Title

FEASIBILITY STUDY FOR USING MECHANICAL VENTILATION SYSTEMS WITH AIR-TO-AIR HEAT EXCHANGERS TO MAINTAIN SATISFACTORY AIR QUALITY WITHOUT LOSING THE ENERGY EFFICIENCY OF A TIGHTLY CONSTRUCTED HOUSE

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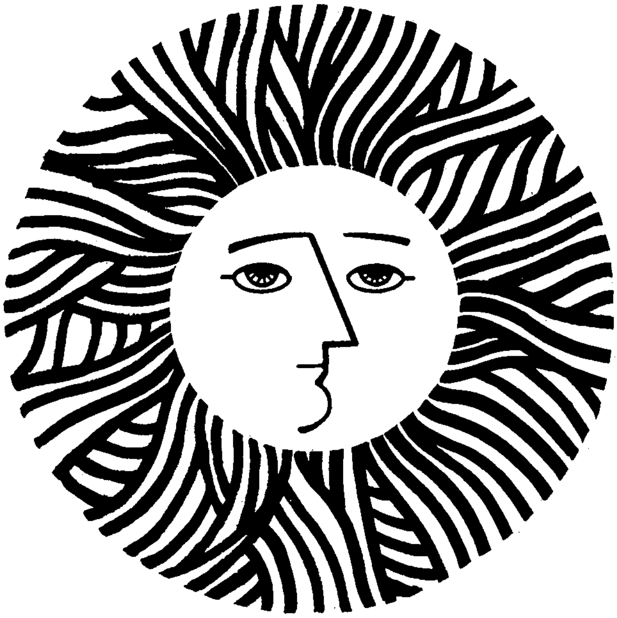

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DISCLAIMER

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August 1981

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Final Report

Prepared by
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For
The Regents of the University of California
Lawrence Berkeley Laboratory

For the Period
August 20, 1979 through April 30, 1980

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ABSTRACT

Escalating costs for energy have led the building industry to increase levels of thermal protection and to reduce natural ventilation rates (infiltration/exfiltration). As a direct consequence, indoor air contaminants have risen to higher levels. Concentrations of some contaminants have been found which may pose a potential health hazard.

An energy efficient residence (EER) in Maryland was found to have radon concentrations in excess of the recommended guidelines. Two mechanical ventilation systems with air-to-air heat exchangers were installed to test the effectiveness of an energy efficient control technique for indoor radon. By constant monitoring over a period of several months under varying ventilation conditions (0.01 to 0.90 air changes per hour (ACH)), radon concentrations were measured using a "Continuous Radon Monitor" (CRM). Additional samples were measured by grab-sample techniques at scheduled intervals.

During periods when mechanical ventilation was not employed, radon levels rose to higher levels than the recommended guidelines. When forced ventilation was employed at an air exchange rate of 0.60 ACH and higher, the levels of radon concentrations dropped to below the guideline levels for indoor concentrations.

The use of mechanical ventilation systems with air-to-air heat recovery capabilities (heat exchanger) may offer a practical, cost effective and energy efficient means of providing the necessary ventilation.

Introduction

One of the most promising methods of conserving energy in residential buildings which can help reduce the nation's dependence on imported oil is to build energy efficient homes.

Much attention is currently being focused in this direction. Building codes are being modified, local and state building departments are adopting standards, including several governmental agencies (DOE, EPA, HUD), all designed to make residences more energy efficient.

One target has been to reduce the infiltration rate. A number of builders have reduced the air exchange rate (ACH) by as much as 75% (1 ACH to .25 ACH). When the natural infiltration rate is reduced, which minimizes the amount of outside air entering into the structure, the house is clearly more energy efficient. Unfortunately, excessive humidity levels, odors from human activities, increased levels of contaminants such as nitrogen dioxide, formaldehyde, carbon monoxide, and radon, plus many more have been found in houses with these lower air exchange rates.

This report describes the research done by the NAHB Research Foundation (NAHBRF) under contract to the Lawrence Berkeley Laboratory (LBL) on the measurement of one of these indoor contaminants (radon) and the use of mechanical ventilation systems with heat exchangers to determine the feasibility of using such equipment to reduce the levels of radon to acceptable levels while continuing to conserve energy.

Indoor Air Quality

The nation's concern about air pollution has almost exclusively been directed toward the outdoor environment. The indoor environment has, until recently, virtually been ignored. When the outdoor air quality indices are exceeded the recommendations have been to stay indoors.

Results of some recent studies have found evidence that under certain conditions the indoor environment can have concentrations of pollutants which exceed those levels commonly associated with the outdoor environment.[1]

Now that energy prices have risen and are continuing to rise, the need to conserve energy has become a major concern. The area with which this study is concerned is in residential construction. It has been estimated that 12% of this nation's energy consumption is used for the heating/cooling of residential buildings. Based on 1978 usage figures, this represents about 4.5 million barrels of oil per day.[2]

Conventional houses constructed prior to 1974/75 had an estimated average air exchange rate of perhaps one complete air change per hour.[3] Some of today's more energy efficient homes may have an air exchange rate of one every 5 hours (0.20 ACH). This fact alone clearly indicates that these houses are more energy efficient than those of a decade ago. As the natural air exchange rate was reduced, the levels of indoor-generated air pollutants have increased.[4, 5, 6]

Model building codes which many jurisdictions have adopted over the past several years have attempted to set minimum ventilation rates as a function of the number of occupants or per square foot area. These standards have included commercial, industrial and, more recently, residential requirements. In addition to the model codes such as BOCA,[7] ICBO[8] and SBCCI[9], ASHRAE[10] has published a standard entitled "Standards for Natural and Mechanical Ventilation," Std. 62-73R which lists ventilation rates per occupant for commercial buildings, while residential requirements are specified at 10 CFM per bedroom (B.R.).

Radon and Radon Daughters

Radon-222 (radon) gas is the decay product of the naturally occurring radionuclide radium-226.

Radon daughters are radioactive atoms that attach themselves to particulates normally found in the atmosphere. Being airborne, radon daughters can be inhaled and deposited next to live, moist cells in the lungs.[11] Radon daughters are measured in units of working levels (WL).[12]

Both the EPA and the Federal-Provincial Task Force of Canada[13] have established guidelines for radon daughter levels of 0.02 WL for inhabited structures. ASHRAE in its proposed standard 62-73R has fixed the limit at 0.01 WL.

Possible Solution

One method of alleviating the IAQ problem is to maintain an adequate ventilation rate by using an air-to-air heat exchanger combined with a mechanical ventilating system (MVS/HE). By using this method the polluted air is exhausted to the outdoors and replaced by fresh outdoor air. The two streams of air are passed through the heat exchanger where a major portion of the energy (heat) being exhausted can be reclaimed by the incoming air.[14]

Objectives

The primary objective of this study was to find the answers to the following three questions.

1. What ventilation rate is required to maintain satisfactory indoor air quality in the EER (considering humidity, radon and formaldehyde)?
2. What are the installation and operating problems?
3. How do energy costs/savings obtained using an MVS/HE in an airtight house compare to costs in a normal house having no mechanical ventilation system?

The overall scope of the test program was outlined by LBL and implemented by NAHBRF with the exception of a few weeks in September during which LBL personnel conducted a series of special tests. This is noted within the body of the report.

Test House Description

The residence selected for the test program was the Energy Efficient Residence (EER) built by the NAHBRF in Mt. Airy, Maryland for the U.S. Department of Housing and Urban Development[15] (Figures 1 through 4). This residence was built utilizing the latest state of the art techniques in energy conservation applicable to residential construction. It was occupied by a family of four (two small children) from February 1978 through January 1979. During this time accurate records were kept on all categories of energy usage (Table 1). The final tally was that the cost for heating was 75% less than a comparison house of similar size, but of more conventional construction (Table 2).

During this test program (August 79 to January 80), the house was unoccupied, without furniture except carpeting and window coverings (drapes). Figure 3 presents the basic floor plan. The basement (not shown) is full, corresponding to the 46'0" x 26'0" dimension.

A typical wall section shown in Figure 4 is taken through the rear wall (south) and illustrates some of the energy saving features incorporated in the structure. All windows were double glazed with storm sash.

All major electrical circuits in the EER were individually submetered. Energy usage in Kwh for heating/air conditioning, hot water, cooking, etc. were thereby individually monitored. Tables 1 and 2 represent the summary of energy usage (Kwh) for periods shown. The data shown in these tables verifies that the EER is indeed an energy efficient residence and was ideally suited for this test program.

Program Outline

Following is the program outline as delineated by LBL and implemented by NAHBRF.

Phase 1 - Installation of weather tower and indoor/outdoor dry bulb and relative humidity instruments.

Phase 2 - Infiltration vs. wind speed and directional measurements: Radon monitoring before installation of heat-exchangers.

Phase 3 - Install heat exchangers and related equipment.

Phase 4 - Infiltration and ventilation rate measurements with heat exchangers.

Phase 5 - Radon monitoring with MVS/HE

Phase 6 - Final Report

Equipment

Figures 5 and 6 illustrate the mechanical ventilation systems installed at the EER. The unit shown in Figure 5 was built at LBL based on a design developed at the University of Saskatchewan, Saskatoon, Canada[16] (Besant). The second mechanical ventilation system which was installed in the EER was manufactured by Mitsubishi Electric Co., Model No. VL-1500 (Figure 6).

The Besant unit consisted of a plywood box approximately 2x3x7 feet. Two squirrel cage blowers (1/12 H.P.), mounted to the box provided separate exhaust and supply circuits. Supply and exhaust ducts (6") were routed to the outdoors and the indoor supply duct directed toward the return air duct or plenum of the central air handling unit located in the basement. This house was equipped with a return air grille in the basement, therefore, the MVS/HE supply duct was installed so that the supply air was directed into this grille. The exhaust duct drew from the general basement area approximately 6'-0" above the slab level. The unit was mounted in a vertical position resting on a pair of 2"x4" sleepers. The unit was steady, and there was no apparent vibration or noise with the fans operating. In new construction the unit could be built in; it would also be better received if reduced in overall size.

The general configuration of the Mitsubishi VL-1500 Heat Exchanger is that of a small window type air conditioner (Figure 6). Total weight was less than 30 pounds. The principle of operation is based on the heat transfer properties of treated paper (Figure 7). The heat exchanger element is a cross-flow exchanger. Figure 7 illustrates the basic structure of the heat exchanger element with air flow patterns.

Each unit was equipped with a multi-speed fan - the VL-1500 with a simple 3-way switch with preset LOW, MEDIUM and HIGH speeds. The Besant was equipped with a variable transformer control for each fan. Air flow was calibrated by using a Dwyer draft gage, and pitot tubes fitted in both the supply and exhaust ducts. The desired air velocities were obtained by adjusting the respective fan control.

Installation of the Mitsubishi Model VL-1500 heat exchanger was simple. The unit was installed in the basement window after removal of the lower sash. The opening was closed with a sheet of plywood cut to fit around the unit and sized to fit the window jamb. Duct tape was applied both inside and out to provide an airtight seal.

Equipment used for measuring the air exchange rate (ACH) was a sulfur hexaflouride gas (SF_6) analyzer and strip chart recorder. Gas (SF_6) was injected into the return air duct and distributed throughout the house via the ducted supply air system. A single "shot" of gas was injected to bring the SF_6 concentration to approximately 50 ppm. The gas was then turned off for the duration of each test run.

