2. Analytical methods

The following methods were used as a routine in all the studies. Individual experimental procedures are described later below in relation to each particular study.

Direct determinations of deposited lead were carried out using the irrigated moss bag technique which has been fully described by Al-Radady et al. (1993b). Essentially, a small (11 × 11 cm) nylon mesh bag is supported over a flat box containing water and connected by capillary matting. The bag is filled with damp moss (*Sphagnum* spp) and then left exposed to the air for a period of time during which it collects deposited aerosols.

After exposure, the moss was removed from the bag and oven dried at 80°C for 6 h. Following overnight wet digestion in 20 ml concentrated HNO_3 acid (Analar grade), the solutions were evaporated to dryness and made up to 10 ml. Concentrations of lead were analysed by atomic absorption spectrophotometry (AAS) with background correction using the 283.3 nm line. To check the accuracy of analyses, the lead content of NBS standard reference material 1573 (tomato leaves) was determined. The certified value is 6.3 (± 0.3) μg/g; for 10 replicates a mean value of 6.2 μg/g (S.D. = 0.2) was obtained representing 98.4% recovery.

Airborne lead concentrations were measured directly using portable high volume dust samplers (Rotheroe and Mitchell L30: flow rate 35 l/min). Samples of airborne particulates were collected by drawing air through a cellulose filter (4.5 cm, Whatman No 41). During use, filters were replaced every other day. Each filter was carefully transferred from the monitoring head into a clean, labelled, self-sealing, plastic bag. In the laboratory, the filters were transferred, using plastic

forceps, to a 50-ml acid-washed beaker, 10 ml of 70% nitric acid (B.D.H. Analar) was added and the sample digested at 100°C. In order to reduce volatilisation from the beakers, watch glasses were placed over the beakers. After 60 min, the watch glasses were removed and the samples heated to reduce the volume of acid to near dryness. When cool, the sample was filtered through a Whatman No. 541 filter into a 25-ml volumetric flask, made up to mark with 1% nitric acid (B.D.H. Analar) and analysed by atomic absorption spectrophotometry. Blanks for the reagents and filter papers were obtained by digesting filter papers in the same manner as the samples and diluting the resulting solution to 10 ml in a volumetric flask. The blank value determined was subtracted from each sample.

Lead on surfaces was assessed using the swabbing technique of Sayre et al. (1974) and further developed by Gallacher et al. (1984) to estimate the amount of lead on a child's hand. Pre-moistened tissues [HomeFresh Family Fresh Wipes: Homefresh Labs., Ltd.; Knutsford, Cheshire (size, 14 × 20 cm)] were used to wipe surfaces. Each area was wiped with a single opened towel which was then placed in a clean, labelled, self-sealing plastic bag. All wipes were taken by the same person whilst wearing polyethylene gloves and an effort was made to ensure that a consistent technique was employed for the wiping. The wipes were transferred to a 250-ml beaker and 30 ml of 70% concentrated nitric acid (Analar) were added. The beaker was covered with a watch glass and heated gently (at around 60°C) on a hot plate until the wipes had disintegrated. The temperature was then increased to 110°C for 48 h and the sample frequently shaken to aid digestion. After 48 h, the watch glass was removed, the sample evaporated to near dryness and 5 ml of 1% nitric acid (Analar) added. The sample was then gently heated (at 50°C) for 10 min, the solution filtered into a 25-ml volumetric flask through Whatman 540 filter and made up to the mark. The lead concentration in the filtrate was determined by flame atomic absorption spectrophotometry. Quality control was achieved through simultaneous analysis of an NBS Standard Reference Material (SRM 1645, River Sediment; lead concentration 714 ± 28 μg/g: experimental value 671 ± 40 μg/g). The percentage recovery of the extraction technique was also determined, through the spiking of clean tissues with the Reference Material, as 94 ± 6%.

Settled house dust was collected from carpeted areas using an adapted Philips P60 vacuum cleaner following the method of Davies et al. (1987). The cleaner had a 24 × 80 mm cellulose filter thimble (Whatman 2800228) mounted at the far end of a suction tube. The collected dust was dried in the thimble at 80°C for 24 h and the < 125 μm fraction collected after sieving. A 0.25-g sub-sample was then taken, in a 50-ml beaker, from the dust collected in each experiment and 5 ml of concentrated nitric acid (70%, Analar) added. The beaker was covered with a watch glass and heated (at around 80°C) on a hot plate for 1 hour. The watch glass was removed and rinsed with 1% (v/v) nitric acid into the beaker, the temperature increased to 105°C and the sample evaporated to near dryness. Five millilitres of 1% nitric acid (Analar) was added, the sample gently heated (at 50°C) for 10 min, the solution filtered through a Whatman 541 filter paper into a 50-ml volumetric flask and made up to volume. The lead concentration in the extract was determined by flame atomic absorption spectrophotometry.

Soils were oven dried at 105°C for 6–7 h, gently disaggregated using an acid-washed porcelain pestle and mortar and sieved through a 1-mm aperture nylon sieve. Two grams of the sieved soil was digested with 20 ml of hot nitric acid and the lead, copper and zinc concentrations determined by AAS.

