LBL-8894 Rev. c.2
UC-95d
EEB-Vent 80-8

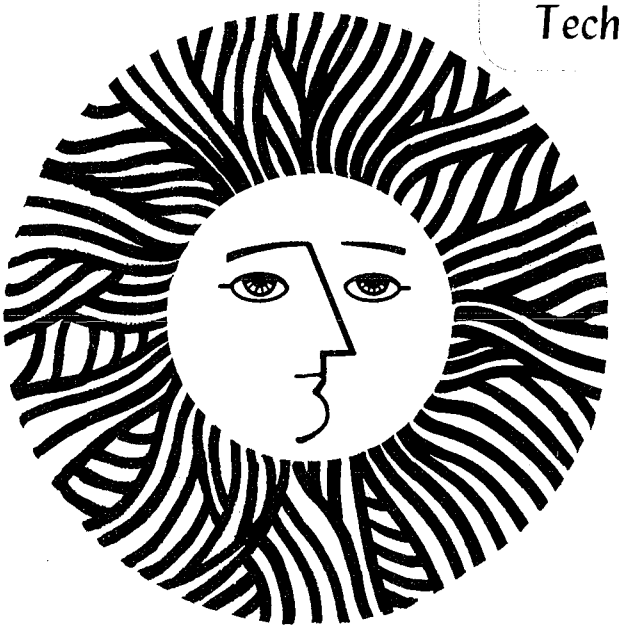
Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

ENERGY & ENVIRONMENT
DIVISION

INDOOR AIR QUALITY MEASUREMENTS IN ENERGY-EFFICIENT RESIDENTIAL BUILDINGS

James V. Berk, Craig D. Hollowell, James H. Pepper, and Rodger Young

May 1980



Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

Revised and Expanded Version of Paper
79-14.2 presented at the Air Pollution
Control Association 72nd Annual Meeting,
Cincinnati, Ohio, June 1979.

LBL-8894 Rev.
EEB-Vent 80-8

Indoor Air Quality Measurements in Energy-Efficient Residential Buildings

James V. Berk, Craig D. Hollowell
James H. Pepper and Rodger Young

James V. Berk, Ph.D., Craig D. Hollowell, Ph.D., James H. Pepper, B.S., and Rodger A. Young, M.S., are staff scientists at the Lawrence Berkeley Laboratory.

Energy Efficient Buildings Program
Energy and Environment Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

May 1980

The work described in this report was funded by the Office of Buildings and Community Systems, Assistant Secretary for Conservation and Solar Energy of the U.S. Department of Energy under contract No. W-7405-ENG-48.

ABSTRACT

The potential impact on indoor air quality of energy-conserving measures that reduce ventilation is being assessed in a field monitoring program conducted by the Lawrence Berkeley Laboratory. Using a mobile laboratory, on-site monitoring of infiltration rate, carbon dioxide, carbon monoxide, nitrogen dioxide, nitric oxide, ozone, sulfur dioxide, formaldehyde, total aldehydes, and particulates was conducted in three houses designed to be energy-efficient. Preliminary results show that energy-conserving design features that reduce air-exchange rates compromise indoor air quality; specifically, indoor levels of several pollutants were found to exceed levels detected outdoors. Although the indoor levels of most pollutants are within limits established by present outdoor air-quality standards, considerable work remains to be accomplished before health-risk effects can be accurately assessed and broad-scale regulatory guidelines revised to comply with energy-conservation goals.

Keywords: air pollution, aldehydes, energy conservation, energy-efficient, carbon dioxide, carbon monoxide, formaldehyde, houses, indoor air quality, infiltration, nitric oxide, nitrogen dioxide, ozone, particulates, sulfur dioxide, ventilation

INTRODUCTION

Residential, institutional, and commercial buildings together account for approximately one-third of the energy consumed annually in the United States, as shown in Figure 1. Residential structures alone account for approximately 25% of this figure and, in all building types, more than half of the energy used is for heating, cooling, and ventilating.

The Department of Energy (DOE) is supporting ventilation research aimed at developing new building energy performance standards (BEPS) and energy budgets for institutional, commercial and residential buildings in various climatic zones. Periodic updates of these standards, which, by congressional mandate, are to be promulgated in 1980, will consider advances in state-of-the-art building technology as well as construction and energy technologies. The Ventilation and Indoor Air Quality Program (VIAQ) at the Lawrence Berkeley Laboratory (LBL) is being conducted as part of DOE's research and development programs. These programs frequently support and are intended to influence decisions for standards such as BEPS.

Ventilation requirements are currently set by state and local governments and vary from one jurisdiction to another. Most of the ventilation requirements found in existing building codes are based on rather vague health and safety considerations and generally ignore energy conservation. (LBL) has been conducting laboratory and field research on building ventilation requirements that consider both energy conservation demands and indoor air quality. These factors are important in establishing ventilation needs, for as the building envelope is "tightened" to reduce leakage and infiltration, e.g., by improving insulation and reducing ventilation, less fresh air is introduced into a building and the quality of the indoor air may deteriorate.

Ventilation standards for various classes of buildings have existed for over half a century. They are generally conservative and, since they have been established by a variety of groups, frequently vary for the same application. An important objective of our research, thus, is to evaluate the bases for all such existing standards, and to provide recommendations for establishing energy-efficient ventilation standards in residential, institutional and commercial buildings that do not compromise the health and comfort of occupants.

In the residential sector, many houses are now being designed and built with energy-conservation goals in mind. To this end, a primary consideration has been to minimize air leakage. Air exchange in buildings takes place through: infiltration (the uncontrolled leakage of air to or from any space); natural ventilation (controlled air exchange, e.g., opening windows and doors); and mechanical ventilation. (In the United States, the latter mechanism is essentially limited to non-residential buildings.) Adequate air exchange is required in all occupied buildings to:

- o Establish a satisfactory balance between the metabolic gases (oxygen and carbon dioxide) released into the environment;
- o Remove excess heat and moisture from internal sources;
- o Dilute human and non-human odors to acceptable olfactory levels;
- o Remove contaminants produced by activities, furnishings, construction materials, etc. in occupied spaces.

Until recently, air pollution research has focused almost exclusively on pollution in the outdoor environment, even though the major proportion of the population spends far more time indoors than outdoors. Recent evidence suggests that concentrations of some pollutants in residential buildings frequently exceed those commonly occurring in the outdoor environment.[1] Chemical and biological contaminants released into indoor environments are undesirable but often unavoidable by-products of occupant activities. For example, typical indoor contaminants are gaseous and particulate pollutants from indoor combustion processes (e.g., cooking, heating, cigarette smoking), toxic chemicals and odors from cooking and cleaning activities, odors and viable microorganisms from occupants, odor-masking chemicals used in cosmetics and air fresheners, and a wide assortment of chemicals released from indoor construction materials and furnishings -- asbestos, formaldehyde, vinyl chloride.

Among those studies that have focussed on indoor air pollution, most have assumed that indoor pollution arises from or is directly related to outdoor sources. These studies have been concerned mainly with SO_2, CO, and O_3, and total suspended particulate matter -- species which are, indeed, in lower concentrations in indoor air than in outdoor air. Neglected in this research have been other potentially important indoor air pollutant species, such as NO, NO_2, nitrates, sulfates, metals, organics, and the respirable fraction of particulate matter. Table 1 lists some of the major indoor air pollutants and their sources.

Recognition of the importance of indoor air pollution is expected to have a major impact on 1) energy conservation strategies that restrict indoor-outdoor air exchange, 2) the overall assessment of the effect of air pollution on human health, 3) the design of epidemiological studies that must consider indoor as well as outdoor air pollution, and 4) the need for more stringent control of air pollution from indoor sources.

Field Monitoring Sites

The Lawrence Berkeley Laboratory of the University of California initiated a research project in 1975 to study the chemical and physical character of indoor-generated air pollutants in residential and commercial buildings. Recently, this project expanded to include a research, development, and demonstration program in energy-efficient buildings, including many energy-efficient houses. This paper is concerned with the impact of reduced ventilation rates on indoor air quality in three

test houses, each of which is discussed in turn below.

MED-I A Minimum Energy Dwelling in Mission Viejo, California

The Minimum Energy Dwellings (MED-I) research project[2] was conceived in 1975 by the Southern California Gas Company, as a means of demonstrating that quality living standards could be maintained in a home where total energy consumption was reduced by at least 50%. Principal sponsors of the project are DOE, the Southern California Gas Company and the Mission Viejo Company. Two identical MED-I houses were designed and built, side by side, using available energy-saving construction techniques and materials, advanced gas-fired household appliances, and a solar/natural gas, central energy system for space heating, cooling, and water heating. The two MED-I houses are instrumented to monitor energy consumption and building performance. One is occupied by a "typical" family (two adults and one child); the other is an unoccupied but furnished demonstration model. Both are one-story structures and have a total floor area of 1,150 ft^2. LBL's Energy Efficient Buildings (EEB) Mobile Laboratory (described under "Experimental Methods") monitored the indoor air quality of the MED-I houses from mid-August to mid-September, 1978, spending approximately two weeks on each house. Data shown in this report are for the occupied house only.

ISUERH

The Iowa State University Energy Research House (ISUERH)[3] in Ames, Iowa was a project jointly sponsored by the Engineering Research Institute and the Iowa State University Research Foundation, Inc. The overall objective of this project is to obtain data on various active and passive methods of reducing energy consumption under operating extremes of the midwestern environment, and to document the results in a format useful and meaningful to communities, industries, and residents of the midwest. A total of sixteen different active modes of heating and cooling will be evaluated before the project is completed.

The structure is nearly cubical in shape (30′ x 35′ x 27′) and provides a living area of 2,385 ft^2 distributed over three levels (see Figure 2). All kitchen appliances are electric and the heating system utilizes both forced-air and radiant-ceiling systems. A greenhouse, accessible from all three levels through sliding glass doors, is located on the south wall. Energy consumption in this house is expected to be 50% less than typical energy-efficient housing in Iowa built to the new requirements of ASHRAE Standard 90-75.[4] The EEB Mobile Laboratory monitored this house during the month of December, 1978. The house was unoccupied during this period (except for workmen and visitors) with the exception of a single day when a group of eight people gathered to simulate occupancy. During this day, cooking, dining, and other typical household activities took place.

ERHM

The Energy Research House (ERHM) in Carroll County, Maryland, was specifically built to develop data on cost-effective design and construction of energy-efficient houses. The most promising and practical energy-conserving options were incorporated into this demonstration house: a nominal 7'6" ceiling to reduce interior volume and many non-standard construction techniques designed to reduce infiltration and thermal load. All appliances are electric and energy-efficient. The electric space heating system is comprised of a heat pump, a heat-circulating fireplace and individual bath heaters. This two-story house provides a living area of approximately 1,200 ft^2 and is expected to require 1/3 to 1/2 less energy than its typical counterpart.

The EEB Mobile Laboratory was used to monitor this house from mid-March to mid-April, 1979. The house was furnished and occupied by LBL field personnel as their residence during this period; activities such as cooking, dining and cleaning occurred routinely.

Experimental Methods

The EEB Mobile Laboratory is a facility designed to conduct on-site field studies of ventilation requirements and energy utilization in buildings. Its instrumentation and the contaminants it is designed to monitor are shown in Table 2. The mobile laboratory, containing sampling, calibration, and monitoring systems, was positioned outside each of the houses studied. For inorganic gaseous pollutants, air was sampled through teflon sampling lines from three rooms within the structure and from one outdoor site. The four lines were sampled for ten-minute intervals in sequence; that is, ten-minute samples were taken from each site every forty minutes.

Infiltration rates were monitored continuously at the ISUERH and ERHM houses using a tracer-gas system, developed at LBL, which continuously injects controlled amounts of N_2O during monitoring.[5] The data are recorded and processed to yield continuous infiltration rates. Infiltration at the MED-I house was measured with a simple exponential decay-rate method using ethane as the tracer gas. At all three locations, outdoor weather parameters were monitored in order to determine whether changes in infiltration correlated with meteorological changes.

The particulate matter in the air was monitored at the four sampling points using dichotomous air samplers (DAS)[6] developed at LBL specifically for indoor monitoring. These devices separate the particulate matter by size (above and below 2.5 μm) and collect the samples on teflon filters; these samples are subsequently analyzed for total mass concentration (by beta gauge techniques) and chemical content (by X-ray fluorescence).

Total aliphatic aldehydes were sampled from indoor and outdoor air by means of a flow-control system developed at LBL[7,8]. Aldehydes, sampled in individual bubbler tubes containing MBTH solution, were refrigerated and brought back to LBL for analysis. Sample solutions

containing aldehydes were oxidized to yield a blue-green dye, and the concentration of aldehydes was measured and calibrated spectrophotometrically at 628 nm. Chromotropic acid and pararosaniline methods were used simultaneously to measure the formaldehyde fraction of the total aldehydes.

Radon-222, an inert, radioactive, naturally-occurring gas present in soil, rock, sand and spring water produces "daughters" that can be inhaled into the lower respiratory tract and cause damage to lung tissue[9]. Radon concentrations were measured in these houses by means of passive environmental radon monitors (PERMs) fabricated for LBL,[10] and by analyzing grab samples with an alpha particle counting system.

Most of the gas analyzers were calibrated daily by supply zero and span gases. Analyzer linearity was verified at the beginning and end of each field experiment. In addition, the EEB Mobile Laboratory was periodically audited to assure the quality of the data collected. Three audits were performed by outside firms: in September, 1978 (Research Triangle Institute-EPA), in November, 1978 (California Air Resources Board), and in March, 1979 (Rockwell International-EPA). Agreement was generally within 10%; instruments were corrected and/or data discarded when larger discrepancies were found.

RESULTS AND DISCUSSION

Air-exchange rates at the MED-I house were measured by using a simple ethane decay curve which yielded values of approximately 0.2 air changes per hour (ach). At the Iowa and Maryland houses the outside air flow rates were measured using an N_2O continuous tracer gas system. These flow rates (in cfm) were then divided by the respective house volumes to express the results in air changes per hour(ach).

Figure 3 illustrates variations in infiltration observed over a 24-hour period at the ISUERH. (It should be emphasized that on some days these rates varied over wider ranges than shown.) Figure 4 shows the frequency distribution of infiltration rates for this house measured over a six-day period. The air-exchange rate varied from about 0.1 ach to 0.4 ach with an average of approximately 0.2 ach -- in good agreement with earlier measurements made in this house using simple exponential decay methods.

Figure 5 shows a similar frequency distribution for the infiltration measurements made at the ERHM house. A vapor barrier had been installed during construction of this house and thus it was somewhat tighter than the MED-I and ISUERH houses. Air-exchange rates varied from about 0.05 to 0.3 with an average of 0.15 ach.

Results from field monitoring at these sites indicated that the pollutants fall into three major classes: those whose primary source is indoors, those for which indoor and outdoor sources seem to be comparable, and those whose primary source is outdoors. As houses are made tighter and infiltration rates reduced, indoor-generated pollutants show higher concentrations whereas outdoor-generated pollutants are largely shielded from entering the indoor environment. The indoor

concentrations of pollutants in the intermediate class depend on relative source strengths. When reviewing the pollutant concentrations detected at these field sites, it should be remembered that only the MED-I house had gas-fired kitchen appliances and typical family occupancy; the Iowa State house was unoccupied except for workmen and visitors, and the Maryland house was occupied by our field personnel only.

Figures 6, 7, and 8 show the frequency distributions of CO in the MED-I, ISUERH, and ERHM, respectively. In all cases, the indoor and outdoor concentrations were comparable, with indoor levels being slightly higher at the MED-I house, presumably because of natural gas combustion and/or cigarette smoking. The one-hour National Ambient Primary Standard for CO is 40 mg/m^3 (35 ppm)[11] which is considered to be the level of air quality necessary, with an adequate margin of safety, to protect the public health.

Figures 9, 10, and 11 show the frequency distributions for NO_2 at these test houses and Figures 12, 13, and 14 show the distribution for NO. The nitrogen oxides, NO_2 and NO, are produced by both outdoor and indoor combustion processes. At the MED-I house (with gas appliances) indoor concentrations of NO_2 and particularly NO exceeded those found outdoors. At the ISUERH house, indoor and outdoor levels were very similar with the exception of a few instances where indoor welding activities elevated the indoor levels. At the Maryland house, indoor levels of NO_2 were somewhat lower than those found outdoors although the reverse was found for NO. The proposed National Ambient Primary Standard for a one-hour exposure to NO_2 is 470 $\mu g/m^3$ (250 ppb), which is well above any of the levels observed in these field studies. No standard exists for NO.

Carbon dioxide (CO_2) can be produced by combustion processes within the house and by the occupants themselves. As a natural constituent of outdoor air, CO_2 is generally not monitored as an outdoor pollutant. In buildings such as educational institutions, which have high occupant densities, CO_2 may be the most important parameter for setting ventilation standards.[12] Figures 15, 16, and 17 show the CO_2 frequency distributions in the three houses. As evident from these data, indoor concentrations exceed those found outdoors. The recommended standards, as defined for occupational environments, begin at 5,000 ppm. In these studies, CO_2 concentrations remained under 2,000 ppm.

Ozone (O_3) is a highly reactive component of photochemical smog; it is in dynamic equilibrium with the nitrogen oxides. Because of the reactive nature of O_3, indoor concentrations tend to decrease as buildings are tightened. Figures 18, 19, and 20 show the frequency distributions for O_3 at the three field sites. Although outdoor concentrations in southern California were considerably higher than the concentrations found elsewhere, the indoor concentrations at all three sites were significantly lower than those found outdoors. The only indoor concentrations exceeding 16 ppb were measured at the ISUERH house where welding activities took place within the house. The short-term (one-hour) air-quality standard for O_3 is 120 ppb.

Sulfur dioxide (SO_2) is another reactive pollutant whose primary source is outdoors. Figure 21 shows indoor and outdoor concentrations observed at the Maryland house. Indoor concentrations were generally lower than outdoor concentrations and both were well below the 24-hour ambient standard of 140 ppb. SO_2 measurements from the other two sites were not completed because of equipment problems.

Figures 22 through 29 show the analysis of particulate data taken with the dichotomous air samplers. (These units were not installed at the MED-I house.) Particles were separated by size -- above and below 2.5μm -- the typical bimodal size distribution of urban aerosols. Fine particles (<2.5μm) are generated predominately by combustion processes and are more hazardous since they are less likely to be filtered out by the nasal passages. The coarse particles are generated by natural and mechanical processes and do not reach the lower respiratory tract.

