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HOUSE-SPECIFIC CHARACTERIZATION OF INDOOR AND OUTDOOR AEROSOLS

Yoon Shin Kim[a] and Thomas H. Stock
Department of Environmental Sciences, School of Public Health, University of Texas, Houston, Texas 77225, USA

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Simultaneous air monitoring inside and outside of 12 homes in the Houston area were performed for fine inhalable particulate matter by means of dichotomous samplers. The patterns of house-specific indoor mean concentrations, indoor/outdoor ratios, and probable source of indoor fine aerosol are discussed, along with pertinent information on household characteristics. The results suggest that most of indoor aerosol appears to be affected by infiltration of outdoor air as well as by indoor generation, with the most important single determinant being the presence or absence of cigarette smoking. However, it is likely that the typical complexity of indoor environments make it difficult to explain sources of indoor aerosol.

Introduction

Several studies have found significant differences between indoor and outdoor airborne particulate levels (Anderson, 1972; Moschandreas *et al.*, 1979; Colome *et al.*, 1982). Moschandreas *et al.* (1979) and Alzona *et al.* (1979) reported that some elements of indoor and outdoor aerosols might be of indoor origin and fluctuate independently of outdoor concentrations. Thompson *et al.* (1973) reported that indoor particulate levels were heavily influenced by traffic from outdoors. McCarthy *et al.* (1981) suggested that some elements of indoor aerosol were present in housekeeping products and cigarette smoke.

However, it is difficult to determine the major source of indoor aerosol since indoor air pollution is emitted from plentiful sources (Spengler and Sexton, 1983). A few studies have attempted to identify sources of indoor aerosols using principal components analysis, while McCarthy *et al.* (1984) reported on source identification of indoor and outdoor aerosols using cluster analysis.

It is the purpose of this work to characterize the indoor-outdoor relationships of fine inhalable particulates (0–2.5 μm) and examine probable sources inside and outside aerosols of individual homes in the Houston area.

[a]All correspondence should be addressed to: Dr. Yoon Shin Kim, College of Medicine, Hanyang University, Sungdong-Ku, Seoul 133 KOREA

Methodology

Selection of homes for air sampling by the mobile monitoring van was not done randomly, but rather as an attempt to provide a representative sample of study subject housing types.

Site Selection

The residential sites were chosen from the two study neighborhoods in Clear Lake and Sunnyside (Fig. 1). Twelve homes were selected for van monitoring as part of the residential air monitoring program established for the epidemiological study of the health effects of air pollution on asthmatics conducted by the University of Texas School of Public Health (Kotchmar *et al.*, 1982). Eight homes in Clear Lake and four homes in Sunnyside were monitored in this study (Fig. 2).

Information concerning several factors known to affect air quality, such as home location, building construction and materials, cooking appliances, ventilation system, and cigarette smoking was collected at each home. Table 1 summarizes some household characteristics of the 12 homes. Indoor concentrations of respirable particulate matter and other pollutants in homes with smokers and gas cook-

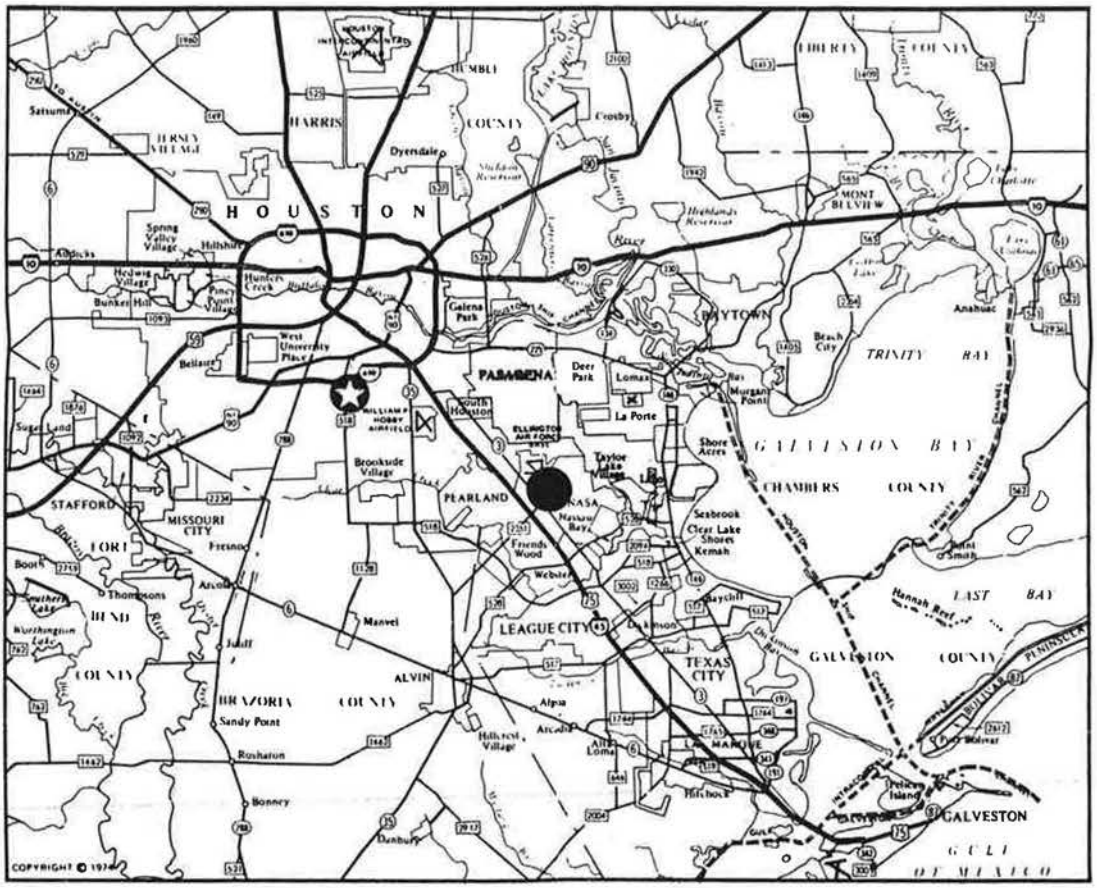

Fig. 1. Map of Houston area study sites (● Clear Lake, ✪ Sunnyside)

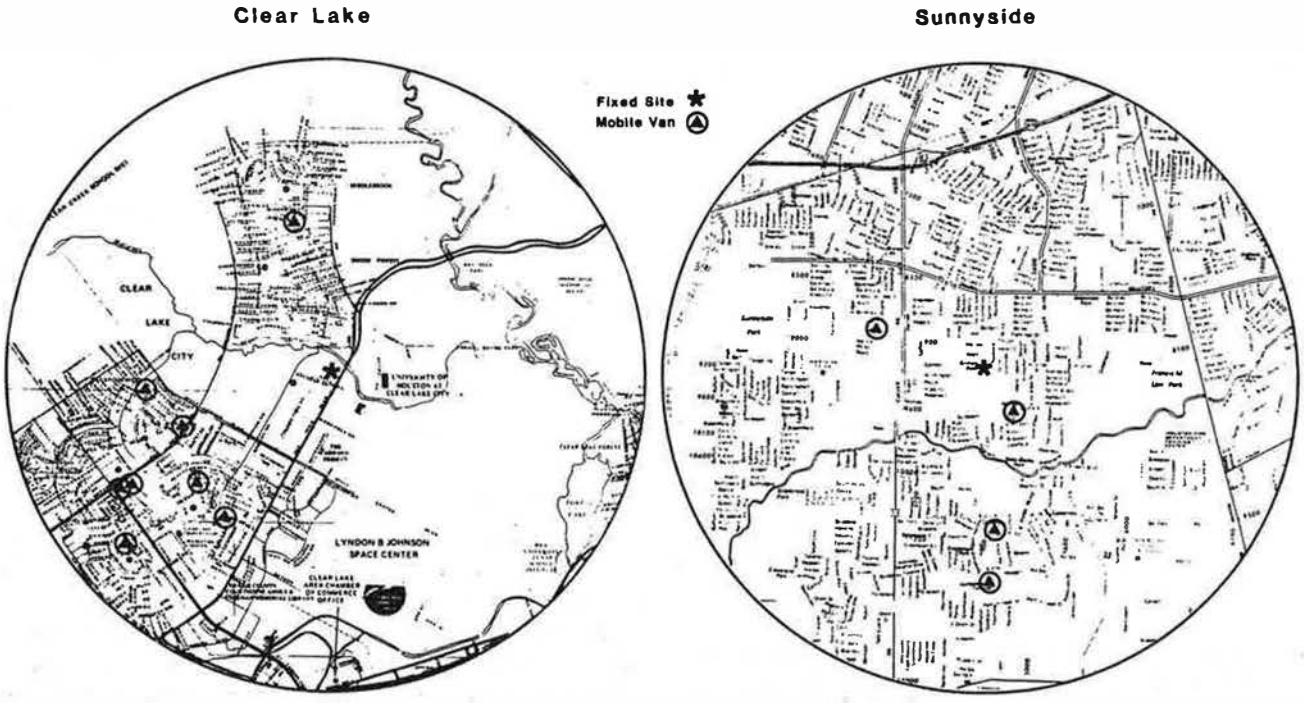

Fig. 2. Map of sampling site locations in the Clear Lake and Sunnyside areas

Table 1. Selected household characteristics of homes monitored during June–October 1981.

Home Number	Study Area	Construction	Air exchange/h	Kitchen Ventilation[a]	Air Conditioning	Cooking Fuel	Number of Resident Cigarette Smokers
1	Clear Lake	Brick	0.34	Good	Central	Electric	1
2	Clear Lake	Brick	0.88	INF	Central	Electric	2
3	Clear Lake	Brick	0.62	INF	Central	Gas	0
4	Clear Lake	Brick	0.28	INF	Central	Electric	0
5	Clear Lake	Combination	0.30	INF	Central	Electric	0
6	Sunnyside	Wood	0.24	No	Window	Gas	1
7	Sunnyside	Wood	0.68	No	Window	Gas	1
8	Clear Lake	Combination	1.00	Good	Central	Gas	1
9	Sunnyside	Combination	0.35	INF	Central	Gas	1
10	Clear Lake	Combination	0.35	No	Central	Electric	0
11	Clear Lake	Combination	0.07	INF	Central	Electric	0
12	Sunnyside	Brick	0.18	No	Central	Gas	0

[a]Kitchen ventilation to the outside in homes: Good = regular use, INF = infrequent use, No = no use.

ing stoves are generally higher than those corresponding levels in homes with nonsmokers and electric stoves (NAS, 1981).

Therefore, based on these two major characteristics, the 12 homes can be classified as follows: the first is a "source" effect group of four homes (nos. 6, 7, 8, 9) with gas stoves for cooking and resident indoor cigarette smokers; the second is a "nonsource" effect group of four homes (nos. 4, 5, 10, 11) with electric stoves for cooking and no resident smokers; the third is a "pure gas stove" effect group of two homes (nos. 3, 12) with gas stoves for cooking and no resident smokers; the last is a "pure smoking" effect group of two homes (nos. 1, 2) with electric stoves for cooking and resident smokers.

Sampling

The sampling procedure and analysis of fine inhalable particulate samples have been previously described elsewhere (Stock *et al.*, 1985). For most homes, two daily 12-hr samplings (day and night) were conducted for a period of about 1 week. Based on an assessment of the reliability of measurements of the 30 elements (Prichard *et al.*, 1985), if either indoor or outdoor elemental values were flagged, that element was deleted from the analysis for consistency. Thus, 15 chemical species including total mass, nitrate, and sulfate were available for comparisons of indoor and outdoor aerosol samples collected at the homes.

