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Indoor Air Quality and Ventilation Measurements in 38 Pacific Northwest Commercial Buildings. Volume 1: Measurement Results and Interpretation

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Indoor Air Quality and Ventilation Measurements in 38 Pacific Northwest Commercial Buildings

Volume 1: Measurement Results and Interpretation

Final Report

B.H. Turk, J.T. Brown, K. Geisling-Sobotka, D.A. Froehlich, D.T. Grimsrud, J. Harrison, J.F. Koonce, R.J. Prill, and K.L Revzan

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INDOOR AIR QUALITY AND VENTILATION MEASUREMENTS IN 38 PACIFIC NORTHWEST COMMERCIAL BUILDINGS

FINAL REPORT TO THE BONNEVILLE POWER ADMINISTRATION

Volume 1: Measurement Results and Interpretation

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EXECUTIVE SUMMARY

Through their involvement in energy conservation programs, the Bonneville Power Administration (BPA) may make recommendations leading to reductions in ventilation rates in commercial and institutional buildings. The effects of these recommendations on indoor air quality were uncertain. Because of these uncertainties BPA initiated the survey of ventilation rates and pollutant concentrations in the stock of existing Pacific Northwest buildings described in this report.

Specific study objectives included:

1. To provide baseline information about pollutant concentrations and ventilation rates in a sample of the existing building stock. This sample should reflect conditions in large, mechanically-ventilated buildings.
2. If possible, to demonstrate relationships between indoor air pollutant levels and ventilation rates.

Thirty-eight buildings were monitored, each for a two-week period (two buildings at two separate times). Pollutants sampled included radon (Rn), formaldehyde (HCHO), respirable suspended particles (RSP), polycyclic aromatic hydrocarbons (PAH), nitrogen dioxide (NO_2), carbon monoxide (CO), carbon dioxide (CO_2), and water vapor (H_2O). This study did not measure/evaluate volatile organic compounds (other than formaldehyde) or microbiological pollutants. Average ventilation rates were measured using tracer decay techniques.

In general, measured ventilation rates were high compared to design standards and pollutant concentrations were generally quite low and seldom exceeded commonly recognized standards and guidelines.

- High water vapor concentrations may have caused problems of occupant comfort at sites in six buildings, most of which were monitored during higher temperature summer months. One site with high water vapor was associated with elevated concentrations of formaldehyde.

- Carbon dioxide eight-hour averages ranged from a low of 340 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 - 7 ppm) were generally associated with vehicular exhaust 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 exceeded the EPA ambient annual air standard of 50 ppb. Most sites with elevated concentrations were exposed to outside air containing NO_2 from vehicular exhaust. Local smoking appeared to increase concentrations a small amount (2 ppb).

- Of all pollutants monitored, respirable suspended particle (RSP) concentrations most frequently exceeded conservatively recognized guidelines, with occurrences usually related to nearby tobacco smoking. Building mean RSP concentrations ranged up to 67 $\mu g/m^3$ and one smoking site reached 308 $\mu g/m^3$. It is estimated that approximately 34% of the smoking sites in a similar sample would have RSP concentrations above the annual EPA limit of 50 $\mu g/m^3$ for suspended particles whose diameters are larger than 10 μm (a larger subset of all suspended particles than RSP). Concentrations at indoor non-smoking sites had weak correlation with both outdoor concentrations (lower than outdoor at 65% of the sites) and smoking at other locations in the building. Since localized smoking has only a small impact on RSP concentrations in non-smoking areas, processes such as dilution by building volume and removal by filtering and chemical interaction must be occurring.

- Polycyclic aromatic hydrocarbon concentrations, including benzo[a]pyrene, were positively correlated to RSP concentrations, with a maximum B[a]P concentration of 9.67 ng/m^3, considerably above the U.S. ambient urban concentration of 2 ng/m^3.

- Formaldehyde concentrations were quite low. The averages at only 21 buildings were above the 20 ppb detection limit. It is estimated that only 3% of all similarly selected sites would have concentrations above the ASHRAE 100 ppb guideline.

- The geometric mean of all radon measurements was 0.5 pCi/l, similar to levels found outdoors, with only one building having a concentration of concern at 7.8 pCi/l. The latter condition is likely due to open soil in the basement and a network of underground service tunnels allowing ready entry of the gas.

- The one-time ventilation measurements from all buildings average 1.5 ach and ranged from a low of 0.2 ach to 4.1 ach. Buildings with low ventilation rates were not usually associated with indoor air quality problems, although local ventilation, i.e., ventilation rates in specific regions or rooms, may fall below ASHRAE recommendations of 5 cfm/occupant in non-smoking areas and 20 cfm/occupant in smoking areas.

Correlation is very weak between pollutant concentrations and ventilation rates (both with outside and recirculated air). This is probably due to the fact that pollutant source strengths are more variable (between buildings) than ventilation rates. Tests for correlation are also handicapped by the difficulty in measuring local ventilation.

Whole building ventilation rate per occupant appears to be inappropriate as a measure of adequate ventilation, since unoccupied building volumes are included in the calculation. The ability to measure local ventilation is essential to understanding the appropriate ventilation to balance energy use and air quality needs.

Design ventilation rates may not correlate well with actual operating ventilation rates since the latter are dependent on proper HVAC system operation and maintenance. System operators were occasionally unfamiliar with their equipment and unable to manipulate the control system properly. Despite the fact that some of the operators were unaware of the implications of reduced ventilation, there were few observed instances of poor air quality.

The benefits of increasing outside air ventilation rates to 35 cfm/occupant throughout a building where smoking occurs may be minimized if outdoor air pollutant concentrations are higher than the non-smoking indoor concentrations, as was the case for RSP at 65% of the sampling sites.

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 allergic-like reactions. The sources of the offending agents were never conclusively identified. Generally, the indoor atmosphere in most buildings appeared to be satisfactory.

I. INTRODUCTION

In the relatively short period of time since the issue of air quality inside non-industrial structures has become a concern, most exposure studies have focused on the indoor residential environment (Spengler et al., 1985; Hawthorne et al., 1986; Sexton et al., 1986; Turk et al., 1987). Yet for employed men and women, 23-32% of their time is spent in non-residential indoor locations (NAS, 1981), including places of business, restaurants, and places of employment. The same percentage may also be appropriate for children of school age. Although the air quality in the industrial workplace may be monitored and regulated, air quality in commercial and institutional buildings (offices and education facilities) generally is not.

In 1981, the Pacific Northwest Power Planning and Conservation Act authorized the Bonneville Power Administration (BPA) to undertake cost-effective conservation programs to help meet the administration's load obligations. These program measures may include recommendations for reductions in infiltration and the mechanical ventilation rate in commercial and institutional buildings. Implementation of these measures may have an impact on indoor air quality.

The effects of inadequate ventilation may play a role in the poor air quality of complaint buildings (Kreiss and Hodgson, 1984; Morey et al. 1984; and Akimenko et al., 1986) leading to phenomena sometimes called "Sick Building Syndrome". However, little is known about pollutant concentrations and ventilation rates in ordinary, non-complaint buildings. Therefore, this survey of existing ventilation and concentrations of some pollutants in buildings in the Pacific Northwest was initiated to provide baseline information and to help answer program-related questions.

STUDY OBJECTIVES

Specific study objectives include:

1. The characterization of a variety of 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. The investigation of the relationships between observed indoor air pollutant levels and ventilation rates.

Information collected in this study will contribute directly to the development of BPA's Commercial and Institutional Conservation Program. However, it will have more general applicability as well. A recent workshop examining air quality problems in commercial buildings sponsored by the Electric Power Research Institute and the Department of Energy pointed to a major need to develop baseline information about air quality in commercial buildings (Whiddon, 1987).

The American Society of Heating, Refrigerating, and Air Conditioning Engineers is currently revising its Standard 62, Ventilation for Acceptable Air Quality. A major issue in the revision is attempting to strike a balance between needs for more ventilation to avoid air quality problems and the concern about the cost of the energy associated with increasing these flows. Little direct information about ventilation in the existing building stock is available. Information from this project has been extremely useful in preparing the revised Standard (ASHRAE, 1986).

Findings from this study indicate that for most pollutants that were monitored only a few percent of the sites monitored have concentrations exceeding recommended guidelines. The exception, respirable suspended particles (RSP), often exceed ambient air quality standards for total suspended particles (TSP) in smoking areas. Since RSP are only a subset of the total suspended particles, this is a significant observation. Ventilation rates averaged higher than those typically observed in residences and appeared to have very poor correlation to the generally low pollutant concentrations. In two buildings that had recent histories of indoor air quality complaints, ventilation rates were found to be large and measured pollutant levels were low.

REFERENCES

ASHRAE Standard 62 (1981). Ventilation for acceptable indoor air quality, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta.

ASHRAE Standard 62-1981R (1986).[Draft standard]. Ventilation for acceptable indoor air quality, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta.

Akimenko, V.V., Andersen, I., Lebowitz, M.D., Lindvall, T. (1986). The "sick" building syndrome, Indoor Air, Evaluations and Conclusions for Health Sciences and Technology, Swedish Council for Building Research, Stockholm, 87-97.

Hawthorne, A.R., Gammage, R.B., Dudney, C.S. (1986). An indoor air quality study of 40 east Tennessee homes, Environment International 12:221-239.

Kreiss, K. and Hodgson, M.J. (1984). Building - Associated Epidemics. In: Indoor Air Quality, pp. 87-106. Eds., by P.J. Walsh, C.S. Dudney, and E.D. Copenhaver, CRC Press, Boca Raton, Florida.

Morey, P.R., Hodgson, M.J., Sorenson, W.G., Kullman, G.J., Rhodes, W.W., Visvesvara, G.S. (1984). Environmental studies in moldy office buildings: Biological agents, sources, and preventive measures. Annals of the American Conference of Government Industrial Hygienists. 10:21-36.

NAS (1981). Indoor pollutants, National Research Council, Washington, DC: National Academy Press.

Sexton, K., Liu, K., Treitman, R.D., Spengler, J.D., Turner, W.A. (1986). Characterization of indoor air quality in wood-burning residences, Environment International 12:265-278.

Spengler, J.D., Treitman, R.D., Tosteson, T.D., Mage, D.T., Soczek, M.L. (1985). Personal exposures to respirable particulates and implications for air pollution epidemiology, Environ. Sci. Technol. 19:700-707.

Turk, B.H., Grimsrud, D.T., Harrison, J.T., Prill, R.J., Revzan, K.L. (1987). Pacific Northwest existing home indoor air quality survey and weatherization sensitivity study, Lawrence Berkeley Laboratory Report No. LBL-23979.

Whiddon, W.I., ed. (1987). Opportunities to improve commercial building indoor environments, Workshop Proceedings, Electric Power Research Institute, Report No. EPRI EM-5530.

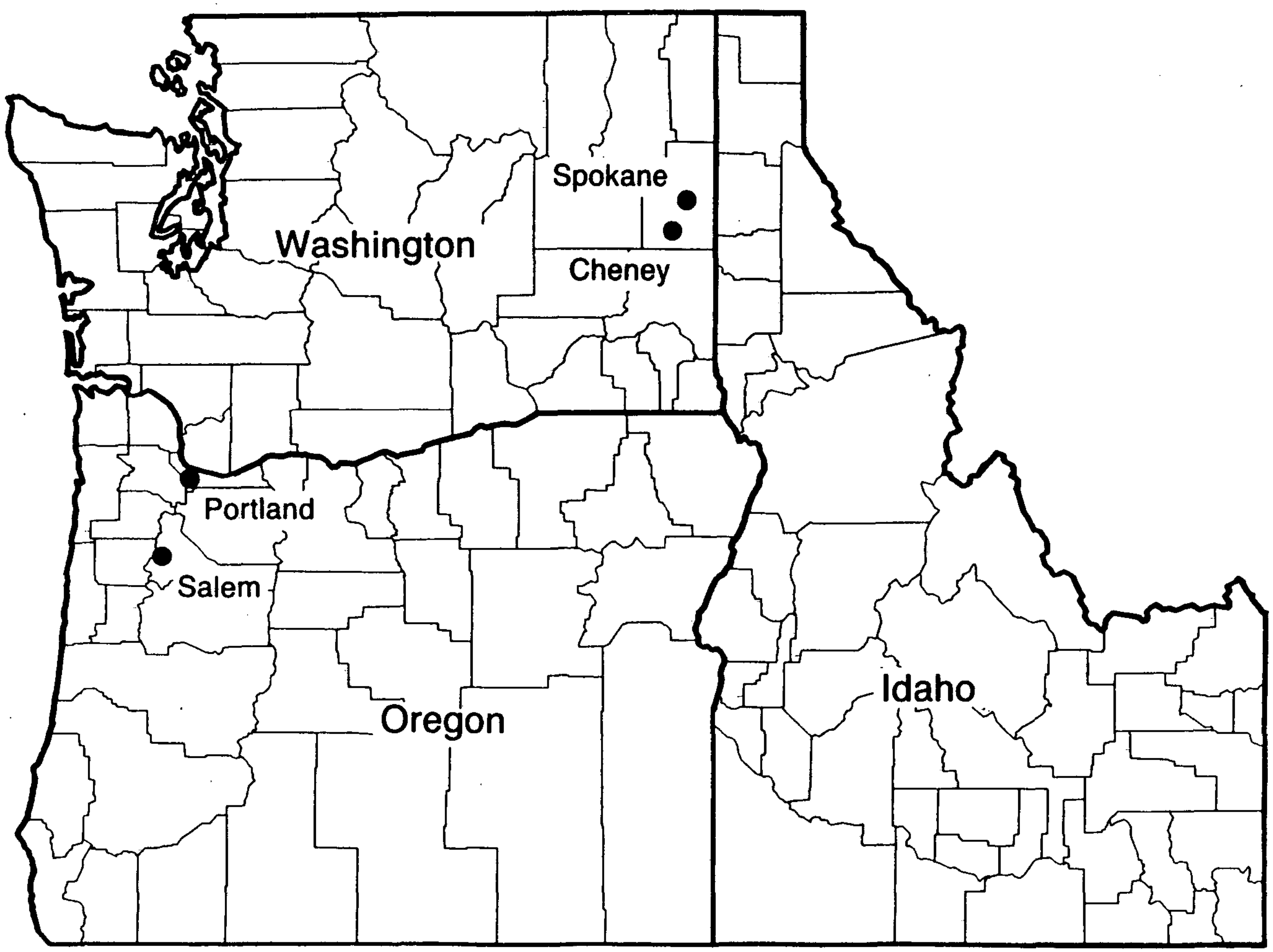
II. METHODS

A. SELECTION AND DESCRIPTION OF BUILDINGS

Thirty-eight buildings were selected for participation in this study to represent a sample of the ages, use, sizes, and ventilation of Pacific Northwest buildings. None were selected because of previous indications of air quality problems or complaints. Two of the buildings (#11 and #17) were monitored a second time under different seasonal conditions for a total of 40 building measurements. A separate section will be devoted to a discussion of the recorded differences in these two buildings. The buildings were located in 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. Figure II.A.1 is a map showing the location of the cities where buildings were monitored. A discussion of the climatological differences is found in Appendix L. 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.

BPA assumed the lead in locating the test buildings by contacting the appropriate officials or managers and inviting them to participate in the study. LBL staff then reviewed the available buildings and made selections based on: ease of access, representativeness of PNW buildings, building size, and occupancy schedule. Several of the buildings in Spokane and Cheney became involved through direct, unsolicited inquiries by LBL.

Commercial Building Study
City Locations



XBL 8512-12794

Our survey emphasized monitoring of larger structures than the average size in the overall Pacific Northwest commercial and institutional building stock. BPA was particularly interested in larger buildings with mechanical ventilation because of the likely direction to be pursued in the commercial buildings conservation programs. Commercial facilities such as restaurants and retail stores were not included in the study (except where they were part of a large office building) because most owners and managers of private buildings declined to participate, due to concern about their liability if an air quality problem were discovered. Therefore, all but four buildings were government or public properties belonging to federal, state, or local agencies. Privately owned buildings are larger in area (average 186,000 ft^2 vs. 84,000 ft^2) than the public buildings. The public buildings are devoted to activities such as education, communication, or public offices. Examples of these public office uses are courtrooms, tax offices, public health facilities, and college administration offices.

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 air handling systems were common 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.

Simple nonparametric rank statistics, Mann-Whitney and Wilcoxon tests, were used to determine that the mean floor area of the samples of office buildings chosen did not differ significantly between the two climate areas or three cities included in the study. Only office buildings were of sufficient number to make a comparison.

Table II.A.1 gives the characteristic features of each building in the sample while Table II.A.2 stratifies the sample by types of use and size versus age, occupancy, and location. All of the buildings chosen and described in Table II.A.1 except one are either located in an urban or suburban setting. Only building #5 is truly remote enough from city traffic and development to be

TABLE II.A.1
BUILDING INFORMATION

BLDG #	CITY	OWNERSHIP	DESCRIPTION	AGE YRS	SMOKING POLICY	OCCUPANCY	HEIGHT STORIES	AREA FT2	HVAC SYSTEMS	SUBSTRUCTURE
1	PORTLAND	P	SU SCHOOL	21	R	318	1	22,900	32	S
2	PORTLAND	P	SU SCHOOL	21	R	421	1	15,100	17	S
3	PORTLAND	P	SU OFFICE	30	O	35	UG	18,800	1	A
4	PORTLAND	P	SU LIBRARY	0.5	R	35	2	26,800	4	FB
5	PORTLAND	P	RU OFFICE	16	R	34	2	9,300	5	FB
6	PORTLAND	P	U OFFICE	1	O	1250	16	369,000	3	FB-UP
7	PORTLAND	P	U OFFICE	90	O	250	3	83,000	NV+1	FB
8	SALEM	P	U MULTI	20	O	150	2	52,500	2	FB
9	SALEM	P	U OFFICE	3	O	669	5	184,000	2	FB-UP
10	SALEM	P	U OFFICE	40	O	1286	5	170,000	2	FB-ST
11	SALEM	P	U OFFICE	9	R	400	4	118,000	4	FB-UP
12	SALEM	P	U LIBRARY	40	O	80	4	81,434	2	FB
13	SALEM	P	U OFFICE	30	O	175	2	72,000	3	UB
14	SALEM	P	U OFFICE	40	O	136	2.5	33,500	2	FB
15	SALEM	P	U OFFICE	22	O	750	4	185,000	2	FB
16	SPOKANE	P	SU SCHOOL	3	R	700	2	47,136	4	S
17	SPOKANE	P	SU SCHOOL	25	R	550	1	76,266	6	C
18	SPOKANE	P	U OFFICE	34	O	84	3	22,620	NV	UB
19	SPOKANE	P	U OFFICE	15	O	65	4	19,185	NV	S-UP
20	SPOKANE	P	U SCHOOL	3	R	835	3	102,000	4	FB
21	SPOKANE	P	U MULTI	8	O	150	4	46,000	2	UP
22	SPOKANE	P	U OFFICE	62	O	450	8	151,000	1	FB
23	SPOKANE	P	SU LIBRARY	8	R	25	1	12,264	2	S-BR
24	SPOKANE	P	SU OFFICE	8	O	50	1	15,552	1	S
25	SPOKANE	P	SU OFFICE	12	O	80	2	16,640	2	FB
26	SPOKANE	P	U OFFICE	18	O	550	12	225,900	7	FB
27	SPOKANE	P	U OFFICE	4	O	110	5	38,790	2	FB
28	SPOKANE	P	U MULTI	15	O	92	5	55,191	1	FB
29	SPOKANE	P	SU SCHOOL	15	R	678	3	75,000	2	FB
30	SECOND TEST OF BUILDING 17					659				
31	SPOKANE	P	SU MULTI	10	R	250	1	38,400	10	S
32	CHENEY	P	SU OFFICE	72	R	300	4	78,000	2	UB-ST
33	CHENEY	P	SU MULTI	5	O	600	3	53,338	4	S
34	SPOKANE	PR	U OFFICE	9	O	1200	15	206,686	1	FB
35	SPOKANE	PR	U OFFICE	75	O	1200	15	179,062	11	FB-UB
36	SECOND TEST OF BUILDING 11									
37	PORTLAND	P	U OFFICE	35	O	930	8	158,725	15	FB-UP
38	PORTLAND	P	U OFFICE	34	O	1100	10	165,280	23	FB
39	PORTLAND	PR	U OFFICE	8	O	1500	5	161,842	11	FB-UP
40	PORTLAND	PR	U OFFICE	8	O	2500	18	196,050	9	FB-UP

LETTER CODES:

A - ALL BELOW GRADE
BR - BERMED
C - CRAWLSPACE
FB - FINISHED BASEMENT
MULTI- MULTI-PURPOSE
NV - NATURALLY VENTILATED
O - OPEN SMOKING
P - PUBLIC
PR - PRIVATE

R - SMOKING RESTRICTED TO CERTAIN AREAS
RU - RURAL
S - SLAB ON GRADE
ST - SERVICE TUNNEL
SU - SUBURBAN
U - URBAN
UB - UNFINISHED BASEMENT
UG - UNDERGROUND
UP - UNDERGROUND PARKING

TABLE II.A.2

COMMERCIAL AND INSTITUTIONAL BUILDING CLASSIFICATION

CLASSIFICATION	PORTLAND/SALEM #	PORTLAND/SALEM AVG. OCCUP.	PORTLAND/SALEM AGE/ YRS.	SPOKANE #	SPOKANE AVG. OCCUP.	SPOKANE AGE/ YRS.	TOTALS #	TOTALS OCCUP.	TOTALS AGE/ YRS.
NATURAL VENTILATION							3	399	15-90
	1	250	90	2	75	15-34	3	399	15-90
MECHANICAL VENTILATION							35	19589	0.5-75
EDUCATIONAL:	2	370	21	4	691	3-25	6	3502	3-25
LIBRARIES:	2	58	0.5-40	1	25	8	3	140	0.5-40
OFFICE BLDGS.: >100,000 FT^2							13	13785	1-75
SINGLE SYST.	-	-	-	2	825	9-62	2	1650	9-62
MULTIPLE SYSTEM	9	1154	1-40	2	875	18-75	11	12135	1-75
OFFICE BLDGS.: <100,000 FT^2							8	920	4-72
SINGLE SYST.	1	35	30	1	50	8	2	260	8-30
MULTIPLE SYSTEM	3	115	16-40	3	163	4-72	6	835	4-72
MULTI-USE BLDGS.:							5	1242	3-20
SINGLE SYST.	-	-	-	1	92	15	1	92	15
MULTIPLE SYSTEM	1	150	20	3	333	3-15	4	1150	3-20
TOTAL	19	12019		19	7969		38	19988	0.5-90
						AVERAGE		526/BLDG.	
						PERSON-HOURS MONITORED		1,683,760	

classified as rural. Two buildings (#32 and #33) are located in a very small town but are considered suburban because of the density of building development and relative congestion of vehicles including city buses which occur in the immediate environs.

Designating building use is based on the greatest percentage of building floor space devoted to a particular activity. Schools include three elementary (#1, #2, and #16), two junior high (#17 and #29), and one high school (#20); one junior high (#17/30) was tested twice. Public office buildings are comprised primarily of office space or ancillary facilities, but the private office buildings have a large minority of their space devoted to retail outlets or banking functions especially in their lower levels.

Buildings characterized as multi-use buildings are devoted to such diverse or equally divided use types that no clear pattern of primary occupant activities emerges. Of the five multi-use buildings, three are college buildings (#28, #31, and #33) which contain offices, cafeterias, large kitchen facilities, lounges, meeting, and game rooms. The other two (#8 and #12) combine office and laboratory space.

Building ages at the time of the test period ranged from 0.5 to 90 years. Four of the buildings are over fifty years old and fourteen are less than ten years of age. The buildings built since the 1973-74 energy crisis may incorporate more efficient ventilation systems and energy conservation techniques.

Public smoking policies have become more restrictive nationally because of the growing concern over the potential health risks to non-smokers in close proximity to heavy smoking. This pattern is reflected in restricted smoking policies for some public buildings in this study; only certain areas of twelve buildings, i.e., cafeteria smoking sections and lounges are open to smokers. In many buildings, where smoking is not directly prohibited, it is discouraged in common areas. An open smoking policy describes buildings where smoking is decided on an office or work-space basis. Areas of non-smoking will be encountered throughout these buildings. Generally, an open policy in a single-agency governmental building (#38) is more restrictive (less area where smoking is permitted) than in a privately-owned office (#34) where common areas, i.e., hallways, lobbies, offices and customer waiting areas are freely open to smoking. Restricted smoking policy refers to buildings where specific areas are set aside for smoking and the bulk of the building is smoke-free. Extreme examples are most schools where smoking is only permitted in a teacher's lounge.

Occupancy is reported as the normal number of occupants who work in the building during regular open hours. These hours may extend up to twelve hours a day for buildings where flex time is allowed. In other buildings, the times are more limited. This is most pronounced in the schools where buildings fill and empty on a precise schedule. Some buildings (e.g., #39) have areas where twenty-four hour operations take place but involve only a small fraction of the total occupancy during evening and late night hours. Only building #3, housing an emergency services agency, was fully staffed around the clock. In buildings such as libraries (#4, #12, and #23) members of the public may outnumber the regular occupants. Because their numbers and the length of their stays in the building vary unpredictably, they are not included in the reported occupancy. Note that the occupancy figures used in Table II.A.1 were reported to the test team on a questionnaire. No actual daily count was made to verify the numbers.

Height in stories includes all regularly occupied levels of each building even though measurements, particularly for radon, were made in subgrade and basement levels where there may have been few, if any, persons present. Only one underground building (#3) was sampled. This building is used as a disaster-emergency communication and services control center for a large metropolitan area and is built into a hillside with only one wall exposed to the outside.

Area includes all the floor space within the building envelope including unoccupied storage spaces, finished basements, and mechanical rooms where these are an integral part of the building.

The number of heating, ventilation and cooling (HVAC) systems is a count of the ventilation units that provide outside or recirculated air (or both) regardless of their heating or cooling functions. These systems may range from small single room units (#1) to extremely large systems which serve an entire building (#34). Naturally ventilated buildings were few (#7, #18 and #19) and relatively small in size (less than 83,000 ft^2). One of these buildings (#7) has a small roof-mounted air conditioning unit for the top floor, but the remainder of the building relies on infiltration as the source of outside air.

Substructures are described because of their importance in radon gas entry. Underground parking areas are also potential sources for combustion-generated gases or particles.

B. REPRESENTATIVENESS OF STUDY BUILDING STOCK

A survey of the non-residential building stock was made in Portland, Seattle, and Tri-Cities (Richland-Pasco-Kennewick, WA) metropolitan areas between 1979 and 1981 under the auspices of the Energy Information Administration and the Bonneville Power Administration of the U.S. Department of Energy (Cameron and Windell, 1982). This three volume report (PNW Survey) contains a comprehensive compilation of data and statistics on the composition of the building stock of the Pacific Northwest. Some of the relevant statistics from that report have been extracted for comparison to the building sample covered in the present study (Tables II.B.1 - II.B.5). The results presented in the five tables indicate clearly that the sample in this study is not representative of the non-residential building stock in the Pacific Northwest. Indeed, one should not expect it to be so since the motivation for this study was to examine baseline indoor concentrations and ventilation rates in large, mechanically ventilated buildings. The differences between this study (labeled Bonneville Study) on the tables and the PNW Survey are informative.

Tables II.B.1, .2, and .4 demonstrate that the occupancy and physical size of the buildings in this study are substantially larger, particularly for office buildings. Table II.B.3 illustrates the emphasis in this study on mechanical ventilation systems; Table II.B.5 demonstrates that the buildings of this study are modestly newer than the base building stock of the region, another indication of interest in large, mechanically ventilated buildings. To reiterate, the comparison of

Tables II.B.1-.5 indicate that the samples are substantially different. Therefore, care should be taken in any attempt to extrapolate these results to the general PNW building stock.

C. MONITORING PROTOCOL

Each building was monitored for approximately ten working days over a two-week period during occupied hours. An accumulated minimum of 75 hours sampling was necessary to achieve an adequate sample for accurate quantitation of the formaldehyde passive sampler. From three to twenty inside sampling site locations were chosen (based on the size of the building) to include a distribution of various ventilation conditions, floor levels, structural configurations, occupant activities, and proximity to observed potential pollutant sources (photocopy centers, cafeterias, smoking lounges). While the initial intent was to measure overall air quality in the 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 at least one cigarette, cigar, or a pipe within a 30-foot 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 average building concentrations are not true spatial averages. Instead they are arithmetic (or geometric as indicated) means of all interior samplers. Beginning with Building 29, the number of sampling sites was specified based on structure floor area as in the following Table II.C.1. These guidelines were based on 1) a review of data from the first 28 buildings that suggested a minimum number of locations necessary to adequately represent a buildings indoor environment and 2) the amount of available test equipment and technical manpower.

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 determined. Outdoor sampling sites were located near the outside air inlet at some of the structures.

TABLE II.B.1

AVERAGE NUMBER OF OCCUPANTS
IN EACH BUILDING TYPE
BY LOCALITY

PNW SURVEY

	PORTLAND	SEATTLE	TRI-CITIES[1]
EDUCATION	23	14	17
OFFICES	46	68	32
OTHER	24	27	27

(1) RICHLAND-PASCO-KENNEWICK

BONNEVILLE STUDY

	PORTLAND	SALEM	SPOKANE
EDUCATION (Includes students)	370	N/A	684
OFFICES	950	545	476
MULTIUSE[2]	N/A	150	273
OTHER	35	80	25

(2) BUILDINGS WITH NO SINGLE PREDOMINANT USE - USUALLY COLLEGE STUDENT UNION BUILDINGS

TABLE II.B.2

PERTINENT BUILDING CHARACTERISTICS
(MEAN SQUARE FOOTAGE)

PNW SURVEY

	PORTLAND	SEATTLE	TRI-CITIES(1)
EDUCATION	33,700	22,000	23,000
OFFICE	12,500	22,000	13,000
OTHER	15,000	24,800	13,400

(1) RICHLAND-PASCO-KENNEWICK

BONNEVILLE STUDY

	PORTLAND	SALEM	SPOKANE-CHENEY
EDUCATION	19,000	N/A	75,100
OFFICE	145,000	127,000	95,300
MULTIUSE(2)	N/A	52,500	48,200
OTHER	26,800	81,500	12,300

(2) BUILDINGS WITH NO SINGLE PREDOMINANT USE - USUALLY COLLEGE STUDENT UNION BUILDINGS

TABLE II.B.3

NUMBER OF HVAC AIR HANDLERS PER BUILDING
BPA VS. PNW SURVEY

Number Air Handlers	Bonneville Study: Number Buildings	% All Buildings	% With Air Handlers	PNW Survey: Portland(%)	Tricities(%)
0	2	5	-	50[1]	30[1]
1	6	16	17	22	25
2	12	32	33	6	18
3	2	5	6	11	8
4	5	13	14	2	9
5	1	3	3	2	1
6-10	4	11	11	4	6
11-20	4	11	11	1	3
> 20	2	5	6		
	38				

(1) Percent of all buildings

TABLE II.B.4

PERTINENT BUILDING CHARACTERISTICS
FLOOR AREA SIZE DISTRIBUTION

PNW SURVEY

FT^2 x 1000	PORTLAND	SEATTLE	TRI-CITIES(1)
5-10	4119	2105	375
10-25	3575	2448	259
25-50	1828	745	83
50-100	737	392	80
>100	324	251	8
	10,583	5,941	805

(1) RICHLAND-PASCO-KENNEWICK

BONNEVILLE STUDY

	PORTLAND	SALEM	SPOKANE-CHENEY
5-10	1	N/A	N/A
10-25	3	N/A	5
25-50	1	1	4
50-100	1	3	5 [1]
>100	5	4 [1]	5
	11	8 [1]	19 [1]

[ ] INDICATES BUILDING TESTED TWICE

TABLE II.B.5

BUILDING AGES
(MEAN YEARS)

PNW SURVEY

	PORTLAND	SEATTLE	TRI-CITIES[1]
EDUCATION	38	41	25
OFFICE	30	38	24
OTHER	32	36	29

(1) RICHLAND-PASCO-KENNEWICK

BONNEVILLE STUDY

	PORTLAND	SALEM	SPOKANE
EDUCATION	21	N/A	11
OFFICE	28	24	28
MULTIUSE[2]	N/A	20	9.5
OTHER	0.5	40	8

(2) BUILDINGS WITH NO SINGLE PREDOMINANT USE - USUALLY COLLEGE STUDENT UNION BUILDINGS

Table II.C.1

Guidelines for Minimum Number of Interior Sampling Sites

Buildings 29 - 40

Building Size (ft^2)	Passive Monitoring Sites	Respirable Suspended Particle Sites
<15,000	4	4
15,000-30,000	6	4
30,000-60,000	9	5
60,000-120,000	12	6
120,000-180,000	15	7
180,000-240,000	18	8
>240,000	21	8

Radon Passive Monitors: 1 each in basement

1 on each floor above the basement monitored for other pollutants

In the two repeat building tests, the sampling sites were, where possible, exactly the same for both tests.

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. Depending on the size and complexity of the building, initial installation and set-up of equipment and samplers required two technicians from four to eight hours to complete.

In addition, data were collected on building age, construction, materials, occupancy, tobacco smoking policies, activities, and occupants' complaints.

C.1 Pollutant Monitoring

Table II.C.2 summarizes the pollutants sampled during monitoring. Pollutant passive samplers manufactured and analyzed at LBL included nitrogen dioxide (NO_2), formaldehyde (HCHO), and water vapor (H_2O). These devices sample air by establishing a pollutant-selective concentration gradient within a tube of known dimensions capped at one end (Palmes et al., 1976; Geisling et al., 1982; Girman et al., 1986). The pollutant is collected on a sorbent at the capped end. The tubes were originally developed to sample continuously for a seven-day period and upon analysis provide a measure of the average pollutant concentration. This traditional method of continuous exposure 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. Laboratory experiments on formaldehyde passive samplers at LBL indicate that this method of intermittent sampling has no significant effect on the accuracy of concentration measurements (Appendix A). Thus, the passive sampler data represent time-weighted average pollutant concentrations for hours when the buildings were occupied and ventilated. All of Building #3 and various departments and sections within other buildings were occupied 24 hours a day. At these locations, passive samplers were continuously open for 75-100 hours. At all monitoring sites, an aluminum deployment rack, similar to the one in Figure II.C.1, was placed in a representative location to sample air in the breathing zone (approximately four to six feet above the floor). Passive samplers for HCHO, H_2O, and NO_2 were included at outdoor sampling sites beginning with Building #26. This location varied from below street level to rooftop depending on building design. The quality of preparation and analysis of passive samplers was evaluated annually during an in-house audit and simultaneous exposure experiment.

TABLE II.C.2

Air Sampling Instrumentation and Analytical Techniques

Pollutant	Sampling Device	Analytical Technique
HCHO	LBL Passive Sampler[1]	Spectrophotometric[2]
H_2O	LBL Passive Sampler[3]	Gravimetric
Rn	Terradex Corp. Type SF Track Etch Sampler	Count number of tracks on alpha-sensitive film, performed by Terradex Corp.
NO_2	Palmes' Passive Sampler[4]	Spectrophotometric
RSP	LBL Flow-Controlled Filtration Device with 3μ cut-point cyclone[9,10,11]	Gravimetric
PAH's	Same as RSP	HPLC[5], 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[6,7]
Multiple Perfluorocarbons	Source: Permeation Tubes Sampler: Passive Adsorption Tubes	Brookhaven National Lab. AIM System. Thermal Desorption and ECD/GC Analysis[8]

REFERENCES FOR TABLE II.C.2

1. Geisling, K.L., M.K. Tashima, J.R. Girman, R.R. Miksch, and S.M. Rappaport. (1982). A passive sampling device for determining formaldehyde in indoor air, *Environ. Int.*, 8, 153-158.

2. National Institute of Occupational Safety and Health. (1977). NIOSH Manual of Analytical Methods, 2nd ed., NIOSH 77-157A, Cincinnati, OH.

3. Girman, J.R., J.R. Allen, and A.Y. Lee. (1984). A passive sampler for water vapor, *Environ. Int.* 12:361-465.

4. Palmes, E.D., A.F. Gunninson, J. DiMattio, and C. Tomezyk. (1976). Personal sampler for NO_2, *Am. Ind. Hyg. Assoc. J,* 37:570-577.

5. May, W.E., S.N. Chesler, H.S. Hertz, and S.A. Wise. (1982). Analytical standards and methods for determination of polynuclear aromatic hydrocarbons in environmental samples, *Int. J. Environ. Anal. Chem.*, 12:259-275.

6. American Society for Testing and Materials. (1983). 1983 Annual Book of ASTM Standards, Section 4, Philadelphia, PA.

7. Grot, R.A., C.M. Hunt, and D.T. Harrje. (1980). Automated Air Infiltration Measurements in Large Buildings, AIC Conference on Instrumentation and Measuring Techniques, Windsor, England.

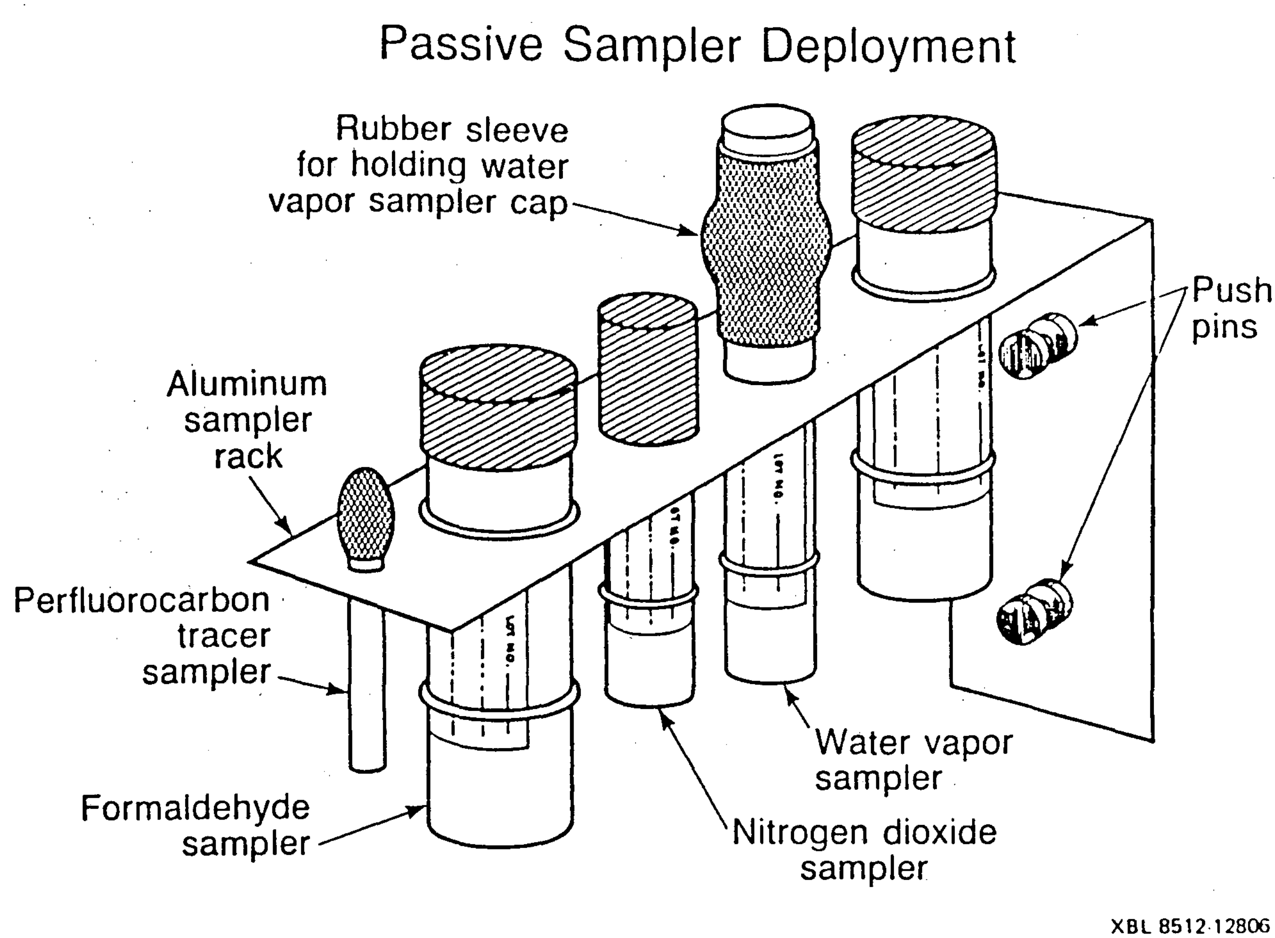
8. Dietz, R.N., E.A. Cote. (1982). Air Infiltration Measurements in a Home Using a Convenient Perfluorocarbon Tracer Technique, *Environ. Int.*, Vol. 8:419-433.