Figure 22 shows the mass concentrations for total suspended particulates (TSP) and the fine particle fractions (less than 2.5μm) at the ISUERH. The National Ambient Standard for TSP for a 24-hour sampling period is 260 $\mu g/m^3$. Indoor concentrations of TSP at the ISUERH house were consistently lower than those found outdoors with the exception of the December 4-5 and the December 13-16 time intervals. During the former time period, workmen were welding in the house and cigarette smoking was observed. Between December 12 and 15, welding and other construction activities took place in the boiler room and greenhouse. (Particulates collected on December 16 presumably had been generated during this period.) Other than these activities and the gathering which took place on December 14, the house was relatively unoccupied.

Figure 23 shows similar data collected at the Maryland house, which was occupied by LBL field personnel. Here, fine particle concentrations approximated and often exceeded the outdoor concentrations. The primary sources of these indoor particulates were cooking and cleaning activities. Chemical analysis of the fine particle fractions by X-ray fluorescence techniques allows us to compare indoor and outdoor concentrations for elements known to have outdoor sources. Figures 24 and 25 show the indoor and outdoor lead concentrations for the fine particle fraction at the ISUERH and ERHM respectively. The primary source of this pollutant is automobile exhaust. Indoor levels of lead were consistently lower than outdoor levels at the ISUERH and very much lower at the EHRM. There is presently no national standard for lead, but the California ambient standard is 1.5 $\mu g/m^3$ for a one-month average concentration. Figures 26 and 27 show the bromine content of the fine particulates at the same houses. This pollutant also is known to have automobile exhaust as its primary source. Again, indoor concentrations are consistently lower than outdoor, particularly in the tighter house, and outdoor/indoor correlations are easily seen.

Figures 28 and 29 show fine particulate sulfur at these houses. The primary sources for sulfur are emissions from power plants; most are assumed to be in the form of sulfate and implies that sulfate concentrations might be three times as high as those shown for sulfur. Again, the consistently lower indoor levels and the very low indoor/outdoor ratios at the Maryland house illustrate the shielding effects of

structures having low air-exchange rates.

The specific elements known be generated outdoors have very low indoor/outdoor ratios. However, the indoor/outdoor ratios for the total suspended particulate mass are not nearly as low and in fact sometimes exceed unity. These facts indicate that most of the particulates found indoors are probably generated from indoor sources. Presumably, indoor levels of those particulates would be even higher under normal occupancy conditions and higher still in houses using natural gas appliances.

Figure 30 represents the frequency distributions at the MED-I house for total indoor and outdoor aldehyde levels. As a comparative, data from the adjacent unoccupied house are also given. These data represent 24-hour samples. Indoor concentrations varied between 33 ppb and 104 ppb with an average of 64 ppb in the occupied house. Outdoor concentrations were less than 20 ppb. Indoor sources of aldehydes appear to be common building materials such as plywood and particleboard constructed with urea formaldehyde resin, as well as the activities of building occupants, e.g., cooking and smoking.

Figure 31 is a histogram showing the range of total aliphatic aldehydes and formaldehyde during monitoring at the ISUERH. The concentrations of total aliphatic aldehydes were between 36 and 97 ppb during the unoccupied period and 76 ppb during the one occupied period. Simultaneous sampling of outdoor air yielded an average aldehyde concentration of 6 ppb with a maximum value of 12 ppb and a minimum value of 2 ppb. The formaldehyde fraction of the indoor air was between 28 and 61 ppb and averaged 42 ppb. The outdoor formaldehyde concentrations were below 7 ppb for the entire sampling period. Figure 32 shows the distributions for the same parameters at the Maryland house. Indoor formaldehyde concentrations ranged from 44 ppb to 148 ppb with an average of 98 ppb, while total aldehyde concentrations indoors during the same period ranged from 104 ppb to 226 ppb with an average of 150 ppb. All outdoor concentrations were less than 10 ppb. Again, these data represent 24-hour samples. These values should be compared to the formaldehyde standard of 120 $\mu g/m^3$ recently promulgated in Europe for residential buildings.[13] Using this figure as a standard, we see that formaldehyde levels in these houses are occasionally excessive and total aldehyde levels frequently exceed this guideline.

Radon monitoring at the ISUERH using the PERMs yielded a value of 0.5 nCi/m^3 for a 2-week integrated measurement. Grab samples, collected in a tedlar bag and sent to LBL for analysis by means of an alpha counting system, yielded a value of approximately 1 nCi/m^3. In contrast, several one- to two-week integrated measurements at the ERHM, also using the PERMs, yielded values of 20-30 nCi/m^3 and grab samples gave comparable results.

As a reference point, it is useful to know that the Environmental Protection Agency in evaluating the radon problem in houses constructed on reclaimed phosphate lands in Florida set a value of 4 nCi/m^3 as an upper limit. The levels found at the ERHM were considerably above these EPA recommendations. We are planning to conduct follow-up tests to correlate radon and radon daughter concentrations with air-exchange

rates. In addition, we will evaluate the effectiveness of various control strategies (such as sealing floors and wall-floor joints and coating some of the building materials) in minimizing radon emission into interior living spaces.

CONCLUSIONS

This report gives preliminary results from our field-monitoring program in energy-efficient residences and is intended to identify pollutant species exhibiting high concentrations in houses having low ventilation rates. Although the sample consisted of only three houses, monitored under minimal occupancy conditions, we did observe some formaldehyde and radon problems. Other studies undertaken as part of the LBL Indoor Air Quality Program have indicated that gas stove emissions are potential problems in houses with gas appliances and low air-exchange rates. In general, our program is providing substantial evidence that the concentrations of a wide range of indoor-generated pollutants increase as air-exchange rates are lowered. While the effects on the health, safety, and comfort of building occupants is variable, depending on the type of pollutant and the concentration levels reached, in many cases there is cause for concern, particularly as we move more determinately toward an energy-efficient society. Reducing infiltration and ventilation rates in an effort to conserve energy in buildings and homes clearly has an effect on indoor air quality which must be taken into account as national conservation programs are implemented. Specifically, our findings indicate the need to delineate more precisely the sources and levels of indoor pollutants, the effects of conservation measures on indoor pollutant levels, and the health risks of lowering infiltration and ventilation.

We know that indoor pollution levels are strongly affected by occupant activities and, in addition, by the manner in which materials are incorporated into a building. Emanation rates also vary for the same material depending on how the material is fabricated. Some strategies for limiting increases in most indoor air pollutants are to:

1) Install mechanical ventilation systems coupled with air-to-air heat exchangers to transfer heat (and not contaminated air) from the exhaust air to the fresh air stream in winter and vice versa in the the summer.

2) Circulate indoor air through contaminant control devices.

3) Seal out or eliminate certain contaminants (e.g., radon) at the source.

4) Select building materials that have low emanation rates of pollutants.

In terms of national and/or local directives in the area of conservation, two regulatory approaches are possible for limiting exposure to indoor contaminants. The first, which has a precedent in the way occupational exposure standards are set, is to specify a maximum permissible level and to accept the disease incidence, if any, that may be

associated with increases in contaminant levels to this limit. An alternative approach is to set standards based on an explicit cost comparison between the disease incidence that may be caused by increased indoor pollution and the cost of preventing these increases. In either case, substantial work must be accomplished in characterizing the sources of the multiple contaminants of our indoor environment and in assessing the impact of various building designs, materials, and retrofits on indoor air quality.

ACKNOWLEDGMENTS

The work described in this report was funded by the Office of Buildings and Community Systems, Assistant Secretary for Conservation and Solar Energy of the U.S. Department of Energy under contract No. W-7405-ENG-48.

The authors acknowledge the assistance of Rick Casper and his staff at the Southern California Gas Company, and Jim Boulware and his colleagues at the Mission Viejo Company for their cooperation in the study of the MED-I house. Many thanks to Jim Woods, Paul Peterson, the staff of the Iowa State University Energy Research Foundation, Inc., and the owners of the research house in Carroll County, Maryland, for their helpful assistance.

REFERENCES

1. C.D. Hollowell and G.W. Traynor, "Combustion-generated Indoor Air Pollution," in Proceedings of the 13th International Colloquium on Polluted Atmospheres, Paris, France (April 25-28, 1978).

2. U.S. Department of Energy, Minimum Energy Dwelling (MED) Workbook: An Investigation of Techniques and Materials for Energy Conscious Design, SAN/1198-1 (December 1977).

3. J.E. Woods and P.W. Peterson, "Evaluation of an energy conserving research house including multimodal operation of solar and heat pump systems," in Proceedings of the 1977 Annual Meeting of the American Section of the International Solar Energy Society, vol. I (1977), pp. 6-8.

4. The American Society of Heating, Refrigerating, and Air Conditioning Engineers, Energy Conservation in New Building Design, Standard 97-75, (New York, 1975).

5 P.E. Condon, D.T. Grimsrud, M.H. Sherman, and R.C. Kammerud, An Automated Controlled-flow Air Infiltration Measurement System, Lawrence Berkeley Laboratory Report, LBL-6849 (March 1978).

6. B.W. Loo, R.S. Adachi, C.P. Cork, F.S. Goulding, J.M. Jaklevic, D.A. Landis, and W.L. Searles, A Second Generation Dichotomous Sampler for Large-scale Monitoring of Airborne Particulate Matter, Lawrence Berkeley Laboratory Report, LBL-8725, January 1979. Presented at the 86th Annual Meeting of the American Institute of Chemical Engineers, Houston, Texas, April 1-5, 1979.

7. C. Lin, R.N. Anaclerio, D.W. Anthon, L.Z. Fanning, and C.D. Hollowell, Indoor/Outdoor Measurements of Formaldehyde and Total Aldehydes, Lawrence Berkeley Laboratory Report, LBL-9397 (July 1979). Presnted at the 178th National Meeting of the American Chemical Society, Washington, D.C., September 1979.

8. D.W. Anthon, L.Z. Fanning, C.D. Hollowell, and C. Lin. A Flow Control System for Accurate Sampling of Air, Lawrence Berkeley Laboraatory Report, LBL-9403 (December 1979). Submitted for publication in Analytical Chemistry.

9. R.J. Budnitz, J.V. Berk, C.D. Hollowell, W.W. Nazaroff, A.V. Nero, and A.H. Rosenfeld, "Human disease from radon exposures: The impact of energy conservation in buildings," Lawrence Berkeley Laboratory Report LBL-7809 (1980). Energy and Buildings, 2: 209 (1980).

10. A.C. George, "A Passive Environmental Radon Monitor," in Radon Workshop, February 1977, HASL-325 (Energy Research and Development Administration, Health and Safety Laboratory, New York, July 1977).

11. U.S. Environmental Protection Agency, National Primary and Secondary Ambient Air Quality Standards, Code of Federal Regulations, Title 40, Part 50 (40 C.F.R. 50) p. 4-53. Revised July 1, 1979.

12. J.V. Berk, C.D. Hollowell, C. Lin and I. Turiel, The Effects of Energy-Efficient Ventilation Rates on Indoor Air Quality at a California High School, Lawrence Berkeley Laboratory Report, LBL-9174 (July 1979).

13. R. Baars, "The Formal Aspects of the Formaldehyde Problem in the Netherlands," Presented at the International Indoor Climate Symposium, Copenhagen, Denmark, August 30-September 1, 1978. In Indoor Climate, edited by P.O. Fanger and O. Valbjorn (Danish Building Research Institute, Copenhagen, 1979), pp. 77-81.

Table 1. Indoor air pollution in residential buildings.

SOURCES	POLLUTANT TYPES
OUTDOOR	
Ambient Air	SO_2 NO, NO_2, O_3, Hydrocarbons, CO, Particulates
Motor Vehicles	CO, Pb
INDOOR	
Building Construction Materials	
Concrete, stone	Radon
Particleboard	Formaldehyde
Insulation	Formaldehyde, Fiberglass
Fire Retardant	Asbestos
Adhesives	Organics
Paint	Mercury, Organics
Building Contents	
Heating and cooking combustion appliances	CO, SO_2, NO, NO_2, Particulates
Furnishings	Organics, Odors
Water service; natural gas	Radon
Human Occupants	
Metabolic activity	CO_2, NH_3, Organics, Odors
Human Activities	
Tobacco smoke	CO, NO_2, HCN, Organics, Odors
Aerosol spray devices	Fluorocarbons, Vinyl Chloride
Cleaning and cooking products	Hydrocarbons, Odors, NH_3
Hobbies and crafts	Organics

Table 2. Instrumentation used in the Lawrence Berkeley Laboratory Energy Efficient Buildings Mobile Laboratory.

Parameter	Principle of Operation	Manufacturer/Model
Field		
Continuous Monitoring Instruments:		
Infiltration		
N_2O or C_2H_6 (Tracer gas)	IR	LBL
Indoor Temperature and Moisture		
Dry-Bulb Temperature	Thermistor	Yellow Springs 701
Relative Humidity	Lithium Chloride Hygrometer	Yellow Springs 91 HC
Outdoor Meteorology		
Dry-Bulb Temperature	Thermistor	Meteorology Research 915-2
Relative Humidity	Lithium Chloride Hygrometer	MRI 915-2
Wind Speed	Generator	MRI 1074-2
Wind Direction	Potentiometer	MRI 1074-2
Solar Radiation	Spectral Pyranometer	Eppley PSP
Metric Rain Gauge	Tipping Bucket	MRI 382
Gases		
SO_2	UV Fluorescence	Thermo Electron 43
NO, NO_x	Chemiluminescence	Thermo Electron 14D
O_3	UV Absorption	Dasibi 1003-AH
CO	NDIR	Bendix 8501-5CA
CO_2	NDIR	M.S.A. Lira 303
Radon	Alpha Dosimetry	LBL
Particulate Matter		
Size Distribution	Optical Scattering	Royco Particle Counter 225
Radon Progeny	Under Development	LBL
Sample Collectors		
Gases		
Formaldehyde Total Aldehydes	Chemical Reaction/Absorption (Gas Bubblers)	LBL
Selected Organic Compounds	Adsorption (Tenax GC Adsorption Tubes) for GC Analysis	LBL
Particulate Matter		
Aerosols (Respirable/ Non-respirable)	Virtual Impaction/Filtration	LBL
Bacterial Content	Inertial Impaction	Modified Anderson Sampler
Data Acquisition System		
Microprocessor		Intel System 80/20-4
Multiplexer A/D Converter		Burr Brown Micromux Receiver MM6016 AA Remote MM6401
Floppy Disk Drive		ICOM FD3712-56/20-19
Modem		Vadic VA-317S

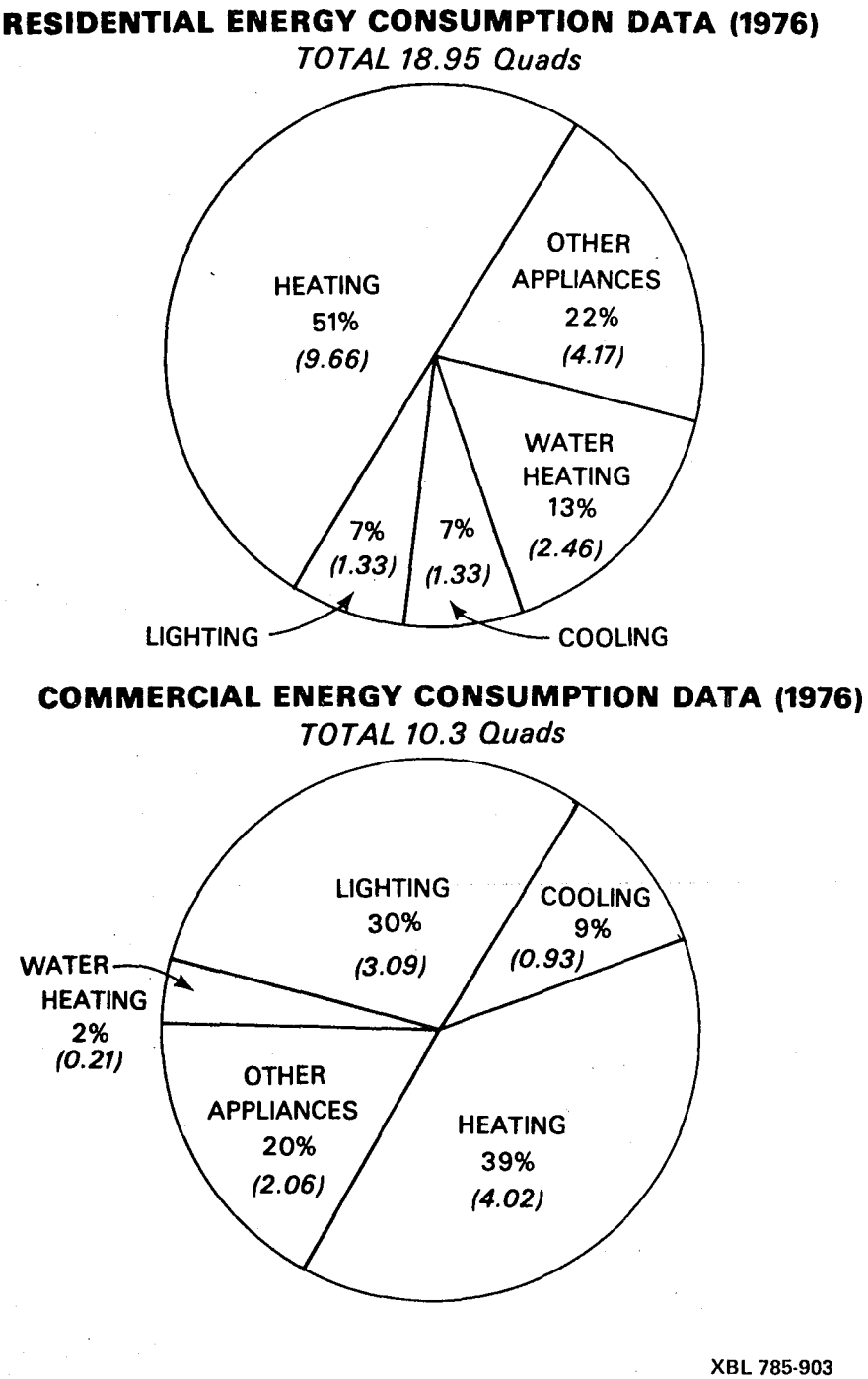


Figure 1. Primary energy use for residential and commercial buildings in the U.S. Numbers in parentheses are in units of quads or 10^{15} Btu.