Results

From among the 12 homes, a final set of 11 homes was selected for this analysis. Home 1 was excluded due to a lack of samples. The results are presented in three parts. First, a comparison of indoor and outdoor concentrations for each of the 11 homes is presented. Second, comparisons among the homes are presented. The probable sources of fine aerosols measured inside specific homes are discussed with regard to selected household characteristics.

Comparisons between indoor and outdoor fine aerosol concentrations for each home

In this section, comparisons of indoor and outdoor aerosol samples are presented for each of 11 homes. The fine aerosol samples are tested for significance of differences between indoor and outdoor concentrations of individual homes using paired *t*-statistics and associated probability.

Home 2 (Clear Lake). As indicated in Table 2, indoor concentrations of mass and K are significantly higher than the values observed outdoors. NO_3 concentrations indoors also exceed the corresponding outdoor levels, but insignificantly. The I/O ratios of all aerosol sample species means ranged from 0.13 to 3.16.

Mochandreas *et al.* (1979) reported that potassium may be associated with indoor organic sources including cooking, smoking, emissions from wood fires, and human activity. As shown in Table 1, there are two residents who smoke cigarettes in this home. Assuming that the higher indoor K concentration in this home may be related to a cigarette smoking source, this supports the results of Moschandreas *et al.* (1979).

Home 3 (Clear Lake). This home, as with home 2, shows moderately high outdoor concentrations for most aerosol samples, except for mass and Cl (Table 3). Indoor concentrations of mass and Cl exceed slightly the corresponding outdoor levels, but the differences between indoor and outdoor levels are insignificant. The I/O ratios of means ranged from 0.12 to 1.28.

McCarthy *et al.* (1981) reported that chlorine is elevated in cigarette smoke, residential heating emissions, and household products. This home is centrally air-conditioned, but there is a gas stove for cooking with infrequent use of kitchen ventilation. The slightly

Table 2. Comparisons of indoor to outdoor mean concentrations ($\mu g/m^3$) of fine aerosol for home 2 in Clear Lake.[a]

	Indoor			Outdoor			t-Test	I/O
	n	$\bar{X}$	SE	n	$\bar{X}$	SE	Value	Ratio
Mass	15	35.467	2.597	13	17.308	2.610	−4.91**	2.05
Al	6	0.133	0.084	4	0.434	0.101	2.28	0.31
Br	6	0.064	0.059	4	0.064	0.059	1.14	1.00
Ca	6	0.017	0.003	4	0.038	0.004	4.21**	0.45
Cl	6	0.009	0.009	4	0	0	−0.80	NA
Fe	6	0.043	0.009	4	0.196	0.028	6.14**	0.22
Pb	6	0.009	0.008	4	0.068	0.015	3.77**	0.13
P	6	0.143	0.026	4	0.238	0.038	2.14	0.60
V	6	0	0	4	0.002	0.001	2.42*	NA
Si	6	0.164	0.076	4	0.342	0.086	1.52	0.48
Zn	6	0.020	0.007	4	0.128	0.072	1.87	0.16
S	6	1.438	0.291	4	2.472	0.347	2.24	0.58
K	6	0.297	0.035	4	0.094	0.017	−4.41**	3.16
NO_3^-	15	0.232	0.017	13	0.158	0.093	−0.85	1.47
SO_4^{2-}	15	3.147	0.517	13	6.400	0.849	2.77*	0.49

[a] n = number, $\bar{X}$ = mean, SE = standard error; t-test value is based on paired t-test, * = $p < 0.05$, ** = $p < 0.01$, NA = not available.

higher Cl concentrations indoors than outdoors may be related to product usage characteristics of this home.

Home 4 (Clear Lake). In this home, none of the indoor concentrations are found to be higher than the concentrations observed outdoors (Table 4). The I/O ratios of the means ranged from 0.08 to 0.65. These results are consistent with the classification of this home as a "nonsource" effect home with an electric stove and no resident who smokes cigarettes.

Home 5 (Clear Lake). This home located in Clear Lake is another "nonsource" home containing an electric stove and no resident smoker. The I/O ratios of species means ranged from 0.03 to 0.84; none of the indoor concentration means were found to be higher than those of the outdoor means at this home (Table 5).

Home 6 (Sunnyside). This home located in Sunnyside has a gas stove for cooking, window units for air conditioning, no kitchen ventilation, and one smoker. The indoor concentrations of mass, K, and S are slightly higher than outdoors, but the differences between indoor and outdoor levels for these three species are not statistically significant (Table 6).

The I/O ratios of the means are in the range of 0.03

Table 3. Comparisons of indoor to outdoor mean concentrations ($\mu g/m^3$) of fine aerosol for home 3 in Clear Lake.[a]

	Indoor			Outdoor			t-Test	I/O
	n	$\bar{X}$	SE	n	$\bar{X}$	SE	Value	Ratio
Mass	13	13.529	2.230	16	10.563	1.782	−1.06	1.28
Al	6	0.055	0.055	6	0.200	0.102	1.25	0.28
Br	6	0.006	0.004	6	0.030	0.004	4.23	0.20
Ca	6	0.028	0.007	6	0.029	0.007	0.18	0.97
Cl	6	0.027	0.012	6	0.022	0.022	−0.20	1.23
Fe	6	0.026	0.019	6	0.132	0.061	1.67	0.20
Pb	6	0.017	0.009	6	0.144	0.026	4.57**	0.12
P	6	0.084	0.040	6	0.220	0.080	1.52	0.38
V	6	0.005	0.003	6	0.010	0.003	1.18	0.50
Si	6	0.151	0.058	6	0.380	0.165	1.31	0.40
Zn	6	0.006	0.006	6	0.023	0.020	0.79	0.26
S	6	0.730	0.235	6	1.733	0.594	1.57	0.42
K	6	0.078	0.009	6	0.093	0.010	1.04	0.84
NO_3^-	13	0.077	0.014	16	0.128	0.030	1.41	0.60
SO_4^{2-}	13	1.800	0.431	16	3.931	0.822	2.15*	0.46

[a] See Table 2 for explanation of terms.

Table 4. Comparisons of indoor to outdoor mean concentrations ($\mu g/m^3$) of fine aerosol for home 4 in Clear Lake.[a]

	Indoor			Outdoor				
	n	$\bar{X}$	SE	n	$\bar{X}$	SE	t-Test Value	I/O Ratio
Mass	11	5.909	0.889	13	9.077	1.047	2.26*	0.65
Al	4	0	0	4	0.160	0.094	1.71	NA
Br	4	0	0	4	0	0	–	NA
Ca	4	0.007	0.007	4	0.027	0.011	1.60	0.26
Cl	4	0	0	4	0	0	–	NA
Fe	4	0.021	0.012	4	0.027	0.141	1.77	0.08
Pb	4	0.018	0.011	4	0.105	0.027	3.02*	0.17
P	4	0.020	0.012	4	0.127	0.045	2.27	0.16
V	4	0	0	4	0	0	–	NA
Si	4	0.153	0.021	4	0.550	0.139	2.82*	0.28
Zn	4	0	0	4	0	0	–	NA
S	4	0.419	0.099	4	1.244	0.393	2.04	0.34
K	4	0.027	0.005	4	0.082	0.013	4.02**	0.33
NO_3^-	11	0.027	0.010	13	0.266	0.048	4.46**	0.10
SO_4^{2-}	11	0.946	0.152	13	2.692	0.258	3.57**	0.35

[a]See Table 2 for explanation of terms.

to 1.65; this home environment represents a mix of potential source of indoor pollutants.

Home 7 (Sunnyside). The household characteristics of this home located in Sunnyside are similar to those of home 6. This house uses window units instead of a central air-conditioning system. This suggests that aerosols from outdoor sources may penetrate more easily into the home through the window into and/or aerosols from indoor sources may affect the outdoor levels.

The I/O ratios of all means ranged from 0.09 to 3.44 in this home. As indicated in Table 7, indoor concentrations of mass, Zn, K, and NO_3 are higher than those corresponding levels observed outdoors; however, none of these differences are statistically significant. Zn is considered to be emitted from refuse incineration outdoors (Kleinman *et al.*, 1980). The household sources such as smoking and gas stove use in this home may generate the elevated indoor concentrations of these elements.

Home 8 (Clear Lake). Table 8 shows that most of the mean concentrations indoors are higher than the levels observed outdoors, while the elements of Pb and Si are found to be significantly lower indoors. Either the indoor or outdoor measurement means of Al, Br, Cd, Fe, V, and Zn were below detection and therefore, reliable I/O ratios could not be calculated. This home, classified as a member of the "source" group with a

Table 5. Comparisons of indoor to outdoor mean concentrations ($\mu g/m^3$) of fine aerosol for home 5 in Clear Lake.[a]

	Indoor			Outdoor				
	n	$\bar{X}$	SE	n	$\bar{X}$	SE	t-Test Value	I/O Ratio
Mass	14	8.714	1.024	15	10.333	1.410	0.92	0.84
Al	5	0	0	5	0.670	0.340	1.97	NA
Br	5	0	0	5	0	0	–	NA
Ca	5	0.003	0.002	5	0.105	0.054	1.89	0.03
Cl	5	0.031	0.025	5	0.102	0.050	1.27	0.30
Fe	5	0.038	0.016	5	0.320	0.146	1.91	0.12
Pb	5	0.006	0.006	5	0.071	0.021	3.08	0.08
P	5	0	0	5	0.028	0.017	1.63	NA
V	5	0	0	5	0	0	–	NA
Si	5	0.079	0.049	5	0.682	0.259	2.29	0.16
Zn	5	0	0	5	0.003	0.003	1.00	NA
S	5	0.192	0.021	5	0.680	0.064	7.18**	0.28
K	5	0.023	0.006	5	0.109	0.043	1.94	0.21
NO_3^-	14	0.023	0.011	15	0.318	0.045	6.16**	0.07
SO_4^{2-}	14	0.593	0.047	15	1.760	0.109	9.57**	0.34

[a]See Table 2 for explanation of terms.

Table 6. Comparisons of indoor to outdoor mean concentrations ($\mu g/m^3$) of fine aerosol for home 6 in Sunnyside.[a]

	Indoor			Outdoor			t-Test	I/O
	n	$\bar{X}$	SE	n	$\bar{X}$	SE	Value	Ratio
Mass	14	25.643	5.318	15	19.267	3.580	−1.01	1.33
Al	5	0.014	0.104	5	0.994	0.302	2.79*	0.10
Br	5	0	0	5	0.010	0.006	1.63	NA
Ca	5	0.009	0.006	5	0.058	0.020	2.29	0.16
Cl	5	0.015	0.009	5	0.087	0.035	1.96	0.17
Fe	5	0.057	0.045	5	1.911	1.801	1.03	0.03
Pb	5	0.027	0.018	5	0.141	0.060	1.81	0.19
P	5	0.022	0.022	5	0	0	−1.00	NA
V	5	0	0	5	0	0	–	NA
Si	5	0.114	0.062	5	0.305	0.036	2.66*	0.37
Zn	5	0.024	0.011	5	0.040	0.013	0.98	0.60
S	5	1.939	1.161	5	1.869	1.155	−0.04	1.04
K	5	0.107	0.049	5	0.065	0.016	−0.82	1.65
NO_3^-	14	0.087	0.015	15	0.109	0.027	0.68	0.80
SO_4^{2-}	14	3.100	1.221	15	5.420	2.007	0.93	0.57

[a]See Table 2 for explanation of terms.

gas stove and smoker, reports regular use of ventilation in the kitchen and is centrally air-conditioned. Comparing the indoor concentration levels of this home with those of other "source" group homes, the I/O ratios of K and NO_3 are higher, and Ca and Cl are much higher in this home. These elements may be related to some important indoor source other than gas cooking and smoking in this home.

