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Trace elements in fine particulate matter within a community in western Riverside County, CA: focus on residential sites and a local high school

Kwangsam Na[a], Aniket A. Sawant[a,b], David R. Cocker III[a,b,*]

[a] *Bourns College of Engineering, Center for Environmental Research and Technology (CE-CERT), University of California, Riverside, CA 92521, USA*

[b] *Department of Chemical and Environmental Engineering, Bourns College of Engineering, University of California, Riverside, CA 92521, USA*

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Abstract

Measurements of mass concentrations of 35 trace elements (TEs) and of total fine particulate matter ($PM_{2.5}$) were conducted at 20 residences and six high school rooms in Mira Loma, California, from September 2001 to January 2002. Sulfur (S) and silicon (Si) were the most abundant TEs measured (excluding a residence with heavy smokers). On average, total TE concentrations were lower indoors relative to outdoors; the proportion of TEs in total $PM_{2.5}$ was also lower indoors relative to outdoors. Among indoor sites, TE concentrations were found to be lower inside the schoolrooms relative to inside the residences. Environmental tobacco smoke (ETS) was found to contribute significantly to elevated levels of total TE inside residences; however, concentrations of carcinogenic TEs were not significantly different between residences with and without smokers. Potassium (K) and chlorine (Cl) were the most abundant species in a residence with frequent indoor smokers. Combustion-related elements were more enriched inside the residences relative to crustal elements.

Keywords: Trace elements; $PM_{2.5}$; Environmental tobacco smoke; Indoor air quality; Outdoor-to-indoor ratio

1. Introduction

Fine particulate matter with aerodynamic diameter smaller than 2.5 μm ($PM_{2.5}$) has received considerable attention in recent years as it is easily inhaled and deposited within the lungs, leading to respiratory distress and increased mortality rates (Seaton et al., 1995; Monn et al., 1997). It has been documented that the average person spends approximately 85% of their time indoors (Jenkins et al., 1992). Therefore, one might expect a significant fraction of total personal exposure to $PM_{2.5}$ to occur within the indoor environment.

Indoor particulate matter concentration is influenced by indoor emission sources (e.g., environmental tobacco smoke (ETS), cooking, resuspension by movement, etc.), outdoor-to-indoor transport (e.g., ventilation and infiltration) and removal mechanisms (e.g., deposition and filtration during outdoor-to-indoor transport) (Quackenboss et al., 1989; Thatcher and Laytol, 1995; Moriske et al., 1996). An indoor environment may shield against outdoor pollutants because outdoor air must penetrate the envelope surrounding the indoor environment, offering ample time for filtration and deposition. However, when particles are emitted from indoor sources, particle concentrations remain at elevated levels in a confined space.

Some trace elements (TEs) present in $PM_{2.5}$ are human or animal carcinogens including As, Be, Cd,

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*Corresponding author. Tel.: +1-909-781-5695; fax: +1-909-781-5790.

E-mail address: dcocker@engr.ucr.edu (D.R. Cocker III).

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Cl, Co, Cr, Hg, Ni, Pb, Rn, and Se (ATSDR, 2003). Even though most of these elements are associated with outdoor emission sources (e.g., coal and oil combustion, incinerators, motor vehicles and metal industries (ATSDR, 2003)), they may still contribute significantly to indoor $PM_{2.5}$ via outdoor-to-indoor transport. Other sources of TEs may include crustal material from road dust, construction activities, tire/brake wear, cement factories, etc. Areas that are strongly affected by these sources are expected to have elevated levels of TEs. Studies have shown that Mira Loma and the surrounding areas have elevated $PM_{2.5}$ levels (Allen et al., 2000; Kim et al., 2000; Sawant et al., 2004) and are likely influenced by multiple sources of TEs. Furthermore, Gauderman et al. (2000) reported that school children in Mira Loma had among the lowest forced expiratory volume (FEV) of 12 communities studied in Southern California.

In this study, we focus on indoor–outdoor relationships of TEs in the Mira Loma area. Our aim was to determine the relative importance of indoor and outdoor loadings of TEs in the indoor environment. Mira Loma was chosen for this study because of its historically large outdoor $PM_{2.5}$ loading and its proximity to multiple $PM_{2.5}$ sources (e.g., transport of agricultural and mobile emissions from upwind sources). The study focused on indoor microenvironments that children are exposed to most frequently. This study is part of a larger investigation of Mira Loma air quality reported by Sawant et al. (2004).

2. Experimental methods

The community of Mira Loma (33° 59′N, 117° 31′W) is located in western Riverside County, California, approximately 90 km east of downtown Los Angeles. Sampling was conducted at 20 residences from 18 September 2001, to 26 January 2002, covering the greater part of the fall and winter seasons for this region. A "sampling period" consisted of 12 calendar days with sampling occurring on alternating days (six 24-h samples per period). For each sampling period, the residences were chosen in sets of two in the same neighborhood, normally within 400 m of each other. The two residences in each set were named "A" and "B" for convenience. One outdoor sampler (located in the backyard of one of the two residences) was used for each pair of residences. Outdoor sampling locations for residences were located away from major roads to minimize the influence of local emission sources.