During the first series of tests air samples were drawn from the kitchen, master bedroom, living room and basement through sampling tubes located in each of these areas. Switching was accomplished by quick connectors at 15 minute intervals. Results showed that this switching procedure was unnecessary, the distribution of the gas was equal in all of these areas, including the basement, which was a conditioned area having 2 supply registers and a low return grille. After the first 3 days of testing only the living room sampling line was used for infiltration monitoring.

This method of testing was to measure the rate of decay or dilution of SF_6 gas as a function of time - the rate of decay being the rate that the indoor air is being replaced with outdoor air.

The rate of decay of the gas concentrations is plotted on the strip chart. By using a series of equal time intervals, the rate of gas decay can be established by a simple mathematical procedure.

Early Findings

Several recent field studies conducted by LBL[17] at various locations in the U.S., including the EER house in Maryland, established the fact that this house had high levels of radon and formaldehyde.

Table 4 illustrates the measured radon concentrations found in the 4 test sites by LBL. The EER listed as Carroll County, Maryland, is the Mt. Airy, Maryland, test house (EER). The high levels of radon concentration were unexplained, however, subsequent samplings were made in an effort to determine the source of radon. The determination of the source radon in this house will require further study.

Measured infiltration rates ranged from 0.05 to 0.15 air changes per hour (ACH). This was a tenfold reduction as compared to the typical range of 0.5 to 1.5 ACH.[3]

There are currently no national standards which limit the permissible concentration of radon and radon daughters in the residential environment. The EPA[18] has formulated a recommendation which states that remedial action should be taken when concentrations exceed 0.02 WL, and that in all cases, radon daughter concentrations should be reduced to levels as low as reasonably achievable. These guidelines were established by the EPA for the State of Florida for homes built on land reclaimed from phosphate mining.

Testing by LBL

With the use of the MVS/HE, the basic goal was to establish the minimum ACH rate necessary to control the radon levels in the test house.

By using the "Continuous Radon Monitor" (CRM) (developed by W.W. Nazaroff of LBL), in conjunction with the MVS/HE, a series of tests were conducted in September 1979 at the test site. A team from LBL (Nazaroff and Boegel) conducted these tests and reported their findings in a paper published by LBL in March 1980.[19] Conclusions of that report are presented here, with Figures 8 and 9 for reference.

> ### Conclusions
>
> We have demonstrated the effectiveness of mechanical ventilation with heat recovery in reducing the concentrations of radon and radon daughters in a low infiltration house. By a simple analysis, we were able to show that the strategy of building tight houses and installing mechanical ventilation systems with air-to-air heat exchangers may satisfy energy conservation goals in a cost-effective manner without compromising indoor air quality.
>
> This approach cannot, by itself, eliminate indoor air quality problems in situations where source levels of pollutants are high. In the case of radon, for example,

> the ventilation rate in houses built on land where the radon source is characteristically high cannot be increased to the magnitude that would be necessary for effectively controlling indoor radon concentrations. In such cases, methods of eliminating or blocking the source must be adopted; however, mechanical ventilation with heat recovery may still be desirable to maintain low concentrations of other indoor air contaminants.
>
> As more experience with air-to-air heat exchangers is gained, other important issues must be resolved - among them, the long-term reliability and efficiency of heat exchangers and public acceptance of maintaining an additional home appliance.

Natural Infiltration

With the installation of the monitoring equipment, the first series of tests was conducted to establish the natural infiltration rate (without mechanical ventilation). In addition to the initial series of 10 consecutive tests in August, periodic tests were conducted in November, December and January. Table 3 illustrates the average ACH for the entire test series. The average duration in time for each test was approximately 4 hours.

Radon Monitoring

Early measurements of the radon levels in the EER house conducted prior to this program revealed concentrations of radon in excess of 20 picocuries per liter (pCi/l). This concentration probably corresponds to working levels (WL) in excess of 0.05. Studies conducted in Canada at four communities engaged in uranium mining resulted in remedial action being recommended where average radon daughter working levels exceeded 0.02 WL.[11] The U.S. EPA has recommended similar limits for houses built on phosphate reclaimed land in Florida.[18]

Radon concentrations were monitored continuously during the entire test period. Figures 10 through 15 show the radon concentrations as a function of time, at selected ventilation rates (expressed in ACH). For this analysis the output of the CRM was averaged over three-hour intervals. References to the HE-1 indicate that the Besant heat exchanger was in operation, and HE-2 refers to the VL-1500 heat exchanger. Notations LR and B refer to the radon sampling line which was used (living room or basement). Fan On and Fan Off notations refer to the central heat pump fan coil unit.

Radon concentrations ranged from a high of 17 pCi/l to a low of 1 pCi/l during the period from December 10, 1979, through January 31, 1980. The most significant feature revealed in these Figures are the effects of ventilation rates on radon concentrations. Figures 10 through 15 show radon concentration in units of picocuries per liter (pCi/l). For the purpose of this study a radon concentration of 4 pCi/l is approximately the same as a working level of 0.02.

As is clearly indicated in Figures 10 through 15 the radon concentrations are influenced by the ventilation rate. The radon concentration dropped below 4 pCi/l and remained so only when the ventilation rate was maintained at 0.60 ACH or higher. There were periods where the concentrations dipped below the 4 pCi/l levels at lower ventilation rates, but these were for relatively short periods and were not considered to have any serious impact on the overall findings.

Figure 10 shows the radon concentration averaged 4.5 pCi/l with an average ACH of 0.44 during the period December 17 through December 20.

This would indicate that the minimum ventilation rate (ACH) required in the EER would be a nominal 0.50 ACH.

The earlier test performed by LBL in September 1979[19] at the EER house indicated that the minimum ventilation rate to achieve 0.02 WL was 0.60 ACH. Radon concentrations during this period ranged from a high of 35 pCi/l to less than 1 pCi/l. Whereas during the period December 10 through January 31 the maximum concentration reached a high of less than 18 pCi/l.

Figures 14 and 15 illustrate the operations and results of the radon monitoring program during the period of March 27, 1980 through April 10, 1980, and April 14, 1980 through April 23, 1980, respectively.

During this period the house was operated without the central air handling in operation. Heat was provided by means of two portable electric resistance heaters. Figure 14 depicts the radon levels without the use of the heat exchanger, whereas the heat exchanger was operating during the period shown in Figure 15. The significant fact is that radon levels were reduced substantially with only the heat exchanger in operation. From this experiment it can be concluded that the heat exchanger is an effective method of reducing radon levels in homes without central forced air heating systems where the main source of radon is from the basement.

Mechanical Ventilation with Heat Recovery

The fact that mechanical ventilation is usually an effective means of reducing indoor air contaminants has been established.

To construct an energy efficient house with a low natural ventilation rate, and then use mechanical ventilation to increase the ventilation rate without any means of recovering the energy (heat) which is being exhausted, is obviously an exercise in false economics.

An effective means of alleviating the problem of exhausting the indoor air and bringing in tempered outdoor air is to introduce a mechanical ventilation system with a heat exchanger. The two air streams are brought into thermal contact with each other in the exchanger. The incoming outdoor air is preheated (or precooled) before entering the house. This is accomplished by a simple heat transfer process.[14, 20]

Figure 5 illustrates the "Besant" type heat exchanger which was employed in the EER during this test program.

Figure 6 illustrates the VL-1500 heat exchanger which was also employed in the EER.

Heat Exchanger Efficiencies

Published efficiencies of heat exchangers used in this study range from 72% to 75% depending on the air volume being passed through the unit (CFM). In general terms for a given heat exchanger, the greater the air flow the lower the effectiveness. The effectiveness rating of the MVS/HE is in direct relationship to the unit's capability to recover the exhausted heat under a given set of conditions. Therefore, a unit rated 75% efficient would have the capability of delivering 56°F air when the exhausted air is 68°F and the outdoor air is 20°F if no condensation or freezing occurs in the exchanger. This relationship is represented in the following equation which assumes equal flow rates and heat capacities.[21]

$$e = \frac{Ws(T_1 - T_2)}{Wmin\ (T_1 - T_2)} = \frac{We(T_4 - T_3)}{Wmin\ (T_1 - T_3)}$$

Where:

e = Sensible heat effectiveness
T_1 = Exhaust air entering temperature
T_2 = Exhaust air leaving temperature
T_3 = Supply air entering temperature
T_4 = Supply air leaving temperature
W_s = Mass flow rate of supply (lbs. of dry air per hour)
W_e = Mass flow rate of exhaust (lbs. of dry air per hour)
W_{min} = Smaller of Ws and We

LBL built the heat exchanger which was used in this test program based on a design by R. W. Besant of the University of Saskatchewan.[16] Being a lab built model, rated efficiencies were not available. LBL has since tested a duplicate of this heat exchanger and found that at a flow rate of 150 CFM the unit was 46% effective.

During the month of January three tests with the VL-1500 were made. Temperatures were recorded with the unit operating on "High" fan (71 CFM), resulting in the following efficiencies (E).

Date	Supply	Exhaust	Outdoor	"E"%
1/02	55	66	32	.676
1/14	55	65	35	.667
1/17	56	65	38	.667

The recorded apparent average efficiency for this unit is 67%. Published manufacturer's data states that the heat exchanger efficiencies at rated air flow (CFM) are:

High Fan = 72%
Med. Fan = 73%
Low Fan = 75%

Table 5 illustrates the efficiencies of "Besant" type exchanger under varying operating conditions which averaged 62.6 at 151 CFM. Temperatures were taken using a standard sling psychrometer at the supply outlet, exhaust inlet and outdoors. All readings were taken at approximately 10 a.m. on the dates indicated.

The disparity between the field measured efficiency at 63% and the laboratory measured efficiency of 46% is thought to be because of long uninsulated duct runs inside the house that would tend to add heat to the incoming air stream, plus the fact that both ducts (exhaust and supply) were located in the south facing wall exposed to direct solar exposure. The room temperature plus the passive solar gain on the metal duct could make the unit appear to be more efficient.

Even though LBL in their laboratory measured the efficiency of Besant at 46%, other types were also tested with results of 68% to as high as 78% at 250 and 150 CFM respectively. Therefore, for the purpose of the model, it will be assumed that a heat exchanger will have a minimum rate of effectiveness of 65% at 150 CFM, which was the air flow rate required for this test house to achieve 0.60 ACH.

Energy Savings

LBL has calculated the expected energy dollar savings to be gained by employing mechanical ventilation systems with air-to-air heat exchangers.[14] Values and data established from the tests performed in the EER will be substituted in this model.

The EER is a single story, single family detached house with a floor area of 1200 ft^2 (finished). There is also a full basement (unfinished) of equal area which is conditioned. Total area equals 2400 ft^2. The house was 7'-6" high ceilings with a total volume of 18000 ft^3. One ACH is equal to 300 CFM of outside air entering the house.

To evaluate the energy savings in the EER test house, three modes of operation were considered:

Mode #1 - Natural infiltration, without benefit of mechanical ventilation of heat exchanger
Mode #2 - Forced mechanical ventilation without heat exchanger
Mode #3 - Forced mechanical ventilation with heat exchanger

Mode #1 represents the average air exchange rate (ACH) recorded during the test period from November 12 through January 31, 1980. A set of 7 tests were conducted during this period resulting in an overall average of 0.2 ACH. The average outdoor temperature during this same period was recorded at 34°F or 8°F below the seasonal average for the area, which is stated as 42°F in Frederick, Maryland.[13]

For the purpose of this analysis, an average outdoor temperature of 42°F will be assumed.