Home 9 (Sunnyside). This home located in Sunnyside is centrally air-conditioned, has a gas stove for cooking, and uses kitchen ventilation infrequently. There is also one resident who smokes cigarettes.

The indoor concentrations for Cl, K, and NO_3 exceed the corresponding outdoor levels (Table 9). The I/O ratios for species means ranged from 0.21 to 1.72, except for 7.85 for NO_3. There was a statistically significant difference between indoor and outdoor NO_3 concentrations. Smoking and gas stove use in this home are again likely sources of some aerosols.

Home 10 (Clear Lake). This home located in Clear Lake seems to have no significant potential sources. However, indoor concentrations of Br, Ca, Pb, V, and Zn are approximately 1.1–14.0 times the corresponding levels observed outdoors (Table 10). The high I/O ratio for Ca appears to be due to an usually low outdoor mean.

Table 7. Comparisons of indoor to outdoor mean concentrations ($\mu g/m^3$) of fine aerosol for home 7 in Sunnyside.[a]

	Indoor			Outdoor			t-Test	I/O
	n	$\bar{X}$	SE	n	$\bar{X}$	SE	Value	Ratio
Mass	12	37.583	4.202	6	26.667	4.910	−1.58	1.41
Al	4	0.235	0.234	2	2.128	0.170	5.16**	0.11
Br	4	0	0	2	0.027	0.007	6.30**	NA
Ca	4	0.027	0.010	2	0.312	0.059	7.26**	0.09
Cl	4	0.359	0.129	2	0.583	0.059	1.14	0.62
Fe	4	0.170	0.042	2	0.916	0.069	9.82**	0.19
Pb	4	0.039	0.039	2	0.066	0.018	0.44	0.59
P	4	0.123	0.123	2	0	0	−0.67	NA
V	4	0	0	2	0.003	0.001	8.16**	NA
Si	4	0.376	0.148	2	3.947	0.289	12.60**	0.10
Zn	4	0.031	0.025	2	0.009	0.009	−0.59	3.44
S	4	0.612	0.253	2	1.005	0.071	1.03	0.61
K	4	0.756	0.126	2	0.334	0.038	−2.22	2.26
NO_3^-	12	0.682	0.099	6	0.411	0.074	−2.06	1.66
SO_4^{2-}	12	0.958	0.153	6	2.856	1.106	1.96	0.34

[a]See Table 2 for explanation of terms.

Table 8. Comparisons of indoor to outdoor mean concentrations ($\mu g/m^3$) of fine aerosol for home 8 in Clear Lake.[a]

	Indoor			Outdoor			t-Test	I/O
	n	$\bar{X}$	SE	n	$\bar{X}$	SE	Value	Ratio
Mass	13	31.385	4.101	6	24.167	4.246	−1.07	1.30
Al	6	0.734	0.349	3	0	0	−1.44	NA
Br	6	0	0	3	0.007	0.007	1.53	NA
Ca	6	1.711	0.711	3	0.015	0.006	−1.63	114.00
Cl	6	1.209	0.692	3	0.132	0.014	−1.06	9.16
Fe	6	0	0	3	0.099	0.029	5.19**	NA
Pb	6	0.005	0.005	3	0.096	0.042	3.20*	0.05
P	6	0.021	0.052	3	0.016	0.016	−0.17	1.31
V	6	0.003	0.000	3	0	0	−0.68	NA
Si	6	0.032	0.031	3	0.255	0.016	4.73**	0.13
Zn	6	0	0	3	0.049	0.010	7.51**	NA
S	6	2.759	0.613	3	2.682	0.465	−0.08	1.03
K	6	0.329	0.089	3	0.097	0.015	−1.77	3.39
NO_3^-	13	0.775	0.224	6	0.195	0.061	−2.21*	3.97
SO_4^{2-}	13	7.600	1.173	6	7.220	1.518	−0.20	1.05

[a]See Table 2 for explanation of terms.

These elements are enriched in automobile exhaust (Pb and Br), and emissions from fuel oil combustion (V), and refuse incineration (Zn) in outdoor air. Moschandreas *et al.* (1979) reported that Pb and Br indoors may be generated by reentrainment of indoor dust. The higher concentrations of those elements in this home may come from a detached automobile garage.

Home 11 (Clear Lake). This home is centrally air-conditioned and has an electric stove. There were no smokers in this home. According to Table 11, only mass was found to be higher indoors than outdoors. Since this home is classified as a "nonsource" home, the low I/O ratios are probably due to the predominance of aerosols from outdoor sources.

Home 12 (Sunnyside). Table 12 presents the data for Home 12 located in Sunnyside. This home is a gas cooking home without ventilation in the kitchen and is centrally air-conditioned. No smoker resided in this home (Table 1). Cl and K were found to be higher indoors than outdoors (Table 12), with I/O ratios of 3.76 and 1.32, respectively. It is possible that the elements of Cl and K may be emitted from gas stove use or household product use as potential sources.

Table 9. Comparisons of indoor to outdoor mean concentrations ($\mu g/m^3$) of fine aerosol for home 9 in Sunnyside.[a]

	Indoor			Outdoor			t-Test	I/O
	n	$\bar{X}$	SE	n	$\bar{X}$	SE	Value	Ratio
Mass	16	34.813	3.247	15	36.200	3.578	0.29	0.96
Al	6	0.516	0.097	5	1.669	0.193	5.64**	0.31
Br	6	0.057	0.007	5	0.063	0.005	0.65	0.90
Ca	6	0	0	5	0.102	0.021	5.43**	NA
Cl	6	0.049	0.012	5	0.036	0.010	−0.78	1.36
Fe	6	0.062	0.017	5	0.184	0.082	1.60	0.37
Pb	6	0.102	0.015	5	0.235	0.072	1.97	0.43
P	6	0.055	0.023	5	0.224	0.032	4.39**	0.25
V	6	0	0	5	0.001	0.001	1.11	NA
Si	6	0.223	0.024	5	0.620	0.100	4.24**	0.36
Zn	6	0.013	0.006	5	0.062	0.041	1.31	0.21
S	6	1.903	0.260	5	5.232	0.615	5.33**	0.36
K	6	0.153	0.021	5	0.089	0.023	−2.05	1.72
NO_3^-	16	0.306	0.040	15	0.039	0.014	−6.11**	7.85
SO_4^{2-}	16	4.638	0.496	15	12.800	0.787	8.89**	0.36

[a]See Table 2 for explanation of terms.

Table 10. Comparisons of indoor to outdoor mean concentrations ($\mu g/m^3$) of fine aerosol for home 10 in Clear Lake.[a]

	Indoor			Outdoor			*t*-Test	I/O
	n	$\bar{X}$	SE	*n*	$\bar{X}$	SE	Value	Ratio
Mass	15	7.067	0.836	11	10.000	1.395	1.91	0.71
Al	4	0.124	0.124	4	0.567	0.092	2.87*	0.22
Br	4	0.035	0.007	4	0.030	0.020	−0.22	1.17
Ca	4	0.014	0.003	4	0.001	0.001	−3.67**	14.00
Cl	4	0	0	4	0.062	0.020	3.08*	NA
Fe	4	0	0	4	0.029	0.017	1.73	NA
Pb	4	0.196	0.029	4	0.182	0.077	−0.17	1.08
P	4	0	0	4	0.167	0.030	5.57**	NA
V	4	0.010	0.003	4	0.003	0.002	−1.82	3.33
Si	4	0.123	0.027	4	0.262	0.036	3.08*	0.47
Zn	4	0.025	0.009	4	0.015	0.009	−0.74	1.67
S	4	0.399	0.109	4	1.535	0.357	3.04*	0.26
K	4	0.013	0.007	4	0.021	0.010	0.63	0.62
NO_3^-	15	0.041	0.013	11	0.109	0.020	3.05*	0.38
SO_4^{2-}	15	1.327	0.139	11	4.155	0.509	6.11**	0.32

[a]See Table 2 for explanation of terms.

Comparisons across homes by fine aerosol samples

Indoor and outdoor mean concentrations of aerosol samples across homes are presented in Figs. 3–16. These figures also show the mean concentrations grouped according to the study neighborhoods, homes 2, 3, 4, 5, 8, 10, and 11 in Clear Lake and homes 6, 7, 9, and 12 in Sunnyside.

Mass. Fine particulate mass in residential environments has been associated with both indoor and outdoor sources (Moschandreas *et al.*, 1979; Spengler *et al.*, 1981). Indoor mean concentrations across the homes ranged from 5.9 to 37.6 $\mu g/m^3$, while mean I/O ratios ranged from 0.7 to 2.1.

As shown in Fig. 3, the four lowest indoor mean concentrations are associated with homes with electric stove use and no smokers (4, 5, 10, 11), while the five highest indoor mean concentrations are found in homes which include one "pure smoking" home (2) and four "source" homes (6, 7, 8, 9).

The considerably higher indoor concentrations found in many of the homes indicates possible sources of fine particulate mass within the homes. The indoor and outdoor concentrations in the Sunnyside homes tend to exceed the corresponding levels in the Clear Lake homes, except for homes 2 and 8. The excess outdoor concentrations over indoor concentrations in homes 4, 5, 9, 10, and 12 may suggest a greater

Table 11. Comparisons of indoor to outdoor mean concentrations ($\mu g/m^3$) of fine aerosol for home 11 in Clear Lake.[a]

	Indoor			Outdoor			*t*-Test	I/O
	n	$\bar{X}$	SE	*n*	$\bar{X}$	SE	Value	Ratio
Mass	14	10.429	2.013	11	8.000	0.884	−1.01	1.30
Al	4	0	0	4	0.338	0.050	6.74**	NA
Br	4	0.044	0.008	4	0.061	0.001	1.97	0.72
Ca	4	0.027	0.005	4	0.042	0.006	2.08	0.64
Cl	4	0.016	0.009	4	0.141	0.104	1.19	0.11
Fe	4	0.033	0.019	4	0.078	0.021	1.62	0.42
Pb	4	0.123	0.035	4	0.261	0.027	3.05*	0.47
P	4	0	0	4	0.026	0.015	1.68	NA
V	4	0.006	0.003	4	0.020	0.002	4.06**	0.30
Si	4	0.023	0.023	4	0.145	0.023	3.74**	0.16
Zn	4	0.026	0.009	4	0.065	0.017	1.97	0.40
S	4	0.355	0.062	4	0.800	0.145	2.83*	0.44
K	4	0.021	0.014	4	0.044	0.014	1.19	0.48
NO_3^-	14	0.058	0.016	11	0.146	0.029	2.82*	0.40
SO_4^{2-}	14	1.093	0.168	11	2.109	0.301	3.11**	0.52

[a]See Table 2 for explanation of terms.