Table 1 summarizes the characteristics of each residence. All but one residence (3B) used natural gas for cooking, and all but two (1B and 3A) used natural gas for heating. Five of the residences (3B, 4B, 5A, 7A and 7B) had occupants that smoked. Of the five residences, only residence 5A had frequent indoor smokers (average of 40 total cigarettes per day); from this point onwards, the term "residence 5A" should be interpreted as the one residence in this study having frequent indoor smokers. All residences except two (2A and 3A) had pets.

The samplers were installed inside the houses based on the following criteria: convenience of residents, proportion of time spent by residents in particular areas of the house, availability of power and ease of accessibility. In the case of residences with small children or pets, child security gates were installed for safety and security. The equipment was electronically set to operate for 24 h starting at 8:00 PM. Participating residents were given logbooks to record household activities such as cooking, cleaning, use of air-conditioning/heating, smoking (inside/outside), etc. Additionally, samples were collected from a total of six rooms within the local high school during different sampling periods (one per sampling period). These included a library, an administrative office, and four classrooms. Sampling at the school and at the residences began simultaneously.

All samples reported in this paper were collected approximately 1.5 m above ground level. A particle trap impactor (Biswas and Flagan, 1988) removed particles larger than 2.5 μm aerodynamic diameter. $PM_{2.5}$ was collected on 47 mm Teflo™ (Pall-Gelman, Ann Arbor, MI, USA) substrates. Parallel substrates collected samples for anions, elemental/organic carbon, carbonyls, nitric acid and ammonia (Sawant et al., 2004).

Teflo™ filters were weighed a minimum of two times on different days in a controlled temperature/relative humidity (RH) chamber at 25°C and 40% RH on an ATI-Cahn® C-35 microbalance, both before and after sampling. Weights were only accepted if duplicate weights were within 3 μg of each other. The average of these two weights for each case (initial and final) were taken to be the initial and final weights, respectively. X-ray fluorescence (XRF) analysis for 35 TEs was performed by the research laboratories at the South Coast Air Quality Management District (SCAQMD, Diamond Bar, CA).

3. Results and discussion

3.1. Residences

3.1.1. General results

Table 2 summarizes the average indoor and outdoor concentrations of total trace element and $PM_{2.5}$, together with indoor/outdoor (I/O) concentration ratios. The oxidation state (Allen et al., 2000) of each element was used to determine the mass of TEs as a percentage of total $PM_{2.5}$. The average indoor concentrations of total TEs were lower than those measured outdoors

Table 1
Summary of residential sites sampled

Sampling period	Site ID	Smoking	Pets/Livestock[a]		Cleaning frequency[b]			Cooking		Ventilation and climate control			
			Outdoors	Indoors				Type	Frequency[b]	Heating type	Frequency[b]		
					Vac	Dust	Solv				H	W	AC
9/17–9/28	1A	No	7	0	0.5	0.3	0.5	Gas	1.6	Gas	0	0.6	0.9
	1B	No	2	0	1.0	0.4	0.9	Gas	2.0	Electric	0.1	0.9	0
9/29–10/10	2A	No	0	0	0	0.3	1.0	Gas	1.8	Gas	0.1	1.0	0
	2B	No	3	0	0.5	0.5	0.7	Gas	1.7	Gas	0	0.9	0
10/11–10/22	3A	No	0	0	0.3	0.2	0.1	Gas	0.9	Gas	0	0	0.9
	3B[c]	Yes	33	6	0.4	0.1	0.3	Electric	2.4	Electric	0	0.5	0
10/23–11/3	4A	Yes[d]	1	0	0.3	0.3	0.3	Gas	0.7	Gas	0	0.8	0
	4B[c]	Yes	116	2	0.1	0.1	1.0	Gas	2.8	Gas	0.1	1.0	0
11/4–11/15	5A[e]	Yes	0	5	0.5	0.5	0	Gas	2.5	Gas	0.5	0.9	0
	5B	Yes[d]	15	7	0	0.3	0.4	Gas	2.3	Gas	0.5	0.9	0
11/16–11/29	6A	No	2	0	0.5	0	0.2	Gas	1.2	Gas	0	0.4	0
	6B	No	0	4	0.2	0.3	0.1	Gas	2.0	Gas	0.9	0.3	0
11/30–12/11	7A[c]	Yes	0	5	0	0.3	0	Gas	1.2	Gas	0.8	0	0.2
	7B[c]	Yes	0	8	0.5	0.8	0.2	Gas	2.3	Gas	1.0	0.8	0
12/12–12/23	8A	No	2	2	0.5	0.8	0.8	Gas	2.5	Gas	1.0	0.1	0
	8B	No	1	0	0.2	0.2	0	Gas	1.3	Gas	0.6	0.1	0
1/3–1/14	9A	No	5	7	0	0.1	0.2	Gas	1.1	Gas	1.0	0.9	0
	9B	No	2	0	N/A	N/A	N/A	Gas	N/A	Gas	N/A	N/A	N/A
1/15–1/26	10A	Yes[d]	8	0	0.3	0.1	0.1	Gas	1.0	Gas	0.9	0.4	0
	10B	No	15	0	0.3	0.2	0.2	Gas	0.6	Gas	0.8	1.0	0

Key to abbreviations—Vac: vacuuming; Dust: dusting; Solv: use of solvents; H: use of heater; W: opening of windows; AC: use of air conditioning.