3. Description and results of individual studies

3.1. Airborne lead

(a) Air lead inside and outside the house. Indoor and outdoor airborne lead concentrations were investigated using two portable high volume dust samplers. The dust samplers were exposed on a 10-m long board, inserted through an open window (0.5 m^2 aperture) in a room in the Department of Environmental Science during July 1990. Six metres of the board were exposed to the outside atmosphere and 4 m were inside the room. This plank was also used as a platform for the

Table 1
Indoor (2 m in from window) and outdoor (outside sill) airborne lead concentration ($\mu g\ Pb \cdot m^{-3}$) at the Department of Environmental Science, University of Bradford

	Indoors	Outdoors
Number of samples	20	20
Mean	0.33	0.39
Minimum	0.16	0.19
Maximum	0.52	0.51
Standard deviation	0.09	0.09

moss bag deposition study described below but in order to avoid disturbance of the air during the moss bag exposure (e.g. Yocom, 1982) the inside and outside airborne lead concentrations were measured immediately afterwards. One of the dust samplers was placed on the window sill to measure the outdoor airborne lead concentration and the second was placed 2 m from the window to measure the indoor airborne lead concentration.

Results are given in Table 1. The ratio of the means (in/out) is 0.86 and the means are significantly different (*t*-test; $P < 0.001$).

(b) Air lead up stairs and down stairs in a home. This study took place in an inner-city terrace house (House A) in Bradford. Due to the limited number of samplers available, concurrent measurements of the airborne lead concentrations were possible in only two rooms (the ground floor living room and the second floor attic room) of the house. The results of the experiment are shown in Table 2. The means do not differ significantly.

Table 2
Airborne lead concentrations ($\mu g\ Pb \cdot m^{-3}$) in the attic and living room of House A

	Living room	Attic room
n	30	30
Mean	0.48	0.43
Minimum	0.14	0.13
Maximum	0.94	0.84
Standard deviation	0.18	0.16

n is the number of filters anaysed over 60 days.

Table 3
Indoor and outdoor deposition rates of lead ($\mu g/m^2$ per day) on to irrigated moss bags exposed at the Department of Environmental Science, University of Bradford

	Indoors	Outdoors
n	12	18
Mean	20.6	53.7
Minimum	11.7	40.7
Maximum	30.8	63.9
Standard deviation	6.3	5.6

n is the number of bags analysed.

3.2. Lead deposition on moss bags

(a) Deposition of lead on either side of an open window. As air blows through a window its velocity decreases and suspended particles progressively sediment out. The irrigated moss bag technique was used to investigate the overall deposition of lead-rich particles on either side of an open window.

Thirty irrigated moss bags were placed on the 10-m plank poking through an open window as described above for the airborne lead study. Three replicate moss bags were fixed to the plank at distances of 0.5, 1.5, 2.5 and 3.5 m from the window for indoors samples and 0.5, 1.5, 2.5, 3.5, 4.5 and 5.5 m for outdoor samples. Thus, there were 12 moss bags inside and 18 outside and they were left exposed during July, 1990. For 2 weeks of the experiment a vane anemometer was used to measure air velocity indoors at each moss bag location. Velocities were measured in the morning and in the afternoon; five readings were taken at each position and the velocities were averaged over the reading period.

The lead results of this experiment are given in Table 3. The indoor/outdoor ratio of the mean deposition is 0.38 and the means differ significantly ($P < 0.001$).

The change in lead deposition along the plank is shown in Fig. 1 together with the wind velocities.

(b) Variation of metal deposition rates in different types of room within a typical house. This experiment was also conducted in House A. Measurements were made in a living room and a front sitting room located on the ground floor, as well as in a bedroom located on the first floor and

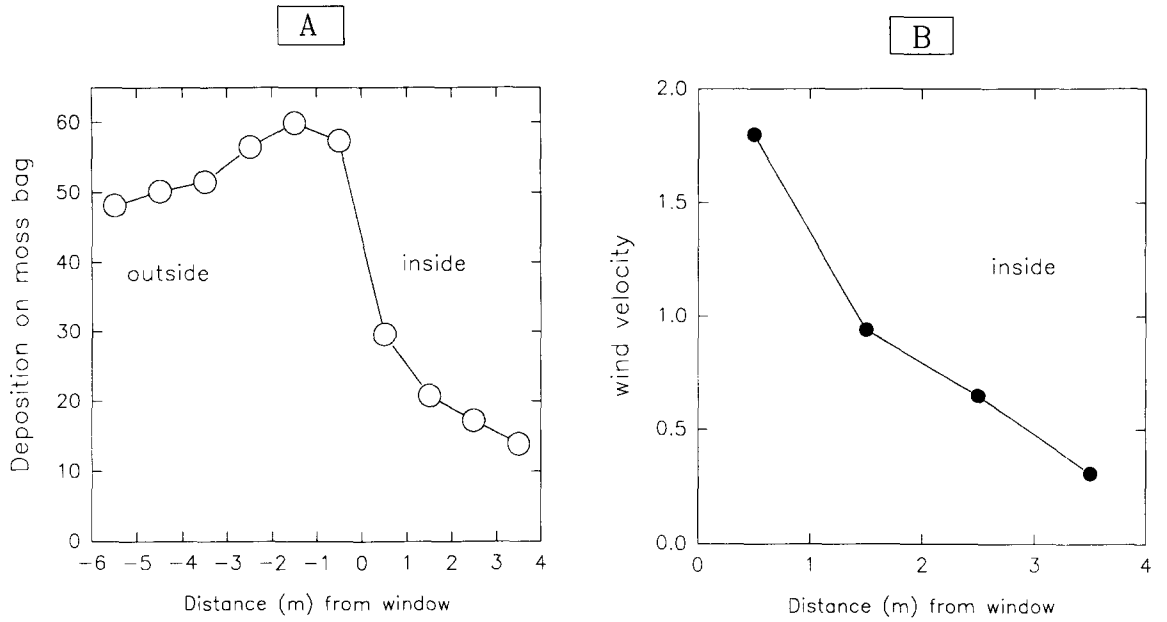

Fig. 1. Results of an experiment at an open window. A: Deposition of lead ($\mu g/m^2$ per day) on moss bags. B: Wind velocity (m/s).

an attic room located on the second floor. Twenty irrigated moss bags were distributed in the four rooms (five samples in each room) and were exposed for 4 weeks in suitable locations (window sills, tables, cupboards) at a height of 1–2 m above the floor level. Two replicate experiments were performed in the months October and November 1988. Results are presented (Table 4) for the means of each group of moss bags and averaged over the 2 months.