Table 12. Comparisons of indoor to outdoor mean concentrations ($\mu g/m^3$) of fine aerosol for home 12 in Sunnyside.[a]

	Indoor			Outdoor				
	n	$\bar{X}$	SE	n	$\bar{X}$	SE	t-Test Value	I/O Ratio
Mass	18	19.333	3.913	21	23.762	2.982	0.91	0.81
Al	4	0.493	0.139	2	0.832	0.068	1.59	0.59
Br	4	0.033	0.024	2	0.053	0.052	0.40	0.62
Ca	4	0.001	0.001	2	0	0	−0.67	NA
Cl	4	0.169	0.099	2	0.045	0.021	−0.84	3.76
Fe	4	0.074	0.062	2	0	0	−0.79	NA
Pb	4	0.142	0.079	2	0.167	0.167	0.16	0.85
P	4	0.140	0.035	2	0.142	0.045	0.03	0.99
V	4	0	0	2	0	0	–	NA
Si	4	0.304	0.071	2	0.323	0.023	0.19	0.94
Zn	4	0.029	0.021	2	0	0	−0.91	NA
S	4	1.608	0.265	2	2.629	0.429	2.14	0.61
K	4	0.045	0.027	2	0.034	0.008	−0.27	1.32
NO_3^-	18	0.108	0.025	21	0.155	0.029	1.23	0.70
SO_4^{2-}	18	2.916	0.537	21	5.467	0.940	2.29*	0.53

[a]See Table 2 for explanation of terms.

influence of outdoor air infiltration on indoor concentrations measured in these homes.

Sulfate (SO_4 and Sulfur (S). Indoor sulfate concentrations across homes are generally lower than the corresponding outdoor levels (Fig. 4), except for home 8. Indoor mean concentrations ranged from 0.6 to 7.6 $\mu g/m^3$, while the mean I/O ratios are less than 0.6, except for home 8.

The home I/O ratios less than 1.0 are consistent with a mechanism whereby air infiltration from the outdoor air is the major determinant of concentrations indoors. Indoor concentrations in home 8 are abnormally high and are 1.7–13 times the indoor levels observed in other homes.

The indoor sulfur values across the homes in Fig. 5 show patterns similar to that for sulfate levels shown in Fig. 4, except for home 6. The indoor S concentrations are in the range of 0.2–2.8 $\mu g/m^3$; the I/O ratios range from 0.3 to 1.0. The three highest indoor concentrations appear in three "source" homes, while the four lowest indoor concentrations are found in "non-source" homes.