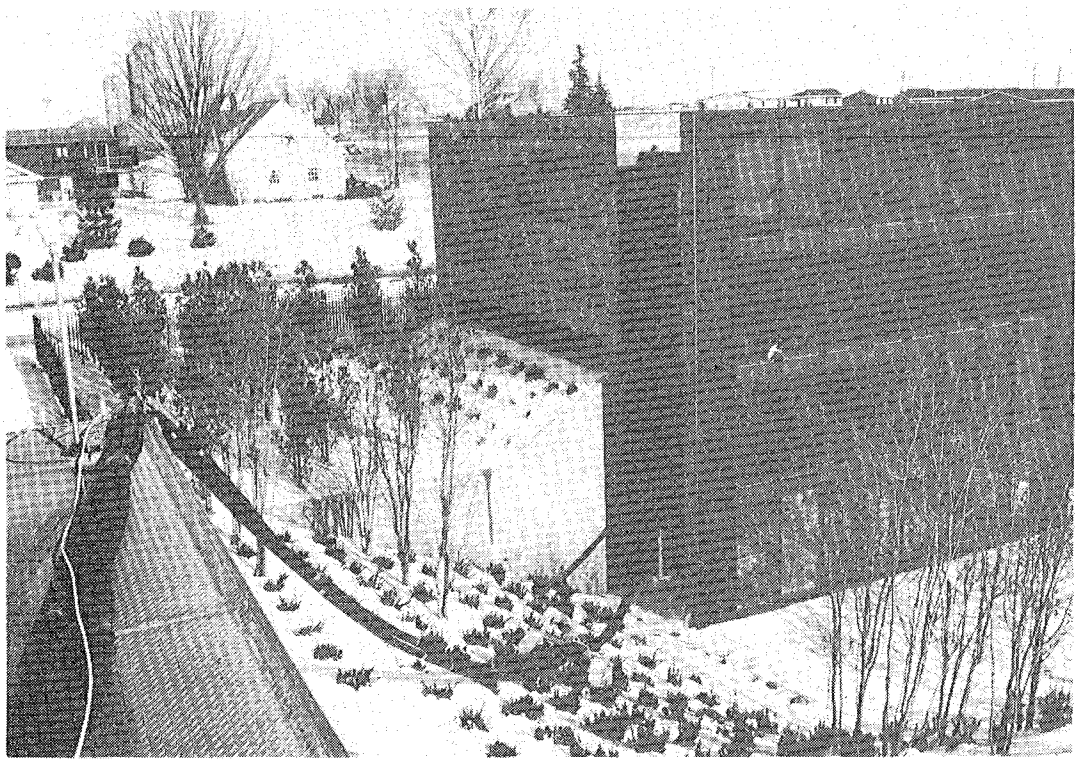
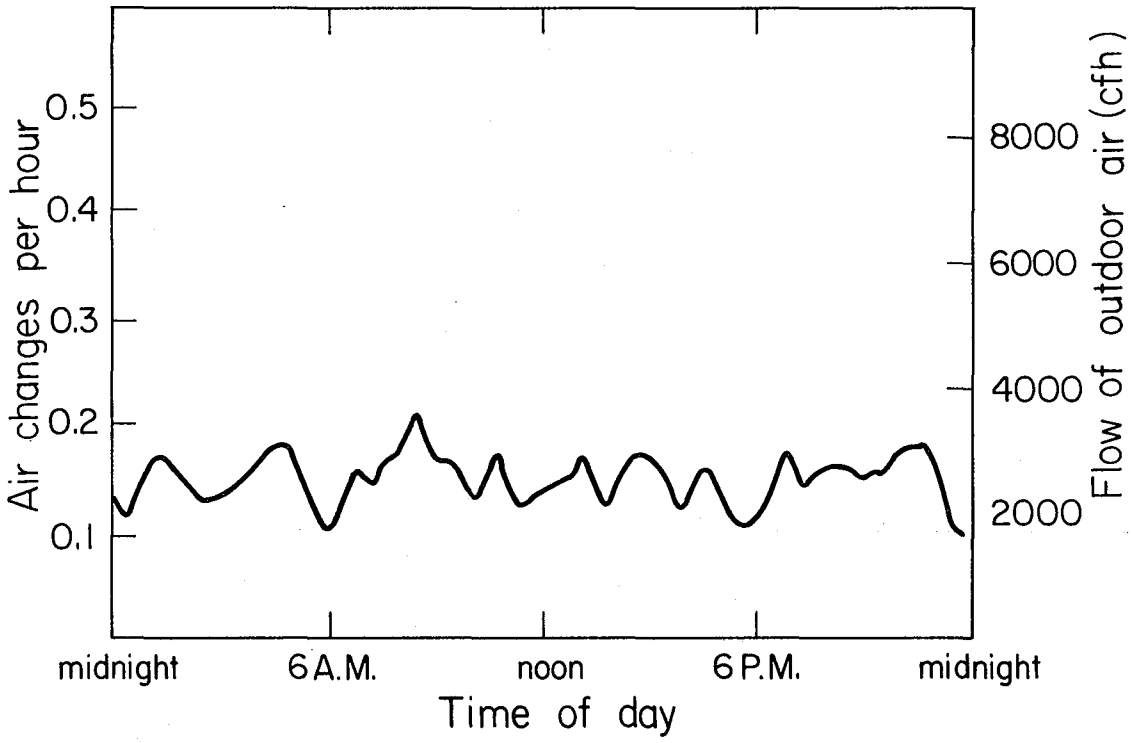


Figure 2. Top: EEB Mobile Laboratory at the ISUERH. XBB 804-5262

Bottom: Insulated sampling lines extending from the roof of the mobile laboratory to the sampling sites.



XBL 795-1426A

Figure 3. Time dependence of infiltration rate at the ISUERH for December 8, 1978.

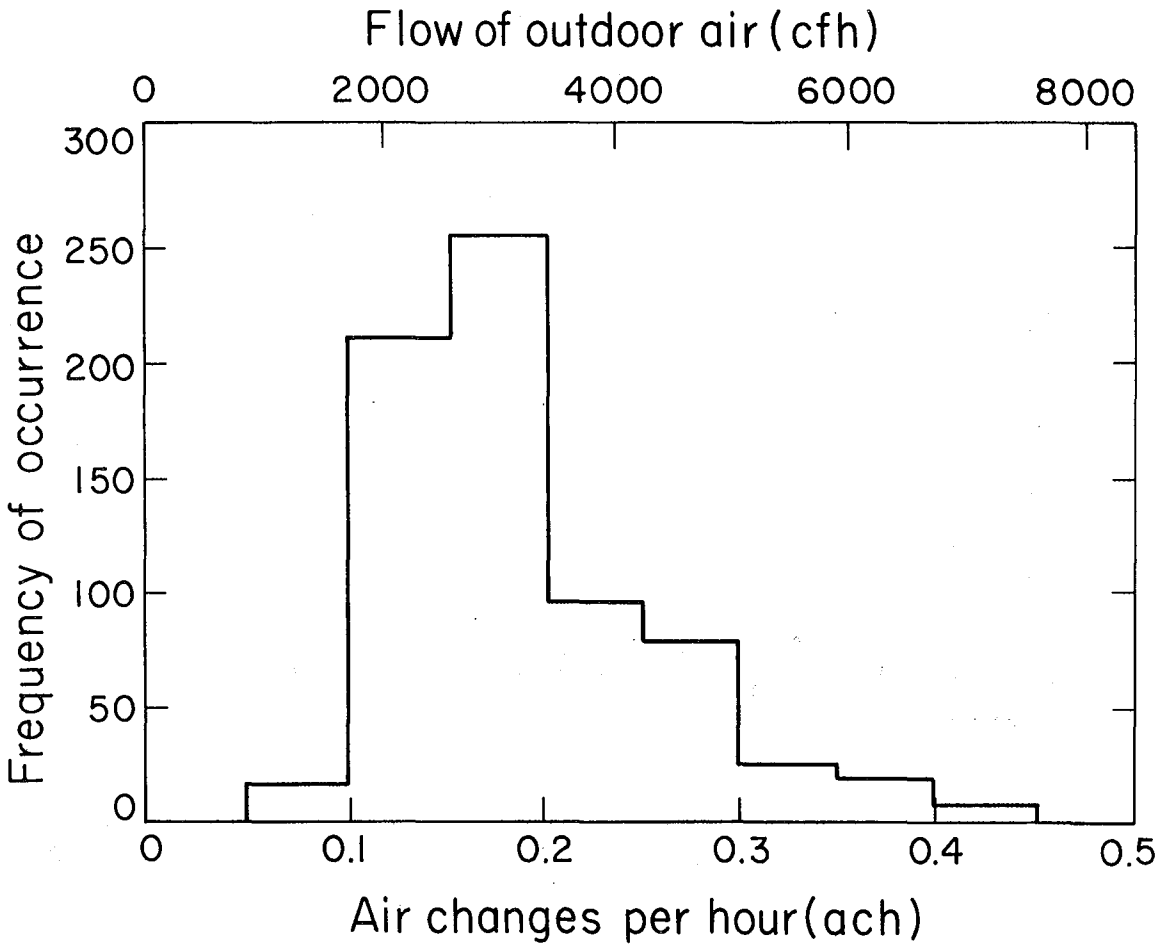


Figure 4. Frequency distribution of air exchange rates at the ISUERH, 6 day summary.

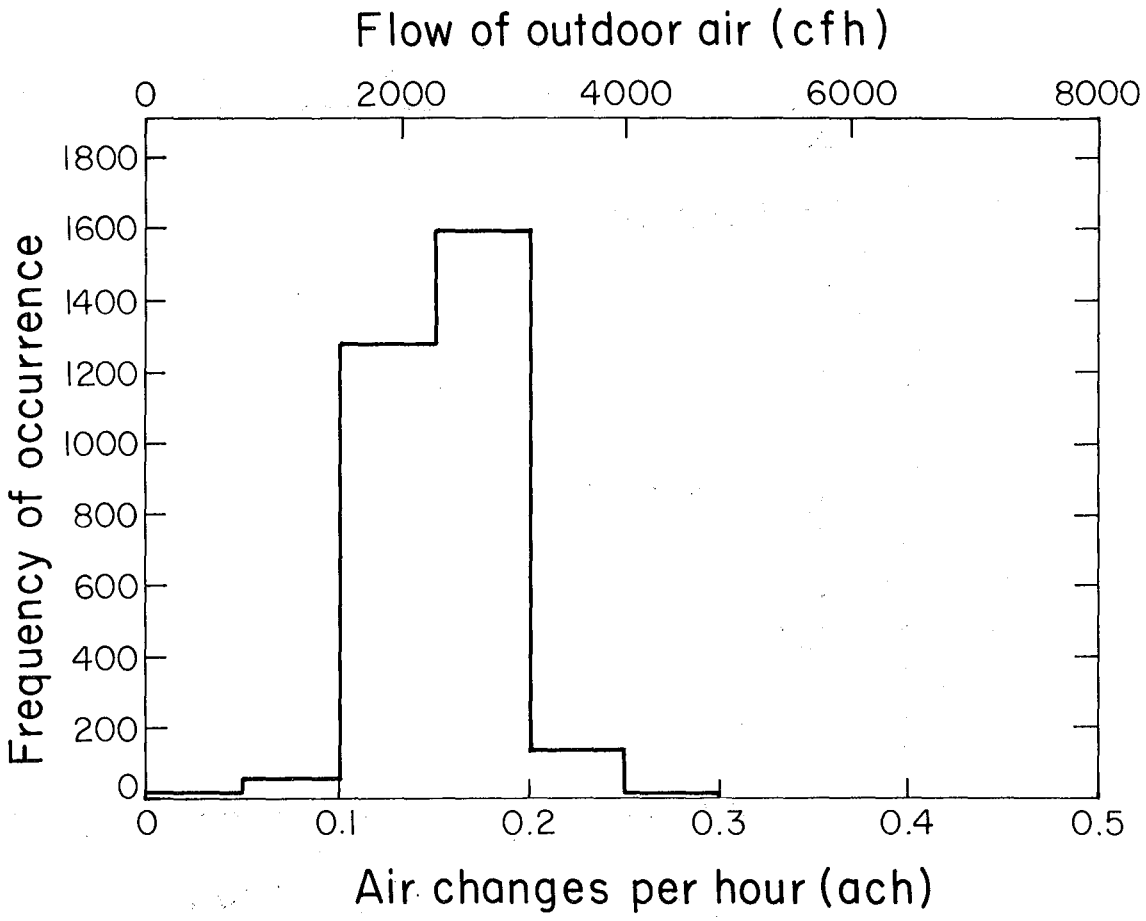


Figure 5. Frequency distribution of air exchange rates at the Energy Research House, Carroll County, Maryland.

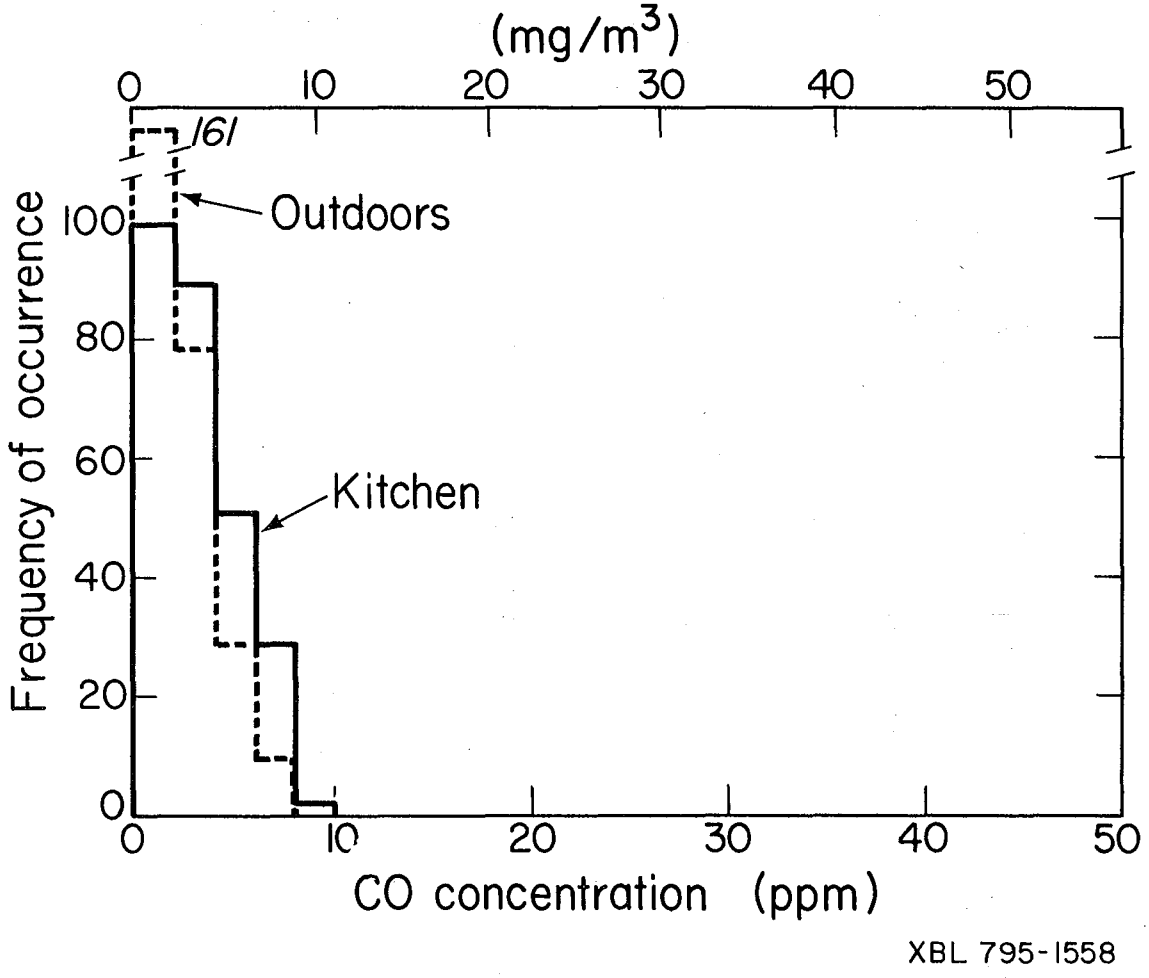
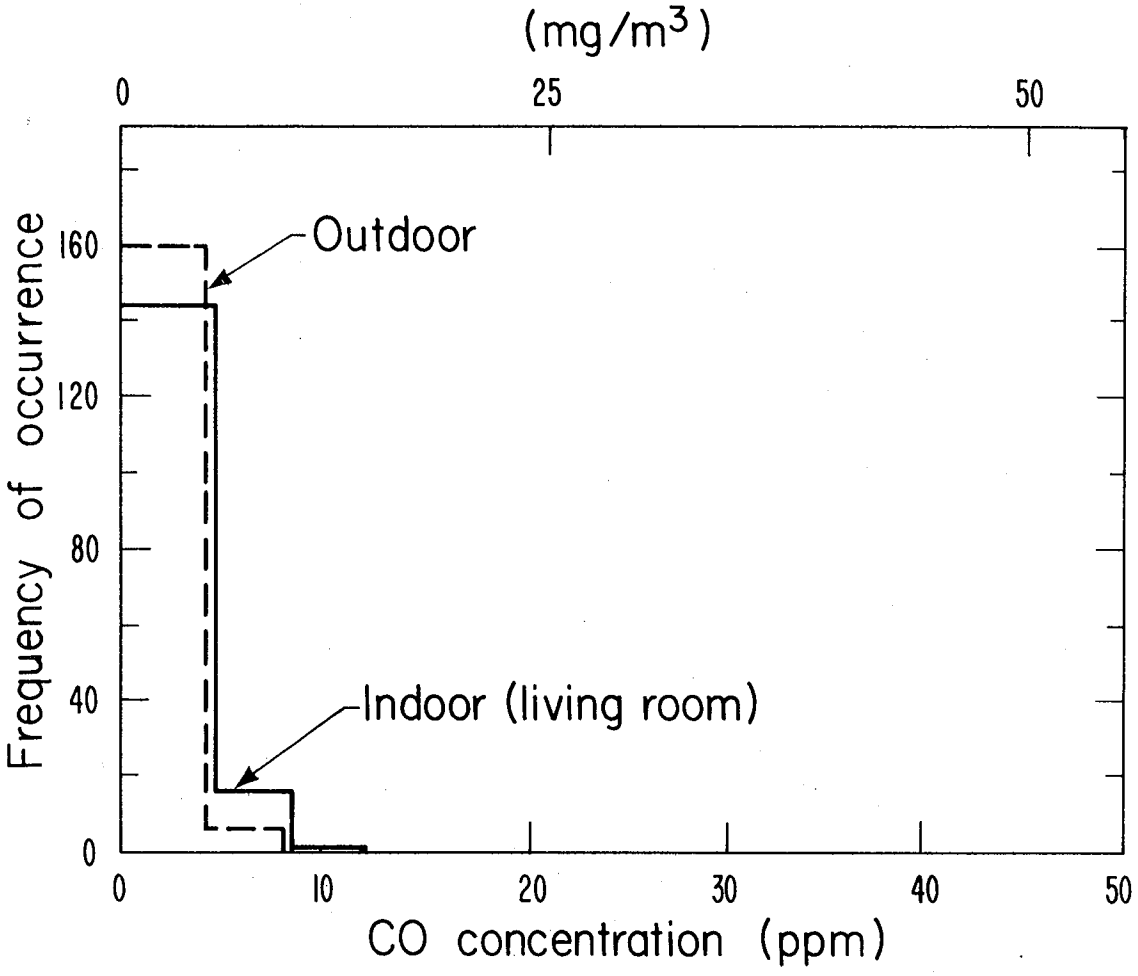


Figure 6. Frequency distribution of indoor and outdoor CO concentrations at the MED-I House.