9. Ayre, H.E., Sutton, G.W., Davis, I.H.(1967). Report on size-selective gravimetric sampling in foundaries, Bureau of Occupational Safety and Health, U.S. Public Health Service, Cincinnati, Ohio.

10. Caplan, K.J., Doemeng, L.J., Sorenson, S.D.(1977). Performance characteristics of the 10mm cyclone respirable mass sampler: Part II-- coal dust studies, *Am. Ind. Hyg. Assoc. J.* 38:83-95.

11. Turner, W.A., Spengler, J.D., Dockery, D.W., Colome, S.D.(1979). Design and performance of a reliable personal monitoring system for respirable particulates, *APCA Journal* 29:747-749.

Figure II.C.1


Passive Sampler Deployment
Rubber sleeve for holding water vapor sampler cap
Aluminum sampler rack
Perfluorocarbon tracer sampler
Formaldehyde sampler
Nitrogen dioxide sampler
Water vapor sampler
Push pins
XBL 8512-12806

Radon (^{222}Rn) was monitored passively, for 2-1/2 to 4 months, using Terradex Type SF TrackEtch® monitors. Fewer radon monitors were deployed; they were frequently placed separately from the other sampling devices. Protocol required placing two radon monitors in each basement for Buildings #1 through #28 (one in each basement for Building tests #29 through 40) and one on each floor above the basement that was monitored for other pollutants. 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. (Ayre et al., 1967; Caplan et al., 1977; Turner et al., 1979) The flow rate of sample air through the system was maintained at 1.7 LPM independent of filter particle loading up to 50" W.C. pressure drop. Using a standard reference rotameter, flow rates were checked and adjusted twice a day during the technician visits. Air flow through the filters continued during occupied hours and was stopped when the building was vacated. Calculated volumes of the sampled air were compared with a dry test meter installed in-line with the filter. If particle loading was sufficient to reduce the system air flow (as occurred in some tobacco smoking areas), the filters were removed and a new filter was installed. The combined weight of particles on all filters from a site was used in determining the average RSP concentration. Filters were prepared and weighed at LBL for buildings #1 through #19. Filters for Buildings #20 through #40 were prepared and analyzed by McKesson Environmental Laboratories.

Typically, two or three buildings were monitored concurrently which meant that only 5 to 12 RSP sampling systems were available for each building. Therefore, not all sites with passive samplers were accompanied by an RSP system. Site selection was intended to represent common building environments. In buildings with a restrictive smoking policy (Table II.A.1), an RSP sampling system was placed in the major smoking area, usually a cafeteria or designated lounge space. Starting with Building #4, outdoor samples of RSP were collected at sites near the buildings.

During the course of laboratory experimentation and field testing of filters, it was discovered that filter loading could be extended by reversing the filter orientation with respect to airflow. The filter used in this study initially was a Millipore one micron cellulose acetate membrane. Beginning with buildings 8, 9, and 10, we used Zefluor filters. When placed in the "correct" orientation, the filters would load with up to 1000 μg of particulate matter before air flow occlusion. By orienting filters so that the 60 micron backing acted as a pre-filter, particulate loads of 1000 μg to 2500 μg were achieved prior to a drop in airflow rate.

Starting with Building #8, selected RSP filters were analyzed for up to 16 polycyclic aromatic hydrocarbons (PAH) including benzo(a)pyrene (B[a]P) (see Table II.C.3).

TABLE II.C.3

POLYCYCLIC AROMATIC HYDROCARBONS

Measured In This Project

Naphthalene	Benz[a]anthracene
Acenaphthylene	Chrysene
Acenaphthene	Benzo[b]fluoranthene
Fluorene	Benzo[k]fluoranthene
Phenanthrene	Benzo[a]pyrene
Anthracene	Dibenz[a,h]anthracene
Fluoranthene	Benzo[g,h,i]perylene
Pyrene	Indeno[1,2,3 - cd]pyrene

McKesson Environmental Laboratories performed the analysis by solvent extraction followed by high performance liquid chromatography (May et al., 1982). Initially, this organic analysis was performed on all filters. Later in the study, only those filter samples meeting one of the following criteria were selected for analysis of all 16 PAH:

1. particle loading greater than 400 μg
2. sample of air from outdoors
3. at least one indoor sample per building regardless of weight.

Analysis for only B[a]P was made on filters whose particle loading was greater than 100 μg and less than 400 μg. All other filters received only gravimetric analysis. Data from a spiked-sample experiment indicates that the nine lower molecular weight PAH which were included in the original analysis are poorly retained on teflon filters. Therefore, a spiked-sample evaluation of the analytical system was conducted and, as a result, only the seven higher molecular weight PAH are summarized and reported here. See Appendix B.

Carbon dioxide (CO_2) was measured with a portable Horiba continuous non-dispersive infrared analyzer. Time permitting, walk-through spot checks of CO_2 were made. The analyzer was then set up for continuous eight-hour monitoring 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 the building maximum. Time averages were calculated from the data logged on a chart recorder, which ran continuously for eight hours, by taking the arithmetic mean of the readings made at 15-minute intervals during the day. The instantaneous maximum and minimum values from the set of 15-minute interval readings were also recorded. Therefore, the CO_2 data usually represent only a one-day average concentration at a single location. Calibration using CO_2-free air, 201 ppm, 505 ppm, and 995 ppm CO_2 calibration gases was conducted immediately prior to and at the conclusion of the eight-hour monitoring period.

Carbon monoxide (CO) was sampled using constant-flow peristaltic pumps to fill Tedlar sample bags. Up to seven locations in each building, corresponding to passive sampler sites, were sampled for one 7- to 10-hour day. One outdoor location at each of 12 buildings was also monitored. CO data are one-day time-weighted averages and do not indicate transient peaks. The contents of the bags were analyzed using a portable General Electric electrochemical analyzer usually within 24 hours and always within five days of their collection. The instrument was calibrated with CO-free air and 20 ppm CO calibration gas prior to each analysis. Only concentrations above 2 ppm were reliably quantitated. A test evaluating CO sample stability in the Tedlar bags is briefly described in Appendix C.

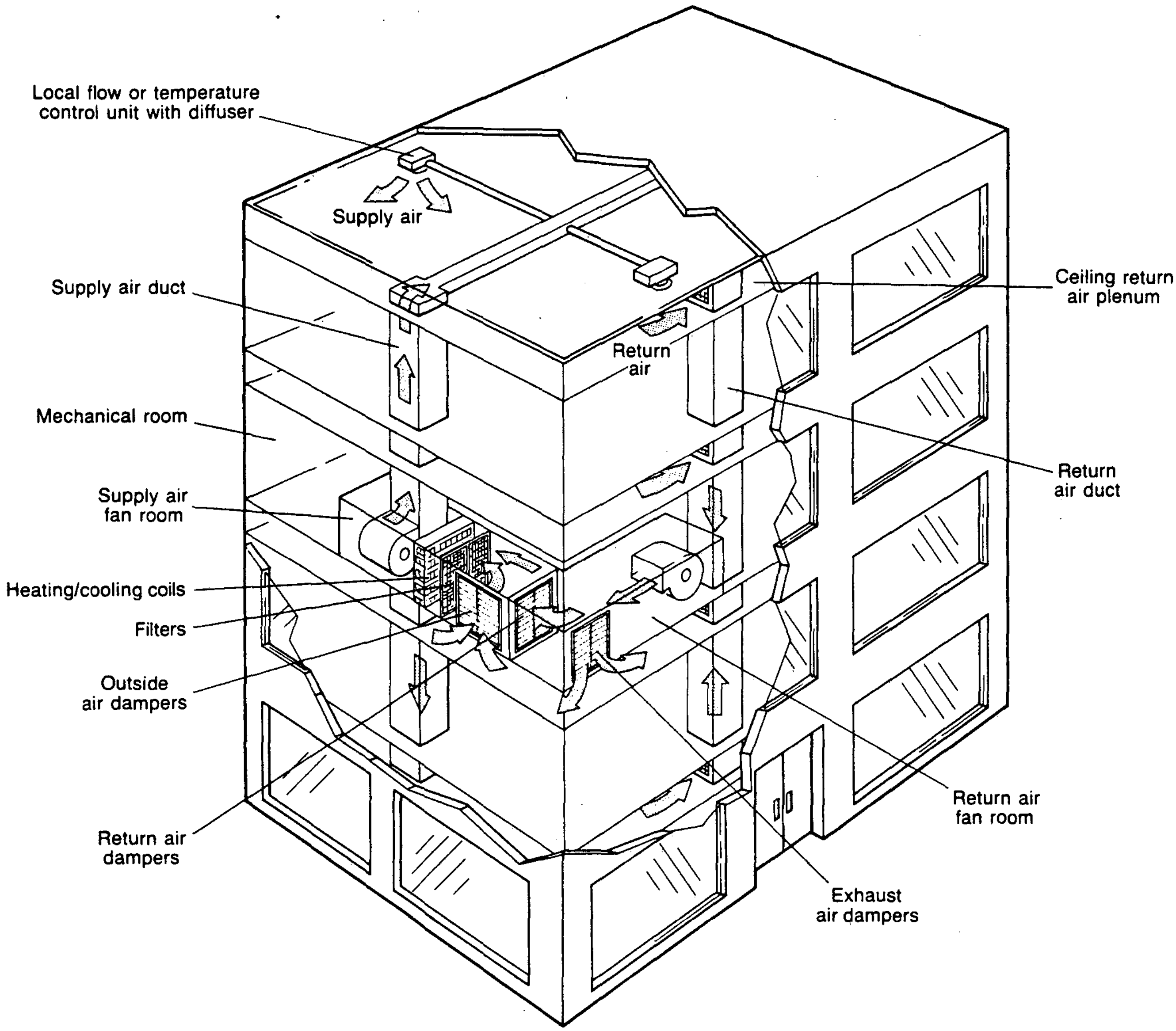
C.2 Ventilation Measurements

Although no two buildings in the 38 building study had identical ventilation systems, Figure II.C.2 depicts a generic system that incorporates the most commonly utilized designs and components. In general terms, a ventilation system is comprised of a fan that pulls stale (return) air from the building, a portion of which is exhausted through dampers to the outside. The remainder of this return air is recirculated, passing through dampers to a chamber (the mixed air chamber) where it is mixed with a certain amount of fresh (outside) air that is drawn in through dampers from the outside. This mixed air is then filtered and conditioned (heated, cooled, humidified, dehumidified) as needed by a set(s) of coils. At this point, another fan forces this mixed and conditioned (supply) air via ductwork throughout the building. In modern systems, modules at the terminus of the ductwork may provide additional local cooling/heating, or regulate the amount of supply air, or both. Most ventilation guidelines (e.g., ASHRAE 62-1981) specify the amount of outside air that must be provided to support a comfortable and healthful environment. (ASHRAE, 1981)

Tracer gas dilution was used to quantify the amount of outside air entering the building. This technique applied sulfur hexafluoride (SF_6) in a single tracer dilution and decay measurement for all buildings. The protocol was similar to the procedures described in ASTM E741-83 (1983) and used by Persily and Grot (1985), and others for estimating outside air infiltration rates. However, since all but three buildings (#7, 18, 19) in this study were mechanically ventilated, some procedural modifications were necessary.

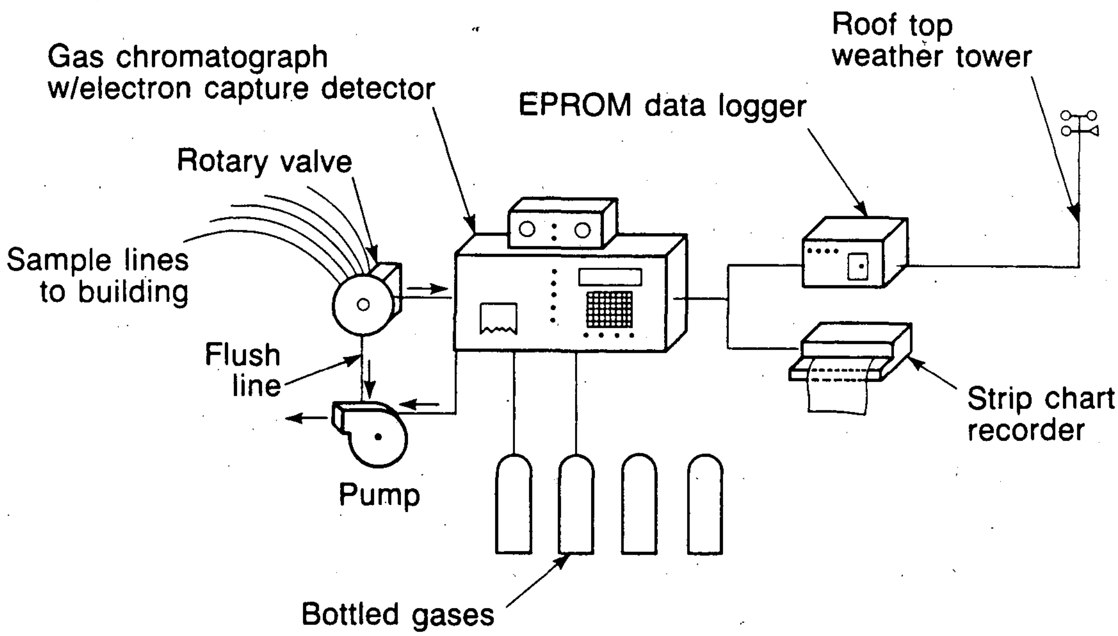
Figure II.C.3 illustrates the basic instrumentation of the system. A gas chromatograph (GC) with an electron capture detector (ECD) was placed at a central position building location. Small diameter (1/16" ID) polyethylene tube sample lines were run to three to nine locations that, when practical, coincided with pollutant sampling sites. To introduce SF_6 into the building, the outside air dampers were closed while the air handling system continued to recirculate inside air. A known amount of SF_6 was slowly metered (0.25 LPM to 6 LPM) into each of the mixed air chamber(s) and distributed throughout the building by the supply fan to achieve a building target concentration of approximately 1000 ppb.

Typical Commercial Building Air Handling System



XBL 8512-12793

Single Tracer Ventilation Measurement Apparatus



XBL 851-6945A

Pure SF_6 was added to the air in small buildings to achieve a target concentrations using large syringes or bags. Larger buildings required the use of mechanical flow control devices attached to pressurized cylinders of SF_6 to provide a sustained, controlled flow of relatively large volumes of SF_6 (up to 140 liters). The ventilation systems were operated at 100% recirculation for from 30 to 90 minutes after tracer gas injection to achieve admixing. In buildings that had little or no mechanical ventilation, windows were closed while the pure SF_6 was manually distributed through the interior space. Good mixing of the SF_6 was assumed when concentrations at the sampling sites in the building were within 10% of one another. Unfortunately, in buildings with more than two mechanical ventilation systems, the SF_6 injection system was inadequate to achieve and maintain uniform mixing easily. Once the space was determined to be well-mixed, the outside air dampers were opened to a position that was typical of conditions during the pollutant monitoring period (during the monitoring period, technicians had recorded the outside air damper positions twice daily). Building air was then pulled by a pump through the sample tubes to the GC/ECD where a valve under microprocessor control sequentially selected sampling sites at one minute intervals. As the outside air diluted the SF_6 in the building, the GC/ECD analyzed samples containing constantly declining concentrations and output data to the chart recorder as a series of successively smaller chromatographic peaks. The measurement was continued until one of the following conditions were met:

1. Concentrations fell by two orders of magnitude

   or

2. Two hours of successful data collection

   or

3. Twelve consecutive sampling cycles.

The GC/ECD was calibrated on-site before and after the decay measurement using SF_6 calibration gases of 49.5 ppb, 515 ppb, and 1000 ppb to verify instrument linearity over the range of detector sensitivities used during the test. From start to finish, each decay measurement took 9 to 14 hours by a team of at least three researchers. Meteorological data was collected from the nearest National Weather Service location for the periods of all ventilation measurements (Appendix D). These measurements were usually performed when the building was unoccupied because of the disruption due to the tubing and instrumentation and thermal discomfort caused by manipulation of the air handling equipment. Sampling was conducted in as many different ventilation system zones as possible, although limitations on the elapsed sampling cycle time restricted the number of locations to nine. Since the number of ventilation systems ranged from none to 32, it was not possible to monitor all systems in some buildings. Supply and return air tracer concentrations were sampled in 14 buildings to give an indication of the outside air/return air flow ratio.

The time series of data generated during the measurements was then graphed as a log-linear plot and a least squares regression line was computed (Appendix E). The governing relationship is:

$$C(t) = C_o \exp(-It) \qquad [2.1]$$

or

$$I = (1/t) \ln (C_o/C(t)), \qquad [2.2]$$

where: I = air exchange rate (hr^{-1})

t = time (hr)

C_o = initial concentration (peak height-mm)

$C(t)$ = concentration at time t (peak height-mm)

Chromatographic peak heights were substituted for concentration and the air exchange rates (I) were determined as the slope of best fit line.

The quality of fit of the line to data was estimated by determining the 90% confidence interval for each line. However, in most cases, the variations in ventilation rate caused by HVAC system sensors and controllers during the decay measurement period assured that this statistic was a poor estimator of the quality of our measurement.

Other researchers, Grimsrud et al., (1980), Shaw (1984), and Blomqvist and Sandberg(1985), have shown that a measurement error of ~ 10-20% can be expected when using SF_6 in the dilution (decay) technique. Sources of this error include the degree to which zones are compartmentalized and the thoroughness of tracer mixing between these zones, and the measurement of time and concentration. In this study, our inability to achieve good mixing in some buildings was probably the main factor contributing to errors in the ventilation rate measurement.

REFERENCES

ASHRAE Standard 62(1981). Ventilation for acceptable indoor air quality, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta.

American Society for Testing and Materials (1983). 1983 Annual Book of ASTM Standards, Section 4, Philadelphia, PA.

Ayre, H.E., Sutton, G.W., Davis, I.H.(1967). Report on size-selective gravimetric sampling in foundaries, Bureau of Occupational Safety and Health, U.S. Public Health Service, Cincinnati, Ohio.

Blomqvist, C., Sandberg, M.(1985). Determination of the total ventilation flow rate in buildings by tracer gas technique -- a quantitative estimate of the accuracy, Building and Environment 20:139-150.

Cameron, L.A. and Windell, P.A., (1981). Documentation of the Pacific Northwest Nonresidential Buildings Feasibility Survey, Vol I. U.S. Department of Energy EI-78-C-01-6367.

Caplan, K.J., Doemeng, L.J., Sorenson, S.D.(1977). Performance characteristics of the 10mm cyclone respirable mass sampler: Part II-- coal dust studies, Amer. Indust. Hyg. Assoc. J. 38:83-95.

Geisling, K.L., Tashima, M.K., Girman, J.R., Miksch, R.R., Rappaport, S.M.(1982). Environment International 8:153-158.

Girman, J.R., Allen, J.R., Lee, A.Y.(1986). A passive sampler for water vapor, Environment International 12:461-465.

Grimsrud, D.T., Sherman, M.H., Janssen, J.E., Pearman, A.N., Harrje, D.T.(1980). An intercomparison of tracer gases used for air infiltration measurements, ASHRAE Trans. 86:258-267.

May, W.E., Chesler, S.N., Hertz, H.S., Wise, S.A.(1982). Analytical standards and methods for determination of polynuclear aromatic hydrocarbons in environmental samples, Int. J. Environ. Anal. Chem. 12:259-275.

Palmes, E.D., Gunnison, A.F., DiMattio, J., Tomczyk, C.(1976). Personal sampler for nitrogen dioxide, Am. Ind. Hyg. Assoc. J. 37:570-577.

Persily, A.K., Grot,R.A.(1985). Ventilation measurements in large office buildings, ASHRAE Trans 91(2A):488-502.

Shaw, C.Y.(1984). The effect of tracer gas on the accuracy of air-change measurements in buildings, ASHRAE Trans. 90(I):

Turner, W.A., Spengler, J.D., Dockery, D.W., Colome, S.D.(1979). Design and performance of a reliable personal monitoring system for respirable particulates, APCA Journal 29:747-749.

III. POLLUTANT MEASUREMENT RESULTS

Measurement results of pollutant concentrations are presented in this chapter; the ventilation values are presented and discussed in chapter IV. Data from both are summarized for each building in Appendix F. Values for each pollutant are presented as a building average, the range of individual values seen in each building, and an outdoor value at the site, if available. It is important to note that pollutant concentrations at individual sites are a better indicator of personal exposure than are building-wide averages. However, building averages are necessary to obtain information about the baseline concentrations in a particular stock of buildings, such as the large, mechanically-ventilated buildings of this study.

A. POLLUTANTS

The following section discusses each pollutant monitored in some detail. For comparison, Table III.A summarizes the most commonly referenced guidelines and standards of various organizations and agencies. Many were established for industrial occupational environments while some are for regulated outdoor levels. The comparisons are not always exact, for example in the case of RSP, where only levels for TSP and PM_{10} are promulgated. Although concentrations of pollutants measured in this study are generally low, total personal exposure for certain individuals could be elevated when residential, transportation, and outside exposures are included. Little information is available on the long-term health effects of the low concentrations of the pollutants measured in this study.

B. WATER VAPOR (H_2O)

Water vapor (H_2O) is a normal and variable constituent of the atmosphere which is usually reported by meteorologists in terms of the relative humidity. However, relative humidity depends on the temperature of the air. Therefore, we have chosen to measure a more fundamental quantity, the humidity ratio, i.e., grams of water per kg of dry air. For reference, at 21°C, a water vapor concentration of 6.5 g/kg corresponds to a relative humidity of 42%.

TABLE III.A

AIR QUALITY AND VENTILATION

GUIDELINES AND STANDARDS

	Formaldehyde	Water Vapor	Nitrogen Dioxide	Radon	Carbon Dioxide	Carbon Monoxide	Respirable Particles	Ventilation	
	Parts per billion parts of air (ppb)	Grams per kilogram of air (g/kg)	Parts per billion parts of air (ppb)	picoCuries per liter of air ($pCil^{-1}$)	Parts per million parts of air (ppm)	Parts per million parts of air (ppm)	Micrograms per cubic meter of air (μgm^{-3})	Cubic feet per min. of outside air per occupant (cfm/occ.)	
								smoking	non-smoking
Occupational Safety & Health	3000	--	5000 (ceiling)	--	5000	50	--	--	--
NAAQS	--	--	50 annual average	--	--	35 (one-hr avg.) 9 (eight-hr avg.)	Total suspended particles 75/year or or 260 per 24 hrs. PM^{10}: 50/year or 150 per 24 h	--	--
ASHRAE Guidelines	100 (ceiling)	--	same as NAAQS	~2	2500	same as NAAQS	same as NAAQS	20[a]	5[a]
California	In - 50 Out - 100 proposed	--	250 one-hour	--	--	--	--	--	--
National Council on Radiation Protection	--	--	--	~8	--	--	--	--	--
BPA Mitigation Action Level	same as ASHRAE	--	--	5	--	--	--	--	--

(a) For a "typical" public or classroom space - see Appendix K.

In this report, indoor RH are often presented parenthetically. Since building temperatures were not monitored, the conversion is made assuming a constant 68°F during the winter and 75° in the summer when H_2O was being sampled.

Outside humidity ratios have not been converted to relative humidity (RH) because outdoor temperatures were not measured on-site and distant monitoring sites were probably not representative.

Relative humidity or vapor pressure is used frequently in human comfort indices, since moisture in the air affects the rate of heat loss from the human body (Givoni, 1976). Because it is a gas that is a normal constituent of the air, both indoors and outdoors, H_2O is not usually considered to be a pollutant. However, high H_2O levels may permit the growth and maintenance of organisms such as fungi, bacteria, and mites, which are known to cause either allergic or pathologic reactions in susceptible segments of the population. The presence of these biologically derived airborne pollutants was not measured in this study.

Water vapor also interacts with other pollutants: for example, through its involvement in the mechanism of HCHO release from construction materials (Meyer and Hermanns, 1985; Fisk et. al., 1984). Formaldehyde release from wood products incorporating urea-formaldehyde resins has been shown to increase due to higher air humidities. Section I discusses the HCHO concentrations measured in this study.

Primary indoor sources of H_2O include human respiration and evaporation, deliberate humidification or dehumidification (air conditioning), and processes evolving water or steam (kitchens, public showers, etc.). Combustion is a very small contributor in mechanically ventilated buildings since waste gases are typically vented to the outdoors. Outside air H_2O concentrations are probably the greatest contributing factor where a constant humidity is not maintained by the HVAC system.

Results

A total of 398 H_2O passive samplers were analyzed from the 40 building measurement sets. At least one passive sampler was installed at each site in all buildings. The histograms of building average and site water vapor concentrations are shown in Figures III.B.1 - III.B.2. The results from the indoor samplers ranged from the lowest building average of 3.2 g/kg (22% RH) in Building #29 to a high of 9.8 g/kg (57% RH) in Building #25. The arithmetic average value for all buildings was 6.4 g/kg with a standard deviation of 1.6 g/kg. At thirteen buildings, H_2O samplers were attached to the outside monitoring station. Outside humidity measurements ranged from a low of 2.1 g/kg at Building #30 to a high value of 9.9 g/kg at Building #28.

The lowest water vapor concentrations were found during Spokane winter measurements with six of seven building averages below 5.0 g/kg. This probably was a result of ventilating with cold, dry, outside air. Measured outdoor concentrations were between 2.1 g/kg and 6.3 g/kg for this winter period. Building #29 (a Spokane, WA junior high school) had the lowest single site concentration of 3.1 g/kg (22% RH) during this winter test period with an outdoor concentration of 3.2 g/kg. These dry indoor conditions can lead to discomfort to persons working in this environment. Excessive drying of the exposed mucous membranes of the nose and throat and irritation of the skin can occur at very low humidities (Givoni, 1976).

Three buildings (#23, #24, and #25) monitored in Spokane during the summer had the highest average humidity ratios of 9.4, (50% RH) 9.7 (53% RH), and 9.8 g/kg (57% RH) respectively. While these are not at levels of concern for direct damage to building interior finishings or for comfort, the indirect effects may be significant at some sites within the buildings. For example, a site in Building #23 recorded a humidity ratio of 12.0 g/kg, (65% RH) and a HCHO reading of 57 ppb. From what is known about the relationship between HCHO release and humidity it is possible that the high H_2O levels contributed to elevating the HCHO at this site above the building background (32 ppb). No other pollutants are noticeably elevated for Building #23.

Figure.III.B.1

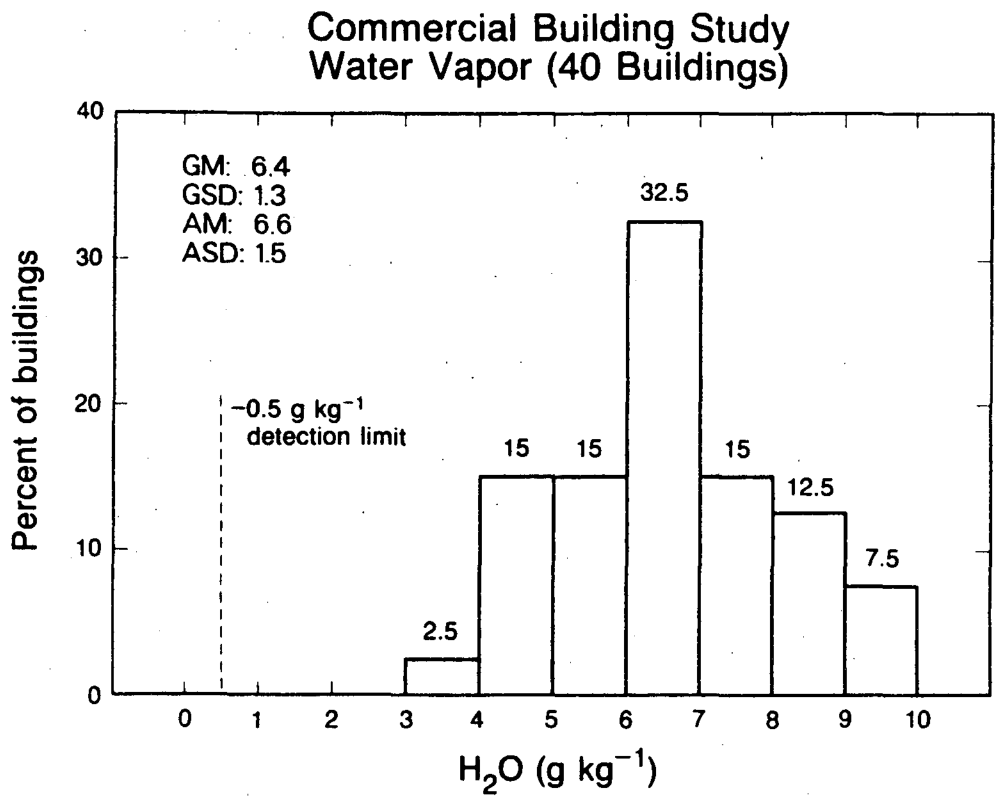
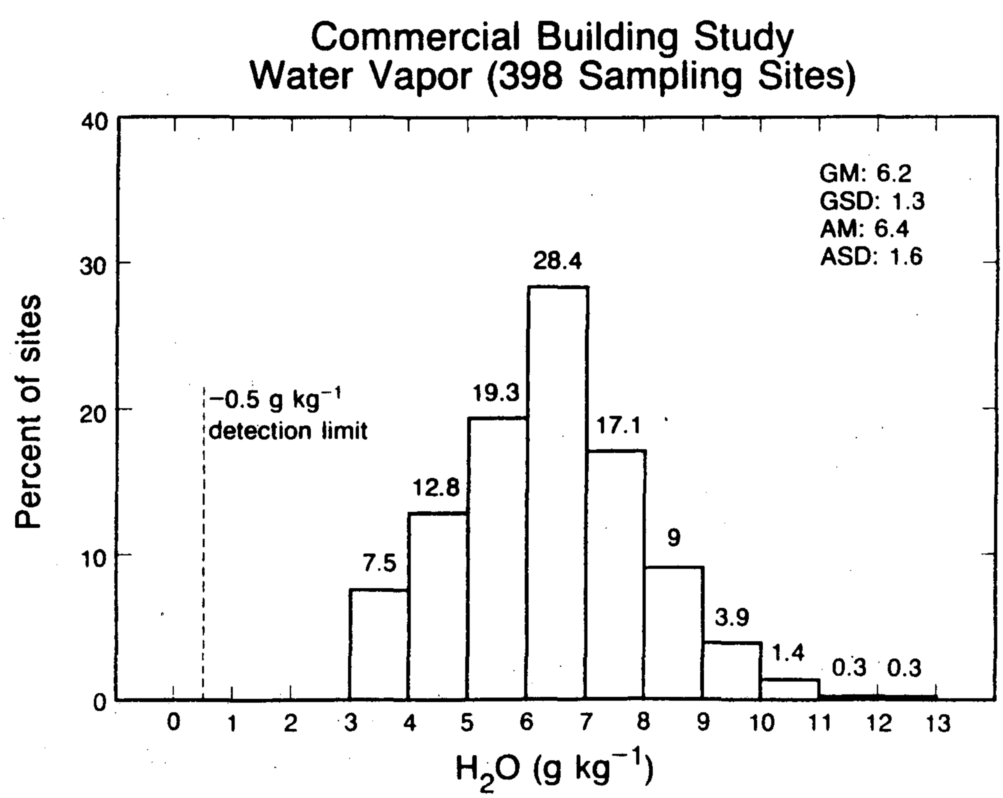


Figure.III.B.2



Three other sites had elevated H_2O concentrations. Building #8 had one site with an H_2O concentration of 10.2 g/kg (69%). Site B-2 in Building #14, had a humidity ratio of 10.08 g/kg (68%). The third high humidity ratio site is 3-C in Building #39 which is a computer center with an around-the-clock operation cycle. The measured concentration was at 11.8 g/kg. All three sites are much higher than the building average concentrations (#8 - 7.5 g/kg. #14 - 6.1 g/kg, #39 - 7.3 g/kg). No apparent source for the high water vapor concentrations can be identified. Relative humidities above 70% may cause, at high temperatures, discomfort to individuals due to the failure of normal evaporative skin cooling. In addition, it encourages microorganisms such as fungi, bacteria, and mites, all of which have been implicated in allergic and pathogenic episodes, to thrive on the available organic matrix of furnishings, paper and dust. At extremely high humidities, higher than observed in this study, direct damage to interior surfaces through condensation may also occur.

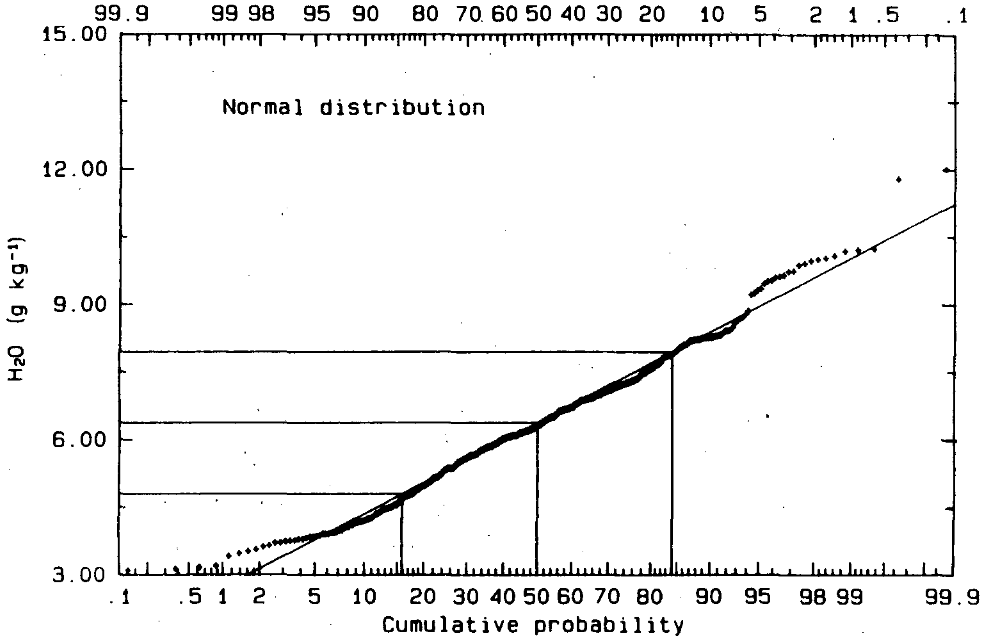
The frequency distribution of the 398 sampling sites fits either a normal distribution (6.4 g/kg mean, 1.6 standard deviation) Figure III.B.3, or a lognormal distribution (6.2 geometric mean with 1.3 geometric standard deviation) Figure III.B.4, equally well.

With few exceptions, the H_2O concentrations in this sample of buildings fall within the expected range for comfort and control of secondary humidity effects.

C. CARBON DIOXIDE (CO_2)

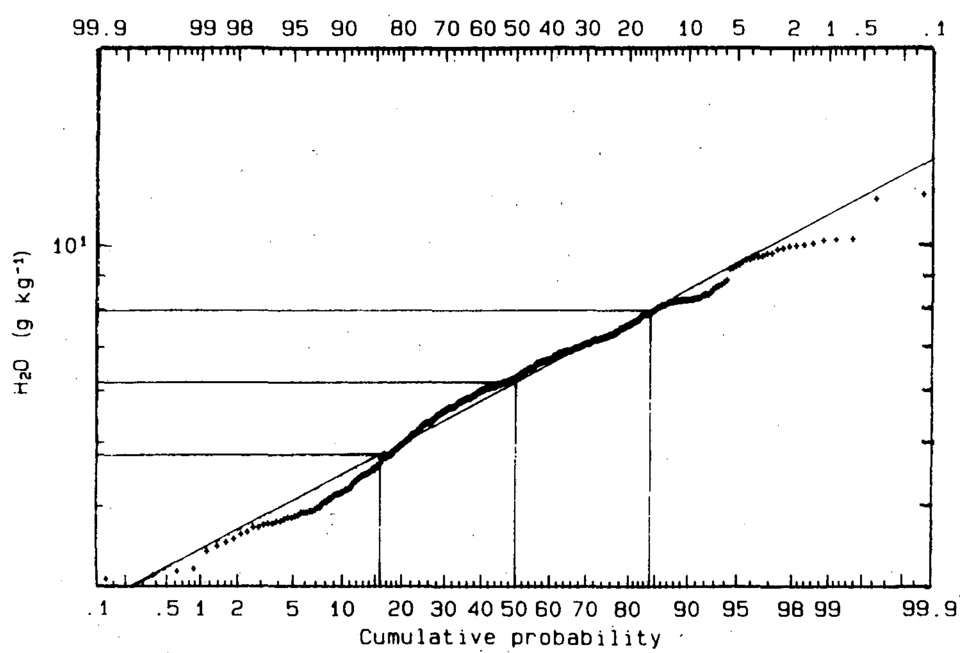
Carbon dioxide has two major sources in buildings: outdoor air and human metabolism. Globally, concentrations in well-mixed outdoor air usually average 300-350 ppm. Indoor levels above these concentrations are usually due to local outdoor (or indoor) combustion sources or to the occupants in the building. Studies by Sodergren and Puntilla (1983), Turiel and Rudy (1982), and others have clearly demonstrated the occupant effect on CO_2 concentrations. Humans involved in sedentary activities, including desk work, produce, on average, 0.018 m^3/hr CO_2 as the byproduct of respiration (ASHRAE, 1981; Turiel and Rudy, 1982). The daily measurements clearly follow occupancy levels.

Figure III.B.3



COMMERCIAL BUILDING STUDY (398 SAMPLING SITES)

Figure III.B.4



COMMERCIAL BUILDING STUDY (398 SAMPLING SITES)

Carbon dioxide is not normally a pollutant of concern except in circumstances of overcrowding or high levels of concentration in industrial situations. The level set for industrial exposures is 5,000 ppm while ASHRAE 62-81 recommends 2500 ppm. The draft revision of standard 62 recommends 1000 ppm as a maximum value for CO_2 concentrations in a building (ASHRAE, 1986).

Results

Thirty-nine eight-hour average measurements were made in 37 of the 38 study buildings (Appendix F) and are compiled as a histogram in Figure III.C.1. Building #10 was not monitored due to equipment failure and Buildings #6 and #9 had two separate tests made. Building means ranged from a high of 840 ppm in Building #1 to a low of 337 ppm in Building #39. The lowest 15-minute reading of 306 ppm ($\pm$10 ppm) occurred in Building #39. Only five buildings (13%) had 15-minute maxima over 800 ppm, with the highest (1290 $\pm$10 ppm) found in a crowded elementary school classroom in Building #1. Figure III.C.2 is a time-series chart of the data from this site. Periods when the children left the classroom, such as recess at 1100 and 1300 and the noon lunch break are obvious.

Two buildings were tested a second time under different ventilation conditions. As observed in other studies, a reduction in ventilation rate, here due to the change in outdoor temperatures, results in an increase in the CO_2 concentration in an office (Building #11) and a school (Building #17). Test #30 is a winter retest of Building #17 and test #36 a retest of Building #11 (see Table III.C.1).

In the original (spring) tests, Building #11 had a ventilation rate of 3.6 ACH and a mean eight-hour CO_2 concentration of 467 ppm (400-540 ppm). Under winter conditions, with the building ventilation system set on maximum recirculation the ventilation rate was measured at 1.1 ACH with a mean CO_2 concentration of 604 ppm (424-878 ppm). Building #17 had a ventilation rate of 2.2 ACH and CO_2 concentration of 520 ppm (340-670 ppm) in the spring monitoring period. During the mid-winter test with a reduced amount of outside air, the ventilation rate was 1.3 ACH with a measured CO_2 concentration of 641 ppm (374-863 ppm).