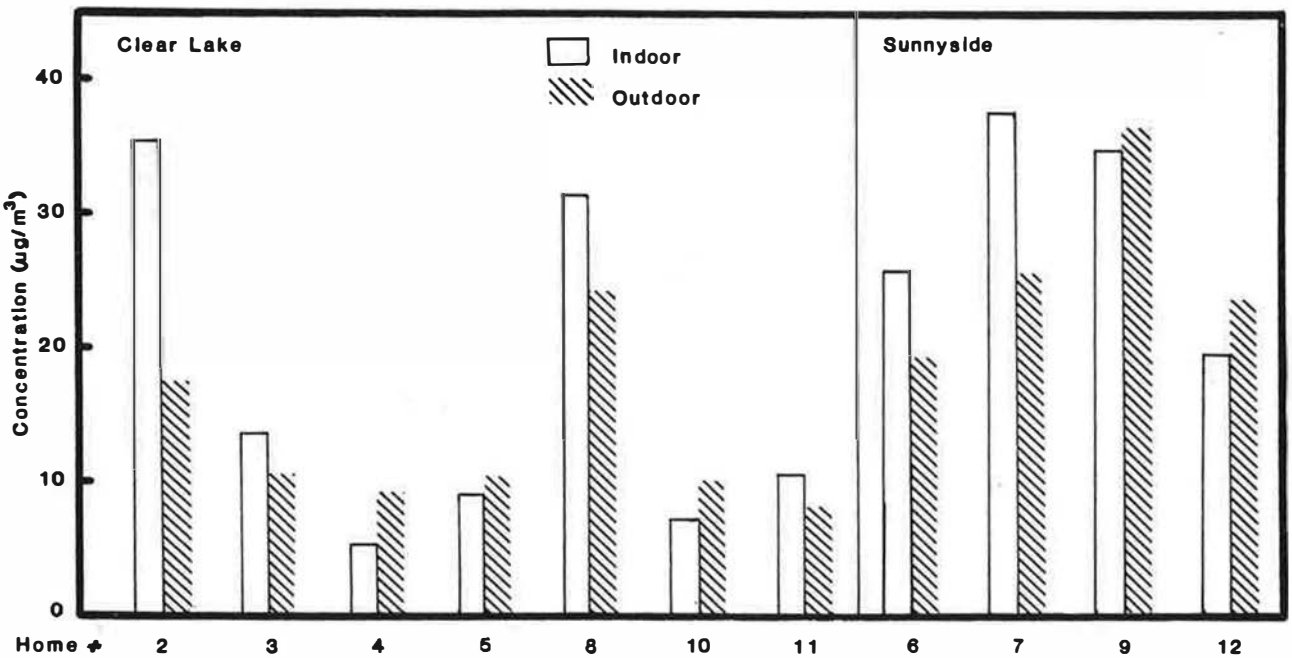

Fig. 3. Mean concentrations ($\mu g/m^3$) of fine mass for homes

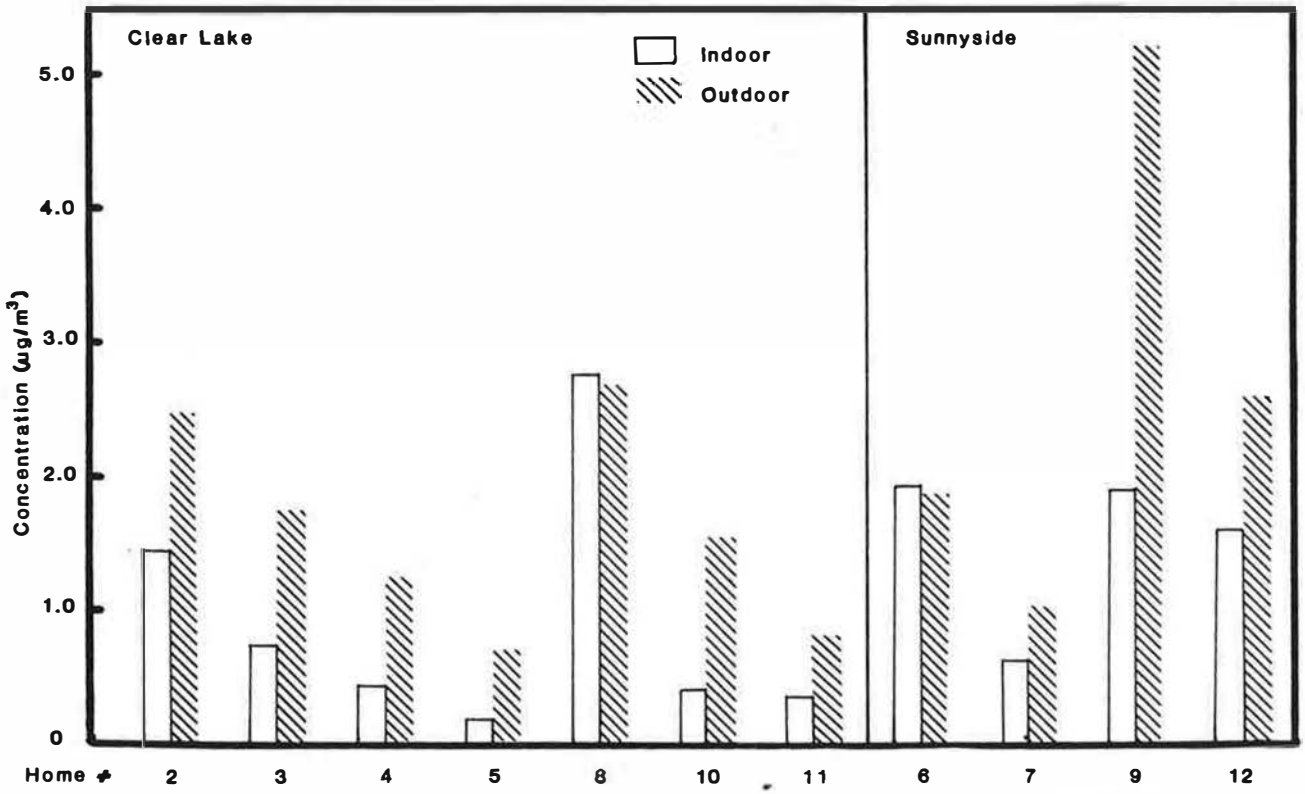

Fig. 4. Mean concentrations ($\mu g/m^3$) of fine $SO_4^=$ for homes

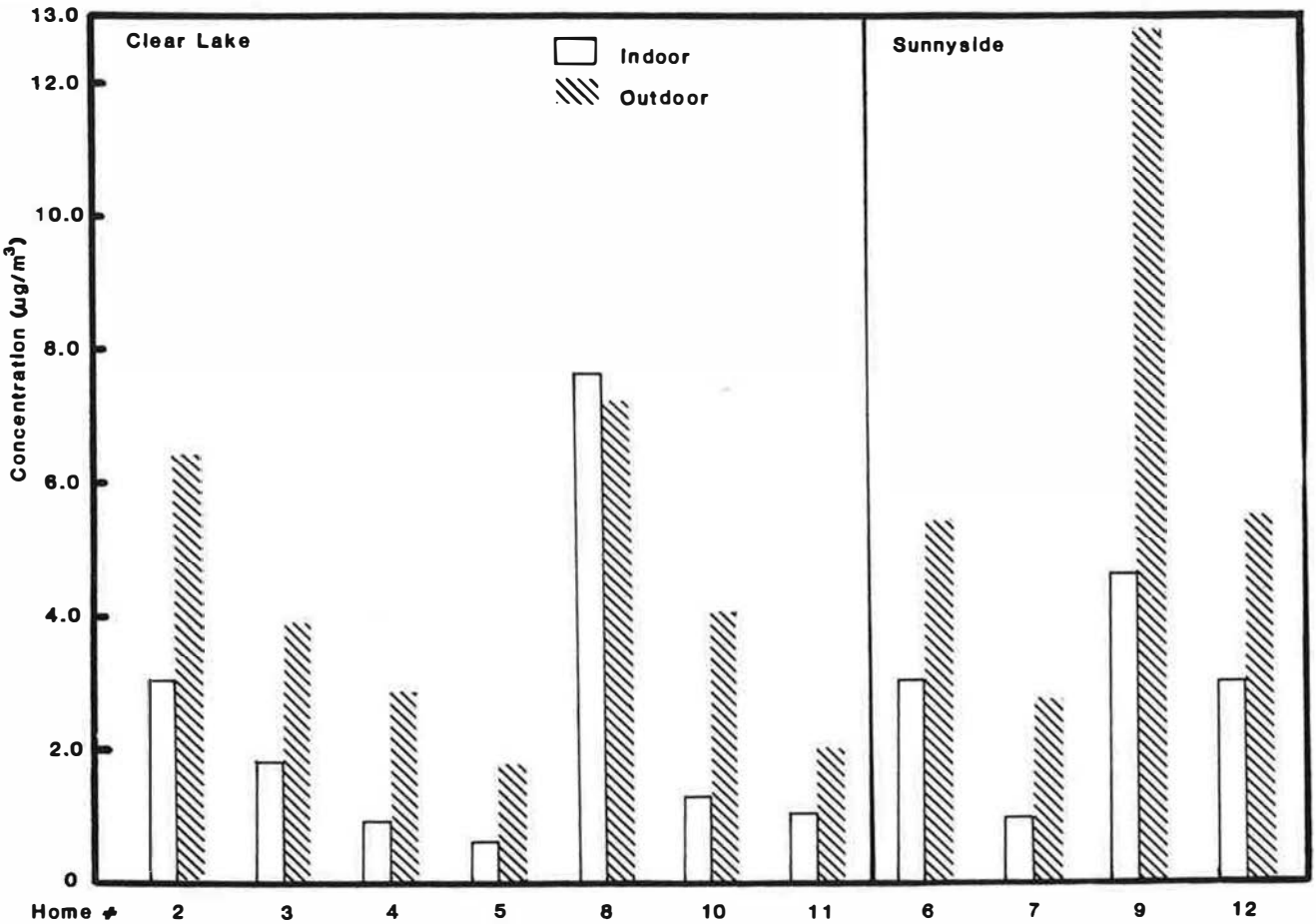

Fig. 5. Mean concentrations ($\mu g/m^3$) of S for homes

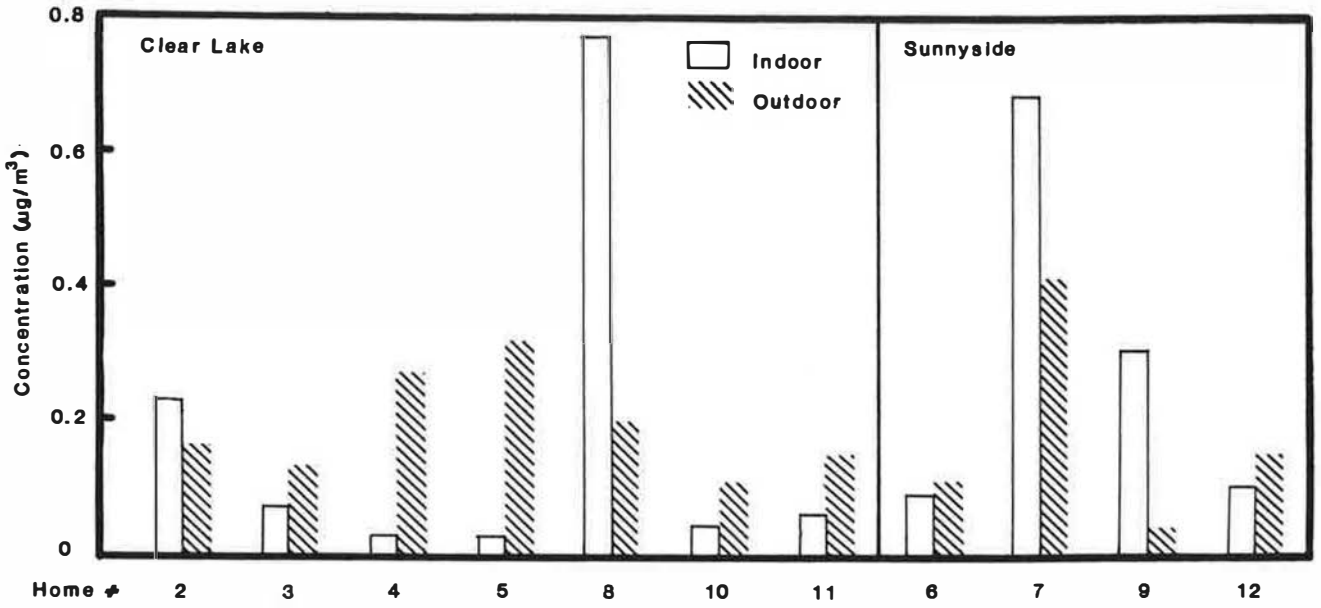

Fig. 6. Mean concentrations ($\mu g/m^3$) of NO_3^- for homes

Nitrate. Indoor mean concentrations of nitrate across homes are shown in Fig. 6, ranging from 0.03 to 0.78 $\mu g/m^3$. The I/O ratios appear to vary from home to home and ranged from 0.1 to 7.9. The four ''non-source'' homes have the four lowest indoor concentrations as well as the four lowest I/O ratios.

The indoor levels in three ''source'' homes (7, 8, 9) and one ''pure smoking'' home (2) are higher than the outdoor levels, while the indoor levels in the two ''pure gas stove'' homes (3, 12) are found to be lower than outdoors.

Aluminum (Al), Silicon (Si), Calcium (Ca), and Potassium (K). These elements are enriched in crustal materials giving rise to soil-dust outdoors. Indoor aluminum and silicon concentrations across each home are generally lower than the corresponding outdoor levels, except for Al in home 8 (Figs. 7 and 8).

Indoor mean concentrations of Ca and K in home 8 are much higher than the corresponding levels observed outdoors (Figs. 9 and 10). The five highest indoor K concentrations were found in the four ''source'' homes and the one ''pure smoking'' home,

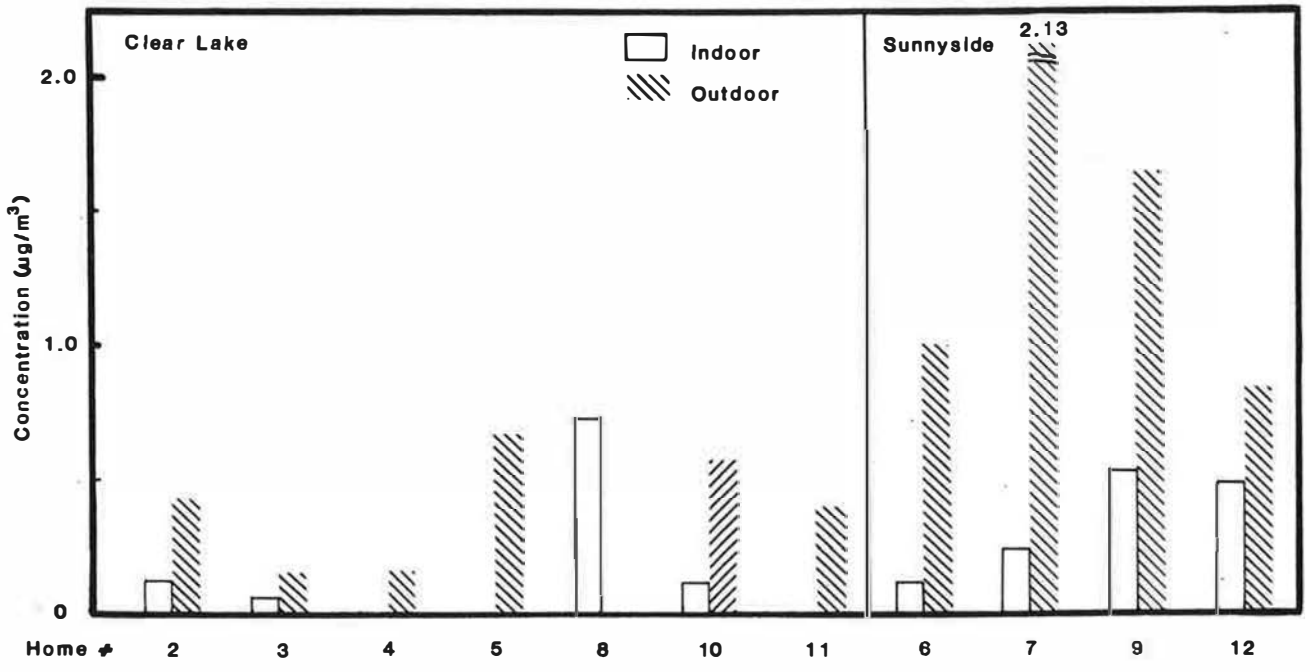

Fig. 7. Mean concentrations ($\mu g/m^3$) of Al for homes

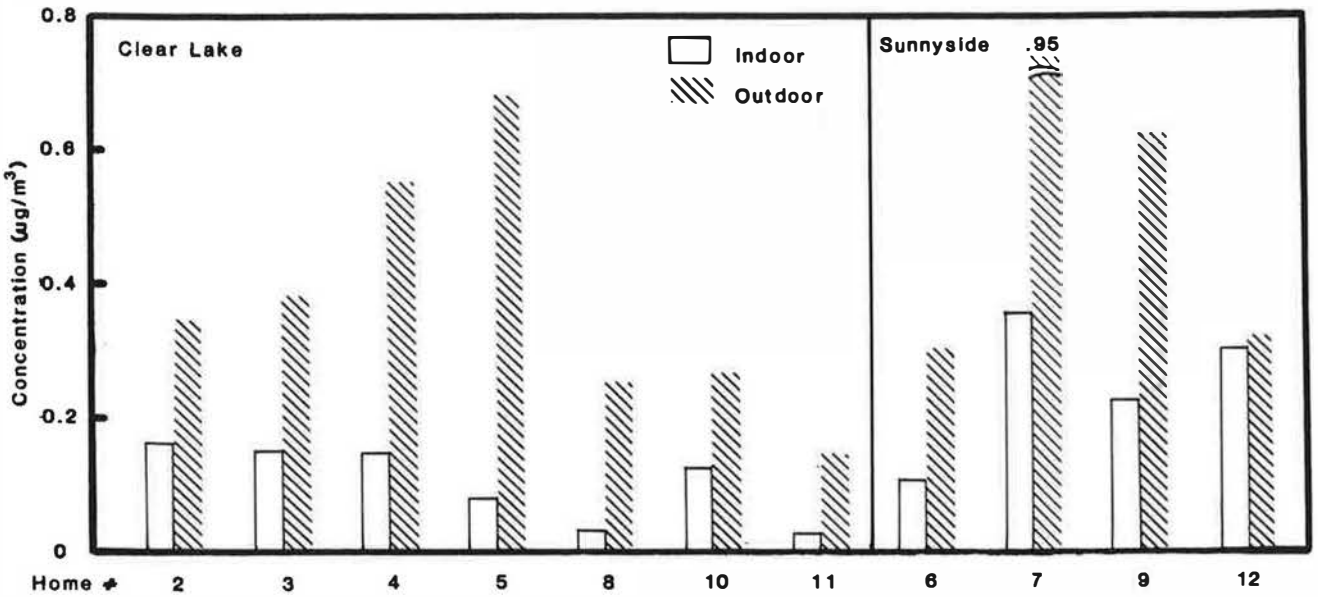

Fig. 8. Mean concentrations ($\mu g/m^3$) of Si for homes

while the four "nonsource" homes had the lowest indoor K concentrations.

Lead (Pb) and Bromine (Br). Both Pb and Br are primarily derived from automobile exhaust outdoors, but may arise from reentrainment of dust indoors (Moschandreas *et al.*, 1979). The Pb and Br concentrations observed outdoors across homes are generally higher than the corresponding levels indoors, except for home 10 (Figs. 11 and 12). This suggests that the outdoor Pb and Br aerosol may penetrate into homes with outdoor air, so that the original outdoor concentrations become decreased indoors. In addition, indoor concentrations of these components may be augmented by automobile exhaust contamination transported from car garages.

Chlorine (Cl) and Zinc (Zn). Indoor-outdoor concentrations and ratios of Cl and Zn are quite variable across homes (Figs. 13 and 14). Mean measurable indoor concentrations of Cl ranged from 0.010 to 1.21 $\mu g/m^3$, while the I/O ratios ranged from 0.1 to 9.2.

