LBL--21453

DE87 000078

Paper #86-52.3. To be presented at the
79th Annual Meeting of the Air Pollution
Control Assocation, Minneapolis, Minnesota,
June 22-27, 1986.

Indoor Air Quality Measurements in 38 Pacific Northwest Commercial Buildings

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DISCLAIMER

This work is supported by the Bonneville Power Administration under Contract No. DE-A179-83BP12921, and by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Energy Research and Development, Buildings Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

ABSTRACT

A Bonneville Power Administration-funded study monitored ventilation rates and a variety of indoor air pollutants in 38 Pacific Northwest commercial buildings. The buildings ranged in age from 6 months to 90 years, in size from 864 to 34,280 m^2, and occupancy from 25 to 2,500 people. Building average formaldehyde (HCHO) concentrations were below the 20 ppb detection limit in 48% of the buildings. Nitrogen dioxide (NO_2) concentration averages ranged from 5 ppb to 43 ppb and were lower than outdoor concentrations in 8 of 13 buildings. At only one site, an elementary school classroom, did carbon dioxide (CO_2) exceed 1,000 ppm. Radon (Rn) levels were elevated in one building with an average concentration of 7.4 $pCiL^{-1}$. Respirable particles (RSP) concentrations in smoking areas in 32 buildings had a geometric mean of 44 $\mu g\ m^{-3}$ and ranged up to 308 $\mu g\ m^{-3}$ at one site. In non-smoking areas the geometric mean RSP was 15 $\mu g\ m^{-3}$. Outside air ventilation rates did not appear to be the single dominant parameter in determining indoor pollutant concentrations. Measured pollutant concentrations in 2 "complaint" buildings were below accepted guidelines. The cause of the complaints was not identified.

INTRODUCTION

Since the issue of air quality inside non-industrial structures has become a concern, most exposure studies have focused on the indoor residential environment.[1,2] Yet for employed men and women, 23-32% of their time is spent in non-residential indoor locations[3] including places of business, restaurants, and places of employment. The same percentage may also be appropriate for children of school age. The air in the industrial workplace is frequently monitored and regulated, while the air of the non-industrial workplace (including offices and educational facilities) may be regulated by the Occupational Safety and Health Administration, but is not often monitored.

Through their involvement in energy conservation programs, the Bonneville Power Administration (BPA) may make recommendations for reductions in infiltration and the mechanical ventilation rate in commercial and institutional buildings. Although the effects of inadequate ventilation may play a role in the poor air quality of building-related epidemics[4,5,6] ("Sick Building Syndrome"), the detailed mechanisms involved in pollutant generation and removal are poorly understood. To better understand the relationships between ventilation and indoor air quality, BPA initiated this survey of existing ventilation rates and concentrations of some indoor air pollutants in Pacific Northwest buildings.

Specific study objectives include:

1. Characterize indoor pollutant concentrations and ventilation rates in 38 commercial and institutional buildings in the Pacific Northwest. Buildings were to be selected from existing stock and not necessarily exhibit symptoms of poor air quality.

2. If possible, demonstrate observed relationships between indoor air pollutant levels and ventilation rates.

This paper summarizes many individual measurements and highlights the significant findings.

METHODS

Selection and Description of Buildings.

Thirty-eight buildings were selected for participation in this study. None were selected because of previous indications of air quality problems or complaints. Two of the buildings were monitored a second time under different seasonal conditions for a total of 40 building measurements. The number was equally divided between two distinct climate zones: the moderate Pacific Northwest coastal region that includes Portland and Salem, Oregon; and the more extreme climate of the continentally-influenced inland region that includes Spokane and Cheney, Washington. Winter condition measurements were made in 14

Portland-Salem buildings and in seven Spokane-Cheney buildings. Six Portland-Salem buildings and four Spokane buildings were monitored during spring conditions, while the remaining nine buildings were measured during the summer in Spokane. Monitoring of the buildings began in January, 1984 with the final building tests concluding in April, 1985.

Table I summarizes the main building characteristics of the structures involved. Our survey monitored a greater portion of larger structures as compared to the overall Pacific Northwest commercial and institutional building stock.[7] Commercial facilities such as restaurants and retail stores were not monitored (except where they were part of a large office building) because most private building owners and managers were concerned about their liability if an air quality problem was discovered. Therefore, all but four buildings were government or public properties belonging to federal, state, or local agencies.

Table I. Building Characteristics

	Portland/ Salem, OR.	Spokane/ Cheney, WA.	Total
Use Type:			
Educational	2	4	6
Libraries	2	1	3
Office Bldgs. > 9300m^2	9	4	13
Office Bldgs. < 9300m^2			
Naturally ventilated	1	2	3
Mechanically ventilated	4	4	8
Multi-use	1	4	5
TOTAL	19	19	38
Floor Area (m^2):			
Median	7711	4955	6828
Range: Max	34281	20987	34281
Min	864	1139	864
Occupancy:			
Mean	633	419	526
Median	400	300	359
Range: Max	2500	1200	2500
Min	34	25	25
Age (Yrs.):			
Median	21	12	15
Range: Max	90	75	90
Min	0.5	3	0.5
Height (stories):			
Median	4	3	4
Range: Max	18	15	18
Min	Under-ground	1	Under-ground
No. of Air Handlers/Bldg.			
Median	3	2	2
Range: Max	38	11	38
Min	0	0	0

This sample of 38 buildings is too small to permit a detailed statistical analysis or inter-comparison of the buildings, since each building has sufficient unique features of siting, size, occupancy, use, and ventilation systems to allow a total of 38 separate classifications. For example, no two mechanical system air handling systems were identical in design, operation or maintenance. The time elapsed since construction or remodeling was also different, which may affect the emission rates of pollutants such as formaldehyde.

Monitoring Protocol.

Each building was monitored for approximately ten working days over a two-week period during the occupied hours. An accumulated minimum of 75 hours sampling was necessary to achieve adequate detection sensitivity of the formaldehyde passive sampler. From three to twenty indoor sampling site locations were chosen (based on the size of the building) to include a distribution of various ventilation conditions, floor heights, structural configurations, occupant activities, and proximity to observed pollutant sources (photocopy centers, cafeterias, smoking lounges). While the initial intent was to measure overall air quality in buildings rather than worst case conditions, in practice, complaint and tobacco smoking areas were often singled out and may be over-represented. Smoking sites were defined as areas where at least one person smoked cigarettes, cigars, or a pipe within a 9-meter radius of the sample location. It is important to note that because of limitations on available instrumentation, sample site locations were not randomly selected. Therefore, results presented for building average concentrations are not true spatial averages (Table II). Instead they are simply arithmetic (or geometric) means of all interior samplers.

More than one floor in multi-story buildings was monitored. If a floor was monitored, generally more than one site on a floor was sampled. In this way, the spatial distribution of a pollutant on a floor or among floors might be detected. Outdoor sampling sites were located near the outside air inlet at some of the structures.

During monitoring, technicians usually visited each building twice a day. Once, in the morning to start the sampling and then in late afternoon to stop sampling. At those times, instruments were calibrated and notes were made on operations in the buildings. In addition, data was collected on building age, construction, materials, occupancy, tobacco smoking policies, activities, and occupants' complaints.