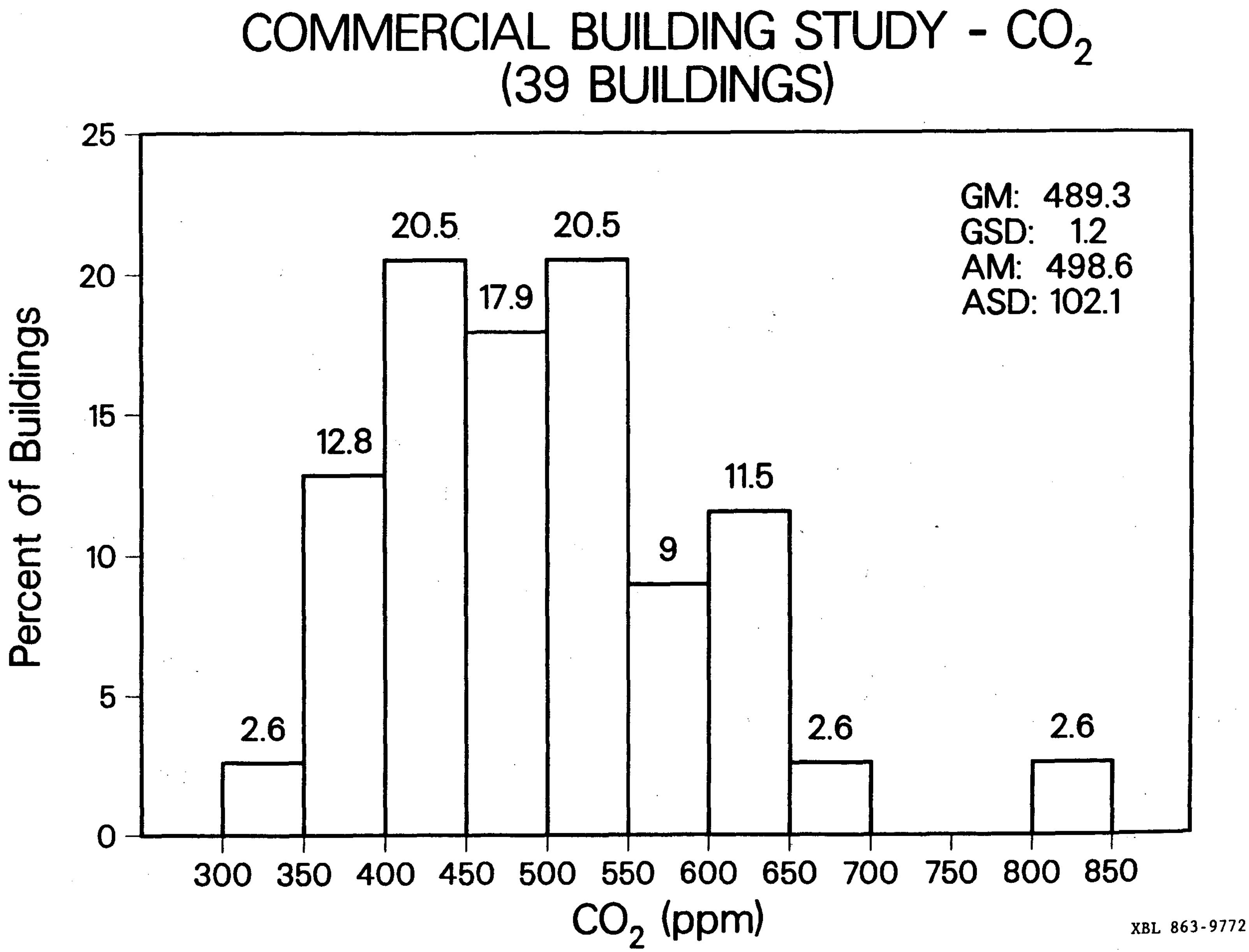


Figure III.C.1

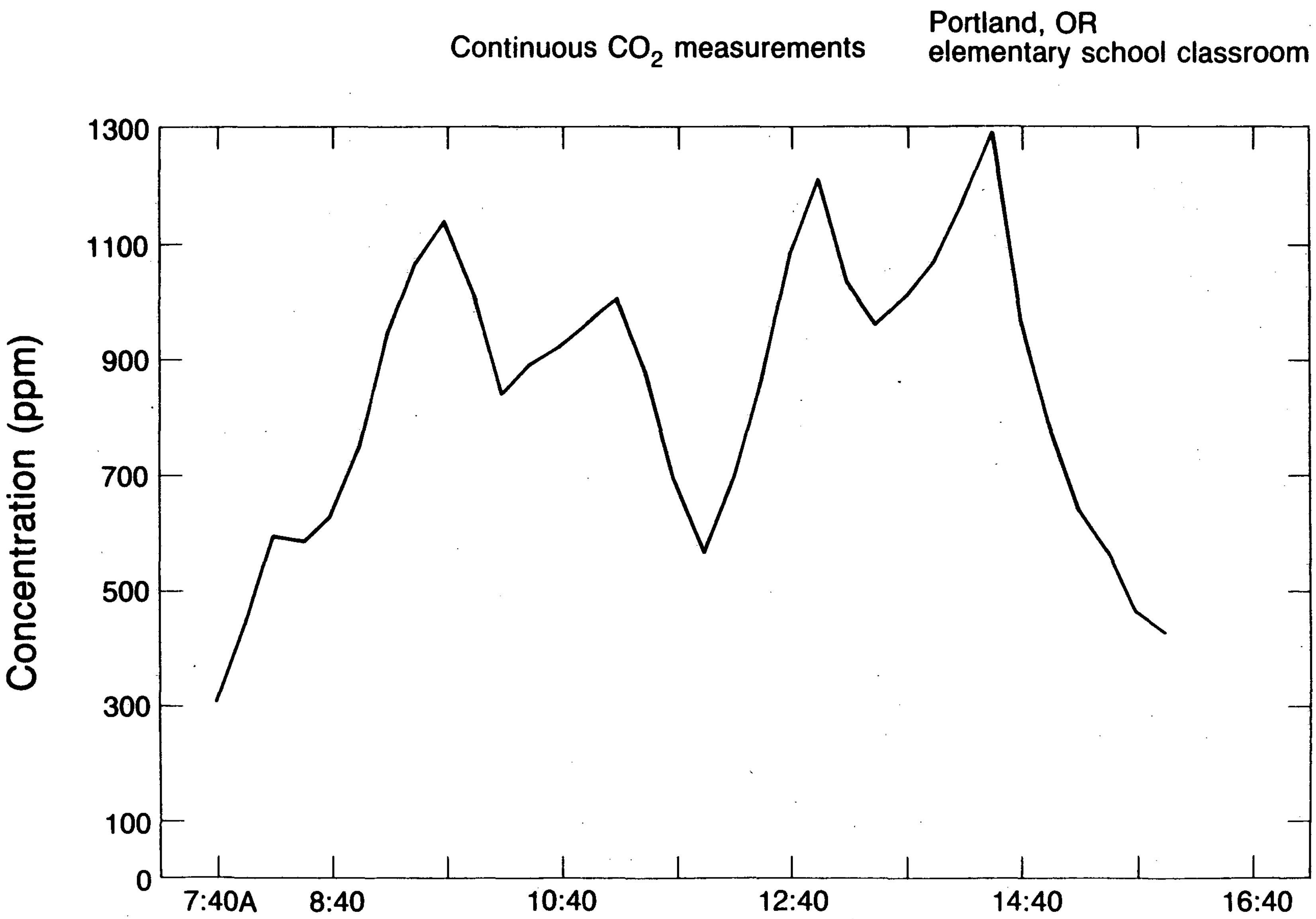


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Figure III.C.2

TABLE III.C.1

Seasonal CO_2 Concentration Comparison

Building	Season	ACH	Mean CO_2(ppm)	Range CO_2 (ppm)	Occupancy
#11	Spring	3.6	467	400-540	400
#11 Test2(#36)	Winter	1.1	604	424-878	400
#17	Spring	2.2	520	340-670	550
#17 Test2(#30)	Winter	1.3	641	374-863	659

None of these values is of concern from either a health or comfort standpoint but they do illustrate the inverse dependence of CO_2 concentration upon ventilation rate. Some recent studies have indicated that exposure to CO_2 concentrations above 600 ppm may be associated with an increase in the number of complaints about discomfort in the work area (Rajhans, 1983). At 1000 ppm, according to Rajhans's survey, complaints became much more common. In our study, no records of complaints were kept.

Carbon dioxide has been used to indicate the building ventilation rate under certain restricted conditions (Turiel and Rudy, 1982). One analysis using this method in a building in this study is reported in more detail in Section IV.H.

D. CARBON MONOXIDE (CO)

Carbon monoxide acts upon the human cardiovascular system by replacing oxygen on the hemoglobin receptor sites and thus depriving the blood of the ability to transport oxygen from lungs to organ systems. Exposure to 15 ppm CO for 10 hours is enough to reach a 2.5% carboxyhemoglobin blood content; a level at which physiologically adverse effects begin to occur in humans (NRC, 1977). Sources of CO in commercial buildings generally are 1) outdoor air contaminated by vehicular exhaust, and 2) tobacco smoking.

Results

Indoor sampling for carbon monoxide (CO) was conducted at 32 buildings while outdoor CO samples were taken at 11 buildings. Ambient CO concentrations measured by local air pollution control agencies are available for 26 buildings (Appendix G).

The 32 building indoor results yielded only six building-average values higher than 2 ppm, the minimum detectable level of the sampling system. Table III.D.1 presents a summary of the values of those six buildings.

Table III.D.1 Summary of Elevated Carbon Monoxide Concentrations

				CO Concentration (ppm)			
Building	Underground			Indoor		Building	Other Agency[a]
No.	Parking	City	Season	Mean	Max	Outdoor	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

In four of these buildings, all sample sites recorded above the detection limit while only 36 of the 126 total indoor sample sites were above the detection limit. Although these readings are lower than the eight-hour EPA (NAAQS) standard and ASHRAE guidelines (Table III.A.1); short-term concentrations could be much higher since the sampling method averages over an eight-hour period. Buildings #7 and #35 show outdoor CO concentrations equal to or slightly exceeding 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 the outdoor air, presumably from locally heavy vehicular traffic.

Elevated CO concentrations in Buildings #6, #27 and 37 are probably the result of heavy automobile exhaust emissions in their underground parking areas. During the test of Building #6, the local air pollution monitoring agency reported only 2 ppm average outdoor CO concentration, whereas this value was exceeded by six of the seven interior readings taken in this building. Therefore, the parking garage is suspected to be the major CO source.

Only in Building #34, where a CO level of 6 ppm was measured in a smoky lunch room, is tobacco smoking suspected to be the dominant source. Outdoor levels were below our detection limit at the building and were 3 ppm as measured by the Spokane County Air Pollution Control Authority approximately 0.3 km from the building. Another indication of smoking in this area is the respirable suspended particulate (RSP) concentration of 116 $\mu g/m^3$, well above average. Nitrogen dioxide was 29 ppb (for an 80-hr test period), the highest recorded for this building. Formaldehyde, which might also be expected to occur at high levels where heavy smoking occurs, was below detection at this site. While not unequivocal, it seems justified to conclude that heavy smoking in this lunchroom is the dominant CO source.

Only two site measurements approach the EPA-NAAQS outdoor standards and ASHRAE guidelines for CO concentration of 9 ppm for eight hours exposure. The Building #6 reading of 7 ppm occurs near an underground parking garage and exposures to persons working in this area may rise to higher levels under circumstances of heavier parking load, different ventilation regimes, or higher personal travel in the garage space. The Building #34 local reading of 6 ppm seems to be due to heavy smoking. During high use periods, i.e., lunch hours, the concentration may rise much higher.

E. NITROGEN DIOXIDE (NO_2)

Nitrogen dioxide (NO_2) is a gaseous atmospheric pollutant which arises from combustion when temperatures exceed 2800°F (1525°C). The most common large sources of this reactive gas are open gas flames and automobile exhaust. NO_2 undergoes a largely unknown sequence of chemical reactions in indoor settings which tend to remove it from the air at a rate different from that to be expected by ventilation dilution/removal processes (Fisk et al., 1984). At present, the EPA ambient (outdoor) air quality standard level for human exposure is an annual average of 50 ppb.

Results

Of the 40 building measurement periods, 33 included sampling for NO_2 at a total of 245 sites. Outdoor samples were taken at 13 buildings. Comparative outdoor measurements from the Oregon Department of Environmental Quality (ODEQ) are available for four buildings in Portland (Table III.E.1). Potential indoor sources of NO_2 are largely limited to unvented combustion appliances, which are commonly not found in commercial buildings. As expected, few measurements showed high values; there are only two sites in two buildings (#6 and #35) which had values above the EPA ambient standard value of 50 ppb. The highest recorded building average (#6) was 43 ppb. For all sites the geometric mean was 18.3 ppb with a geometric standard deviation of 1.7.

A graphic presentation of the NO_2 data for the sample of 33 buildings using building means is given in Figure III.E.1 for 3 ppb intervals. Figure III.E.2 gives a similar histogram presented in 5 ppb intervals for the 245 recorded sites. Both distributions show that the majority of buildings and sites fall well below the established EPA guideline level of a 50 ppb annual average for NO_2. Only 0.8% of the sites are above this level. None of the building means is higher.

Figure III.E.1

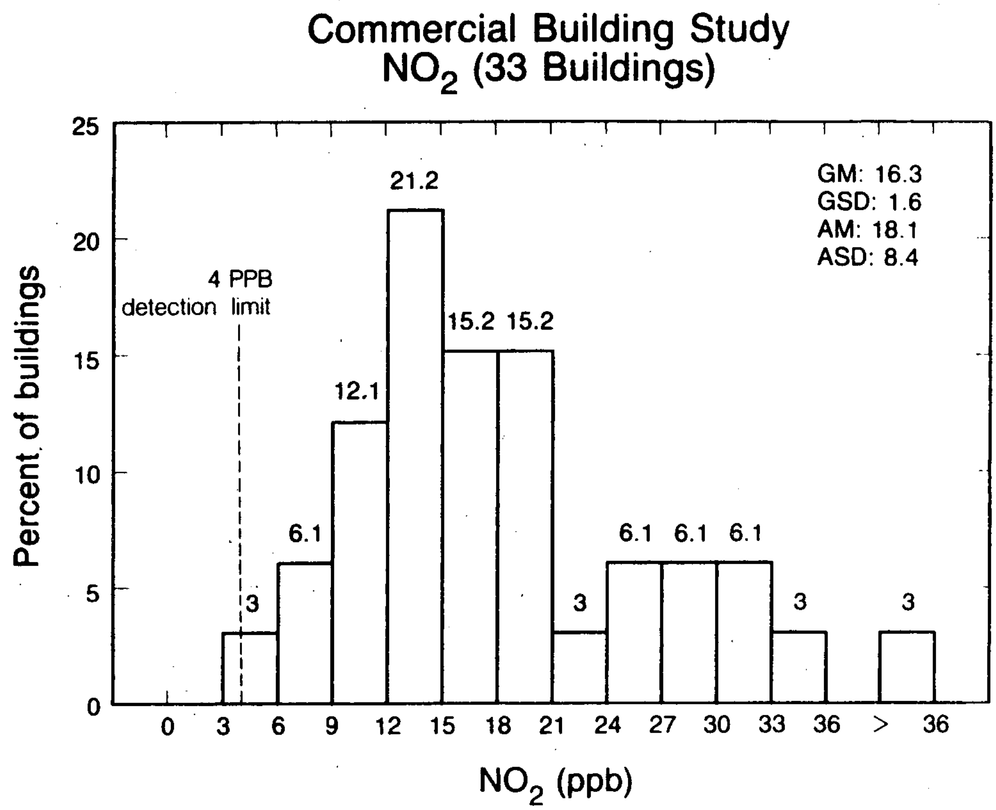
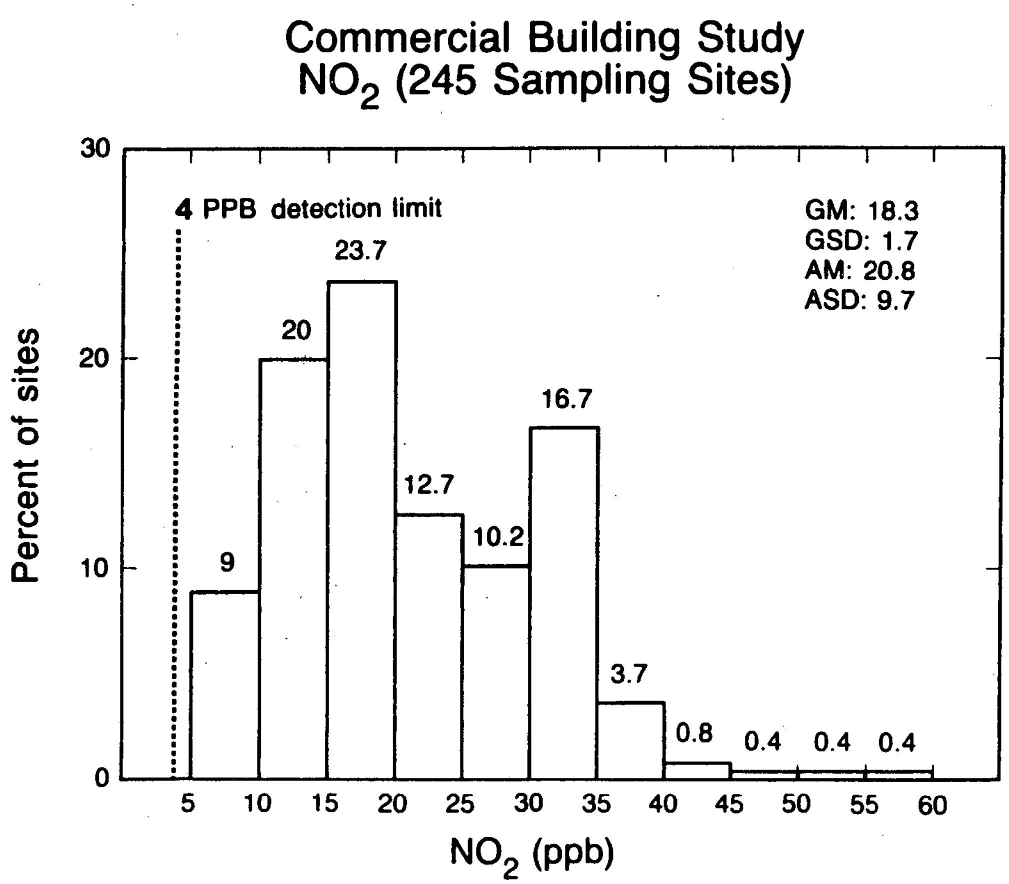


Figure III.E.2



The cumulative probability diagram (Figure III.E.3) show a form typical for the lognormal distribution, which many atmospheric pollutants exhibit. Using the best fit line, it can be predicted that only slightly more than 3% of all sites measured in a similar sample of buildings would have a concentration greater than 50 ppb (Figure III.E.3).

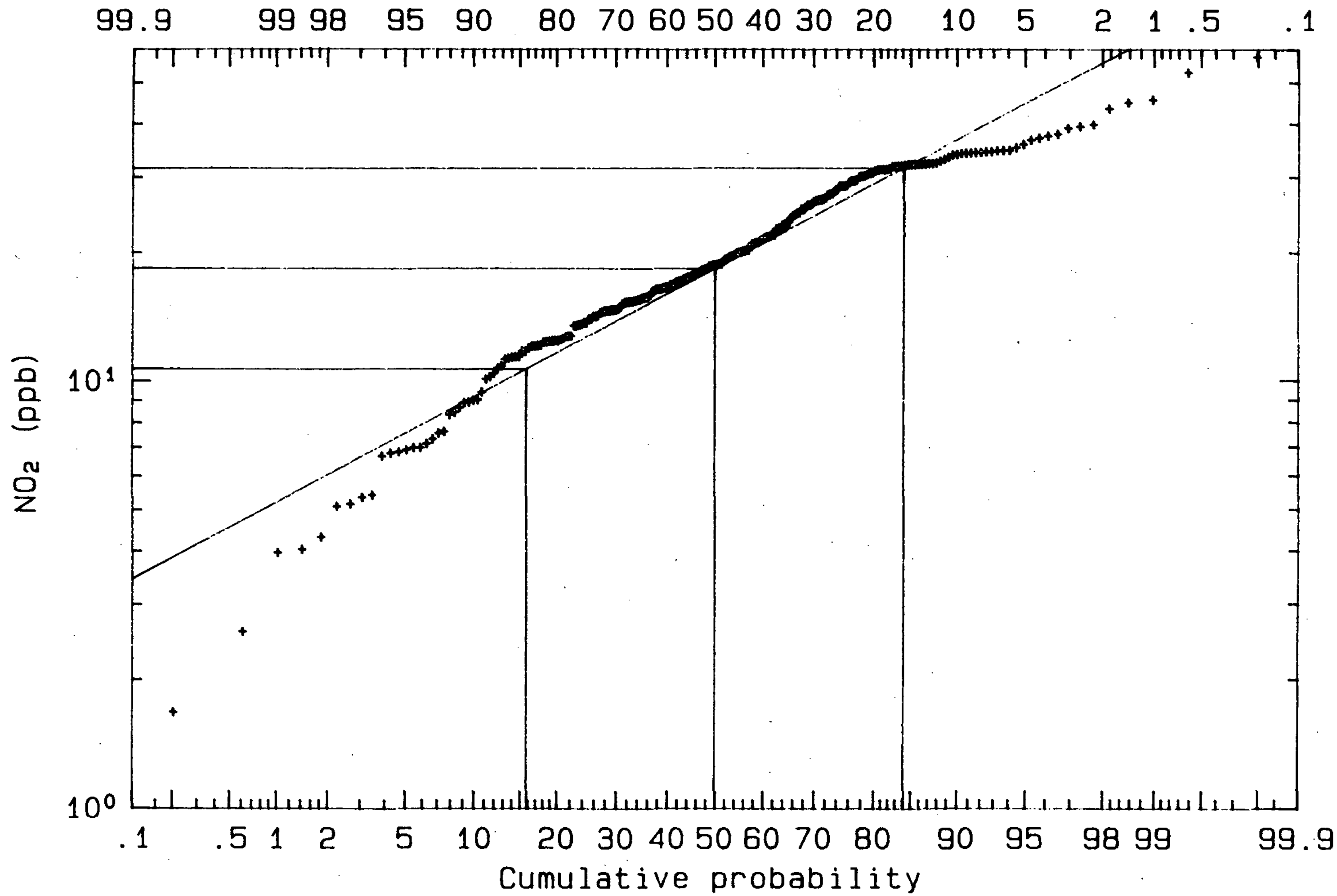
The whole building mean (43 ppb) and single site NO_2 (53 ppb) maximum readings found in Building #6 are probably related to the same source as is the relatively high CO reading of 7 ppm. This building has an underground parking garage and the interior air is well mixed by its ventilation system. Apparently NO_2 and CO from the automobile traffic in the basement and on the streets is entering the building where it is distributed by the air handlers throughout the building volume.

The highest reading (58 ppb) in Building #35 is unusually high for this building (average 22 ppb) and has no ready explanation. The site is on the second floor of a 15-story building and there was no value approaching 58 ppb on the same floor. Only one air handler serves the entire floor. The second site on this floor had only a 17 ppb measurement. Floors below and above show near average readings.

Buildings #37 - #40 in downtown Portland, OR have relatively high average indoor NO_2 concentrations at 31 ppb, 27 ppb, 33 ppb and 31 ppb respectively. However, these values are less than the outside measured values of 37-40 ppb. Buildings #39 and #40 used the same outdoor site (#39) since they are nearly adjacent. It would seem that these levels are largely due to the exhaust from heavy vehicular traffic in the center of this large urban area.

Outdoor NO_2 measurements were made by the ODEQ in Portland OR at a location approximately four miles from downtown, the location of buildings #37 - #40. The ODEQ measurement are not necessarily representative of those made in the center of the city where the buildings in this study are located. ODEQ concentrations are approximately one-half the values measured by the outdoor passive samplers used in this study (Table III.E.1).

Figure III.E.3



COMMERCIAL BUILDING STUDY (245 SAMPLING SITES)

TABLE III.E.1

PORTLAND OUTDOOR NO_2 CONCENTRATIONS

Building	NO_2 Concentration (ppb)		Ratio ODEQ/BPA
	BPA	ODEQ	
37	40	23	0.56
38	37	16	0.43
39	37	16	0.42
40	37	18	0.46

Table III.E.2 and Figure III.E.4 give summary representations of the relationships between average indoor NO_2 concentrations and the respective outdoor levels for 15 buildings. Since the primary source of NO_2 is usually located outside the building shell, there should be a substantial correlation between the indoor and outdoor concentrations with the outdoor concentration being the larger of the two. The linear regression line of Figure III.E.4 illustrates that 83% (r^2) of the variation of building average of indoor NO_2 concentrations is related to changes in outdoor NO_2 concentrations.

Some of the variation seen may be attributable to tobacco smoking. Ordinarily, the indoor non-smoking concentration is less than outdoors. However, in Buildings #26 and #31, where smoking area concentrations are unusually higher than the non-smoking areas, we also find the non-smoking area concentrations to be higher than outside. It has been reported that NO_2, usually considered a high temperature combustion byproduct from gas or petroleum based fuels, is also produced in significant quantity from the lower temperature burning of tobacco. In residential studies, a slight increase in the NO_2 concentration has been observed in houses without gas fired appliances where cigarette smoking occurred (Good et al, 1982; Berk, et al., 1981). This agrees with the observations here. NO_2 concentrations at smoking sites are higher than at non-smoking sites in eleven of fifteen buildings and are only lower in the remaining four buildings where outdoor NO_2 is clearly elevated. If only indoor non-smoking area concentrations are regressed against outdoor levels, the r^2 improves to +0.87. It would seem that the presence of smoking has a small

TABLE III.E.2

NITROGEN DIOXIDE INDOOR-OUTDOOR CONCENTRATIONS AND RATIOS

BUILDING NO:	OUTDOOR (ppb)	INDOOR: (ppb) NON-SMOKING	SMOKING[1]	MEAN[2]	RATIOS: INDOOR NON-SMOKING÷ OUTDOOR	INDOOR SMOKING÷ OUTDOOR	INDOOR MEAN÷ OUTDOOR
26	21	23	31	27	1.1	1.5	1.3
27	20	14	18	16	0.7	0.9	0.8
28	23	24	25	24	1.0	1.1	1.0
29	21	15	19	16	0.7	0.9	0.8
30	15	13	15	13	0.9	1.0	0.9
31	10	13	20	14	1.3	2.0	1.3
32	6	5	7	5	0.8	1.2	0.8
33	6	10	11	10	1.7	1.8	1.7
34	26	18	20	18	0.7	0.8	0.7
35	25	19	22	22	0.8	0.9	0.9
36	17	18	19	18	1.1	1.1	1.1
37	40	31	30	31	0.8	0.8	0.8
38	37	28	24	27	0.8	0.6	0.7
39	37	34	32	33	0.9	0.9	0.9
40	37	32	31	31	0.9	0.8	0.8
AM	23	20	22	20	1.4	1.1	1.0
ASD	11	9	7	8	1.6	0.4	0.3
GM	20	18	20	18	1.1	1.0	0.9
GSD	2	2	2	2	1.2	1.4	1.3

(1) SMOKING WITHIN 30' RADIUS OF SITE
(2) ARITHMETIC AVERAGE OF ALL SITES IN BUILDING

AM - ARITHMETIC MEAN
ASD - ARITHMETIC STANDARD DEVIATION
BD - BELOW DETECTION LIMIT OF 10 PPB
GM - GEOMETRIC MEAN
GSD - GEOMETRIC STANDARD DEVIATION
NA - NOT APPLICABLE

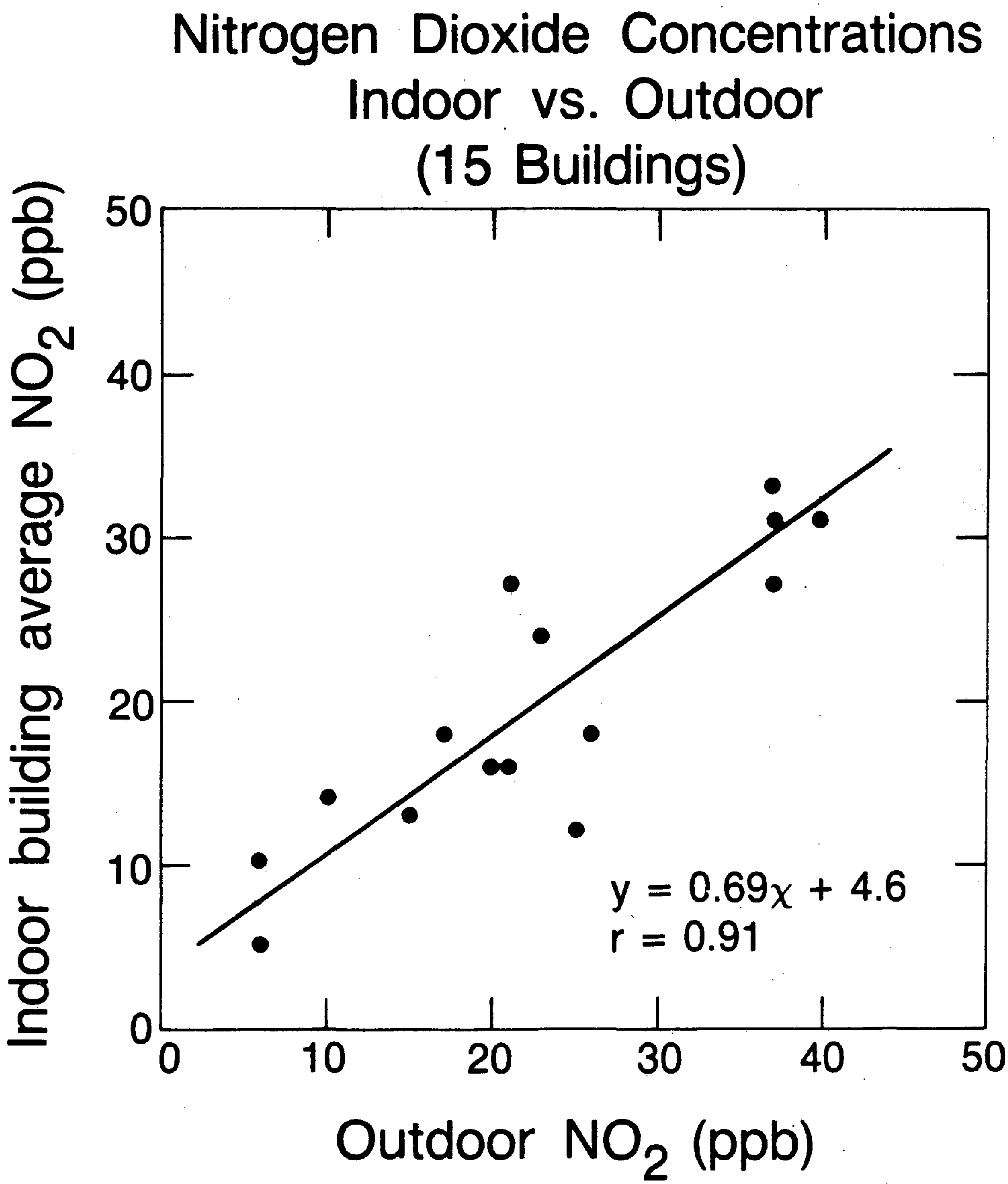


Figure III.E.4

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(2 ppb), but measureable effect upon NO_2 concentrations. Even better correlation could be expected if indoor source terms (parking garages, local combustion sources) and removal mechanisms (ventilation, chemical reactions) are taken into account.

Only two sites were found where potentially hazardous levels of NO_2 occur. One of these is a building (#6) with an underground parking garage. It is surrounded by heavy, congested traffic as well and also has an elevated CO level. Some considerations should be made to alleviate the problems here.

F. RESPIRABLE SUSPENDED PARTICLES (RSP)

Total suspended particulate (TSP) material is regulated in the outdoor environment. A certain fraction of the TSP is of inhalable size, ≤ 15 μm in diameter. While particles of this size and smaller can be taken into the human respiratory system, those between 15 μm and 3 μm are filtered out by the normal screening mechanisms of the respiratory tract. Particles less than 3 μm in size, known as respirable suspended particles (RSP), are small enough to penetrate deep into the bronchial passages and lungs where they may lodge on the tissue surfaces and cause damage.

Indoors the suspected chief source of respirable suspended particles is tobacco smoke, although general house and photocopy dust may also occur in this size range. Many respirable-size particles with an outdoor source do penetrate the building envelope and enter the occupied space through infiltration or with the normal influx of outside air via the HVAC system. Filtration of incoming outside air is never perfect; virtually all respirable particles will normally pass through the filter system and mix with the return air to form the supply air.

Results

Table III.F.1 gives a summary of the whole building and sampling site RSP data, while Table III.F.2. is a more detailed breakdown of the values of the outdoor, non-smoking, smoking, and whole building measurements. Ratios between the areas are also shown. Figure III.F.1 is a histogram of average

TABLE III.F.2

SMOKING, NON-SMOKING AND OUTDOOR RSP CONCENTRATIONS AND RATIOS

BUILDING NO.	OUTDOOR (μgm^{-3})	INDOOR: (μgm^{-3}) NON-SMOKING	SMOKING[3]	MEAN[4]	RATIOS: INDOOR NON-SMOKING÷ OUTDOOR	INDOOR SMOKING÷ OUTDOOR	INDOOR MEAN÷ OUTDOOR
1	ND	25(19-36)	ND	25(19-36)	NA	NA	NA
2	ND	19(18-21)	ND	19(18-21)	NA	NA	NA
3	ND	ND	20(16-25)	20(16-25)	NA	NA	NA
4	8	7(6-8)	ND	7(6-8)	0.9	NA	0.9
5	BD	13(13)	14(14)	13(13-14)	NA	NA	NA
6	35	12(11-13)	35(23-59)	28(11-59)	0.3	1.0	0.8
7	35	38(32-44)	39(39)	38(32-44)	1.1	1.1	1.1
8	8	7(7-8)	ND	7(7-8)	0.9	NA	0.9
9	8	11(11)	16(13-20)	15(11-20)	1.3	2.0	1.9
10	9	63(53-74)	95(67-127)	86(53-127)	7.0	11.0	9.6
11	8	23(9-49)	209(209)	63(9-209)	2.9	26.1	7.9
12	ND	10(10)	63(63)	36(10-63)	NA	NA	NA
13	10	5(5-6)	ND	5(5-6)	0.5	NA	0.5
14	6	ND	30(26-34)	30(26-34)	NA	5.0	5.0
15	BD	11(7-14)	12(12)	11(7-14)	NA	NA	NA
16	10	9(8-11)	73(73)	31(8-73)	0.9	7.3	3.1
17	7	11(10-13)	105(105)	40(10-105)	1.6	15.0	6.1
18	7	ND	19(19)	19(19)	NA	2.7	2.7
19	7	ND	20(11-29)	20(11-29)	NA	2.9	2.9
20	18	11(10-11)	ND	11(10-11)	0.6	NA	0.6
21	17	11(9-12)	ND	11(9-12)	0.7	NA	0.7
22	20	18(18)	57(22-165)	50(18-165)	0.9	2.9	2.5
23	11	9(BD-20)	ND	9(BD-20)	0.8	NA	0.8
24	11	44(10-77)	24(24)	37(10-77)	4.0	2.2	3.4
25	68	35(32-38)	109(109)	60(32-109)	0.5	1.6	0.9
26	32	45(20-70)	82(55-123)	67(20-123)	1.4	2.6	2.1
27	52	36(33-38)	61(33-89)	48(33-89)	0.7	1.2	0.9
28	65	36(29-43)	BD	24(BD-43)	0.6	NA	0.4
29	29	10(8-12)	144(144)	32(8-144)	0.3	5.0	1.1
30[2]	33	24(20-30)	113(113)	37(20-113)	0.7	3.4	1.1
31	13	12(8-18)	268(268)	64(8-268)	0.9	20.6	4.9
32	ND	13(10-17)	36(21-52)	21(10-52)	NA	NA	NA
33	ND	ND	29(12-74)	29(12-74)	NA	NA	NA
34	16	13(10-16)	54(13-117)	28(10-117)	0.8	3.4	1.8
35	18	20(6-35)	50(50)	23(6-50)	1.1	2.8	1.3
36[1]	20	14(9-18)	72(17-127)	28(9-127)	0.7	3.6	1.4
37	19	21(12-32)	27(11-62)	25(11-62)	1.1	1.4	1.3
38	14	7(BD-9)	308(308)	46(BD-308)	0.5	22.0	3.3
39	11	8(8-9)	13(11-14)	11(8-14)	0.7	1.3	1.0
40	11	10(8-12)	26(11-40)	15(8-40)	0.9	2.4	1.4
AM	18.9	18.9	69.6	29.8	1.2	6.0	2.3
ASD	16.3	13.6	72.8	18.9	1.3	7.2	2.2
GM	14.1	15.4	44.2	24.2	0.9	3.6	1.7
GSD	2.2	1.9	2.7	2.0	2.0	2.6	2.3

(1) REPEAT TEST OF BUILDING #11
(2) REPEAT TEST OF BUILDING #17
(3) SMOKING WITHIN 30' RADIUS OF SITE
(4) ARITHMETIC AVERAGE OF ALL SITES IN BUILDING

NA = NOT APPLICABLE
ND = NO DATA COLLECTED
BD = BELOW DETECTION LIMIT

building concentrations, while Figure III.F.2 is a histogram of the 178 individual site concentrations. Both can be approximated by lognormal distributions.

Within the sample of 40 building tests, the range of building mean RSP values ranged from 5μg/m^3 (Building #13) to 86 μg/m^3 (Building #10), with an arithmetic mean of 30 μg/m^3 and a geometric mean of 24 μg/m^3.

Building averages for smoking areas ranged from below the detection limit of 50 μg (Building #28) to 308 μg/m^3 at Building #38. This latter was based on only one smoking site in that building. For non-smoking areas, the building averages ranged from 5 μg/m^3 (Building #13) to 63 μg/m^3 (Building #10).

Individual site measurements ranged from below detection (Buildings #23 and #38) to 77 μg/m^3 (Building #24), for non-smoking areas; and from below detection (Building #28) to the 308 μg/m^3 site mentioned above for smoking areas.

Clearly, when tobacco smoking is present, RSP concentrations are elevated significantly. On the other hand, non-smoking area average concentrations are lower than outdoor levels at 20 of the 29 buildings, even though the outdoor and non-smoking averages for all buildings are similar. Figure III.F.3 shows the comparison of all smoking, non-smoking, and outdoor sites. Note that two sites were not identified as either smoking or non-smoking and are not incuded here. Also note that on four occasions, outdoor RSP measurements from a building were also used at a nearby building that had no outdoor measurement (Building #6 at #7, #18 at #19, #23 at #24, and #39 at #40) for computations on Table III.F.2. Thus, the total number of outdoor sites on Figure III.F.3 is reduced to 30. Outdoor RSP values ranged from below detection limits at Buidings #5 and #15 to a maximum of 68 μg/m^3 at Building #25. A measurement of 118 μg/m^3 was made for Buildings #32 and #33 in Cheney, but was considered an outlier and was deleted based on a local outdoor air quality measurement of 29 μg/m^3 TSP for the same period (Appendix G) and the low indoor concentrations for non-smokings in Building #32.