XBL 796-2032

Figure 7. Frequency distribution of indoor and outdoor CO concentrations at the ISUERH.

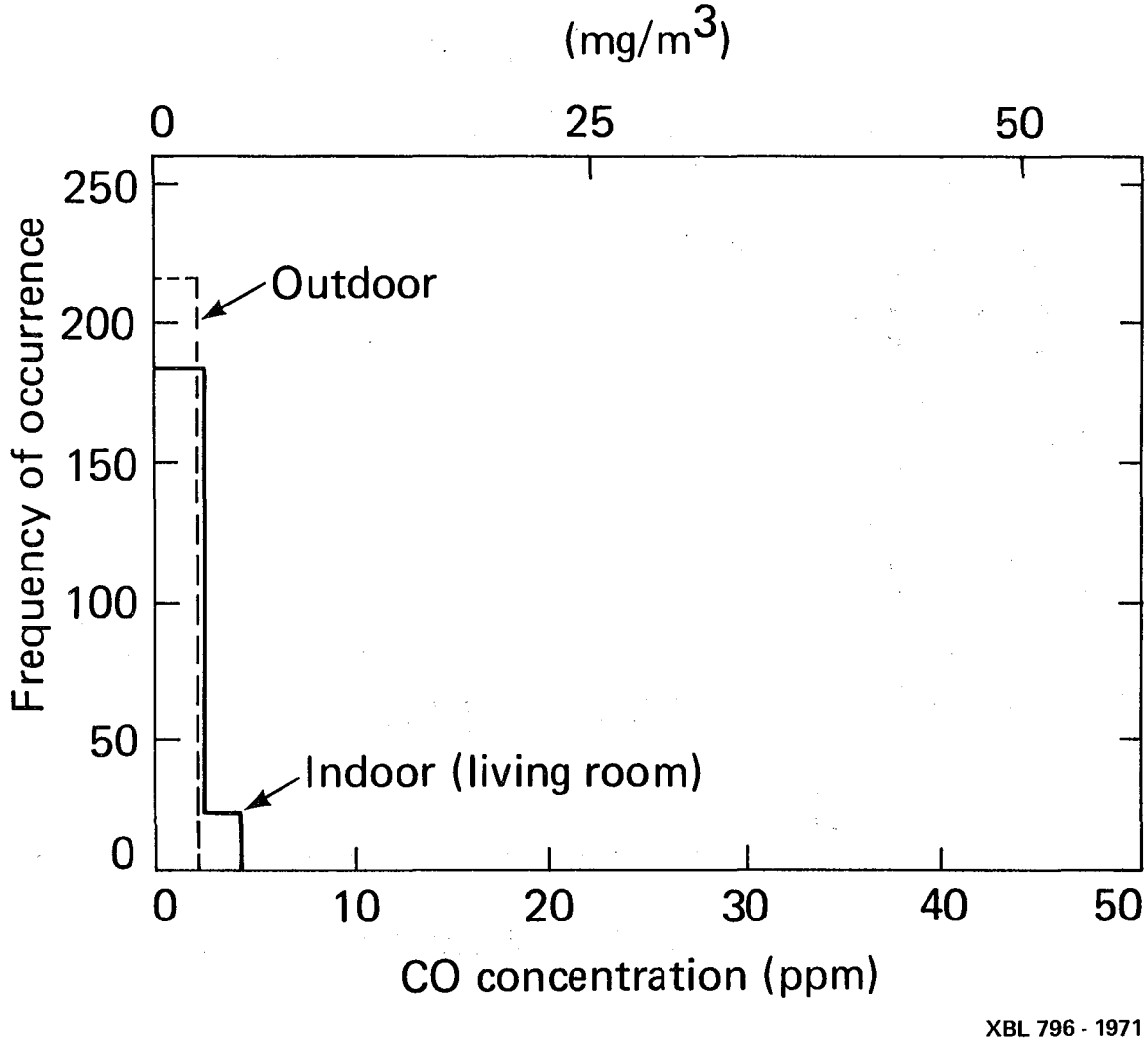
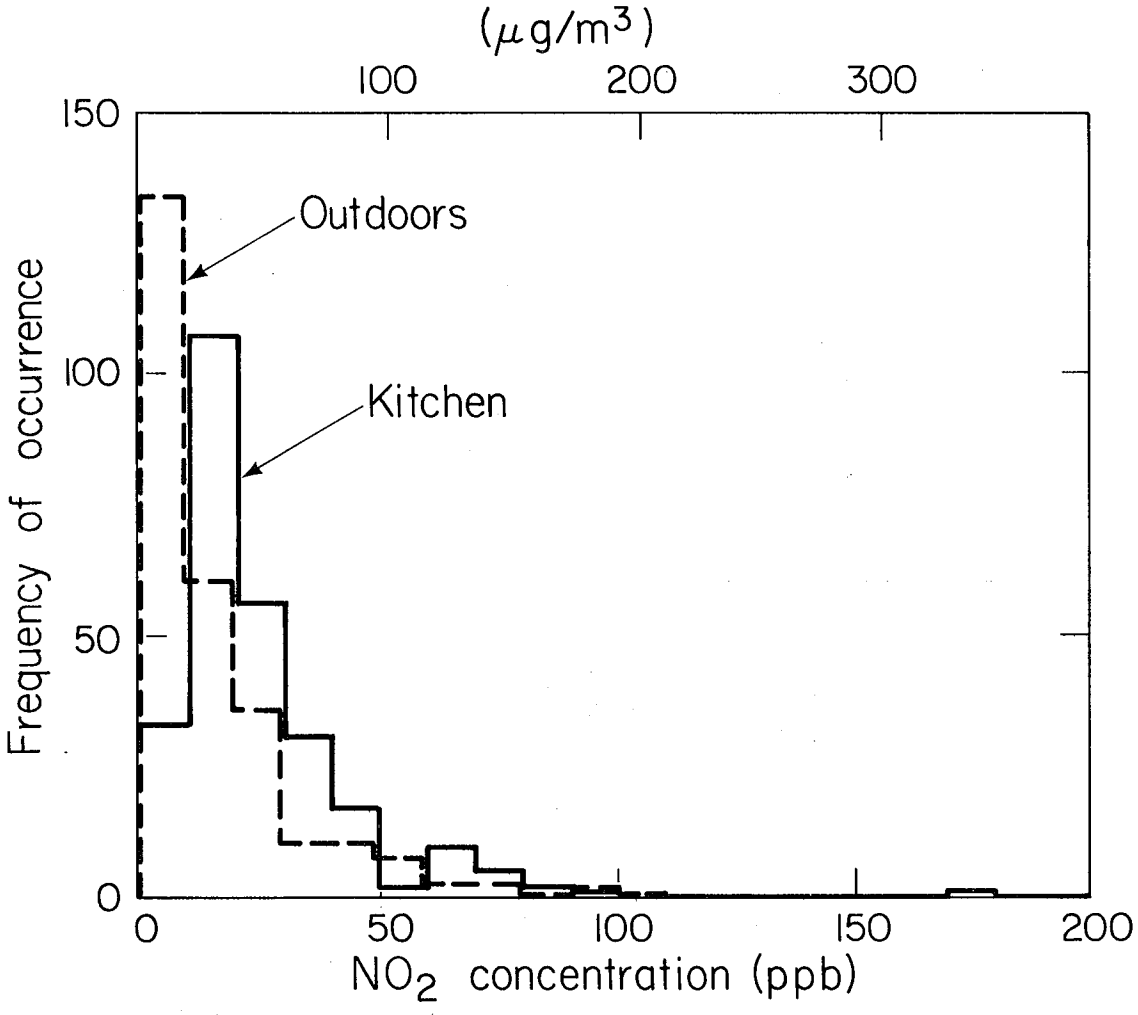
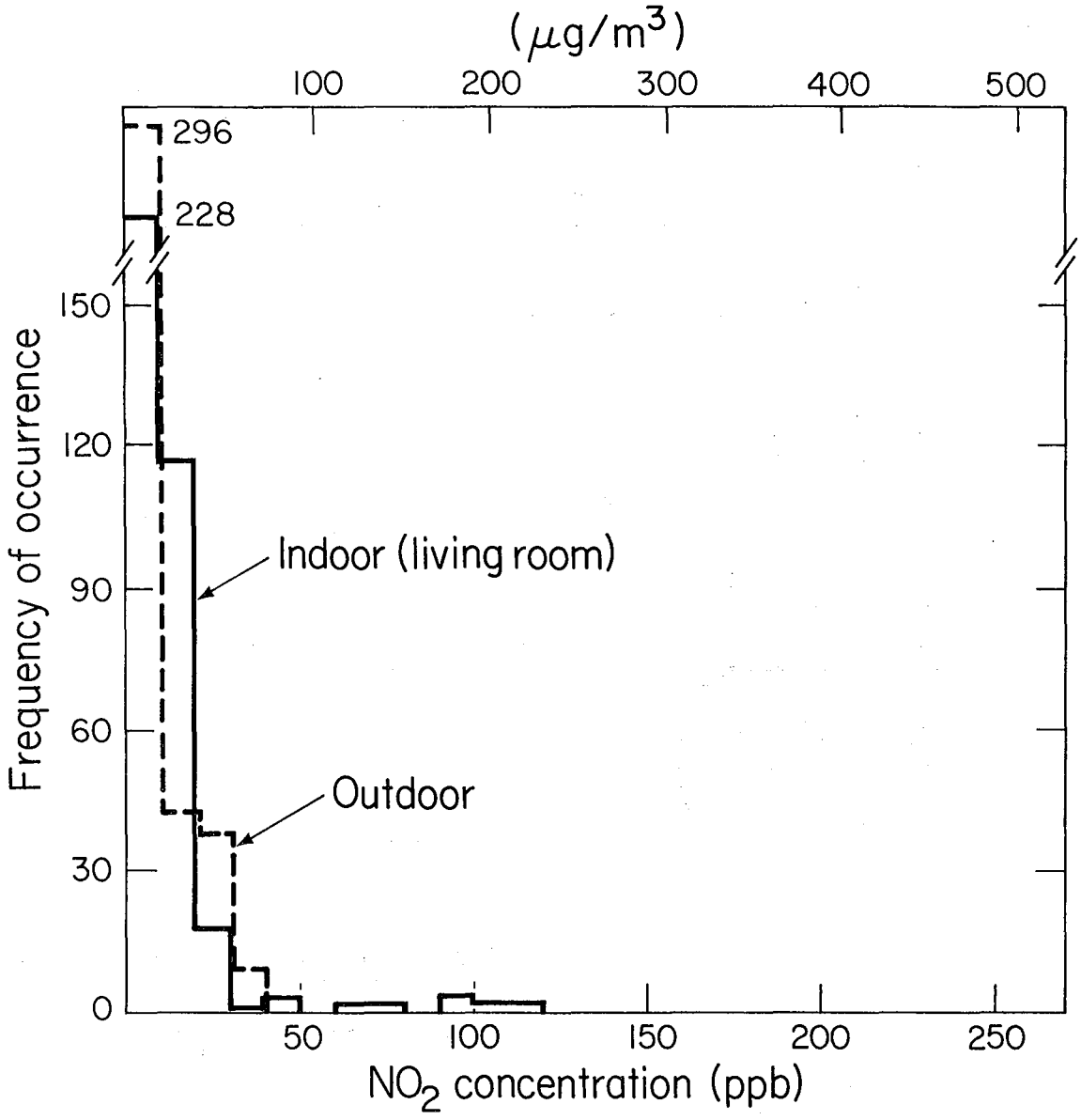


Figure 8. Frequency distribution of indoor and outdoor CO concentrations at the ERHM.



XBL 795-1423

Figure 9. Frequency distribution of indoor and outdoor NO_2 concentrations at the MED-I House.



XBL 797-2320

Figure 10. Frequency distribution of indoor and outdoor NO_2 concentrations at the ISUERH.

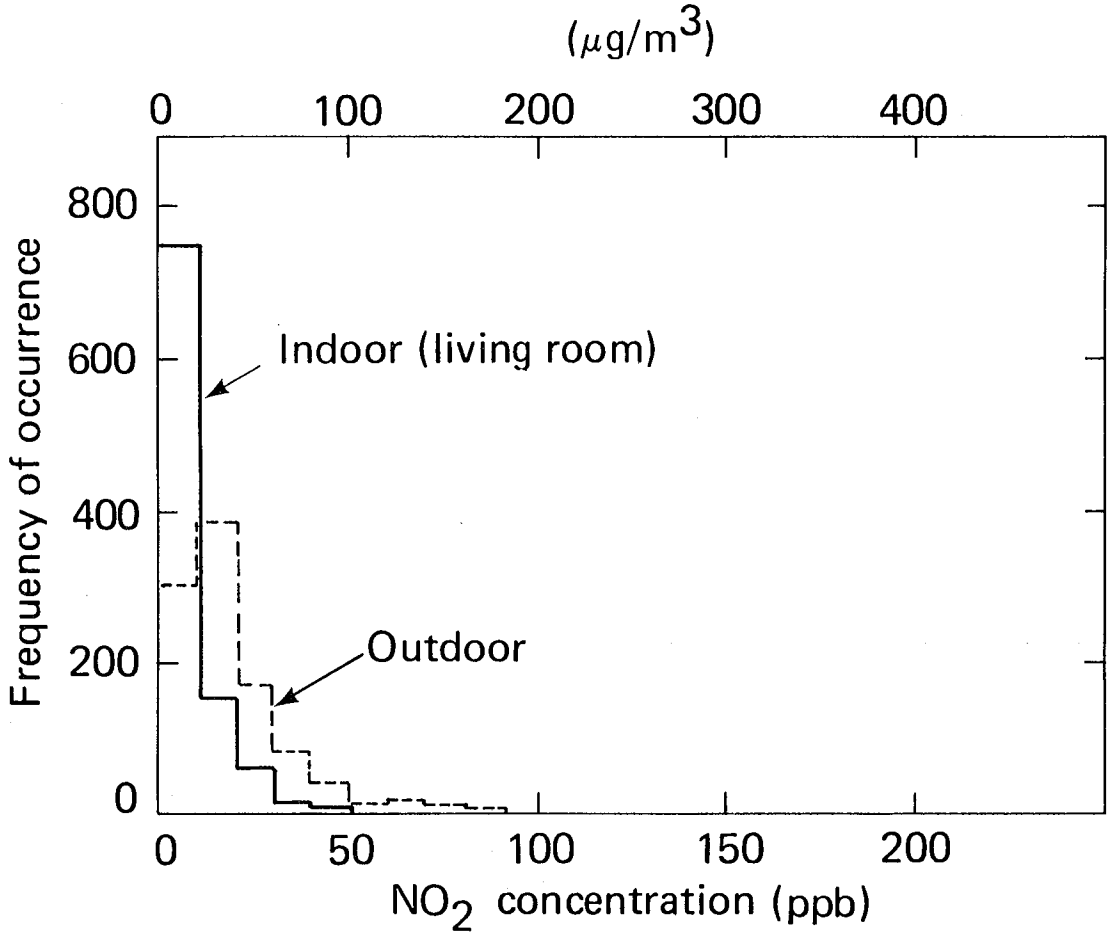
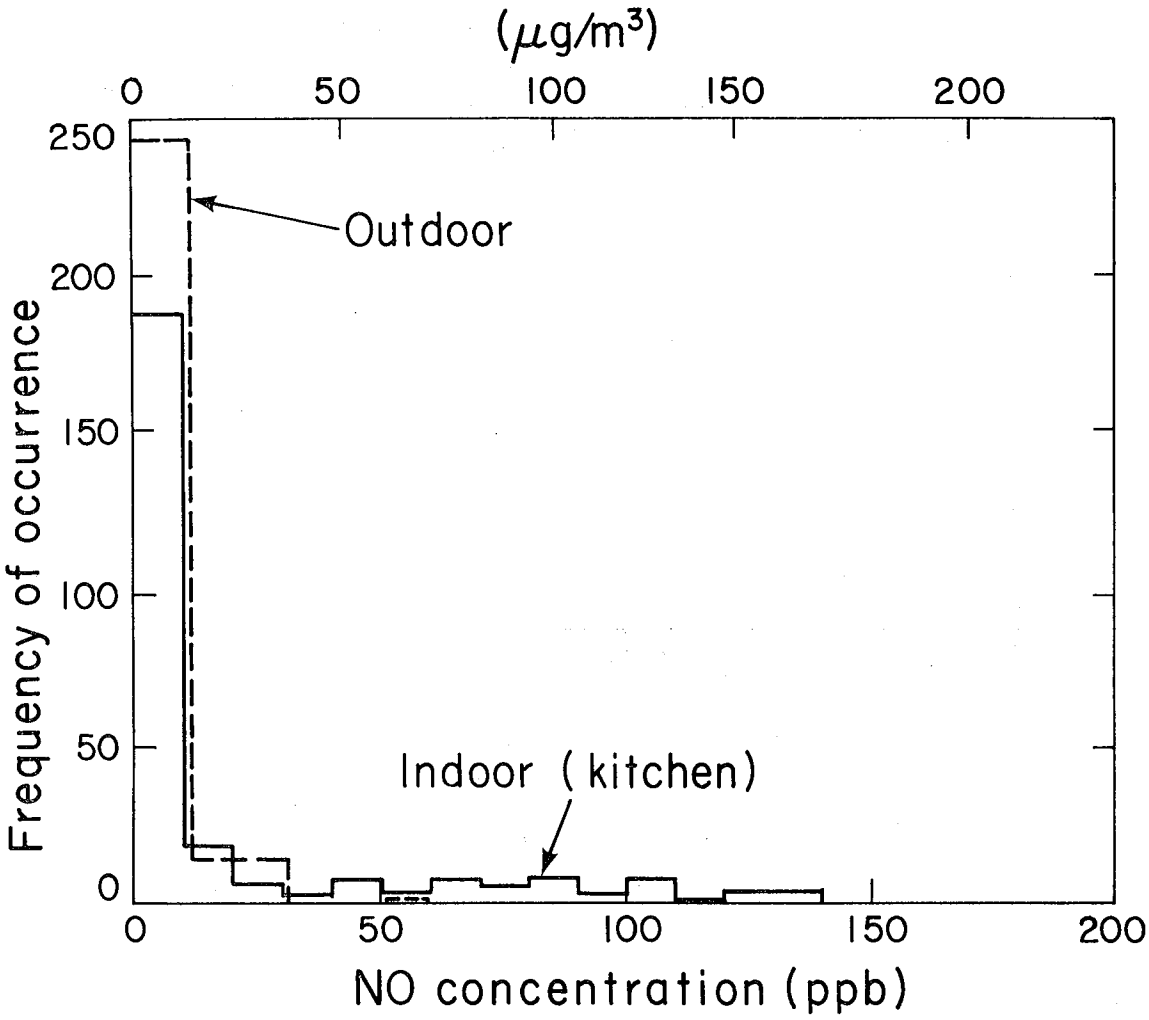


Figure 11. Frequency distribution of indoor and outdoor NO_2 concentrations at ERHM.