Table III summarizes the pollutants sampled during monitoring. Pollutant passive samplers manufactured and analyzed at LBL included nitrogen dioxide (NO_2)[8], formaldehyde ($HCHO$)[9], and water vapor (H_2O).[10] The traditional method of continuous seven-day exposure for passive samplers was modified, since the buildings in this study were generally occupied during only a portion of the monitoring period. Each day for ten working days, samplers were uncapped at the start of occupancy and capped when the building emptied for a total exposure ranging from 75-100 hours. Thus, the passive sampler data represent time-weighted average pollutant concentrations for hours when the

Table II. Air Sampling Instrumentation and Analytical Techniques

Pollutant	Sampling Device	Analytical Technique
HCHO	LBL Passive Sampler	Spectrophotometric
H_2O	LBL Passive Sampler	Gravimetric
Rn	Terradex Corp. Type SF Track Etch Sampler	Count number of alpha tracks on film, performed by Terradex Corp.
NO_2	Palmes' Passive Sampler	Spectrophotometric
RSP	LBL Flow-Controlled Filtration Device with 3μ cut-point cyclone	Gravimetric
PAH's	Same as RSP	HPLC, performed by McKesson Laboratory
CO_2	Horiba Model #APBA-210 CO_2 Detector	Non-dispersive Infrared. Direct Reading
CO	LBL Constant-Flow Gas Collection Bag	General Electric Model 15EC53C01 Electrochemical Analyzer
Tracer	**Ventilation Measurement Device**	**Analytical Technique**
SF_6	Baseline Model 1030A Gas Chromatograph, Valco Electron Capture Detector Mod. 140B	Continuous Monitoring of Tracer Decay

buildings were occupied. At building locations that were occupied 24 hours a day, passive samplers were continuously open for 75-100 hours. All monitoring was conducted at representative locations to sample air in the breathing zone (approximately one to two meters above the floor).

Exceptions to the above occurred when monitoring for radon and respirable particles. Radon (^{222}Rn) was monitored passively, for 2-1/2 to 4 months, using Terradex type SF TrackEtch® monitors. The devices sampled continuously for the entire period.

Respirable suspended particles (RSP) were collected on an in-line one-micron, 37-mm diameter, teflon filter, after passing through a Dorr Oliver 10-mm nylon cyclone with a size-segregating cut point of 3 microns. Air flow through the filters continued during occupied hours and was stopped when the occupants vacated. Typically, two or three buildings were monitored concurrently which meant that the number of RSP sampling systems available for each building was limited to 5 to 12. Therefore, not all sites with passive samplers were accompanied by an RSP system.

Table III. Building Average Pollutant and Ventilation Summary

	Means		Std. Deviations		Extremes		No. of	Std. or	Number of Bldgs. Greater
	Arithmetic	Geometric	Arithmetic	Geometric	Max	Min	Buildings	Guideline	Than Guideline
Water Vapor, H_2O (g/kg)	6.6	6.4	1.5	1.3	9.8	3.4	40	--	--
Indoor/Outdoor ratio	1.06	1.01	0.39	1.35	2.00	0.76	13		
Carbon Dioxide, CO_2 (ppm)	499	489	102.1	1.2	840 1290[a]	337 306[a]	39	2500 ppm[b]	0
Carbon Monoxide, CO (ppm)	Below 2ppm detection		--	--	3.3 7.0[c]	BD BD[c]	32	9 ppm[b]	0
Nitrogen Dioxide, NO_2 (ppb)	18	16	8.4	1.6	43	5	40	53 ppb[b]	0
Indoor/Outdoor ratio	0.94	0.92	0.22	1.24	1.40	0.69	13		
Respirable Suspended Particles RSP ($\mu g/m^3$)									
Smoking areas	70	44	73.0	2.7	308	BD[d]	32	75 $\mu g/m^3$ -TSP[b]	9
Nonsmoking areas	19	15	13.6	1.9	63	5	35	"	0
TOTAL	30	24	18.9	2.0	86	5	40	"	1
Indoor/Outdoor ratio	2.20	1.46	2.20	2.54	9.60	0.19	34		
Formaldehyde, HCHO (ppb)	23	21	10.1	1.6	56	BD[d]	40	100 ppb[b]	0
Radon, ^{222}Rn (pCi/l)	1.0	0.8	1.2	2.1	7.4	0.2	40	~2 pCi/l[b]	3
								5 pCi/l[e]	1
								8 pCi/l[f]	1
Ventilation (ach)	1.5	1.3	0.87	1.89	0.3	4.1	40	17.5 l/s /occ.[g]	28

(a) 15-minute interval extremes
(b) ASHRAE 62-1981
(c) Sampling location extreme
(d) Detection limits: HCHO - 20 ppb, NO_2 - 4 ppb, RSP - 50 µg, CO - 2 ppm, H_2O - 0.5 g/kg
(e) BPA mitigation action level
(f) NCRP guideline
(g) Proposed ASHRAE guideline for buildings where smoking is allowed

Selected RSP filters were analyzed for up to 16 polycyclic aromatic hydrocarbons (PAH) including benzo(a)pyrene (B[a]P). McKesson Environmental Laboratories performed the analysis by solvent extraction followed by high performance liquid chromatography. Analysis of these data is not yet complete.

Carbon dioxide (CO_2) was monitored for a continuous eight-hour period at a minimum of one location in each building. The sample location was usually an area of relatively high occupant density so that CO_2 concentrations would be near their maximum. Carbon dioxide data are presented for a one-day average concentration at a single location. The instantaneous maximum and minimum values from a set of readings at 15-minute intervals were also recorded.

Carbon monoxide (CO) was sampled using constant-flow peristaltic pumps to fill Tedlar sample bags which were then analyzed with a General Electric electrochemical analyzer. Up to seven locations in each building, corresponding to passive sampler sites, were sampled for one 7 to 10-hour day. CO data are one-day time-weighted averages and do not indicate short-term transients.

Sulfur hexafluoride (SF_6) was used in a single tracer dilution and decay ventilation measurement in all buildings. The protocol was similar to the procedures described in ASTM E741-83 [11] and used by Grot (1982)[12] and others for estimating outside air infiltration rates. However, since all but three buildings in this study were mechanically ventilated, some procedural modifications were necessary.

A gas chromatograph with electron capture detector was placed at a central building location. Sampling lines were run from three to nine locations in the building that, when practical, coincided with pollutant sampling sites. After the injected SF_6 had thoroughly mixed throughout the building, the gas chromatograph sequentially monitored the decay of the SF_6 at each site. The time series of data from the electron capture detector was then graphed as a log-linear plot and a least squares regression line was computed. The ventilation measurements generally were made when the building was unoccupied because of the disruption due to the tubing and instrumentation and discomfort caused by manipulation of the air handling equipment. However, the ventilation systems were operated as they had been when the building was occupied.

RESULTS

Data from the ventilation and various pollutant measurements are briefly discussed below. Detailed sampling location references are kept to a minimum, except where interesting occurrences of high (or low) values were observed. It is important to keep in mind that pollutant concentrations at individual sites are a better indicator of personal exposure than overall building averages. However, building averages are useful when comparing between groups of large numbers of measurements. Table III summarizes the building averages, while Figures 1,3,4,6-8 are frequency distributions of the pollutant levels measured at the individual sample locations.

Water Vapor.

A more fundamental quantity than relative humidity, the humidity ratio (g/kg), is measured by the H_2O passive sampler and is reported here. For reference, at 21°C, a water vapor concentration of 6.5 g/kg corresponds to a relative humidity of 42 %.

With a few exceptions, water vapor levels in this sample of buildings fall within the expected range for comfort and control of secondary humidity effects.[13] The frequency distribution (6.4 g/kg mean, 1.6 g/kg std. dev.) of the 398 sampling sites (Figure 1), is probably best approximated by a skewed normal distribution since the capacity of air to retain water vapor at a given temperature is limited and therefore, there is a very low probability of very large values occurring.