Figure III.F.1

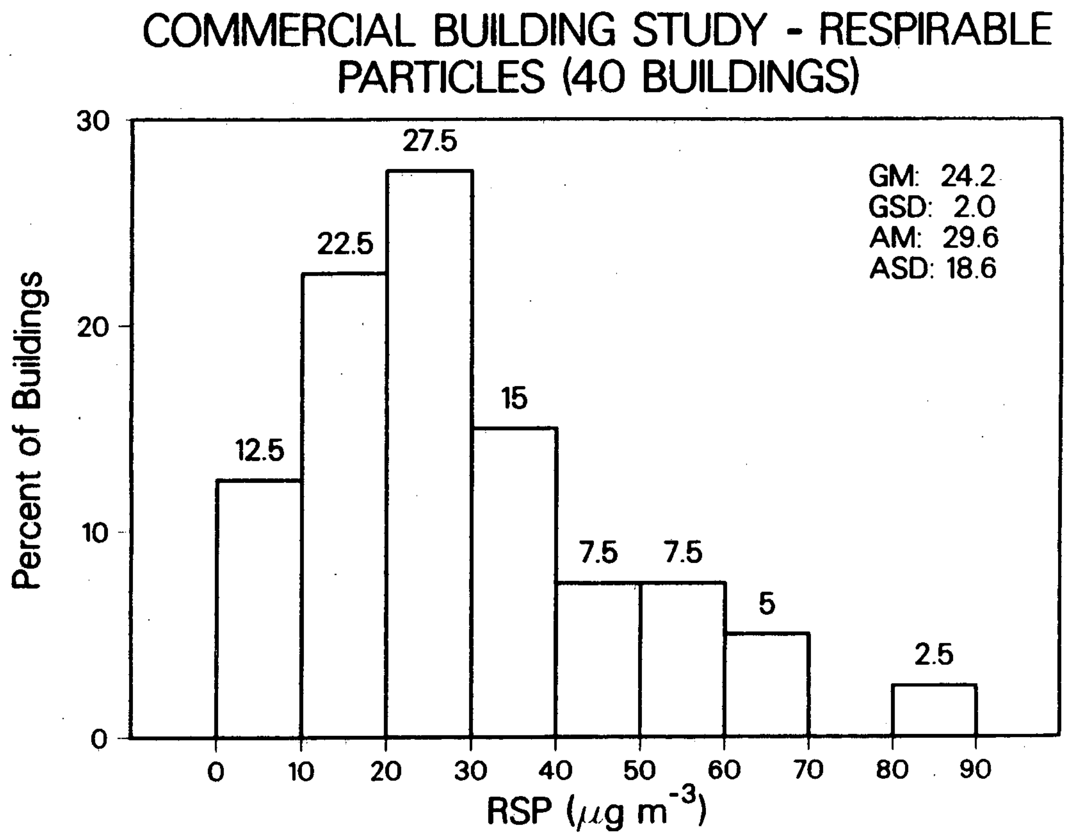
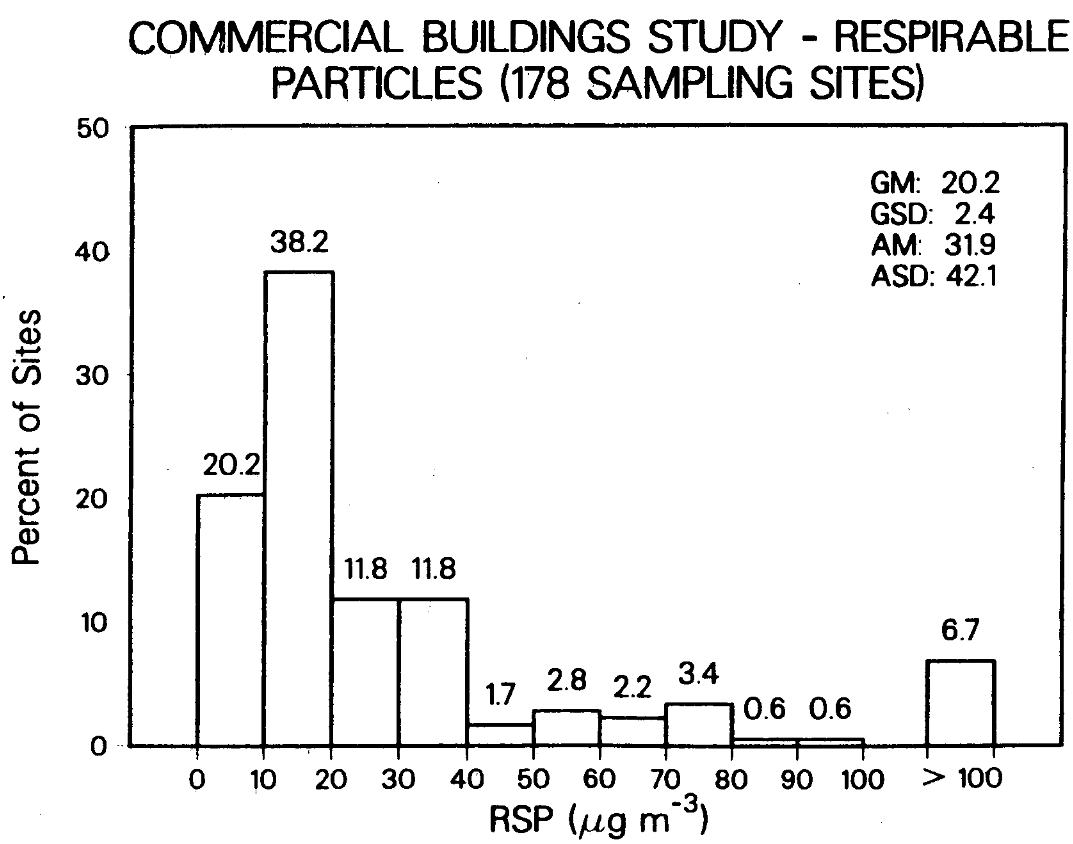


Figure III.F.2



COMMERCIAL BUILDING STUDY - RESPIRABLE PARTICLES (206 SAMPLING SITES)

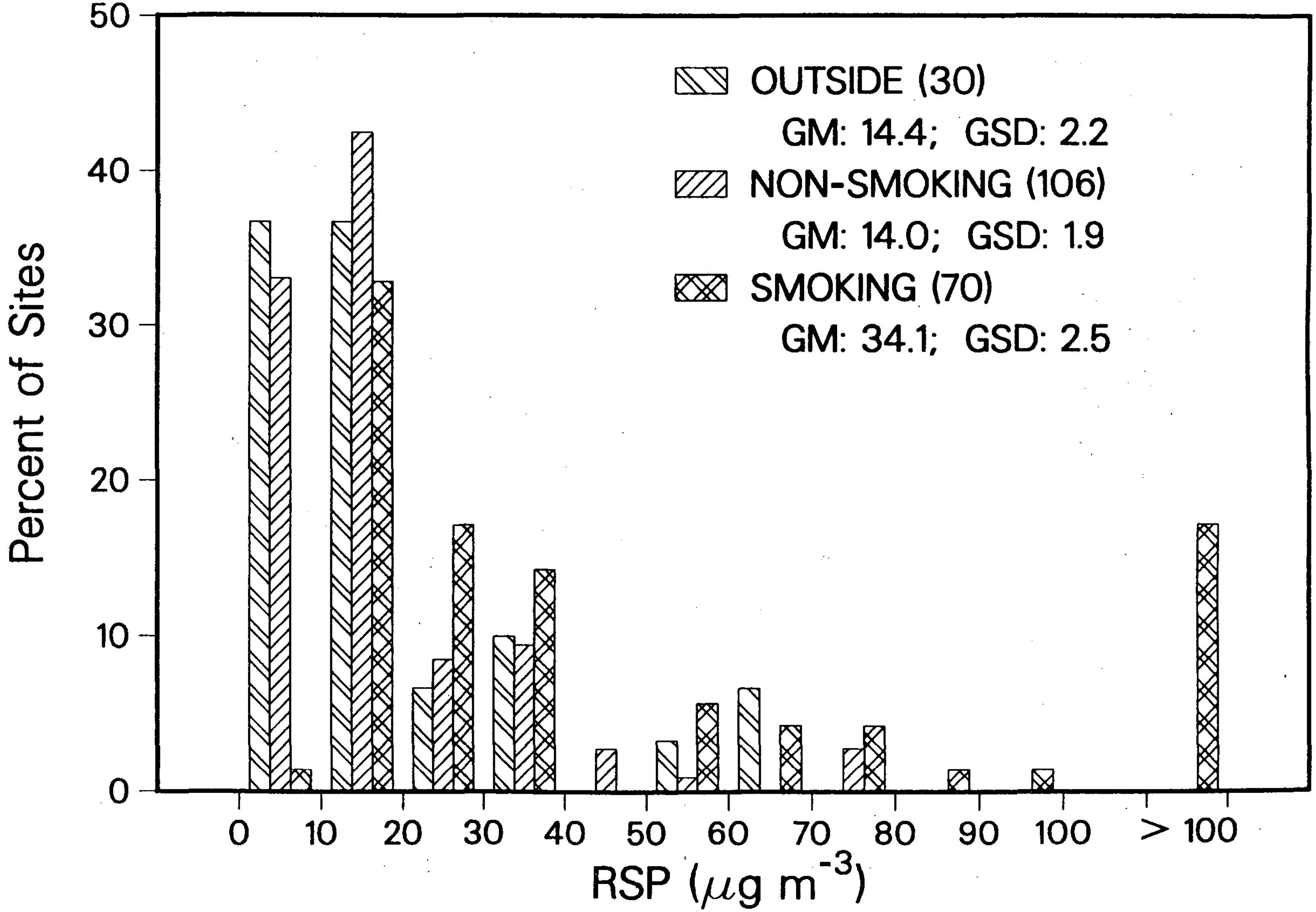


Figure III.F.3

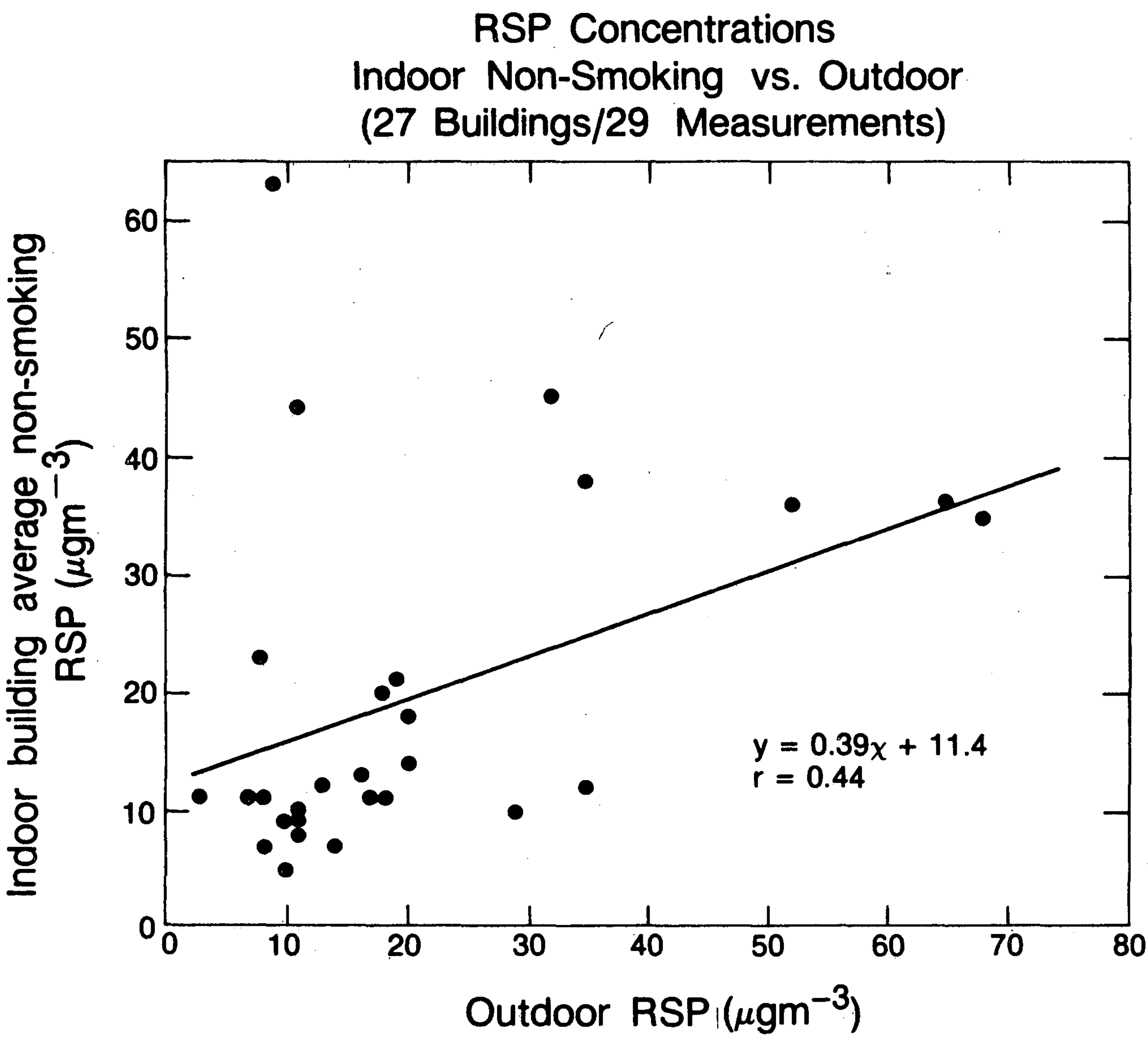


Figure III.F.4

Not surprisingly, when indoor average non-smoking RSP concentrations are regressed against one variable, outdoor air concentrations, the fit is poor (R^2 = 0.19) as seen in Figure III.F.4. The unexplained variation in this comparison is due to various indoor sources (predominantly tobacco smoking) and removal and dilution processes.

Table III. F.1

Respirable Suspended Particle Summary

	Arithmetic Mean ($\mu g/m^3$)	Geometric Mean ($\mu g/m^3$)	Number	Range ($\mu g/m^3$) Max.	Min.	No. Building $\geq 75 \mu g/m^3$ (TSP NAAQ-Standard)
Whole Building Averages:						
Smoking Sites	70	44	32	308	BD	9
Nonsmoking Sites	19	15	35	63	5	0
Total of All Sites	30	24	40	86	5	1
Averages of All Sample Sites:						
Indoor	31	20	180	308	BD	16
Outdoor	19	14	34	68	BD	0

For smoking sites the geometric mean was 34 $\mu g/m^3$ with a geometric standard deviation of 2.5 (Figure III.F.3). This is more than twice the outdoor (14.4 $\mu g/m^3$) and the non-smoking (14.0 $\mu g/m^3$) values.

Figure III.F.5 shows the cumulative frequency of RSP values in the entire sample of 178 indoor sites. The geometric mean of the 178 sites is 20.2 $\mu g/m^3$ with a geometric standard deviation of 2.4. The linearity of the data in this figure demonstrates a close association with the lognormal distribution found to describe many atmospheric pollutant distributions. Using the best fit line

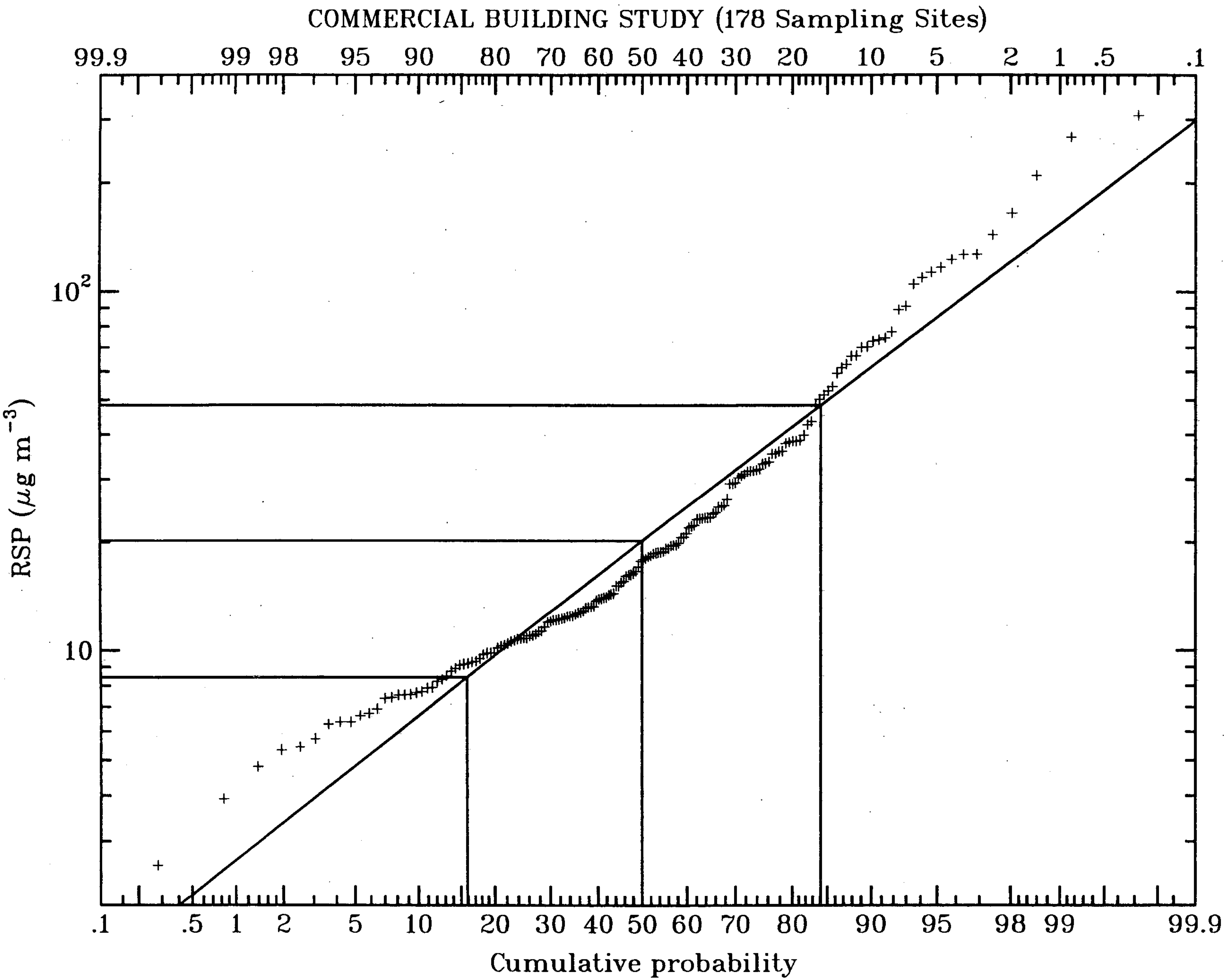


Figure III.F.5

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applied to the data on Figure III.F.3 it is estimated that in a similar sample, approximately 15% of the sites chosen would exceed the 50 $\mu g/m^3$ standard for annual exposure set by the EPA for PM_{10}, i.e., particles less than 10 μm in diameter. If the probability is restricted to smoking sites, the fraction above 50 $\mu g/m^3$ increases to 34%.

Smoking as a Particle Source

RSP takes on considerable significance as a health risk through its association with tobacco smoking, where almost all particulate emissions are smaller than 3 μm. Tobacco smoke aerosols released in the sidestream (non-inhaled smoke) and from exhaled puffs (which are called environmental tobacco smoke or ETS) contain a wide range of toxic and carcinogenic substances. Smoking as a hazard to the smoker has been clearly documented for years by health authorities, hence the warnings on tobacco products. The increasing voluntary and involuntary regulation of smoking in public places is a result of an awareness of the dangers of ETS to non-smoking persons in the vicinity of smokers. Each cigarette smoked may release 15 mg of respirable particulate matter to the environment (Offermann et al., 1984). Some of the carcinogenic material in ETS occurs in the form of polycyclic aromatic hydrocarbons (PAH) which was collected on the filters along with RSP and later quantified (Section III.G).

An additional problem is the immediate and residual odor of tobacco smoke which is distinctive and irritating. A welfare problem is the discoloration which occurs when tobacco smoke condenses on furnishings, walls, and windows.

Smoking, where it is permitted, is a cause of nearby elevated RSP concentrations. Its influence upon the RSP burden of an entire ventilation zone or building is not clearly marked. A building with a very high RSP burden in a smoking area may have a low concentration in the remainder of the building due to a number of removal and dilution processes.

Overall, 106 sites were classified as non-smoking (no observed smoker within 30 ft.) and 70 were smoking sites. In this study, no distinction was made with respect to the average number of smokers present or the number of cigarettes, cigars, or pipes smoked during a given period of time. In some instances, there may have been only one smoker in a relatively small area or many smokers in a designated area of a larger cafeteria in the same building, for example, in Building #36.

The localization of high RSP concentrations to smoking areas in buildings is seen in summary data (Tables III.F.1 and 2) and in a discussion of a few individual buildings, which follows.

In Building #38, smoking was confined to approximately one-third the floor space of a cafeteria which is served by three small air handling units supplying only outside air. This smoking area had a concentration of 308 $\mu g/m^3$, while the highest found at any other non-smoking site was 9 $\mu g/m^3$. The outside air registered 14 $\mu g/m^3$. We suspect that the RSP load of the cafeteria was isolated from the remainder of the buildings by the separate ventilation systems in the cafeteria itself and by the two ventilation systems on almost every floor of the building.

Building #34 with only one large HVAC system (plus the usual bathroom exhausts) had a mean smoking area concentration of 54 $\mu g/m^3$ (13 to 117 $\mu g/m^3$) compared to a non-smoking area mean of 13 $\mu g/m^3$ (10 to 16 $\mu g/m^3$). The outdoor measurement, taken at the air intake for the HVAC system, was 16 $\mu g/m^3$. Ventilation rates throughout this large, 15 story building were close to its average of 1.5 ACH (1.4 to 1.6 ACH) and no special exhaust ventilation was provided in a smoking area with the highest RSP concentration of 117 $\mu g/m^3$. Even with the excess RSP due to smoking, the concentrations in non-smoking areas remained low, possibly due to dilution of particle concentrations by the large building volume (2,700,000 ft^3).

In other buildings (for example, Building #31), designated smoking areas have separate exhaust-only ventilation systems to increase the local ventilation and remove the pollutant before it can enter the remainder of the structure. The one smoking area monitored in Building #31 had an RSP level of 268 $\mu g/m^3$, whereas the non-smoking sites averaged 12 $\mu g/m^3$ (8 to 18 $\mu g/m^3$), which was approximately equal to the outdoor concentration of 13 $\mu g/m^3$. It appears that the exhaust system was partly responsible for the low non-smoking site levels in this relatively small (384,000 ft^3) building. The following section attempts to integrate the various factors affecting indoor RSP concentrations and assign a relative importance to their impact.

Sensitivity Studies

In most mechanical ventilation systems, the mixture of outside air and return air passes through some type of particle filtering that often includes coarse panel filters occasionally followed by a more efficient bag filter. During our investigations, the condition of the filters varied considerably, from clean to virtually occluded. The condition and efficiency of these filters may be important in controlling the RSP load in buildings where outdoor air is already contaminated and smoking is allowed. Air from smoking areas is not always exhausted directly to the outdoors. It is returned with air from the rest of the building to the main air handling systems which partially dilutes it with outside air and then distributes it throughout the building, including nonsmoking areas. Some smoke particles are filtered, or removed by other mechanisms (e.g., physical deposition, chemical transformation, coagulation), while many of the gas phase contaminants are unaffected. It is likely that these removal processes, along with dilution by the large building volumes, account for the comparatively low RSP concentrations in non-smoking areas even when smoking is allowed in certain areas of the building and the outdoor air is contaminated.

In order to examine this process more carefully we chose to model the RSP concentration using the steady state mass balance equation for calculating indoor pollutant concentrations:

$$C_{\infty} = \frac{C_o IP + S/V}{I + K} \qquad [3.1]$$

The numerator in equation 3.1 represents the pollutant source terms; the denominator, the removal processes. The individual terms are:

K = All removal mechanisms, other than dilution by outside air. Specifically for air handlers with intentional filtration:

$$K = k + \eta R \qquad [3.2]$$

where:

η = Filter removal efficiency (dimensionless) for particles <3 micron aerodynamic diameter

R = Air recirculation rate (h^{-1})

k = Removal processes including physical deposition, chemical transformation (h^{-1})

I = Ventilation rate (h^{-1})

P = Penetration factor for particles entering from outdoors. This is commonly assumed to be unity for infiltrating air in residences. In this analysis, all outside air is assumed to enter through the mechanical system filters. Thus,

$$P = 1 - \eta \qquad [3.3]$$

S = Total of all indoor particle generation source strengths.

$$S = s_1 + s_2 \qquad [3.4]$$

where:

s_1 = source strength of tobacco smoke ($\mu g\ h^{-1}$)

s_2 = source strength of other particle sources including photocopier and background dust, lint, and microorganisms ($\mu g\ h^{-1}$)

V = Volume of the space (m^3)

C_o = Outdoor concentration ($\mu g m^{-3}$)

and

C_∞ = Steady-state indoor concentration ($\mu g m^{-3}$).

Collecting the terms in expressions 3.2 - 3.4 gives equation 3.5 that we examine parametrically.

$$C_\infty = \frac{IC_o(1-\eta) + (s_1 + s_2)/V}{I + k + \eta R} \quad ; \qquad [3.5]$$

Values for the physical, mechanical, and operational characteristics of one of the buildings studied in this project, #34, were chosen to evaluate the sensitivity of the steady-state indoor concentration, C_∞, on filter efficiency and number of smokers. The results are summarized in Fig. III.F.6.

The values used in equation 3.5 for the sensitivity analysis and their sources are:

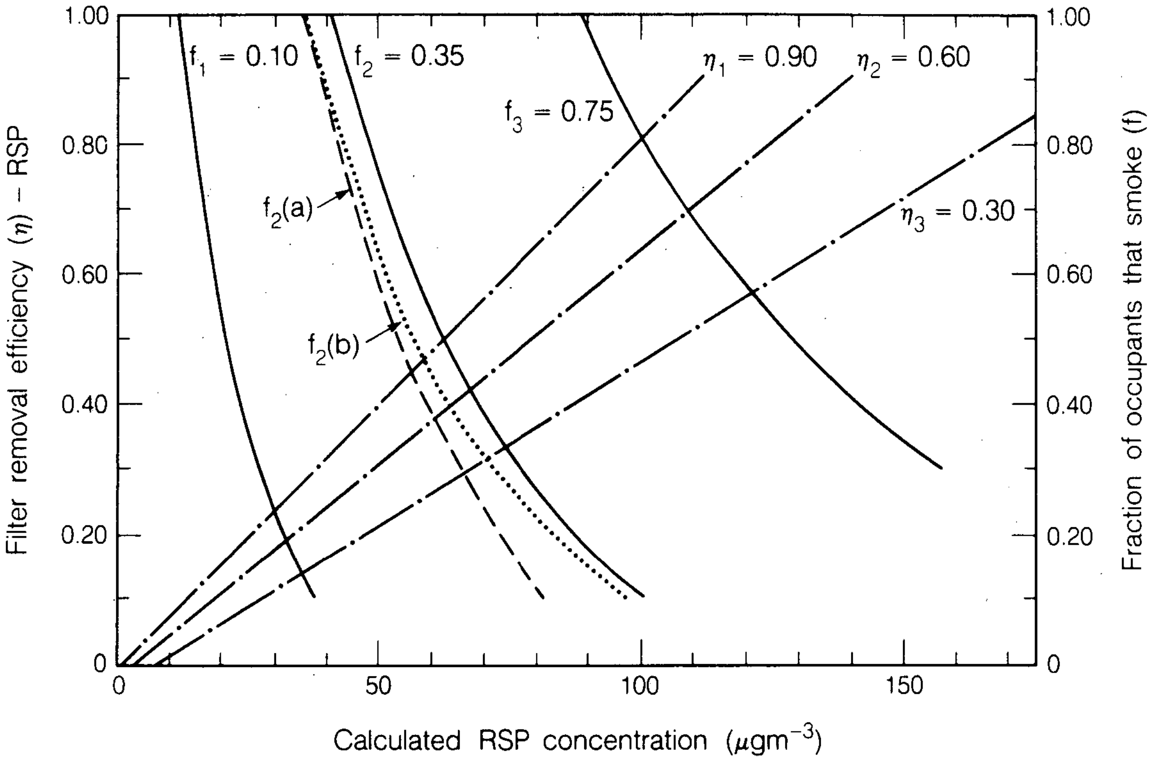
C_o =	16 μgm^{-3} (Measured in this study)
Occupancy =	1200 (Building manager's report)
I =	1.5 h^{-1} (Measured in this study by SF_6 tracer decay)
R =	2.4 h^{-1} (Calculated from observed return-supply SF_6 concentrations)
V =	76,400 m^3 (Building Plans)
k =	0.15 h^{-1} (Offermann et al., 1984)
η =	varied 0.1 to 1.0 (Rivers, 1982)
s_1 =	(2.0 cigarettes/smoker-hour)*(15x$10^3$$\mu$g/cigarette)*(Fraction of occupants that smoke) (occupancy) [fraction of occupants smoking 0.0 to 0.9 (Offermann, et al., 1984)]
s_2 =	(1.5 $\mu gm^{-3}h^{-1}$)*V (Offermann, et al., 1984)

A reasonable solution giving the average measured RSP concentration in nonsmoking areas (13 $\mu g/m^3$) has a filter efficiency of 86% with 10% of the occupants smoking. A 10% smoking rate in offices has been referred to by other researchers (Leaderer et al., 1984). However, other solutions involving fewer numbers of smokers and a lower (and more realistic) filter efficiency will yield the same concentration. If smoking area concentrations are included in the average, then a smoking rate of 10% and a filter efficiency of 28% will produce the observed arithmetic average concentration of 28 $\mu g/m^3$.

Filtering has an important impact on RSP concentrations. Yet its effect is overwhelmed by the increased source strength of additional smokers. For example, approximately doubling of the smoking rate from 35% to 75% would require increasing the filtering efficiency by a factor of five, from 20% to 100%, to maintain the same average RSP concentration of 87 $\mu g/m^3$. A calculation of the effectiveness of increasing the total recirculation rate by 0.5 ACH (21%) is shown by curve f_2(b) of Figure III.F.6. Concentrations should be reduced since the air is now passing through the filters more frequently. This is the case, but reductions are small, ranging from 2 to 11% as the filter efficiency improves. By comparison, a 0.5 ACH increase (33%) in the outside air ventilation rate (shown by curve f_2(a)) results in larger reductions, ranging from 11 to 19% as filter efficiency is reduced. It is also important to notice that the outdoor RSP concentrations (16 $\mu g/m^3$) are substantially lower than most of the calculated indoor concentrations in this example, whereas outdoor concentrations were actually higher than indoor nonsmoking concentrations at 65% of the buildings in this study. If a higher outdoor concentration is assumed, then indoor concentrations will also be higher, except for instances of filter efficiencies near 100%.

Additional study is necessary to refine and validate such calculations. In particular, the other natural removal processes in smoking areas may be more important than assumed. Aggregation followed by deposition on surfaces, electrostatic precipitation, filtering by occupant inhalation, and other unidentified effects could be effective mechanisms for removing smoke particles from the air before it circulates into the remainder of the building. They could help explain the observation that RSP concentrations remain high only in the localized smoking areas.

Sensitivity Analysis of HVAC Filter Efficiency and Source Strength on RSP Concentration (Building 34)



Filter removal efficiency constant; η_1, η_2, η_3 fraction of occupants smoking varied ——·——

Fraction of occupants that smoke constant; f_1, f_2, f_3 filter removal efficiency varied ————

f_2(a) Outside air ventilation increased from 1.5 to 2.0 ACH — — — —

f_2(b) Recirculation rate increased from 2.4 to 2.9 ACH ················

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Figure III.F.6

G. POLYCYCLIC AROMATIC HYDROCARBONS (PAH)

Seven polycyclic aromatic hydrocarbons (PAH) were chosen for analysis from the RSP samples taken in the study buildings. Table III.G.1 gives some basic information on the chosen compounds.

Table III.G.1

CHARACTERISTICS OF SELECTED POLYCYCLIC AROMATIC HYDROCARBONS

PAH	CHEMICAL FORMULA[1]	MELTING POINT(^{o}C)[1]	SUBLIMATION PT(^{o}C)	CARCINOGENICITY
CHRYSENE	$C_{18}H_{12}$	254	190	CARCINOGENIC
BENZO[b]-FLOURANTHENE	$C_{20}H_{12}$	168		CARCINOGENIC
BENZO[k]-FLUORANTHENE	$C_{20}H_{12}$	217		CARCINOGENIC
BENZO[a]-PYRENE	$C_{20}H_{12}$	178		CARCINOGENIC
DIBENZ[a,h]-ANTHRACENE	$C_{22}H_{14}$	262		CARCINOGENIC
BENZO[g,h,i]-PERYLENE	$C_{22}H_{12}$	279		?
INDENO[1,2,3-cd]-PYRENE	$C_{22}H_{12}$	---		CARCINOGENIC

[1] CLAR, 1964

The lower molecular weight PAH, naphthalene through benz[a]anthracene (nine in all) were originally to be included in the analysis. However, their stability under the test condition could not be guaranteed. The lower molecular weight PAH's tend to be more volatile at room temperature and since our samples were collected for 80 hours, it was doubtful that the amount remaining on the filters would be representative of the amount present in the air throughout the sampling period. A description of tests determining the retention and recovery of PAH by our system is discussed in Appendix B. The association of PAH, which are known to be carcinogenic, with RSP material, which can be lodged in the lungs of people, was the rationale for analyzing the RSP sample for its PAH content.

Results

The data presented in the following paragraphs have been corrected where values were below instrumental detection limits by assuming that these values were equal to one half of the detection limit and for the technique recovery fraction reported routinely by the contractor, McKesson Environmental. The actual PAH mass was calculated from the ratio of measured PAH to the recovery fraction. Because there is an estimated error between 25 and 50% for sampling and analysis, the results are tentative and exploratory.

Figure III.G.1 is a histogram of the distribution of all indoor measurements. Summary concentrations of the PAH are given in Appendix H where they are not segregated by the character of the site, i.e., smoking vs non-smoking. A comparison of the total PAH burden indoors, sorted into smoking vs non-smoking sites, is given in Table III.G.2 as are the ratios between indoor categories and the outdoor PAH concentrations. For the comparison, it can be seen that in five of the six cases, the PAH concentration is higher outdoors than in indoor non-smoking areas. The reverse is true in the comparison between indoor smoking and outdoor sites where only two of twelve (17%) of the outdoor sites exceed the building average smoking sites (Table III.G.2). For smoking sites, the geometric mean value is 9.4 ng/m^3 with a minimum of 2.0 ng/m^3. The high value of 50.4 ng/m^3 is associated with the highest RSP value (308 μg/m^3) from the cafeteria smoking section of Building #38. In this test (#38), the smoking area had a PAH concentration approximately 16 times greater than that found outdoors at nearby Building #39. Since PAH are known carcinogens (Table III.G.1), these concentrations should be regarded with concern where they are elevated above the ambient PAH burden. Almost all instances of high PAH concentrations are a result of high RSP concentrations.

To investigate whether certain PAH (or all PAH) have differentially higher concentrations in smoking, non-smoking, or outdoor atmospheres, Table III.G.3 was created. PAH concentrations were normalized by their respective RSP concentrations. Two sets of data are presented: the first contains data from buildings that have either smoking or non-smoking area PAH samples

COMMERCIAL BUILDING STUDY - POLYAROMATIC HYDROCARBONS (31 BUILDINGS)

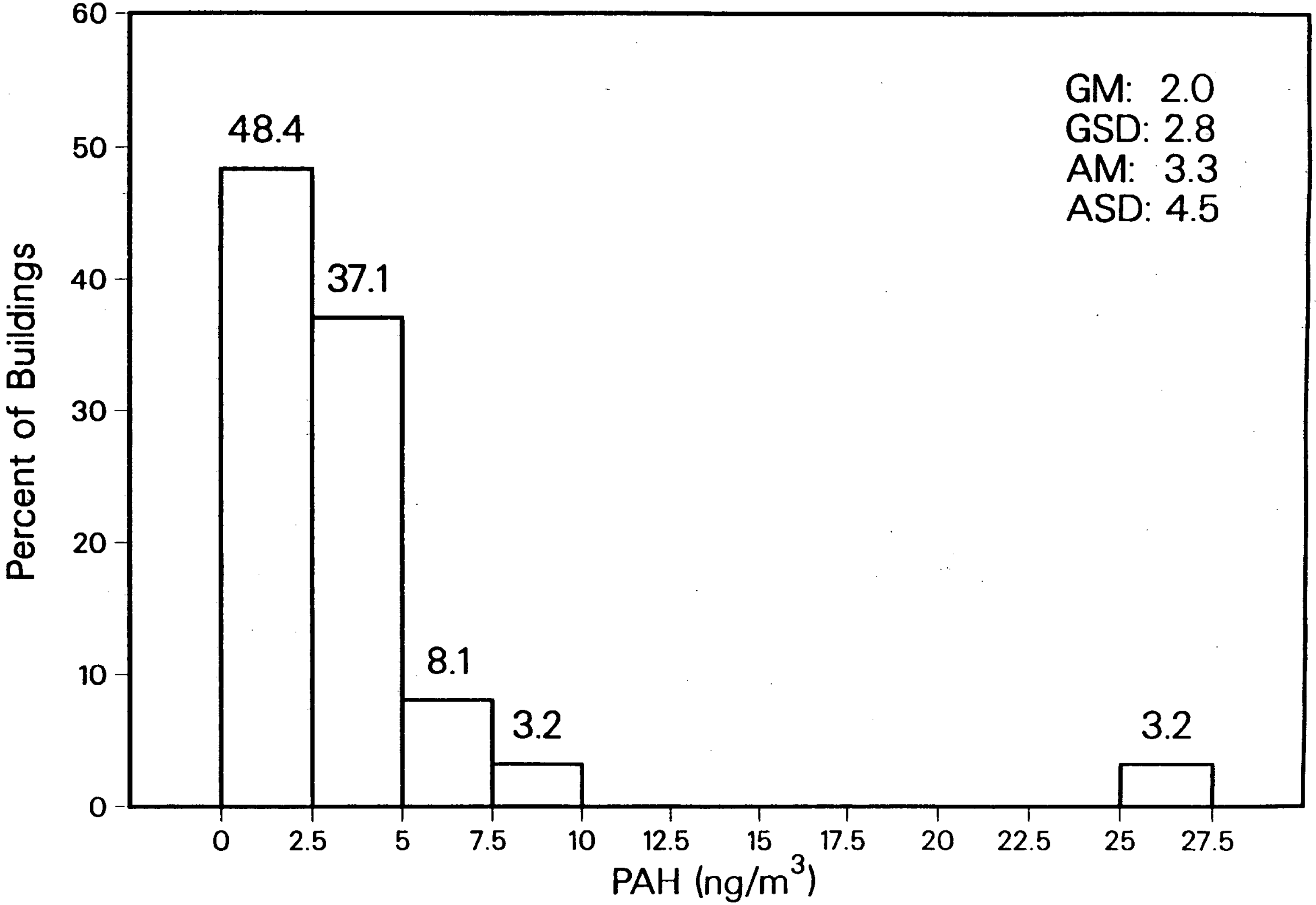

Figure III.G.1

TABLE III.G.2

POLYCYCLIC AROMATIC HYDROCARBON INDOOR-OUTDOOR CONCENTRATIONS AND RATIOS

BUILDING NO.	OUTDOOR (ngm^{-3})	INDOOR: (ngm^{-3}) NON-SMOKING	SMOKING(2)	MEAN(3)	RATIOS: INDOOR NON-SMOKING÷ OUTDOOR	INDOOR SMOKING÷ OUTDOOR	INDOOR MEAN÷ OUTDOOR
8	2.89	2.67	ND	2.67	0.93	NA	0.93
9	3.44	1.67	3.53	3.16	0.49	1.03	0.92
10	1.53	5.43	6.14	5.97	3.55	4.01	3.90
11	1.92	2.16	14.23	6.18	1.13	16.01	3.22
15	3.38	2.01	3.95	2.66	0.59	1.17	0.79
23	1.75	1.55	ND	1.55	0.89	NA	0.89
25	1.94	ND	2.38	2.38	NA	1.23	1.23
27	2.03	ND	2.04	2.04	NA	1.00	1.00
28	1.63	1.30	ND	1.30	0.80	NA	0.80
30	19.66	ND	12.62	12.62	NA	0.64	0.64
31	5.64	ND	23.74	23.74	NA	4.21	4.21
34	10.32	ND	12.24	12.24	NA	1.20	1.20
35	14.86	ND	8.69	8.69	NA	0.58	0.58
36(1)	4.85	ND	13.68	13.68	NA	2.82	2.82
37	6.26	ND	9.13	9.13	NA	1.46	1.46
AM	5.47	2.40	9.36	7.20	1.20	2.95	1.64
ASD	5.41	1.41	6.36	6.28	1.06	4.30	1.24
GM	3.84	2.15	7.32	5.02	0.96	1.73	1.31
GSD	2.29	1.60	2.18	2.46	1.90	2.58	1.94

(1) Repeated test of building #11
(2) Smoking within 30' radius of sites
(3) Arithmetic average of all sites in buildings

AM - ARITHMETIC MEAN
ASD - ARITHMETIC STANDARD DEVIATION
GM - GEOMETRIC MEAN
GSD - GEOMETRIC STANDARD DEVIATION
NA - NOT APPLICABLE
ND - NO DATA COLLECTED

Table III.G.3

RATIO OF PAH TO TOTAL RSP

		CHRYSENE (X 10-5)	BENZO(B)-FLUORO ANTHENE (X 10-5)	BENZO(K)-FLUORO ANTHENE (X 10-5)	BENZO(A)-PYRENE (X 10-5)	DIBENZ (A,H)-ANTHRA CENE (X 10-5)	BENZO (G,H,I) PERY LENE (X 10-5)	INDENO (1,2,3 -CD)-PYRENE (X 10-5)	TOTAL PAH (X 10-5)	RSP (ug/m-3)
BUILDINGS WITH NEARBY OUTDOOR AIR MEASUREMENTS										
SMOKING:										
	AM	1.77	2.99	1.24	1.79	0.93	3.41	1.34	13.48	77.5
	ASD	1.18	2.3	1.07	1.1	1.19	2.71	0.96	10.5	64.4
	GM	1.37	2.15	0.75	1.36	0.41	2.22	1.03	10.38	54.1
	GSD	2.19	2.43	3.23	2.34	3.77	3.06	2.19	2.2	2.5
NO. OF LOCATIONS = 22 NO. BUILDINGS = 15*										
NONSMOKING:										
	AM	1.98	3.4	1.31	1.42	2.07	6.41	2.64	19.23	14.5
	ASD	1.76	1.98	0.88	0.83	1.68	4.2	1.65	12.99	12.8
	GM	1.43	2.71	1	1.2	1.44	4.58	2.23	16.21	11.3
	GSD	2.35	2.23	2.28	1.86	2.58	2.66	1.82	1.91	2
NO. OF LOCATIONS = 13										
NO. BUILDINGS = 9**										
OUTDOOR:										
	AM	3.21	6.23	2.62	2.76	2.02	7.75	6.13	30.72	22.3
	ASD	3.16	4.66	2.01	2.46	2.65	5.75	6.83	27.52	18.9
	GM	1.66	3.53	1.53	1.62	1.04	4.42	4.05	20.34	16.8
	GSD	3.98	3.99	3.66	3.23	3.37	3.82	2.45	2.94	2.1
NO. OF BUILDINGS = 18^^										
FIVE BUILDINGS WITH SMOKING, NONSMOKING, AND OUTDOOR MEASUREMENTS\\										
SMOKING:										
	AM	1.8	3.42	1.39	1.78	1.51	4.65	1.01	15.56	63.4
	ASD	1.64	2.98	1.36	1.23	1.44	3.06	0.78	11.74	64.7
	GM	1.19	2.31	0.82	1.35	0.91	3.74	0.77	11.64	38.9
	GSD	2.69	2.66	3.13	2.38	3.08	2.05	2.21	2.29	2.9
NO. OF LOCATIONS = 10										
NONSMOKING:										
	AM	2.47	2.91	1.05	1.2	1.6	5.34	2.12	16.7	16.4
	ASD	2.27	1.24	0.58	0.55	0.8	4.58	1.16	5.96	16.2
	GM	1.91	2.67	0.9	1.07	1.43	2.66	1.85	15.64	12.8
	GSD	2.07	1.58	1.91	1.71	1.71	1.93	1.78	1.5	1.9
NO. OF LOCATIONS = 7										
OUTDOORS:										
	AM	2.45	6.72	2.73	2.32	4.31	10.61	3.56	32.67	7.8
	ASD	1.96	5.13	2.02	2.48	4.18	3.86	1.03	19.35	1.4
	GM	1.6	5.4	2.32	1.37	3.01	10.1	3.43	28.59	7.7
	GSD	3.19	2.05	2.39	3.25	2.52	1.41	1.35	1.77	1.2

* Building No.'s 9,10,11,12,14,15,25,27,30,31,34,35,36,37,40

** Building No.'s 8,9,10,11,12,13,15,23,28

^^ Building No.'s 8,9,10,11,15,20,21,23,25,27,28,30,31,34,35,36,37,39

\\ Building No.'s 9,10,11,12,15

AM - Arithmetic Mean ASD - Arithmetic standard deviation GM - Geometric mean GSD - Geometric standard deviation along with nearby outdoor samples; the second is from five buildings where smoking, non-smoking, and nearby outdoor air samples were simultaneously collected. This five-building set provides direct correspondence between these atmospheres. However in some cases, only one sample from a building represents a smoking or non-smoking zone. Although the lognormal distribution best represents these data, arithmetic statistics are included.

