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MARTIN MARIETTA

Investigation of Radon Entry and Effectiveness of Mitigation Measures in Seven Houses in New Jersey: Midproject Report

T. G. Matthews
C. S. Dudney
K. P. Monar
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ORNL/TM-10671

Health and Safety Research Division

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Final thanks and recognition go to the study participants for willingness to contribute to this advancement of science.

1. SUMMARY

A detailed radon mitigation study is in progress in 14 homes in the New Jersey Piedmont area. Three research teams, one each from Lawrence Berkeley Laboratory, Oak Ridge National Laboratory, and Princeton University are involved. Seven homes are investigated by Lawrence Berkeley Laboratory. Seven homes are investigated by Oak Ridge National Labs and Princeton University. This intensive, instrumented study is cooperatively funded by the U.S. Environmental Protection Agency, the U.S. Department of Energy, and the New Jersey Department of Environmental Protection. The principal goals are an improved understanding of the physical parameters most important in causing elevated indoor radon levels, the refinement of diagnostic measurements for selection and implementation of mitigation systems, and the reduction of radon concentrations to acceptable levels inside the study houses.

Monitoring stations were installed in each home in October, 1986. Instrumented measurements included (1) basement and upstairs radon, (2) differential pressures across the basement/subslab, basement/upstairs and basement/outdoor interfaces, (3) temperatures at basement, upstairs and outdoor locations, and (4) central air handler usage. A weather station was located at one house, monitoring (1) wind speed and direction, (2) barometric pressure, (3) precipitation, (4) soil temperature, and (5) outdoor temperature and relative humidity. A time-averaged value of all of the above parameters was recorded every 30 min. Several additional parameters were monitored on an intermittent basis in all or selected homes. These include multizone air infiltation rates which have been measured in all homes using passive perfluorocarbon tracers (PFT) and in two homes using a constant concentration tracer gas system (CCTG). Total radon progeny, soil gas radon concentration and permeability characteristics, and gamma radiation levels were also monitored periodically in all study homes.

Pre-mitigation diagnostic measures have been evaluated and refined in all seven ORNL/Princeton study homes. Procedures for measuring and observing building dynamics, building structure, and soil/water characteristics have been streamlined. In these studies, the principal source of indoor radon was

assumed and confirmed to be predominantly convective transport of soil gas into the house substructure. In the general pre-mitigation diagnostics procedure, several 1/2 in. diameter holes were drilled through the basement slab and into basement block walls. Using these holes, radon levels, air pressure differentials and directions of air flows were mapped throughout the substructure under ambient or depressurized conditions. A variable speed vacuum cleaner was used to evaluate potential communication (i.e., air flow) between pertinent subslab and wall locations. The result of applying suction at one subslab location (i.e., a 1.5 in. hole) was observed at the test holes throughout the substructure via measures of pressure differential and air velocity across the subslab and/or wall membranes. Blower door tests of the whole house and basement/crawlspace only (where feasible) provided estimates of building and substructure leakage, respectively, which were useful for consideration of substructure ventilation or pressurization measures. The impact of operation of major appliances (e.g., HVAC, clothes dryer, large exhaust fans) on differential pressures across the basement/subslab, basement/upstairs and basement/outdoor interfaces was examined. Soil gas and permeability measures were performed for research interest but have not been useful for design of mitigation systems.

Mitigation measures were installed in six of seven ORNL/Princeton study homes. Control house mitigation will be completed in July, 1987. The principal technique used was subslab depressurization/ventilation, with suction points located for optimal evacuation of radon-containing soil gas. Air flow communication between subslab and wall regions has been enhanced via sealing of cracks, closure of perimeter drains via backer-rod-suspended caulk (allowing direct basement-wall communication), and painting (i.e., sealing) of porous walls in selected homes. These sealing techniques provide improved radon mitigation with a reduced energy penalty due to removal of less conditioned basement air. Post-mitigation (weekly-average) radon levels in Houses #1, #3, #4, and #7 were consistently less than 1-2 pCi/L in the basement. This corresponds to mitigation efficiencies of typically >95%, considering that the initial basement concentrations (weekly-average) ranged from approximately 25 to 120 pCi/L. Radon in House #5 was reduced to this same level after a subslab ventilation system was installed in late February. The initial mitigation measure in this house was to pressurize the basement.