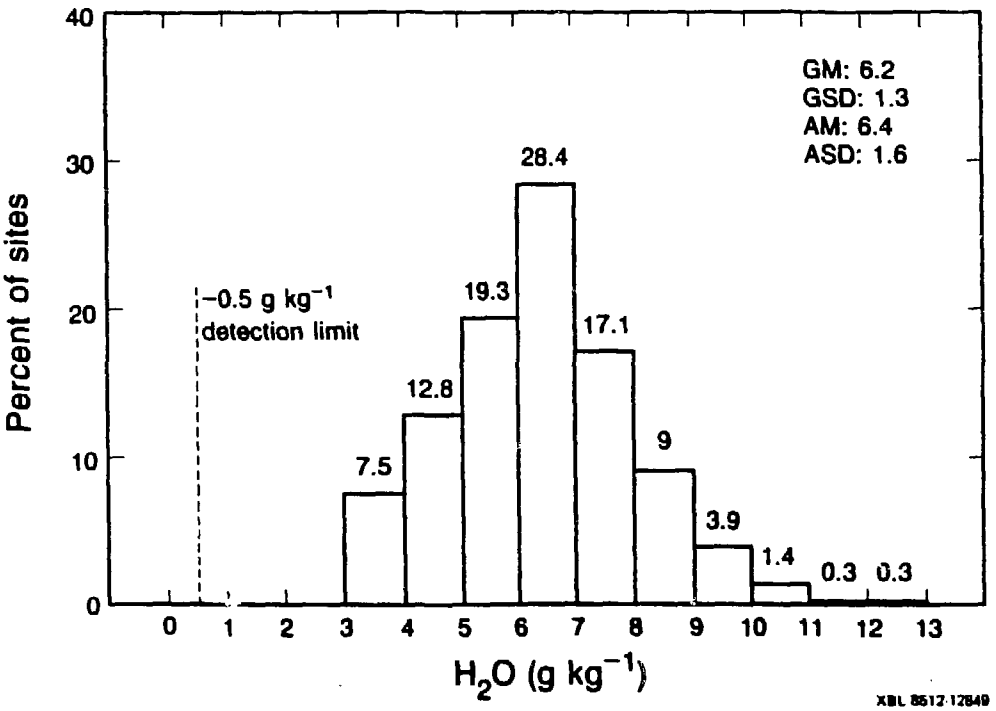

Figure 1. Frequency distribution of indoor water vapor concentration from 398 sampling sites in 40 large building measurements.

Three buildings, monitored in Spokane during the summer, had average humidity ratios from 9.4 g/kg to 9.8 g/kg with one site at 12.0 g/kg. At temperatures normally experienced in conditioned buildings during the summer (24°C), this site would have a relative humidity of 65%. Three other sites had estimated relative humidities of between 65-70%, one of which was located in a carefully controlled environment in a computer center. That high value is unexplained. The other two (10.1 g/kg and 10.2 g/kg) were measured in separate office buildings in Salem in the spring and may result from the local effects of temperature and occupancy, since the building averages were 7.5 g/kg and 6.1 g/kg respectively.

The lowest water vapor concentrations were found in Spokane winter measurements, with six of seven building averages below 5.0 g/kg. This is probably a result of ventilating with cold, dry outside air. Outdoor concentrations were between 3.4 g/kg and 5.4 g/kg for this winter period.

Carbon Dioxide.

Carbon dioxide has two major sources in these buildings: outdoor air and human metabolism. Globally, concentrations in well mixed outdoor air usually average from 300-350 ppm. Indoor levels above these concentrations may be due to local outdoor (or indoor) combustion sources or to the occupants in the building. Studies by Berk, et al., [14] Turiel and Rudy, [15] and others have clearly demonstrated the occupant effect on CO_2 concentrations.

Of the 41 building measurements made in 37 buildings, only one 15-minute reading in a crowded elementary school classroom exceeded 1000 ppm (1290 ppm). Figure 2 is a time-series chart of the data from this site. Periods when the children left the classroom such as recess at 1000 and 1300 and the noon lunch break are obvious. Only four other buildings had instantaneous maxima over 800 ppm. Building eight-hour averages ranged from 337 ppm to 840 ppm and are shown in Figure 3.

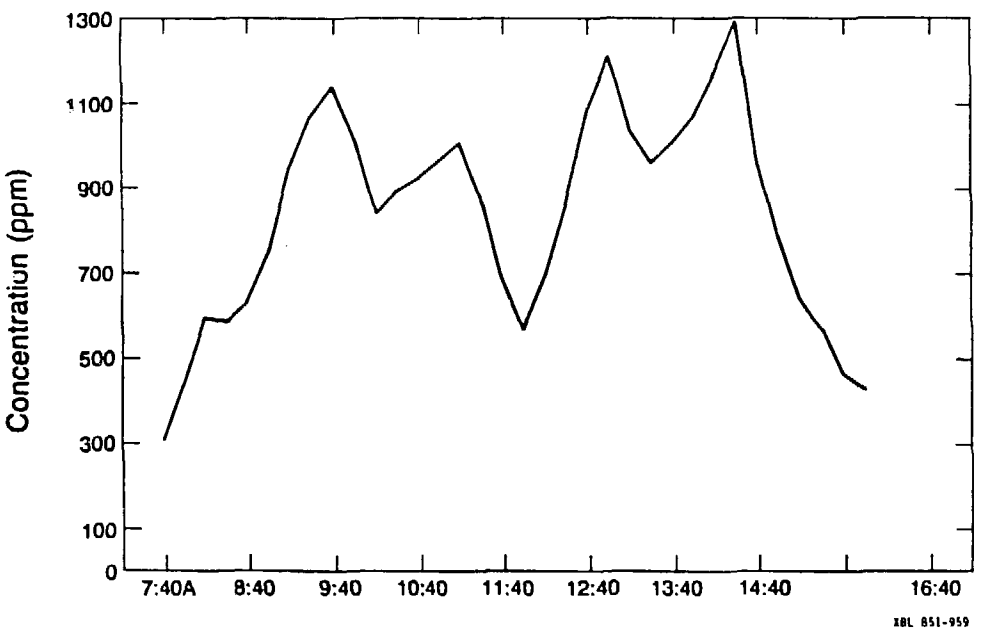

Figure 2. Continucus CO_2 measurements from a Portland, OR elementary school classroom.

Recent studies have indicated that exposure to CO_2 concentrations above 600 ppm may increase the number of complaints about discomfort in the work area (Rajhans, 1983).[16] In our study, complaints were not specifically noted in those areas with CO_2 concentrations greater than 600 ppm.

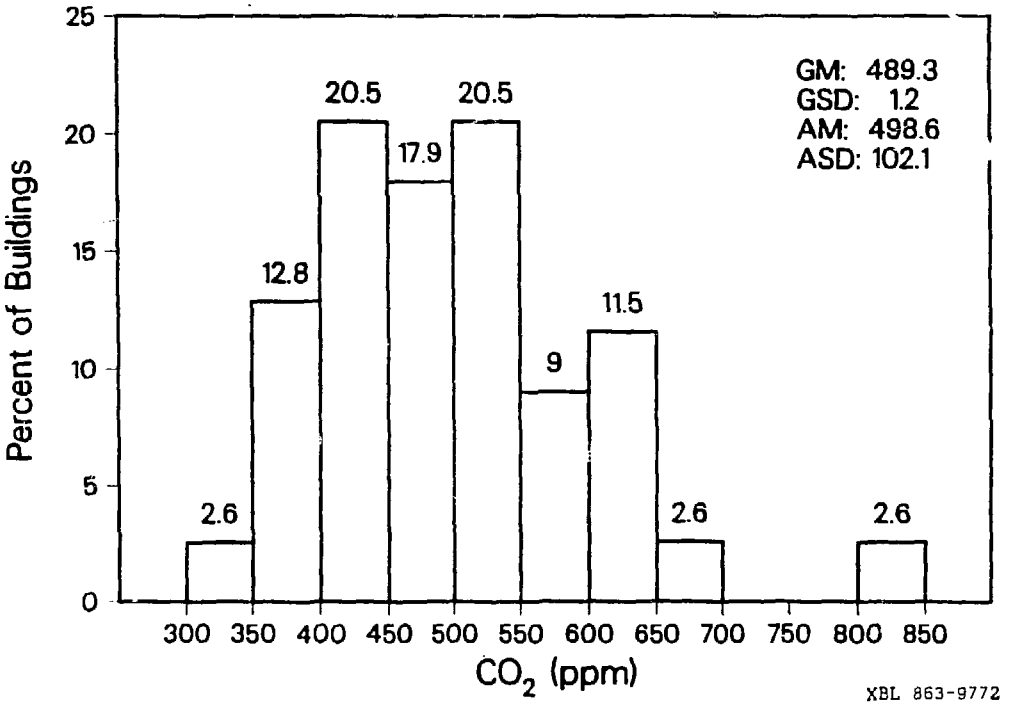

Figure 3. Frequency distribution of one-day, one-location average indoor CO_2 concentrations from 39 buildings.