3.3. Measurements of the amount of lead deposited on different surfaces within a house

A series of investigations was undertaken to determine how much lead is found on different surfaces within a house, namely, immobile hard surfaces (walls, ceilings, window sills and furniture) and mobile soft surfaces (curtains). In addition to determining the amount of lead on these surfaces, changes with time were determined experimentally.

(a) Lead concentrations on immobile surfaces. The wiping technique was used for the measure-

Table 4
Mean (± S.D.) deposition rates of Pb ($\mu g/m^2$ per day) in different rooms of House A

	n	Metal deposition
Front room	10	223.1 ± 188.0
Living room	10	71.0 ± 10.3
Bed room	10	45.6 ± 8.36
Attic room	10	30.0 ± 6.7

n is the number of moss bags analysed.

Table 5
Lead ($\mu g/m^2$) deposited on different surfaces of an old (F) and a new house (B)

	House B	House F
Wipes taken from the wall	25.6 ± 9.1	27.4 ± 18.0
n	12	21
Wipes taken from furniture	64.5 ± 26.6	230.2 ± 142.9
n	10	10
Wipes taken from window sill	109.4 ± 18.5	665.0 ± 424.1
n	8	6
Wipes taken from ceiling	6.5 ± 2.2	12.6 ± 4.8
n	8	7

Mean values ± S.D.
n is the number of wipes analysed.

Table 6
Lead deposited ($\mu g/m^2$ per day) on previously cleaned immobile solid surfaces in three houses over a 28-day period in March 1990

	House B	House C	House D
Walls	0.60 ± 0.19	0.60 ± 0.26	0.73 ± 0.20
n	20	40	20
Furniture	1.28 ± 0.41	1.92 ± 0.68	3.06 ± 0.68
n	10	40	10
Window sills	3.37 ± 0.79	3.28 ± 1.88	5.79 ± 1.52
n	8	20	8

Values are means of *n* samples ± S.D.
n is the number of wipes analysed.

ment of lead concentrations on the walls, ceiling, window sills and furniture in various rooms of a modern house in Bradford (House B) and a Victorian semi-detached house in Manchester (House F). Wipes were taken from 1 m^2 areas of walls and ceilings and from measured areas of window sills and furniture. Results are given in Table 5.

(b) Seasonal changes of lead concentrations on immobile surfaces. The work described in (a) above was followed up by investigating deposition with regard to time. In the first instance a survey was conducted simultaneously in three houses (B, C and D) in March, 1990.

Initially the selected surfaces (walls, furniture, window sill) were carefully wiped, three times on the same day, with a moistened tissue. After the initial cleaning three wipes were taken directly from each surface to determine the residual lead content and the values subtracted from those of later samples. Subsequently, after 28 days, the same surfaces were again wiped using a moist tissue. Results are given in Table 6.

At one of these houses (House C) the survey was extended for a further 4 months. These data are presented in Table 7.

(c) Lead concentrations on curtains. Metal concentrations were determined in net curtains from houses B and F. As far as was known, the curtains had been in normal use and unwashed for a period of at least 1 year. The curtains were transferred to a large plastic bottle, 1 l of 10% nitric acid at around 90°C added and the bottle shaken for 1 hour. During shaking, the bottle was rotated through 90° every 15 min. Initially, three consecutive washes were employed and the results of

Table 7
Lead deposited ($\mu g/m^2$ per day) on immobile solid surfaces in House C monthly over a 4-month period In 1990

	Walls	Furniture	Window sills
April	0.49 ± 0.14	1.84 ± 0.55	2.57 ± 0.63
n	22	10	5
May	0.35 ± 0.11	1.22 ± 0.43	1.97 ± 0.36
n	21	10	5
June	0.75 ± 0.29	2.16 ± 0.61	4.89 ± 1.30
n	22	10	5
July	0.89 ± 0.40	2.41 ± 0.53	5.86 ± 1.32
n	22	10	5

Values are means of *n* samples ± S.D.

Table 8
Mass and fraction of Pb recovered from three net curtains after each wash with 10% (v/v) nitric acid. The fraction is expressed as the percentage of the cumulative mass of lead removed over three washes

	Pb (μg)	%
Sample 1		
First wash	407	76
Second wash	116	22
Third wash	12	2
Total	535	100
Sample 2		
First wash	584	73
Second wash	179	23
Third Wash	34	4
Total	797	100
Sample 3		
First wash	355	69
Second wash	123	24
Third wash	38	7
Total	516	100

Table 9
Lead ($\mu g/m^2$) deposited on curtains In a new house (B) and an old house (F)

	B	F
Mean	708	2991
Standard deviation	359.4	468.5
n	6	7

Table 10
Lead deposited ($\mu g/m^2$ per day) on net curtains in House C over a 4-month period in 1990.