House #6 radon levels were reduced to an average of 2-4 pCi/L in late spring, after several adjustments in the mitigation system. House #6 provided the greatest difficulty because of a complex substructure, representing several additions to the original home.

Several compilations and preliminary analyses of the experimental data have been initiated and/or completed. All continuously acquired data obtained through April, 1987, have been entered into data management systems for subsequent proofing, conversion to calibrated engineering units, and statistical analysis. Weekly summary data are presented in this report in graphical and tabular form. Field and laboratory calibration data taken through April, 1987, have been summarized. Preliminary data relating radon to selected environmental parameters are presented. For example, heavy rainfall and reduced barometric pressure resulted in temporary 2-3 fold increases in basement radon levels. Initial results of the time-averaged PFT and the continuous CCTG tracer gas techniques are discussed. In one home, for example, the CCTG system quantified a 2-3 fold increase in air infiltration into the basement with operation of the HVAC air-handler, which could then be compared against much smaller (i.e., about 20%) measured decreases in basement radon concentrations. Blower door data and soil permeability data from the fall and winter tests are tabulated. A geological investigation of the region around the test homes and ground water testing for radon are also discussed. Test homes appear to rest on either Martinsburg Shale of Ordivician age, undifferentiated Precambrian gneissoid granites, or the Triassic Brunswick formation. Although homes on the Precambrian granites have among the highest well water concentrations of radon, the well water is only a minor source of indoor radon. The results of periodic measures of soil radon gas and permeability, gamma radiation, respirable particulates and total working level measures is summarized. Data analysis of the seven ORNL/Princeton research homes are ongoing. Additional analyses and data will be presented in the final project report.

2. PROJECT OBJECTIVES AND IMPLEMENTATION

This section provides the study objectives and an overview of the project implementation, including a summary of associated documenation.

2.1 PROJECT OBJECTIVES

The primary objectives of this radon mitigation study are:

1. an improved understanding of the physical processes underlying elevated levels of radon and radon progeny in homes and the impact of control measures on radon entry processes,

2. the field evaluation and refinement of diagnostic protocols for selection and implementation of effective mitigation strategies, and

3. development/refinement of cost effective control measures while systematically reducing radon levels in study houses.

This mid-project report summarizes several of our efforts in achieving these goals. Interim diagnostic protocols used in the selection of mitigation measures and descriptions of implemented mitigation measures are reported. Monitoring and diagnostic instrumentation packages in use in the study homes are described. Preliminary results from continuous monitoring packages in pre-mitigation, mitigation, and post-mitigation time periods are reported, including extensive summary statistics. Non-continuous measures including house and site characterizations, and laboratory and field calibration data are summarized. The flow and documentation of experimental results between the ORNL/Princeton team and sponsors, homeowners, and LBL are reviewed.

2.2 PROJECT IMPLEMENTATION

2.2.1 House Selection

House screening and final selection were completed by August, 1986. LBL and the New Jersey Department of Environmental Protection were responsible for developing the data base of homes from which the final study houses were chosen.

2.2.2 Development and Installation of Instrumentation Packages

The development of instrumentation packages for the New Jersey Piedmont studies was initiated by ORNL and Princeton researchers in August, 1986. Calibration of the instrument packages and installation in the seven study homes by the ORNL/Princeton team were largely completed by mid-October, 1986.

2.2.3 Initial (Fall) Pre-mitigation Monitoring Phase

Near-continuous, pre-mitigation baseline monitoring of all study homes was conducted from mid-October to about mid-December, 1986. The exact period depended on house-specific differences in the start of pre-mitigation diagnostics and mitigation installation.

2.2.4 Pre-mitigation Diagnostics

Pre-mitigation diagnostic measurements to characterize the entry of and potential control measures for radon were performed between mid-November and the end of December, 1986. Diagnostic measures continued in selected homes through the winter and spring of 1987 to improve mitigation efficiency. A discussion of diagnostic procedures and instrumentation is given in Sections 3 and 4.