The data base developed during this test program has shown that for this particular test site an air exchange rate of 0.60 ACH must be maintained to bring the indoor air quality (IAQ) to within acceptable limits with regard to radon daughter concentrations.

For Mode #2 a total air exchange rage of 0.60 ACH was established, which is the rate required to maintain the IAQ at acceptable levels. Mode #2 does not have heat recovery capabilities. The sum of forced ventilation and natural infiltration is assumed to equal 0.6 ACH. The sensible heat load due to ventilation would be the heat required to heat the incoming air from the outdoor conditions to approximately 68°F.

For Mode #3 a total ventilation rate of 0.60 ACH is also required; 0.4 ACH is vented through the heat exchanger - the balance of 0.2 ACH is credited to the natural ventilation rate. Thus, the ventilation rate for Mode #3 is the same as if the heat loss to the outside air were equal to an infiltration rate of 0.34 ACH. That is:

$$0.2 + .4(1-E) = 0.34 \quad (2)$$

E = Heat Exchanger Efficiency (.65)

The EER test house inside volume is 18000 ft^4 (509.7 M^3). The indoor temperature is assumed to be a constant 68°F (20°F) with an average outdoor temperature of 42°F (5.6°C). For this well insulated "tight" house a balance point of 55°F (12.8°C) was assumed. The balance point of 55°F was assumed to be constant for the three different ventilation conditions. The balance point represents the lowest outdoor temperature at which the house does not require heat from the heating plant to maintain an indoor temperature of 68°F (20°C). In the test area the number of hours during which the outdoor temperature falls below 55°F (12.8°C) is 3926. However, this listing is for Andrews AFB near Washington, D.C., where the average winter outdoor temperature is 46°F (7.8°C). For Frederick, Maryland, the average outdoor temperature is stated as 42°F (5.6°C). A 9% correction factor was therefore applied to bring this factor into line with conditions at the test site - the result equals 4278 hours.

A simple method to estimate the total seasonal winter heating load for infiltration, expressed in therms (1.0 therms = 10^5 Btu), can be represented by the following equation.

$$\frac{(ACH)(CFM)(1.08)(t_1 - to)(H)}{10^5} = \text{Therms} \qquad (3)$$

Where:

(ACH) = Desired infiltration rate in air changes per hour.

(CFM) = Cubic feet per minute of air to equal one complete air change in one hour ($ft^3 \div 60$)

ti = Indoor temperature (DB)

to = Outdoor temperature (DB) - (average winter)

H = Total hours when temperature is below balance point (55°F) (in winter)

10^5 = 1 Therm (100,000 Btu)

From the data established, the seasonal (heating) loads for heating the incoming outside air in the three different ventilation modes described above are:

Mode #1 = 74.9 Therms

#2 = 232.9 Therms

#3 = 130.0 Therms

Costs

The EER house was constructed for the purpose of developing information and data for costing effective energy efficient design and construction.

Many energy conserving options were investigated including design and building orientation.

The total increase in capital cost attributable to the energy conserving options in the EER demonstration house was $5,400.00 (1978 dollars).[15] This figure was established through on-site observations by in-house industrial engineers. This cost figure does not include materials and equipment required for this study.

Availability of air-to-air type heat exchangers suitable for residential application is currently somewhat limited. Of those that are available (mostly of foreign manufacture) prices range from $200 to $800 (new reference manufacturer list available from LBL).[22]

The heat exchanger used in the EER was built by LBL in their laboratory, therefore the commercial price for this unit is not available. In a report prepared by LBL[19], a price for a unit of the size and capacity required for the EER was stated at $550. The referenced report states that installation costs were assumed to be $100. Installation in the EER including the sheetmetal ductwork amounted to a nominal $200. Therefore, the total initial cost for installing this heat exchanger would be $750. Roseme in his analysis has assumed that with increased production of residential type heat exchangers the commercial price should drop to about $200.00. Applying the same logic, the modified capital cost would be $400.

Capital costs related to the "built-in" energy saving features of this EER test house are not considered. It has been assumed that these costs are part of the basic construction costs.

Energy usage for the operation of the fan motors (intake and exhaust) was assumed to be 150 watts or 642 Kwh per heating season. That is:

$$\text{Kwh/year} = \frac{(\text{Heating Hours})(150\text{ w})}{1000} \qquad (4)$$

The assumption is that the heat exchanger operates continuously during the heating season (4278 hours). It is further assumed that during the cooling season and mild weather (spring and fall) more natural ventilating methods (open windows, etc.) will be used by the respective homeowner thereby nullifying the need for the heat exchanger.

Fuel costs for 1980 in the test site area were:

Gas = 0.38/Therm

Oil = 0.95/Gallon

Elec. = 0.06/Kw

As a common unit of measure, it is necessary to convert the fuel unit prices to cost per therm (1 Therm = 10^5 Btu).

Gas = \$/Therm

Oil has the capacity to deliver 135,000 Btu for each gallon consumed. There the price per therm would be:

$$\frac{\$/\text{Gal} \times 10^5}{135 \times 10} = \$/\text{Therm} \qquad (5)$$

To convert electric Kw to therms the following method is used:

$$\$\text{Kw} \times 29.3 = \$/\text{Therm} \qquad (6)$$

Applying the above, the respective unit cost of fuel per therm is:

Gas = 0.38/Therm
Oil = 0.70/Therm
Elec= 1.76/Therm

Seasonal performance efficiencies (SPE) of heating systems vary depending on fuel type, equipment sizes, distribution systems, plus geographical locations. ASHRAE cites[23] effective seasonal efficiencies from 0.50 to 0.78 for natural gas and 0.44 to 0.69 for fuel oil with 40% equipment oversizing. Direct electric heating systems are rated at 0.77 to 1.20, with 10% equipment oversizing. The higher values apply to the colder climates while the lower values apply to warmer climates. Based on the above, the following seasonal efficiencies were selected for this study:

Gas = 65%
Oil = 55%
Elec. = 100%

The benefit cost ratios for comparison between the three ventilation modes are shown in Table 6A and 6B shown in 1980 dollars.

Table 6A lists the calculated energy usage in therms for the three modes of operation cross referenced with the fuel and equipment efficiencies.

Table 6B lists the calculated annual cost for heating using the unit energy cost and therms listed in Table 6A in 1980 dollars.

In addition to the cost of the energy that is being exhausted to outdoors (Modes #2 and #3) the cost of operating the fans must be added. It has already been estimated that an annual energy usage of 642 Kwh will be required, or approximately $38.52 per heating season.

For this scenario it had been established that the house was "tight" and that forced ventilation was required to improve the IAQ. Therefore, the direct cost impact for providing the required ventilation is a comparison between Modes #2 and #3.

Capital costs for a ventilating system without heat exchanger is estimated at $150 (exhaust fan only); with a heat exchanger, $600 - a net cost for improvement of $400 plus $200 for installation.

Economic Feasibility

Assuming a direct cost of improvement of $450.00 ($600 - $150 = $450) for a mechanical ventilating system with a heat exchanger over and above a mechanical ventilating system without a heat exchanger, the time-to-recoup the investment for the different fuels can be expressed in the following equation:

$$n = \frac{\text{Log}\ [\frac{P}{aS}(a-1) + 1]}{\text{Log}\ a} \qquad (8)$$

Where:

n = Period of years or time-to-recoup investment

P = Added cost for improvement (est. $450.00)

S = Cost savings for first year of operation

$$a = \frac{1 + f}{1 + i} = \frac{1 + 0.10}{1 + 0.12} = 0.9821$$

f = Estimated annual percentage rate of price increase for fuel, expressed as a decimal (estimated).

i = Percentage interest rate on mortgage or loan, expressed as a decimal (estimated).

Assuming that "a" equals 0.9821, the time-to-recoup the investment for each fuel equals (mode 3 vs. mode 2):

Gas = 9.3 years

Oil = 4.5 years

Elec. = 2.6 years

The preceding cost effectiveness argument does not take into account the energy saved during the cooling cycle. This would be difficult to estimate because an energy wise homeowner that had invested in a ventilation system would utilize it, plus natural ventilation (open windows, etc.) thereby reducing the total cooling hours perhaps as high as 60%. In any case the total energy savings during the cooling season would be minimal, as compared with the heating cycle figures.

Perhaps the most significant factor to be considered during the cooling cycle is peak power savings. Since a large portion of air conditioning energy is spent for removing water vapor from the air, a heat exchanger that transfers water vapor would be beneficial during the cooling season and help to reduce the peak power consumption.[14] Benefits of reducing the cooling load have not been included in this study. Further study is required to determine the full extent of these benefits.

Conclusions

The answers to the three basic questions posed (see Objectives, this report) can be summarized as follows:

1. The optimal total ventilation rate required for this test house appears to be a nominal 0.60 ACH. The minimum air change rate which still maintained a radon daughter working level of 0.02 WL appears to be 0.57 ACH. The proposed ASHRAE Standard 62-73R which sets a maximum working level (WL) of 0.01 would require an air exchange rate of 0.80 ACH for this house.

   The natural ventilation rate (infiltration) is not a fixed quantity. It is directly influenced by the 1) height of the structure 2) the level of thermal protection 3) orientation 4) wind velocity 5) indoor/outdoor temperature difference. The most significant being the height of the structure and temperature difference.

Homes which may require forced ventilation with a heat exchanger because of IAQ requirements must have properly sized units. Improperly sized units will have a direct impact on the economic feasibility of the installation. The unit need only have sufficient capacity to make up the difference between the natural ventilation rate and required total ventilation rate required to maintain acceptable levels of indoor air quality. Heat exchangers are not 100% efficient as 25% to 40% of the heat is lost.

It is conceivable that there are areas where radon and radon daughters have such high levels of contamination that forced ventilation would be impractical. These areas would require other forms of remedial action involving the structure itself. Other areas could have radon levels which are of such low levels that natural ventilation would suffice. While this report deals primarily with radon and radon daughters, other pollutants can be present. Ventilation rates which may be capable of maintaining radon within acceptable levels may not be capable of maintaining acceptable levels with regard to other contaminants.

2. Installation and operating problems do not appear to be insurmountable. The units installed in the test house were of such different configurations that each will be dealt with separately.

The Mitsubishi Model VL1500 is a small, compact unit, weighing approximately 30 lbs. This unit can be installed in a window, much the same as a small window-type air conditioning unit, or through the wall. Power is 115V, therefore requiring no special wiring. The unit has no automatic controls, it is either "off" or "on" at one of the three factory-set fan speeds (low, medium, high). A three-position switch is located on the front of the unit providing selection of one of three fan speeds. This unit is ideally suited for retrofit applications. It is totally self-contained and does not require any sheetmetal ductwork. This unit did not have the capacity to handle the entire house. At an air exchange rate of 0.60 ACH, this unit could only handle an area of 525 ft^2 or about 4200 ft^3 on the high fan setting (70 CFM). To properly ventilate the entire test house (18,000 ft^3), possibly three or more units would be required. Three or four window units would add substantially to the capital and operating costs.

Installation of the Besant unit presented a different set of problems. Its physical size and weight required four men to carry it into the basement area. This unit was not a factory model, but one that was manufactured in the LBL laboratory and was not intended to represent a production model. The unit is equipped with two individual fans (supply and exhaust) of the same size.