XBL7910-4306

Figure 12. Frequency distribution of indoor and outdoor NO concentrations at the MED-I House.

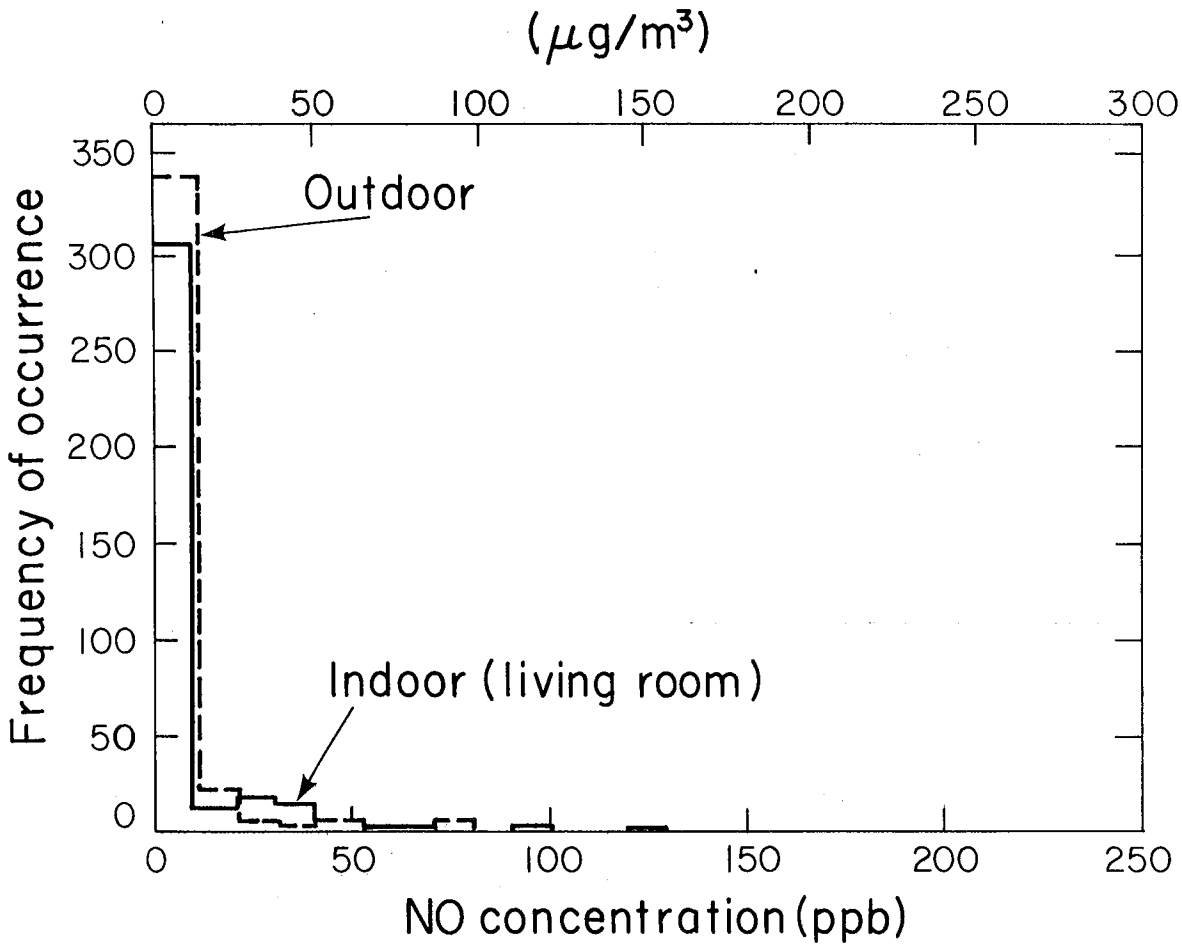
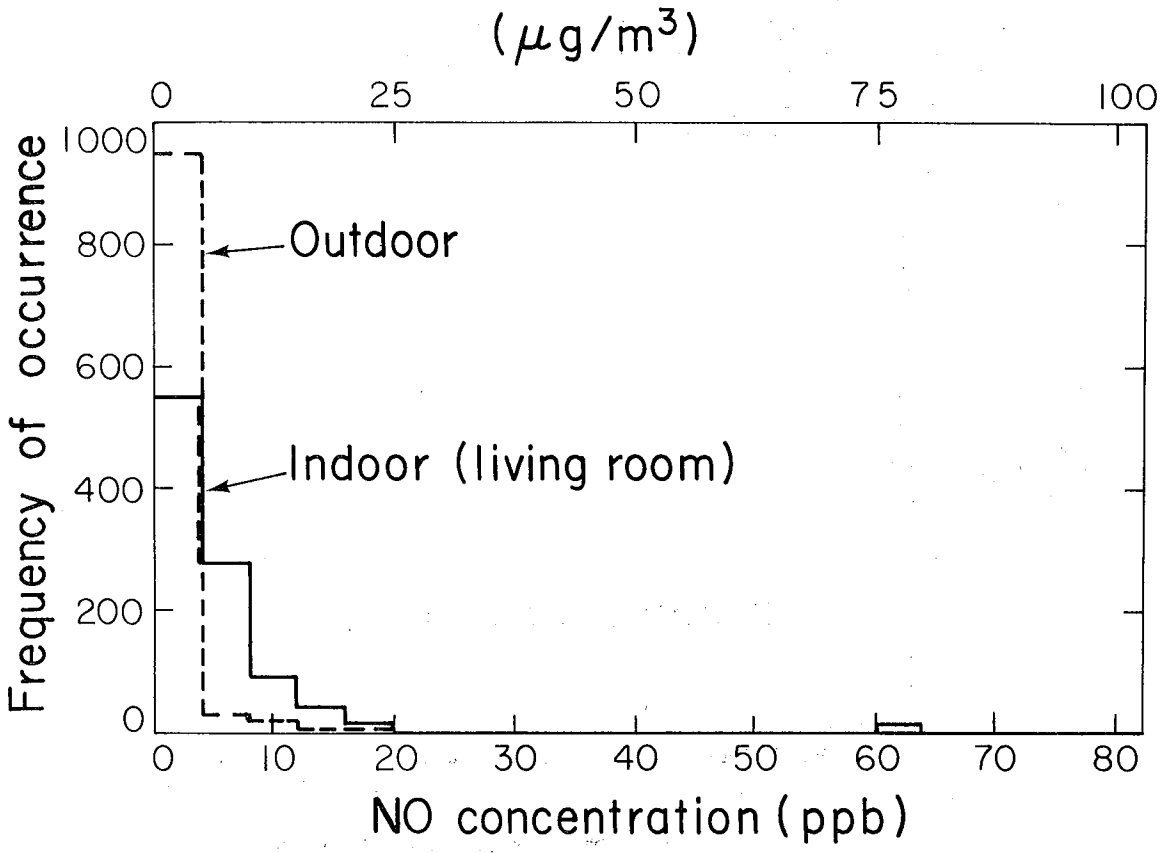


Figure 13. Frequency distribution of indoor and outdoor NO concentrations at the ISUERH.



XBL 7910-4308

Figure 14. Frequency distribution of indoor and outdoor NO concentrations at the ERHM.

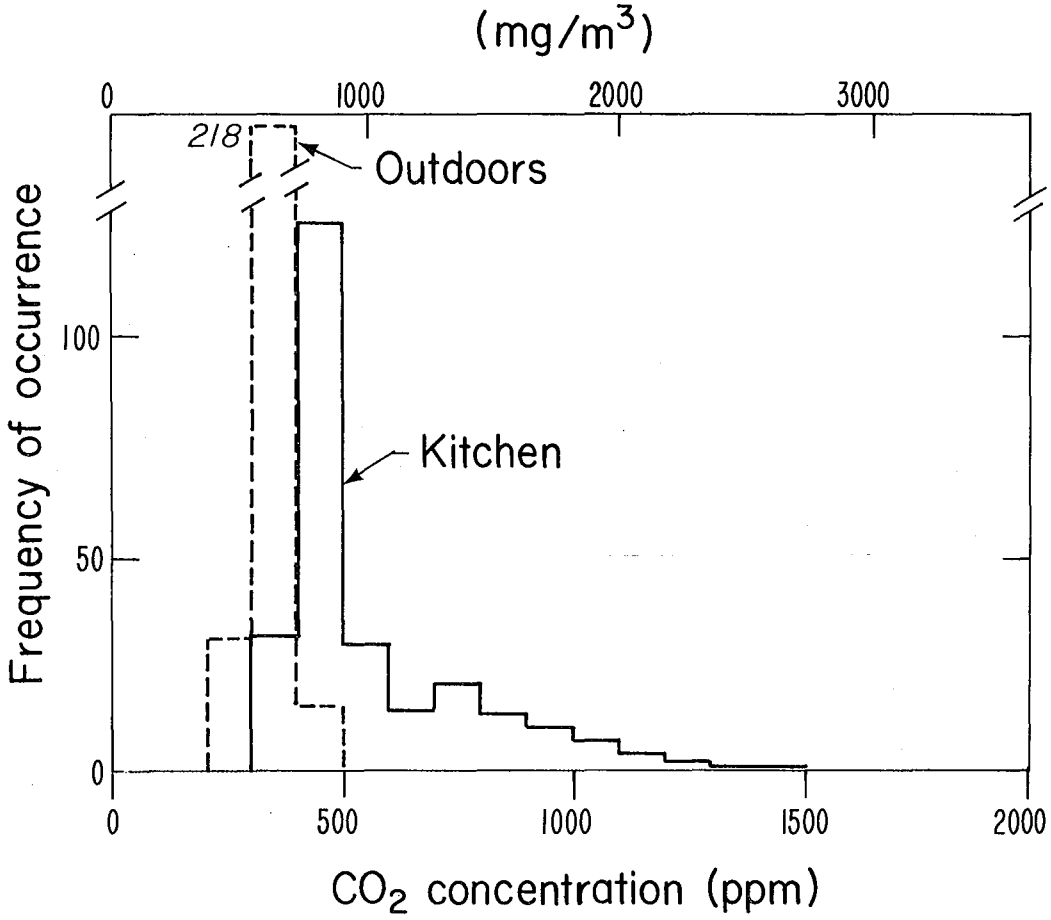


Figure 15. Frequency distribution of indoor and outdoor CO_2 concentrations at the MED-I House. XBL795-1489

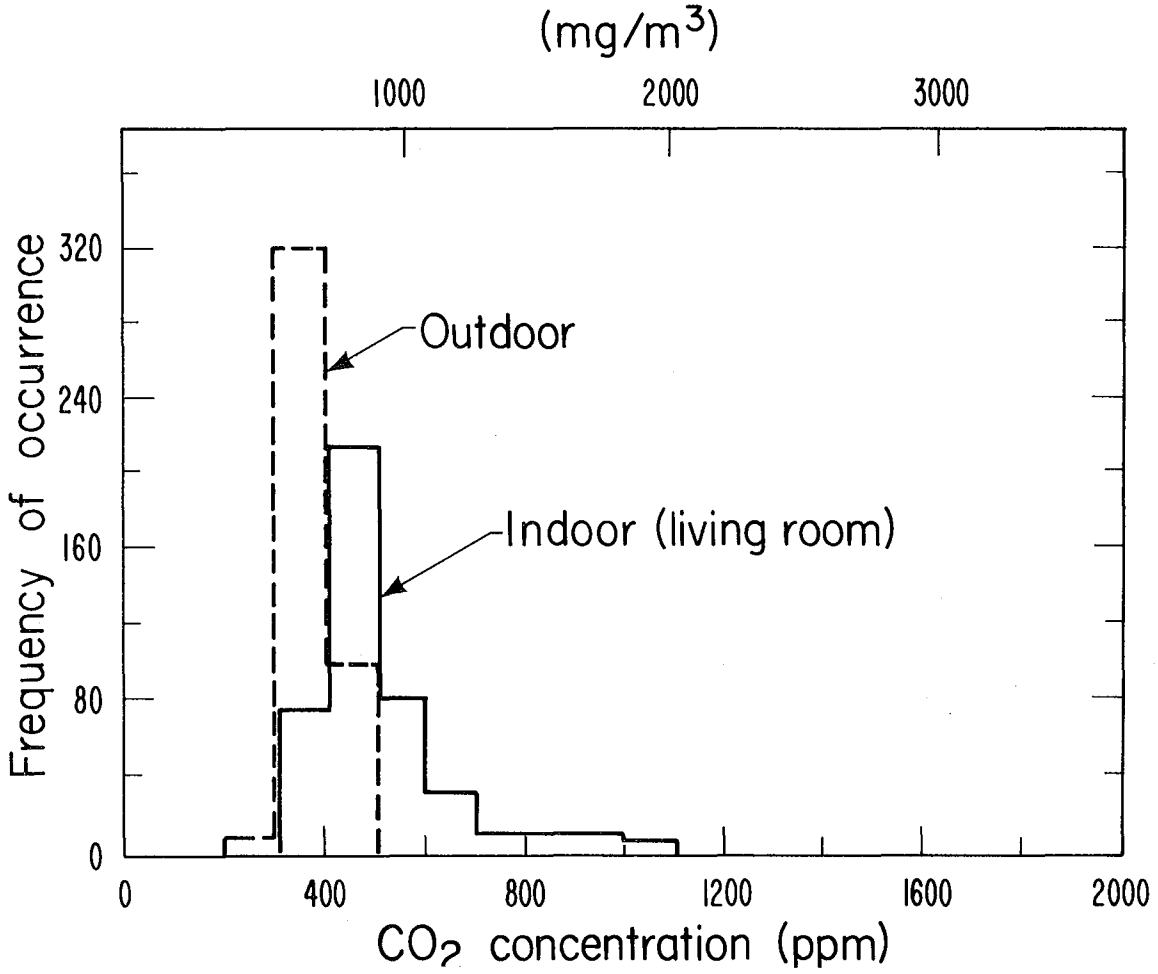


Figure 16. Frequency distribution of indoor and outdoor CO_2 concentrations at the ISUERH.