2.2.5 Mitigation Selection and Implementation

The selection and implementation of mitigation measures in the study homes were commonly divided into two major phases. Phase I mitigation measures were installed principally between mid-December and mid-January. Evaluation and refinement of these mitigation measures occurred principally during January and February, 1987. Phase II mitigation measures were installed and refined over a period of time spanning from January through May, 1987. Most of this work was performed in Houses #1, #5 and #6 where two or more mitigation approaches were used. Phase I and II mitigation measures are discussed in Section 5.

2.2.6 Control House Studies

The control house (i.e., House #2) will be mitigated on July 22, 1987. The extended pre-mitigation data set provides for interhouse comparisons and the potential for inter-season (e.g., fall vs winter vs spring) modeling.

2.3 PROJECT DOCUMENTATION

The proposal, planning, implementation and reporting of this project have involved an extensive flow of documents between the ORNL/Princeton team, LBL, homeowners, and the sponsoring agencies. The status of this documentation is briefly summarized in this section.

2.3.1 Proposals

A research proposal entitled "Investigation of Radon Entry And Effectiveness of Mitigation Measures", prepared by ORNL, outlining the scope of research activities to be conducted in New Jersey and the Tennessee Valley in FY87-88, has been approved by the U.S. Environmental Protection Agency, U.S. Department of Energy and the Tennessee Valley Authority.

2.3.2 Subcontractual Agreement with Princeton University

A project work statement, detailing collaborative research with Princeton University in the study of seven houses in New Jersey was approved as the basis for a subcontractual agreement between Martin Marietta Energy Systems, Inc., and Princeton University.

2.3.3 Project Workplan

A project workplan detailing the technical design and objectives of the radon-mitigation research in seven New Jersey houses has been approved by EPA. This document was based on a detailed outline that was discussed by Princeton University, ORNL, and EPA at a meeting in Research Triangle Park on 8/12/86. The Project Workplan follows the general outline of the draft LBL Project Plan.

2.3.4 Project Quality Assurance/Quality Control Plan

A draft Category III QA/QC Plan has tentatively been approved by EPA. Minor changes resulting from independent reviews of the plan are being adopted. The QA/QC Plan for the ORNL/Princeton team incorporates several elements of the LBL QA/QC Plan. The plan also emphasizes pertinent differences between the LBL and ORNL/Princeton research efforts.

2.3.5 Agreements Between ORNL and the Homeowners

Homeowner agreements between ORNL and study participants have been signed and approved. These agreements discuss conditions of entry into the homes, the monitoring of radon and pertinent parameters both inside the homes and on the property, and the anonymity of homeowner identity in future publication of study results.

2.3.6 House Specific Mitigation Plans

Mitigation plans for each study house were written for approval by ORNL/Princeton and LBL teams, the sponsoring agencies, and the homeowner. The plans consisted of a two-page description and houseplan of the proposed mitigation activity. These plans are presented in Section 5 and Appendix 9.B. In addition, the homeowner and mitigation contractors were given a description of the mitigation plan by Princeton researchers during a house walk-through before mitigation began.

2.3.7 Monthly Reporting

Letter reports detailing previous month accomplishments, project problems and solutions, and plans for future work have been submitted to sponsoring agencies on a monthly basis. Trip reports have been separately submitted.

3. PROJECT INSTRUMENTATION PACKAGES AND MATERIALS

This section summarizes the instrumentation and monitoring packages in use in the ORNL/Princeton radon mitigation studies.

3.1 INDOOR MONITORING STATION

The indoor and weather station monitoring packages currently in use are listed in Tables 3.1 and 3.2, respectively. These packages are quite similar to those outlined in the Project Workplan.

3.2 WEATHER STATION

Only one weather station was operated (House #5) due to budgetary constraints. As a consequence, detailed modeling of the impact of variation in meteorological parameters will be limited to House #5. Under routine operation, data from the weather station data logger is downloaded via the indoor modem.

3.3 MITIGATION DIAGNOSTICS INSTRUMENTATION

The following is a list of the instrumentation and special tools used by Princeton University staff in pre- and post-mitigation diagnostics. The list includes the product name, specifications, cost, and a short description of the use of each of the instruments. The soil permeameter is described in Section 3.7.

3.3.1 Instrumentation

3.3.1.1 Dwyer Microtector Electronic Point Gage ($365)

This instrument is used to calibrate pressure transducers and to measure small pressure differentials in a range of 0 to 2.0 in. water and is accurate to ±0.00025 in water column. It is accurate but can be difficult to use in

most radon testing field operations such as differential pressure measurements because of normal pressure fluctuations.