Carbon Monoxide.

Only six of the 32 buildings sampled for carbon monoxide had time-weighted average concentrations greater than the minimum detectable level of 2 ppm (Table IV), with the highest building average being 7 ppm. In four of the buildings, all sample sites recorded above the detection limit, while 36 of the 126 total sample sites were above the detection limit. Outdoor samples were collected at 11 buildings. Although all readings are lower than the 10-hour EPA standard and ASHRAE guideline of 9 ppm[17], short term exposures could be much higher because the sampling method averages over an eight-hour period. Generally, elevated CO levels in these buildings can be attributed to vehicular exhaust originating outside from heavy traffic or from underground parking garages.

Table IV. Elevated Carbon Monoxide Summary

Building No.	Underground Parking	City	Season	CO Concentration (ppm) Indoor Mean	Indoor Max	Building Outdoor	Other Agency[a] Outdoor
6	Y	Portland	Winter	3.3	7.0	NM	2
7	N	Portland	Winter	3.0	3.0	NM	5
27	Y	Spokane	Summer	2.5	3.0	5.0	5
34	N	Spokane	Winter	2.2	6.0	BD	3
35	N	Spokane	Winter	2.1	3.5	NM	3
37	Y	Portland	Winter	2.7	3.0	NM	3

(a) Fixed site monitoring by outside agency
NM - Not Measured
BD - Below 2 ppm detection limit

As seen in Table IV, at buildings #7 and #35, outdoor CO concentrations equaled or slightly exceeded building averages. Since neither building has an attached parking garage and other indoor sources were not identified, the elevated indoor readings are probably due to locally heavy traffic contaminating the outdoor air used to mechanically ventilate the buildings. Buildings #6, #27, and #37 had underground parking garages that probably also contributed to the relatively high indoor CO levels. For Building #6, the parking garage may have contributed to the elevated indoor CO levels, since the outdoor air concentration (reported by the Oregon Department of Environmental Quality approximately 0.6 km from the building) was lower (2 ppm) than the mean indoor concentration (3.3 ppm).

Only in Building #34, where a CO level of 6 ppm was measured in a smoky lunch room, is tobacco smoking suspected to be a significant source. Outdoor levels were below our detection limit at the building and 3 ppm as measured by the Spokane County Air Pollution Control Authority approximately 0.3 km from the building.

Nitrogen Dioxide.

Thirty-three buildings were sampled for NO_2 at a total of 245 sites. Outdoor air was monitored at 13 buildings. Building averages are summarized in Table III and the frequency distribution of the individual sites is shown in Figure 4. An examination of the distribution and cumulative probability for the observed concentrations suggests that the data approximate a lognormal distribution. The slightly bimodal appearance may be due to the distinct differences observed in outdoor concentrations at buildings located in urban areas versus those located in suburban or rural areas. Figure 5 shows that approximately 87% of the variation in building average indoor concentrations can be explained by outdoor air concentrations. Thus, we can conclude that, for these 13 buildings, outdoor sources are the dominant determinant of indoor concentrations.

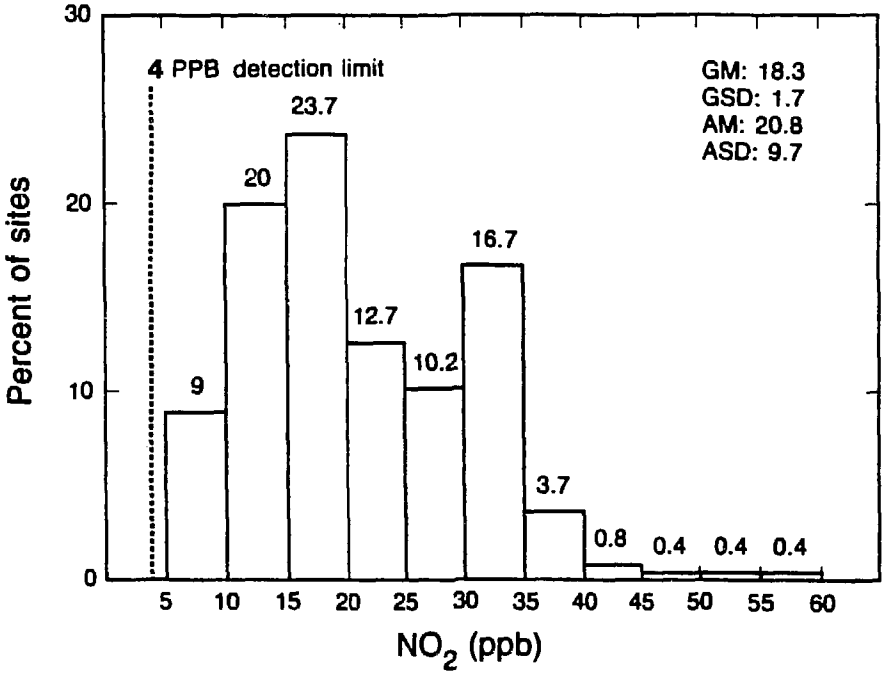

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Figure 4. Frequency distribution of indoor NO_2 concentrations from 245 sampling sites in 40 large building measurements. Two sites were below the 4 ppb detection limit.

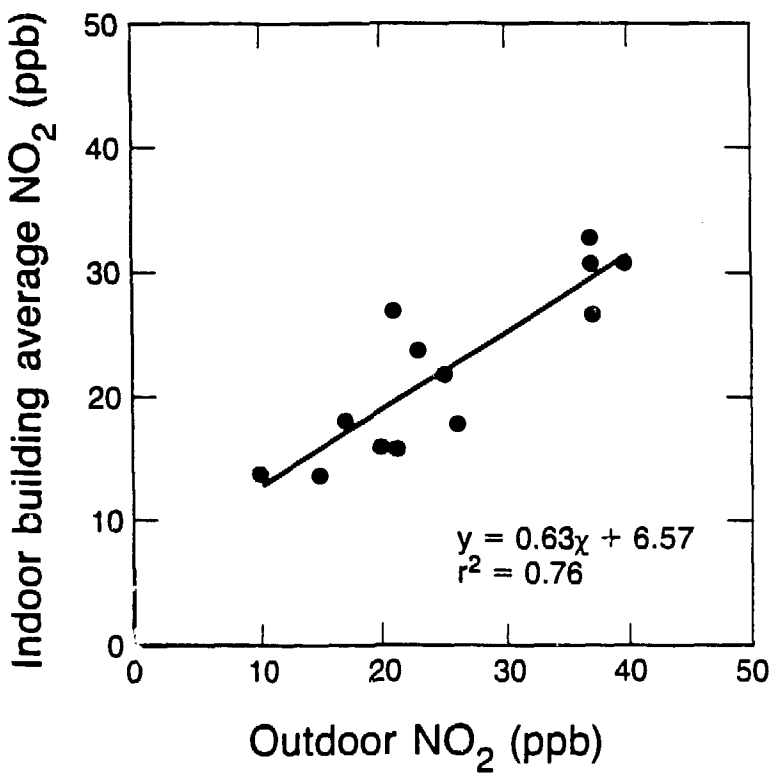

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Figure 5. Average indoor versus outdoor NO_2 concentrations for 13 buildings.

