DIFFERENCE BETWEEN RELATIONS OF DOSE AND EXPOSURE TO HEALTH

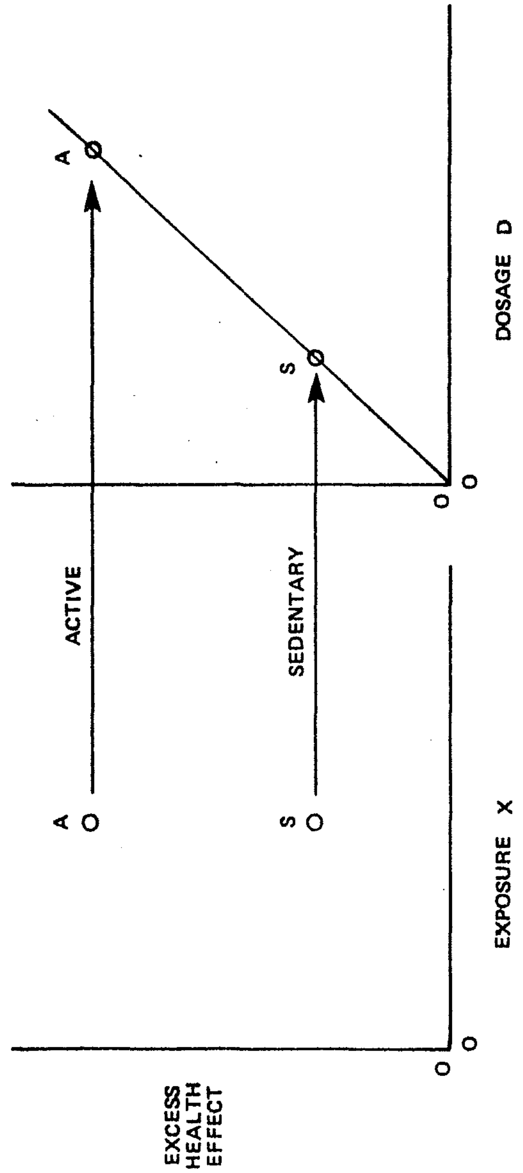

Figure 3A. Relation of excess health effect to pollution exposure.

Figure 3B. Relation of excess health effect to pollution dosage.

INDOOR AIR QUALITY MEASUREMENTS IN ENERGY-EFFICIENT HOUSES

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Abstract

The potential impact of reduced ventilation on indoor air quality is being assessed in a field monitoring program by the Lawrence Berkeley Laboratory. Three houses, designed to be particularly energy-efficient, were monitored using a mobile laboratory. Parameters measured included infiltration rate, carbon dioxide, carbon monoxide, nitrogen dioxide, nitric oxide, ozone, sulfur dioxide, formaldehyde, total aldehydes, and particulates. The purpose of this program is to determine if energy-efficient ventilation rates are compatible with good indoor air quality. Preliminary results show that although considerable energy savings can be achieved, indoor levels of several pollutants exceed levels found outdoors; however, in general, the indoor levels of most pollutants are still within limits established by ambient air quality standards. Overall indoor air quality depends upon air excahnge rates, building materials and occupant activities.

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. More than half of this energy is used to maintain human comfort conditions through the heating, cooling, and ventilating of buildings. Residential structures alone consume approximately 25% of the total energy used in this country and nearly one-half of this is used for residential heating.

Through Public Law 94-385, Congress has mandated that building energy performance standards (BEPS) for new construction be promulgated by 1980 for adoption by state and local government jurisdictions having authority to regulate building construction through building codes and other mechanisms. The Department of Housing and Urban Development (HUD) and the Department of Energy (DOE) are working together to develop these standards. The Ventilation Program at the Lawrence Berkeley Laboratory is performing research necessary for understanding ventilation requirements as part of the effort to develop building energy performance standards.

As energy becomes less available and more expensive, measures are being taken to make buildings more energy efficient. These include tightening the building envelope to reduce leakage and infiltration, improving insulation, and reducing ventilation. As these measures are implemented and less fresh air is introduced into a building, the quality of the indoor air may deteriorate.

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 nonresidential buildings. Ventilation, in general, is required for the following reasons:

- Establishment of a satisfactory balance between the metabolic gases (oxygen and carbon dioxide) in the occupied environment.
- Dilution of human and non-human odors to a level below an unacceptable olfactory threshold.
- Removal of contaminants produced by activities, furnishings, construction materials, etc. in the ventilated spaces.
- Removal of excess heat and moisture from internal sources.

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, in general, ignore energy conservation.

Ventilation standards for various classes of buildings have been in existence 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. A comprehensive effort is being made to evaluate the bases for all such existing standards, to measure the actual levels of indoor air contaminants in several classes of buildings, and to provide recommendations for the establishment of energy-efficient ventilation standards in residential, institutional and commercial buildings. The goal is to minimize the energy needed to provide ventilation while at the same time not compromising human health and comfort.