Outdoor samples most often have the highest PAH/RSP ratio and non-smoking area samples are often higher than smoking area samples. Tukey-Kramer and GT2 methods (Sokol and Rohlf, 1981) for multiple comparisons among pairs of mean ratios were run on these data and show that many of the differences between mean ratios are significant at the 0.05 level (caution is needed here due to the sampling and analysis error). The differences may be due to aging and volatilization of PAH with time. The preferentially elevated outdoor concentration ratios are due to outdoor sources, probably automobile and truck gasoline and diesel combustion byproducts. Benzo[b]fluoranthene, benzo[k]fluoranthene, dibenz[a,h]anthracene, benzo[g,h,i]perylene, indeno[1,2,3-cd]pyrene appear to be the most elevated outdoors. Another reason for the elevated outdoor PAH/RSP ratio may be that the outdoor sample was better preserved by the colder outdoor temperatures. Winter measurements in or near downtown Spokane ranged from 10.3 to 19.7 ng/m^3, whereas the spring measurements in Salem ranged from 1.5 to 3.4 ng/m^3 (Table III.G.2). The higher Spokane values may be due to the colder outdoor temperatures or to the higher density of vehicular traffic near the buildings.

H. BENZO[a]PYRENE (B[a]P)

Benzo[a]pyrene (B[a]P), a PAH, has been long identified as an environmental carcinogen which is produced by the combustion of organic materials. As such, it is the most frequently reported of the PAH group in studies of indoor air quality.

Results

In this study, 126 samples of RSP were analyzed for B[a]P concentrations (Figure III.H.1). Outside samples were analyzed for 20 sites, 52 indoor non-smoking sites, and 54 smoking sites. Figure III.H.2 shows a frequency histogram of the recorded whole building B[a]P concentrations.

Comparisons between the ratios of indoor B[a]P to outdoor are given in Table III.H.1. Concentration ratios of B[a]P in the indoor smoking samples to the outdoor samples are generally much greater than 1.0 with a mean of 7.6. The ratios for building-wide smoking samples to outdoor samples range from 0.3 to 61.2 with 12 of 15 buildings having a higher value than the outdoors. Non-smoking versus outdoor sample ratios range from 0.3 to 14.0 with 4 of 16 tests having non-smoking concentrations higher than the outdoors. As with the other PAH, high B[a]P concentrations are due to high RSP concentrations.

The nonsmoking average over all buildings of 0.4 ng/m^3 and smoking average of 1.1 ng/m^3 compare reasonably well with measurements made by Quackenboss, et al., (1985) in Wisconsin residences, where nonsmoking homes averaged 0.78 ng/m^3 and smoking homes averaged 1.35 ng/m^3.

Measurements of B[a]P outdoors at the test buildings on Table III.H.1 have a geometric mean of 0.31 ng/m^3. This is lower than that reported for typical urban sites in the U.S. at 121 National Air Sampling Network (NASN) sites which have a mean of 2.0 ng/m^3. Non-urban NASN sites ranged from <0.1 to 0.4 ng/m^3. In the United Kingdom suburban sites were reported to have 2-4 ng/m^3 (Butler and Crossley, 1980). Indoor values for B[a]P concentrations have been reported to be as high as 22 ng/m^3 in test chambers with smoking. Cigarette smoking has been shown to produce 3.5 to 4.4×10^{-5} mg/cigarette B[a]P from the mainstream smoke and 1.35 to 1.99×10^{-4} mg/cigarette from the side stream (NAS, 1981). Different sources, however, probably have a different spectrum of PAH depending upon their organic source and temperature of combustion (Baum, 1978). At TSP concentrations of 224-480 μg/m^3 in public smoking areas, concentrations of B[a]P between 7 and 22 ng/m^3 have been reported. Within the same range of values for RSP, a smaller proportion of the

COMMERCIAL BUILDING STUDY - BENZO (a) PYRENE (126 SAMPLING SITES)

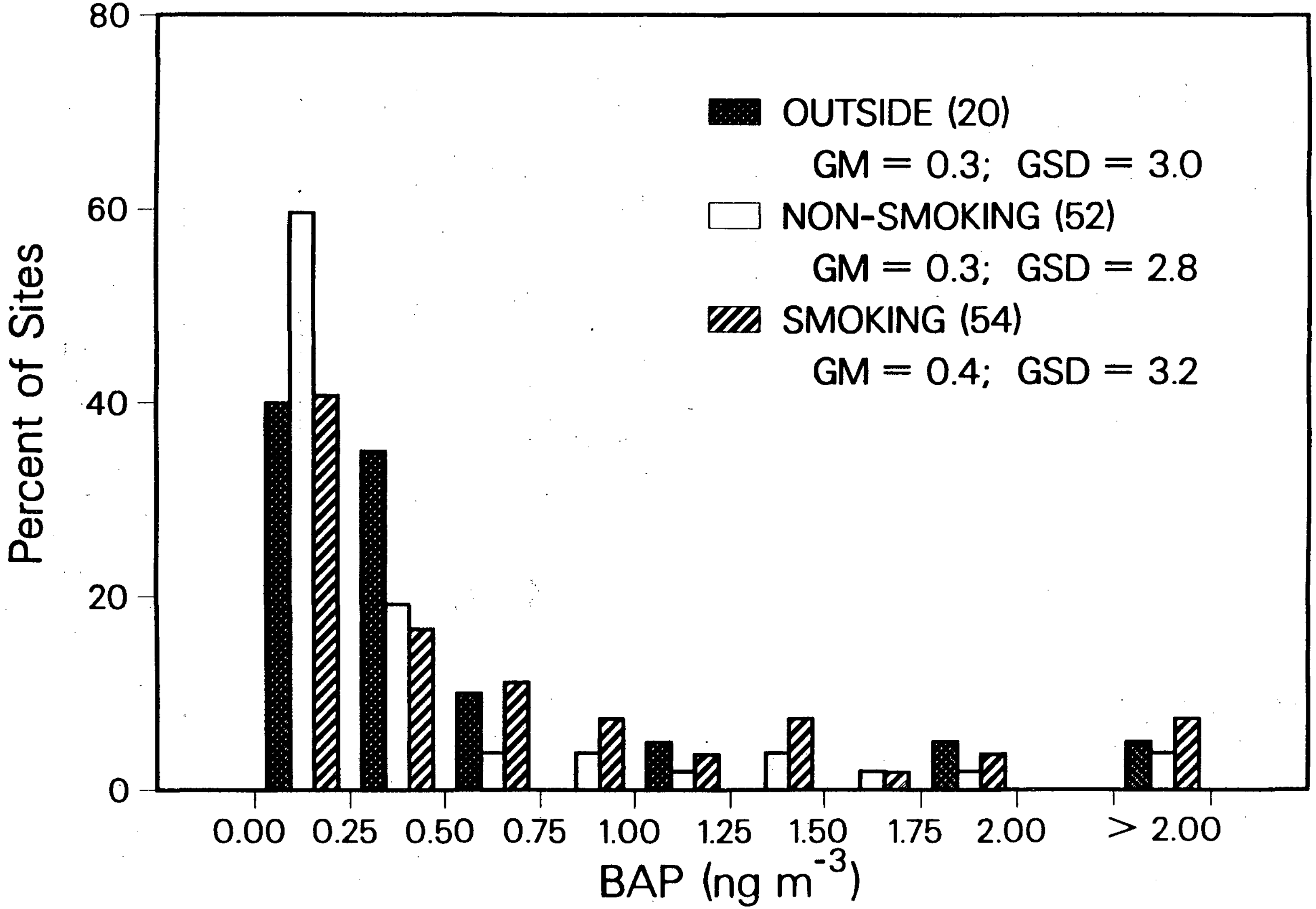

Figure III.H.1

COMMERCIAL BUILDING STUDY -
BENZO (a) PYRENE (31 BUILDINGS)

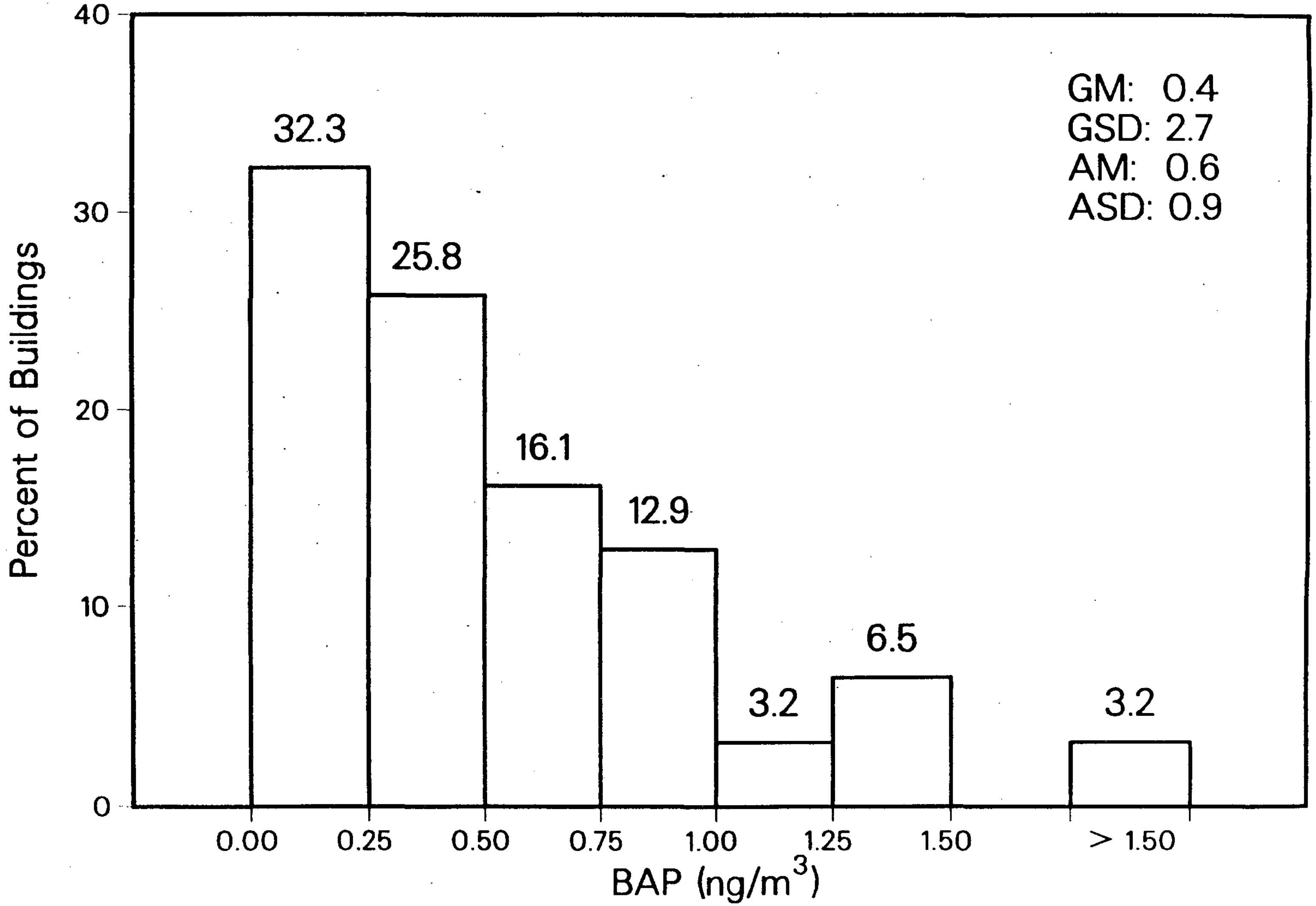

Figure III.H.2

TABLE III.H.1

BENZO-A-PYRENE INDOOR-OUTDOOR CONCENTRATIONS AND RATIOS

BUILDING NO.	OUTDOOR (ngm^{-3})	INDOOR: (ngm^{-3}) NON-SMOKING	SMOKING(2)	MEAN(3)	RATIOS: INDOOR NON-SMOKING÷ OUTDOOR	INDOOR SMOKING÷ OUTDOOR	INDOOR MEAN÷ OUTDOOR
8	0.22	0.18	ND	0.18	0.82	NA	0.82
9	0.27	0.09	0.37	0.31	0.33	1.37	1.15
10	0.04	0.56	1.14	1.00	14.00	28.50	25.00
11	0.09	0.17	2.45	0.93	1.88	61.25	23.25
15	0.34	0.13	0.35	0.20	0.39	1.06	0.59
16	0.29	0.23	0.57	0.43	0.78	1.97	1.48
23	0.11	0.10	ND	0.10	0.91	NA	0.91
25	0.12	0.10	0.25	0.15	0.83	2.08	1.25
26	0.29	0.23	0.57	0.43	0.78	1.97	1.48
27	0.38	0.26	0.26	0.26	0.68	0.68	0.68
28	0.23	0.30	0.28	0.29	1.30	1.22	1.26
30	2.84	1.35	1.44	1.36	0.48	0.51	0.48
31	0.58	0.25	3.60	1.36	0.43	6.21	2.34
34	0.73	0.24	1.45	0.72	0.33	1.99	0.99
35	1.25	1.10	1.65	1.21	0.88	1.32	0.97
36(1)	0.40	0.19	1.44	0.69	0.48	3.60	1.73
37	0.42	0.98	0.67	0.81	2.34	1.60	1.93
39	0.47	ND	0.12	0.12	NA	0.26	0.26
AM	0.52	0.39	1.07	0.60	1.68	7.57	3.83
ASD	0.66	0.40	0.98	0.45	2.33	16.42	7.66
GM	0.31	0.27	0.71	0.43	0.86	2.16	1.43
GSD	2.74	2.36	2.69	2.43	2.56	4.17	3.29

(1) Repeated test of building #11

(2) Smoking within 30' radius of sites

(3) Arithmetic average of all sites in buildings

AM - ARITHMETIC MEAN
ASD - ARITHMETIC STANDARD DEVIATION
GM - GEOMETRIC MEAN
GSD - GEOMETRIC STANDARD DEVIATION
NA - NOT APPLICABLE
ND - NO DATA COLLECTED

particulate sample than TSP, the present study has found B[a]P concentrations of 9.69 ng/m^3 associated with 308 $\mu g/m^3$ of RSP (Tables III.F.1 and III.H.1). These are maximum values for both absolute B[a]P and RSP concentrations in all our tests. As for all PAH and RSP, smoking elevates the B[a]P, PAH, and RSP over the outdoor and non-smoking values throughout this building study. Due to the carcinogenic nature of B[a]P and PAH, any elevation of their concentrations above the clean non-urban air ambient levels of about 0.4 ng/m^3 may be contributing to health risks.

I. FORMALDEHYDE (HCHO)

Formaldehyde (HCHO) is a pungent organic compound usually occurring as a gas where found in the environment. It is an irritant to the mucous membranes and respiratory system in humans. In some cases skin contact causes an allergic reaction (dermatitis). Evidence has been presented that exposure to high levels of HCHO causes cancer in laboratory animals. Therefore, formaldehyde must be considered a suspected human carcinogen. ASHRAE has set a guideline level of 100 ppb for HCHO (ASHRAE, 1981).

The primary indoor sources are urea-formaldehyde bonded wood products such as fiberboard, plywood, and particleboard. The urea - HCHO bonds break down through complex chemical reactions causing HCHO in these materials to outgas to the air at a rate dependent on temperature and humidity (Meyer and Hermanns, 1985).

Results

Formaldehyde (HCHO) monitoring was performed indoors during all 40 building measurement periods at 401 sample sites as described in Section IIB. The samples were analyzed at LBL using methods described by Geisling et al. (1982). Figure III.I.1 is a histogram of average building concentrations for all 40 building measurements, while Figure III.I.2 shows the distribution of concentrations at 401 individual sampling sites. With a minimum detection level of 20 ppb, only twenty one (53%) of the buildings tested had a building mean concentration above the detection limit (Appendix F).

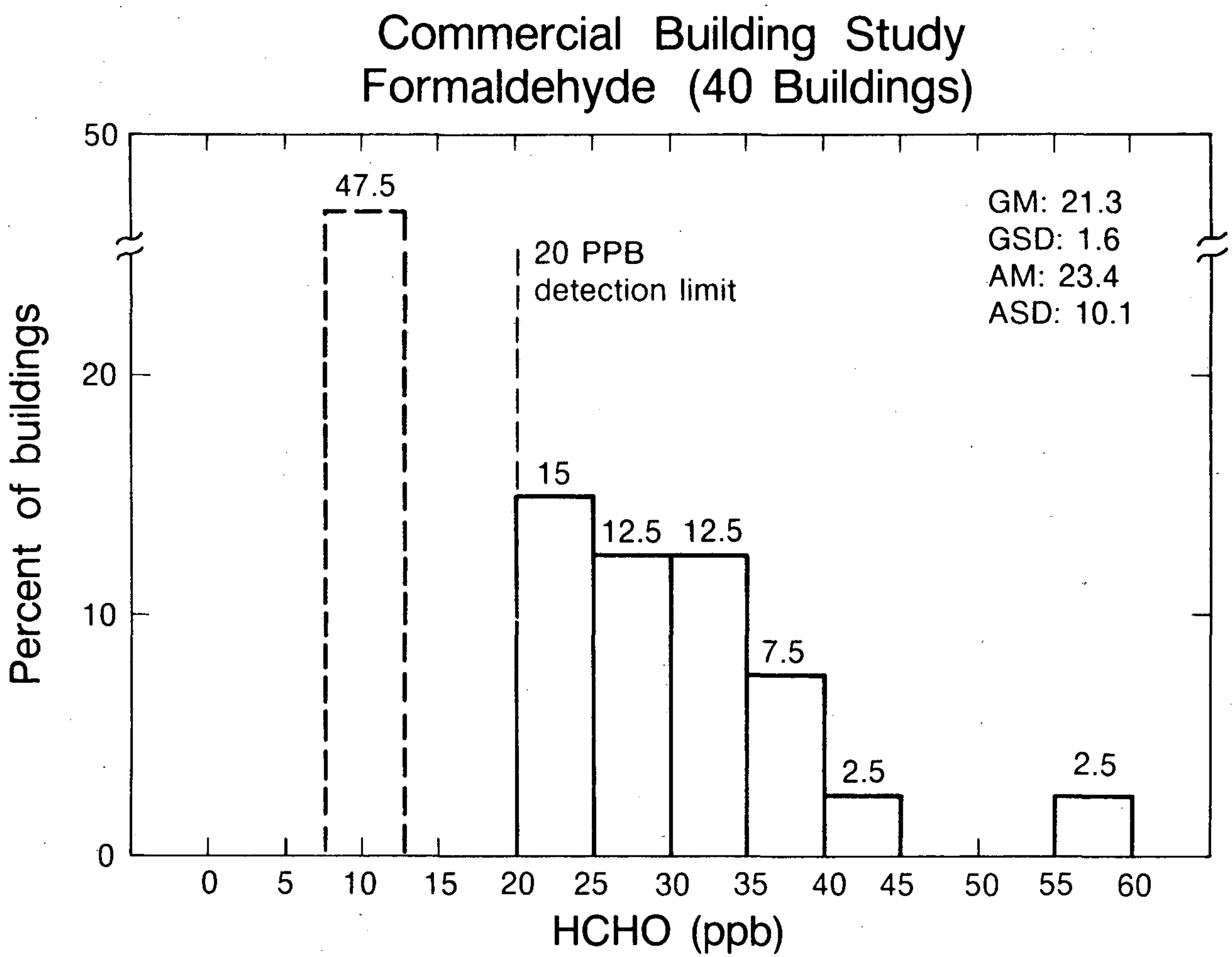

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Figure III.I.1

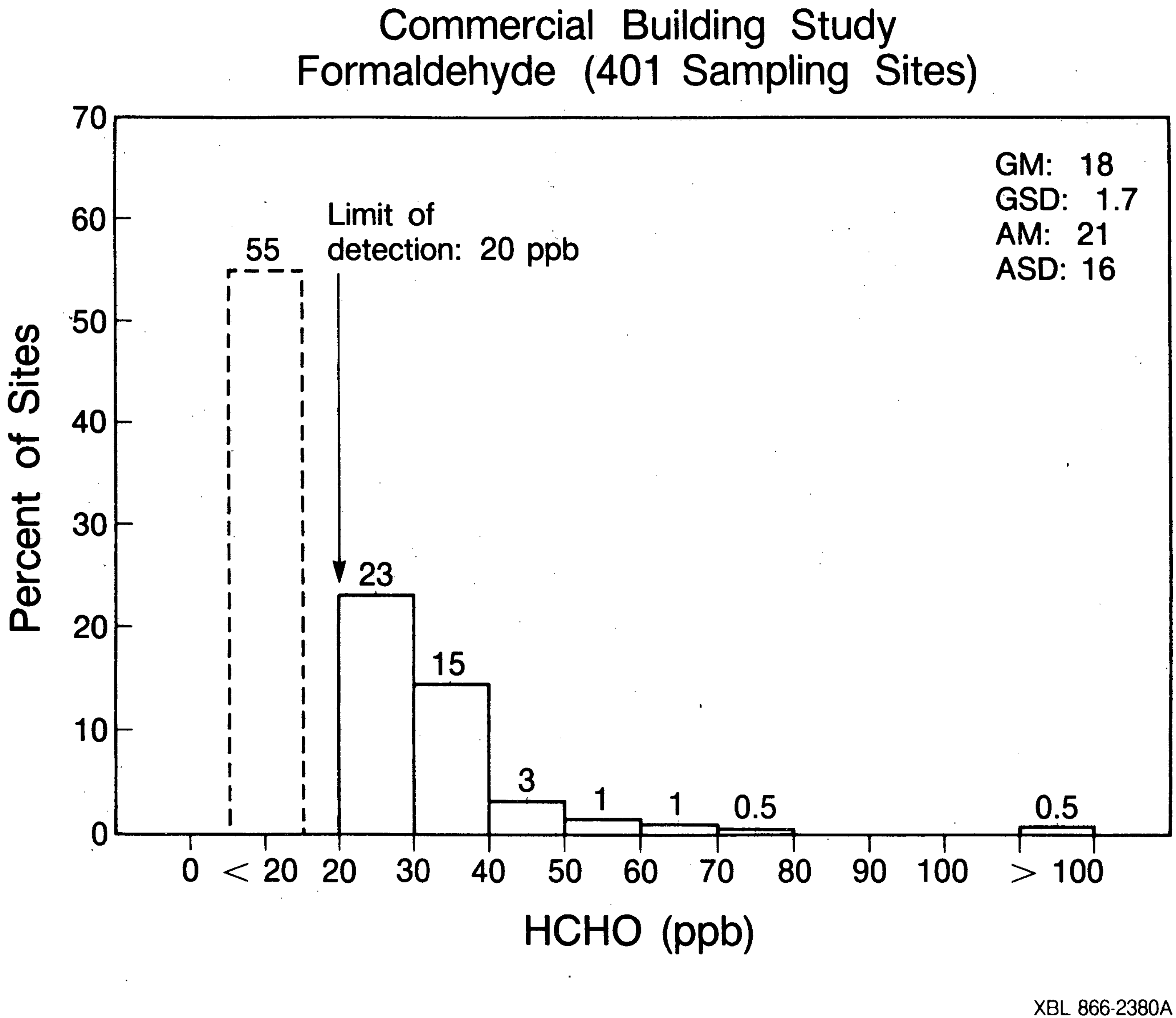


Figure III.I.2

Similarly, 45% of the individual site measurements are above the detection limit. None of the buildings had whole-building means that approached the ASHRAE guideline of 100 ppb; only one of the 401 sampling sites exceeded this value. Therefore, few of these buildings have formaldehyde concentrations of concern. The remaining discussion concentrates on the three buildings in which somewhat elevated levels were observed.

Three buildings (#4, #5 and #27) showed elevated indoor mean HCHO levels. In Building #4, the mean level was 56 ppb with a range from the six sample sites of 38 to 75 ppb. The most probable explanation of the elevated HCHO is the relatively high outgassing rates of HCHO from new HCHO-bonded materials in this new building (0.5 years). This, coupled with a ventilation rate of 0.6 ACH, below the 1.5 ACH average for building in this study, could have resulted in the elevated levels. Although no outdoor measurement was made, nothing pointed to a strong outdoor source.

Building #5, the second smallest building in the sample with a volume of 144,100 ft^3 and with a ventilation rate of 1.7 air changes per hour had a whole-building mean HCHO concentration of 38 ppb. This 16-year-old building had an annex added in 1980 - 1981. We suspect that the extensive use of veneer plywood in the addition may have contributed to the elevated levels.

Building #27 is located near midtown Spokane, WA where fairly heavy urban traffic occurs during peak commute hours. It is a four-story building with distinct ventilation systems in two separate zones. The basement is served by one system with an outside air intake at ground level near a parking area and a low ventilation rate of 0.2 ACH. Elevated HCHO concentrations occur primarily in this basement with the three sites averaging 60 ppb (58 - 62 ppb) HCHO. Only one of five measurements on the above-ground floors registered a concentration (37 ppb) that was above detection limits. Other pollutants measured at basement sites were not significantly elevated. The site with 62 ppb HCHO was located in a print shop with local ventilation provided for two of five printing machines. Possibly the solvents, inks, adhesives, and paper materials used in print production in this shop were responsible for the elevated HCHO levels. If this print shop is the source of the HCHO then apparently little communication exists between the two ventilation zones in this building. In fact, very few areas of communication were observed with only sealed stairwells and elevator shafts connecting the basement with other floors. Since the materials used in printing and report production are a potential source for HCHO, some attention should be paid to other volatile organic chemicals which may be associated with these products.

The maximum single site reading of 192 ppb in for this study Building #20 is inexplicable. No obvious reason for this elevated, HCHO site mean value was found. The site was located in a high school cafeteria during the summer when the use of the area was limited. Since no other single sampler registered above the minimum detectable level throughout the building, the result should probably be viewed as an anomalous reading even though it was the mean of two identically prepared, analyzed, and exposed sample tubes. As a result of the reading at this site, a second specialized test of the HCHO concentration was conducted in this building approximately one month after the first. Five sites were chosen; one at the original location, one 30 feet away in the same cafeteria, and three sites in rooms or areas with direct communication to the suspect site. These samplers all recorded values below detectable limits for HCHO. Therefore, the original high reading should be viewed as a transient event not representative of the building as a system.

In Building #28, a single very high reading (179 ppb) in one of the two sample tubes was not replicated in the companion tube (below detection). Since all the other sites had below detectable levels, this single sample tube result should also be regarded as spurious.

The important finding in the survey of indoor HCHO in these buildings is that levels are generally very low. Presumably, this is the result of there being few strong sources of HCHO in these commercial buildings.

J. RADON (^{222}RN)

Radon (Rn-222) is a chemically inert, radioactive gas which arises naturally in the environment through a series of decay steps from uranium-238. Radon, in turn, decays through a chain of chemically-active daughter products which are a portion of the naturally-occurring radioactive background to which everyone is exposed. Some fraction of the daughters attach to airborne particles while the remainder are unattached. If inhaled, the particles can become attached to lung tissue where the alpha-particle decays of polonium 218 and polonium 214 transfer considerable energy to the near surface cells of the lung. This process is believed to be responsible for induction of lung cancers.

Radon has been implicated as the major cause of lung cancer among non-smokers and it may be a contributing factor in lung cancer initiation among smokers (NCRP, 1984; Nero et al., 1985). Concentrations of radon are usually less than 0.5 pCi/l outdoors, but may exceed BPA guidelines of 5 pCi/l or NCRP guidelines of 8 pCi/l inside buildings, contributing to a substantial background radiation exposure.

Results

One or more radon measurements were made in each of the 38 test buildings using type SF TRAK-ETCH®, detectors which were deployed during the period of intensive testing for each building. These detectors were each left in place for approximately 90 days. A summary of city and site results are given in Table III.J.1. See Figures III.J.1 and III.J.2 for the distributions of building average and site concentrations. Since the detectors are long-term monitors, the results cannot be correlated with as much certainty to the ventilation rate or the other pollutant samplers which measured over different time intervals.

For the set of 40 building measurements, the geometric mean radon concentration measured is 0.5 pCi/l with a geometric standard deviation of 3.1 based upon the full sample set of 163 site measurements (Figures III.J.1 and III.J.2). Plotting the results of individual measurement sites on a cumulative probability plot, Figure III.J.3, indicates that the individual sites fit the expected lognormal distribution. This figure suggests that approximately 11% of the sampling sites taken in a similar building population would have readings above the ASHRAE guideline level of 2 pCi/l, 3.5% above the EPA guideline of 4pCi/L, 2.5% above the BPA mitigation action level of 5 pCi/l, and approximately 0.75% above the NCRP guideline of 8 pCi/l.

TABLE III.J.1

RADON SUMMARY
by
City and Site
(pCi l^{-1})

		West		East	
CITY	Statistic	Portland	Salem	Spokane	Cheney
	AM (ASD)	0.7 (0.4)	0.3 (0.1)	1.2 (0.5)	4.2
	No. Buildings	11	9	18	2
SITE	Floor:	Arithmetic Mean (Standard Deviation)			
	Basement	0.7(0.6)	0.7(0.5)	1.8(0.9)	8.5(-)
	1st	0.8(0.9)	0.1(0.1)	1.2(0.5)	5.1(-)
	2nd	0.6(-)	0.4(0.3)	0.7(0.3)	3.1(-)
	3rd	0.4(-)	0.2(0.1)	0.6(-)	4.1(-)
	4th	0.1(-)	0.2(0.12)	0.5(-)	-
	5th	0.5(-)	0.1(-)	1.6(-)	-
	6-9th	0.4(-)	-	0.7(-)	-
	≥10th	0.6(-)	-	0.3(-)	-

Figure III.J.1

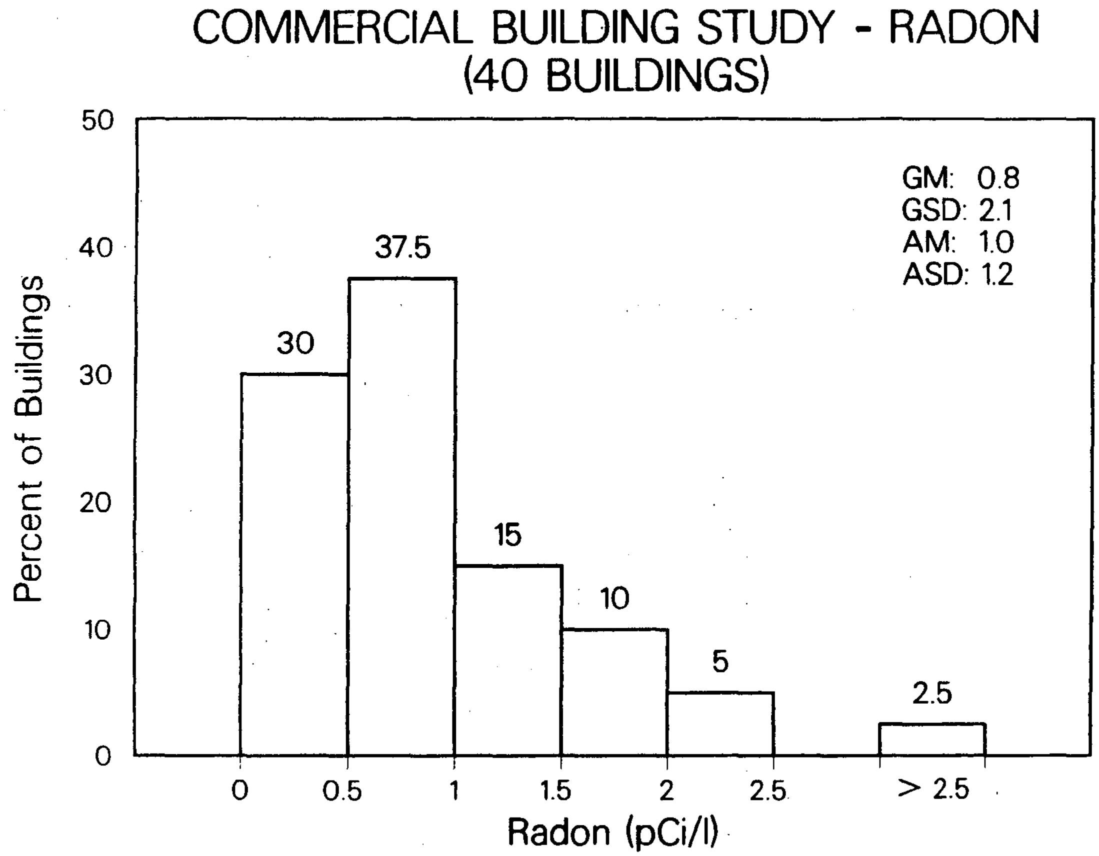


Figure III.J.2

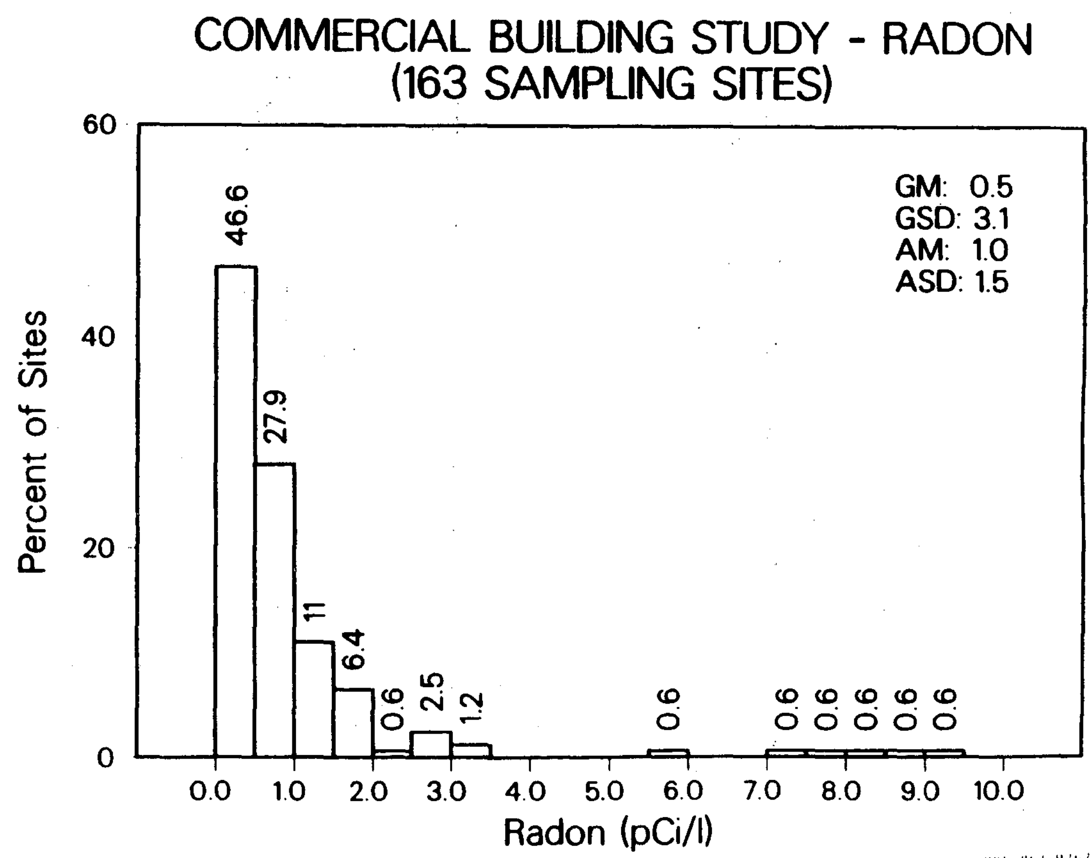
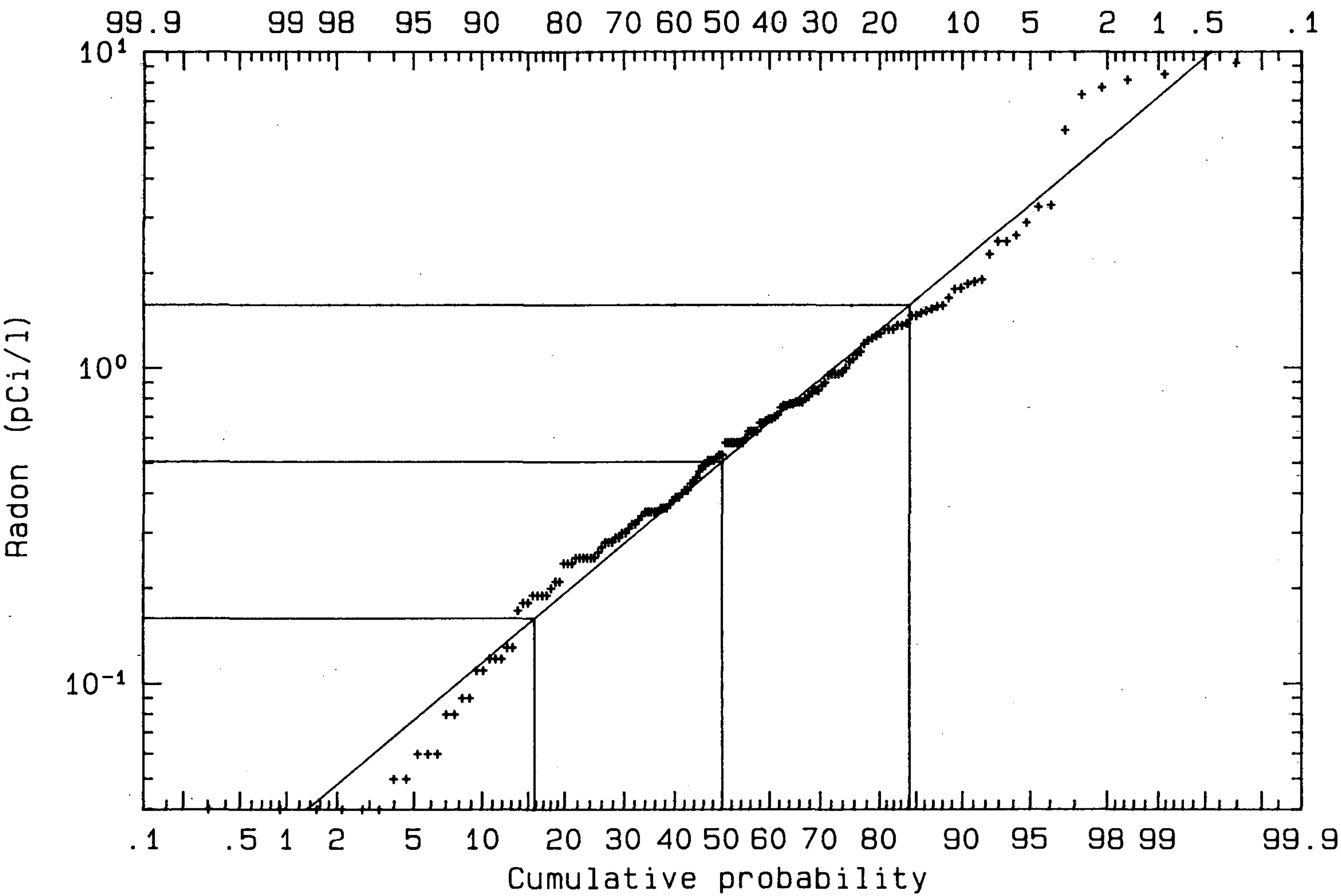


Figure III.J.3



COMMERCIAL BUILDING STUDY (163 SAMPLING SITES)

The arithmetic average of all the sample results for each building range from 0.2 pCi/l (Buildings #8, 10, and #36) to a high of 7.8 pCi/l (Building #32) with an arithmetic mean for all buildings of 1.0 pCi/l and standard deviation of 1.2 pCi/l.