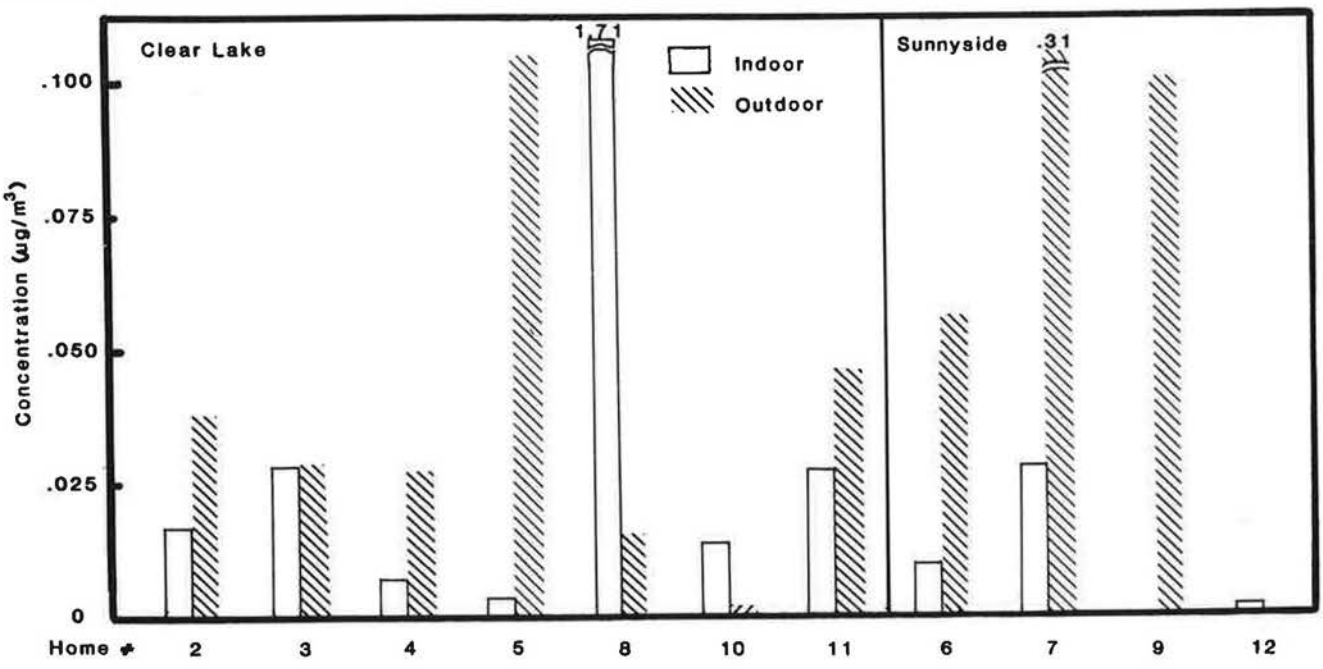

Fig. 9. Mean concentrations ($\mu g/m^3$) of Ca for homes

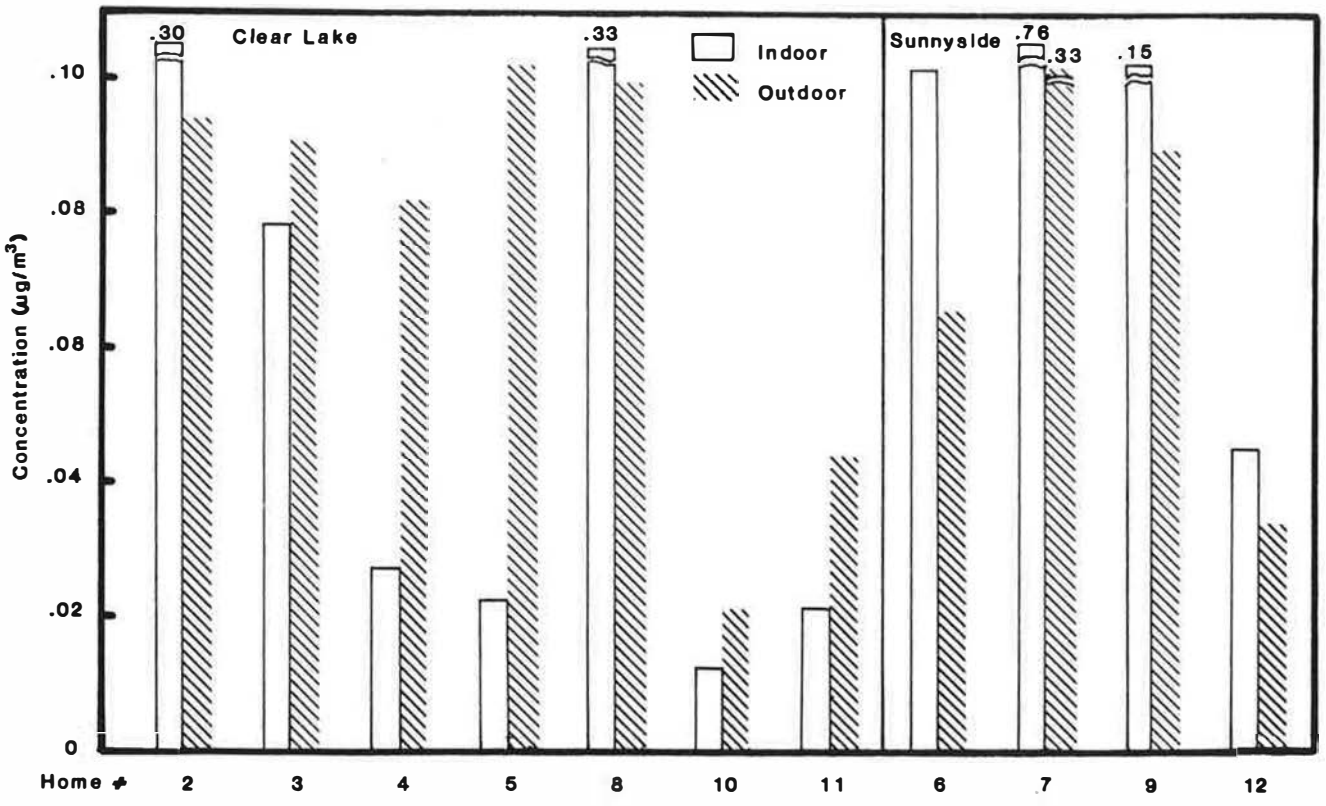

Fig. 10. Mean concentrations (μg/m³) of K for homes

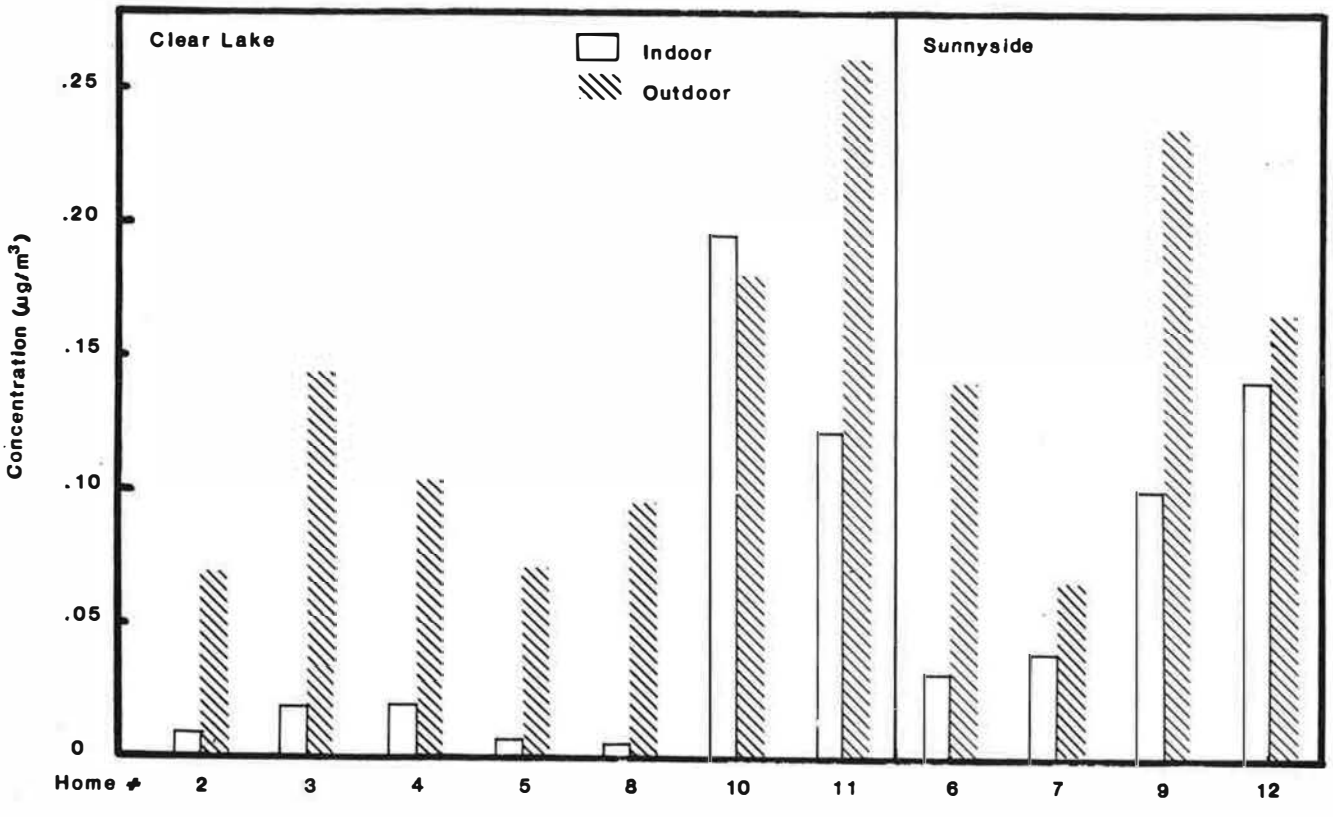

Fig. 11. Mean concentrations (μg/m³) of Pb for homes

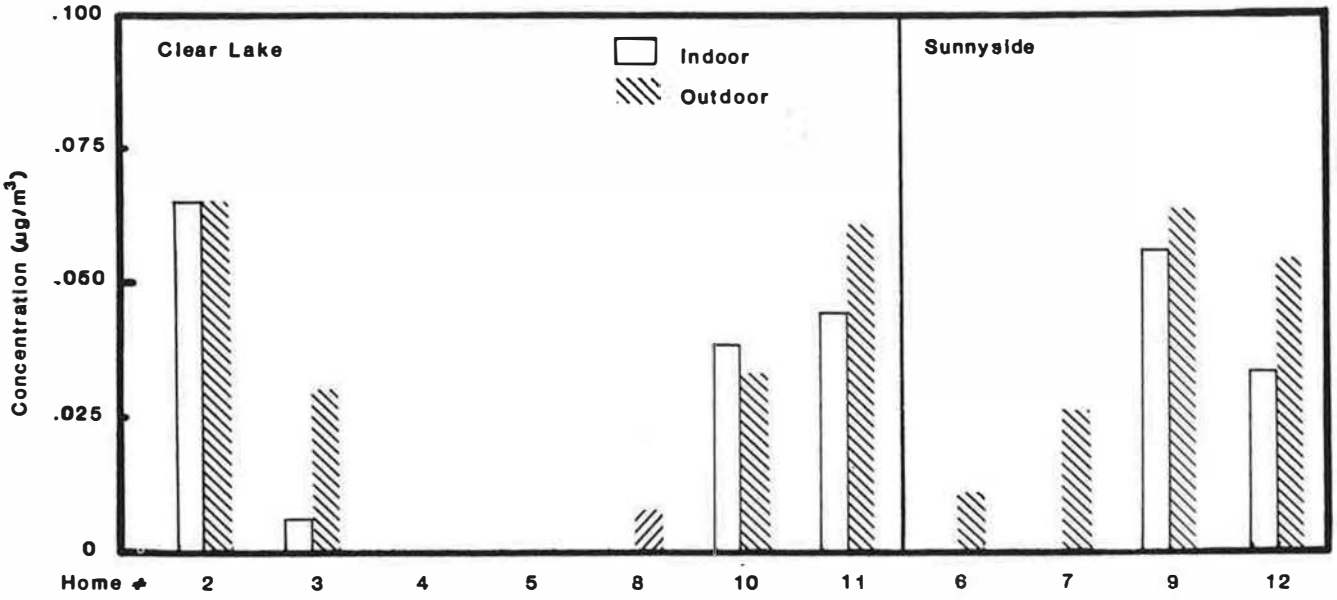

Fig. 12. Mean concentrations ($\mu g/m^3$) of Br for homes

The mean indoor concentrations and I/O ratio of Cl for home 8 were found to be high, while outdoor levels of Cl in home 7 were relatively high. The mean I/O ratios of Zn across homes ranged from 0.16 to 3.44, while the highest indoor mean concentration of Zn was found in home 7.