N/A indicates that data were not available.

[a] The "Pets/Livestock" field shows the actual number of animals present.

[b] The "Frequency" field indicates the number of times an activity was performed per day. For example, a frequency of 2.0 under the "cooking" field indicates that on average two meals were cooked per day.

[c] Residences with occasional indoor smoker(s).

[d] Residents smoked outdoors only.

[e] Residence with frequent indoor smokers (average of 40 cigarettes per day).

(with the notable exception of residence 5A) by a factor of approximately 0.6. This result is consistent with other findings for TEs (Landis et al., 2001; Chao and Wong, 2002; Geller et al., 2002).

Residence 5A had an indoor total TE concentration exceeding outdoor concentrations by a factor of 1.3. All residences with smokers had I/O ratios for total TEs exceeding the average.

The average indoor $PM_{2.5}$ concentration for all residences was lower than that outdoors. However, $PM_{2.5}$ concentration inside residence 5A was approximately 4 times that observed outdoors. The fractional contribution of TEs to indoor $PM_{2.5}$ mass was the lowest in residence 5A as ETS contains a number of particle-phase components (e.g., organic carbon) that are present in greater proportions by mass in $PM_{2.5}$ than are TEs.

3.1.2. Major TEs

Average concentrations of individual TEs measured indoors and outdoors are listed in Table 3. Sulfur (S) and silicon (Si) were the most abundant TEs measured (both outside and inside the residences) when excluding residence 5A. Potassium (K) and chlorine (Cl) were the most abundant species in residence 5A, probably due to ETS. The effect of ETS on indoor TE concentration is discussed in Section 3.1.4.

In general, iron (Fe), calcium (Ca), aluminum (Al), Si, K, and Cl are found to be abundant both indoors and outdoors. These species predominantly originate from crustal materials, fossil fuel combustion and biomass burning (Watson and Chow, 2001). Crustal elements are generated primarily from mechanical disruption of the earth's crust and are more enriched in the coarse mode (2.5–10 μm in diameter) than in the fine mode (<2.5 μm in diameter) (Chao and Wong, 2002; Singh et al., 2002). On average, the proportion of crustal elements to the total TE concentration is lower indoors (excluding 5A) than outdoors.

I/O concentration ratios for S ranged from 0.45 to 1.16 with an average of 0.70. It was reported that contribution of S to the earth's crust is minor,

Table 2
Mass concentration of total TEs (TE) and PM$_{2.5}$ at residences (μg m^{-3})

Residences	Indoors			Outdoors			I/O ratios	
	TE	PM$_{2.5}$	% of TE in PM$_{2.5}$	TE	PM$_{2.5}$	% of TE in PM$_{2.5}$	TE	PM$_{2.5}$
1A	2.80 ± 0.83	33.4 ± 14.2	8.39	10.3 ± 5.8	64.5 ± 18.9	16.0	0.27	0.52
1B	4.19 ± 0.88	53.8 ± 19.5	7.80					
2A	2.64 ± 1.33	28.4 ± 9.4	9.29					
2B	3.89 ± 2.52	26.6 ± 6.8	14.6	7.90 ± 6.22	39.5 ± 12.3	20.0	0.49	0.67
3A	4.76 ± 1.92	41.9 ± 11.5	11.4					
3B[a]	N/A	N/A	N/A					
4A	5.42 ± 4.38	49.4 ± 18.2	11.0					
4B[a]	7.54 ± 1.93	54.2 ± 22.1	13.9	10.2 ± 3.8	63.64 ± 26.6	16.0	0.74	0.85
5A[b]	8.22 ± 1.95	201.4 ± 48.7	4.08	6.25 ± 5.22	49.5 ± 27.4	12.6	1.31	4.07
5B	5.28 ± 4.14	42.7 ± 21.6	12.4					
6A	2.39 ± 0.70	22.8 ± 9.5	10.5	5.58 ± 3.22	49.7 ± 25.4	11.2	0.43	0.46
6B	2.83 ± 1.63	37.3 ± 26.9	7.6					
7A[a]	7.42 ± 4.33	54.4 ± 14.3	13.6	8.24 ± 7.56	48.1 ± 29.7	17.2	0.90	1.13
7B[a]	7.90 ± 4.17	33.9 ± 15.9	23.3					
8A	3.68 ± 0.89	23.6 ± 10.2	15.6	4.98 ± 3.16	42.3 ± 12.0	11.8	0.74	0.56
8B	2.56 ± 1.46	26.5 ± 15.4	9.7					
9A	3.46 ± 3.91	20.4 ± 14.6	17.0	6.12 ± 3.61	33.3 ± 20.9	18.4	0.57	0.61
9B	3.53 ± 0.98	38.2 ± 22.3	9.24					
10A	7.08 ± 3.72	33.7 ± 5.4	21.0					
10B	3.42 ± 1.36	19.6 ± 7.1	17.5					
Mean[c]	4.49 ± 1.90	35.6 ± 12.1	13.0	7.62 ± 2.15	48.7 ± 11.8	15.8	0.59	0.69

N/A: not available.

TE: Total mass concentration of trace elements. Mass concentration includes correction for oxidations state. Sulfur is not considered a trace element for this calculation.

[a] Residences with occasional indoor smoker.

[b] Residence with frequent indoor smokers (average of 40 cigarettes per day).