There were only two indoor sites, in separate buildings, that had NO_2 levels above the EPA annual ambient standard of 50 ppb. One, a Spokane winter measurement, measured 58 ppb and is considerably higher than the building average of 22 ppb. It remains unexplained. The other value occurred in Building #6, already discussed as having elevated CO due to contaminated outside air from vehicular exhaust. This building also had the highest average NO_2 concentration for the study (43 ppb).

For 15 buildings, NO_2 concentrations for smoking sites had a geometric mean (GM) of 20 ppb and geometric standard deviation (GSD) of 2 ppb while nonsmoking sites had a GM of 18 ppb and GSD of 2 ppb. This tends to support data from residential studies that show an increase of approximately 2 ppb in houses without gas-fired appliances where smoking occurred.[14,18]

Using a best fit line to the cumulative probability of all of the observed data, it can be predicted that slightly more than 3% of all sites measured in a similar sample of buildings would have a concentration greater than 50 ppb.

Respirable Suspended Particles.

Figure 6 and Table III summarize the respirable suspended particle data for sampling locations and building averages. The chief suspected indoor source of RSP is tobacco smoke, although general house and photocopy dust may also occur in the RSP size range.[19] Some particles with an outdoor source penetrate the building envelope and enter the occupied space through infiltration or with outside air via the HVAC system. The geometric mean of all building averages was 24 $\mu g/m^3$ with the expected dichotomy between non-smoking areas (GM of 15 $\mu g/m^3$) and smoking areas (GM of 44 $\mu g/m^3$). The ASHRAE annual exposure guideline for total suspended particles (TSP) is 75 $\mu g/m^3$. Since RSP are only a part of the TSP spectrum, the TSP guideline represents a very conservative exposure limit for RSP. Fourteen of the 70 smoking sites and only one of the 106 non-smoking sites were above 75 $\mu g/m^3$. The highest concentration of 308 $\mu g/m^3$ occurred in a Portland office building cafeteria where smoking was allowed. Outdoor concentrations ranged from below detection (less than 50 μg material collected on the filter) to a maximum of 68 $\mu g/m^3$ at a downtown Spokane building during the summer and had a geometric mean of 14 $\mu g/m^3$ with a GSD of 2.2 $\mu g/m^3$.

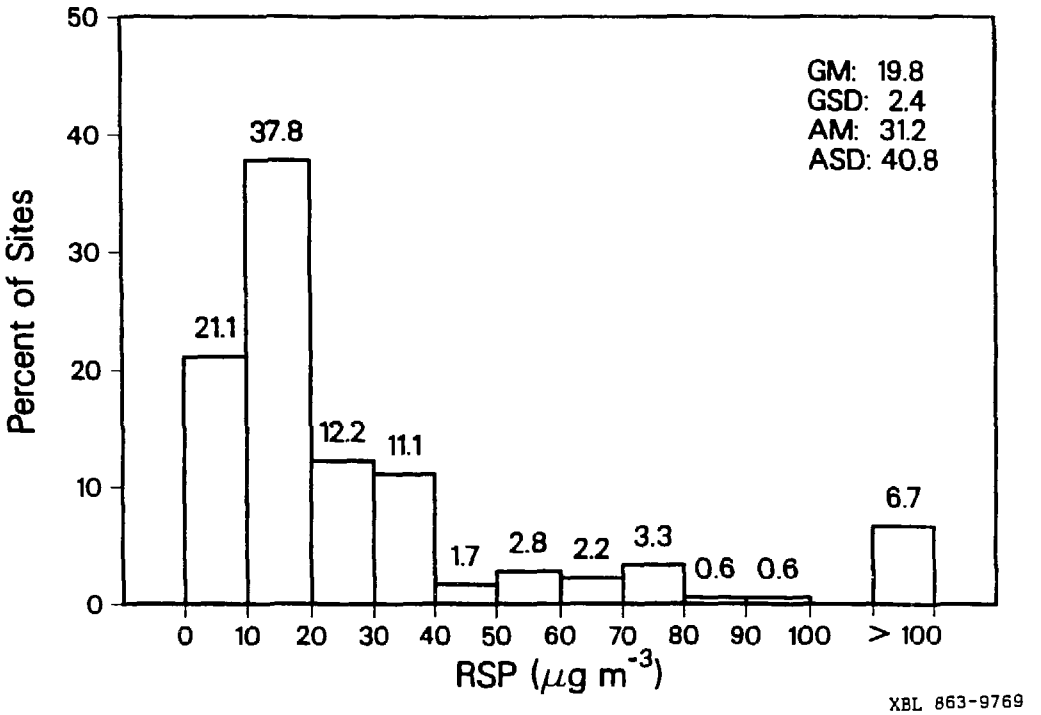

Figure 6. Frequency distribution of indoor RSP concentrations from 180 sampling sites in 40 large building measurements.

Twenty of 29 indoor non-smoking building averages were lower than outdoors (GM of ratio of 0.9, GSD of 2.0), while the smoking area building averages were higher than outdoors at 24 of 25 buildings (GM of ratio of 3.6, GSD of 2.6). A simple linear regression correlating outdoor RSP concentrations to indoor non-smoking mean RSP concentrations at 24 buildings produced the relationship $y = 0.39x + 11.47$ with a correlation coefficient of 0.51. Indoor sources, including tobacco smoking, and various removal mechanisms such as HVAC filters, physical deposition, chemical transformation, and particle agglomeration account in part for the unexplained variation in RSP concentration.

The highest indoor RSP concentrations are, almost without exception, due to nearby tobacco smoking. However, even where local concentrations are high, concentrations in non-smoking areas of the same building can be quite low. Table V compares indoor concentrations for seven buildings that had a maximum site concentration greater than 125 $\mu g/m^3$. Only in Building #10 was the highest non-smoking area concentration within a factor of two of the highest smoking area concentration. This may indicate that local exhaust ventilation near smoking areas, dilution by large building volumes, and removal mechanisms mentioned above are significantly diminishing RSP concentrations in areas away from areas of high RSP concentrations.

Once again, the data are most closely approximated by a lognormal distribution that predicts 7% of all sites chosen in a similar sample would exceed 75 $\mu g/m^3$ criteria for TSP.

Table V. Comparison of Maximum Site RSP Measurement with Building Background Levels (for maximum site greater than 125 $\mu g/m^3$)

Bldg. No.	RSP Concentrations ($\mu g/m^3$) Outdoor	Indoor Nonsmoking Mean (Range)	Indoor Smoking Mean (Range)	Building Average Mean (Range)
10	9	63(53-74)	95(67-127)	86(53-127)
11	8	23(9-49)	209(209)	63(9-209)
22	20	18(18)	57(22-165)	50(18-165)
29	29	10(8-12)	144(144)	32(8-144)
31	13	12(8-18)	268(268)	64(8-268)
36	20	14(9-18)	72(17-127)	28(9-127)
38	14	7(BD-9)	308(308)	46(BD-308)

Formaldehyde

The primary indoor sources of formaldehyde are urea-formaldehyde bonded wood products such as fiberboard, plywood, and particleboard. With time, the HCHO in these materials outgases to the air through mechanisms dependent on temperature and humidity.