3.3.1.2 Neotronics EDM Electronic Digital Micromanometer Model EDM-1. ($1350)

This instrument is used to measure differential pressures, static pressures, velocities (with pitot-static tube) and to balance mitigation systems. Its range is 1-1999 Pa or 1-19.99 in water column. It is an expensive but accurate and reliable instrument with a fast response time. It should not be stored in temperatures less than 0°C as significant drift will occur as the instrument warms up.

3.3.1.3 Solomat Model MPM 2000/1000/500 with Modumeter 2013 ($1500)

This instrument is a combination digital thermometer, RH meter, and anemometer. Our instrument included Solomat Type K and Pt 100 temperature probes, Type 355 RH PT 100 and fast response RH sensor, and Type 128MS hot wire anemometer. It is used to measure indoor and outdoor environmental conditions, velocities in mitigation systems and test holes, etc. It is an expensive but versatile instrument with several applications. The hot wire anemometer should be handled with care; it breaks easily.

3.3.1.4 EDA RDA-200 radon detector with scintillator cells ($7500 with 20 cells)

This instrument is a field portable radon detector with linear response over a wide range of radon concentrations. It is used for evaluating grab samples to locate radon hot spots. It is expensive but useful for mapping radon concentrations under slab, in hollow block walls, in cracks and sumps, and in soil gas.

3.3.1.5 Princeton Blower Door ($3000)

This instrument is used to pressurize and depressurize buildings from 0 to 75 Pa with flows of up to 3000 cfm to determine building leakiness. It can also

be used to maintain a constant depressurization of the basement (to simulate winter conditions) while other diagnostic measurements are being performed.

3.3.2 Special Tools

3.3.2.1 Skil Model 732 ROTO-set hammer drills ($500)

This tool is used to drill test holes in soil, concrete or block walls and concrete slabs or floors. It accomodates drill sizes up to 1.5 in. diameter. It has very fast drilling capabilities.

3.3.2.2 Dayton Model 4Z664A industrial vacuum cleaner ($105)

This device is used while drilling holes in basements and crawlspaces. It is also used as a diagnostic tool in combination with pressure and velocity measuring instrumentation to check subslab and or wall communications.

3.4 MITIGATION MATERIALS

The following is a list of the materials used for sealing cracks, holes, and perimeter drains and for the installed subslab and wall ventilation systems.

3.4.1 Sealants

1. Geocel Construction 1200 high grade siliconized clear-acrylic caulk was used for temporary sealing purposes ($2.00 per 10 oz tube). It has a water based solvent and is non-toxic. It withstands plus or minus 12.5% joint movement and has an installed lifetime of 20 years.

2. Geocel Construction 2000 copolymer caulk ($2.50 per 11 oz tube). This is a high stretch, self-healing caulk. During curing, over exposure to solvent fumes may cause nausea, headache, and fatigue, so adequate ventilation must be supplied. It is not recommended for use in living areas of homes and has an installed lifetime 20 years.

3. Geocel SPEC 3000 single component urethane sealant ($3.00 per 11 oz tube). This sealant cures to high-grade urethane rubber with excellent adhesion. As with most of these products, skin irritation can occur and pulmonary sensitization may occur in some individuals leading to asthmatic spasms. Respirators with organic vapor cartridges should be used. If significant quantities are being installed, local exhaust should be used to prevent accumulation of fumes. Use indoors should be limited.

4. Vulken one part flowable urethane sealant ($10.00 per quart tube). This sealant is used to seal cracks and as the sealant over various perimeter drain mitigation systems. It has excellent self leveling characteristics and adheres well to surfaces. Data on solvent exposure has not arrived from manufacturer, but hazards are probably similar to SPEC 3000 and same cautions should apply.

5. Tremco THC-900 two part flowable urethane sealant ($49.10 per 1.5 gallon). This sealant is used in some applications as Vulken sealant. This material may be mixed before application. It can be applied with a bulk caulking gun or poured into place. The unit cost is about 20 percent less than quart cartridges but careful calculations of required material must be done because once mixed, the material has only a two hour pot life. A coloring agent must be mixed with the material, which allows matching surface coloration. Hazards bulletins have not arrived from manufacturer, but product hazards are probably similar to SPEC 3000.