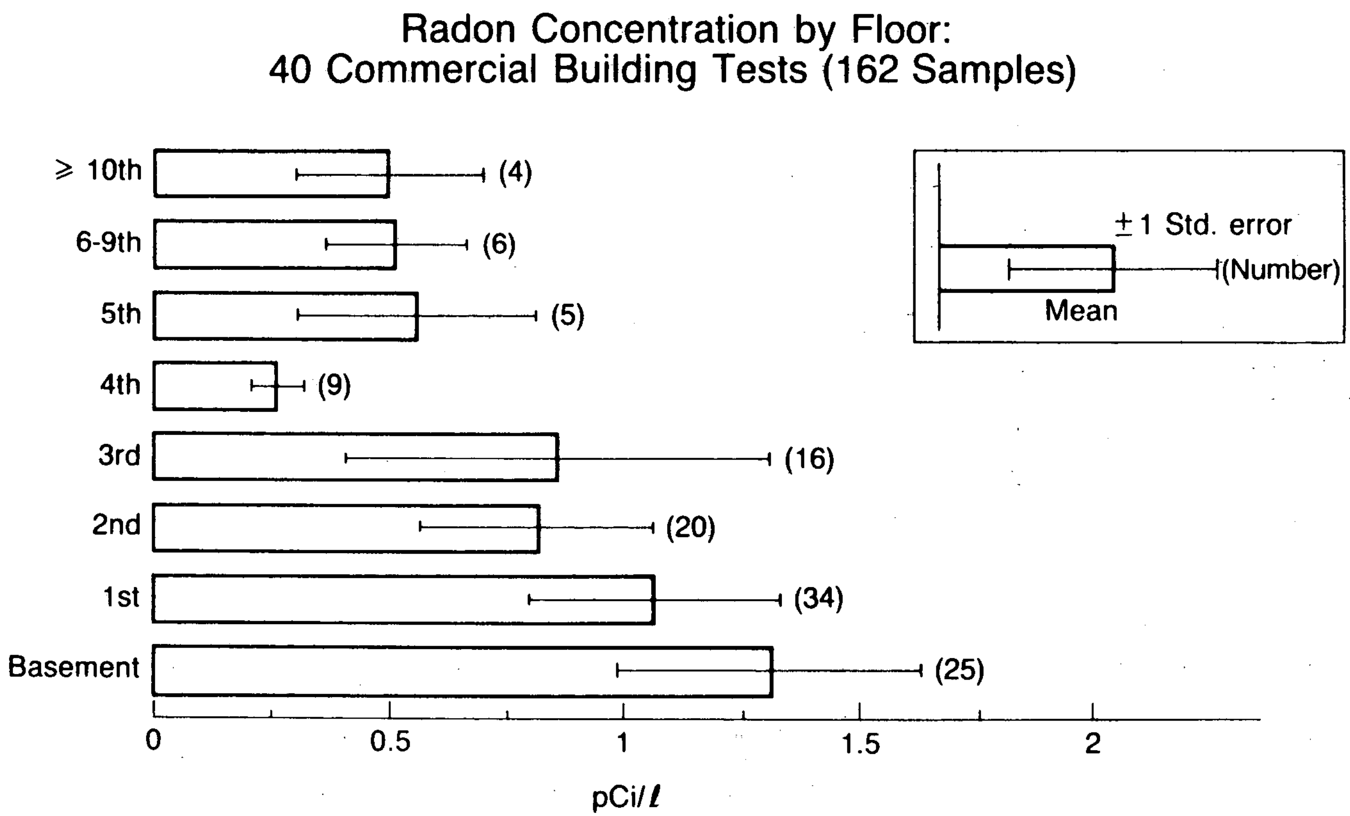
Even when using the ASHRAE guidelines for maximum permissible radon exposure, only three of these buildings have a building mean above this guideline (2 pCi/l); Building #17 at 2.2 pCi/l, Building #20 with 2.1 pCi/l, and Building #32 with 7.8 pCi/l. The latter building (#32) is 72 years old and has a large area of exposed soil in its basement from which ventilation air is drawn. It will be discussed in more detail in Chapter V. Building #17, a junior high school, was tested twice, once in spring and once in winter. The spring radon measurement in Building #17 showed a building average of 2.2 pCi/l. The building average winter measurement (identified as Building #30) was 1.9 pCi/l.

Under spring ventilation conditions (Building #17), the two radon measurement sites recorded 1.9 pCi/l and 2.5 pCi/l. Since this building is only one story and has a crawl space substructure, both sites are on the main floor. During the winter test (Building #30) the two sites were measured at 1.6 pCi/l and 2.3 pCi/l respectively.

Building #20 is a three story high school building with a finished basement where only two summer measurements were taken for the whole building. One of the radon sampling sites was located in the basement and it registered 2.6 pCi/l. The second detector placed on the ground floor, measured 1.5 pCi/l.

Table III.J.1 gives a summary of the distribution of radon concentration by city and by building floor. Figure III.J.4 presents the radon concentration as a function of height. Portland and Salem, Oregon have relatively low readings and the lower floors also tend to be higher than the upper floors. Spokane shows a higher mean (1.2 pCi/l) and Cheney, dominated by the elevated readings in one of only two buildings, average 4.2 pCi/l. In the Spokane summary by floor, it is evident that the basement and ground floors tend to higher levels than the upper floors. The elevated radon level at the fifth floor in Spokane is due to a single reading of 2.5 pCi/l in one site in Building #34

Figure III.J.4



*Means based on floor average

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(5th floor mean 1.6 pCi/l, whole building 0.8 pCi/l) which is probably the result of measurement uncertainty.

Abu-Jarad and Fremlin (1982) reported on a study of radon in two high-rise buildings in Great Britain where they found a similar distribution of radon progeny measured in working levels above the basement and ground floor levels.

In their study of a 17 and 11 story building, correlations of r=0.71 and r=0.63 between radon daughter activity and inverse ventilation rate were found. While noting that the elevated basement concentrations probably were due mainly to emanation from the ground, they concluded that the radon daughter concentration above the first floor was dependent upon the variation of the ventilation rate not strictly upon height above ground.

In studies of residences, radon transport from soil into basements and through crawl spaces to the house interior is accepted as the primary cause of elevated radon levels (Nero and Nazaroff, 1984). The geometric mean concentration for 552 United States residences monitored in several different studies was 0.9 pCi/l (Nero et al., 1986). Similarly, in Thor's study of 267 BPA employee homes, the geometric mean was 0.8 pCi/l (Thor, 1984). These values are above the geometric mean of 0.5 pCi/l found in this commercial buildings study (Figure III.J.1). The elevated levels found in basements and especially in a building with an unfinished basement in this sample also suggests that soil and earth materials are the major sources of radon. Apparently, the soil material from which the radon is derived is either permeable enough or has sufficient radium concentrations, or both, to encourage radon accumulation in the substructure.

The flow of radon gas from the soil to the interior of buildings is driven by a pressure gradient set up by external meteorological factors interacting with the building structure and interior environment. In residential radon studies, higher radon entry rates are known to be due to pressure-driven convective flow rather than molecular diffusion (Nero and Nazaroff, 1984). Convective flow is induced by structure depressurization caused by stack effect from the pressure gradient set up by differing indoor and outdoor temperatures, wind-created pressure differences, and in some cases exhaust ventilation devices. In the mechanically-ventilated buildings of this study, the average ventilation rate is higher than in residences and the forced air system alters these indoor-outdoor interactions and pressure distribution. However, it can still be seen that, in some cases, an obvious source of radon and the location of its entry into the building envelope is through the soil's contact with the basement or open soil/rock in unfinished basements.

REFERENCES

Abu-Jarad, F. and Fremlin, J.H. (1982). The activity of radon daughters in high-rise buildings and the influence of soil emanation. Environment International 8:37-43.

ASHRAE Standard 62(1981). Ventilation for acceptable indoor air quality, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta.

ASHRAE Standard 62-1981R (1986).[Draft standard]. Ventilation for acceptable indoor air quality, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta.

Berk, J.V., Young, R.A., Brown, S.R., Hollowell, C.D.(1981). Impact of energy-conserving retrofits on indoor air quality in residential housing, Paper 81-22.1 presented at the 74th Annual Meeting of the Air Pollution Control Association, Philadelphia, LBL Report # LBL-12189.

Clar, E.J. (1964). Polycyclic hydrocarbons, 2vol., Academic Press Inc., New York.

Fisk,W.J., Spencer,R.K., Grimsrud,D.T., Offermann,F.J., Pedersen,B., Sextro,R.(1984) Indoor air quality control techniques: a critical review", Lawrence Berkeley Laboratory Report No. LBL-16493.

Geisling, K.L., Tashima, M.K., Girman, J.R., Miksch, R.R., Rappaport, S.M.(1982). A passive sampling device for determining formaldehyde in indoor air, Environment International 8:153-158.

Givoni, B. (1976). Man, climate and architecture. Applied Science Publishers, London, UK.

Good, B.W., Vilcins, G., Harvey, W.R., Clabo, D.A., Lewis, A.L.(1982). Effect of cigarette smoking on residential NO2 levels. Environment International 8:167-176.

Leaderer, B.P., Cain, W.S., Isseroff, R., Bergland, L.G.(1984). Ventilation requirements in buildings--II. particulate matter and carbon monoxide from cigarette smoking, Atmos. Environ., 18:99-106.

Meyer B. and Hermanns, K. (1985). Reducing indoor air formaldehyde concentrations. Journal of the Air Pollution Control Association 35:816-821.

NAS (1981). Indoor pollutants, National Research Council, Washington, DC:National Academy Press.

NCRP (1984). Evaluation of occupational and environmental exposures to radon and radon daughters in the United States, National Council on Radiation Protection and Measurements, Bethesda, MD, NCRP Report No. 78.

NRC (1977). Carbon monoxide, National Research Council, Washington, DC:National Academy Press.

Nero, A.V. and Nazaroff, W.W. (1984). Characterizing the Source of Radon Indoors. Radiation Protection Dosimetry 7:23-39.

Nero, A.V., Schwehr, M.B., Nazaroff, W.W., Revzan, K.L.(1986). Distribution of airborne radon 222 concentrations in U.S. homes, Science 234:992-997.

Nero, A.V., Sextro, R.G., Doyle, S.M., Moed, B.A., Nazaroff, W.W., Revzan, K.L., Schwehr, M.B. (1985). Characterizing the sources, range, and environmental influences of radon 222 and its decay products, The Science of the Total Environment 45:233-244.

Offermann, F.J., Girman, J.G., Sextro, R.G.(1984a). Controlling indoor air pollution from tobacco smoke: models and measurements, Proceedings of the 3rd International Conference on Indoor Air Quality and Climate, Stockholm, Vol.I, pp 257-264.

Quackenboss, J.J., Kaarakka, P., Duffy, C.P., Roher, K.M., Kanarek, M.S., Flickinger, J.(1985). Energy conservation through weatherization and indoor air quality, Final Report to Wisconsin Power and Light Co.

Rajhans, G.S.(1983). Indoor air quality and CO2 levels. Occupational Health in Ontario 4:160-167.

Rivers, R.D.(1982). Predicting particulate air quality in recirculatory ventilation systems, ASHRAE Trans. 88(I):929-949.

Sexton, K., Liu, K., Treitman, R.D., Spengler, J.D., Turner, W.A.(1986). Characterization of indoor air quality in wood-burning residences, Environment International 12:265-278.

Sodergren,D., and Puntilla,A. (1983). A CO2-controlled ventilation system, Document D7:1983 of the Swedish Council for Building Research, Stockholm.

Sokal, R.R., and Rohlf, F.J. (1981). Biometry, 2nd ed., W.H. Freeman and Company, San Francisco.

Thor, P.W.(1984). BPA radon field monitoring study, in Doing Better: Setting an agenda for the second decade, ACEEE 1984 Summer Study on Energy Efficiency in Buildings, Santa Cruz CA, B: 283-298, American Council for an Energy Efficient Economy, Washington, DC.

Turiel,I., and Rudy,J.V. (1982). Occupant Generated CO2 as an indicator of ventilation rate, ASHRAE Trans. 88(1):197-210.

IV. VENTILATION MEASUREMENT RESULTS

A. INTRODUCTION

A major portion of this study is the characterization of actual ventilation rates in the commercial building stock of the Pacific Northwest. As described below, this effort is complicated by the diversity of mechanical systems present in the buildings and by the necessity to obtain short-term measurement results. The inability to monitor individual buildings over extended periods of time meant that single measurements in many buildings had to be used to construct a picture of ventilation conditions in the buildings under study. This is somewhat akin to describing the activity of a typical skier at a ski resort by taking a single photograph of the entire resort, counting the number of persons skiing, riding lifts, and relaxing at the lodge to determine the amount of time spent in each activity. In fact, the analogy is not strict since the operation of each building's ventilation system was observed over time to obtain a sense of its average damper settings. The ventilation rate was then measured after adjusting the outdoor air dampers to the average position observed.

B. DESCRIPTION OF SYSTEMS

Although certain HVAC system design elements are similar in many buildings (see SMACNA manual (1983) for generic descriptions), no two actual installations were the same (Appendix I). Placement of supply diffusers, return plenums, and outside air and exhaust dampers, affects air distribution and the quality of incoming outside air. Sizing and selection of various components (filters, damper actuators, blowers, diffusers, controllers) affects filtration, actual air delivery, dependability, and response to environmental parameters. Buildings are occasionally remodeled with changes in size, configuration, partitioning, and occupant activities with no corresponding changes made to the ventilation system. Over the years, systems are modified and added to and additional systems built into a building to produce a complicated and sometimes undocumented interconnection of controls, ductwork and zones. All of the above mentioned elements (and more) combine to make each ventilation system unique. For several of the older buildings (#12, 26, 31, 35, and 37) HVAC system blueprints were not available or the systems had been changed to the point that the existing blueprints were useless. Without these plans, determination of sources of outside air, location of supply ducts, the method of system control and the definition of zone boundaries were difficult.

The training and experience of mechanical system operators (if they exist) is the most important long term factor in maintaining correct system operation, since operators must repair and replace aging components, balance air flows, and make adjustments to accommodate changes in building use or construction. In these five older buildings, the system operators usually were not able to provide detailed descriptions and dealt with changes or problems by using their experience. Consequently the building and its systems were considered to be a "black box" during testing. On the other end of the technological scale, newer buildings had sophisticated computer-controlled systems that were not always well understood by the system operators. Small changes in important program parameters could significantly affect system performance. In one building a sensor/actuator caused the return air dampers to open when they should have closed -- apparently during the eight years since the system was installed. This reversal in damper response was not noticed until the return air dampers were being opened for the mixing of tracer during the decay test.

C. DISCUSSION OF SUMMARY TABLES AND FIGURES OF VENTILATION RESULTS

Table IV.C.1 compiles the SF_6 decay ventilation rate measurements and associated ventilation parameters for all buildings. The corresponding histogram, Figure IV.C.1, summarizes data for the 40 measurements. Appendix D summarizes meteorological conditions during the tests. In Table IV.C.1 columns 7-9 show the whole building average ventilation rates, the standard deviations of the mean (standard error), and the number of sample locations as determined from the individual location decay rates. Usually, the average is a simple arithmetic mean of all individual decay rates. In buildings where tracer concentration was monitored in supply and return plenums, the return decay rates are averaged with the average of the site measurements for that zone

TABLE IV.C.1
BUILDING VENTILATION RATE COMPARISON

BUILDING NO.	SEAS.[9]	VOLUME[1] (FT^3)	OCCUPANCY[2]	VENTILATION DATA CFM/OCC	CFM/FT^2[(3)]	ACH SF_6[(4)]	STD. ERROR[(10)]	# OF LOC.	ASHRAE[(8)] STANDARD 62-1981 SMOK.	NON SMOK.
1	W	230,000	318	9.6	0.1	0.8	0.15	3	--	5
2	W	158,400	421	13.8	0.4	2.2	0.69	3	--	5
3	W	159,970	35	95.2	0.2	1.3	0.07	3	20	7
4	W	206,350	35	57.0	0.1	0.6	0.02	5	--	5
5	W	144,100	34	118.0	0.4	1.7	0.17	4	20	7
6	W	5,032,000	1250	56.4	0.2	0.8	0.03	6	20	7
7	W	876,500	250	53.2	0.2	0.9	0.10	5	20	7
8	W	554,400	150	68.4	0.2	1.1	0.05	6	35	7
9	W	2,591,000	669	47.8	0.2	0.7	0.01	6	20	7
10	W	1,690,000	1286	19.3	0.2	0.9	0.03	8	20	7
11	W	1,454,000	400	88.2	0.3	3.6	0.38	8	20	7
12	W	717,200	80	40.3	0.0	0.3[(7)]	0.03	7	--	5
13	G	602,000	175	84.3	0.2	1.5	0.04	6	20	7
14	G	353,760	136	178.6	0.7	4.1	0.35	5	20	7
15	G	1,954,000	750	74.7	0.3	1.7	0.10	8	20	7
16	G	438,000	700	21.0	0.3	2.0	0.28	6	--	5
17	G	933,000	550	66.2	0.5	2.2[(7)]	0.35	6	--	5
18	G	113,100	84	12.8	0.1	0.6	0.04	5	20	7
19	G	215,831	65	48.1	0.2	0.9	0.06	5	20	7
20	S	790,000	835	28.5	0.2	1.8	0.18	8	--	5
21	S	413,935	150	80.9	0.3	1.8[(7)]	0.09	8	35	7
22	S	1,513,000	450	140.1	0.4	2.5[(7)]	0.12	7	20	7
23	S	165,664	25	113.8	0.2	1.0[(7)]	0.02	6	--	5
24	S	161,431	50	21.0	0.1	0.4[(7)]	0.01	6	20	7
25	S	146,442	80	53.4	0.3	1.8[(7)]	0.13	7	20	7
26	S	2,834,000	550	128.9	0.4	1.5[(7)]	0.15	9	20	7
27	S	527,000	110	22.4	0.1	0.3[(7)]	0.02	8	20	7
28	S	744,969	92	78.3	0.1	0.6[(7)]	0.002	8	35	7
29	W	828,152	678	60.7	0.6	3.0[(7)]	0.14	8	--	5
30[(5)]	W	933,000	659	30.0	0.2	1.3[(7)]	0.09	7	--	5
31	W	384,032	250	48.9	0.3	1.9	0.24	8	35	7
32	W	788,600	300	28.0	0.1	0.6[(7)]	0.05	8	20	7
33	W	523,000	600	22.7	0.3	1.6[(7)]	0.15	9	35	7
34	W	2,700,000	1200	54.8	0.3	1.5[(7)]	0.03	9	20	7
35	W	1,860,000	1200	35.1	0.2	1.4	0.18	9	20	7
36[(6)]	W	1,454,000	400	25.7	0.1	1.1[(7)]	0.01	9	20	7
37	W	1,845,000	930	75.7	0.4	2.4[(7)]	0.12	9	20	7
38	G	2,106,000	1100	60.3	0.4	1.9	0.22	9	20	7
39	G	2,238,000	1500	66.2	0.6	2.7	0.15	8	20	7
40	G	2,816,000	2500	45.2	0.6	2.4[(7)]	0.22	9	20	7
	Arithmetic Mean			59.3	0.3	1.5				
	ASD			37.81	0.16	0.87				

(1) Volume - all space within building shell
(2) Occupancy - reported number of persons in building during normal occupied hours
(3) CFM/FT^2 - based on all building floor space and SF_6 tracer decay measurement
(4) ACH(SF_6) - based on single SF_6 tracer decay measurement
(5) Repeat measurement of Building 17
(6) Repeat measurement of Building 11
(7) Building average ventilation rate includes decay rate measured in return air. Does not include that measured in supply air
(8) From ASHRAE Standard 62-1981 (Table "ASHRAE Standards)
(9) Season Code: G = Spring, S = Summer, W = Winter
(10) Standard error of building ventilation rate using individual measurement values

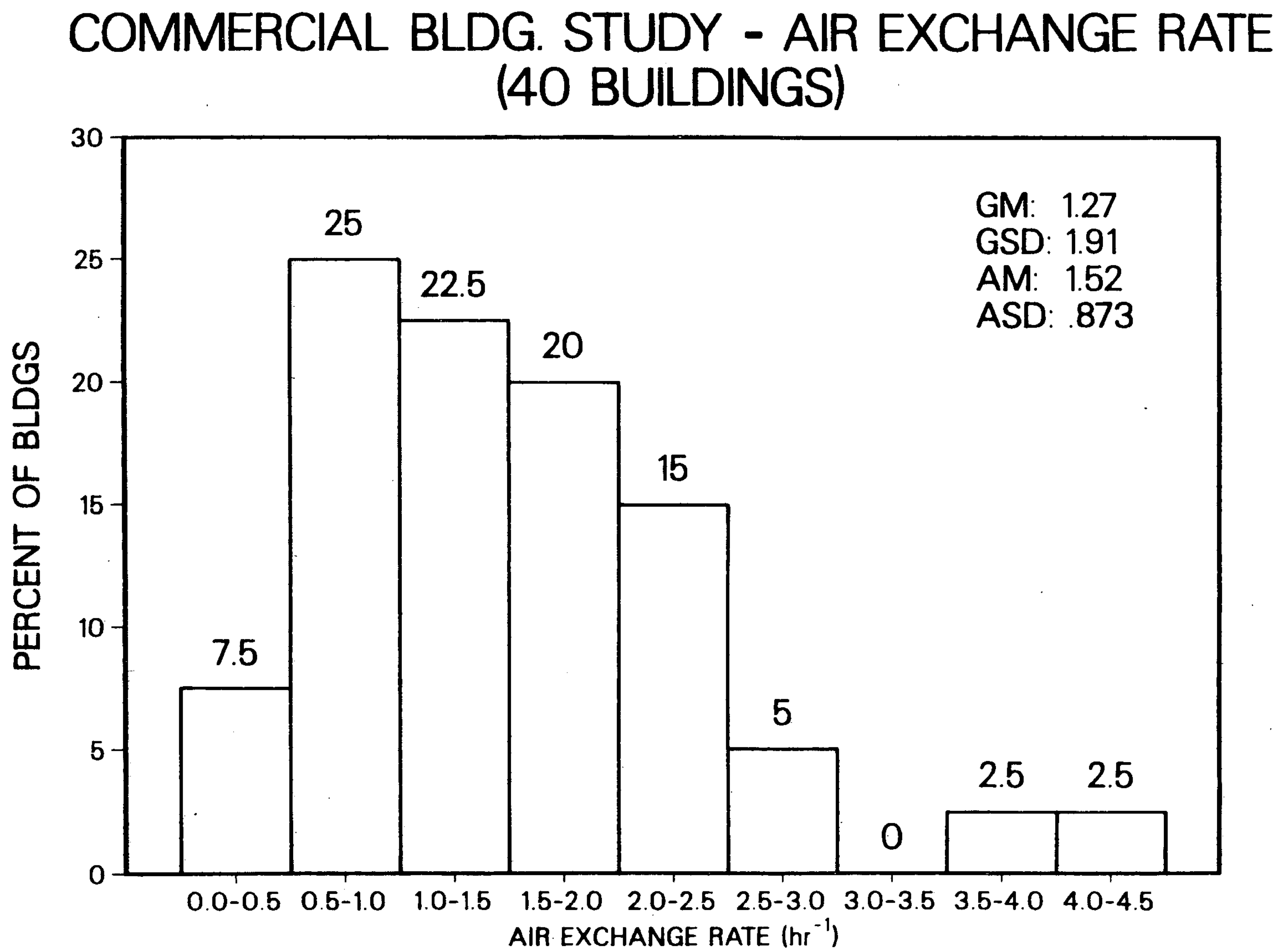

COMMERCIAL BLDG. STUDY - AIR EXCHANGE RATE
(40 BUILDINGS)
GM: 1.27
GSD: 1.91
AM: 1.52
ASD: .873
PERCENT OF BLDGS
0
5
10
15
20
25
30
7.5
25
22.5
20
15
5
0
2.5
2.5
0.0-0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
2.5-3.0
3.0-3.5
3.5-4.0
4.0-4.5
AIR EXCHANGE RATE (hr⁻¹)

Figure IV.C.1

where the return is common for entire zone. This procedure weights the return decay rate more heavily (up to 50% of total average) than individual site measurements. Supply air decay rates are not included in the average. Net (or active) building volumes are presented and are calculated by subtracting 12% from the gross volume to account for the inactive space of furniture, isolated volumes, etc. The net volume and air change rate are used to calculate whole building outside air flow rate in cubic feet per minute (cfm) which is in turn used to derive whole building cfm/ft^2 and whole building cfm/occupant.

The ASHRAE 62-1981 ventilation guidelines for smoking and non-smoking for each building are shown in the last two columns and are based on the predominant building use (office, classroom, library). A summary of selected guidelines are shown in Appendix J.

The arithmetic mean for all 40 air exchange rate measurements is 1.5 ach (the arithmetic standard deviation of the sample is 0.87 ach) and the geometric mean is 1.3 ach. Building average values ranged from 0.3 ach in Buildings #12 and 27 to 4.1 ach in Building #14. Annual average ventilation rates in nine buildings studied by Persily and Grot (1985) ranged from 0.33 ach to 1.04 ach and one building studied by Silberstein and Grot (1985) 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, a relatively high ventilation rate occurs 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 monitoring period so that any air quality problems would be minimized. We have no way of verifying this, except that in some buildings (e.g., #14) occupants commented that they felt the ventilation was increased just prior to our testing.

In comparing the measured whole building ventilation rate (measured in cfm/occupant) with the ASHRAE recommendations, five buildings (#10, 18, 24, 27, 33) are at or below the recommendation when smoking is present. Since the measured flow rate per occupant is based on the entire net building volume, space not associated with high occupancy, such as hallways, storage rooms, mechanical rooms, or unoccupied gymnasiums is included. In this case, the whole building measurement overestimates the amount of outside air actually supplied in local, more densely occupied areas. For example, the whole building outside air ventilation rate per occupant in a school, Building #1, is calculated at 9.6 cfm/occupant, above the 5 cfm/occupant recommended. However, a local ventilation measurement made in a classroom with 30 students and one teacher was 3.4 cfm/occupant, below the recommended 5 cfm/occupant. This same situation is likely to occur in other buildings with more than one zone and uneven occupant densities, i.e., local outdoor air ventilation per occupant may be below recommendations. Therefore, when measuring ventilation with a single tracer decay, whole building cfm/occupant is a useful indicator of local ventilation only in single-zone buildings with uniform occupant density.

D. HIGH AND LOW VENTILATION RATES

Average ventilation rates in Building #2, an elementary school in Portland, are elevated (2.2 ach) because of the high air exchange measured in classroom 23. Two measurements were made in this room as the outside air dampers modulated. As seen from Figure IV.D.1, test A, which has the damper in position 1, shows a ventilation rate of 4.3 ach and test B, with the more tightly closed position 2, shows a rate of 2.4 ach.

Building #11, a Salem office, showed an average ventilation rate of 3.6 ach. Figure IV.D.2 displays the individual decay curves for this building. Because of the unexpectedly high ventilation rate the initial tracer concentration was too low to allow the decay to continue for more than approximately 45 minutes before concentrations fell below GC-ECD capabilities. Tracer dilution was so vigorous that the building never reached decay equilibrium which would have been indicated by parallel curves. Therefore, the average value for this building contains more uncertainty as indicated by the relatively high standard error. The question of why this building was ventilated at such a high rate is unanswered.

Building #11 was tested again a year later (now labeled Building #36) based on conditions during March, 1985. An average air exchange rate of 1.1 ach with a

Figure IV.D.1

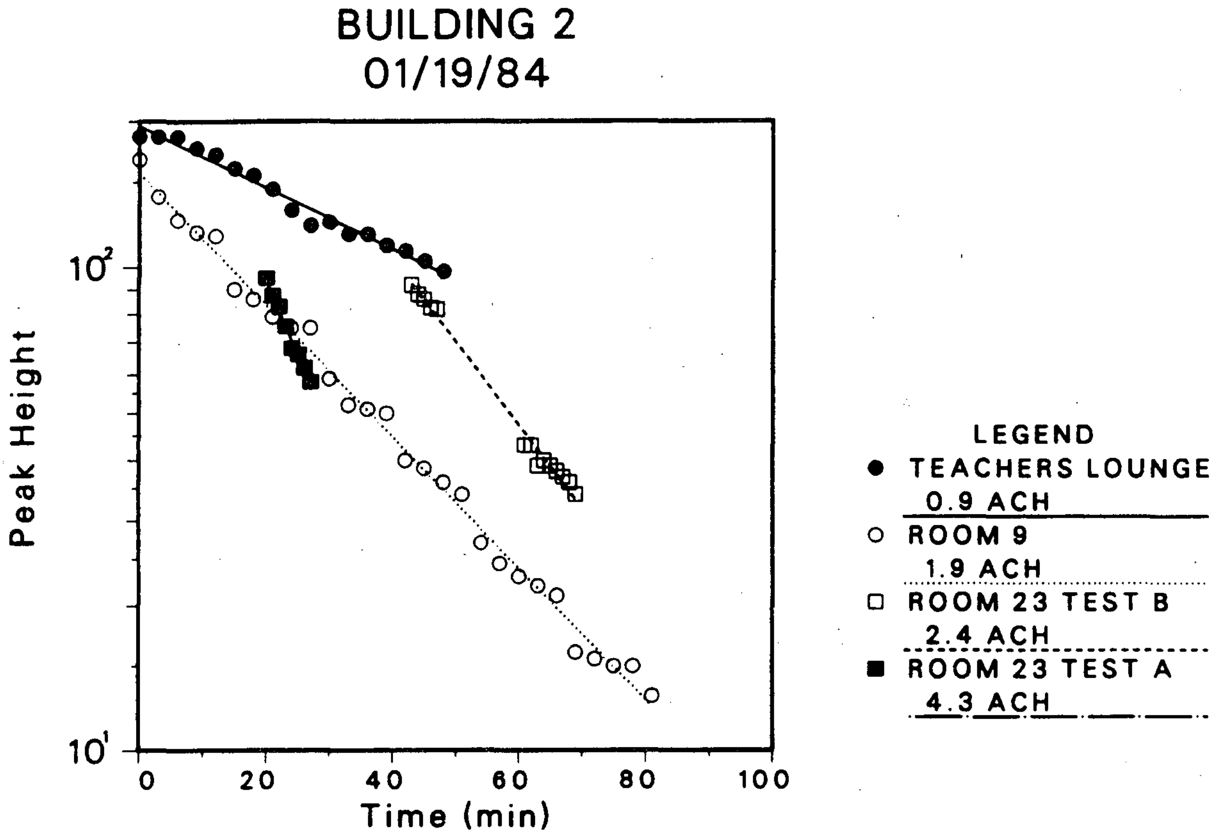
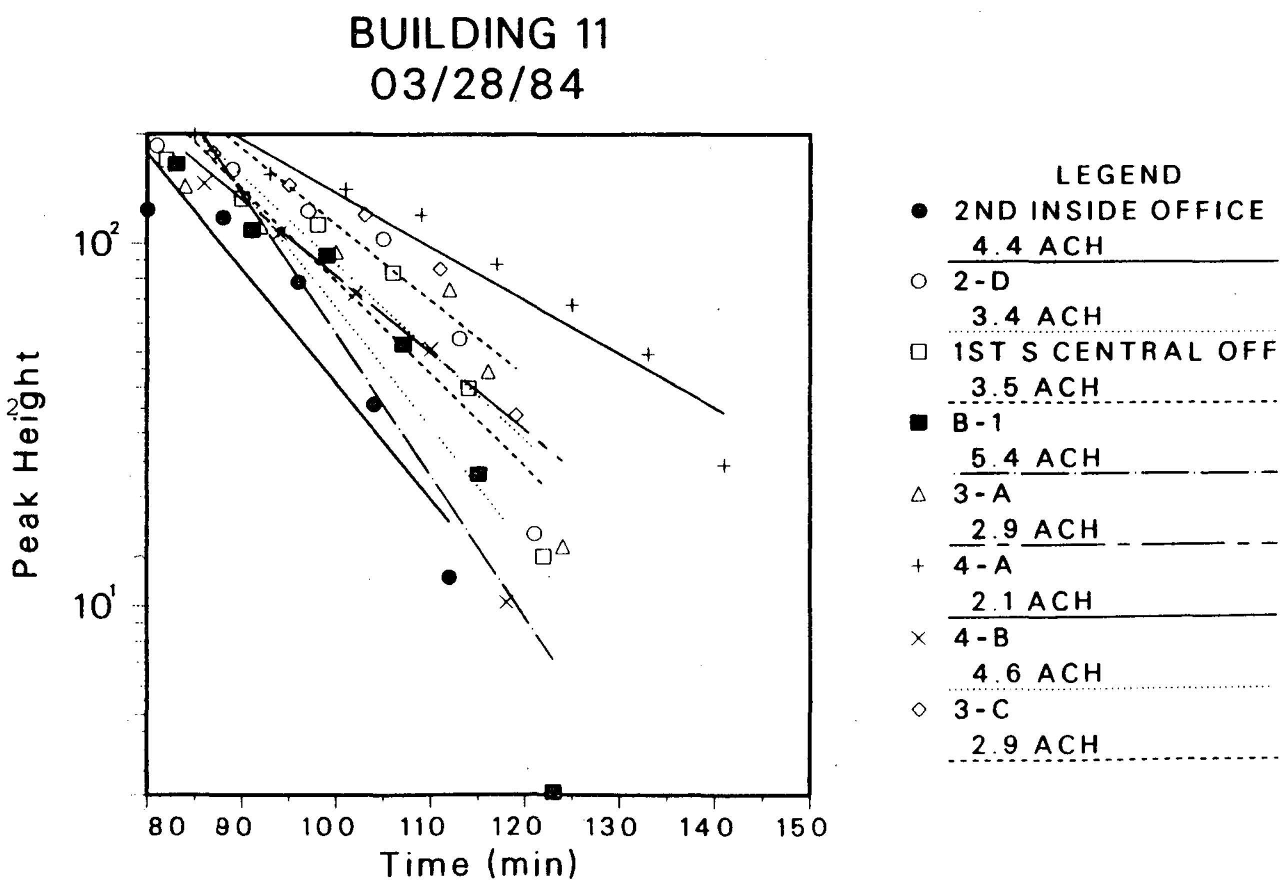


Figure IV.D.2



low standard error of 0.01 was measured for that period. The plot for this second test is shown in Figure IV.D.3. The supply concentration measurements were made in system AH-2, the air handler supplying air to the interior core, while return was common to systems AH-1, 2 and 3. Decay rates were virtually identical at all sites (range = 1.0-1.1 ach), but the data points do not lie on a straight line. The data point variation early in the decay is probably due to main system outside air damper modulation, since all sampling points in the building vary approximately the same amount over the same time interval. An attempt was made to measure tracer concentration stratification in Room 208 by placing one sample line one foot above the floor and another six inches below the ceiling. The small differences in concentration between the locations makes interpretation difficult, however it appears that whenever the ventilation rate begins to change, the ceiling location is affected first, as indicated by an increased difference in concentrations. However, concentrations soon equilibrated. This building is discussed in more detail in Section IV.E.

Building #14's average ventilation rate of 4.1 was the highest in this study. There is no obvious reason for this high rate. After our testing, an episode occurred during the summer of 1984, where, over a period of several days, several office workers collapsed. Apparently, studies by health authorities could not uncover the reasons for this distress and we did not return to repeat our measurements. Neither the pollutant concentrations nor ventilation rates (Appendix F) observed during our study could be responsible. However, Persily and Grot (1985) found seasonal (monthly average) ventilation rates can vary by factors greater than four in the same building. If the effect is exaggerated over the short term (several days) and is coupled with a transient pollutant source problem, the acute health reactions could be explained.

The ventilation rate of 2.5 ach measured in Building #22 was probably due to the building operators still being unfamiliar with the HVAC system. Major renovations to both the building and its mechanical equipment had recently been completed and operation procedures were still being refined during the measurement period. In Building #29, ventilation rates were high (3.0 ach) despite cold outside air temperatures (2° to 30°F) during the monitoring period. The system responded to colder outdoor air temperatures by closing outdoor air dampers slightly, yet mixed air temperatures of 32-36°F were common.

Figure IV.D.4 is the plot of decay curves for Building #37 whose average ventilation was 2.4 ach. Our monitoring was conducted during an unusually warm period and during HVAC system maintenance. As a result, reliable measurements of representative outside air damper positions were difficult. This figure also illustrates the difficulty in achieving uniform mixing of a single tracer in a multi-zone, multi-system (15) building. Approximately six hours elapsed while tracer concentrations were adjusted up or down to attempt to bring them within $\pm$ 10% of one another before opening outside air dampers and initiating the decay. As can be seen, the attempt was unsuccessful since concentrations could not be brought closer together than a factor of 15 difference (locations A-4 and 4-B). Evidently, outside air was being introduced into the building through various systems at different rates, even though all outside air dampers were "closed". Local infiltration and exhaust fans may have aggravated the problem. The east and west returns were common to the main portions of the building and provided return air to six independent systems that supplied outside air at different rates to various zones that included 2-A, 1-B, 4-B, 8-A, (average = 2.6 ach). Entirely separate systems served reproduction services (1.7 ach) and an annex containing the cafeteria (1.8 ach) and location A-4 (2.0 ach). The poor communication between systems is apparent in the relative difference in concentrations and ventilation rates.

The moderate outside temperature conditions during the monitoring of Buildings #39 and 40, where whole building averages were 2.7 and 2.4 ach respectively, are probably the cause of the systems operating at high rates of outside air supply. By using large amounts of 55 to 75°F outside air, a minimum of mechanical heating or cooling is necessary to maintain comfortable building temperatures, and is referred to as an "economizer cycle".

For each instance of a low ventilation rate (<0.5 ach), the outside air dampers were found to be completely closed during monitoring. In Building #12, a Salem building 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.