Many houses today are designed and built with energy conservation goals in mind; some are built to minimize energy consumption in order to demonstrate that the living standards and comforts enjoyed by an average family today can be maintained or even improved while reducing energy consumption substantially. Most of these houses are constructed to minimize air leakage rates. This has led to concern that air pollution levels may build up inside these tight buildings.

Until recently, air pollution research has focused almost exclusively on pollution in the outdoor environment, virtually neglecting the indoor 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 can frequently exceed thos levels commonly occurring in the outdoor environment.[1]

Chemical and biological contaminants released into indoor environments are undesirable but often unavoidable by-products of the occupants' activities. Typical indoor contaminants include 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 (e.g., asbestos, formaldehyde, vinyl chloride). Table I lists some of the major indoor air pollutants and their sources.

The complex mix of indoor air pollutants has been recognized only very recently. Most studies of indoor air pollution have assumed that indoor pollution arises from and is directly related to outdoor sources. These studies have been concerned mainly with SO_2, CO, and O_3, or total suspended particulate matter. They have found, in general, that the concentrations of these species in indoor air are lower than in outdoor air. Surprisingly little has been concerned with other potentially important indoor air pollutant species, such as NO, NO_2, nitrates, sulfates, metals, organics, and the respirable fraction of the particulate matter. Even more surprisingly, indoor-generated pollution has been neglected in most studies until quite recently, although a number of air pollution sources exist inside buildings, notably sources associated with combustion (heating, cooking, and smoking).

The importance of indoor air pollution, now recognized, is expected to have a major impact on 1) energy conservation strategies for buildings that might 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 (LBL) of the University of California initiated an indoor air pollution research project in 1975 to study the chemical and physical character of indoor-generated air pollution in residential and commercial buildings. A recent expansion of this project has led to the formation of 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 in three such houses:

- MED-I - The Minimum Energy Dwelling in Mission Viejo, California
- ISUERH - The Iowa State University Energy Research House in Ames, Iowa
- ERHM - An energy research house in Carroll County, Maryland.

MED-I

The Minimum Energy Dwelling (MED-I) research project,[2] conceived in 1975 by the Southern California Gas Company, was designed to demonstrate that quality living standards could be maintained in a home while reducing the family's total energy consumption by at least 50%. Principal sponsors are the United States Department of Energy, the Southern California Gas Company and the Mission Viejo Company. Two identical MED houses were designed and built for research and demonstration purposes. The houses utilize available energy-saving construction techniques and materials, along with advanced gas-fired household appliances, and a solar/natural gas central energy system for space heating, cooling, and water heating. The MED houses are instrumented to monitor energy consumption and building performance, as part of the U.S. effort to foster construction of energy-efficient houses in the near future. The two MED houses are adjacent to each other; one is occupied by a "typical" family with two adults and one child; the other is an unoccupied, furnished, demonstration model. Both are one story and have 1150 square foot floor areas. LBL's Energy Efficient Buildings (EEB) Mobile Laboratory (described below) monitored the indoor air quality of the MED houses from mid-August to mid-September, 1978. Approximately two weeks were spent monitoring each house.

ISUERH

The Iowa State University Energy Research House[3] (ISUERH) in Ames, Iowa, was jointly sponsored by the Engineering Research Institute and the Iowa State University Research Foundation, Inc. The design of this house incorporates numerous methods of reducing energy consumption. A total of sixteen different active modes of heating and cooling will be evaluated before the project is completed. 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.

The structure (Figure 2) is nearly cubical in shape (30 x 35 x 27 feet) and provides a living area of 2385 square feet distributed over three levels. Kitchen appliances are all 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 energy-efficient housing built in Iowa meeting the requirements of ASHRAE Standard 90-75,[4] the standard for energy conservation in new building design. 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 about eight people gathered to simulate occupancy. During this day, cooking, dining, and other typical household activities took place.

ERHM

An energy research house (ERHM) in Carroll County, Maryland, was built to develop information and data for cost-effective design and construction of energy-efficient houses. The most promising and practical energy-conserving options were incorporated into this demonstration house. Included among these is a nominal 7'6" ceiling to reduce interior volume and many non-standard construction techniques to reduce infiltration and thermal load. Appliances are all electric and energy efficient. The electric space heating system includes a heat pump, a heat circulating fireplace and individual bath heaters. This two-story house provides a living area of approximately 1200 square feet and is expected to require 1/3 to 1/2 less energy than a typical existing home.

The EEB Mobile Laboratory monitored 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 took place routinely.

Experimental Methods

The EEB Mobile Laboratory is a facility designed for field studies of ventilation requirements and energy utilization in buildings. It is equipped with the instrumentation listed in Table II in order to monitor the contaminants shown in the same table. 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 an outdoor site. The four lines were sampled for ten-minute intervals in sequence to allow monitoring of the gas concentrations in all four locations; consequently, ten-minute samples were taken from each site every forty minutes.

Infiltration rates were monitored continuously at the latter two homes using an N_2O tracer gas system. This system, developed at LBL, continuously injects controlled amounts of N_2O while monitoring the indoor concentrations.[5] The data is recorded and processed to yield continuous infiltration rates. Infiltration at the MED 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 see if they could be correlated with changes in ventilation rates.