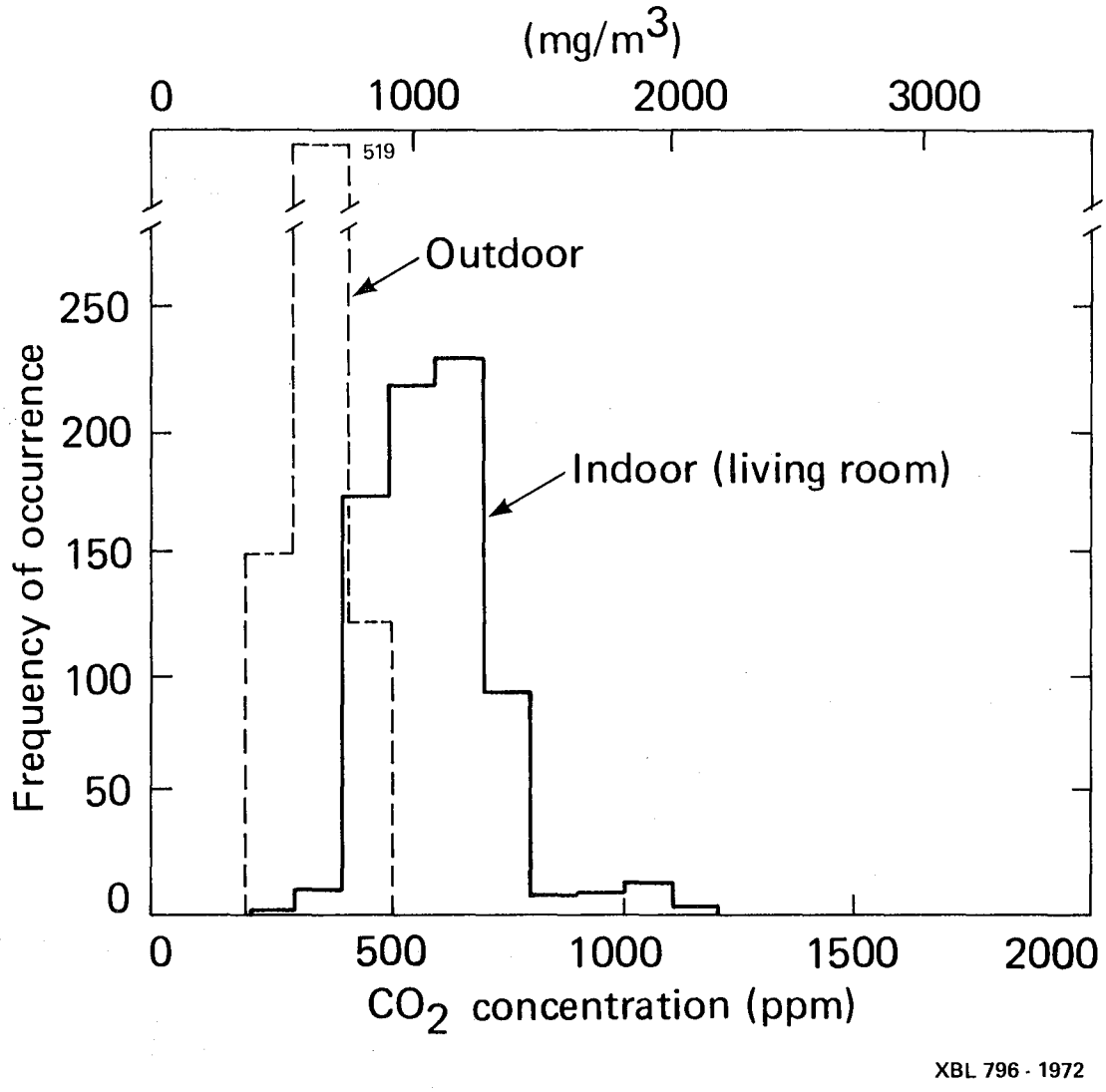
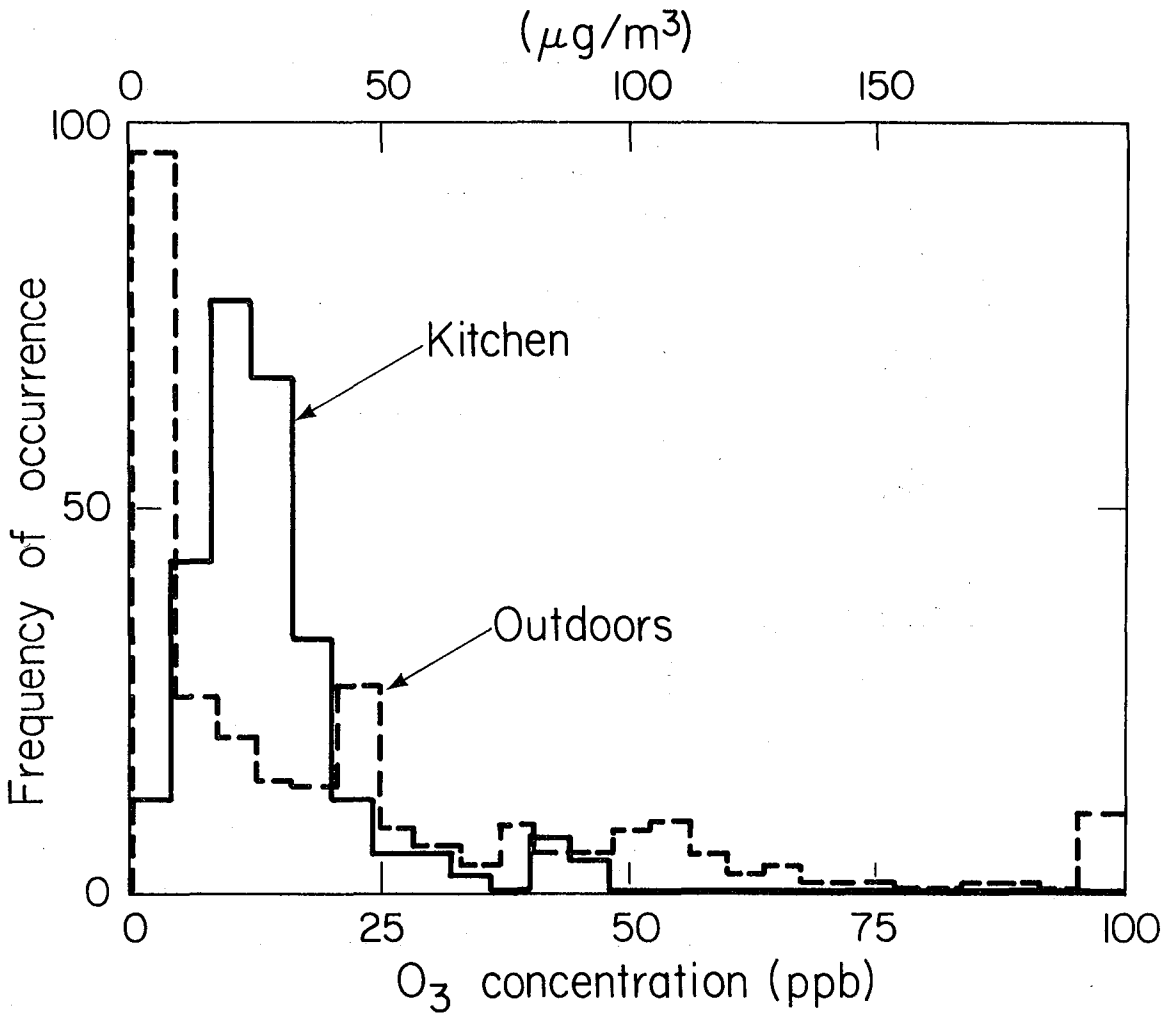


Figure 17. Frequency distribution of indoor and outdoor CO_2 concentrations at the ERHM.



XBL 795-1422

Figure 18. Frequency distribution of indoor and outdoor O_3 concentrations at the MED-I House.

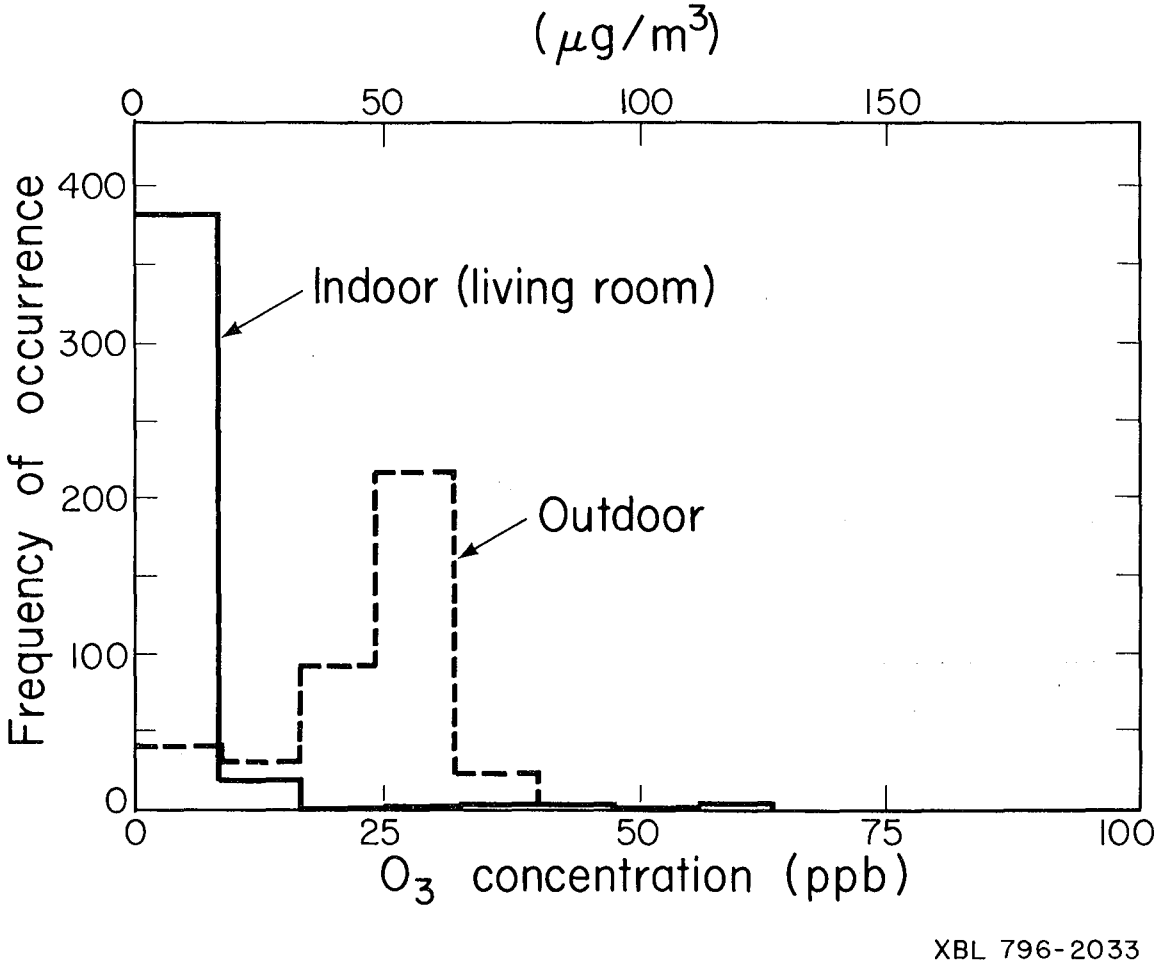


Figure 19. Frequency distribution of indoor and outdoor O_3 concentrations at the ISUERH.

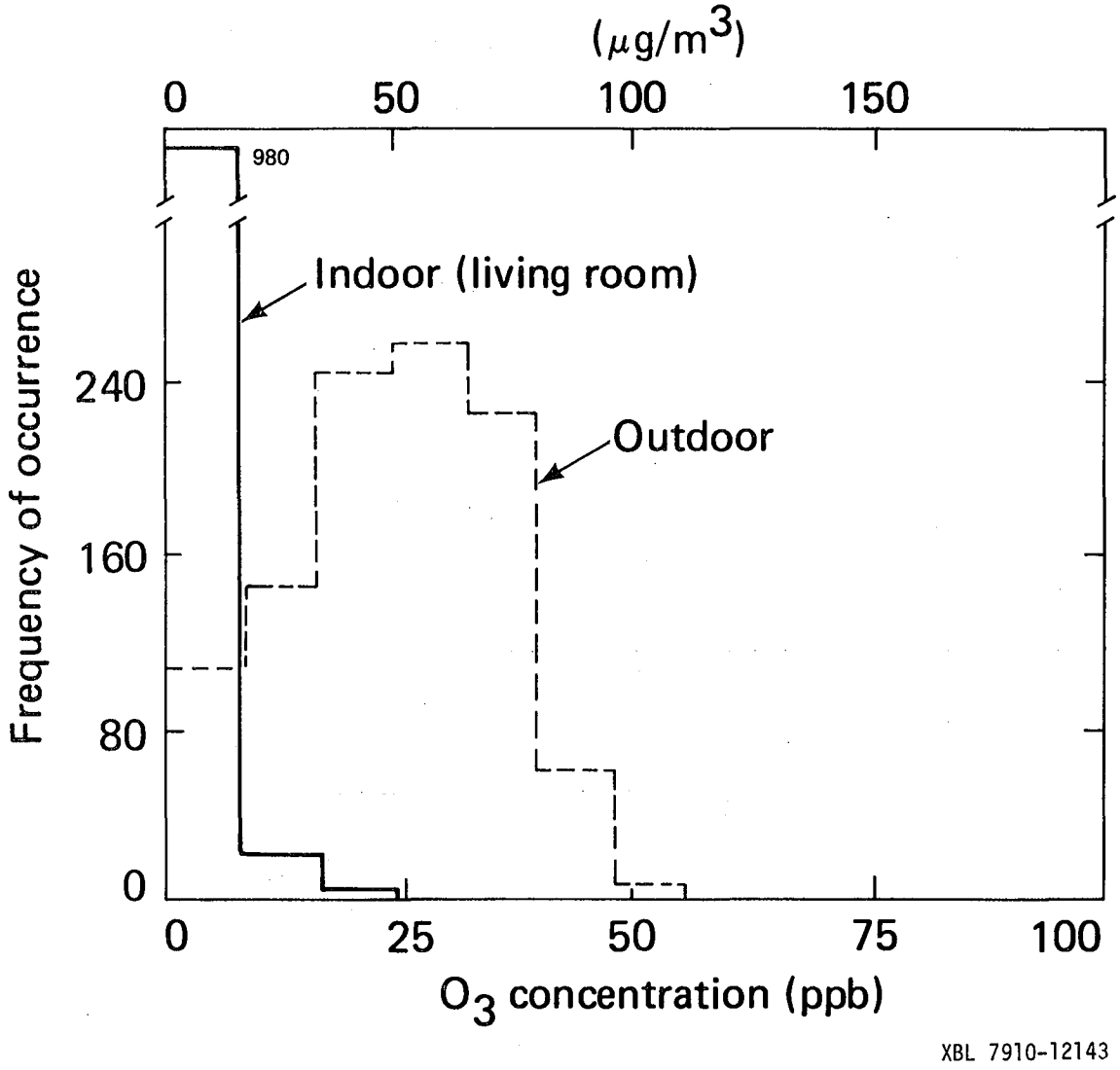


Figure 20. Frequency distribution of indoor and outdoor O_3 concentrations at the ERHM.

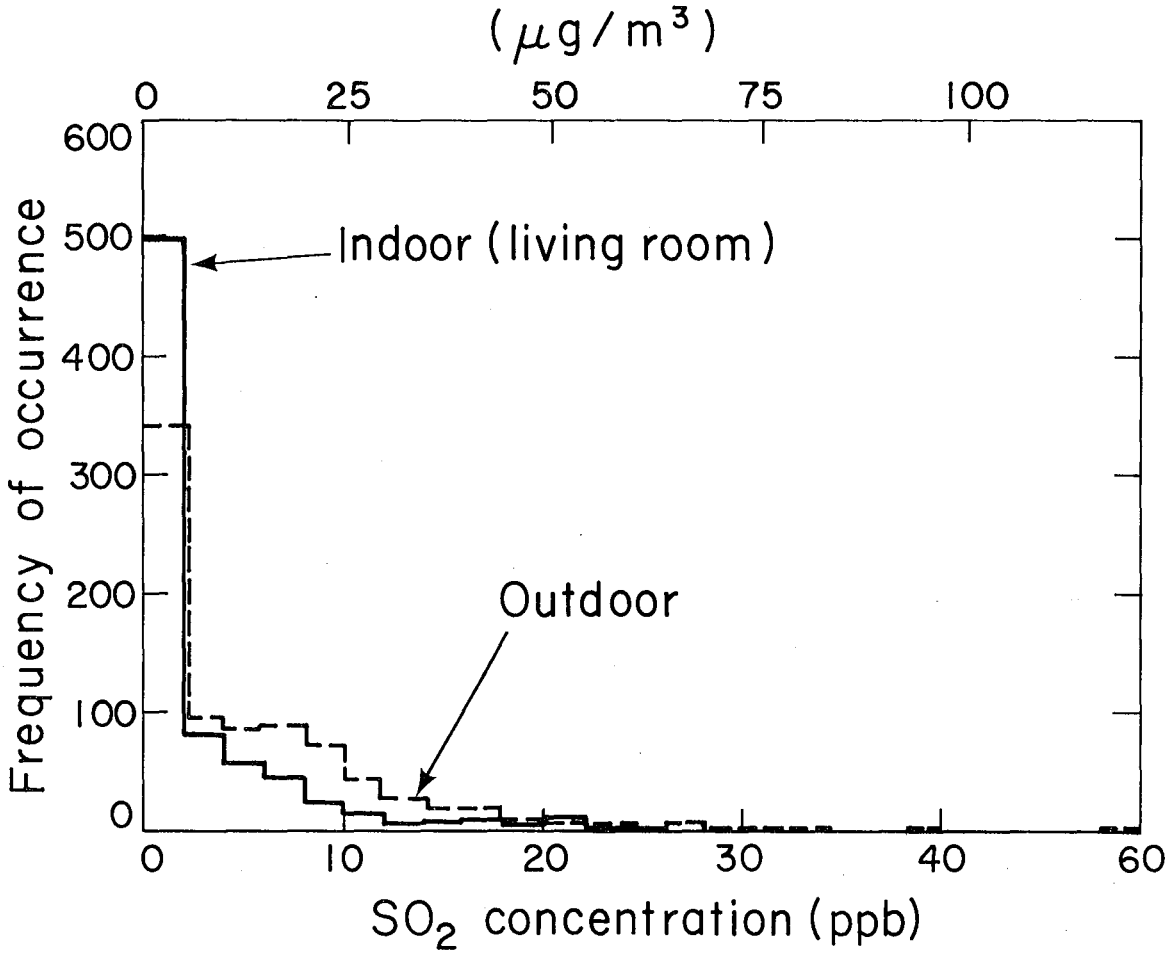


Figure 21. Frequency distribution of indoor and outdoor SO_2 concentrations at the ERHM.