Sheetmetal ductwork is required for both the supply and exhaust systems. Installers will need to properly balance the unit. Improper balance on either side (supply or exhaust) would seriously affect the efficiency of the unit. The heat recovery capabilities could be reduced to such low levels that the unit could become a financial liability.

> In general, more study and design work is required to develop: 1) a unit capable of handling an average size residence, and 2) a unit which could be built into or contiguous to the furnace or air handling unit. Serious consideration must also be given to the installation problems in houses that do not have central air handling equipment with a related ducted air distribution system.

In summary it can be stated that the results from this test program have shown that the use of a MVS/HE is potentially practicable and economically feasible. Test results indicate that a considerable reduction in heat loss was realized as compared with straight ventilation without a heat exchanger. Depending on the fuel used for heating the residence, payback periods ranged from a nominal 3 to 9 years.

It cannot be assumed that the supply and exhaust ducted systems would be in perfect balance. Each of these systems would inherently be of different developed lengths. Therefore, to achieve maximum efficiency the air flow rates for the supply and exhaust airstreams must be adjusted so that they are balanced (equal).

ACKNOWLEDGEMENTS

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Electric and Hot Water Consumption
(KWH) (Gals)

EER HOUSE

Energy Use	Feb 1978	March 1978	April 1978	May* 1978	June* 1978	July 1978	Aug 1978	Sept* 1978	Oct* 1978	Nov 1978	Dec 1978	Jan' 1979
Heat Pump-Heating (EER only)	476	336	141	145	0	0	0	0	0	212	486	754
Cooling (less blower)	0	0	0	0	170	267	395	166	31	0	0	0
Resistance Heat	60	30	5	5	0	0	0	0	0	14	23	86
Blower	140	100	20	45	55	86	144	72	63	69	105	155
Bath Heaters (EER only)	2	2	1	1	0	0	0	0	4	5	8	6
Subtotal Heating (Cooling)	678	468	167	196	225	353	539	238	98	300	622	1001
Water Heater**	340	390	330	396	264	236	152	206	286	364	388	373
Range	85	85	68	98	71	57	79	68	67	79	75	85
Refrigerator	85	101	83	104	36	98	118	111	108	113	115	105
Dishwasher	10	10	10	18	12	12	14	14	12	12	12	13
Clothes Washer	5	5	5	5	5	4	5	4	4	6	5	2
Clothes Dryer	43	63	68	83	60	67	62	55	65	87	87	65
Dehumidifier (EER only)	0	0	0	45	0	0	0	0	0	0	0	0
Lighting and Misc.	148	140	96	125	168	108	239	178	119	137	146	108
Subtotal Appliances	716	794	660	879	616	582	669	636	661	798	828	751
Instrumentation	21	23	22	23	22	23	23	22	23	22	23	23
TOTAL HOUSE	1,415	1,285	849	1,098	863	958	1,231	896	782	1,120	1,473	1,775
Hot Water Consumption (Gallons)				2,470	1,760	1,670	1,760	1,730	1,770	2,220	2,120	1,810

TABLE-1

*Heat pump heating power consumption includes both heating and cooling power consumption.
**Approximate water heater temperature: 115° F EER House, 150° F Comparison House.

Electric & Hot Water Consumption
(KWH) [illegible] ls)

COMPARISON HOUSE

nergy Use	Feb 1978	March 1978	April 1978	May* 1978	June* 1978	July 1978	Aug 1978	Sept* 1978	Oct* 1978	Nov 1978	Dec 1978	Jan 1979
eat Pump-Heating (EER only)	-	-	-	-	-	-	-	-	-	-	-	-
ooling (less blower)	0	0	0	0	363	586	806	288	0	0	0	0
esistance Heat	2,483	1,604	519	259	0	0	0	0	294	1,089	2,122	2,966
lower	80	60	20	10	55	105	138	42	10	35	66	89
Bath Heaters (EER only)	-	-	-	-	-	-	-	-	-	-	-	-
Subtotal Heating (Cooling)	2,563	1,664	539	269	418	691	944	330	304	1,124	2,188	3,055
Water Heater** 7330	594	867	629	597	482	509	492	506	598	601	731	724
Range	39	53	13	34	28	41	30	39	50	61	51	63
Refrigerator	107	130	113	145	152	167	176	162	139	153	139	127
Dishwasher	3	5	4	6	2	7	5	5	4	5	6	5
Clothes Washer	8	9	9	9	10	8	9	10	12	11	12	10
Clothes Dryer	92	98	94	124	75	64	68	83	88	83	85	81
Dehumidifier (EER only)	-	-	-	-	-	-	-	-	-	-	-	-
Lighting and Misc.	223	135	107	113	102	109	118	129	143	162	181	147
Subtotal Appliances	1,066	1,297	969	1,028	851	905	898	934	1,034	1,076	1,205	1,157
Instrumentation Load	17	19	18	19	18	19	19	18	19	18	19	19
TOTAL HOUSE	3,646	2,980	1,526	1,316	1,287	1,615	1,861	1,282	1,357	2,218	3,412	4,231
Hot Water Consumption (Gallons)				1,960	1,620	1,810	1,790	1,870	2,110	1,930	2,430	2,360

*Resistance heat consumption may reflect some cooling power consumption.
**Approximate water heater temperature: 115° F EER House, 150° F Comparison House.

TABLE-2

Date	ACH	Outdoor Temp °F
8/20	.029	80
8/21	.024	66
8/22	.041	77
8/23	.062	74
8/24	.072	82
8/28	.049	80
8/29	.068	78
8/30	.038	90
8/31	.045	88
11/12	.108	45
11/15	.162	46
12/03	.132	38
1/04	.274	25
1/07	.291	36
1/28	.150	29
1/31	.234	21

TABLE 3 - NATURAL VENTILATION AVERAGES FOR DURATION OF TEST

Table 4. Radon concentrations measured in four energy-efficient houses.

Location	Approximate Air Exchange Rate (ach)	Radon Concentration nCi/m^3
Ames, Iowa	0.2	<1
Carroll County, Maryland	0.2	24
Mission Viejo, California	0.4	<1
Northfield, Minnesota	0.1	6[a]

[a] Determined using grab sample analyzed at LBL.

TABLE 5

Besant Heat Exchanger
Unit Efficiencies (E)

	LOW (75 CFM)				MED (151 CFM)				HIGH (190 CFM)			
DATE	SUP	EXH	O.D.	E	SUP	EXH	O.D.	E	SUP	EXH	O.D.	E
10/24									60	68	52	.50
10/26									56	62	48	.57
10/29									57	60	44	.81
11/01									64	65	62	.67
11/19					71	72	65	.86				
11/21					68	69	64	.80				
12/10					63	68	55	.62				
12/13					60	68	45	.65				
12/17					49	62	35	.52				
12/20					49	58	29	.69				
1/24					53	62	18	.80				
1/24					51	65	38	.48				
12/26	65	68	49	.84								
12/28	60	69	42	.67								

Where:

SUP = Supply Air Temp. F°
EXH = Exhaust Air Temp. F°
O.D. = Outdoor Temperature F°
E = Efficiency (%)

ANNUAL HEATING LOAD

Therms

Fuel	Eff %	Mode 1	Mode 2	Mode 3
Gas	.65	101.1	314.4	175.5
Oil	.55	108.6	337.7	188.5
Elect	1.00	79.9	232.9	130.0

Table 6A

ANNUAL HEATING COST

Fuel	Unit Cost	Mode 1	Mode 2	Mode 3
Gas	.38	38.42	119.47	66.69
Oil	.70	76.20	236.39	131.95
Elect	1.76	140.62	409.90	228.80