Figure IV.D.3

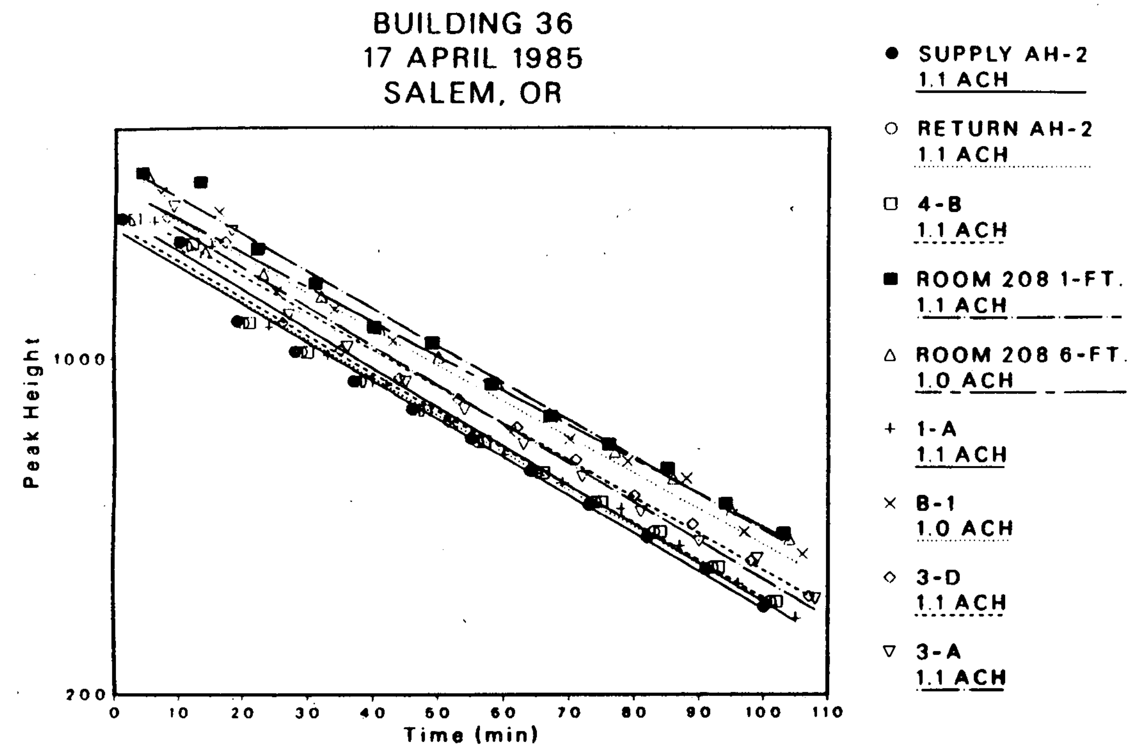


Figure IV.D.4

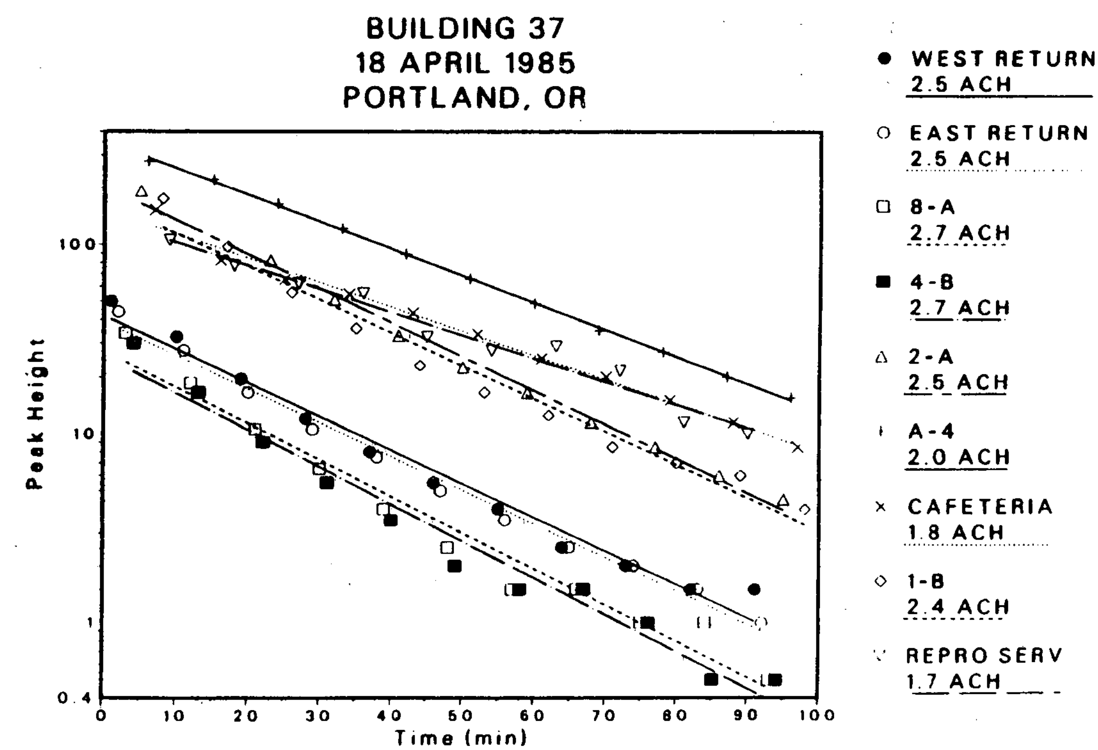
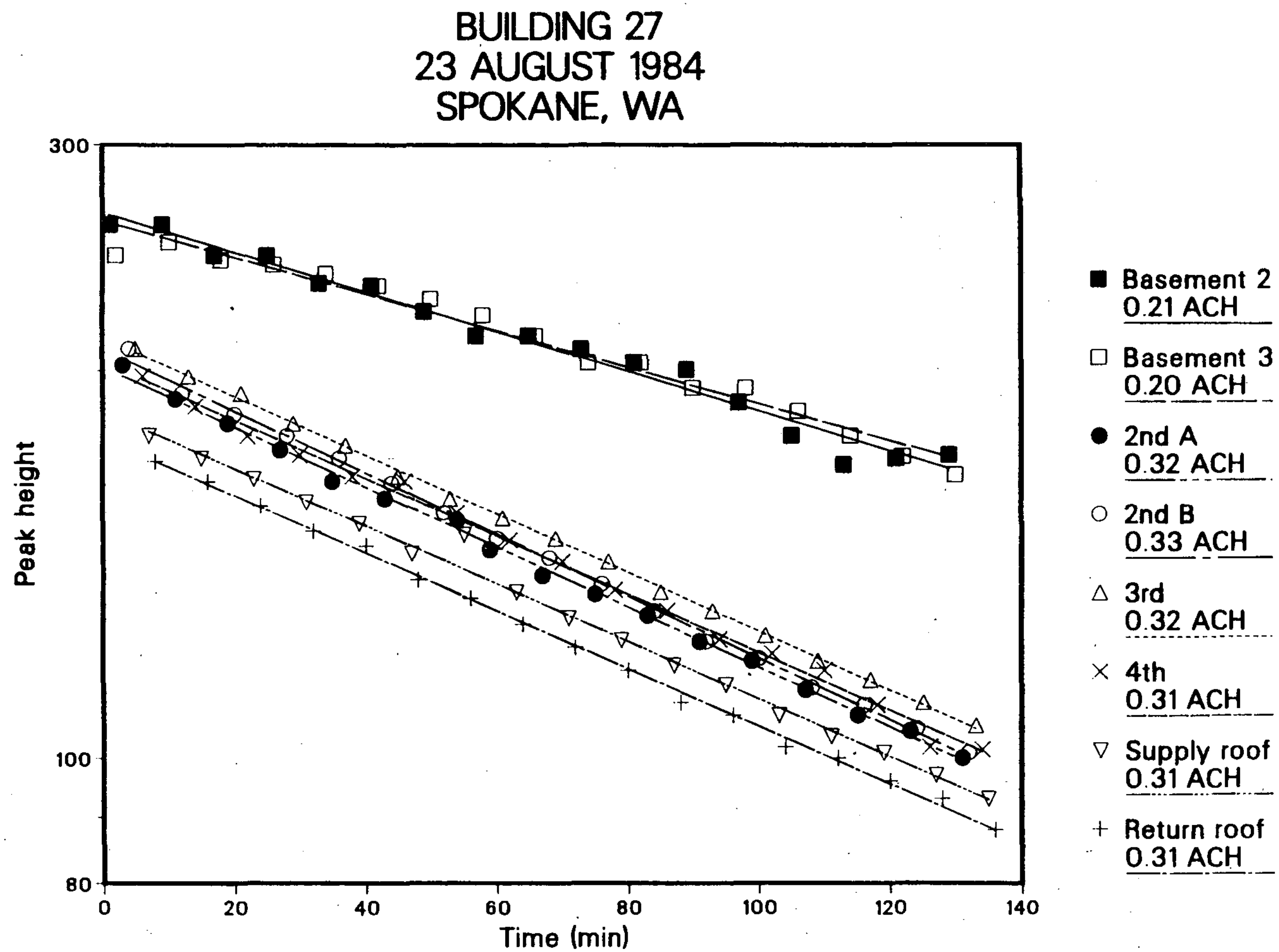


Figure IV.D.5



XBL 851-956

The minimum damper settings in Buildings #24 (0.4 ach) and #27 (0.3 ach) were energy conservation measures to reduce the cooling load during the summer. The decay plot for #27 (Figure IV.D.5) shows two well isolated zones; the basement has small systems for a computer room and print shop, while the floors above the basement are served by a separate roof-top system. Rates in both zones are low, with the basement ventilation rate (0.2 ach) the lowest in the study. It may be contributing to the higher formaldehyde concentrations observed there. (Refer to discussion in pollutant section III.A8.). The whole building cfm/occupant for building #24 (21 cfm/occupant) and #27 (22.4 cfm/occupant) approach the ASHRAE recommendation of 20 cfm/occupant. However, none of the pollutants monitored in these two buildings approach guideline limits with the possible exception of respirable particles (48 $\mu g/m^3$ average in Building #27). In this case, the concentrations were lower than those outdoors (52 $\mu g/m^3$).

E. MODULATION OF VENTILATION RATES

Figure IV.E.1 once again shows the difficulty in achieving good initial tracer gas mixing in a building with multiple-systems (4) and zones with poor communication. Building #20 is a Spokane high school with systems serving a gymnasium, auditorium, cafeteria/study hall, and classrooms. Even with outside air dampers closed, unequal amounts of outside air enter the building and cause poor initial mixing, making a determination of local ventilation rates impossible. Also note that several of the curves have points that stray from the normal slope of the decay. This response has been observed in other buildings and is probably due to modulation of system and local dampers by the control devices. An intense thunderstorm passed by in the midst of the decay measurement and the sudden outdoor air enthalpy changes may account for the change in the slope of the curves at 90 minutes.

The effects of local variable air volume box modulation are probably seen most dramatically in Building #23, Figure IV.E.2. Although one air handler ventilated most of this library (a second system separately served a TV studio) there were several small study/conference rooms that had local ventilation controlled by a VAV box. Sample location "north middle" is an example. With

Figure IV.E.1

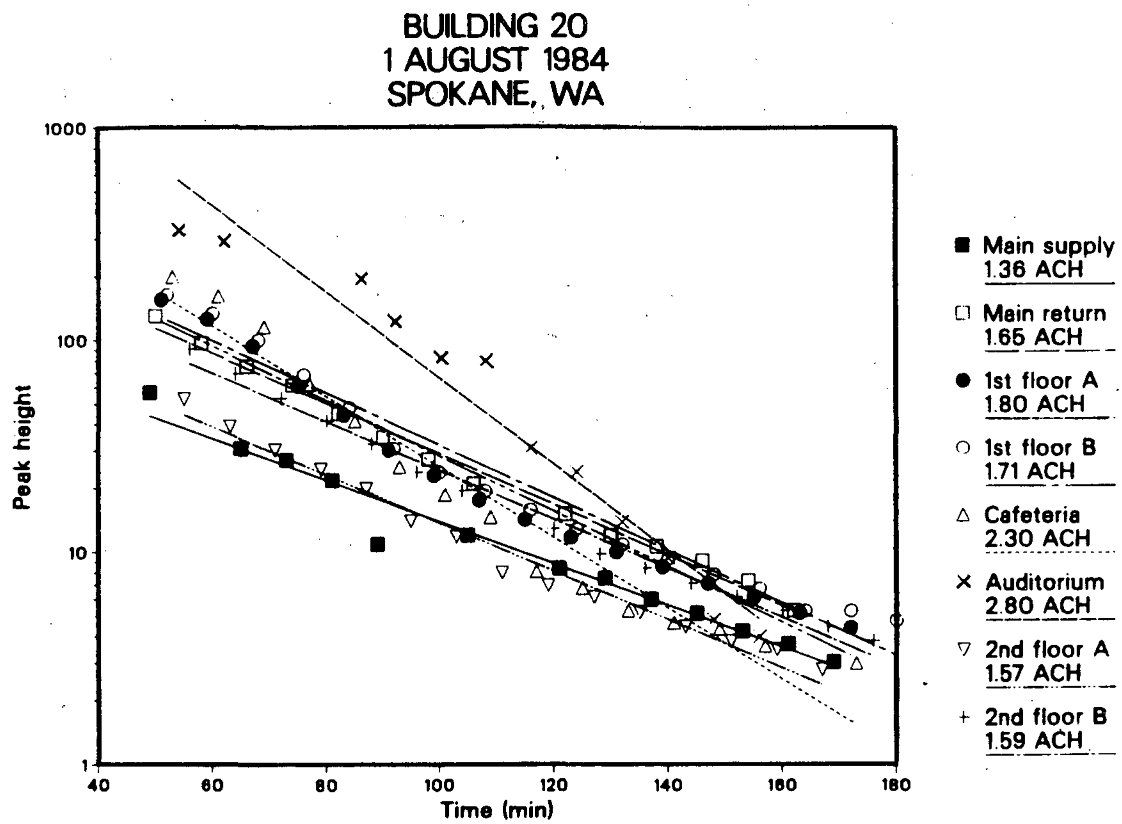
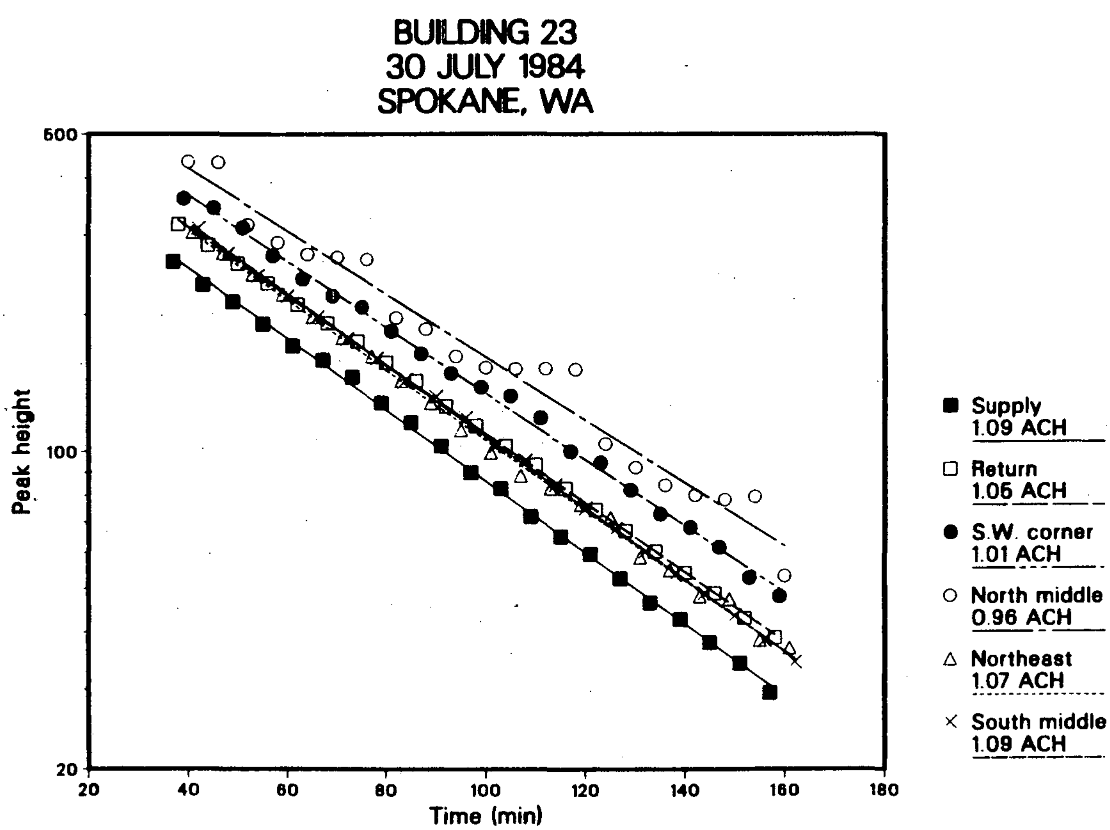
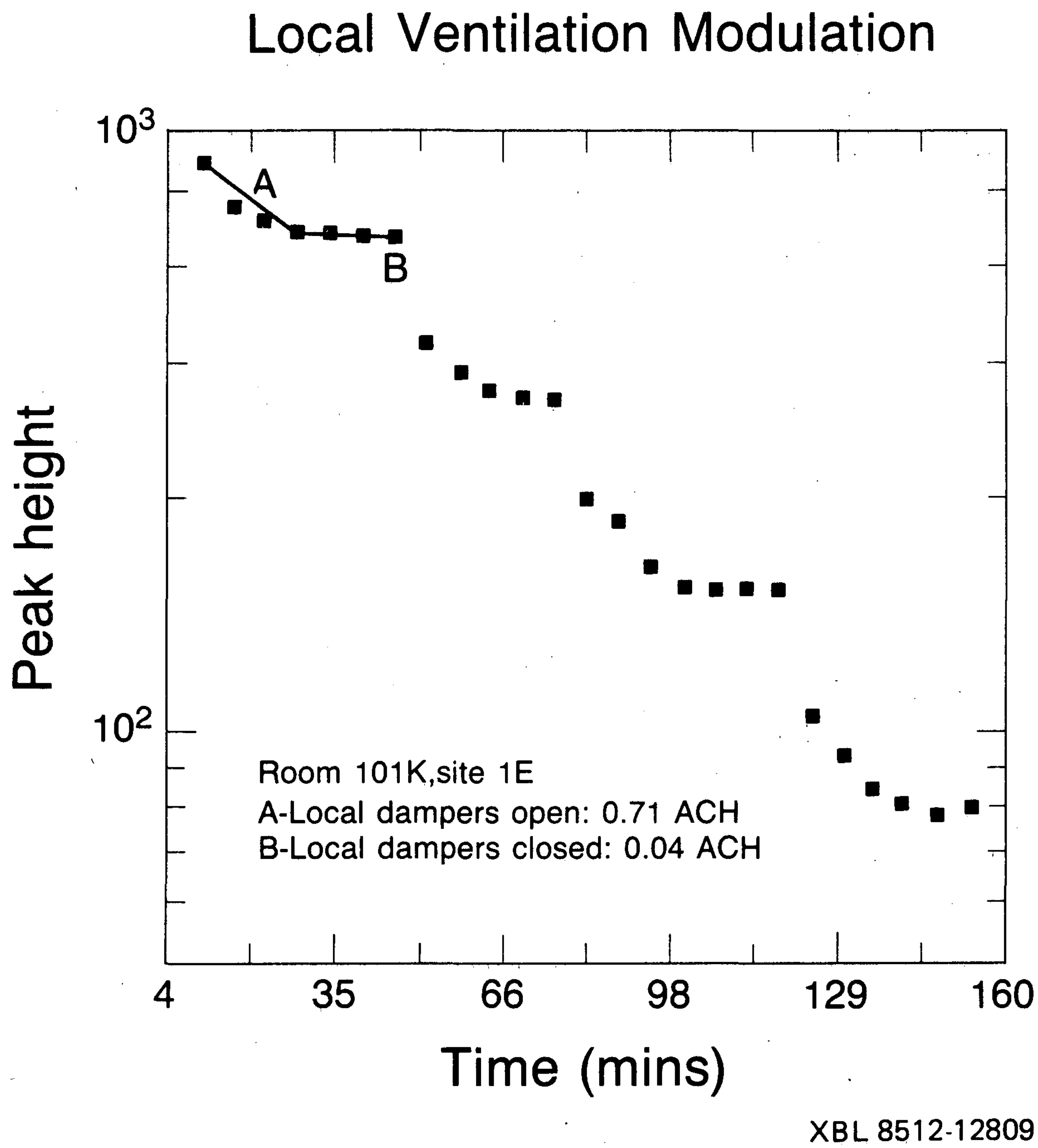


Figure IV.E.2





Local Ventilation Modulation
10^3
10^2
A
B
Peak height
Room 101K,site 1E
A-Local dampers open: 0.71 ACH
B-Local dampers closed: 0.04 ACH
4
35
66
98
129
160
Time (mins)
XBL 8512-12809

Figure IV.E.3

the door closed, this room was effectively isolated from any ventilation other than that supplied through the VAV and modulated by a room temperature controller. In Figure IV.E.3, this sample location is shown separately and the short term air exchange rate of a typical "tread" and "riser" section of the curve step are indicated. The period of zero ventilation implies that if it were of long enough duration and a pollutant source existed, then a potential air quality problem could exist. The duration is approximately 20 minutes, not sufficient for pollutant build-up, and the two-hour average ventilation rate is 1.0 ach, ordinarily considered adequate.

F. OTHER VENTILATION PARAMETERS

Tracer concentrations were measured in some of the buildings at the main supply and return ducts of the primary air handling systems. From these values, estimates could be made of total circulation and recirculation rates. Generally, return air was sampled immediately (one minute) after the supply air. This was intended to minimize the error of not being able to make exactly simultaneous measurements. Solving equation (2.1) for the ratio of decaying concentrations,

$$C(t)/C_o = e^{-It} \qquad [4.1]$$

where:

C_o is the concentration of tracer at time $t = 0$
$C(t)$ is the concentration at time t, and
I is the ventilation rate $[h^{-1}]$

we find that after a one-minute interval over the range of ventilation rates measured in the applicable buildings (0.4-3.0 ach), the concentrations only decline to 99% - 95% of the previous value, an acceptable error. In addition, errors of approximately 5% are due to differences of up to 100 ft between supply and return sample tube length. The combined error for time lapse and tube length differences approaches $\pm$ 15% when comparing supply and return concentrations.

The fraction of outside air supplied by the ventilation system was computed at a minimum condition when dampers were closed during mixing and at the operating conditions observed during the decay measurements.

F	=	$(C_R - C_S)/C_R$	[4.2]
C_R	=	Concentration in return duct (peak height, mm)	
C_S	=	Concentration in supply duct (peak height, mm)	
F	=	Fraction of outside air ($0 \leq F \leq 1$)	

Typically, an average was made of three points for the minimum fraction and approximately ten points for the fraction during operating conditions.

The estimated minimum ventilation rate was simply based on a corresponding ratio to the observed operating ventilation rate:

$$I_{min} = F_{min}\, I/F \qquad [4.3]$$

where:

I_{min} = Minimum outside air ventilation rate (ach)

F_{min} = Minimum fraction of outside air

Ventilation rates for minimum damper conditions are only approximate since the actual pressure distribution developed by the HVAC system during those conditions may affect the flow of air in the building.

The estimated total circulation, T, was computed from:

$$T = I/F \qquad [4.4]$$

and the estimated recirculation, R, from

$$R = T - I \qquad [4.5]$$

All of these calculated values are summarized in Table IV.F.1.

This subgroup of 14 buildings appears to fairly represent the ventilation rates measured in the entire sample of 40 buildings (Table IV.C.1). The subsample had a mean ventilation rate of 1.6 ach and arithmetic standard deviation of 0.74 ach compared with 1.5 ach and 0.87 for the entire sample. One half of this group of 14 had a minimum outside air percentage of less than 10%, a widely accepted figure for minimum outside air. Four of the buildings, #20, 24, 32,

TABLE IV.F.1

OTHER VENTILATION PARAMETERS

Building No.	Outside Air: Operating Conditions % Outside Air	Outside Air: Operating Conditions ACH	Outside Air: Minimum Conditions % Outside Air	Outside Air: Minimum Conditions Est. ACH	Outside Air: Minimum Conditions Est.CFM/Occ	Total Circulation Estimated ACH	Recirculation Estimated ACH
17	45	2.2	6	0.3	9.0	4.9	2.7
20	45	1.8	24	1.0	15.8	4.0	2.2
21	86	1.8	8	0.2	9.0	2.1	0.3
22	41	2.5	4	0.2	11.2	6.1	3.6
23	20	1.0	5	0.3	34.1	5.2	4.2
24	19	0.4	19	0.4	21.0	2.1	1.7
26	34	1.5	4	0.2	17.2	4.4	2.9
28	13	0.6	13	0.6	78.3	4.5	3.9
29	61	3.0	13	0.6	12.1	4.9	1.9
30	30	1.3	7	0.3	6.9	4.3	3.0
32	53	0.6	40	0.5	23.3	1.2	0.6
33	40	1.6	-	-	-	4.0	2.4
34	37	1.5	22	0.9	32.9	3.9	2.4
38	35	1.9	2	0.1	3.2	5.4	3.5
Arithmetic mean	40	1.6	13	0.4	21.1	4.1	2.5
ASD	18.6	0.74	10.9	0.28	19.63	1.39	1.15

34, had significant amounts of outside air entering the system despite closed dampers. This outside air was entering the system through poorly fitting dampers, since in Building #20, which had a high pressure air handler, the negative pressure created upstream of the supply fan was sufficient to cause the outside air dampers to open slightly against the linkages and actuators. Outside air dampers would not seal tightly in Building #24, and Building #34 had a measurable gap of 1/8" to 1/4" between its dampers. Although the designated outside air dampers in Building #32 were closed, a large, uncontrolled amount of "alien" air was pulled into the basement fan room through a 3-mile network of underground service tunnels. In fact, this is the suspected source of the relatively high concentrations of radon in the building. (cf. Sections III.J and V.B).

Comparing the minimum whole building cfm/occupant from Table IV.F.1 with the ASHRAE 62-81 on Table IV.C.1, Buildings #21, 22, 26, 38, drop below the recommendations when the outside air dampers close. These buildings were not operating at minimum levels during the monitoring period, but could conceivably ventilate at these low rates under certain environmental conditions.

Total circulation is an indicator of the amount of air movement within a building and may have an important effect on occupant comfort. The mean total circulation rate for these 14 buildings was 4.1 ACH with a relatively small standard deviation of 1.4 ACH. Fifty percent of these buildings had total circulation rates between 4.0 and 5.0 ACH. This rather tight clustering suggests that the buildings were designed to certain specifications. The most obvious exception is building #32 which has a total rate of 1.2 ACH. It is the oldest building in this group (72 years) with the original, low-capacity air handler still in operation.

Recirculation rates are important in buildings that have some form of conditioning or cleaning of the air as it passes through the main air handlers. Temperature and humidity control and particle filtration are common examples of air quality management than can occur without the introduction of outside air. Therefore, the more often that building air is recirculated through these devices, the better opportunity there is for control of indoor humidity and particle concentrations. However, factors mentioned before such as improper system maintenance and operation can overcome the intended benefits.

G. VENTILATION BY CLASSIFICATION

Following the example established earlier, ventilation rates are classified by building type in Table IV.G.1 and on Figure IV.G.1. From the table, it appears that ventilation rate is not strongly related to building type for these structures. Only naturally ventilated buildings (#7, #18, and #19) and libraries (#4, #12, and #23) have significantly lower measured ventilation rates of 0.8 ACH and 0.6 ACH, respectively. However, two of the naturally ventilated buildings (#18 and #19) were monitored during spring conditions when the infiltrating air driving forces are at a minimum, thereby resulting in a seasonally-influenced lower ventilation rate. Also, all three library buildings were investigated during either summer or winter conditions when the amount of outside air brought into buildings has been observed to be at a minimum (Persily and Grot, 1985). Nevertheless, the libraries still are ventilated at lower rates than other building classifications measured during the summer and winter (see Table IV.G.2 below).

Table IV.G.2

	SPOKANE		PORTLAND		TOTAL	
	N	MEAN(ACH)	N	MEAN(ACH)	N	MEAN(ACH)
Libraries	1	1.0	2	0.5	3	0.6
All Other Mechanically Ventilated Buildings Measured in Summer & Winter	15	1.5	11	1.5	26	1.5

TABLE IV.G.1

COMMERCIAL AND INSTITUTIONAL BUILDING VENTILATION RATE SUMMARY

BY CLASSIFICATION

CLASSIFICATION	PORTLAND-SALEM #	PORTLAND-SALEM ACH	PORTLAND-SALEM AVG. CFM/OCC.	SPOKANE-CHENEY #	SPOKANE-CHENEY ACH	SPOKANE-CHENEY AVG. CFM/OCC.	TOTALS #	TOTALS ACH	TOTALS AVG. CFM/OCC.
NATURAL VENTILATION									
	1	0.9 (0.9)	53	2	0.8 (0.6-0.9)	30	3	0.8 (0.6-0.9)	38
MECHANICAL VENTILATION									
EDUCATIONAL:	2	1.6 (0.8-2.2)	12	5	2.1 (1.3-3.0)	41	7	1.9 (0.8-3.0)	33
LIBRARIES:	2	0.5 (0.3-0.6)	49	1	1.0 (1.0)	114	3	0.6 (0.3-1.0)	71
OFFICE BLDGS.: >100,000 FT^2									
SINGLE SYST.	-	-	-	2	2.0 (1.5-2.5)	97	2	2.0 (1.5-2.5)	97
MULTIPLE SYSTEM	10	1.8 (0.7-3.6)	56	2	1.5 (1.4-1.5)	82	12	1.8 (0.7-3.6)	60
CLASSIFICATION TOTAL:	10	1.8 (0.7-3.6)	56	4	1.7 (1.4-2.5)	90	14	1.8 (0.7-3.6)	65
OFFICE BLDGS.: <100,000 FT^2									
SINGLE SYST.	1	1.3 (1.3)	95	1	0.4 (0.4)	21	2	0.9 (0.4-1.3)	58
MULTIPLE SYSTEM	3	2.4 (1.5-4.1)	127	3	0.9 (0.3-1.8)	35	6	1.7 (0.3-4.1)	81
CLASSIFICATION TOTAL:	4	2.2 (1.3-4.1)	119	4	0.8 (0.3-1.8)	32	8	1.5 (0.3-4.1)	75
MULTI-USE BLDGS.:									
SINGLE SYST.	-	-	-	1	0.6 (0.6)	78	1	0.6 (0.6)	78
MULTIPLE SYSTEM	1	1.1 (1.1)	68	3	1.8 (1.6-1.9)	51	4	1.6 (1.1-1.9)	55
CLASSIFICATION TOTAL:	1	1.1 (1.1)	68	4	1.5 (0.6-1.9)	58	5	1.4 (0.6-1.9)	60

Air Exchange Rates
38 Pacific Northwest Commercial Buildings
(40 measurements)

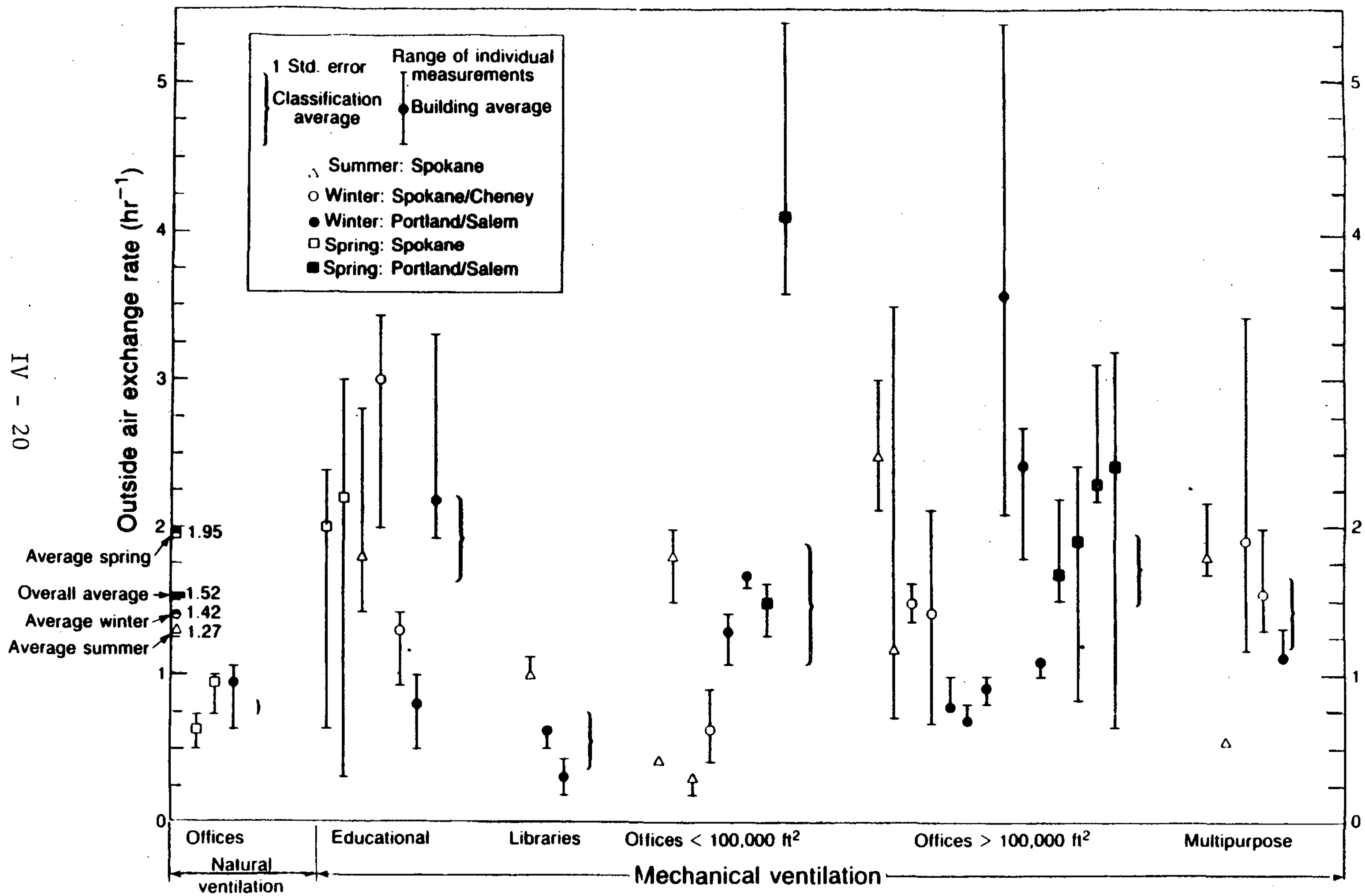


Figure IV.G.1

Another trend to be inferred from the data in Table IV.G.1 is the lower average ventilation per occupant in the seven school tests (33 cfm/occupant) compared to the other buildings (67 cfm/occupant), except for those naturally ventilated (38 cfm/occupant). This is due to the relatively high occupant density in schools (Table IV.G.3) despite the higher than average air exchange rate of 1.9 ACH.

Insert Table IV.G.3 here

Table IV.G.3

OCCUPANT DENSITY

	N	MEAN(FT^2/OCC.)	S.D.(FT^2/OCC.)
Educational	6	91	39.1
Libraries	3	758	264
Offices < 100,000 FT^2	8	325	107
Offices > 100,000 FT^2	13	217	100.4
Multi-Use	5	300	199.0
Naturally Ventilated	3	299	31.7

Other correlations of ventilation rates to these building categories were not observed, probably as a result of the dominating effects of season, air handling equipment differences, and HVAC system operating policies. No relationship between ventilation rates and building height, building age, and number of stories above grade was observed. Seasonal comparisons (Table IV.G.4) show that there is a suggestive, but weak statistical difference between spring ventilation rates (2.0 ACH) and those of winter and summer (1.4 and 1.3 ACH). Economizer controls often cause additional amounts of outside air to be drawn into buildings during the spring and fall to take advantage of the moderate ambient temperatures between 55° - 70°F that require less conditioning by heating or cooling. Considerable energy savings can result.

TABLE IV.G.4

SUMMARY OF VENTILATION RATES BY SEASON

	SPRING				SUMMER				WINTER			
	N	ACH	STD. ERROR	CFM/OCC	N	ACH	STD. ERROR	CFM/OCC	N	ACH	STD. ERROR	CFM/OCC
WEST (Salem, Portland)	6	2.4	0.39	85	0	-	-	-	14	1.3	0.24	55
EAST (Spokane, Cheney)	4	1.4	0.40	37	9	1.3	0.25	71	7	1.6	0.28	40
TOTAL	10	2.0	0.31	66	9	1.3	0.25	71	21	1.4	0.18	50

H. OCCUPANT-GENERATED CO_2 VENTILATION MEASUREMENT

An opportunity to check the validity of the SF_6 decay measurements using occupant-generated CO_2 (Turiel and Rudy, 1982) occurred in Building #1. CO_2 was monitored continuously in a classroom as the room filled with students, throughout the day, and then as the room abruptly emptied at the end of the school day (Figure IV.H.1). Recess periods are obvious at 1000, 1300 , and the noon lunch break. The highest CO_2 concentration of the study, 1290 ppm, occurred at 1430 in this classroom. School concluded at 1430 and the main CO_2 source was removed. Beginning at 1440, a CO_2 dilution and decay measurement was possible and continued for the next 90 minutes at which time CO_2 concentrations in the room had fallen close to ambient levels (approximately 330 ppm). A regression line fit to the data (Figure IV.H.2) indicated a ventilation rate of 0.8 ACH which agrees well with the independent SF_6 decay measurement of 0.9 ACH. In no other building were the conditions suitable for this type of measurement. It required abrupt removal of the occupants and no supply of air from other zones. Since in Building #1 each classroom was served by an independent air handler, CO_2 generated by the students in other parts of the building had minimal effect on the CO_2 concentrations in this room.

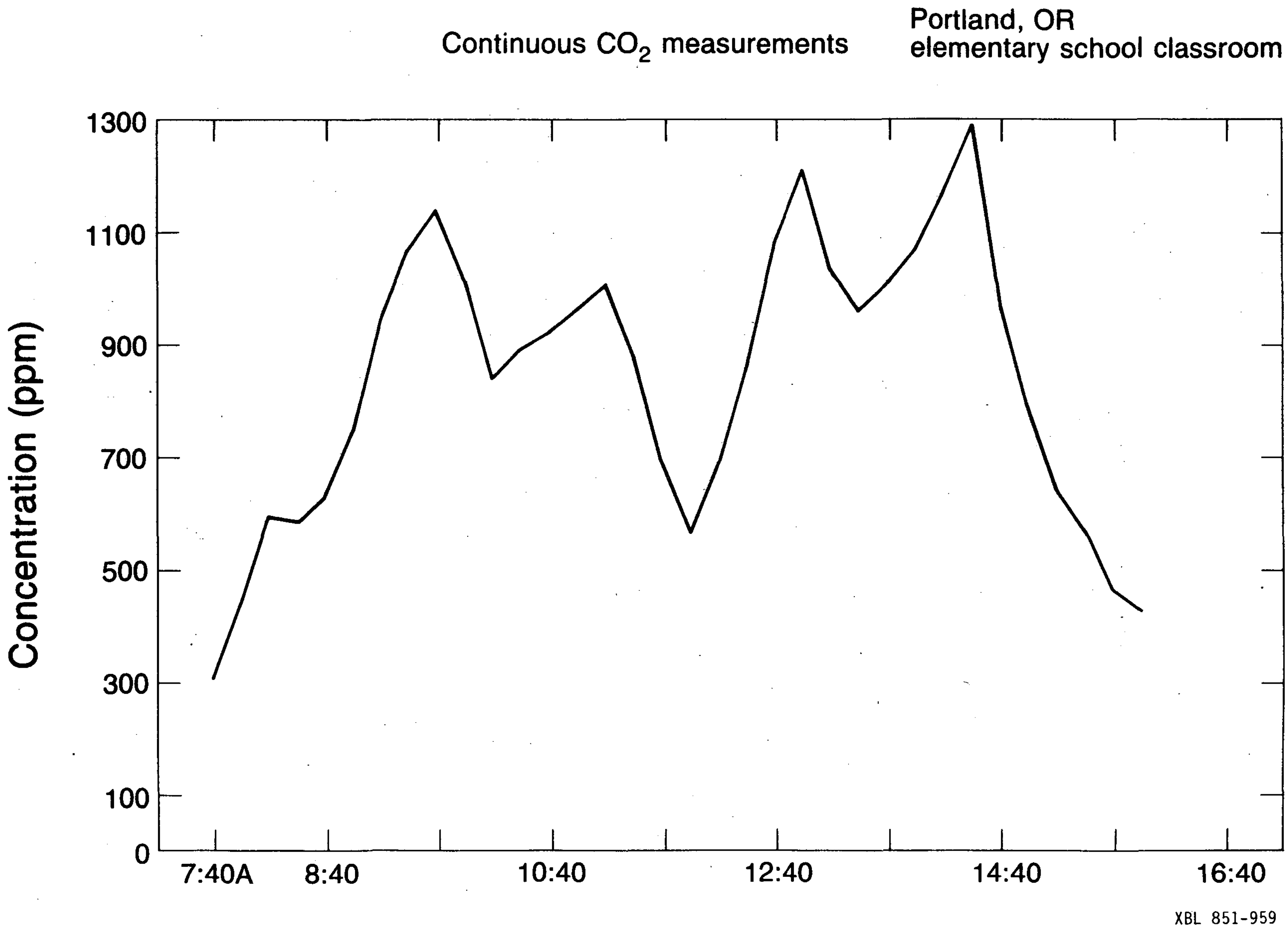
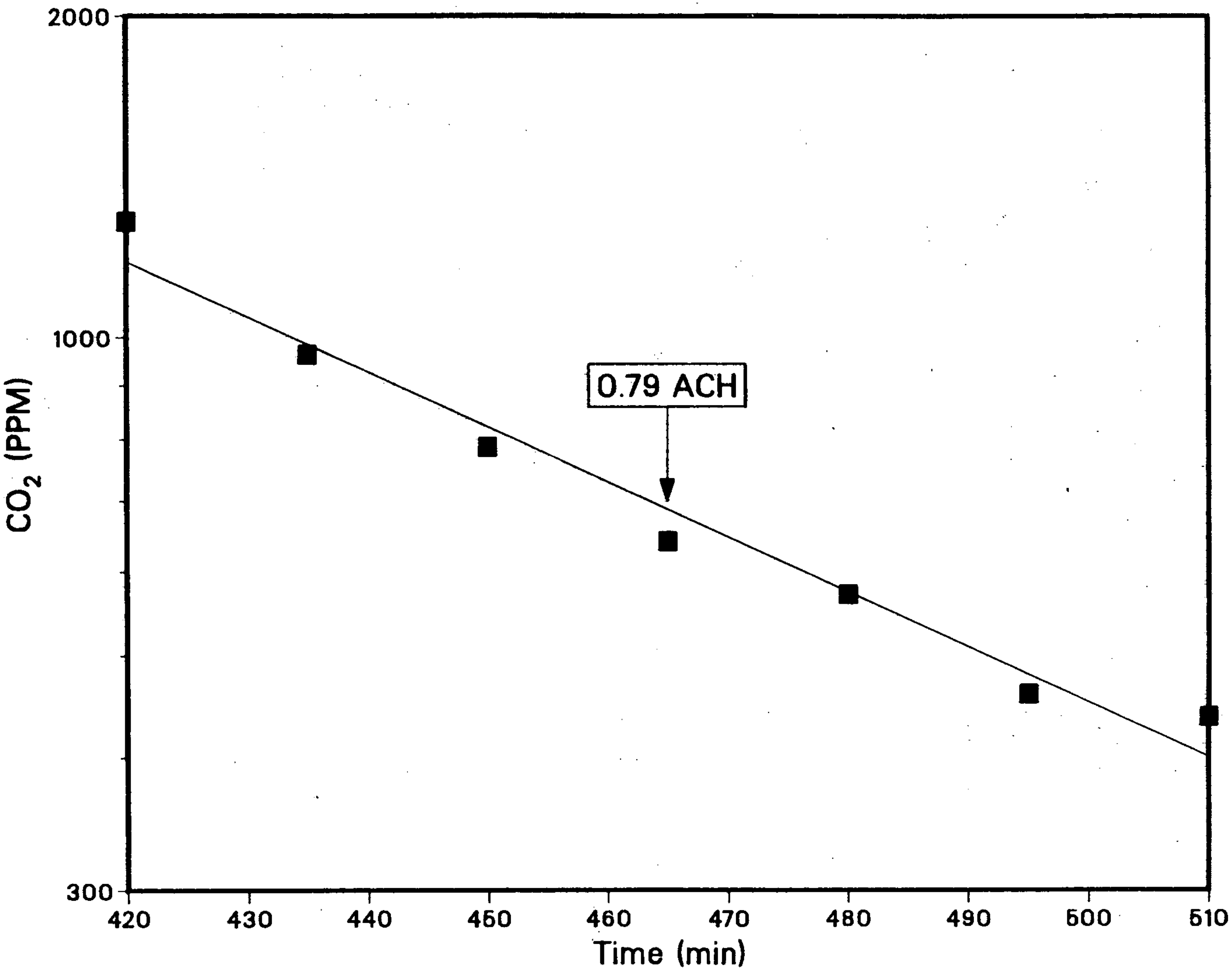

Continuous CO_2 measurements
Portland, OR
elementary school classroom
Concentration (ppm)
1300
1100
900
700
500
300
100
0
7:40A
8:40
10:40
12:40
14:40
16:40
XBL 851-959

Figure IV.H.1

Figure IV.H.2

OCCUPANT GENERATED CO_2 DECAY
ELEMENTARY SCHOOL CLASSROOM
BUILDING 1, PORTLAND, OR (24 JANUARY 1984)



XBL 851-953

I. LIMITATIONS FOR SINGLE TRACER DECAY MEASUREMENT

The use of a single tracer for a decay measurement of ventilation rate in multizone mechanically ventilated buildings was found to have limitations. The snap-shot technique in this study is dependent on careful manipulation of the outside air dampers to mimic conditions observed during the two-week pollutant monitoring period. Unfortunately, during that period, the damper positions were often changing from day to day and throughout the day in response to changing environmental conditions and building requirements. This was especially true during spring monitoring when the outside air temperature variations could cause the HVAC system to provide heating, economizer cooling, and mechanical cooling as the day progressed. The difficulty arose in attempting to select a 'typical' damper setting for the entire period. Depending on the amount of damper variation; the setting was made on an arithmetic average of damper openings for a range of measurements with small variation (less than approximately 50% of the total), or the setting was based on the mode, (the most frequently occurring damper opening), for a range of measurements with variation greater than approximately 50% of the total.