Month	Mean	Standard deviation	n
April	2.55	0.26	4
May	2.25	0.44	4
June	4.60	0.37	4
July	4.45	0.54	4

the three washings are summarised in Table 8. These initial experiments showed that two washes were adequate to remove more than 90% of the metal content of the curtains and therefore only two washes were used in subsequent measurements.

After leaching the curtains, the leacheate was transferred to a beaker (1800 ml) and heated gently on a hot plate until the sample volume was reduced to approximately one-tenth of the original volume and analysed by atomic absorption spectrophotometry. The results for curtains are given in Table 9.

(d) Metal deposition rates on curtains. Variation over time of the lead deposition rates on curtains were also investigated at House C during the period from April to July, 1990.

Net curtains were hung for 28 days in each month and then collected and analysed as above. A blank for the reagents and curtains was obtained by washing three curtains in the same manner as the samples and the blank value subtracted from each sample. Results are given in Table 10.

3.4. Lead in settled house dusts

(a) Consecutive resampling of a carpeted area. The aim of this study was to obtain information on the efficiency of removal of dust from carpets and to study the variation of lead loading as a function of frequency of sampling.

In each of the four houses (Houses B, C, E and F), three sections of each carpet were resampled by vacuum cleaning an area of 1 m^2 six times consecutively. The dust was dried, weighed without sieving and analysed for lead. Results are shown in Fig. 2.

(b) Variations from room to room in a house. The distribution of dust and lead loadings in dif-

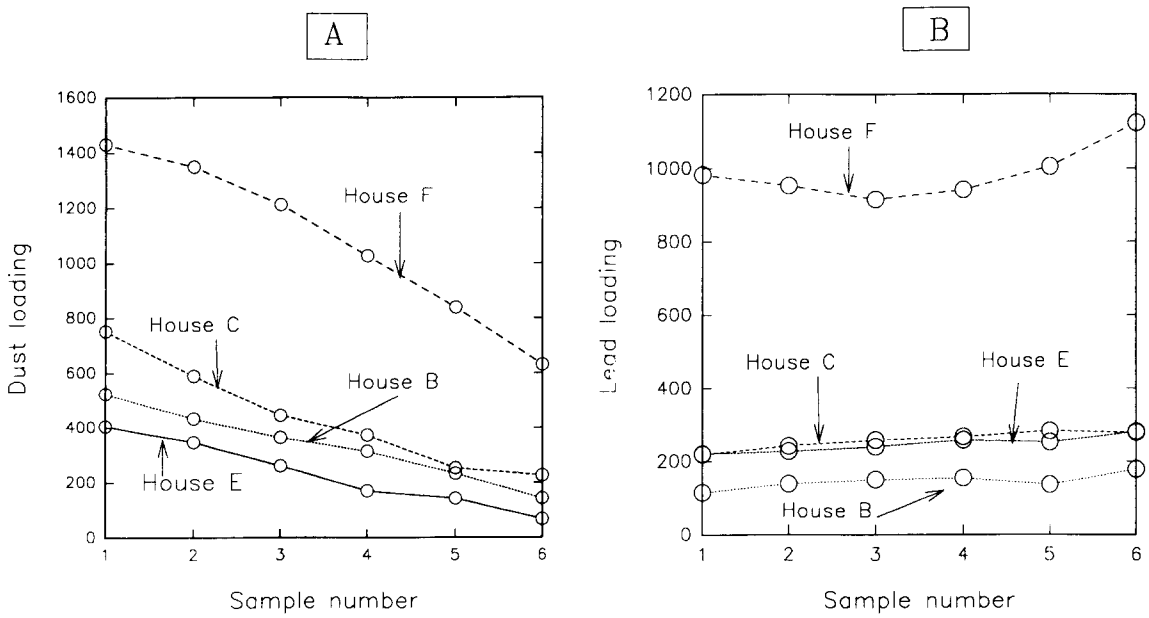

Fig. 2. Results from successive sampling of the same carpet areas by vacuum cleaning; locations of the houses are given in the text. Dust loading (A) is mg/m^2 and lead loading (B) is $\mu g/m^2$.