Table 6B

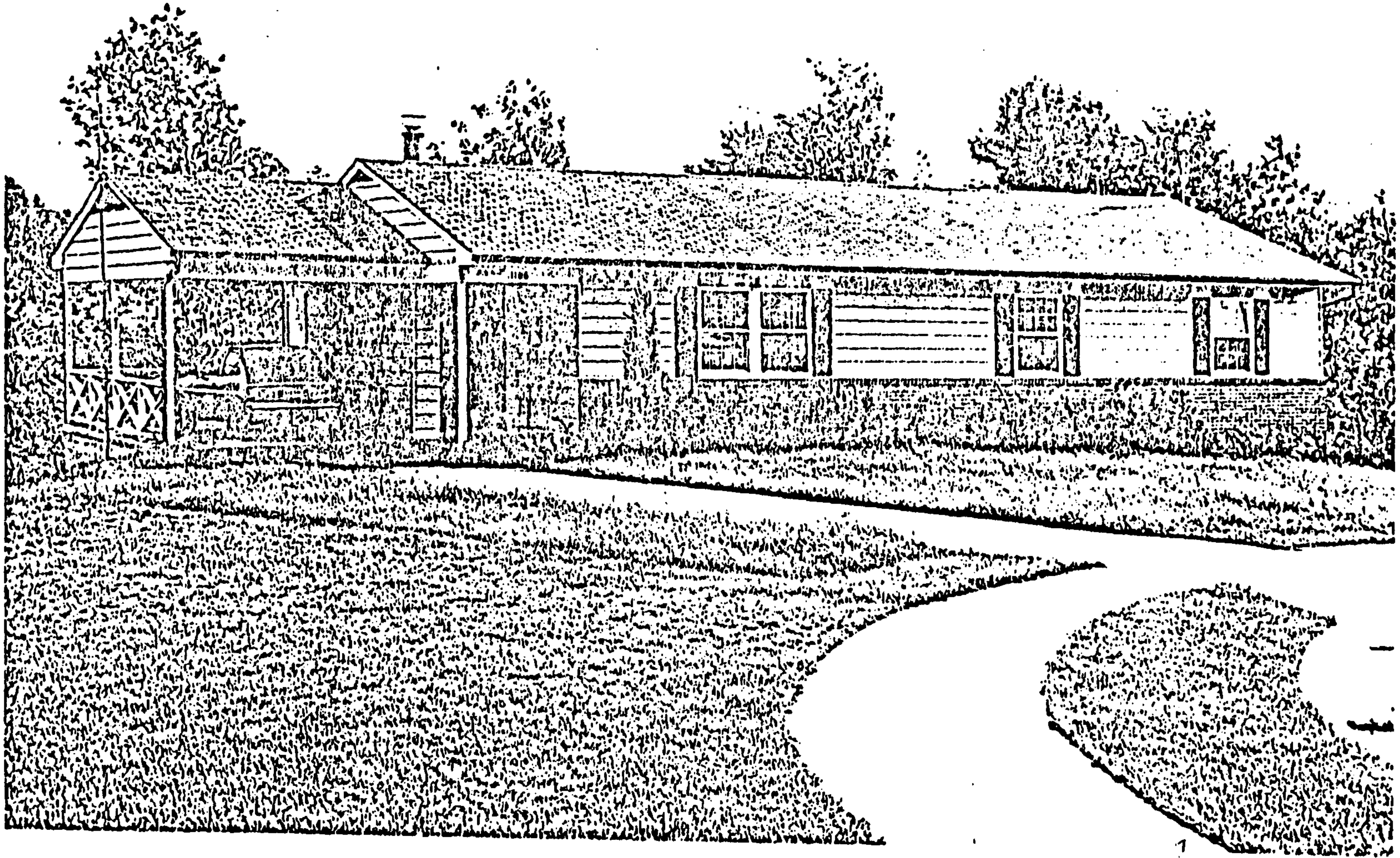


FIGURE 1

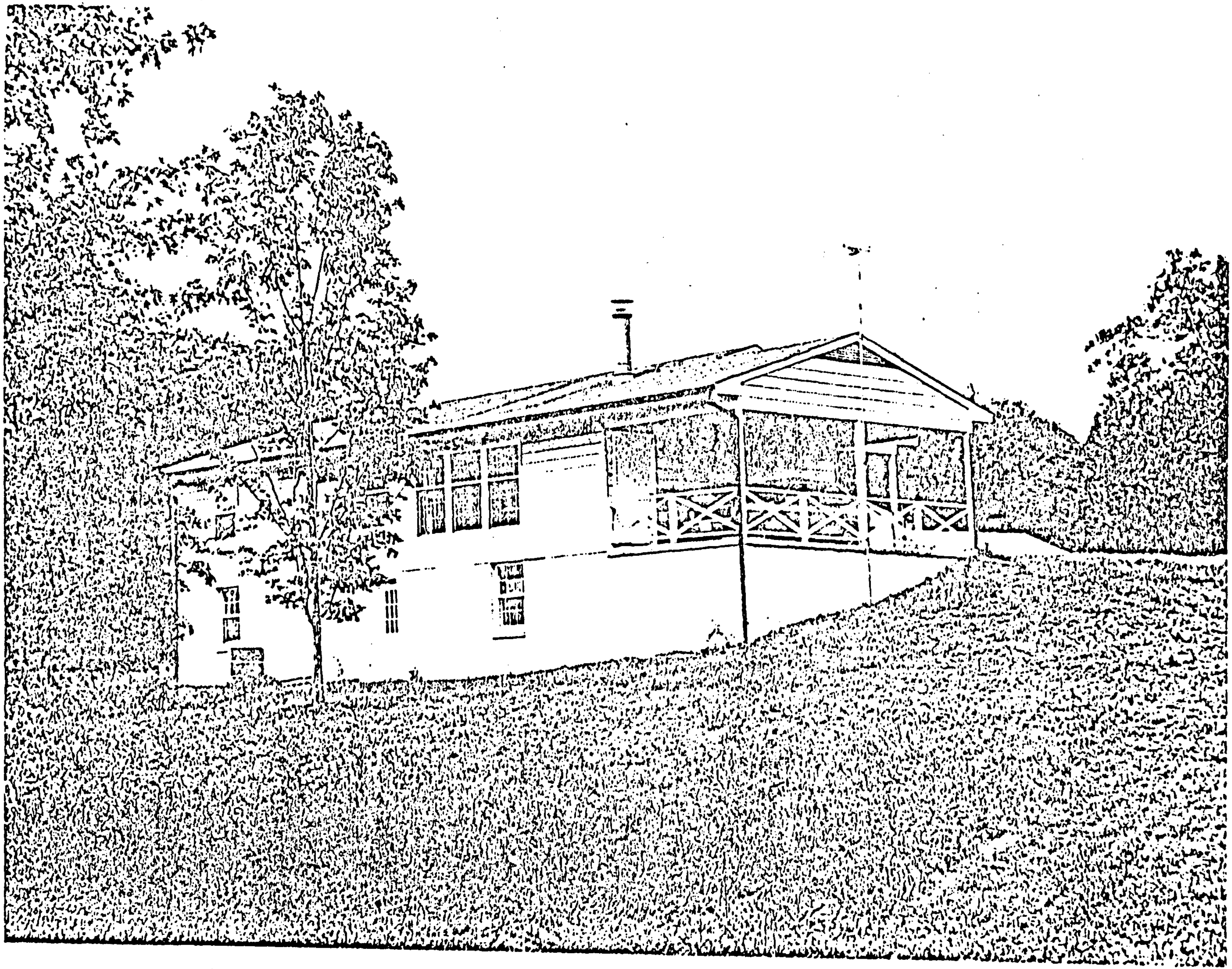
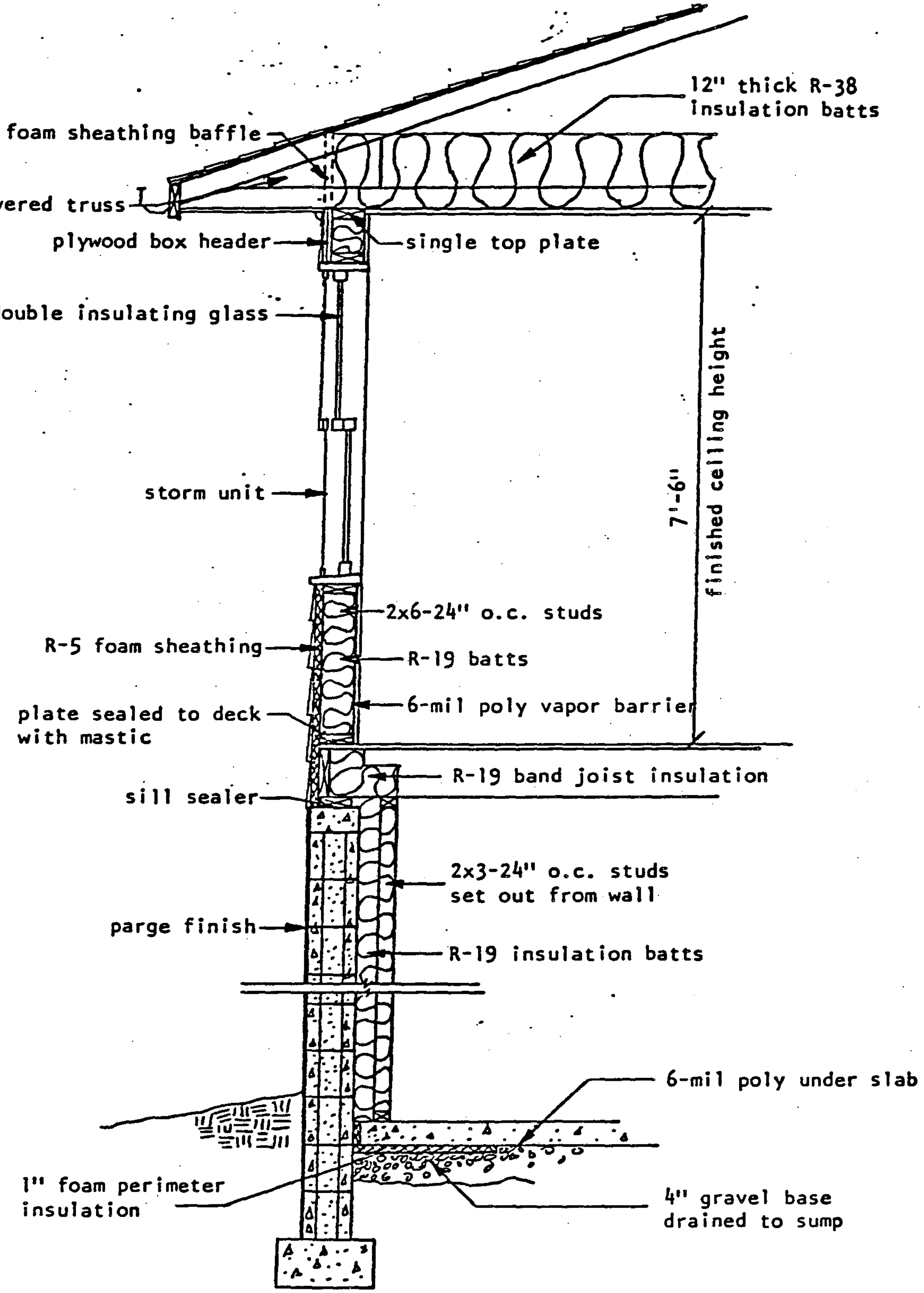


FIGURE 2



EER WALL SECTION

FIGURE 4

HEAT EXCHANGER INSTALLATION

CARROLL COUNTY, MARYLAND

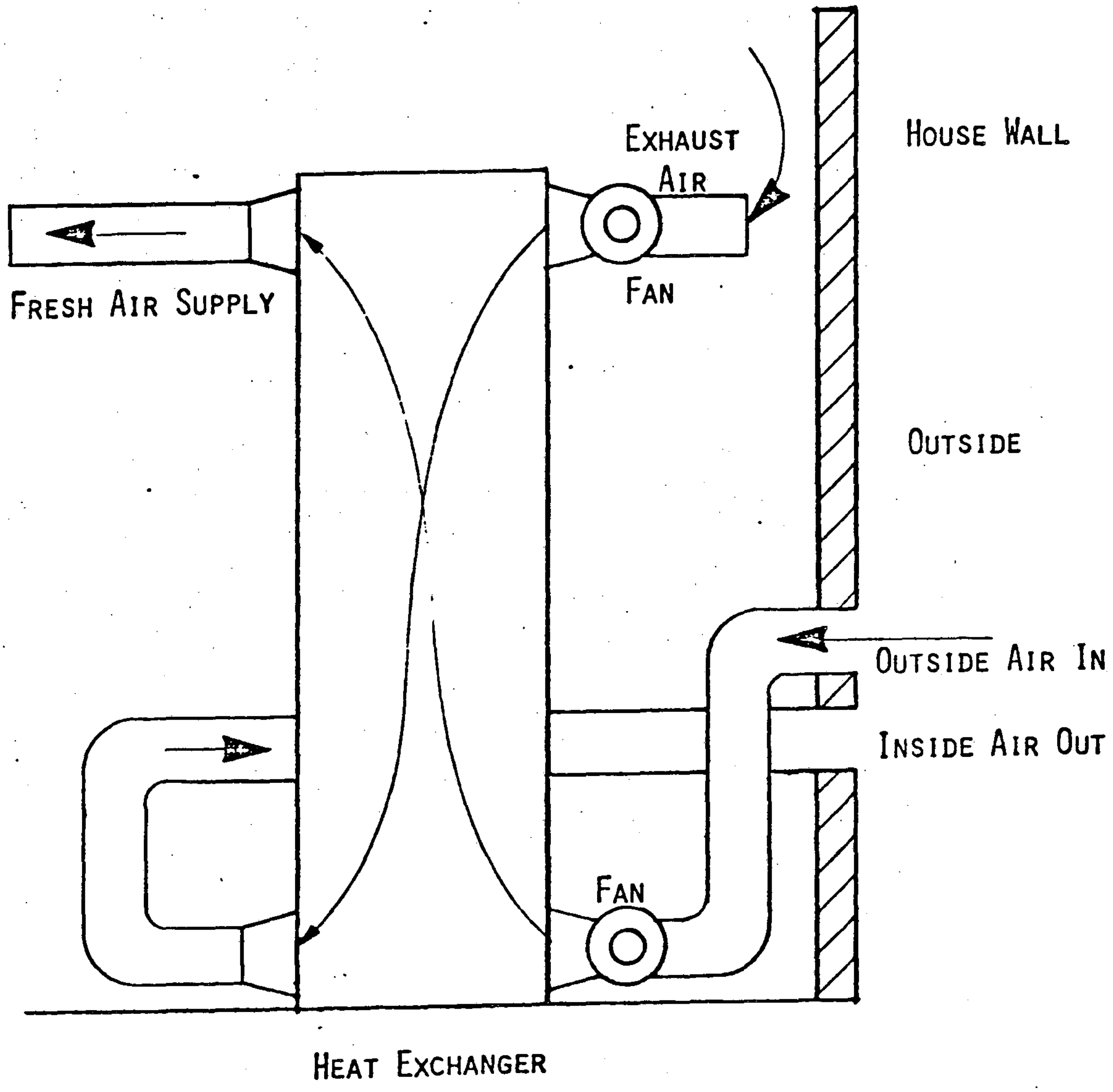
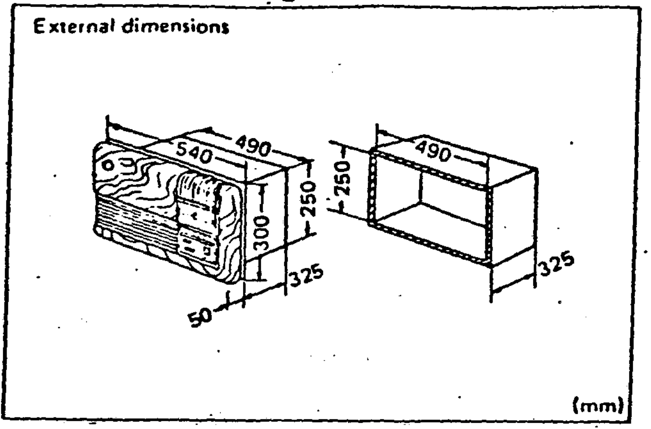