6. Polycel One expanding foam sealant ($5.00 per lb. in 16 lb tanks). This sealant is used to fill holes and openings with diameters ≤ 3 in. It must not be left exposed in living space because of flammability. It has excellent adhesion and void filling characteristics.

Other Materials

1. Backer rod. This is a closed cell foam rod available in diameters from 1/4 in. to 2 1/2 in. It is used to fill large cracks or to close off perimeter drains before applying flowable urethanes or other sealing materials.

2. Pipes. 4 in. sewer and drain (S and D) pipe with associated elbows and tee's were used for radon mitigation primarily because they are commonly available, inexpensive, and, therefore, readily available to the public. Where more structural strength was needed, 4 in. PVC pipe was used. The pipes were fitted with adjustable dampers in all the main lines.

3. Fans. Kanalflakt (6 in) centrifugal duct fans ($110) were used. The plastic T2 fans were installed in Houses #1, #3, and #7 and metal K6 fans were installed in Houses #4, #5, and #6. We have found that the plastic fan gave higher air flows in 4 in. pipe than the metal fans, more closely approximating the Kanalflakt specification of 200 cfm at approximately 100 Pa static pressure in 6 in. pipe.

3.5 CONSTANT CONCENTRATION TRACER GAS SYSTEM

The constant concentration tracer gas (CCTG) system is used to measure infiltration rates into multiple zones inside buildings. The method consists of injecting a required amount of the tracer gas (SF6) into each monitored zone to maintain a target concentration (i.e., about 100 ppb) in all the zones. By keeping the concentration constant, the air infiltration rate into each zone is simply equal to the tracer injection rate for the zone divided by the target concentration. The constant concentration method has the advantage of providing a continuous measure of infiltration flow rates in a multizone building using only one tracer gas. The number of zones is only limited by the length of time needed to read a sample and the capabilities of the sample and injection systems. While the CCTG system normally measures infiltration

rates, intermittent measurements of certain interzone rates are possible by discontinuing injection in selected zones.

In order to maintain the target concentration of tracer gas in each monitored zone, the CCTG system measures the tracer gas concentration, calculates the amount of tracer needed for each zone, and then injects the required amount of tracer gas. The CCTG system consists of an electron capture gas chromatograph, a series of ten sample and injection lines, valve control electronics, and a microcomputer-based data acquisition system. For steady-state operation the system runs on a 60 second cycle during which time the following procedures take place:

1) The concentration of a single zone is measured.
2) The sample valve of the next zone is opened.
3) The estimated concentration, infiltration rate, and injection rate are computed.
4) This new information is displayed on the monitor and saved to disk.
5) Tracer gas is injected into all the zones.

The concentration measurement takes approximately 30 seconds to complete (note: the most recent version of the CCTG system operates with the reduced measurement and cycle times of 10 and 30 seconds). Injection begins at the start of the cycle and can continue until the last half second of the cycle. The injection is followed by procedures (2) - (4), which require a few tenths of a second.

After the cycle is complete the system repeats the procedures on the next zone. When the procedures have been performed on all the zones the process begins again at the first zone. Thus, the length of time between samples in a zone is equal to the product of the cycle time (one minute) and the number of zones. It is important to note that, instead of performing only a single injection in a zone between samples of the zone, the system performs an injection into every zone during each 60 second cycle. This method more closely approximates constant injection. At the end of each hour of operation the average concentration, rms deviation in the concentration from the target,

and the estimated average infiltration rate are stored to a disk file. Recent modifications to the system allow the user to interactively graph this data on the screen or access the data via modem communications from a remote location while continuing the normal operation of the system. In addition, the system records hourly measures of the concentration of a reference tank to adjust for the drift of the gas chromatograph.