The particulate matter in the air was monitored at the sampling points using four dichotomous air samplers[6] (DAS), developed at LBL specifically for indoor monitoring. These devices separate the particulate matter above and below 2.5 microns 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).

The MBTH method is used for measuring total aliphatic aldehydes in indoor studies. An accurate flow control system developed at LBL is used to collect samples from indoor and outdoor air. The aldehydes, sampled in individual bubbler tubes containing MBTH solution, are refrigerated and brought back to LBL for analysis. There, the sample solution containing aldehydes is oxidized to yield a blue-green dye. The concentration of aldehydes is measured and calibrated (as formaldehyde) spectrophotometrically at 628 nm. Simultaneously with the MBTH method, the chromotropic acid and pararosaniline methods are used for measuring the formaldehyde fraction of the total aldehydes.

Results and Discussion

Methods of measuring air exchange rates in which the tracer gas concentration varies, such as simple exponential decay, utilize the "effective volume" of the structure. This represents the volume of air involved in the mixing process. Methods which maintain a constant concentration by continuously injecting tracer gas yield air flow rates (rates at which outdoor or "fresh" air enters the building). The LBL continuous tracer gas system measures air flow rates; however, concentrations vary somewhat and the "effective volume" can be calculated. The flow of fresh air divided by the "effective volume" represents the air exchange in air changes per hour. Air change rates measured at the MED house using a simple ethane decay curve yielded values of approximately 0.2 air changes per hour (ach). Flow rates measured at the ISUERH using the N_2O continuous tracer gas system varied from about 2000 ft^3/hr to 7000 ft^3/hr as shown in Figure 3. Figure 4 illustrates the variation of flow observed over a 24-hour period. It should be emphasized that these rates routinely varied over wider ranges than shown for this day. The air exchange rate varied at the ISUERH from about 0.15 ach to 0.75 ach with an average of approximately 0.3 ach. The average value is in good agreement with results determined by simple exponential decay-rate methods.

Preliminary results from these field monitoring sites show that the pollutants studied fall into two major classes; those for which the primary sources are indoors and those for which the primary sources are outdoors. As houses are tightened and ventilation rates are reduced, substances in the former class show higher concentrations indoors than outdoors, while substances in the latter class tend to be shielded from the indoor environment.

Figures 5 and 6 show histograms of 10-minute carbon monoxide and nitrogen dioxide concentrations both indoors and outdoors at the occupied MED house. In the occupied MED house, CO and NO_2 concentrations are higher indoors; presumably, their source is natural gas combustion from cooking activities. These are to be compared with the National Ambient Primary Standards of 9 ppm (CO for one hour) and 50 ppb (NO_2 annual average), which are considered to be levels of air quality necessary, with an adequate margin of safety, to protect the public health.[7]

Figure 7 shows histograms of the ozone concentrations indoors and outdoors at the occupied MED house. In the case of this pollutant, the house serves to shield the occupants from ozone in the outdoor environment. The short-term (1 hour) air quality standard for O_3 is 120 ppb. Carbon dioxide, shown in Figure 8, is of considerable interest because it is produced both by the combustion processes within the house and by the occupants themselves. The CO_2 levels observed in these energy efficient houses are well below the recommended standards.[8] In buildings such as educational institutions, which have high occupant densities, carbon dioxide may be the most important parameter in determining ventilation rates.[8,9]

Figure 9 illustrates the time dependence of the indoor-generated pollutants NO_2 and CO_2. These data, taken from the ISUERH house, show the effects of cooking and other occupant activities during a day when eight people were present in the house. Figure 10 shows the preliminary results of particulate sampling at the ISUERH. It can be seen that although outdoor levels generally exceed those indoors, increased indoor activities occasionally reverse this situation.

Figure 11 is a histogram showing the range of total aliphatic aldehydes and formaldehyde during the monitoring at the same site. The concentrations of total aliphatic aldehydes were between 109 and 186 ppb during the unoccupied period and 190 ppb during the one occupied period. Simultaneous sampling of outdoor air yielded an average aldehyde concentration of 13.5 ppb with a maximum value of 30 ppb and a minimum value of 2 ppb. The formaldehyde fraction of the indoor air was between 51 and 125 ppb and averaged 74 ppb. The outdoor formaldehyde concentrations were below 5 ppb for the entire sampling period. These formaldehyde concentrations can be compared to the recently promulgated European formaldehyde standard of 100 ppb.[10]

These preliminary results clearly indicate that, in general, indoor air has higher formaldehyde and aldehyde concentrations than outdoor air. Common building materials such as plywood and particleboard, constructed with urea-formaldehyde resin, are possible indoor sources. In addition, the activities of the building occupants, e.g., cooking and smoking, also generate significant amounts of aldehydes.

Conclusions

Preliminary results from this field monitoring program indicate that the indoor pollutant levels do exceed the levels found outdoors; however, in general, the levels of most pollutants are still within limits established by ambient air quality standards. When pollutant levels and air exchange rates are measured over a range of occupancy conditions in a number of energy-efficient houses, we expect to be able 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 such changes.