Since the buildings in this study, and possibly commercial buildings in general, use relatively little of this material in their construction, the low observed HCHO concentrations were expected. Figure 7 shows that approximately 50% of the 407 sample locations were below the detection limit of 20 ppb. Summary Table III indicates that the 40 building measurements had a geometric mean of 20 ppb (GSD of 1.6 ppb) with 19 of the buildings below the detection limit. Individual site values below detection were assigned a concentration of 10 ppb to compute an average for each building. Buildings with site measurements below detection therefore may have numerical averages below detection.

One six-month old building had the highest average concentration of 56 ppb, with site concentrations ranging from 38 ppb to 75 ppb. These relatively higher values were probably due to continuing outgasing of some of the new building materials. A separately ventilated (0.2 ach) basement containing a print shop in a school administration building had three sites that averaged 60 ppb (58-62 ppb). Although the source was not identified, some material used in the print shop along with the low ventilation rate probably contributed to this moderately elevated concentration. Two HCHO samplers at one site in a Spokane high school cafeteria averaged 192 ppb (166 ppb and 218 ppb). Samplers were redeployed at the site, plus four additional nearby sites. These samplers did not replicate the high initial value (averaging 24 ppb). Therefore, the first reading may be due to corruption of the sampler by the occupants or to a transient air quality event.

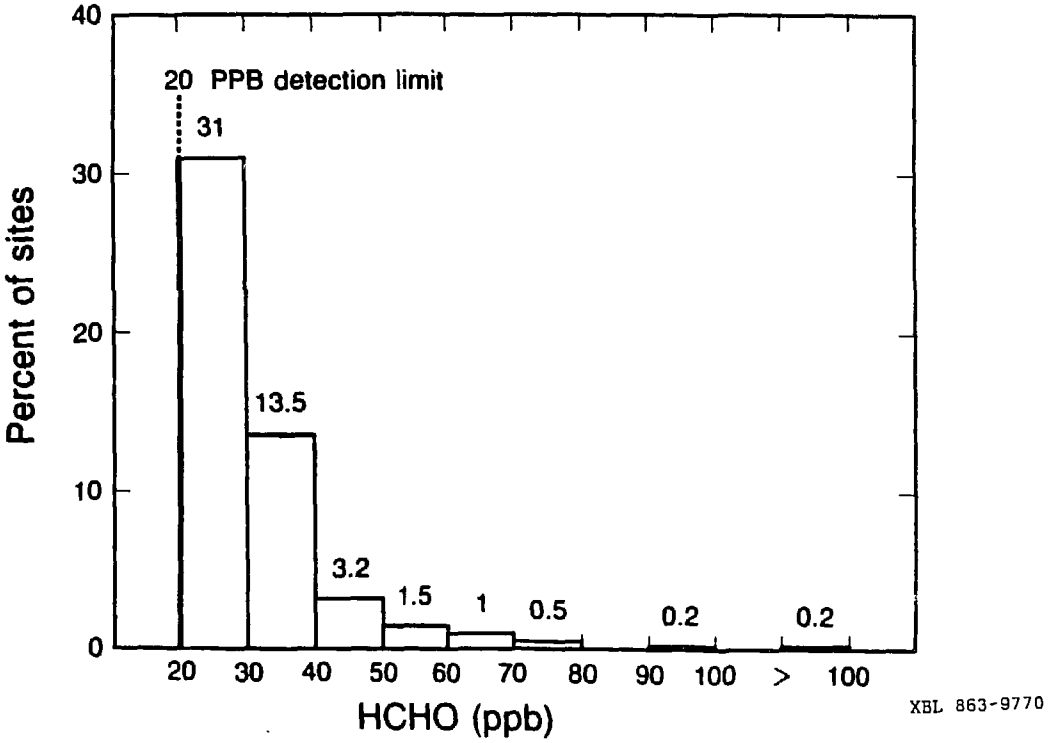

Figure 7. Frequency distribution of indoor HCHO concentrations from 407 sampling sites in 40 large building measurements. Approximately 48.9% of all sites were below the 20 ppb detection limit.

Formaldehyde concentrations were higher outdoors than the indoor average at seven of the 13 buildings where HCHO was sampled outdoors. Outdoor concentrations had a geometric mean of 21 ppb and geometric standard deviation of 1.8 ppb with nine readings higher than the detection limit. There are no corroborating data for outdoor HCHO from other air quality agencies.

Radon

Radon concentrations were generally low in 39 of the 40 building measurements with a geometric mean for all buildings of 0.8 pCi/l and a GSD of 2.1 pCi/l. Figure 8 shows that almost 8% of all 163 site measurements were above the ASHRAE guideline of approximately 2 pCi/l, while 6% were above BPA's mitigation action level of 5 pCi/l. One of these sites was at an infrequently occupied space exposed to an open soil floor and away from the main work area. The other five readings are from an office building in Cheney, WA and range from 3.3 pCi/l to 9.2 pCi/l with a building average of 7.4 pCi/l. The apparent source of this radon is a basement with a partially open soil floor that connects to a 4.8 kilometer long network of underground service tunnels that have rock block and soil walls and floors. The main air handler fan for the building is located in this basement. The fan pulls "outside" air from the basement and tunnels and distributes it throughout the building. Except for the separately ventilated auditorium (3.3 pCi/l), the other measurements are fairly uniform (7.3 - 9.2 pCi/l) regardless of height in this four-story building. Follow-up measurements during the summer were generally lower by a factor of two, but implicated the tunnels as the suspected source of indoor radon with a maximum of 26.3 pCi/l measured in one tunnel.

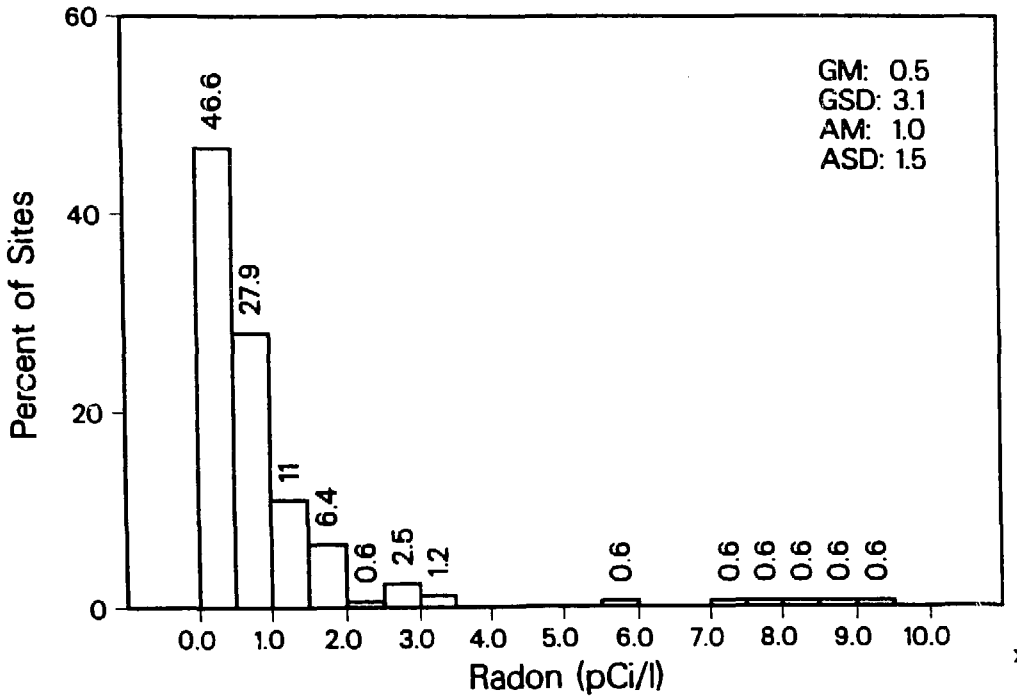

Figure 8. Frequency distribution of indoor radon concentrations from 163 sampling sites in 40 large building measurements.