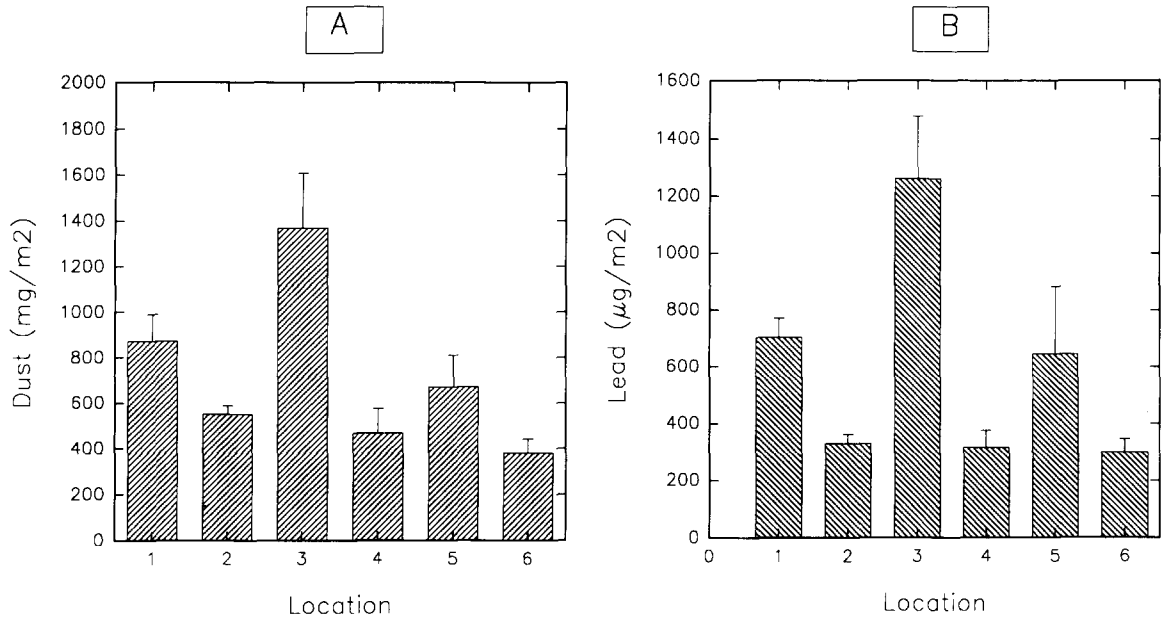

Fig. 3. Dust (A) and lead (B) loadings downstairs and upstairs in House F. Locations: 1, front room downstairs; 2, back room downstairs; 3, hallway; 4, front bedroom; 5, back bedroom; and 6, landing.

ferent rooms was investigated in House F. The settled house dusts were sampled by vacuum cleaning 1 m^2 areas in a front and a back room downstairs, the corresponding rooms upstairs, the front hall and the upstairs landing. The results are shown in Fig. 3.

(c) Dust loading, metal concentrations and metal loading in relation to distance from the main door

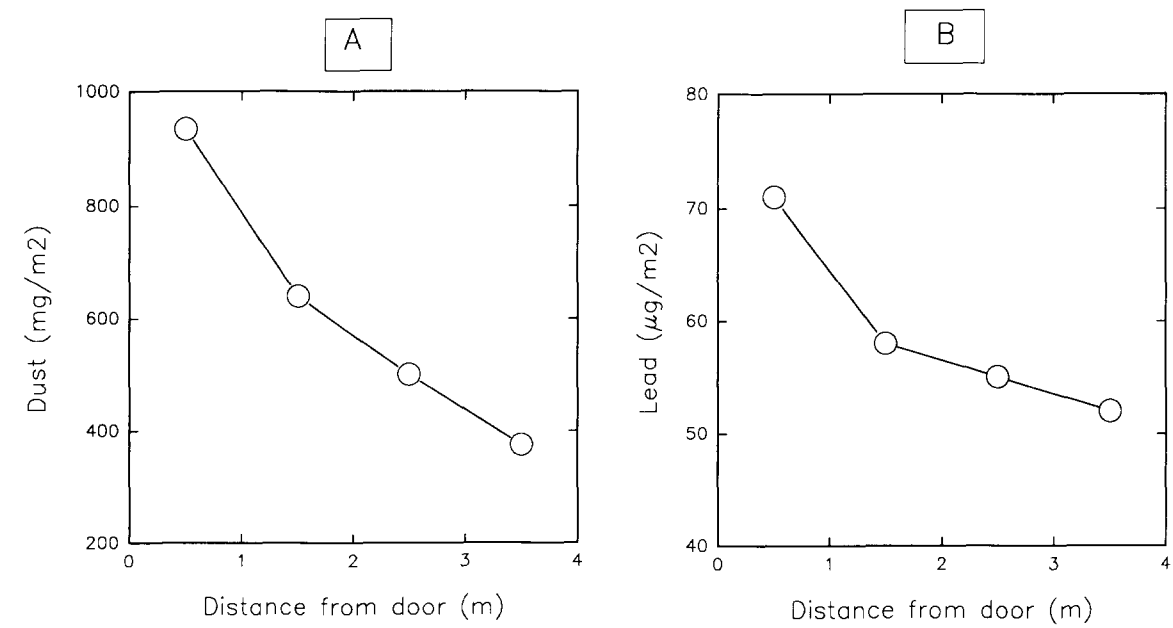

Fig. 4. Dust (A) and lead (B) loadings on a hall floor in relation to the front door.

Table 11
The effect of drier (July–September) and wetter (October–December) weather in 1990 on dust and lead carried in through a front door in House B. (Data from 12 carpet squares)

	Mean	Minimum	Maximum	Standard deviation
Dust Loading (mg/m^2)				
Dry	440	130	960	228
Wet	785	310	1310	302
Lead Loading ($\mu m/m^2$)				
Dry	39.4	14.6	67.4	16.6
Wet	78.4	35.9	128.5	30.3
Lead concentration ($\mu g/g$)				
Dry	95.6	51.5	135.3	24.6
Wet	103.9	57.9	157.4	31.7

and to season. Street dust and soil can contribute to settled house dust when carried in on shoes or on the fur of pets or simply by blowing through an open door. One would expect some decline in dust amounts away from the door. This was investigated in the hallway of House B. Eight new pieces of carpet (50 × 50 cm) were exposed, in pairs, for 28 days at measured distances (0–1, 1–2, 2–3, and 3–4 m) from the main front door. The area of the hallway was 4.0 × 0.6 m. Before exposure, each piece of carpet was vacuum cleaned five times to ensure that it was relatively free from dust. After 28 days exposure, the dust accumulated by each pair of carpets was collected by vacuum cleaning and weighed and analysed, without sieving. This was done at the end of each month from July to December, 1990.

The distribution in relation to distance from the front door is shown in Fig. 4 where the value at each location is the mean of the duplicates ag-

Table 12
Analyses of paint samples from four houses (mean ± S.D.)