Because of increased energy prices, there are financial incentives to construct more energy-efficient houses, reduce air exchange rates and the resulting heat losses. Nevertheless, measures that would reduce infiltration

and ventilation rates currently under consideration could increase exposure to several indoor contaminants, including formaldehyde and radon,[11] and perhaps increase disease rates.

The possible increase in indoor contaminant levels requires considerable attention. Two regulatory approaches are possible for limiting exposure to indoor contaminants. One 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. There is a precedent for selecting such a level in the setting of occupational exposure standards, and standards for the general public are sometimes selected by comparison with occupational standards. The other approach is to set standards based on an explicit comparison of the disease incidence that may be caused by increased indoor contaminant concentrations with the cost of preventing these increases. Such a comparison would be made considering the financial gain from reduced energy usage, balanced with the adverse effects of increased indoor pollutant levels. A decision on this matter must be preceded by substantial work on characterizing the sources of indoor contaminants and the impact of various building designs on indoor concentrations.

Indoor contaminant emanation rates for the same material vary widely due to differences in fabrication. In addition, indoor pollution levels are strongly affected by indoor human activities, and by the manner in which materials are incorporated into a building, as well as other aspects of the building design, particularly the infiltration or ventilation rates. There are several design features that might be adopted specifically to limit increases:

1) Mechanical ventilation could be 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 summer. These could be used to control air exchange rates to maintain contaminant concentrations at acceptable levels while reducing heat losses from air exchange.

2) Indoor air could be circulated through contaminant control devices.

3) Measures could be incorporated to seal or eliminate certain contaminants at the source. Building materials could be selected for low emanation rates.

The effectiveness and advisability of such measures depend on various circumstances, such as the type of building and the geographical location. At this time, however, insufficient information exists to provide a basis for a considered regulatory decision. The effects of elevated indoor contaminant levels are highly uncertain, and the impact of building energy conservation measures is not yet known in detail.

Until all these relationships are understood, it would be premature for the regulatory authorities to formulate low energy-efficient ventilation standards affecting the built environment.

Acknowledgement

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The assistance of the Lawrence Berkeley Laboratory Ventilation Program staff in the preparation of this report is greatly appreciated.

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Table I. Indoor air pollutants 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
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 II. Instrumentation used in the Lawrence Berkeley Laboratory ventilation requirements system.

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	Mine Safety Appliances-Lira 202S
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

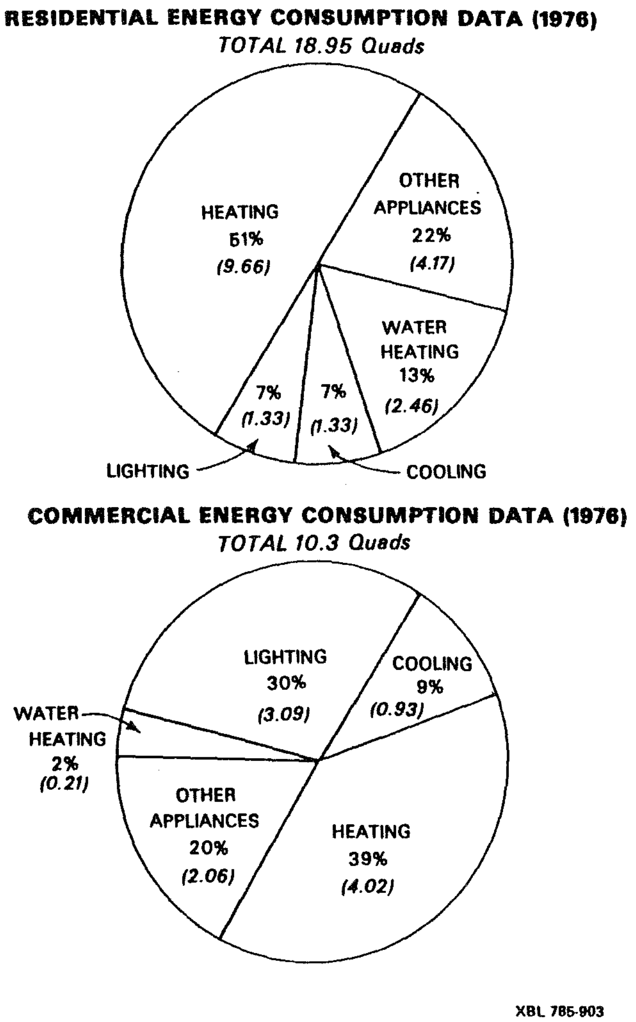


Figure 1. Resource energy consumed in the U.S. by residential and commercial buildings. Number in parentheses are in units of 10^{15} Btu.