[c] This value was calculated excluding residence 5A.

accounting only for 0.09% of that of Si (Mason and Moore, 1982). The major sources of S are SO_2 and H_2SO_4 from combustion of sulfur-containing fuel. SO_2 is oxidized to form secondary sulfate particles (SO_4^{2-}). As both S and crustal element emissions occur principally in the outdoor environment, the presence of soil-related TEs and secondary sulfate in significant quantities indoors suggests that outdoor-to-indoor transport affects indoor air quality.

3.1.3. Penetration of PM$_{2.5}$ as a function of trace element source

Al, Ca, Cl, Fe, magnesium (Mg), Si, sodium (Na), and titanium (Ti) are more enriched in the coarse mode than in the fine mode (Chao and Wong, 2002; Singh et al., 2002). These elements originate from sea salt or crustal material (Mason and Moore, 1982). They may also originate from resuspension of dust from indoor human activities. On the other hand, bromine (Br), K, lead (Pb), nickel (Ni), S, vanadium (V) and zinc (Zn) are more enriched in the fine mode than in the coarse mode (Chao and Wong, 2002; Singh et al., 2002). In general, these elements are emitted from fossil fuel combustion (ATSDR, 2003) and wood combustion. In this study, natural gas for cooking or heating was the only fossil fuel used indoors. It was reported that fine particulate matter emitted from natural gas combustion was negligible in southern California (approximately 0.1% of the total PM$_{2.5}$ mass) (Schauer et al., 1996). In addition, Hildemann et al. (1991) found that TEs account for $<3\%$ of the total PM$_{2.5}$ mass emitted from natural gas home appliances. Throughout the study period, there was no use of fireplaces due to mild weather. Therefore, we believe that indoor TEs originate mainly from outdoor emission sources.

In this study, I/O concentration ratios between the crustal elements (Ai, Ca, Fe, Si) and combustion-related elements (S, V, Ni, Zn, Pb) are compared to observe the degree of penetration of the two groups by emission source. Residences with smokers are not considered for this comparison. I/O concentration ratios for the crustal elements and combustion-related elements are shown in Fig. 1. It is clear that on average, combustion-related elements are more prevalent than crustal elements in

Table 3
Average concentrations of individual TEs indoors and outdoors ($\mu g\,m^{-3}$)

	Without smokers		With occasional smokers		Residence 5A (frequent indoor smokers)		Outdoors	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Mg	0.033	0.009	0.040	0.014	0.030	0.002	0.053	0.034
Al	0.124	0.075	0.299	0.167	0.037	0.030	0.357	0.168
Si	0.497	0.192	1.234	0.643	0.220	0.032	1.377	0.520
P	0.081	0.022	0.121	0.038	0.246	0.094	0.120	0.038
S	0.725	0.507	1.000	0.749	1.172	0.665	1.060	0.672
Cl	0.148	0.071	0.325	0.142	2.371	0.935	0.281	0.176
K	0.132	0.080	0.155	0.067	3.442	0.847	0.177	0.162
Ca	0.293	0.148	0.557	0.273	0.034	0.002	0.681	0.272
Ti	0.091	0.002	0.102	0.011	0.094	0.002	0.106	0.009
V	0.032	0.001	0.032	0.001	0.033	0.001	0.032	0.001
Cr	0.010	0.001	0.012	0.001	0.013	0.006	0.015	0.004
Mn	0.011	0.004	0.016	0.003	0.006	0.001	0.020	0.006
Fe	0.321	0.129	0.596	0.299	0.151	0.063	0.739	0.249
Co	0.013	0.002	0.015	0.004	0.013	0.003	0.018	0.004
Ni	0.011	0.001	0.011	0.001	0.010	0.003	0.011	0.002
Cu	0.072	0.009	0.074	0.008	0.068	0.019	0.071	0.007
Zn	0.036	0.014	0.029	0.013	0.018	0.008	0.039	0.012
Ga	0.059	0.020	0.053	0.012	0.050	0.037	0.048	0.013
As	0.005	0.001	0.006	0.001	0.006	0.001	0.005	0.001
Se	0.007	0.001	0.007	0.001	0.007	0.001	0.007	0.001
Br	0.003	0.001	0.004	0.002	0.016	0.006	0.004	0.001
Rb	0.006	0.001	0.007	0.001	0.010	0.001	0.007	0.001
Sr	0.009	0.001	0.010	0.002	0.009	0.001	0.012	0.003
Y	0.006	0.001	0.006	0.001	0.007	0.001	0.006	0.001
Mo	0.074	0.014	0.077	0.008	0.082	0.021	0.070	0.011
Pd	0.019	0.002	0.019	0.001	0.017	0.002	0.019	0.001
Ag	0.014	0.002	0.015	0.003	0.012	0.004	0.015	0.003
Cd	0.039	0.011	0.045	0.007	0.050	0.011	0.046	0.008
In	0.014	0.001	0.013	0.001	0.014	0.000	0.013	0.001
Sn	0.068	0.001	0.067	0.004	0.070	0.001	0.067	0.002
Sb	0.077	0.002	0.076	0.003	0.080	0.001	0.076	0.002
Tl	0.005	0.001	0.005	0.001	0.005	0.001	0.005	0.001
Pb	0.036	0.006	0.038	0.004	0.037	0.011	0.037	0.005
Sum	3.074	0.904	5.060	1.819	8.427	1.813	5.592	1.675

terms of I/O ratios. A regression analysis performed for the total crustal elements and combustion-related elements verified this result. A higher indoor vs. outdoor correlation was observed for combustion-related elements ($R^2 = 0.68$) compared with for crustal elements ($R^2 = 0.32$). This may be caused by more favorable infiltration of combustion-related elements relative to crustal elements, leading to higher I/O concentration ratios for combustion-related elements. This in turn suggests that TEs enriched in the fine mode can penetrate indoors more easily than TEs enriched in the coarse mode.