Description	Pb ($\mu g/g$)	*n*
White paint from outside window frame of House F	9932 ± 771	4
White paint inside window frame of House F	13 975 ± 1356	4
Green paint from outside of back door of House F	24 602 ± 4930	5
White paint from outside window frames of Houses C, E and B	2120 ± 1244	7

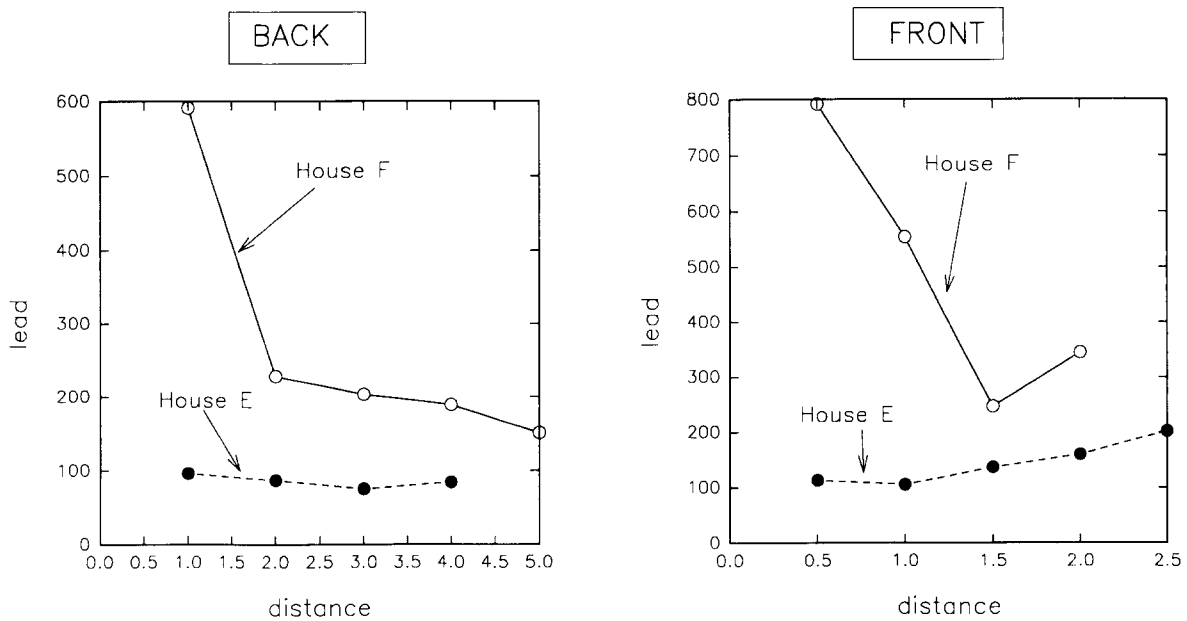

Fig. 5. Lead concentrations ($\mu g/g$) in dry soil in relation to distance from a house.

gregated over the 6 months. The distribution in relation to season is given in Table 11 where July, August and September samples are all combined and regarded as the 'drier' months while the 'wetter' months are the combination of the October, November and December samples.

3.5. Lead in paint

Lead compounds have long been used in paints both as pigments and as promoters of the drying process. The use of leaded paints is discouraged or banned in many countries but flaking leaded paint remains a hazard in many homes.

Samples of accessible peeling paint were collected from Houses B, C, E and F. Paint samples were dried at 100°C and sub-samples (0.5 g) were ashed at 350°C for 30 min and then dissolved in nitric acid (70% v/v: Analar) and analysed for lead. Results are given in Table 12.

3.6. Variation of soil lead content with distance from the house

Soil can contribute to lead in house dust through wind blow or by being carried into a home on shoes. Exterior paint on a house can contribute to soil lead through flaking. The variation of soil lead around two houses was investigated.

Soil samples (0–5-cm depth) were taken with a stainless steel trowel, from the front and back gardens of Houses B and F. Three soil samples were collected at each sampling point which were at measured distances from the houses. Results are shown in Fig. 5.

4. Discussion

Practical considerations made it impossible to carry out all the investigations in a single home. Also, the financial resources available did not allow some measurements (e.g. more sampling of outside air) which would undoubtedly have added to the value of the work. But all the buildings used as study locations were in two similar industrial cities (Manchester and Bradford) and the Bradford buildings were all within 3 km of the city centre. We therefore believe there was a coherence in the study and it is justifiable to draw conclusions from the individual investigations taken together.

4.1. Indoor/outdoor studies

Until 1986 the maximum lead content of petrol was progressively reduced to 0.4 g $Pb \cdot l^{-1}$ and then, in compliance with EEC legislation, to 0.15 g $Pb \cdot l^{-1}$. Page et al. (1988) recorded a 52–61% fall in air lead content in Wales following this reduction. In four urban areas the near-ground air lead concentrations ranged from 0.069 to 0.248 μg $Pb \cdot m^{-3}$. The near-window lead contents for Bradford (Table 1) are higher, but Bradford is more populous than the Welsh urban areas.

Although lead-free petrol is readily available, many British drivers still use petrol containing lead additives and vehicle exhausts continue to pollute the air with lead aerosols. These aerosols infiltrate buildings. Outdoor and indoor air exchange occurs continuously through draughts around doors and windows or intermittently when doors and windows are opened. A number of studies have shown that indoor-air lead concentrations are less than those immediately outside the house. Daines et al. (1972) studied indoor and outdoor airborne lead ratios at different distances from a motorway: ratios varied from 0.5 to 0.7. Roberts et al. (1974) measured indoor and outdoor atmospheric lead concentrations around secondary smelters during the winter months and found that the indoor values were only 20–30% of those recorded outdoors. In Arnhem (Netherlands) Diemel et al. (1981) reported an indoor/outdoor ratio of 0.62. In a more extensive study in Birmingham (England) of over 90 rooms by Davies et al. (1987) a ratio of 0.63 between indoor and outdoor air lead concentrations was reported.