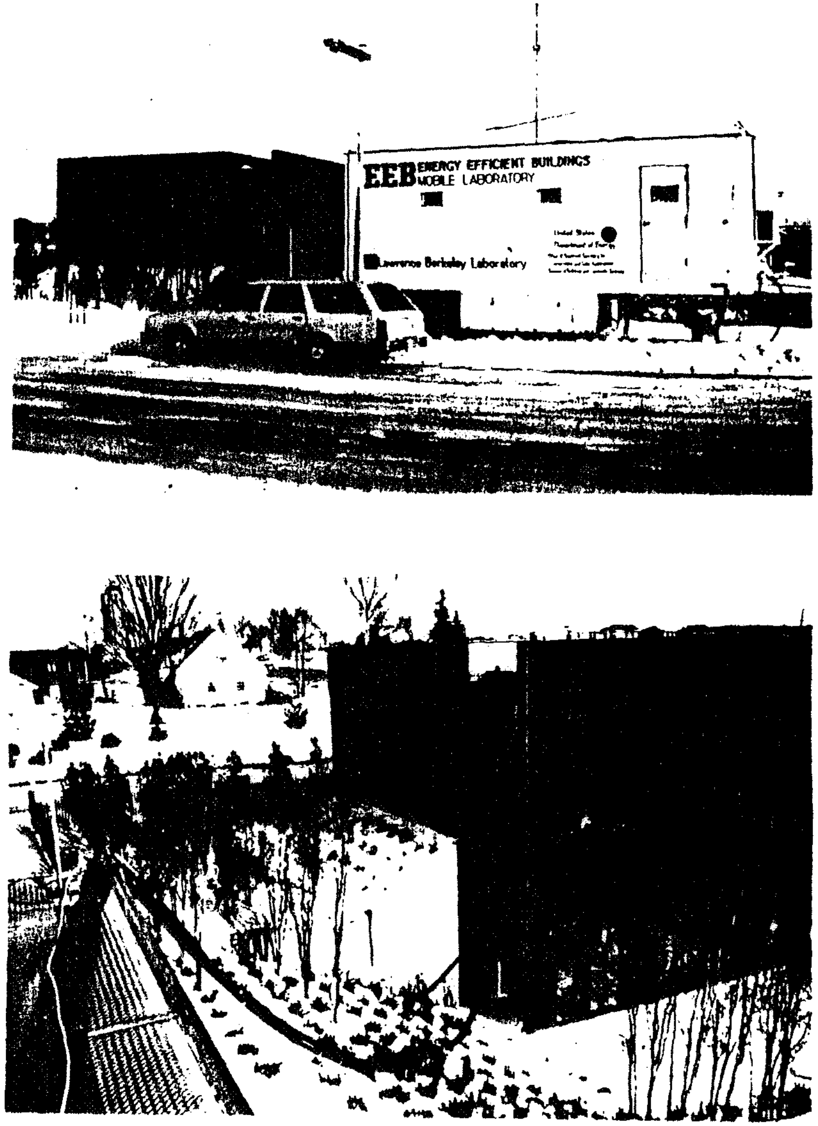
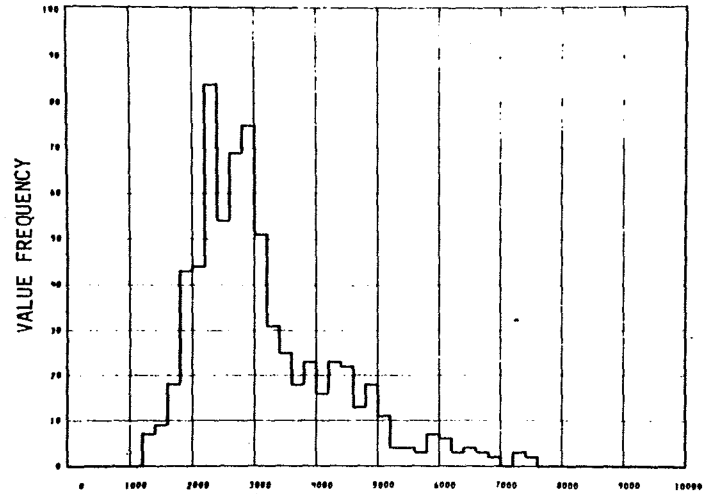
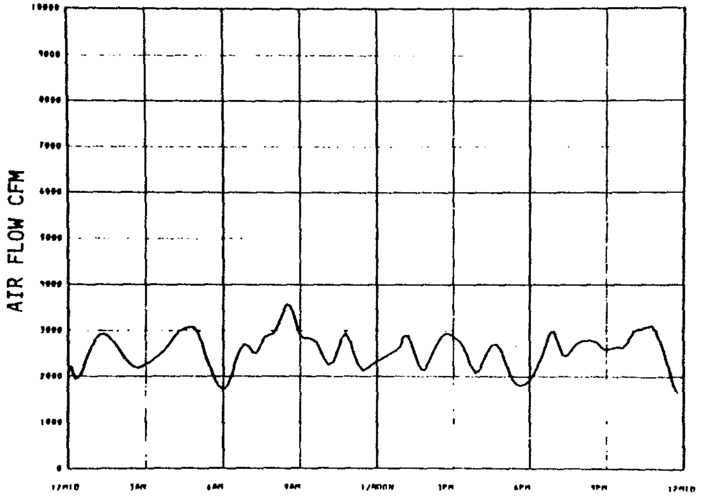


Figure 2. EEB Mobile Laboratory at the Iowa State University Energy Research House.