3.1.4. Impact of ETS on residential trace element concentration

Exposure to ETS indoors has been associated with a number of respiratory symptoms in infants and children (Charlton, 1994; Neas et al., 1994). It is reported that benzene, 1,3-butadiene, polycyclic aromatic hydrocarbons, N-nitrosamines, nicotine, and $PM_{2.5}$ are toxic products released in tobacco smoke (ARB, 1997). Fig. 2 shows a comparison of indoor total TE concentrations based on the frequency of indoor smoking. The highest concentration of total TEs is observed in residence 5A. As seen in Fig. 2, the major difference between residence 5A and residences without smokers is the elevated levels of K and Cl observed in the former. Moschandreas et al. (1979) reported that K is associated with cigarette smoking and wood combustion. K (in the form of KNO_3—potassium nitrate) can account for as much as 10% of the mass of tobacco leaves (King's American Dispensatory, 2004). Therefore, accounting for fireplace usage within the residences in question (which was minimal or zero based on residents' logbook entries), we

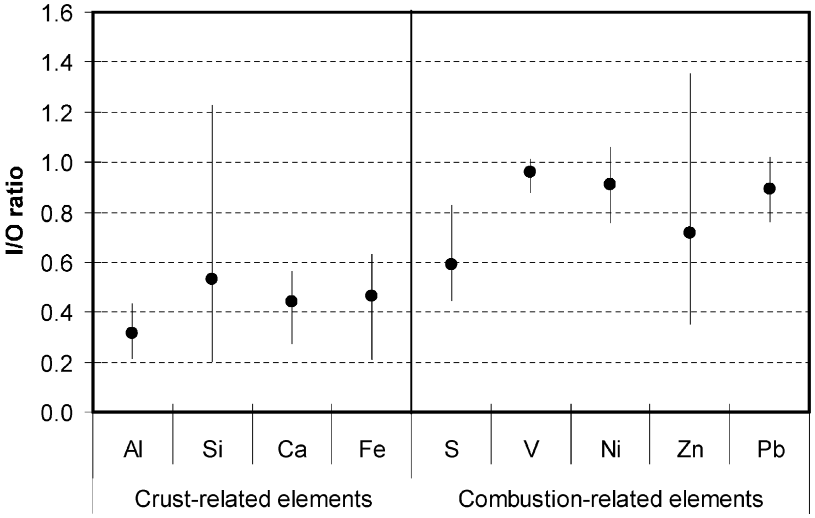

Fig. 1. Representative comparison of I/O concentration ratios between crustal elements and combustion-related elements.

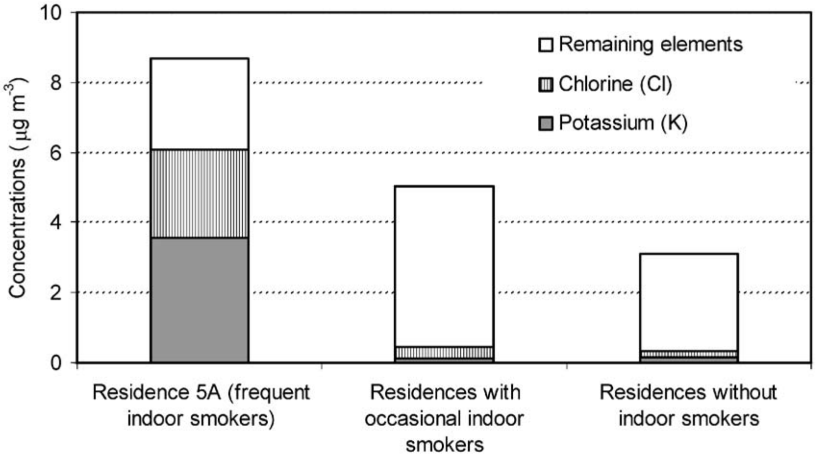

Fig. 2. Comparison of average indoor total TE concentrations by frequency of indoor cigarette smoking.

believe that the higher concentration of K in residence 5A is attributable mainly to cigarette smoke. The reasons for high Cl concentrations remain unclear. These two elements account for approximately 70% of the total TE concentration inside residence 5A.

3.2. Local high school

TEs were also sampled in six schoolrooms (4 classrooms, a library and an administrative office) following the same schedule as for the residences. The TE compositions are summarized in Table 4. The average I/O ratio for total TEs within the school was 0.39 for the classrooms, 0.30 for the library, and 0.26 for the administrative office. The average total elements were the highest in classroom 3 (4.22 $\mu g\,m^{-3}$), while the lowest average concentration was observed in the administrative office (1.40 $\mu g\,m^{-3}$). The total TE concentration at the library was approximately lower than the average value for the four classrooms. On average, S, Si, Fe and Ca were the most dominant TEs, accounting for 57% by mass of the total TEs. These TEs originate from combustion of fossil fuel and soil-related dusts (Watson et al., 2001). Since these emission sources do not exist inside the school, they may be attributed mainly to resuspension of previously deposited elements and penetration from outdoors.