The results presented in Table 1 are consistent with the literature reports. The indoor/outdoor ratio of means (0.86) is larger than the ratios reported by other workers but the experiment was conducted through a completely open window which would maximise the movement of air into the room. The data in Table 2 suggest that within a building the air is relatively homogeneous with respect to lead.

Literature reports also show that dust levels within a home are lower than those outside although the precise relationship depends on many factors. For particulate matter up to 5-μm diameter, Lefcoe and Inculet (1975) found an

increase in dust levels when windows were opened and when there was a good deal of activity in the home. Similarly, Yocom et al. (1971) reported that particulate concentrations were lower during winter when the windows were closed. The effect of opening and closing windows and doors on the indoor/outdoor ratio was investigated by Alzona et al. (1979). Their studies suggested that a person remaining inside, with windows and doors closed, inhales no more than one-third the dust of outdoor origin as they would if they were out-of-doors. Indoor/outdoor ratios in arid climates (Riyadh, Saudi Arabia) were investigated by Rowe et al. (1985). Ratios of 0.25 and 0.59 were reported for total suspended particulate matter and for inhaleable particulate matter (<10 μm), respectively.

These reports serve only to quantify a common sense observation that the interior of a house is likely to be dirtier when windows remain open. But Fig. 1A is interesting in that it reveals that even when a window is completely open, dust fall declines rapidly with distance away from the window. The wind velocity measurements (Fig. 1B) support a hypothesis that this is a sedimentation effect in calmer air. There is also an upturn in the deposition curve outside and close to the window implying that dustfall measurements should be conducted well away (>10 m) from the building. Overall (Table 3), deposition is lower inside by a factor of 0.38.

Solomon and Hartford (1976) showed that soil lead concentrations tended to be highest near the building and then near the street or road, but there was not always any great variation in values. The results for Houses E and F (Fig. 5) are consistent with those observations. The sources of the lead seen to have accumulated in the soil sample nearest to the fabric of House F would include exterior paint. The limited analyses of exterior paint from this house (Table 12) show high lead concentrations, namely approximately 1.0% for white paint on a window frame and approximately 2.5% for green paint on a back door. Fig. 1A shows an increase in deposition of lead close to the outside wall of a building and the wall itself acts as a collection surface off which lead-rich dusts can be washed on to the adjacent soil. In Britain, water draining off a roof is usually taken through gutters and down pipes to drains and therefore any lead deposited on roofs would not contribute to the near-house soil lead.

The soil and lead loadings shown in Fig. 4 for the hallway of House F imply that external soil or street dust is being carried into the house. Davies et al. (1985) concluded from a statistical analysis of their data that external soil lead contributed significantly to interior house dust lead. Culbard et al. (1988) also reached the same conclusion from similar statistical analyses. Fergusson et al. (1986) proposed that 45–50% of house dust came from soil or street dust judged by enrichment factors for lead compared with a group of elements (Al, Fe, rare earths etc.) which were soil-derived.

4.2. Deposition of dust and lead on floors

The data in Table 2 show that the air lead concentrations are essentially the same in the main living room of a house and in an unused attic. In contrast, the deposition on to moss bags did vary from room to room. Moss bags are efficient collectors of both fine and coarse particles (Al-Radady et al., 1992). Deposition was highest in the front room of this terrace house which was separated from a busy city street by only a narrow garden strip (some 3 m). In the back, away from the street, the deposition rate was much lower (32%) and rates were lower upstairs.

Consecutive resampling of carpets with a vacuum cleaner (Fig. 2) shows that each successive cleansing removes dust, but less each time, whereas the lead concentrations stay essentially the same. A single sampling would be enough to provide an estimate of carpet dust lead concentrations, but a much more vigorous removal technique is needed if total lead and dust amounts are to be measured.

In House F (Fig. 3) there are room-to-room differences in carpet lead concentrations and dust contents. Downstairs, the front room has more deposited lead than the backroom and the hallway has more than either. People generally enter a house from the street through the front door into the hallway, although it is not uncommon to go round the side and use a back or side door. It is difficult to generalise but a hall tends to be the part

of a house which gets dirtiest fastest. Any room will be affected by dirt tramped in from a hall or passage but a front room is also the most susceptible to contamination by aerosols entering from the street through a window. Table 2 showed that aerosol settling is greater in the front. Upstairs in this house the carpet lead load was approximately the same on the landing and in the front room. Harrison and Laxen (1981) noted that there is a tendency for particulate lead in street air to be lower 14 m above a street compared with measurements at 4.9 m. It is possible that the amount of lead entering the bedroom through the window was approximately the same as the amount of lead carried upstairs from the hallway. The back bedroom, however, contained more deposited lead (Fig. 3B) than elsewhere upstairs, but it was also dirtier as judged by the deposited dust value (Fig. 3A). A rarely used bedroom may be cleaned relatively infrequently.

The effect of distance from the front door in the hallway is shown in Fig. 4. Away from the door both dust and lead loading decrease. In Table 11 the data used to construct Fig. 4 were classified according to overall weather. July, August and September were regarded as relatively dry while the next three months (autumn and early winter) were regarded as wet. Shoes are more likely to be dirtier in wet weather and therefore track more street dirt or garden soil into a house. This effect is clearly seen in the tabulated data where dust and lead loadings and lead concentrations are all higher during the wetter period.