3.6 PERFLUOROCARBON TRACER GAS SYSTEM

The perfluorocarbon tracer (PFT) gas system measures average air flow rates in multizone buildings. This technique measures both infiltration and interzone air flow rates using passive sources and samplers. The governing equation for the level of concentration of a tracer gas (TG) in a single well-mixed zone is given by:

$$V \cdot dC/dt = S - F \cdot C$$

where:

V = volume of the zone (liters,L)

C = concentration of the Tracer Gas (nL/L)

F = infiltration rate (L/h)

S = tracer gas emission rate (nL/h)

For typical PFT measurements (i.e. testing periods over a couple of days) the derivative term becomes small compared to the right hand side of the equation and S is approximately constant. Thus, the average infiltration rate is approximately equal to the product of the source emission rate and the integral of the inverse of the concentration.

$$\overline{F} \cong (S/\Delta t) * C^{-1} dt$$

For typical winter time situations when large variations due to window openings are not common, the integral of the inverse of the concentration is well approximated by the inverse of the average concentration multiplied by the sample time.

$$\int (1/C)dt \cong \Delta t/\bar{C}$$

Note that this approximation does result in a biased low estimate of the infiltration rate. The degree of the error is dependent on the relative magnitude of the infiltration rate fluctuation. With these approximations the air infiltration rate is equal to the tracer gas emission rate divided by the average concentration.

The tracer gas source is provided by liquid TG contained in a bullet-sized, metal canister that diffuses through the rubber cap of the canister. The diffusion rate is independent of time but exhibits a strong temperature change of 4-5% per degree Celcius. The emission rate is adjusted from its calibrated rate at a standard temperature using the measured average temperature of the zone. The average concentration of the TG is measured indirectly using a small glass tube containing carbon (Ambersorb) pellets. During sampling, one end of the glass tube is left open and the other closed. The TG in the air slowly diffuses into the tube and is trapped by the carbon pellets. At the end of the sample period, the open end of the the glass tube is capped and the tube brought back to the lab. The TG trapped on the carbon is released by heating the tube and the volume of the TG is measured by gas chromatography. The average concentration of the TG during the sample period is computed from the measured volume of TG, the diffusion rate, and the sample time.

For multi-zone measurements, a different type of TG source is placed in each zone. The governing equation for each TG in each zone is established by considering the convective movement of the tracer gases between the zones and to the outside with the derivative term again assumed to be insignificant. Using these equations, those for the conservation of flow into and out of the zones, and the measured concentration and source rate of the tracers, the infiltration, exfiltration, and interzone air flow rates for each zone are computed. For example, the following equations are for air flows in a two-zone building.

$$F10 = (S1C22 - S2C12)/D$$
$$F12 = S2C12/D$$

$$F_{20} = (S_1C_{11} - S_1C_{21})/D$$
$$F_{21} = S_1C_{21}/D$$
$$F_{01} = S_1(C_{22} - C_{21})/D$$
$$F_{02} = S_2(C_{11} - C_{12})/D$$

where:

F_{ij} = air flow from zone i to zone j,
C_{ij} = average concentrations of TG_i in zone j,
S_i = TG emission rate of TG_i,
0 = outside,
1 = basement,
2 = main floor,
$D = C_{11}C_{22} - C_{12}C_{21}$

The Princeton radon group presently has the capability of using three perfluorocarbon tracer gases [perfluoromethylcyclopentane (PMCP), perfluoromethylcyclohexane (PMCH), and perfluorodimethylcyclohexane (PDCH)]. The equipment has been installed so that each of the seven test houses has an emitter for approximately every 50 cubic meters of volume. PMCH is placed in the basement, PDCH on the first floor, and PMCP on the second floor (if there is one). House #6 is the exception to this arrangement. In this house, the basement, crawlspace, and above ground living space are considered to be three separate zones. There are a minimum of two samplers in each zone and, in addition, each house has one replicate and blank. The sampling is usually performed over two week periods.

3.7 SOIL PERMEABILITY MEASUREMENT DEVICE

The following lists the components of the soil permeameter and its operation. Figure 3.1 displays a simple schematic of the soil permeameter.

3.7.1 Components

1. No. 3 Cylinder of Dry Air.
2. Matheson model 8-590 regulator.

3. Circle Seal model no. MV 92T1-1PP micrometer needle control valve.

4. Flowmeters.

   a. Porter Flowmeter model PNB-125-10A with 1 glass and 1 stainless steel float.
   b. Porter Flowmeter model PNB-125-30 with 1 glass and 1 stainless steel float.
   c. Porter Flowmeter model PNB-125-40 with 1 stainless steel and 1 tantalum float.
   d. Gilmont Instrument Co. model PNF 3060 shielded microflowmeter with PNF 3080A static eliminator and synthetic ruby float.