FIGURE 5

XBL 803-8624

Model VL–1500–$\substack{M\\C}$



Characteristics and Performance

Model	Frequency (Hz)	Notch	Power consumption (W)	Air volume (m³/h)	Heat exchange efficiency (%)	Noise (Phon)	Weight (kg) (lbs)
VL-1500	50	High	46	110	72	41	12.0 (26.4)
		Medium	35	90	73	37	
		Low	22	60	75	28	
	60	High	56	71	70	43	
		Medium	40	50	73	36	
		Low	22	28	76	28	

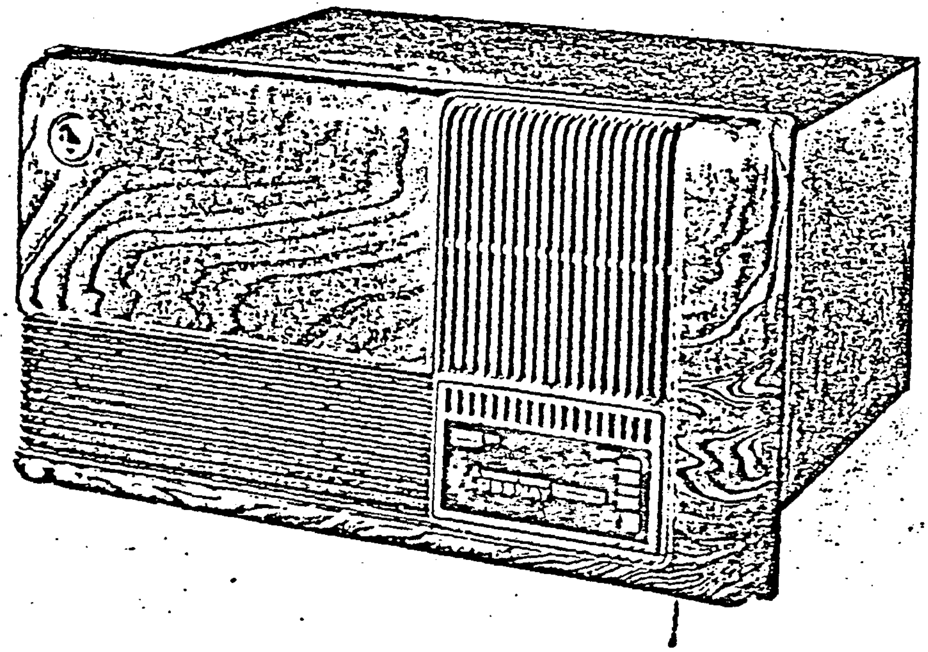


FIGURE 6

VL–1500–M (Wood Panel Type)

1-1 Construction

Lossnay is a cross-flow total heat exchanger constructed of plates and fins made of treated paper. The fresh air and exhaust air passages are totally separated, allowing the fresh air to be preconditioned to the temperature and humidity levels of the room air without mixing with the exhaust air.

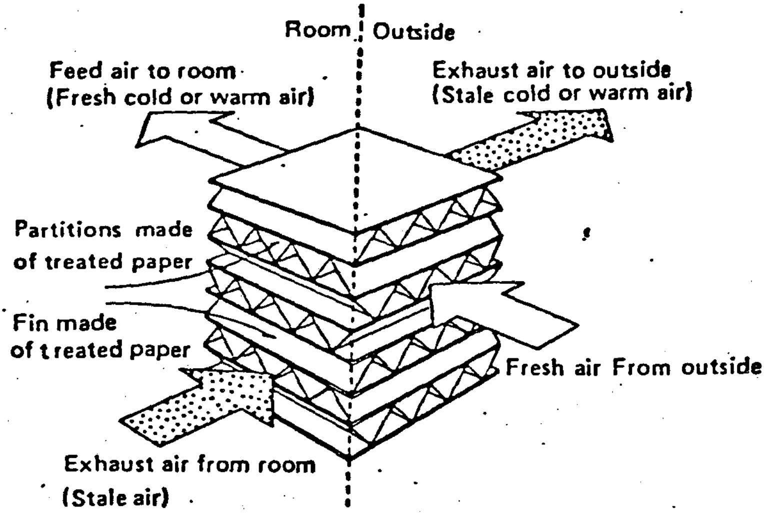


FIGURE 7

VL-1500 - Heat Exchanger Element

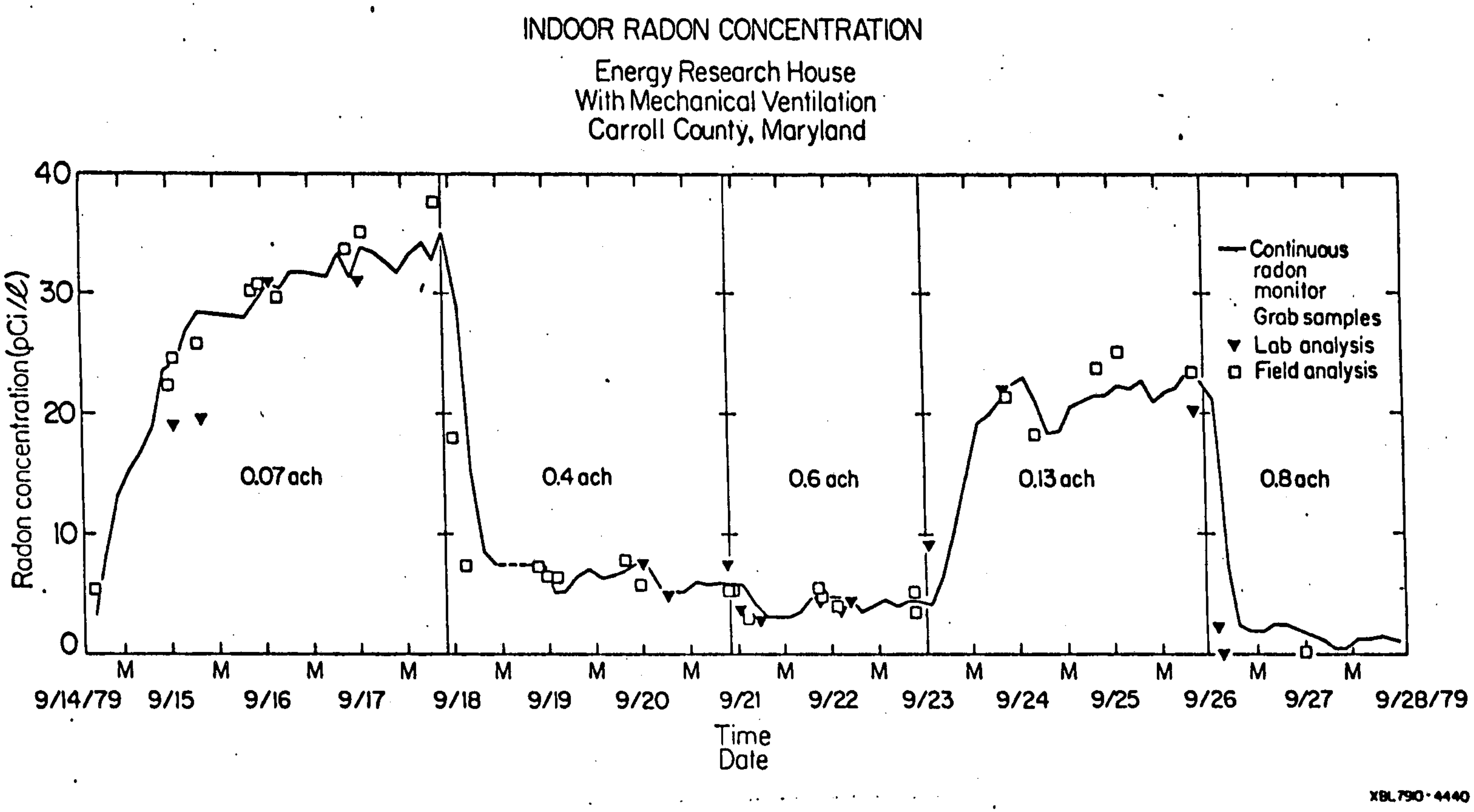

INDOOR RADON CONCENTRATION
Energy Research House
With Mechanical Ventilation
Carroll County, Maryland
Radon concentration (pCi/ℓ)
40
30
20
10
0
0.07 ach
0.4 ach
0.6 ach
0.13 ach
0.8 ach
Continuous radon monitor
Grab samples
▼ Lab analysis
□ Field analysis
M
9/14/79
9/15
9/16
9/17
9/18
9/19
9/20
9/21
9/22
9/23
9/24
9/25
9/26
9/27
9/28/79
Time
Date
XBL 790-4440