The radon measurements for all sites are closely approximated by a lognormal distribution. A cumulative probability plot suggests that approximately 11% of the sampling sites taken in a similar building population would have readings above 2 pCi/l, 2.5% above 5 pCi/l, and 0.75% above the National Council on Radiation Protection Guideline (NCRP) of 8 pCi/l.[20]

Figure 9 is a compilation of radon concentrations by floor height. Values are marginally higher in the substructures that are in intimate contact with the soil than in the upper floors. However, average values are quite low at all floor heights.

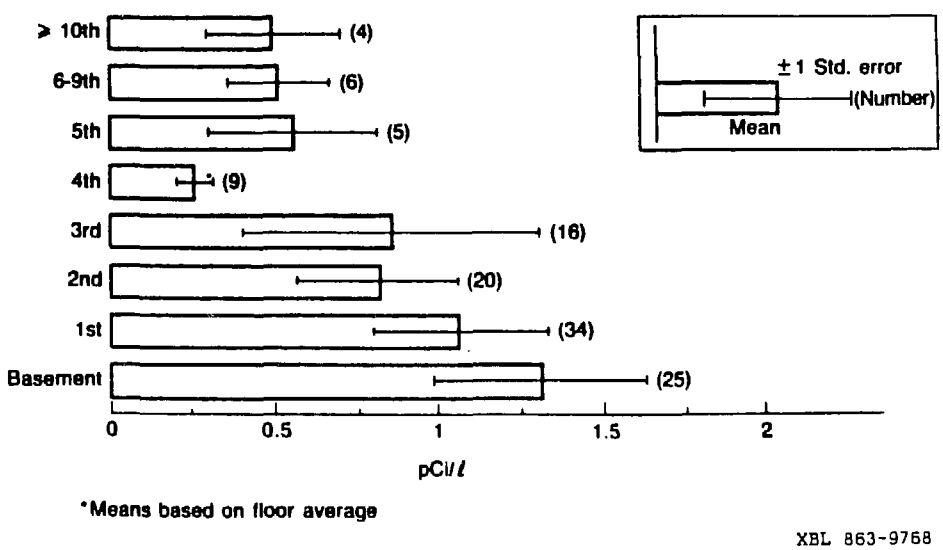

Figure 9. Radon concentrations by floor from 40 commercial building tests and 162 samples.

Ventilation

Ventilation rate measurements in all buildings average 1.5 air changes per hour (ach) with a standard deviation of 0.87 ach and a range of 0.3 to 4.1 ach. For comparison, annual average ventilation rates in nine buildings studied by Persily [21] ranged from 0.33 ach to 1.04 ach and one building studied by Silberstein[22] averaged 0.9 ach. While 75% of our measurements are below 2.0 ach and within the range of the data of the other investigators, relatively high ventilation rates occur in 10 buildings in this study. There is the possibility that in these buildings with higher ventilation rates, the system operators increased the amount of outside air during our pollutant monitoring period to minimize air quality problems. We have no way of verifying this, but in some buildings occupants commented that they believed the ventilation was increased just prior to our testing.

The calculated whole building ventilation rate per occupant averaged 28 l/s with a minimum of 4.5 l/s for an elementary school and a maximum of 84 l/s in a small (3113 m^2) office building. Net (or actively ventilated) building volumes, necessary for this calculation, were arrived at by subtracting 12% from the gross volume to account for the unventilated volume of furniture, isolated compartments, etc. While these whole building ventilation rate per occupant values generally exceed ASHRAE recommendations (only five buildings were below recommendations when smoking is present), local conditions could be much different. For example, in the school with a building average of 4.5 l/s/occupant, the local ventilation in a crowded classroom was only 1.6 l/s/occupant, below the ASHRAE recommendation of 2.5 l/s. It was the same classroom that had the highest peak CO_2 reading of the study at 1290 ppm. Therefore, whole building information regarding ventilation per occupant must be interpreted carefully.

For each instance of a low ventilation rate (<0.5 ach), the outside air dampers were completely closed during monitoring. In a Salem library with a ventilation rate of 0.3 ach, the system operators were not sure of the outside air damper location or the control mechanism. They planned to open these dampers after this situation was brought to their attention. The minimum damper settings for two other buildings, resulting in ventilation rates of 0.4 ach and 0.3 ach, were energy conservation measures to reduce the cooling load during the summer.

Local conditions of low ventilation may be contributing to the accumulation of some pollutants in a few buildings. For instance, the moderate levels of HCHO in the one basement printshop (60 ppb) may be exacerbated by the low ventilation rate of 0.2 ach, and the lower than average ventilation rate in Building #10 (0.9 ach) could be partially responsible for the high indoor-outdoor RSP ratio of 9.6 (indoor mean of 86 $\mu g/m^3$).

Whole building outside air exchange rates are plotted against building average concentrations of HCHO and RSP in Figures 10 and 11. If ventilation is the dominant mechanism in determining the pollutant levels, then the form of these log-log scatter plots would be a

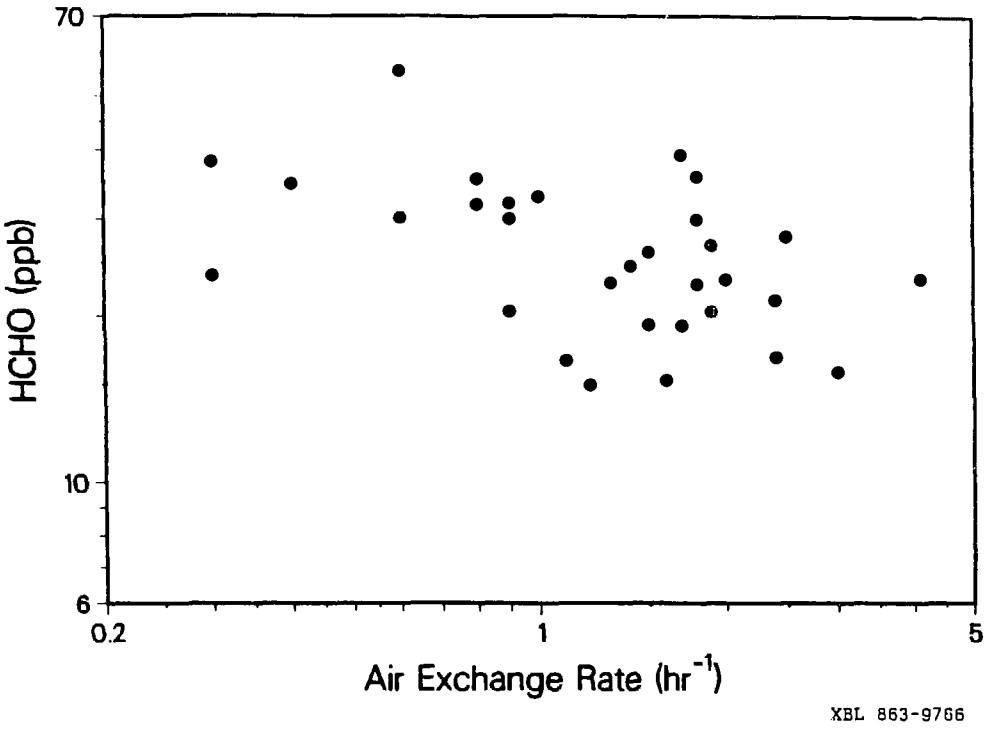

Figure 10. Scatter plot of building average HCHO concentrations (above 20 ppb detection limit) versus outside air ventilation rates from 31 building measurements.