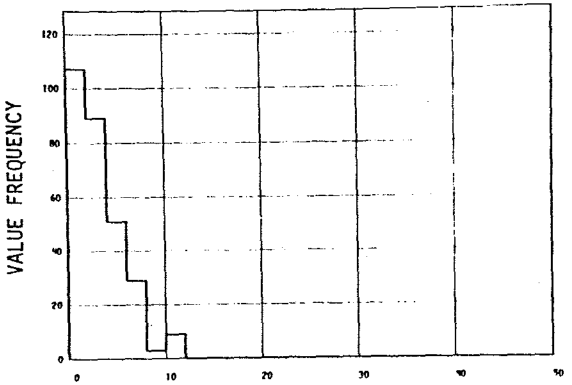
ISUERH FRESH AIR SUPPLY RATE
12/4/78 TO 12/10/78 BIN SIZE = 200 CFM

Figure 3. Summary of fresh air rates measured at the ISUERH.

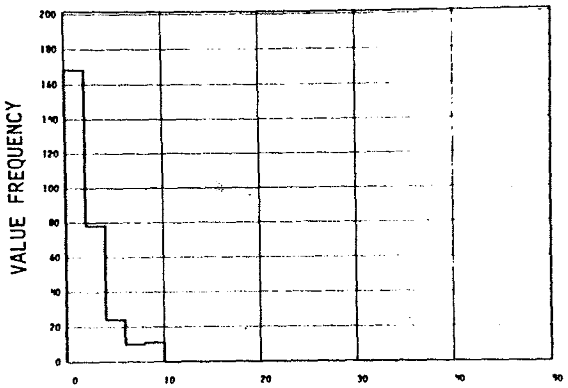


ISUERH FRESH AIR SUPPLY RATE 12/8/78

Figure 4. Fresh air rates at the ISUERH over a 24-hour period.

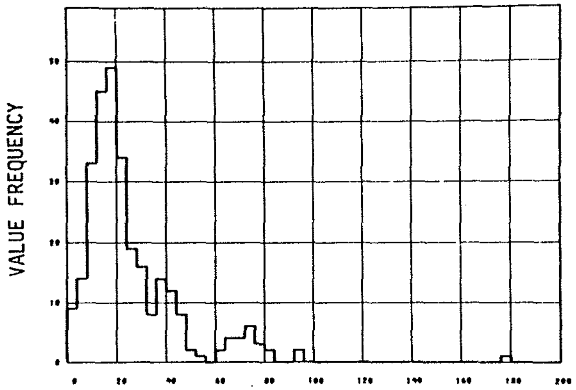


MED-I HOUSE CO KITCHEN
9/1/78 TO 9/9/78 BIN SIZE = 2 PPM

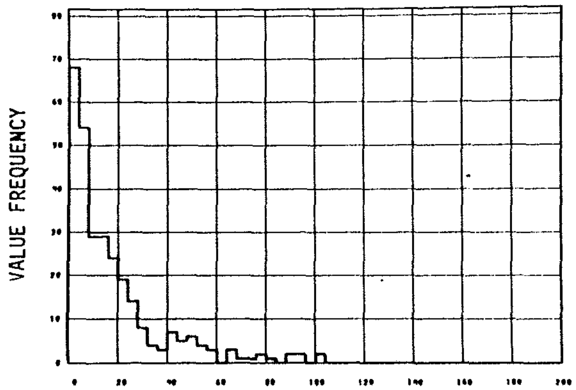


MED-I HOUSE CO OUTDOORS
9/1/78 TO 9/9/78 BIN SIZE = 2 PPM

Figure 5. Summary of indoor/outdoor carbon monoxide measurements at the MED house.

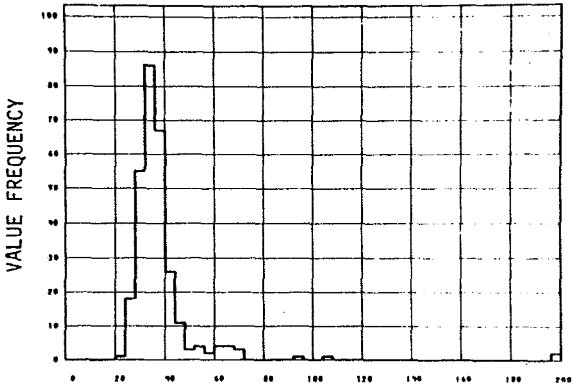


MED-I HOUSE NO_2 KITCHEN
9/1/78 TO 9/9/78 BIN SIZE = 4 PPB

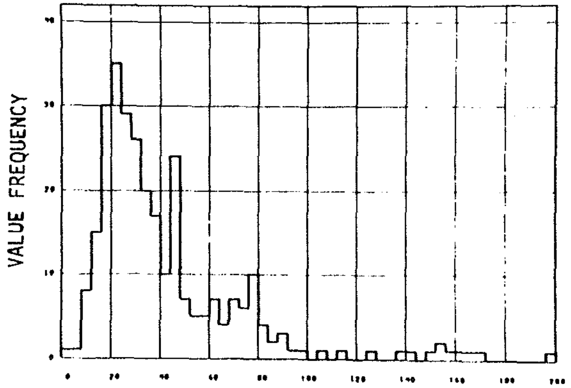


MED-I HOUSE NO_2 OUTDOORS
9/1/78 TO 9/9/78 BIN SIZE = 4 PPB

Figure 6. Summary of indoor/outdoor nitrogen dioxide measurements at the MED house.