The outside air flow rate through the dampers (ventilation rate) may not be proportional to the amount of adjustment of the dampers, depending on the type of damper and damper resistance versus system resistance (SMACNA, 1983). Because of the poor flow characteristics of some dampers, outside air flow can be dramatically reduced through only small reductions in damper opening. Selection of the damper setting then becomes a critical and delicate procedure. Complicating this effort is the natural response of the HVAC system during the tracer decay test to modulate the damper positions. Technicians must be present to return those dampers to the desired position. These factors increase the uncertainty for the representativeness of the ventilation measurement by an undetermined amount.

Occasionally, building temperatures rose during the tracer mixing period when outside air dampers were closed. If the chillers were not activated, the higher interior temperatures could have had the effect of increasing the thermally-driven infiltration rate. The inside-outside temperature differences based on outside temperatures at the time of the ventilation measurements, as well as wind speeds could also impact the infiltration rates. Since the ventilation measurements were not usually conducted during the pollutant sampling periods, the infiltration contribution to total ventilation may have been different between two periods of testing.

It is virtually impossible to determine the exchange of building air between zones with one tracer. The recent developments of Fisk, Howarth, and Perera (Fisk et al., 1985; I'anson et al., 1982; Perera et al., 1983) lay the groundwork for the use of multiple tracers in measuring interzone ventilation in complex structures.

The difficulties in achieving good tracer mixing prohibit the measurement of local ventilation rates. An important assumption in determining these values from a tracer decay experiment is that the tracer be at a uniform concentration throughout the building before initiating the decay (Sandberg,1981). In many of the decay measurements in this study, mixing of the tracer into the air was not complete. Only a few of the buildings with relatively simple HVAC systems offer the possibility of follow-up analysis to compute the local ventilation. This information will be valuable in comparing ventilation throughout a building and against locally higher pollutant concentrations.

REFERENCES

Fisk, W.J. Binenboym, J., Kaboli, H., Grimsrud, D.T., Robb, A.W., Weber, B., (1985). Multi-tracer system for measuring ventilation rates and ventilation efficiencies in large mechanically-ventilated buildings, Proceedings of the Sixth International Conference of Air Infiltration Centre, Het Meerdal, Netherlands, September.

I'anson, S.J., Irwin, C., Howarth, A.T. (1982). Air flow measurement using three tracer gases, Build. and Environ. 17:245-252.

Perera, M.D.A.E.S., Walker, R.R., Trim, M.J.B. (1983). Measurement of intercell airflows in large buildings using multiple tracer gases, Proceedings International Seminar on Energy Savings in Buildings, Hague.

Persily, A.K., Grot, R.A.(1985). Ventilation measurements in large office buildings, ASHRAE Trans 91(2A):488-502.

SMACNA (1983). HVAC Systems Testing, Adjusting and Balancing. Sheet Metal and Air Conditioning Contractors National Association, Vienna, VA.

Sandberg, M. (1981). What is ventilation efficiency, Build. Environ. 16:123-135.

Silberstein, S., Grot, R.A.(1985). Air exchange rate measurements in the National Archive Building, ASHRAE Trans. 91(II):

Turiel, I., and Rudy, J.V. (1982). Occupant Generated CO_2 as an indicator of ventilation rate, ASHRAE Trans. 88(1):197-210.

V. RELATIONSHIP BETWEEN VENTILATION RATES AND POLLUTANT CONCENTRATIONS.

The familiar steady-state indoor air quality model (Eq. 3.1) has successfully been used to predict actual pollutant concentrations in experiments involving controlled source generation rates (Traynor et al., 1985; Hodgson and Girman, 1987). Ignoring outdoor pollutant concentration and all removal parameters except those of dilution and exhaust due to ventilation, it is expected that steady state pollutant levels from a constant source would be proportional to the reciprocal of the ventilation rate, I,

$$C_{\infty} \propto 1/I \qquad [5.1]$$

To see if this general relationship holds for an aggregate of buildings, whole building outside air exchange rates are plotted against average building pollutant concentrations in Figures V.1 - V.4. If ventilation is the dominant mechanism in determining the pollutant levels, then the form of these log-log scatter plots would be a cluster along a straight line of slope = -1. The figures show that the correlation is poor for all pollutants, implying that ventilation is not the most important parameter affecting observed pollutant concentrations. Source strengths, which likely vary from building to building, are as important as ventilation rates in determining concentrations.

Given the sources and emission rates that existed in this set of buildings, pollutant concentrations in excessively ventilated buildings are not significantly lower than in buildings with low to moderate ventilation rates. However, those buildings having high concentrations and low ventilation can be identified and possibly corrected by providing additional ventilation.

Except for Buildings #11/36 and #17/30, this report presents no pollutant data from the same building under varying ventilation conditions. Relationships of pollutant concentrations with other ventilation parameters such as recirculation rate and cfm/occupant and with building characteristics such as age and volume were also reviewed and are collected in Appendix K. No trends or correlations are apparent. We attempted to calculate source strengths for various pollutants in several buildings based on the measurements of concentrations, ventilation rates, and volume. The results were generally

Figure V.1

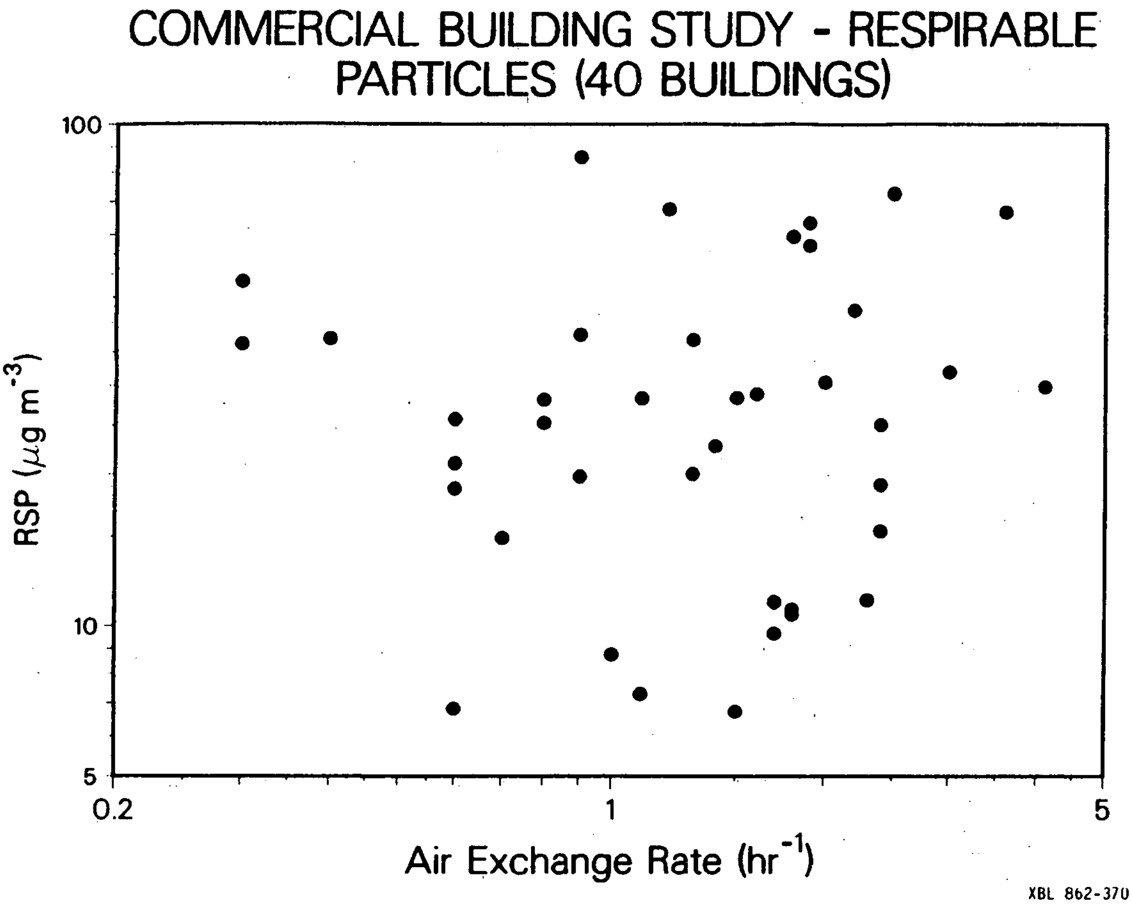


Figure V.2

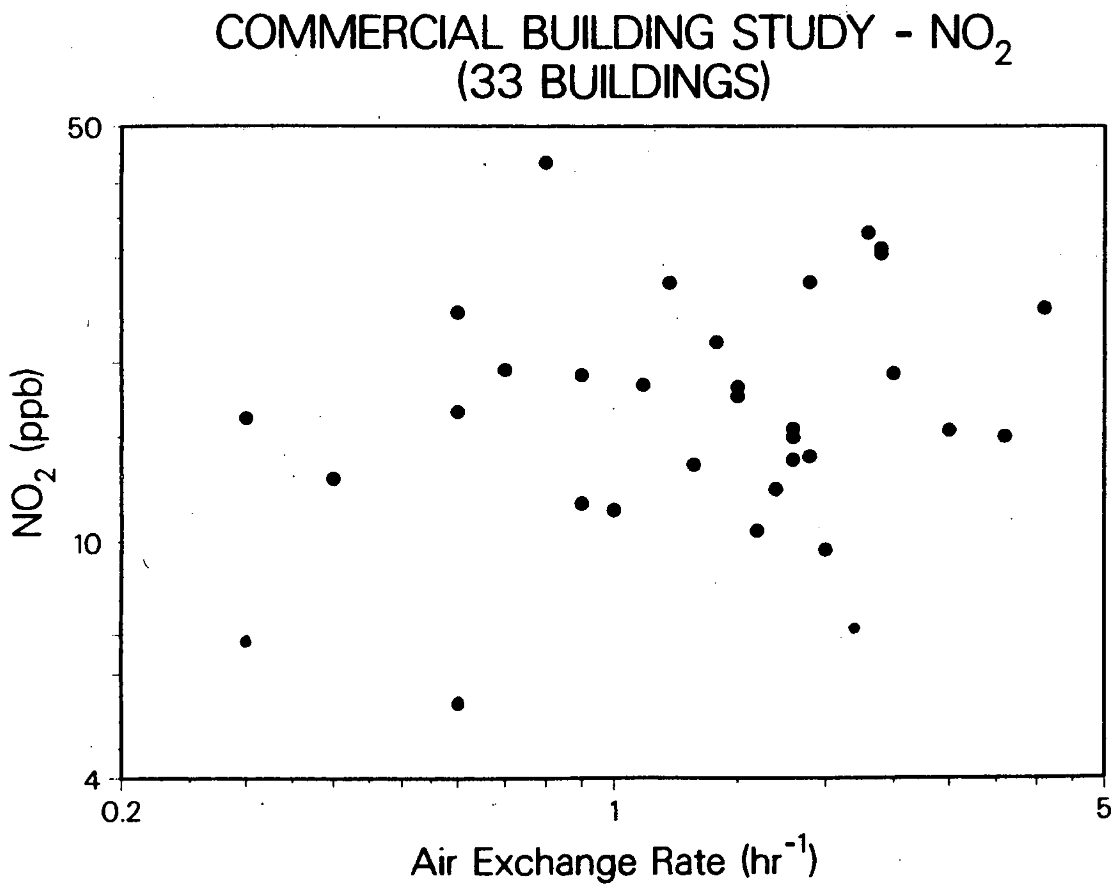


Figure V.3

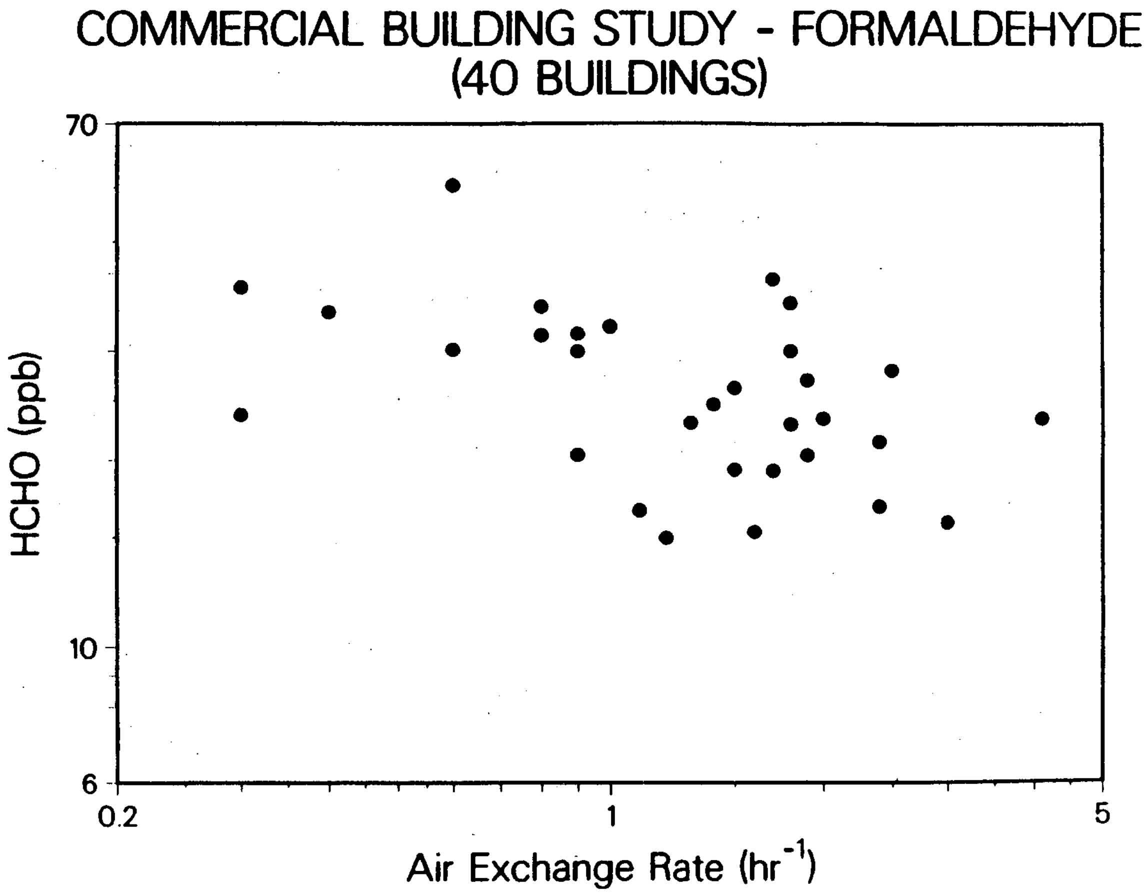
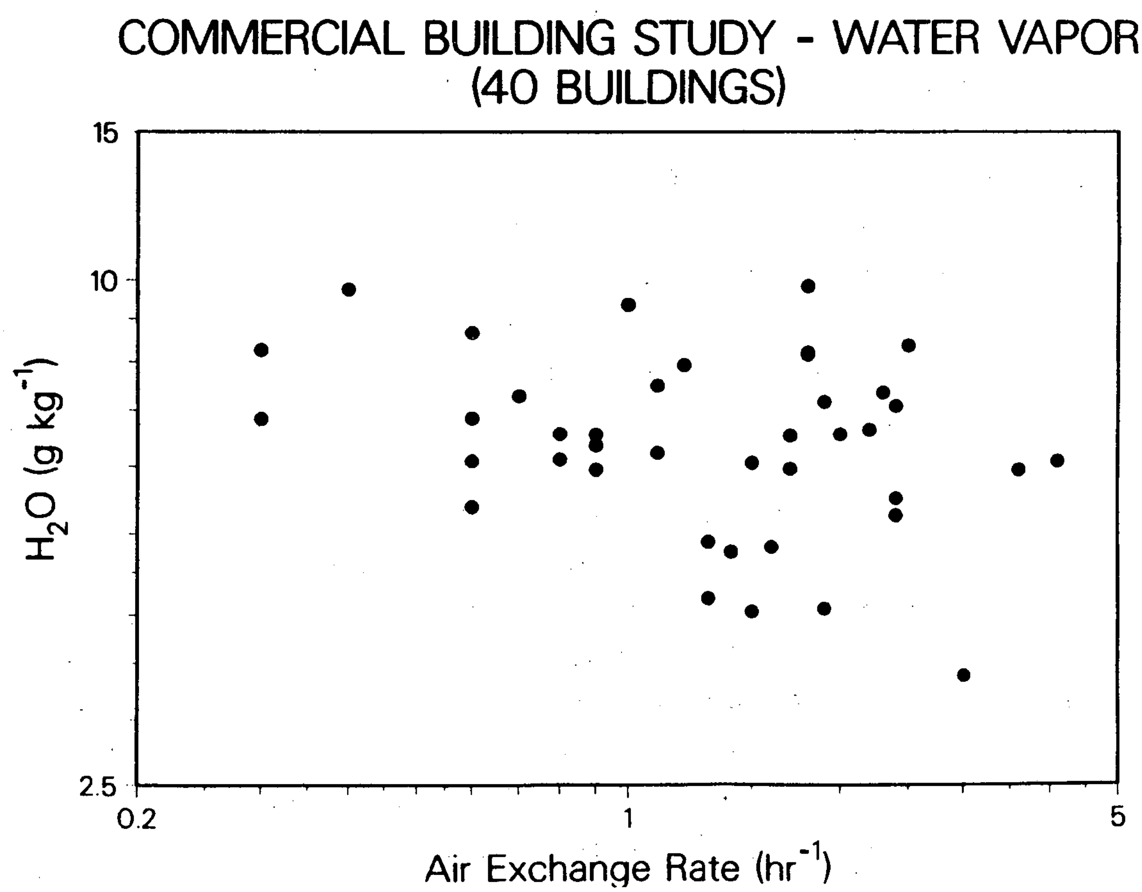


Figure V.4



unsatisfactory because of the low observed concentrations for NO_2 and HCHO and because of the presence of complex removal mechanisms (see Section III.A5).

A. BUILDING RETESTS

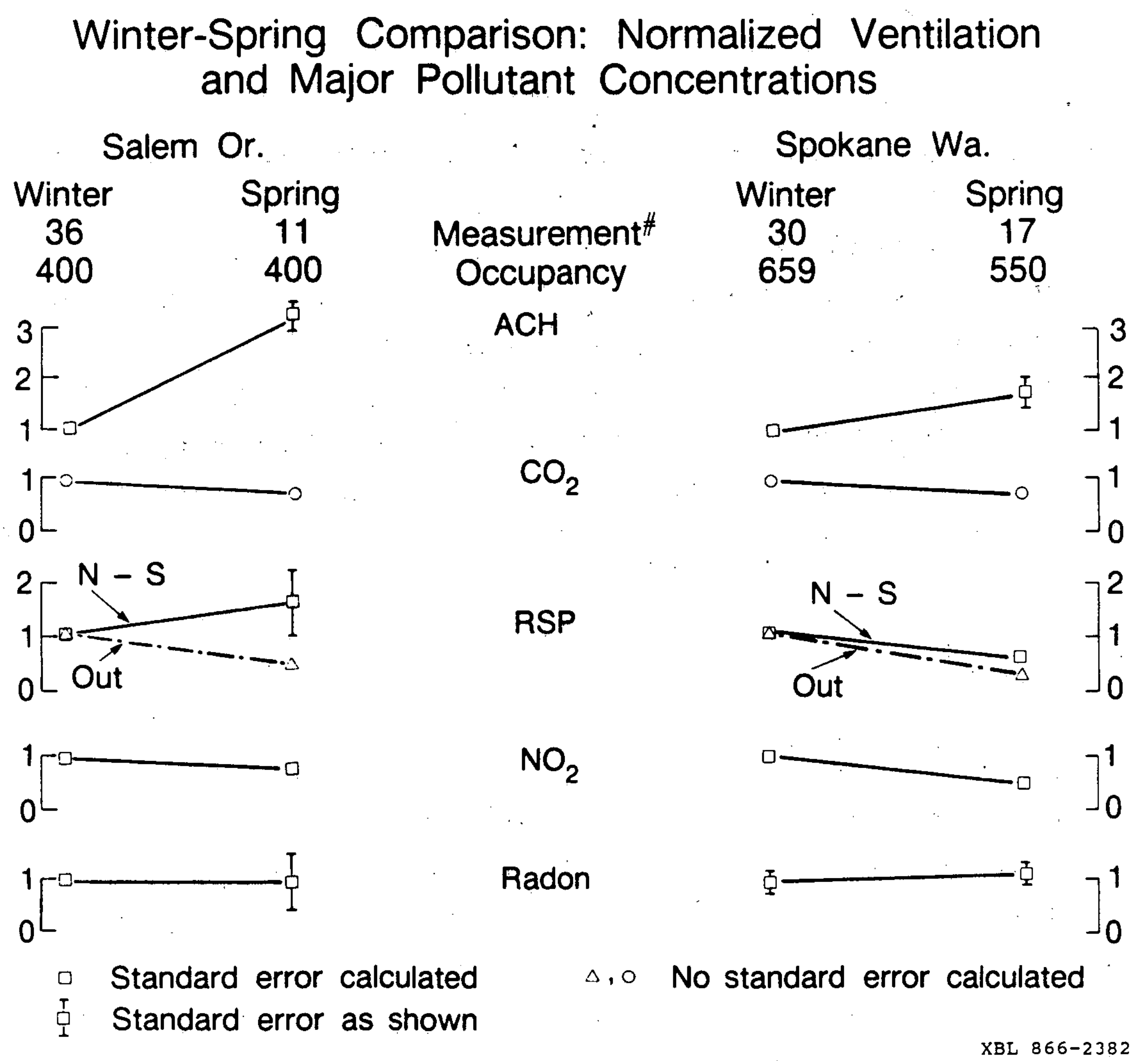
Buildings #11 and #17 were the only two buildings retested in this study. The respective follow-up monitoring periods are identified as #36 and #30. Building #11 was retested (identified as #36) during mild winter weather approximately ten months after the initial monitoring period in the spring. Building #17, a junior high school in Spokane, was also first monitored in the spring and then again (identified as #30) under cold winter conditions. Both buildings were selected for follow-up monitoring because of the unusually high ventilation rates in the first measurement period. Ventilation and pollutant data are summarized in Table V.1 and shown in normalized form in Figure V.5.

Building #11 is a four-story office building in Salem that had few, if any, complaints of poor indoor air quality during the first monitoring period. Prior to the second test period and coinciding with the onset of colder weather, a number of occupants began exhibiting contact dermatitis. The individuals affected were found throughout the building. Symptoms included skin rashes, red, watery and itchy eyes, and respiratory distress. Public health officials and independent consultants interviewed the afflicted individuals, examined the HVAC system and sampled building air for various organic compounds and biogenic material. Results were inconclusive. In response, the building manager increased the amount of outside air ventilation. The symptoms persisted intermittently up until the time of our second monitoring period. For the monitoring, building officials returned the HVAC system to the same condition that had existed during the worst episodes of poor air quality. They also requested that additional sampling sites be included, particularly in areas adjacent to the affected workers. As seen in Table V.1, none of the pollutants measured could have been responsible for the reactions that were observed in the workers. However, stagnant water was noted in the main air handler common return duct that could have been a source for the growth and maintenance of a number of types of organisms.

TABLE V.1

SPRING/WINTER COMPARISON

	Buildings 11 (36) Salem, Oregon		Buildings 17 (30) Spokane, Washington	
	SPRING	WINTER	SPRING	WINTER
BUILDING VOL. (FT^3)	1.454 X 10^6	1.454 X 10^6	933,000	933,000
OCCUPANCY	400	400	550	659
ACH (HR^{-1})	3.6 (2.1-5.4)	1.1 (1.0-1.1)	2.2 (0.3-3.0)	1.3 (0.9-1.4)
CFM/OCCUPANT	88.2	25.7	66.2	30.0
RSP ($\mu g/m^3$):				
Indoors				
Smoking	209	127	105	113
Non-smoking	23 (9-49)	14 (9-18)	11 (10-13)	24 (20-30)
All	63 (9-209)	28 (9-127)	43 (10-105)	37 (20-113)
Outdoors	8.0	20	7	33
PAH (ng/m^3):				
Indoors	5.00	11.76	3.71	12.54
Outdoors	1.92	4.85	--	19.66
B[a]P (ng/m^3):				
Indoors	0.73	0.69	0.78	1.36
Outdoors	0.09	0.40	--	2.84
H_2O ($\mu g/kg$):				
Indoors	5.9 (5.3-6.2)	6.2 (5.4-7.1)	6.6 (6.0-7.1)	4.1 (3.5-4.8)
Outdoors	-	6.0	-	2.1
NO_2 (ppb):				
Indoors	15 (9-19)	18 (15-22)	7 (7)	13 (12-16)
Outdoors	-	17	-	15
HCHO (ppm):				
Indoors	ALL B.D.	ALL B.D.	BD(BD-23)	22 (B.D.-46)
Outdoors	-	B.D.	B.D.	B.D.
RADON (pCi/l)	0.3 (0.0-0.6)	0.3 (0.1-0.4)	2.2 (1.9-2.5)	1.9 (1.6-2.3)
CO_2 (ppm)	467 (400-540)	604 (424-878)	520 (340-670)	641 (374-863)
CO (ppm)	<2	<2	<2	<3-4



Winter-Spring Comparison: Normalized Ventilation and Major Pollutant Concentrations
Salem Or.
Spokane Wa.
Winter
Spring
Measurement#
Occupancy
36
11
400
400
30
17
659
550
ACH
CO2
RSP
NO2
Radon
N - S
Out
N - S
Out
3
2
1
0
Standard error calculated
Standard error as shown
No standard error calculated
XBL 866-2382

Figure V.5

Data comparisons between the two periods show that although the ventilation rate was reduced during the second monitoring period to approximately 30% of that during the first period (1.1 vs. 3.6 ach) pollutant concentrations responded ambiguously. Water vapor, NO_2, CO_2, and PAH concentrations increased, but RSP and B[a]P concentrations decreased. (We note that the high RSP values are seen in smoking areas; smoking rates during the two tests are not known.) Formaldehyde, radon, and carbon monoxide showed no change. A similar result occurred in the retest of Building #17. The combination of colder outside temperatures, installation of double pane windows and an energy management system reduced the ventilation rate during the second period from 2.2 to 1.3 ach. Despite that, pollutant concentrations, on average, did not increase. Results from both buildings support the earlier conclusion that ventilation, by itself, is not the primary determinant of indoor pollutant levels; sources are important as well.

B. BUILDING #32 RADON TESTS

Building #32, located in Cheney, WA, was found to have significantly elevated Rn levels during its winter test period January - March, 1985, (Appendix G). Therefore, a second test with a more widespread sampling grid, both in the building and its associated utility tunnels, was run through the late spring and early summer, May - July, 1985. It is the only one of forty building tests to have a significantly elevated radon concentration. The special conditions of exposure to open soil and an old central ventilation system seem to be the source of the high concentration.

Brick is the major exterior construction material of this building. The interior has plastered walls with much decorative stone work, i.e., marble and granite in the central lobby areas on the first and second floors and in the halls. The original building layout was a "T" with the wings extending northeast to southwest and the large third wing extending northwest from the lobby main entry on the southeast face. There is a basement under the entire building but only the southwest and central portions are in use. During the initial winter sampling period no Rn samplers were placed in unoccupied spaces.

The main mechanical air handling system consists of one large fan located in the basement between the stairwells in the center of the building. The fan appears to be original equipment. The ventilation requirements for this building are met by a fairly simple system of supply ducts from the main ventilation fan to each floor with return through hallways and down the stairwell to a louvered grill, which leads into the mechanical room in the basement. The second floor theater has roof-mounted fans which are turned on during periods when the space is occupied. The ventilation system is described in more detail in Appendix I.

A series of utility tunnels which extend for three miles under the campus connect directly to the basement. These utility tunnels are lined with stone or concrete. The basement area away from the mechanical system has an exposed soil floor. This unfinished area is used for storage and is in direct communication with the air from the utility tunnels and fan. In its winter configuration, the outside air dampers near the ventilation fan were kept closed. Therefore, during the first test period, the only outside air deliberately drawn into the fan came predominantly from these tunnels. We suspect that this large volume of air in contact with the exposed radon-emitting surfaces in the basement and tunnels is then distributed throughout the building by the main air handling fan. In fact, the winter radon levels are quite uniform regardless of location or height above the ground floor as seen in Table V.2. The only exception is the theater which is separately ventilated. This supports the assumption that the radon is being mixed throughout the building by the air handler.

The follow-up summer measurements show the unusually high radon concentration which occurs in the soil-floored south utility tunnel. This particular tunnel ends abruptly and is not connected to the other parts of the tunnel network except where it enters the basement space. Outside air enters the other loop portion of the utility tunnel system through the basements of buildings which are served by the utilities and manhole covers in streets and sidewalks. Radon concentrations in this open portion of the utility tunnel loop are lower than those recorded from the closed tunnel south of the building. (Table V.2) Overall, the summer concentrations are lower than the winter levels.

It cannot be definitely determined from these measurements if radon concentrations are due to molecular diffusion from materials or the pressure-driven flow of soil gas from the soil. However, work by Nazaroff et al., (1986) and residential radon field measurements recently completed in eastern Washington-northern Idaho (Turk et al., 1986) suggest that the high local soil permeability is responsible for large pressure-driven convective-flow soil gas entry rates. The reduction of the driving forces during the summer may, in part, explain the lower summer levels. There may also have been more infiltration of ambient air for radon dilution during the summer months due to occupant behavior, i.e. open windows and doors.

In either case it would seem that the exposed stone, concrete, and/or soil in the basement and attached utility tunnels are the sources of radon-bearing soil gas for this building.

Guidelines for permissible exposure to airborne radon as suggested by regulatory and advisory authorities are given in Table III.A. This building is above the BPA recommended levels in winter and equals NCRP guidelines of 8 pCi/l.

Radon levels would probably be reduced if outside and return air are separately ducted to the main air handler. This would eliminate exposure to the large areas of open soil and broken stone and concrete.

TABLE V.2

COMPARISON OF WINTER - SUMMER RADON SAMPLING IN BUILDING #32

BUILDING SITES - ABOVE GROUND

SAMPLER LOCATION	SITE NO.	WINTER CONC. (pCi/l)	SUMMER CONC. (pCi/l)
1st Floor Office	1-C	9.21	4.93
2nd Floor Office	1-C	7.72	N/A
2nd Floor Theatre	2-B	3.30	1.27
3rd Floor Office	3-A	7.33	3.64
3rd Floor Office	3-B	8.17	N/A
3rd Floor Office	Rm309	N/A	2.13

BELOW GROUND SITES

SAMPLER LOCATION	SITE NO.	WINTER CONC. (pCi/l)	SUMMER CONC. (pCi/l)
Basement	B-1	8.51	2.85
Mechanical Room	N/A	N/A	6.36
South Util. Tunnel	N/A	N/A	26.29
North Util. Tunnel	N/A	N/A	1.77
400' Into N. Tunnel	N/A	N/A	0.27
700' Into N. Tunnel	N/A	N/A	3.85

REFERENCES

Hodgson, A.T., Girman, J.G. (1987). Exposure to methylene chloride from controlled use of a paint remover in residences, Proceedings of the 80th Annual Meeting of the Air Pollution Control Association, New York, Lawrence Berkeley Laboratory Report, LBL-23078.

Nazaroff, W.W., Lewis, S.R., Doyle, S.M., Moed, B.A., Nero, A.V.(1986). Experiments on pollutant transport from soil into residential basements by pressure-driven air flow, accepted for publication in Environmental Science and Technology, Lawrence Berkeley Laboratory Report # LBL-18374.

Traynor, G.W., Girman, J.R., Apte, M.G., Dillworth, J.F., White, P.D.(1985). Indoor air pollution due to emissions from unvented gas-fired space heaters, APCA Journal 35:231-237.

Turk, B.H., Prill, R.J., Fisk, W.J., Grimsrud, D.T., Moed, B.A., Sextro, R.G.(1986). Radon and remedial action in Spokane river valley residences: An interim report, Presented at the 79th Annual meeting of the Air Pollution Control Association, Minneapolis, June, Lawrence Berkeley Laboratory Report # LBL-21399.

VI. SUMMARY AND CONCLUSIONS

Pollutant concentrations, as measured in this study, were generally quite low and seldom exceeded commonly recognized standards and guidelines.

- High water vapor concentrations may have caused problems of occupant discomfort at sites in six buildings, most of which were monitored during higher temperature summer months. One site with high water vapor was accompanied by elevated concentrations of formaldehyde.

- Carbon dioxide eight-hour averages ranged from a low of 340 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 (6ppm - 7 ppm) were generally associated with vehicular exhaust 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 exceeded (53 ppb and 58 ppb) the EPA ambient annual air standard of 50 ppb. Most sites with elevated concentrations were exposed to outside air containing NO_2 from vehicular exhaust. Local smoking appeared to increase concentrations a small amount (2 ppb).

- Of all pollutants monitored, respirable suspended particle concentrations most frequently exceeded conservatively recognized guidelines, with occurrences usually related to nearby tobacco smoking. Building mean RSP concentrations ranged up to 86 $\mu g/m^3$ and one smoking site reached 308 $\mu g/m^3$. It is estimated that approximately 34% of the smoking sites in a similar sample would have RSP concentrations above the annual EPA limit of 50 $\mu g/m^3$ for total suspended particles whose diameters are smaller than 10 μm (a larger subset of suspended particles than RSP). Concentrations at indoor non-smoking sites had weak correlation with both outdoor concentrations (lower than outdoor at 65% of the sites) and smoking at other locations in the building. Since localized smoking has only a small impact on RSP concentrations in non-smoking areas, processes such as dilution by building volume and removal by filtering and chemical interaction must be occurring.

- Polycyclic aromatic hydrocarbon concentrations, including benzo[a]pyrene, were positively correlated to RSP concentrations, with a maximum B[a]P concentration of 9.7 ng/m^3, considerably above the U.S. ambient urban concentration of 2 ng/m^3.

- Formaldehyde concentrations were quite low. The averages in 21 of the buildings were above the 20 ppb detection limit. It is estimated that only 3% of all similarly selected sites would have concentrations above the ASHRAE 100 ppb guideline.

- The geometric mean of all radon measurements was 0.5 pCi/l, similar to levels found outdoors, with only one building having a concentration of concern at 7.8 pCi/l. The latter condition is likely due to open soil in the basement and a network of underground service tunnels allowing ready entry of the gas.

- The one-time ventilation measurements from all buildings average 1.5 ach and ranged from a low of 0.2 ach to 4.1 ach. Buildings with low ventilation rates were not usually associated with elevated concentrations of the pollutants measured, although local ventilation may fall below ASHRAE recommendations of 5 cfm/occupant in non-smoking areas and 20 cfm/occupant in smoking areas.

- In thirteen of the buildings, minimum ventilation rates were measured. In six of the thirteen buildings the minimum ventilation rate was less than 15 cfm/occupant, a value recommended by ASHRAE in its revised ventilation standard as the minimum ventilation rate allowed in any building. In spite of the low minimum rates measured, the six buildings were operating at an average ventilation value nine times higher than their minimum values.

Correlation is very weak between pollutant concentrations and ventilation rates (both with outside and recirculated air). This is probably a result of the weak sources in most buildings and the fact that concentrations are probably most heavily influenced by the building-to-building variability of pollutant sources. Tests for correlation are also handicapped by the difficulty in measuring local ventilation.

Whole building cfm/occupant appears to be inappropriate as a measure of adequate ventilation, since unoccupied building volumes are included in the calculation. The ability to measure local ventilation is essential to understanding the appropriate ventilation to balance energy use and air quality needs.

Design ventilation is not synonymous with actual operating ventilation rates since it is dependent on proper HVAC system operation and maintenance. System operators were occasionally unfamiliar with the equipment and unable to manipulate the control system properly. Despite the fact that some of the operators were unaware of the implications of reduced ventilation, there were few observed instances of poor air quality, based upon the pollutants monitored.

The benefits of increasing outside air ventilation rates to 35 cfm/occupant throughout a building where smoking occurs may be minimized if outdoor air pollutant concentrations are higher than the non-smoking indoor concentrations, as was the case for RSP at 65% of the sampling sites.

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 general irritation. The offending agents were never conclusively identified. Generally, the indoor atmosphere in most buildings appeared to be satisfactory, based upon the pollutants measured in this study.

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

Further detailed research should be conducted to study the dispersion of tobacco smoke and its interactions with other pollutants and the building structure throughout a large building space. This effort would require the use of a reliable system of multiple tracers for determining local ventilation rates and transfer of air from one building zone to another.

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