FIGURE 8

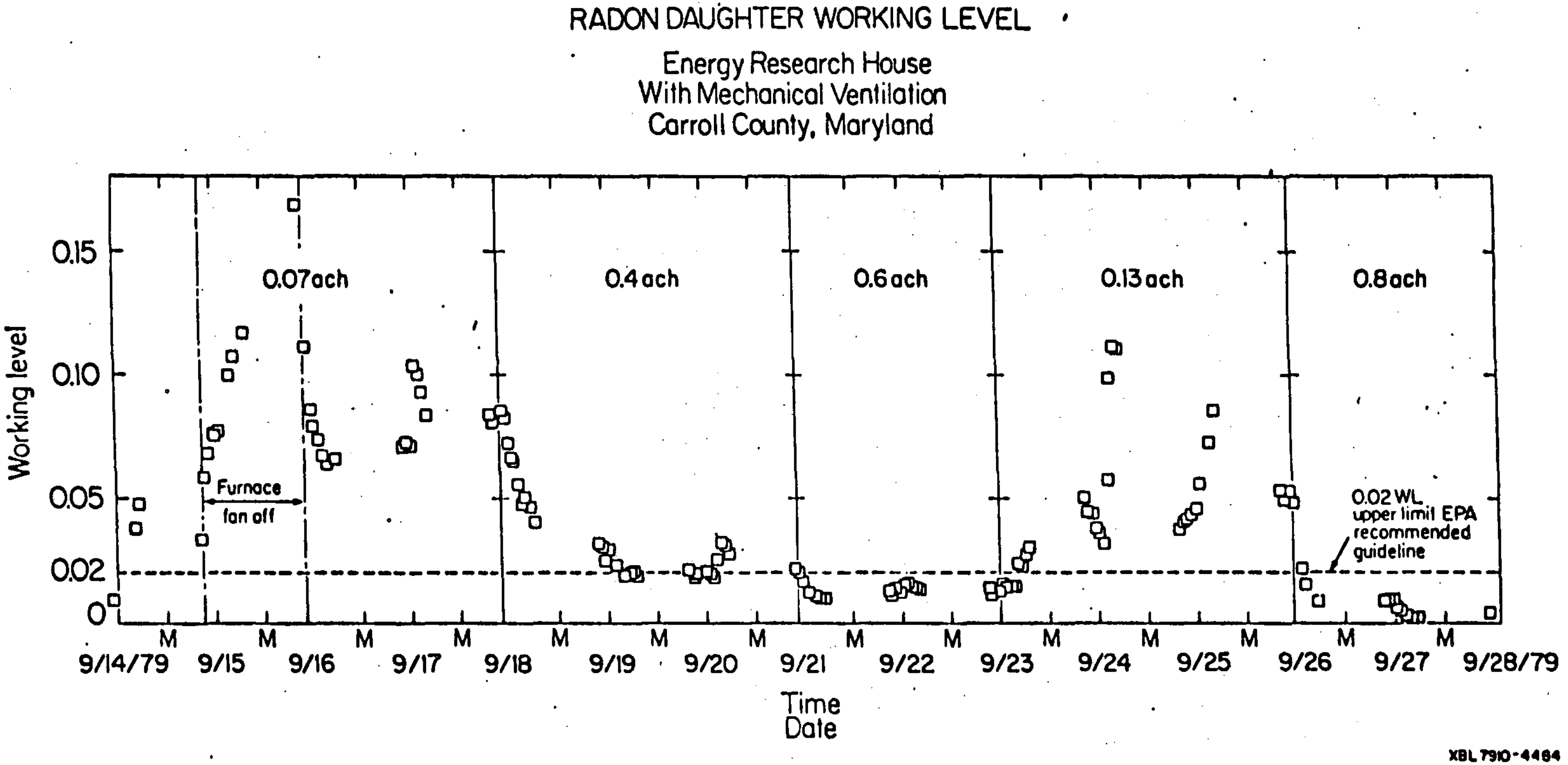
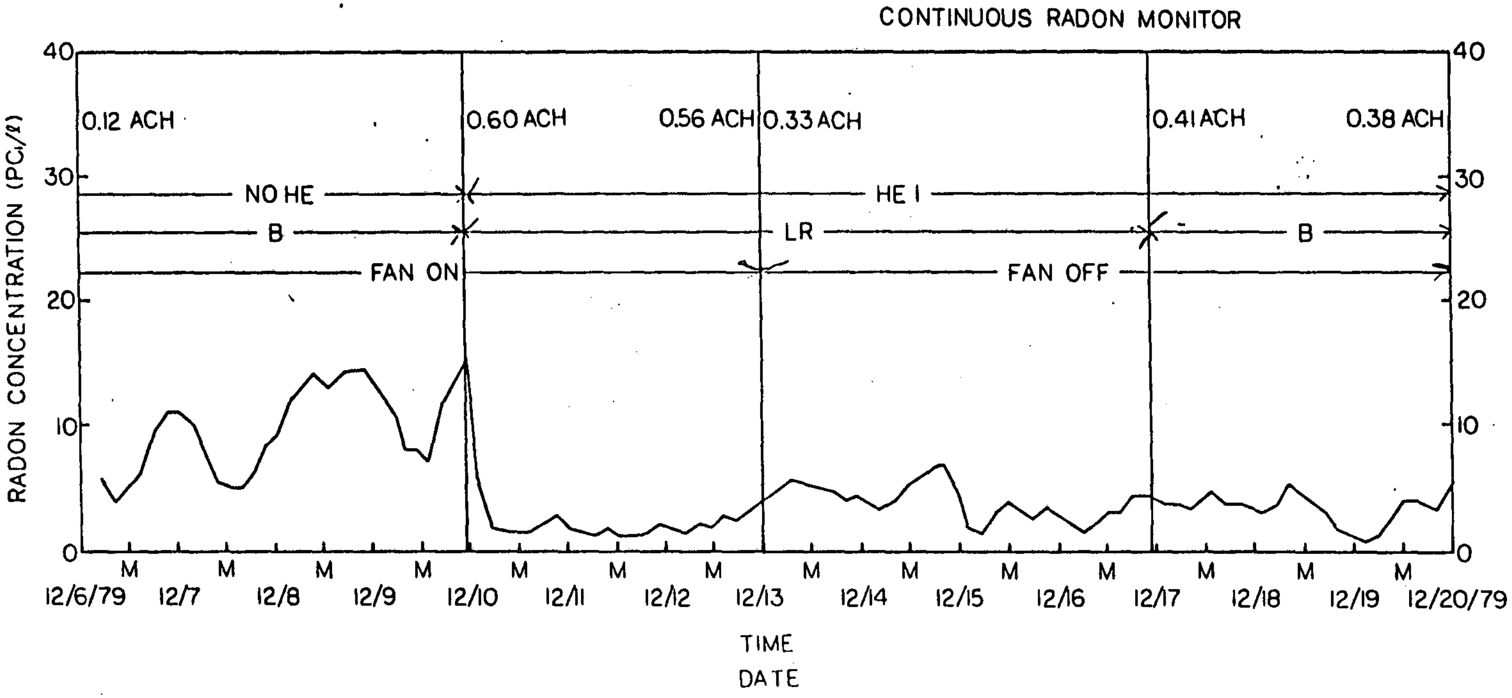
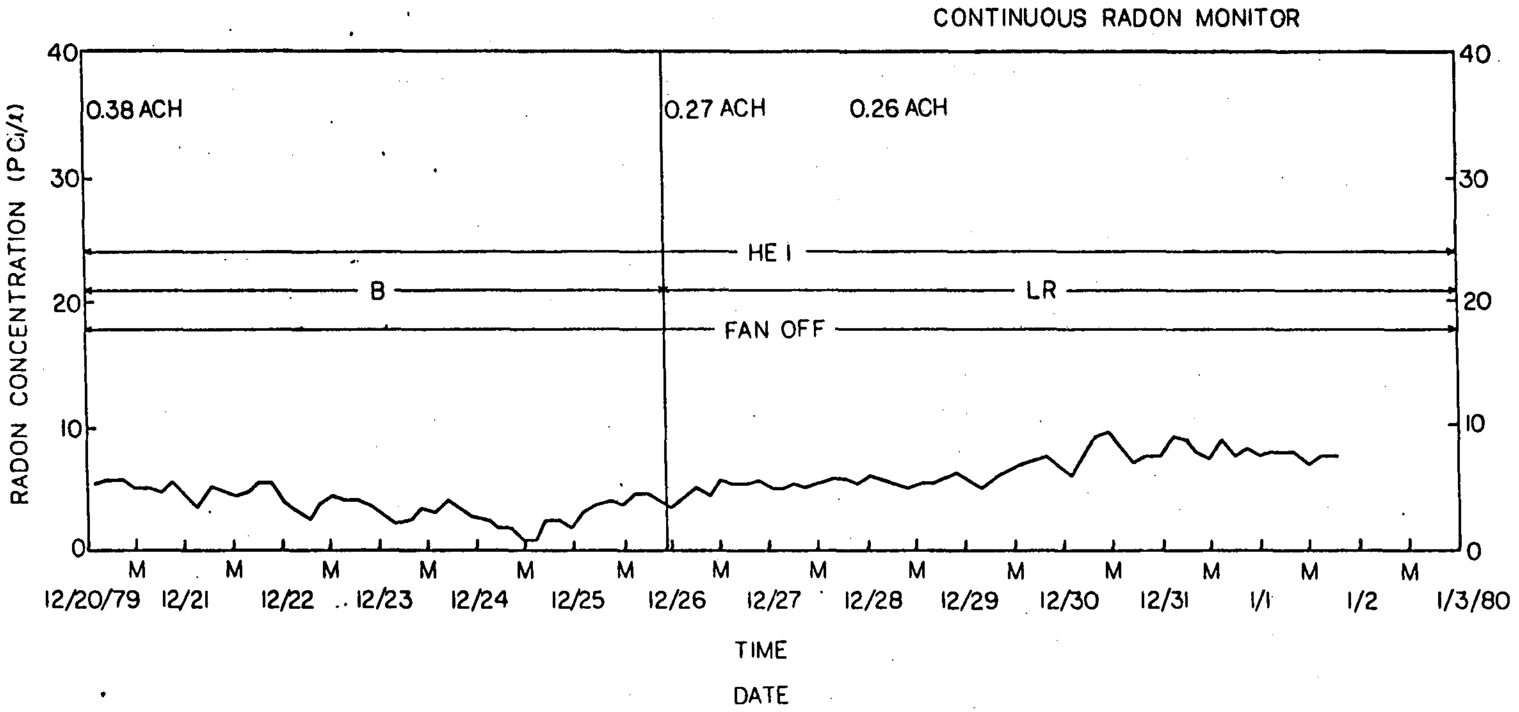

RADON DAUGHTER WORKING LEVEL
Energy Research House
With Mechanical Ventilation
Carroll County, Maryland
Working level
0.15
0.10
0.05
0.02
0
0.07 ach
Furnace fan off
0.4 ach
0.6 ach
0.13 ach
0.8 ach
0.02 WL upper limit EPA recommended guideline
M
9/14/79
9/15
9/16
9/17
9/18
9/19
9/20
9/21
9/22
9/23
9/24
9/25
9/26
9/27
9/28/79
Time
Date
XBL 7910-4484