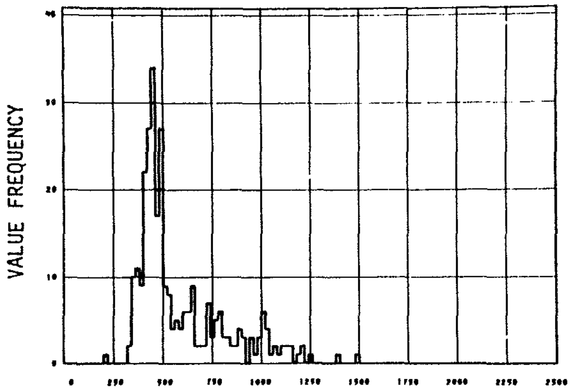


MED-I HOUSE O_3 KITCHEN
9/1/78 TO 9/9/78 BIN SIZE = 4 PPB



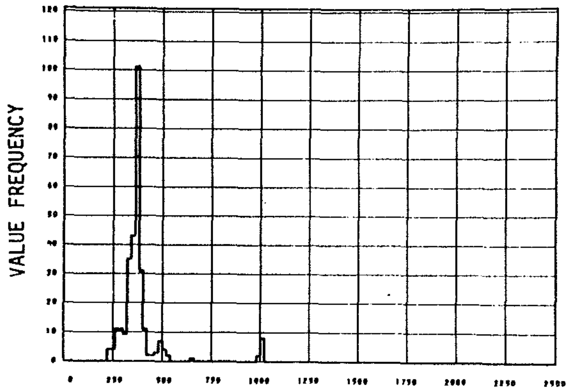
MED-I HOUSE O_3 OUTDOORS
9/1/78 TO 9/9/78 BIN SIZE = 4 PPB

Figure 7. Summary of indoor/outdoor ozone measurements at the MED house.



MED-I HOUSE CO_2 KITCHEN

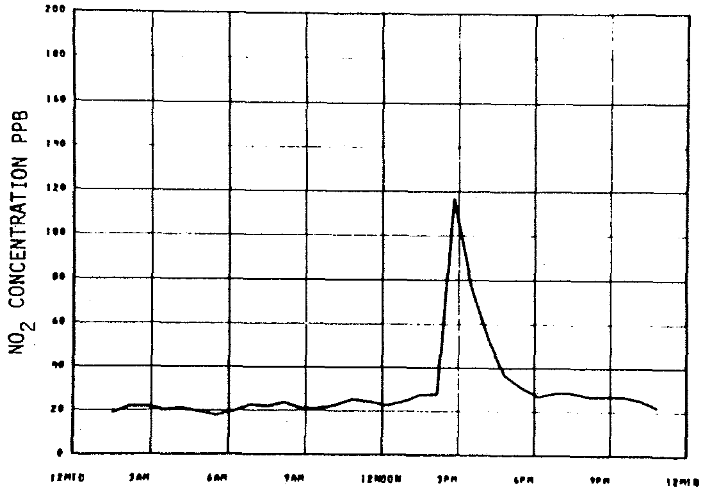
9/1/78 TO 9/9/78 BIN SIZE = 20 PPM



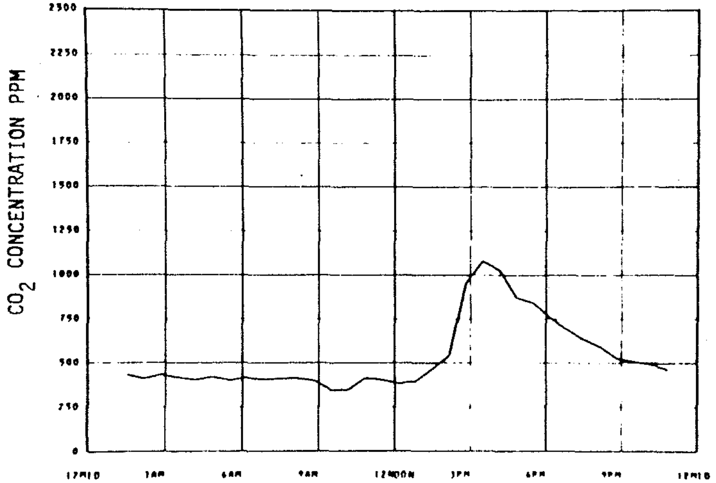
MED-I HOUSE CO_2 OUTDOORS

9/1/78 TO 9/9/78 BIN SIZE = 20 PPM

Figure 8. Summary of indoor/outdoor carbon dioxide measurements at the MED house.