Vanadium (V) and Iron (Fe). Vanadium has been found to be enriched in residual fuel oil combustion outdoors, while iron has been observed in certain industrial emissions related to coal burning (Kleinman *et al.*, 1980). Indoor and/or outdoor concentrations of vanadium were not detected in many homes; only three homes (3, 10, 11) showed detectable means of both indoor and outdoor measurements (Fig. 15). The highest mean indoor concentration of V was found in home 10 (0.01 $\mu g/m^3$), while the I/O ratio for this home was 3.3. Fe concentrations across homes were

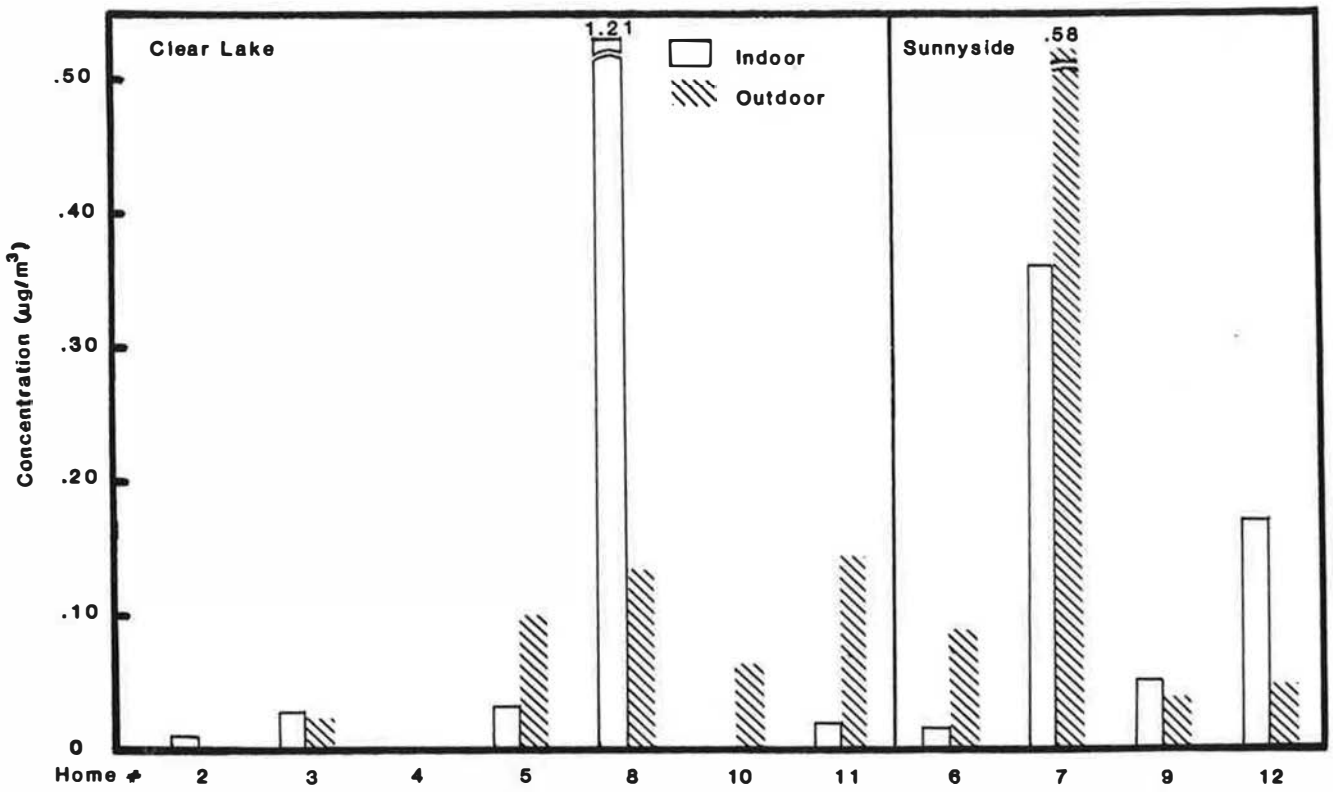

Fig. 13. Mean concentrations ($\mu g/m^3$) of Cl for homes

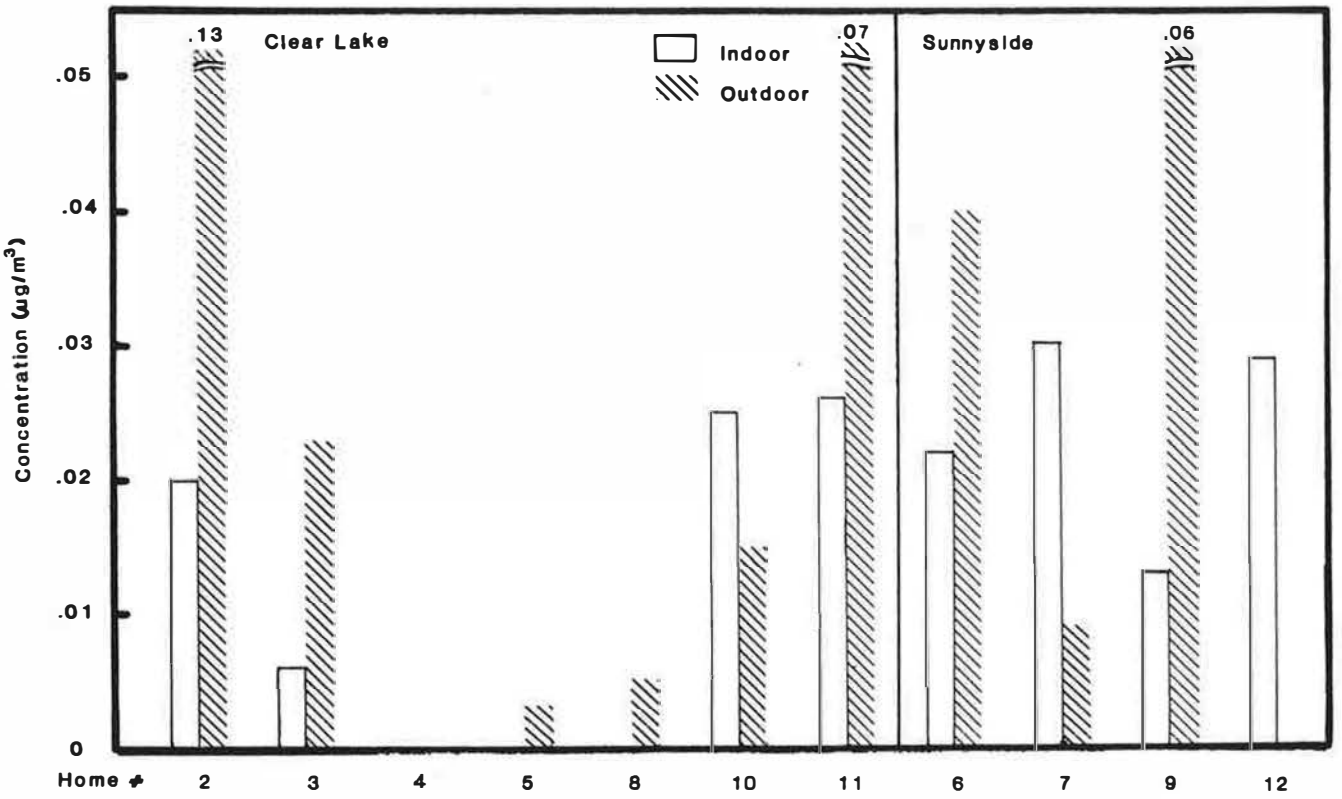

Fig. 14. Mean concentrations ($\mu g/m^3$) of Zn for homes

considerably lower indoors than outdoors, except for home 12 (Fig. 16). The computable I/O ratios of Fe ranged from 0.03 to 0.42.

''Source'' and ''Nonsource'' homes. Figure 17 shows the average indoor and outdoor concentrations of mass, SO_4, and NO_3 in aerosol samples from the four ''source'' homes (6, 7, 8, 9) and the four ''non-source'' homes (4, 5, 10, 11). As shown in Fig. 17, the mean concentrations of these selected aerosol measurements for ''source'' homes are higher indoors than outdoors, except for sulfate, while the outdoor