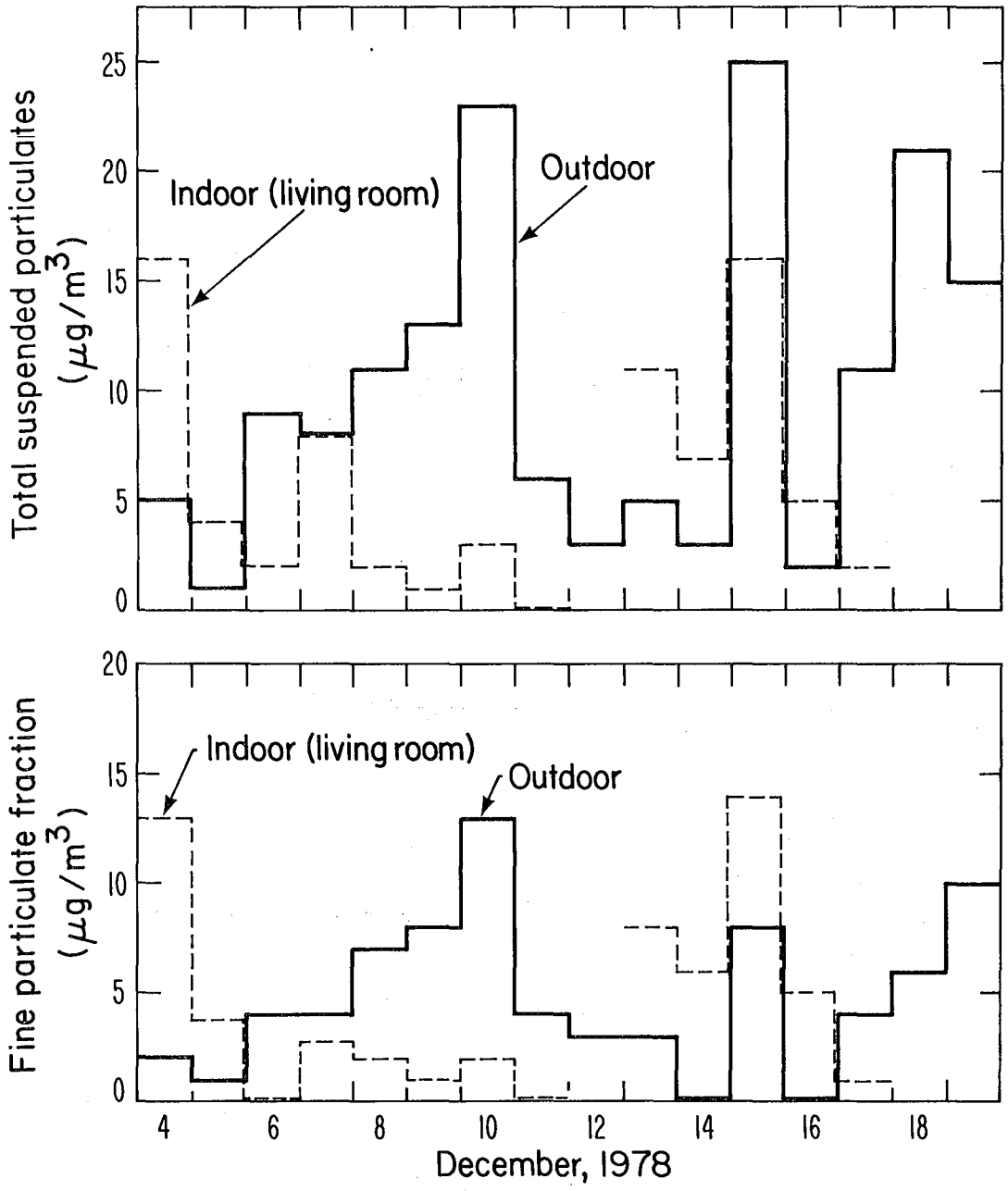
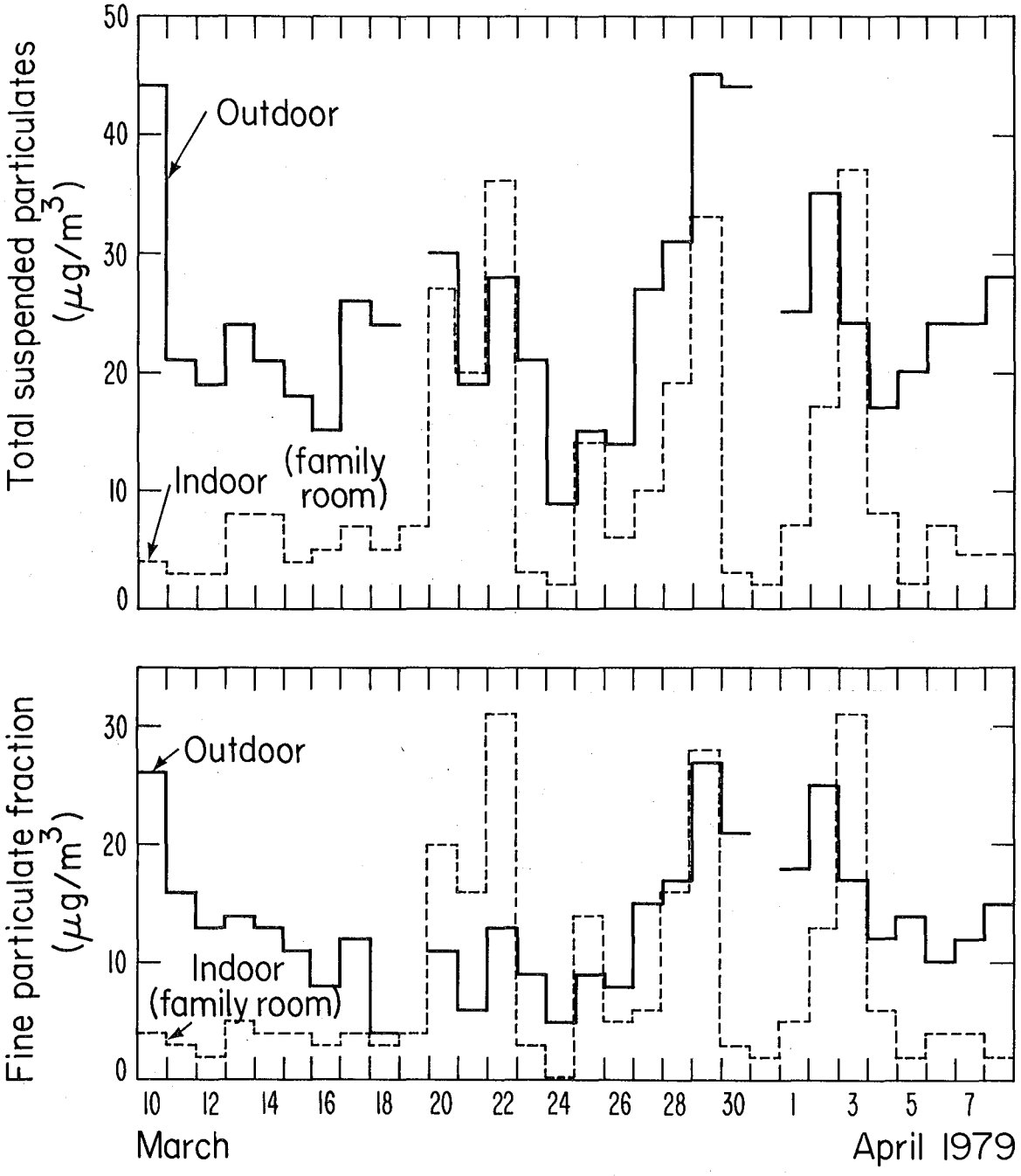


Figure 22. Frequency distributions of indoor and outdoor particulate mass at the ISUERH.



XBL 796-1737

Figure 23. Frequency distributions of indoor and outdoor particulate mass at the ERHM.

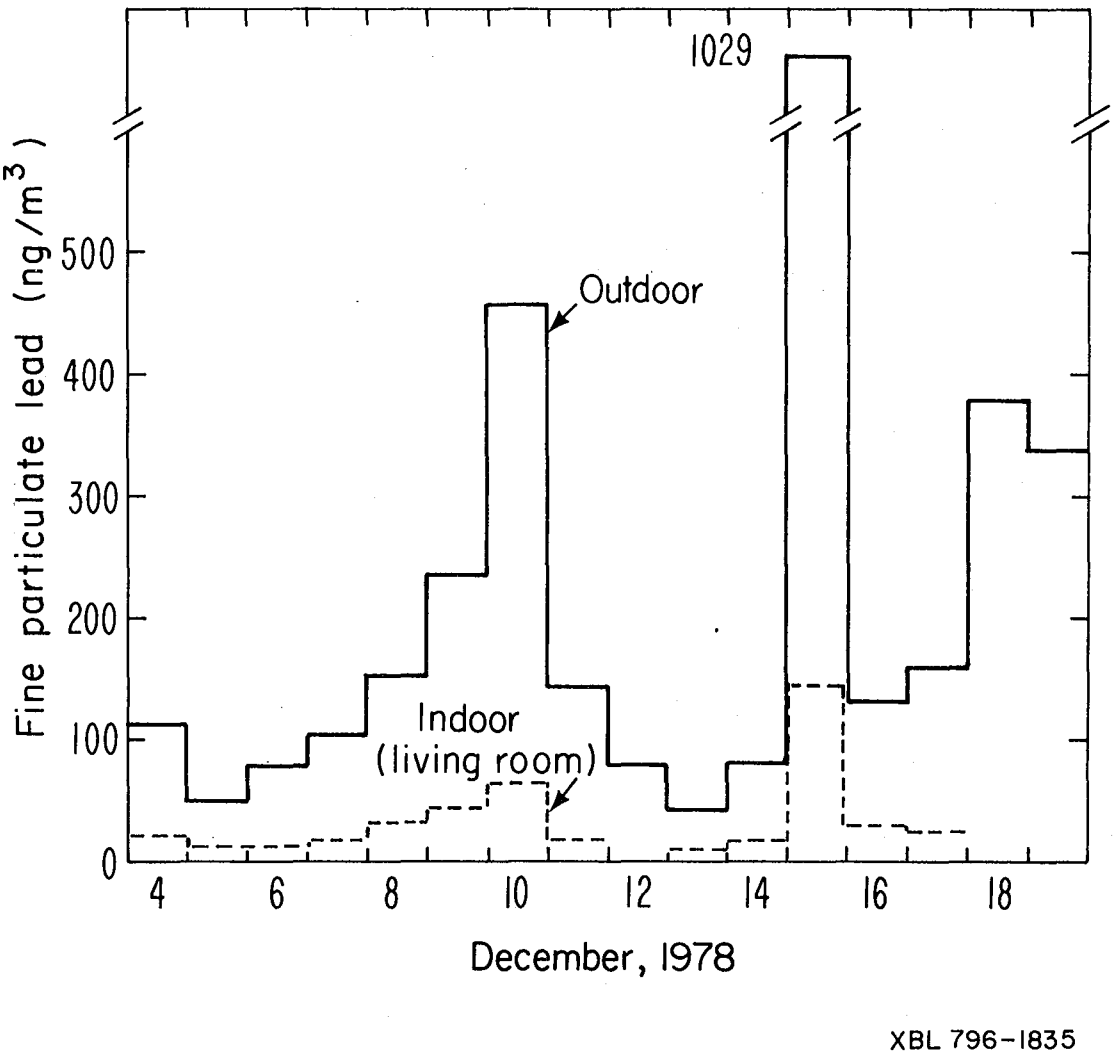


Figure 24. Frequency distribution of indoor and outdoor fine particulate lead at the ERHM.

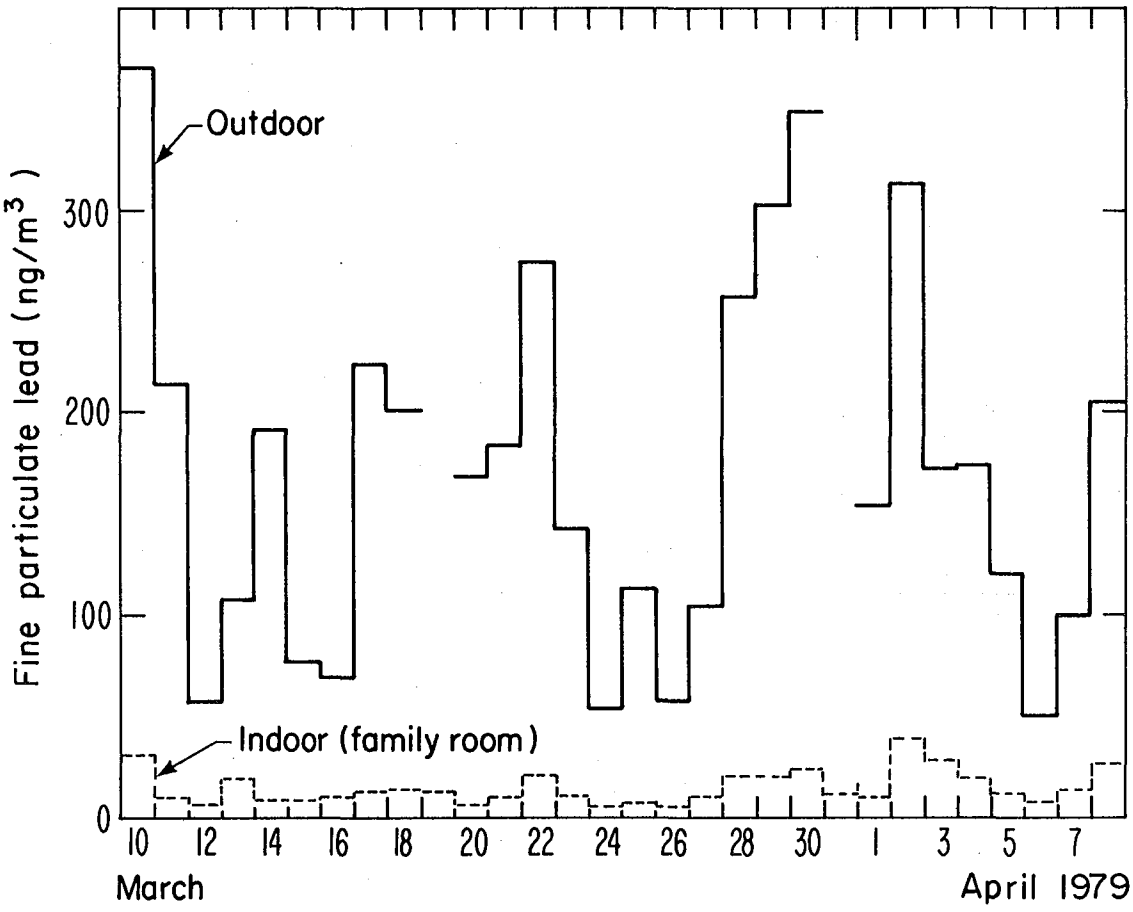


Figure 25. Frequency distribution of indoor and outdoor fine particulate lead at the ERHM.

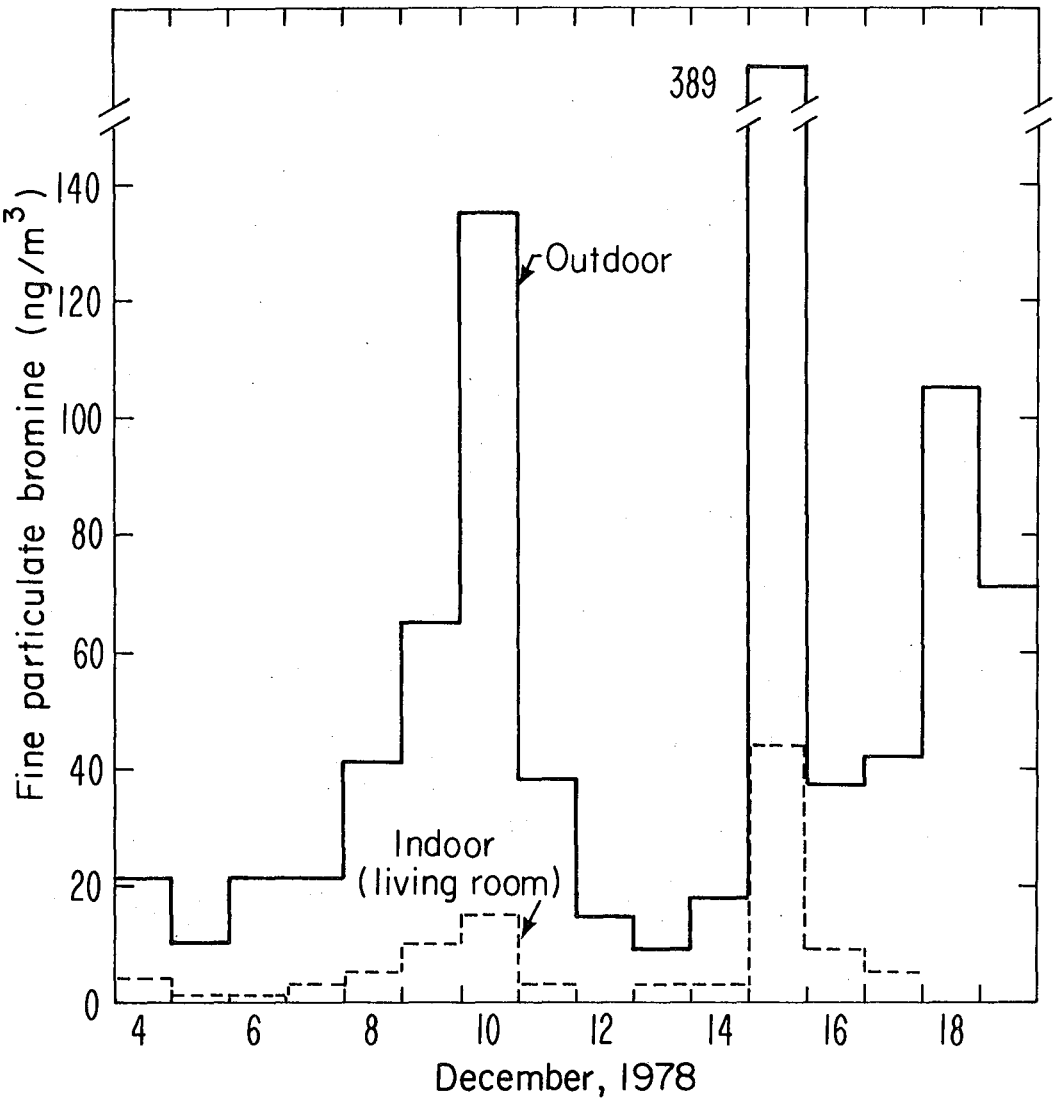
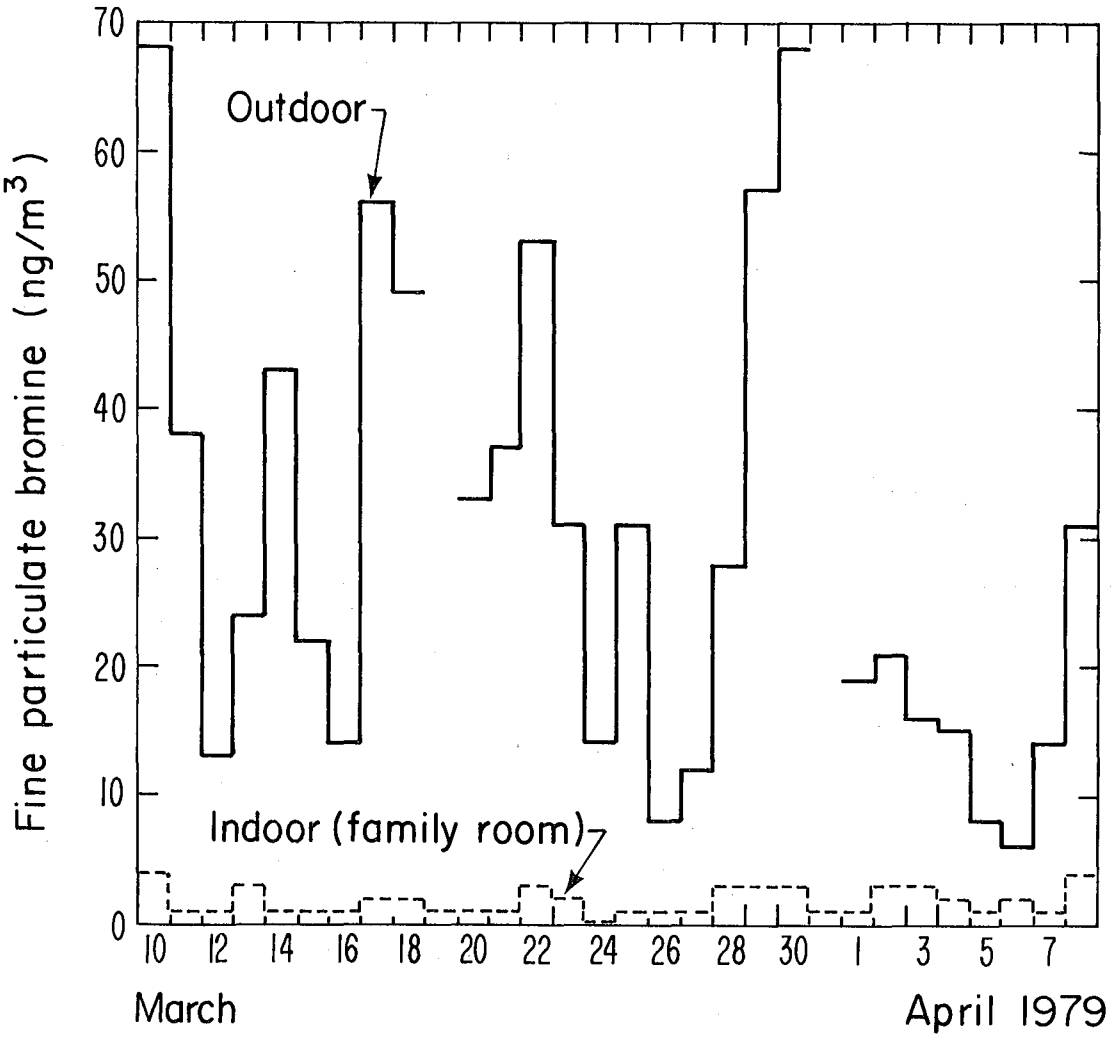


Figure 26. Frequency distribution of indoor and outdoor fine particulate bromine at the ISUERH.