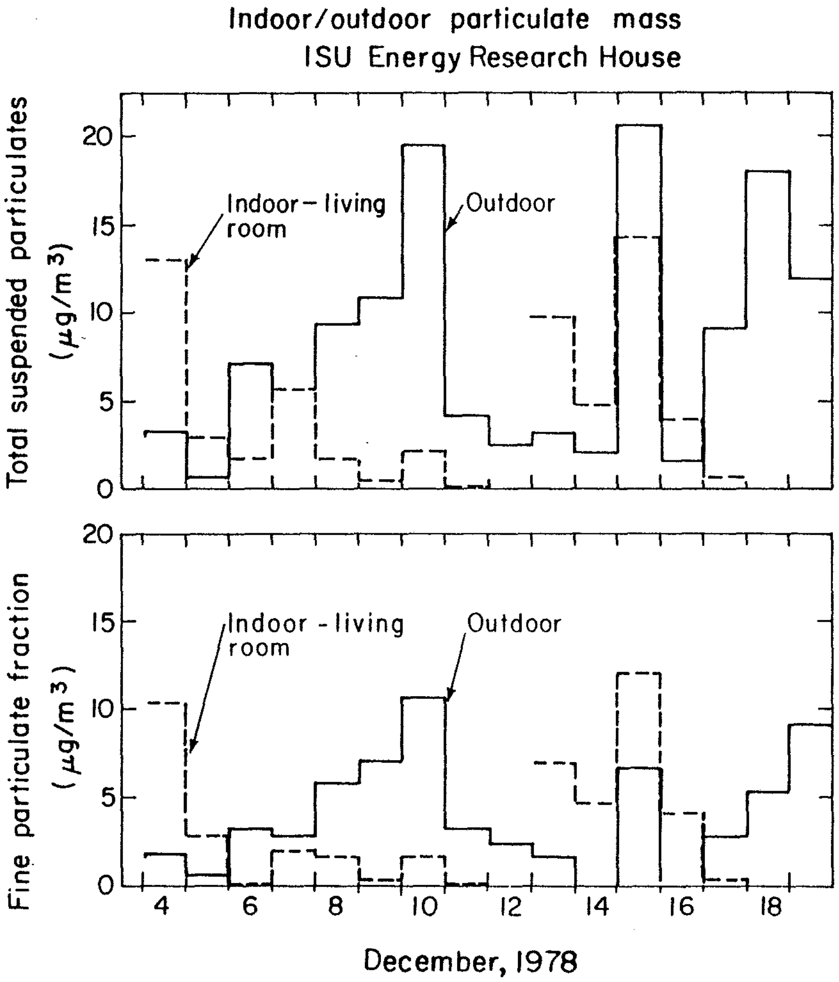


ISUERH NO_2 LIVING ROOM 12/14/78



ISUERH CO_2 LIVING ROOM 12/14/78

Figure 9. Time dependence of NO_2 and CO_2 during a day of occupancy at the ISUERH.



XBL793-766

Figure 10. Indoor/outdoor particulate mass measurements at the ISUERH.

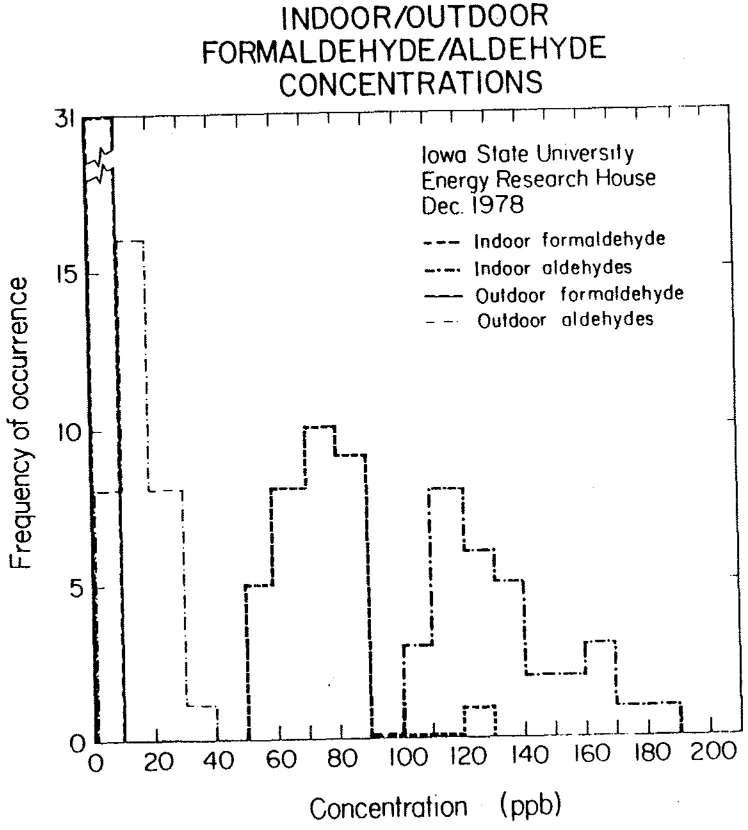


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Figure 11. Summary of indoor/outdoor total aliphatic aldehydes and formaldehyde at the ISUERH.