A *t*-test was applied to the data set to determine if statistically significant differences existed between the weekday and weekend indoor TE concentrations. Here,

Table 4
Concentrations of TE in local high school ($\mu g\,m^{-3}$)

	Classroom 1		Classroom 2		Classroom 3		Classroom 4		Library		Administrative office	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Mg	0.025	0.002	0.028	0.007	0.030	0.009	0.025	0.011	0.025	0.002	0.022	0.002
Al	0.049	0.032	0.112	0.091	0.138	0.145	0.149	0.058	0.058	0.032	0.024	0.013
Si	0.243	0.068	0.409	0.439	0.673	0.777	0.351	0.188	0.213	0.011	0.193	0.010
P	0.070	0.007	0.060	0.002	0.105	0.051	0.059	0.010	0.059	0.002	0.054	0.003
S	0.253	0.268	0.634	0.133	1.549	0.979	0.333	0.187	0.665	0.281	0.157	0.076
Cl	0.056	0.008	0.055	0.016	0.215	0.233	0.050	0.028	0.035	0.009	0.047	0.024
K	0.047	0.004	0.076	0.041	0.055	0.022	0.054	0.027	0.052	0.019	0.067	0.023
Ca	0.075	0.058	0.191	0.160	0.261	0.197	0.223	0.144	0.111	0.046	0.075	0.039
Ti	0.091	0.004	0.089	0.004	0.090	0.019	0.087	0.007	0.091	0.001	0.087	0.002
V	0.032	0.001	0.032	0.001	0.030	0.005	0.031	0.003	0.032	0.000	0.031	0.001
Cr	0.009	0.001	0.008	0.001	0.018	0.013	0.009	0.001	0.010	0.001	0.008	0.001
Mn	0.006	0.002	0.010	0.004	0.015	0.009	0.007	0.004	0.007	0.003	0.007	0.002
Fe	0.082	0.058	0.225	0.147	0.433	0.366	0.241	0.149	0.096	0.022	0.112	0.038
Co	0.010	0.003	0.012	0.004	0.016	0.004	0.013	0.003	0.010	0.003	0.010	0.003
Ni	0.010	0.002	0.011	0.003	0.013	0.004	0.010	0.002	0.009	0.002	0.008	0.002
Cu	0.081	0.029	0.087	0.026	0.081	0.017	0.075	0.012	0.060	0.004	0.071	0.018
Zn	0.016	0.004	0.015	0.010	0.025	0.018	0.023	0.008	0.009	0.004	0.015	0.006
Ga	0.069	0.025	0.066	0.045	0.079	0.026	0.087	0.016	0.045	0.028	0.038	0.024
As	0.005	0.001	0.005	0.002	0.006	0.001	0.006	0.002	0.004	0.001	0.005	0.001
Se	0.007	0.002	0.007	0.002	0.009	0.002	0.008	0.001	0.006	0.001	0.006	0.001
Br	0.002	0.001	0.002	0.001	0.003	0.002	0.002	0.001	0.002	0.001	0.002	0.001
Rb	0.005	0.001	0.006	0.002	0.006	0.002	0.006	0.002	0.005	0.001	0.005	0.001
Sr	0.007	0.001	0.008	0.003	0.009	0.002	0.008	0.002	0.007	0.001	0.007	0.001
Y	0.005	0.001	0.006	0.002	0.007	0.001	0.007	0.001	0.005	0.000	0.005	0.002
Mo	0.054	0.019	0.086	0.029	0.088	0.021	0.084	0.022	0.069	0.004	0.072	0.023
Pd	0.023	0.003	0.017	0.003	0.016	0.005	0.018	0.002	0.020	0.002	0.020	0.005
Ag	0.017	0.004	0.015	0.002	0.012	0.002	0.017	0.004	0.019	0.007	0.015	0.005
Cd	0.020	0.028	0.044	0.011	0.038	0.007	0.036	0.000	0.049	0.025	0.053	0.027
In	0.017	0.003	0.013	0.001	0.012	0.002	0.013	0.001	0.013	0.001	0.013	0.001
Sn	0.072	0.005	0.067	0.003	0.064	0.010	0.065	0.004	0.067	0.002	0.064	0.001
Sb	0.078	0.006	0.075	0.003	0.073	0.012	0.073	0.005	0.077	0.002	0.073	0.002
Tl	0.005	0.001	0.005	0.001	0.005	0.001	0.005	0.001	0.005	0.000	0.005	0.001
Pb	0.029	0.008	0.036	0.015	0.042	0.010	0.039	0.013	0.027	0.005	0.030	0.011
Sum	1.572	0.349	2.509	0.852	4.217	2.470	2.213	0.812	1.963	0.193	1.400	0.112

weekend and weekday samples were defined as ones measured from 8 PM Friday night to 8 PM Sunday night and from 8 PM Sunday night to 8 PM Friday afternoon, respectively. Average concentration ($2.81 \pm 1.61\,\mu g\,m^{-3}$) of weekday samples is significantly higher than that of weekend samples ($1.87 \pm 0.63\,\mu g\,m^{-3}$) ($p < 0.011$ at 95% confidence interval—CI). In addition, the fluctuation of the total TE concentrations on weekdays is larger than that observed for the weekend. This indicates that the indoor air during the weekday is significantly influenced by indoor activities such as resuspension of particles. On the contrary, during the weekend, there is little or no activity; all doors remain closed, and favorable deposition losses occur, leading to lower concentrations during the weekend.