XBL 796-1833

Figure 27. Frequency distribution of indoor and outdoor fine particulate bromine at the ERHM.

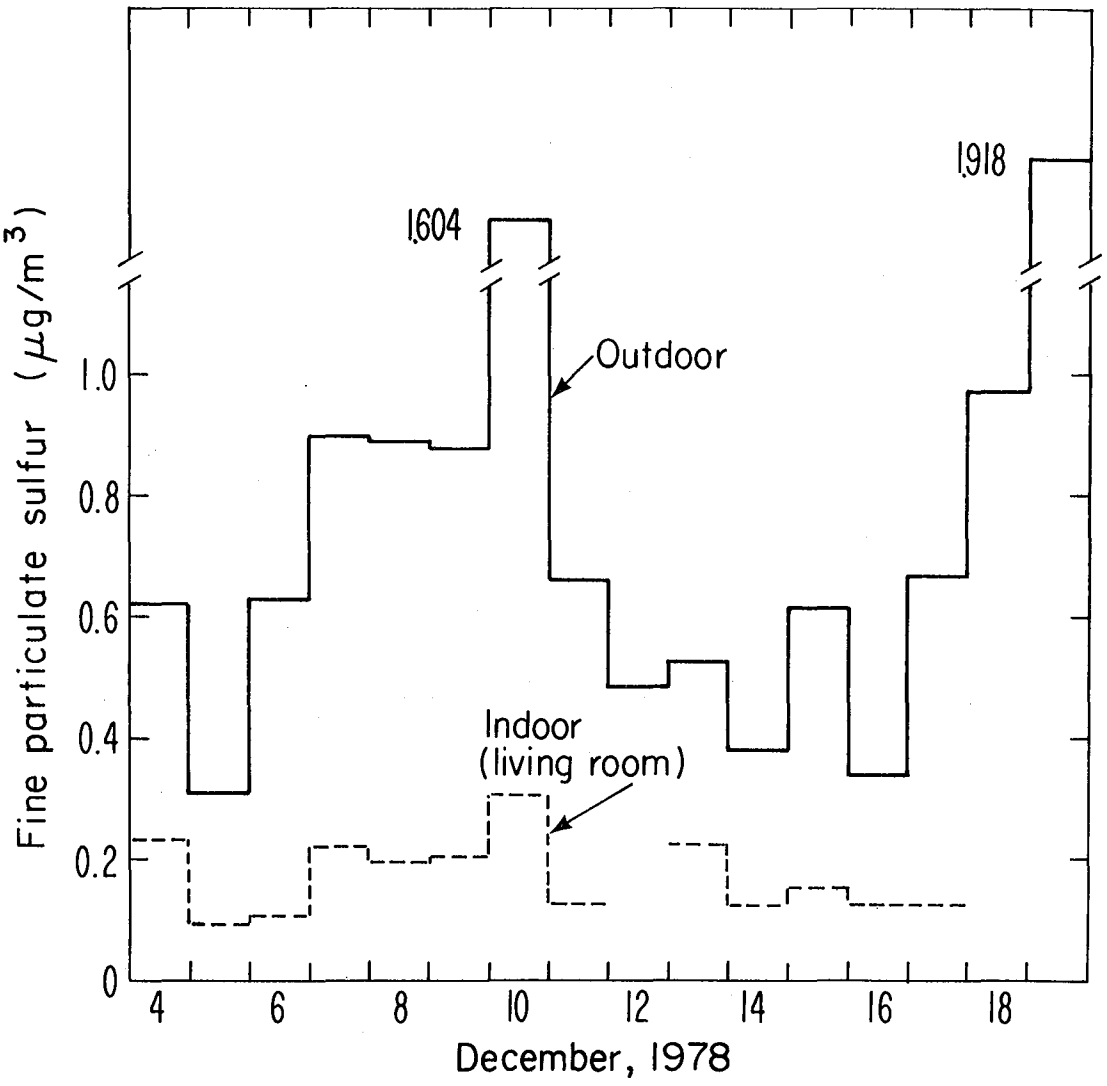


Figure 28. Frequency distribution of indoor and outdoor fine particulate sulfur at the ISUERH.

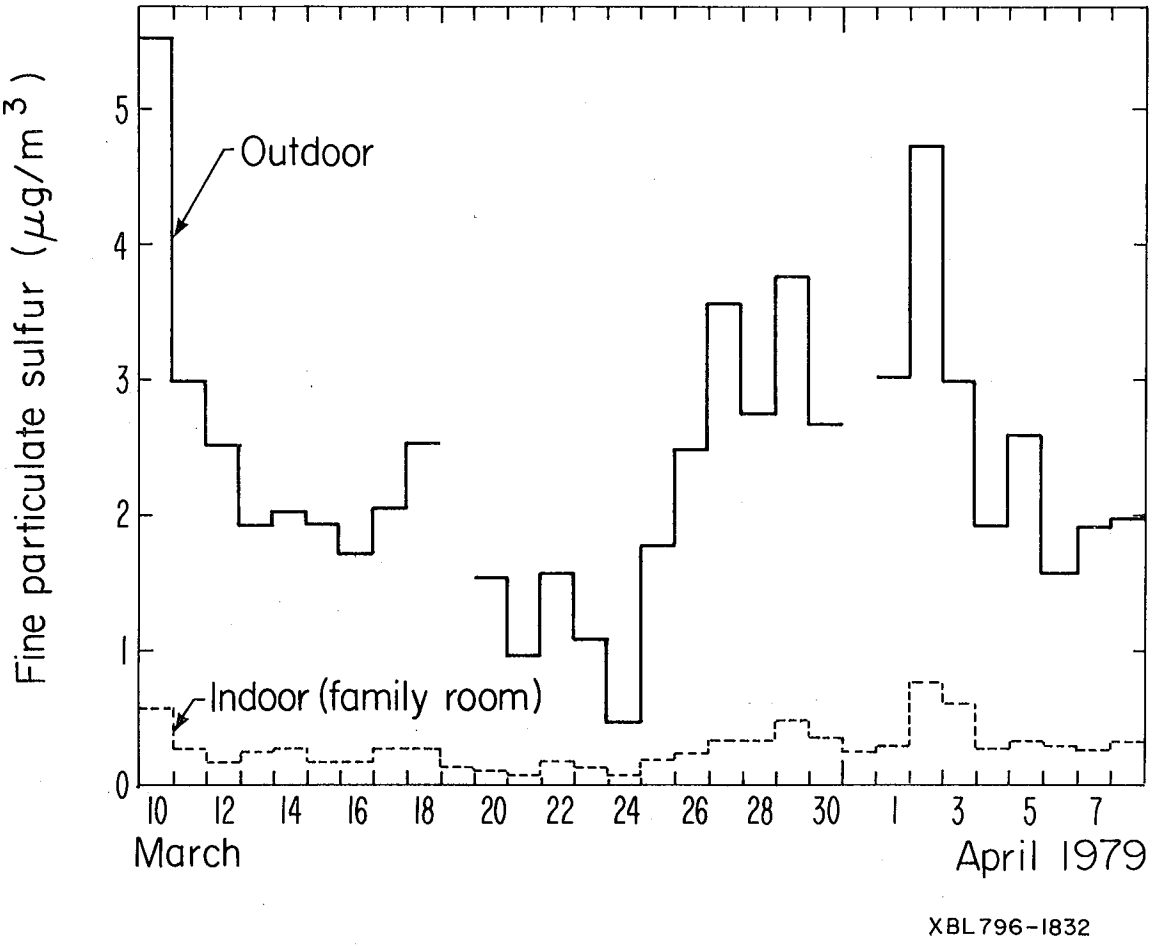
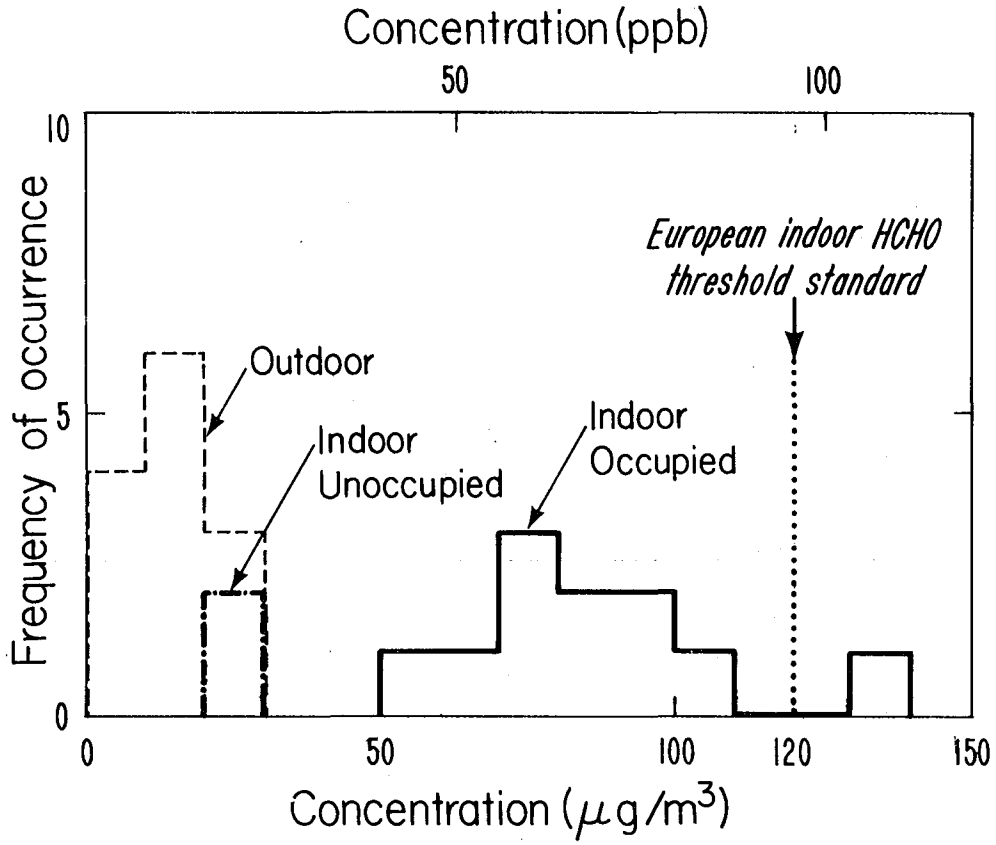


Figure 29. Frequency distribution of indoor and outdoor fine particulate sulfur at the ERHM.



XBL 796-1749

Figure 30. Frequency distribution of indoor and outdoor aldehyde concentrations at the MED-I House.

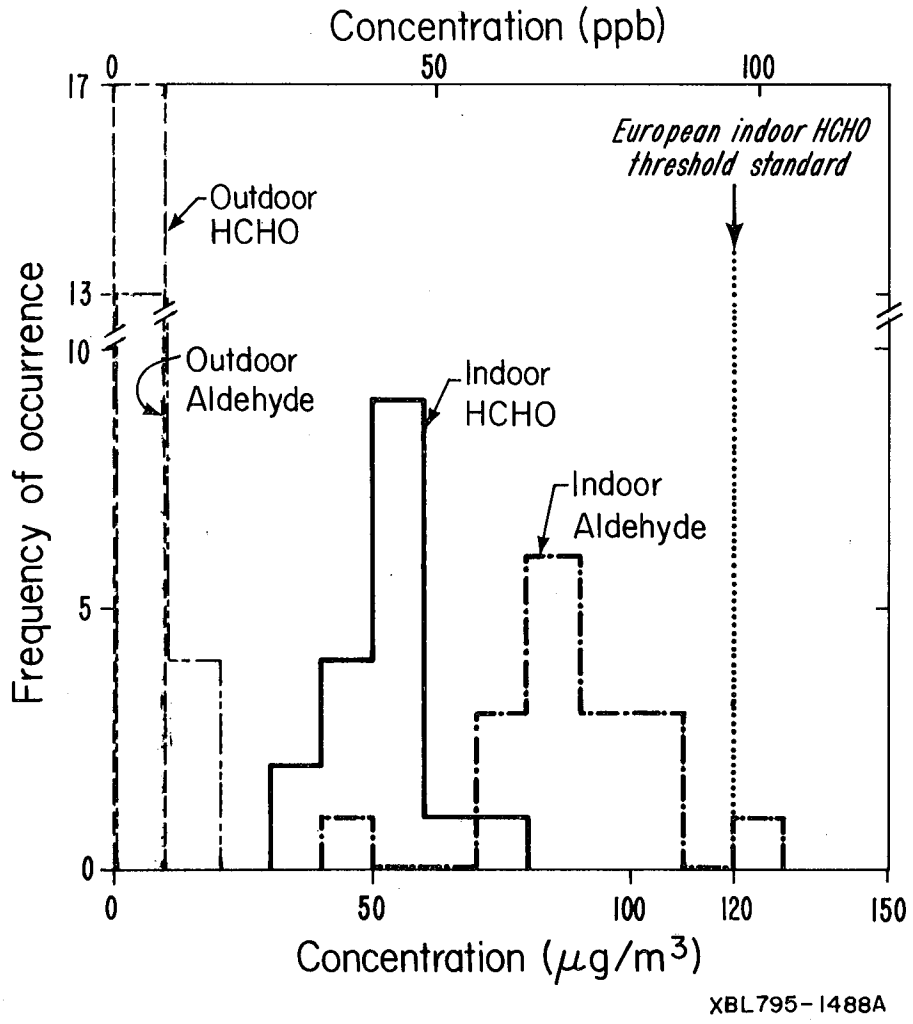


Figure 31. Frequency distributions of indoor and outdoor formaldehyde and aldehyde concentrations at the ISUERH.

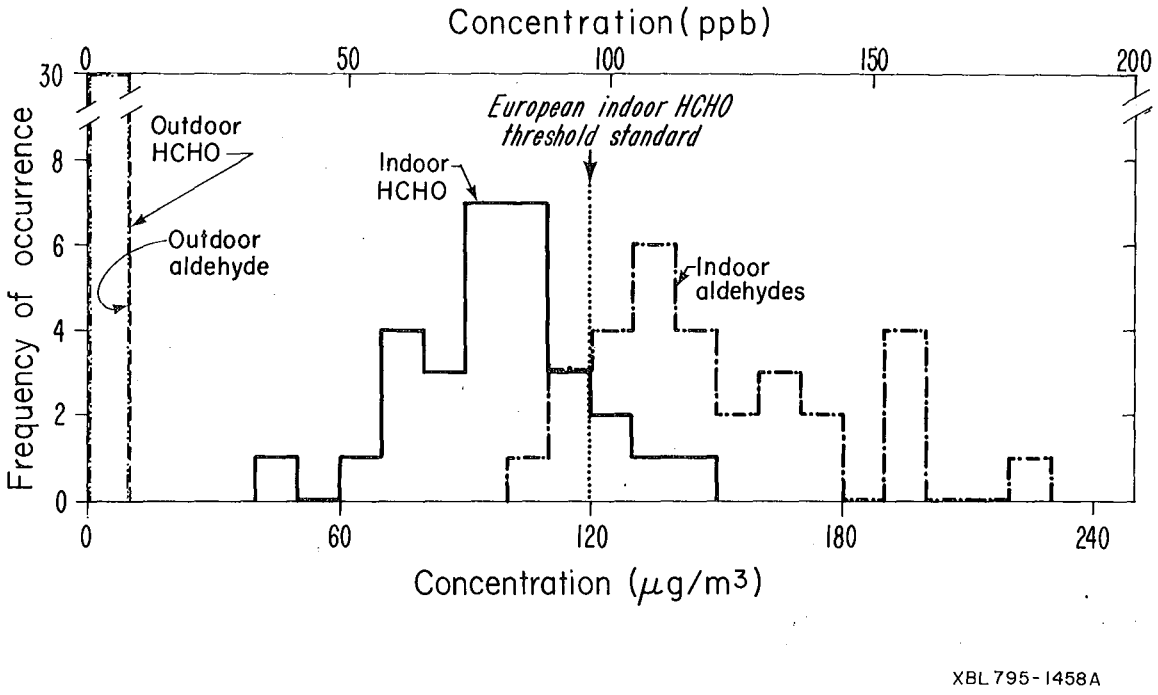


Figure 32. Frequency distributions of indoor and outdoor formaldehyde and aldehyde concentrations at the ERHM.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720