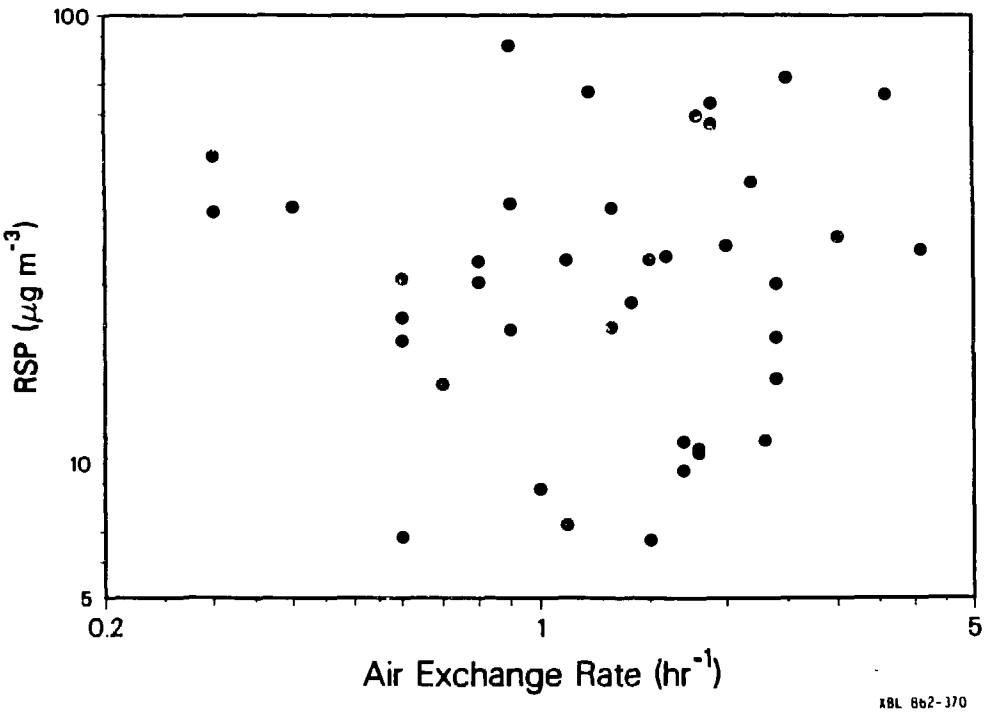

Figure 11. Scatter plot of building average RSP concentrations versus outside air ventilation rates from 40 building measurements.

cluster along a straight line of slope = -1, with the pollutant concentration proportional to the reciprocal of the ventilation rate. This correlation is poor for all pollutants. It implies that ventilation is not the most important parameter affecting observed pollutant concentrations. Rather, variations in pollutant source strength (indoors and outdoors), building volumes, and other removal processes (or a combination of these factors) apparently dominate. Other observations about this set of buildings suggested by the plots:

1. HVAC system operators in existing low ventilation rate buildings are not increasing the amount of ventilation in response to instances of moderately elevated RSP concentrations. In other words, the level of occupant discomfort and complaints regarding this pollutant is not sufficient to encourage additional ventilation.

2. Pollutant concentrations in excessively ventilated buildings are not significantly lower than in buildings with low to moderate ventilation rates.

3. Concentrations of HCHO are quite low which may also be an important factor in the poor correlation with ventilation rates.

Complaint Buildings

This study did not extensively survey occupant complaints, but most buildings had at least a few occupants that had comments or complaints about some air quality problem. They generally referred to vague, non-specific problems such as "stuffy air".

However, two buildings were monitored that had significant episodes of occupant distress most likely related to an air quality problem. One building, monitored in the spring, had the highest measured ventilation rate of the study, 4.1 ach. But several months after our monitoring, in the summer, the building operators reported an incident where several office workers collapsed over a period of several days. Apparently, studies by health authorities could not uncover the reasons for this distress and we did not return to repeat our measurements. Neither pollutant levels nor ventilation rates observed during our study could be responsible.

The other building was monitored twice and had few, if any, complaints during the first monitoring period. Prior to the second measurements period and coinciding with the onset of colder weather, a number of workers exhibited symptoms including skin rashes, red, watery, and itchy eyes, and respiratory distress. The affected individuals were found throughout the building. Public Health officials and independent consultants interviewed the afflicted, examined the HVAC system and sampled building air for various organic compounds and biogenic material. Their results were inconclusive. In addition, neither the pollutants nor ventilation rate (1.1 ach) that we measured were probable causes for the reactions observed in the workers.

SUMMARY

Pollutant concentrations as measured in this study, were generally quite low and seldom exceeded commonly recognized standards and guidelines. High water vapor concentrations may be a problem of occupant comfort at sites in six buildings, most of which were monitored during higher temperature summer months. Carbon dioxide eight-hour averages ranged from a low of 337 ppm to a high of 840 ppm with a peak 15-minute reading of 1290 ppm in one classroom. Readings rarely exceeded 800 ppm. Only 29% of the eight-hour time-weighted average carbon monoxide measurements were above the minimum detectable level of 2 ppm. The highest measurements (6 ppm - 7 ppm) were generally associated with vehicular exhaust being drawn in with outside air from underground parking garages or busy streets, except for one site that had a clearly defined indoor tobacco smoking source. Nitrogen dioxide levels at only two of 245 sites (53 ppb and 58 ppb) exceeded the EPA annual ambient air standard of 50 ppb. Most sites with elevated concentrations were exposed to outside air containing NO_2 from vehicular exhaust. Local tobacco smoking appeared to increase concentrations a small amount (2 ppb). For all pollutants, respirable suspended particle concentrations most frequently exceeded recognized conservative guidelines (for TSP at 75 $\mu g/m^3$), with occurrences usually related to local tobacco smoking. Building mean RSP ranged up to 86 $\mu g/m^3$ with one smoking site reaching 308 $\mu g/m^3$. The geometric mean of all radon site measurements was 0.5 pCi/l, similar to levels found outdoors, with only one building having concentrations of concern at 7.4 pCi/l. The one-time ventilation measurements from all buildings averaged 1.5 ach and ranged from a low of 0.2 ach to 4.1 ach. Buildings with low ventilation rates were not associated with indoor air quality problems, although local ventilation may fall below ASHRAE recommendations of 2.5 l/s/occupant in non-smoking areas and 10 l/s/occupant in smoking areas.

Correlation is very weak between pollutant concentrations and ventilation rates. This is probably a result of the low pollutant concentrations in most buildings and the fact that concentrations are probably dominated by parameters other than ventilation including pollutant generation, other removal mechanisms, and building volumes.

Almost all of the buildings had at least a few occupants that complained of some vague, non-specific air quality problem. Two of the buildings had recent indoor air quality-related episodes of fainting and allergenic sensitivities. The source of the offending agent was never conclusively identified and may have been one of the large spectrum of pollutants not sampled during this study. Generally, the indoor atmosphere in most buildings appeared to be satisfactory.

Future studies should include the monitoring of a range of volatile and semi-volatile organic compounds that may be present in relatively high concentrations in new and remodeled buildings due to the use of synthetic materials and furnishings. The response of sensitive individuals to various airborne microorganisms and biological debris suggests that monitoring of these agents should also be included.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the program assistance of R. Rothman, Bonneville Power Administration; Lawrence Berkeley Laboratory co-workers E. Saegebarth, K. Koshlap, and S. Uno for laboratory analysis and data processing, R. Prill for assistance in conducting field measurements, and S. Sampson for document preparation. We also appreciate the cooperation of the managers, owners, and occupants of the buildings involved in this study.

This work is supported by the Bonneville Power Administration under Contract No. DE-A179-83BP12921, and by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Energy Research and Development, Buildings Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

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