3.3. Comparison of suspended indoor TEs in the residences and the school

3.3.1. Total TE concentration

Average total concentrations of TEs measured inside the residences, outside the residences, and inside the school, are compared in Fig. 3. Average total TE concentrations inside residences without smokers were found to be significantly lower than average total TE concentrations outdoors ($p < 0.001$ at 95% CI). Average total TE concentrations inside the schoolrooms were also found to be significantly lower than outdoor concentrations ($p < 0.01$; 95% CI). This is likely due to a lack of significant indoor TE emission sources inside these indoor sites and removal by filtration of outdoor air through the building envelope. Also, the schoolroom sites were equipped with a heating/ventilation/air conditioning (HVAC) system with HEPA filters, and it is likely that this played a role in the observed average total TE concentrations, as well as total $PM_{2.5}$ concentrations (Sawant et al., 2004).

Among indoor sites, average total TE concentrations were significantly lower in residences without smokers compared with residences with occasional smokers ($p<0.0001$; 95% CI). Average total TE concentrations were also significantly lower inside the schoolrooms compared with inside residences with occasional smokers ($p<0.01$; 95% CI).

Residence 5A had the highest average indoor trace element concentrations, significantly higher than those observed outdoors ($p<0.05$; 95% CI), in residences without smokers ($p<0.0001$; 95% CI), and schoolrooms ($p<0.001$; 95% CI). From Fig. 2, this is mainly due to the elevated levels of K and Cl inside this particular residence (see Section 3.1.4 for more details).

3.3.2. Carcinogenic TE concentrations

As, Be, Cd, Cl, Co, Cr, Hg, Mn, Ni, P, Pb, Rn, Sb and Se are included in the list of 188 hazardous air pollutants (HAPs) designated by US Environmental Protection Agency (US EPA) in 1990. Of the 14 species, As, Be, Cd, Cr, Pb, Mn, Hg, Ni are also included in the list of 33 urban air toxics by the California Air Resources Board (ARB) (ARB, 2002). As, Be, Cd, Co, Cr, Hg, Ni, Pb, and Rn are human or animal carcinogens (ATSDR, 2003). Of these elements, Cd, Cr, Pb, and Ni are reported to be carcinogenic elements in ETS (NIOSH, 1991; Smith et al., 1997). Pb is a naturally occurring

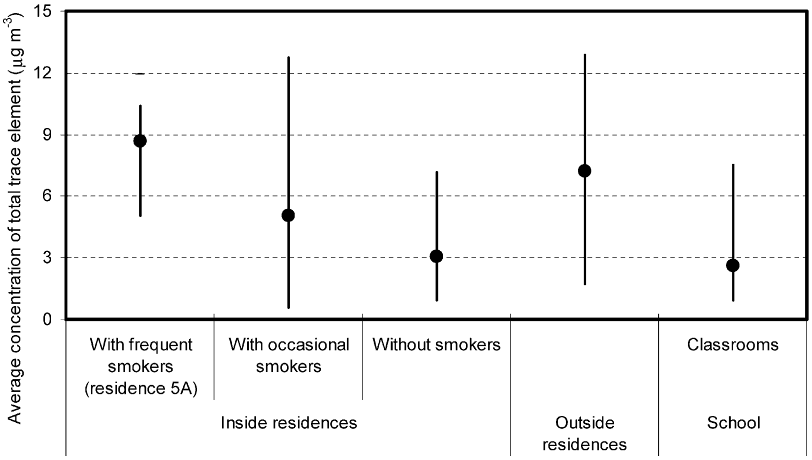

Fig. 3. Comparison of average total TE concentrations between inside residences, outside residences, and inside schoolrooms (circles represent mean concentrations, and bars represent the ranges measured).

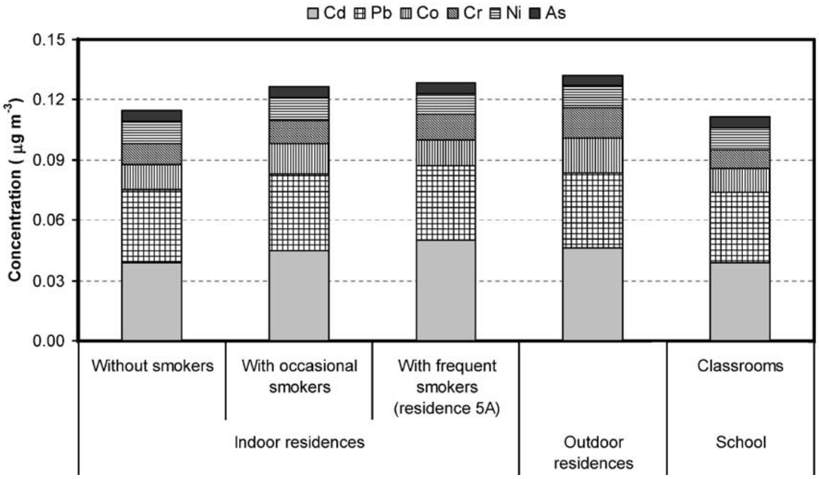

Fig. 4. Comparison of concentrations of carcinogenic TEs between residences (indoors and outdoors) and inside schoolrooms.