4.3. Contribution of lead from paints and the building fabric

Culbard et al. (1988) identified paint as an important contributer to lead in settled dusts. They noted that houses undergoing redecoration at the time of sampling had almost double the concentration of lead in their floor dust than other houses. Schwar and Alexander (1988) observed similar effects in schools where redecoration was in progress. Marino et al. (1990) have described cases of childhood lead poisoning and adult lead toxicity during paint removal in a Victorian farmhouse.

It was not possible within the scope of this study to undertake any comprehensive sampling of interior paint and none of the houses was being redecorated when the research was under way. Table 12 does record that white interior paint in House F contained 1.4% Pb.

There was, however, another source of lead in some houses in the Bradford area. This is leaded windows which have recently been reported as a separate study (Al-Radady et al., 1993a). House A was included in that study. It was found that the dust on window sills adjacent to leaded windows was largely basic lead carbonate. Localised sampling suggested that lead concentrations in carpet dust declined rapidly away from the window.

4.4. Deposition of dust and lead on other interior surfaces

Lead compounds may be incorporated into the dust on other surfaces besides floors. Convection currents in a room slowly dirty the ceiling and suspended dusts will impact on and adhere to the walls. Furniture and sills get dusty. Curtains gather dust.

For large particles, greater than 10 μm, sedimentation is an important removal process and this is particularly true for particles greater than 50 μm in diameter. Particle size plays a major role in the rate of deposition on to surfaces and the retention efficiency within the lungs following inhalation (Nazaroff and Cass, 1989). Coagulation also serves as a sink for very fine dust particles by transferring their mass to larger particles, so that sedimentation may ultimately prove an important removal route even for small particles.

Impaction is a mechanism for removing fine dust particles (< 10 μm) which predominate indoors. Impaction is the adherence of fine dust particles to surfaces such as walls, curtains, ceilings, carpets and furniture. Impaction occurs when the particle fails to follow the fluid streamlines around an obstacle and impacts on the obstacle as a consequence of its inherent inertia.

The values in Table 5 show the lead loadings on different surfaces. Ceilings, to which only finer particles will be carried, carry the lowest lead loadings. Window sills carry the highest lead loadings as aerosols deposit on them after coming through an open window or in draughts around ill-fitting frames. Fig. 1 demonstrates how lead

compounds are rapidly deposited as air velocity decreases through an open window. Walls carry more lead than ceilings but less than furniture. Finally, the older house generally has more deposited lead than the younger house.

This study was not designed to allow modelling of lead inputs and fates within a home. For the most part it was concerned with spatial variations of lead and dust loadings at one time. Some preliminary studies were however undertaken on rates of deposition. Table 6 records the results of a 28-day study in three houses to establish the rate of deposition of lead on clean surfaces. The results are consistent with the 'snapshot' data in Table 5 in that the order of deposition rate is window sills > furniture > walls. House D is older than B or C (both post War) and is located on a busy street, whereas the other two are in quieter residential areas. The rate of deposition in D is somewhat higher than B or C between which there is little difference but the means do not reach a level of significance of $P < 0.1$.

The study was continued in House C for a further 4 months (Table 7). The order of deposition (window sills > furniture > walls) was maintained. There are differences from month to month, for example, deposition of lead on walls was less in May than in April ($P < 0.1$). The largest change was, however, from May to June. The simplest explanation is that June and July are the warmer months when windows are kept open more often.

In Table 5, the lead loading on furniture for House B is given as approximately 65 $\mu g/m^2$ and in Table 6 the rate of deposition for the furniture is 1.28 $\mu g/m^2$ per day. Some 50 days accumulation of lead would be needed to reach the total deposition of lead measured in March.

The data for lead held on net curtains (Tables 9 and 10) for two houses are consistent with the hypothesis that lead aerosols coming through an open window or in draughts around the frame are important contributors to lead in house dust. Net curtains are usually drawn (in order to protect privacy) and the rate of deposition for House C (mean of the 4 months in Table 10) is 3.46 $\mu g/m^2$ per day which compares favourably with a deposition rate of 3.82 $\mu g/m^2$ per day for the window sills of the same house over the same period. Net curtains are worth considering as monitors of aerosol transport through windows since they are far less intrusive than other methods and many British windows are hung with them. Interestingly (Table 9), there is more lead trapped in the curtains of the older house.

5. Conclusions

This study has confirmed that lead in aerosols (assumedly from vehicle exhausts) contributes to the lead deposited inside a house as does lead in paint, unusual sources such as leaded windows, street dirt and garden soil. Interior aerosol deposition declines rapidly away from a window and, outside, increases near a window or wall. Window sills therefore have the highest deposited lead loading and net curtains are also effective traps. These curtains merit further investigation as monitors of lead transportation through windows. Although airborne lead within a house is approximately the same upstairs and downstairs, deposited lead varies. Lead loadings are highest on floors in halls and decrease away from the front door. Within rooms, lead loadings are highest on the floors of those fronting a road, whereas the same front/back differential is not seen upstairs, and upstairs floors tend to have less deposited lead than downstairs. However, room cleaning will affect the carpet lead loading and an irregularly cleaned, intermittently used bedroom may have higher floor lead loadings than other rooms. More lead is tracked through into the hall in wetter weather, but more lead enters through windows in warmer weather when the window is kept open. Furniture carries more lead than other non-floor surfaces.

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