FIGURE 9



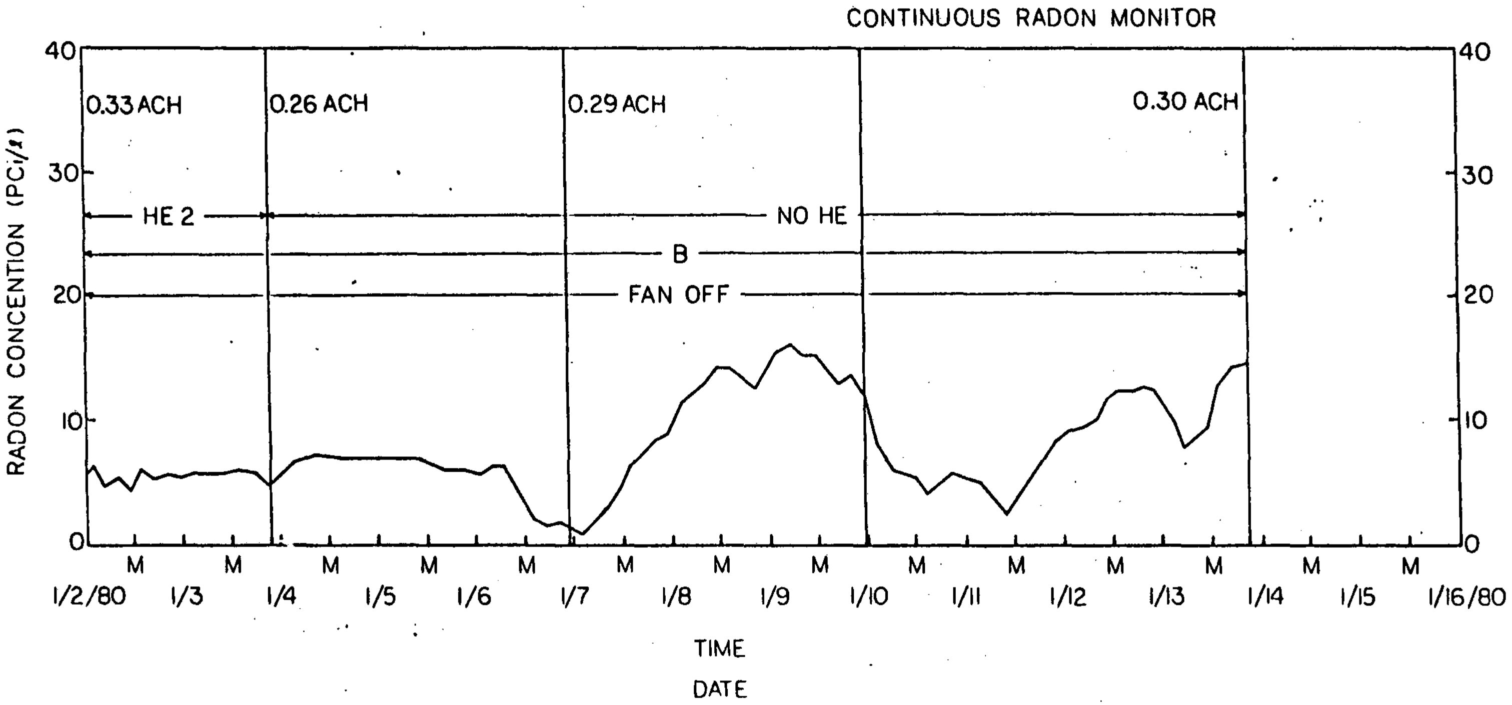
XBL 804-9333

FIGURE 10



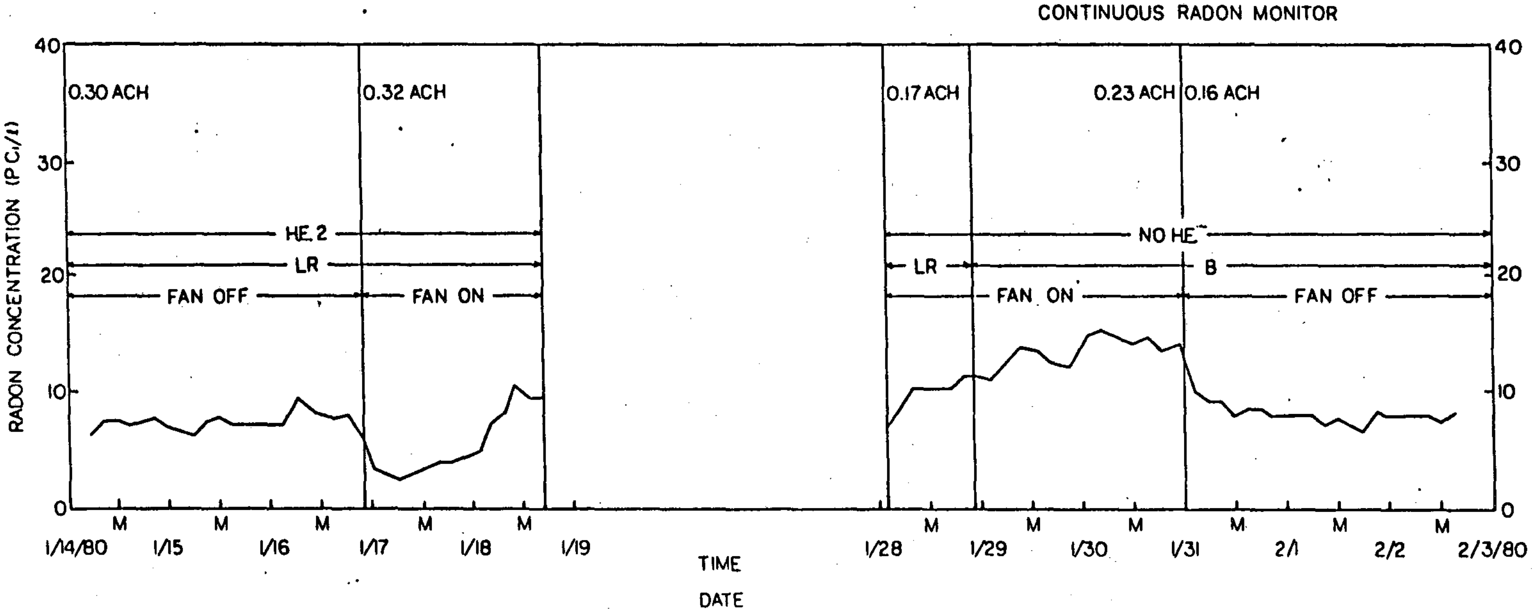
XBL 804-9332

FIGURE 11



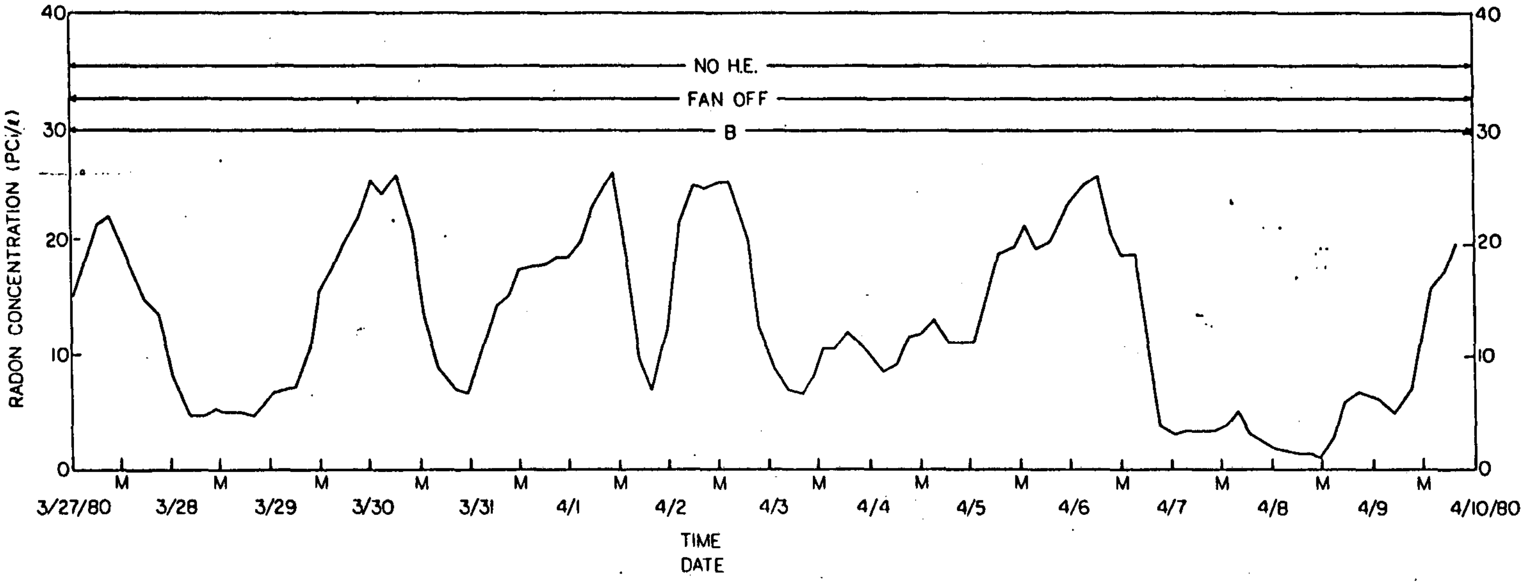
XBL 804-9331

FIGURE 12



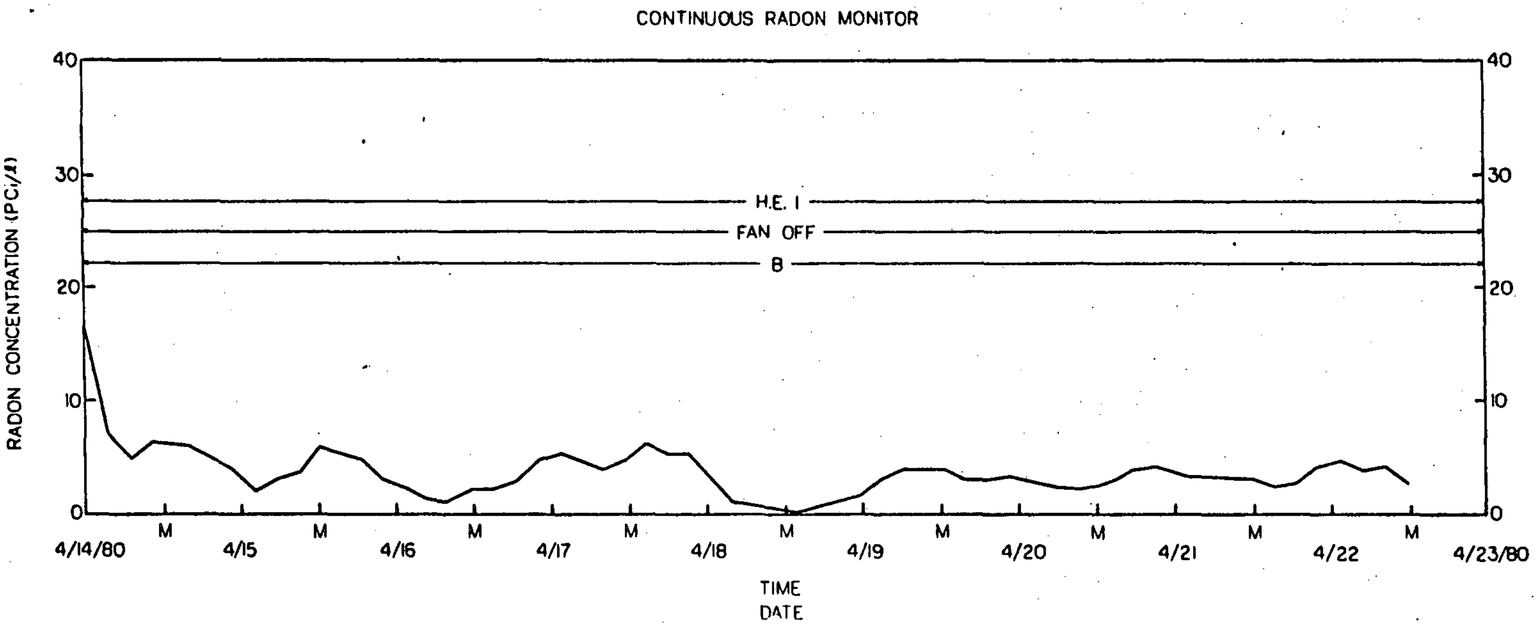
XBL 804-9330

FIGURE 13



XBL 804-9453

FIGURE 14



XBL 804-9454

FIGURE 15

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