Table 5
Coefficient of determination (R^2) between indoor and outdoor data

	Without smokers	With occasional smokers	Residence 5A (frequent indoor smokers)
Mg	0.33	0.49	<0.1
Al	0.54	0.37	<0.1
Si	0.82	0.50	<0.1
P	0.61	0.29	<0.1
S	0.87	0.89	0.59
Cl	0.75	0.49	0.27
K	0.80	0.32	<0.1
Ca	0.42	0.45	0.83
Ti	0.87	0.68	0.14
V	0.89	0.10	<0.1
Cr	0.52	0.29	<0.1
Mn	0.54	0.38	0.41
Fe	0.61	0.42	0.23
Co	0.32	0.58	0.24
Ni	0.54	0.40	0.67
Cu	0.38	<0.1	<0.1
Zn	0.90	0.51	0.86
Ga	0.39	0.73	<0.1
As	0.27	0.17	<0.1
Se	0.78	<0.1	0.10
Br	0.66	0.79	0.26
Rb	0.29	0.22	<0.1
Sr	0.51	0.39	0.22
Y	0.45	0.30	0.53
Mo	0.46	<0.1	<0.1
Pd	0.29	0.37	<0.1
Ag	0.29	0.47	0.39
Cd	0.18	<0.1	<0.1
In	0.39	0.32	<0.1
Sn	0.33	<0.1	<0.1
Sb	0.68	0.15	<0.1
Tl	0.24	<0.1	<0.1
Pb	0.88	0.41	0.18

bluish-gray metal found in small amounts in the earth's crust (Mason and Moore, 1982). Much of it comes from human activities including ETS, mining and manufacturing (Watson et al., 2001; ATSDR, 2003). Cd is a natural element in the earth's crust (Mason and Moore, 1982). It is usually found as a mineral combined with other elements such as oxygen (cadmium oxide), chlorine (cadmium chloride), or sulfur (cadmium sulfate, cadmium sulfide; ATSDR, 2003). Cd enters the air from mining operations, industry, coal burning, and household wastes. ETS is reported to be an important indoor emission source of Cd (ATSDR, 2003). Wu et al. (1995) reported that Cd was a marker for ETS in the presence of low background concentrations ($<1.5\,\mu g\,m^{-3}$).

In this study, average total concentrations of six carcinogenic TEs (As, Cd, Co, Cr, Ni, and Pb) measured inside and outside the residences and outside the school are compared in Fig. 4. Cd is the most abundant species of the six carcinogenic elements followed by Pb, regardless of sampling location. The difference in Cd concentrations between residences without smokers and residence 5A is not significantly different ($p = 0.10$ at 95% CI). It should be noted that average background (outdoor) Cd mass concentrations are $46\,\mu g\,m^{-3}$, or ~ 30 times the background assumed by Wu et al. (1995) to permit use of Cd as a marker for ETS.

Although the total concentration of the six carcinogenic TEs is highest in outdoor air and lowest inside the school, this difference does not appear to be significant ($p = 0.20$ at 95% CI). Also in Fig. 4, the total concentration of the carcinogenic TEs is not significantly different between residences without smokers and residence 5A ($p = 0.25$ at 95% CI).

A regression analysis was performed for indoor and outdoor TE concentrations in residences, the results of which are summarized in Table 5. For example, it is seen that the elements K, Cl and Pb show large differences in coefficients of determination (R^2) for the residences without smokers relative to the residences with occasional smokers (0.80 vs. 0.32, 0.75 vs. 0.49, and 0.88 vs. 0.41, respectively). Lower R^2-values still are observed for residence 5A (<0.1, 0.27, <0.1). In addition, concentrations of these three elements are significantly higher indoors than outdoors for the residences with smokers. These factors suggest that smoking is likely an important contributor to the elevated indoor concentrations of these TEs.

4. Summary

Twenty residences in Mira Loma, CA and six rooms at a local high school were sampled to determine mass concentrations of 35 TEs and $PM_{2.5}$. Both indoor and outdoor samples were obtained between September 2001 and January 2002. S and Si were the most abundant TEs measured (excluding residence 5A, which had high concentrations of K and Cl). Indoor total TE concentrations were typically lower than outdoor concentrations. The proportion of TEs in total $PM_{2.5}$ was also greater outdoors than indoors. The high school had the lowest measured $PM_{2.5}$ and total TE concentrations compared with the outdoor samples and inside the residences. TE concentrations were lower inside the schoolrooms relative to inside the residences. Higher levels of total TEs were seen in residences with smokers; however, no significant differences were found in concentrations of carcinogenic TEs between residences with and without smokers. Analysis of the data demonstrated that penetration of combustion-related $PM_{2.5}$ was higher than crustal $PM_{2.5}$.

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Disclaimer

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