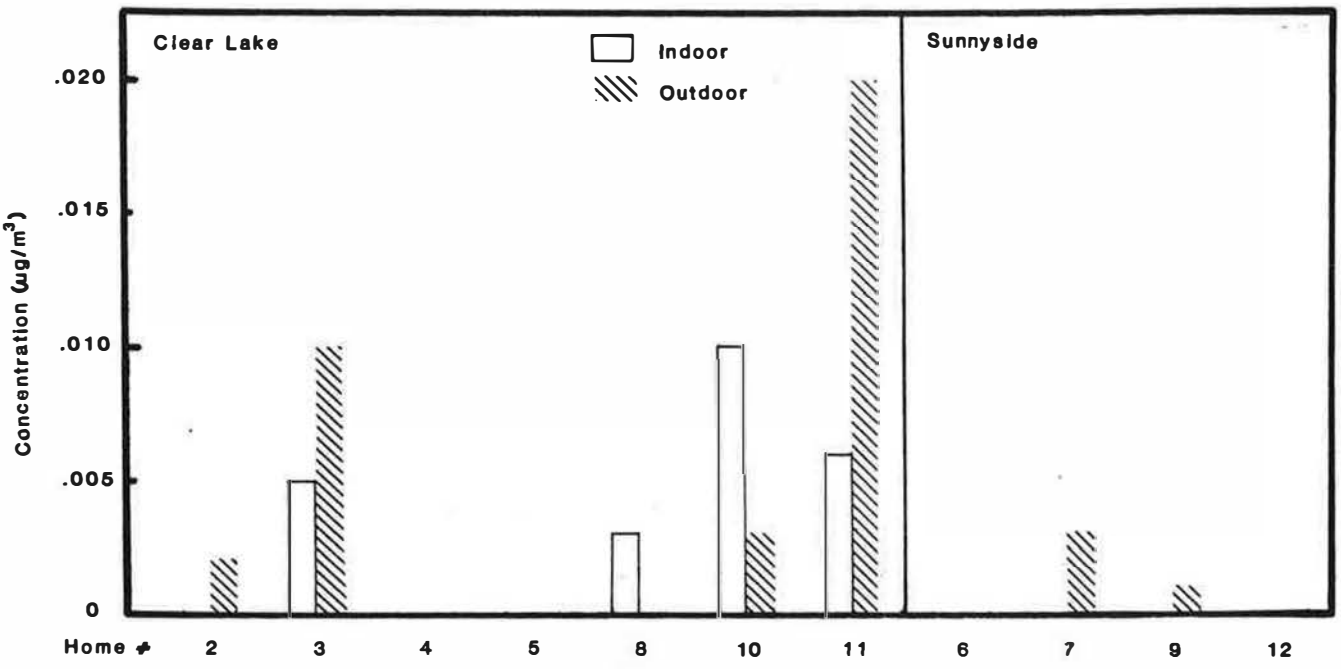

Fig. 15. Mean concentrations ($\mu g/m^3$) of V for homes

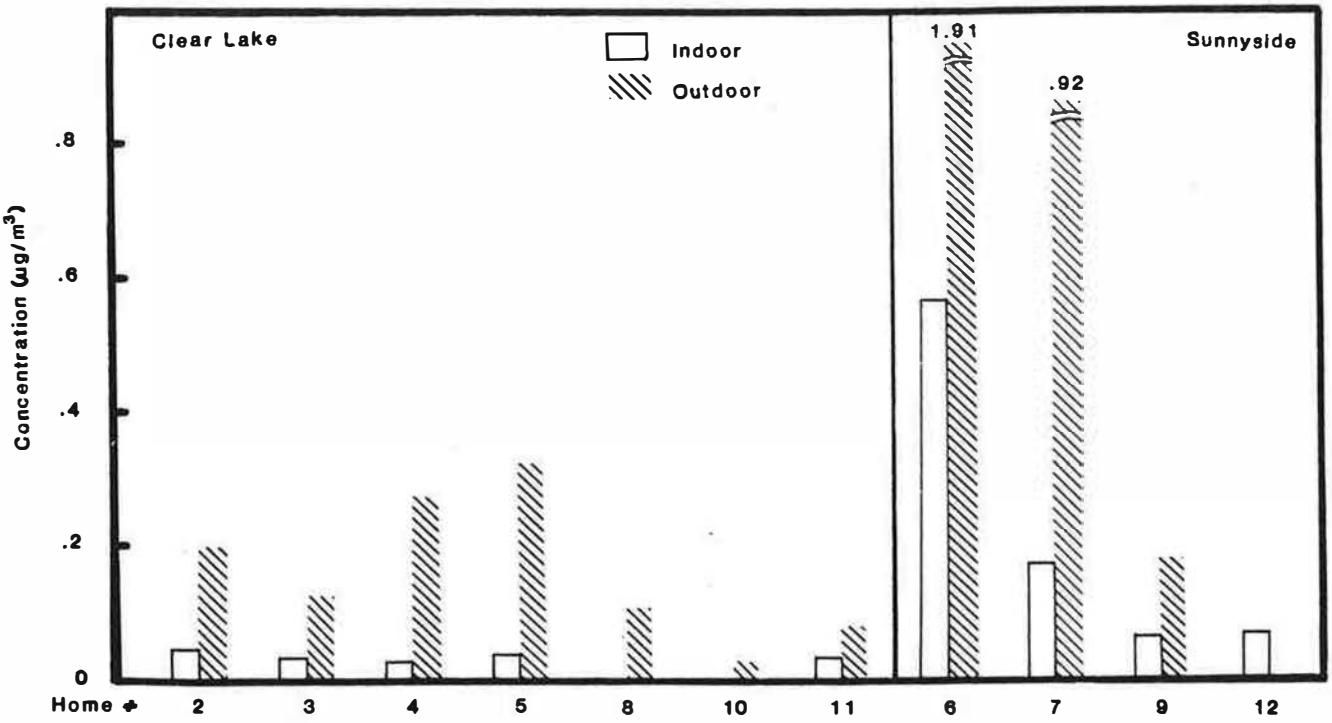

Fig. 16. Mean concentrations ($\mu g/m^3$) of Fe for homes

concentrations for these three aerosol measurements are higher than indoors in "nonsource" homes. This indicates that major indoor sources such as smoking and gas stove use may significantly contribute to nitrate and other non-sulfate constituents of the fine aerosol indoors.

Discussion

This paper presents a comparison of indoor and outdoor fine aerosol mean concentrations for each of 11 individual homes. In addition, comparisons among the homes are made. In general, indoor concentrations in Sunnyside homes are relatively high. This is because the Sunnyside homes (6, 7, 9, 12) include three "source" homes (6, 7, 9) and one "pure gas cooking effect" home (12), and also have higher average outdoor aerosol concentrations.

The "source" homes show higher indoor mean concentrations for fine particulate mass when compared to outdoor levels. The pattern of indoor mean concentrations of mass is consistent with the results of previous work (Spengler *et al.*, 1981; Dockery and Spengler, 1981) that has identified cigarette smoking as the most important determinant of indoor respirable particulate mass.

The relationship between source factors and mass I/O ratios is not so consistent. Elevated mass I/O ratios generally appear in the "source" homes, while the "nonsource" homes show no elevated indoor mass I/O ratios.

Although it is difficult to estimate the effect of smoking on indoor fine particulates in "source" homes, the data from home 2 support a significant smoking effect on fine mass, since this home has the highest mass I/O ratio as well as the second highest indoor mean concentration of particulate mass. This is also consistent with the results of Colome *et al.* (1982) that respirable particulate mass may be associated with indoor smoking.

Indoor fine sulfate concentrations in all homes are generally much lower than the corresponding outdoor levels, except for home 8. The highest indoor levels of sulfate, nitrate, aluminum, calcium, and chlorine are found in home 8, which has a gas stove and smoker, but which has also the highest measured air-exchange rate. One possible source may be the frequent use of a gas clothes dryer (Stock *et al.*, 1985); other sources may be household products.

Ozkaynak *et al.* (1982) concluded that short-term air flow and mixing patterns indoors may be important in controlling pollutant concentrations, and thus, potential exposure characteristics in homes with gas cooking stoves. To understand the relationship between indoor and outdoor concentrations, a model for the relationship should be developed.

Since the immediate outdoor environment of each home is unknown, the outdoor sources of aerosol for each home are uncertain. To understand the dependence of indoor pollutant levels for each home upon ventilation and outdoor pollutant levels, a dynamic theoretical model which allows rapid calculation of

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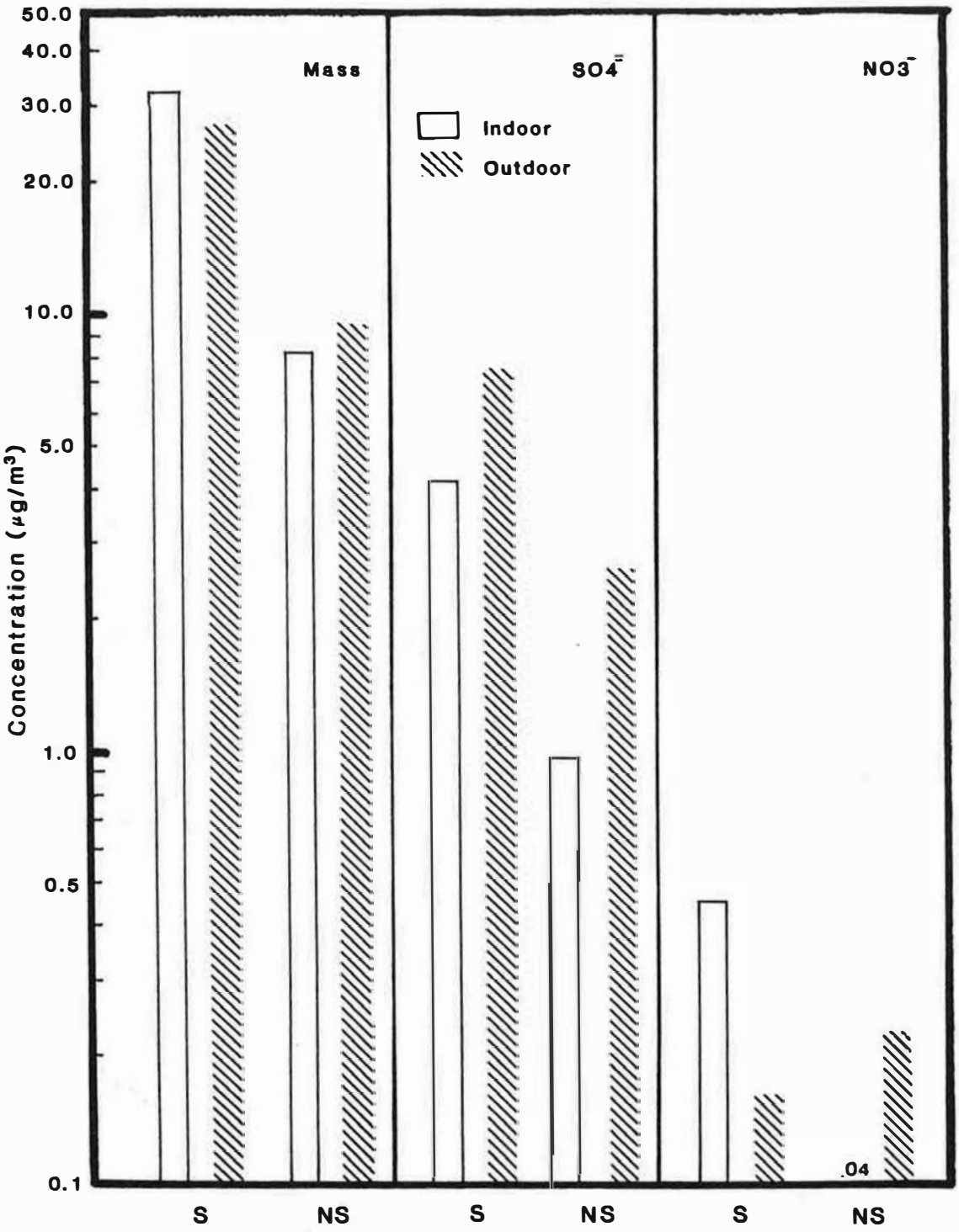

Fig. 17. Mean concentrations (μg/m³) of mass, $SO_4^=$, and NO_3^- for "Source" (S) and "Nonsource" (NS) homes

indoor pollutant levels is needed. Shair and Heitner (1974) have discussed a dynamic model for relating indoor pollutant concentrations to those outdoors.

The results of this analysis suggest that residential indoor fine aerosols are both emitted from source within the home environment, such as smoking and gas stoves, and partly penetrate from outdoor air. However, it is important to recognize the shortcomings inherent in this study to characterize indoor and outdoor aerosols in residences. There are limitations due to the relatively short sampling period at each home (approximately 1 week). It is also essential to remember that these aerosol samples represent only warm season data for fine particle aerosols.

Some indoor aerosol samples may be originally enriched by indoor sources and may subsequently be

affected by outdoor sources through air filtration, while generally known outdoor sources are likely sources of outdoor aerosol. It is likely that the typical complexity of indoor environments makes it difficult to explain sources of indoor aerosol. Additional measurements are needed to determine to what degree the effective indoor aerosol sources are affected by outdoor aerosol sources.

Conclusion

This paper explores the differences between indoor and outdoor concentrations of mass, sulfate, nitrate, and 12 other elemental constituents for each of 11 homes. It is shown that the indoor levels of certain elements are significantly higher over the outdoor levels in specific homes with gas stove use and resident indoor cigarette smokers.

The results suggest the importance of several indoor and outdoor source factors in determining indoor concentrations. It is likely that most of the indoor aerosol appears to be affected by infiltration of outdoor air as well as by indoor generation, with the most important single determinant being the presence or absence of cigarette smoking.

Further studies, involving (1) reliable measurements of coarse particle aerosol, (2) extensive measurements of ventilation rates and other meteorological measurements, and (3) development of models for indoor-outdoor relationships, are necessary to provide a detailed characterization of aerosols inside and outside of home environments. The further understanding of the complex mixture of indoor and outdoor sources is extremely useful in defining the components of healthful indoor air.

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