5. Dwyer Instruments Magnehelic Differential Pressure Gauges.

   a. Model no. 2000-60; 0-60 Pa.
   b. Model no. 2000-125; 0-125 Pa.
   c. Model no. 2000-500; 0-500 Pa.

3.7.2 Operation of Permeameter

The following outlines the procedure used in this study for measuring soil permeability. Calculations and experimental results are presented in Section 6. The 47 in. long pipes were left in the ground and capped for the duration of the field work. These pipes were used both for soil permeability measurements and soil gas grab samples.

1. Drill a 47 in. hole using a rotary hammer drill and a 5 ft, modified, 0.5 in. diameter concrete drill. Check soil characteristics on drill bit at removal.

2. Insert a 47 in., 0.25 in. galvanized pipe 41 in. into hole using a 53 in. hammer shaft inside pipe. This leaves 6. in space open beneath end of pipe. (Protect the threaded end of pipe with a pipe coupling.)

3. Remove the pipe coupling and install a 0.25 in. pipe tee.

4. Connect the regulator to the air cylinder and the line between regulator and flow control valve on permeameter panel. Open air cylinder and adjust regulator to about 15 psig.

5. Choose a flowmeter and connect the line from control valve to the inlet of the flowmeter. Connect the outlet of flowmeter to one leg of the tee on the pipe and connect other leg of the tee to a 0-500 Pa gauge (see schematic).

6. Adjust the control valve to achieve 250 Pa and read the flow on the flowmeter. Repeat 2 times. Repeat these measures for 50 and 10 Pa conditions.

Table 3.1. Typical Indoor Monitoring Package

Parameter	Monitor	Location(s)	No. Sites
Modem	Hayes 1200	Basement	1
Data Logger	Campbell Scien. 21X	Basement	1
Radon	Wrenn Chamber	Upstairs, Basement (Crawlspace)	2-3
Total Progeny	Eberline WLM-1 (intermittent)	Upstairs	0-1
Differential Pressure	SETRA 261-1	Basement-Subslab[a]	1-2
		Basement-Upstairs[b]	1
		Basement-Outdoor[c]	1
Temperature	RTD Probe	Upstairs	1
		Outdoors	1
		Basement	1
Rel. Humidity	Electronic	Basement	1
Soil Moisture	Conductivity Block	Outdoor Soil[d]	1

[a] Typically manifolded to 2 subslab locations

[b] Typically manifolded to 2 upstairs locations

[c] Typically manifolded to 4 outdoor locations, one on each side of the house near ground level.

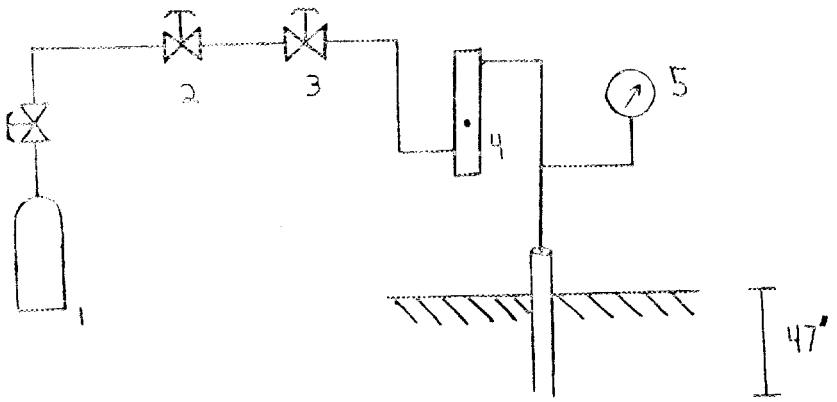
[d] Little credibility is ascribed to this measure without substantial characterization of operation characteristics.

Table 3.2. Weather Monitoring Package

Parameter	Monitor	Location(s)	No. Sites
Data Logger	Campbell Scien. 21X	Outdoor Station	1
Rainfall	Tipping Bucket	Outdoor Station	1
Barometric Pressure	Sierra/Misko	Outdoor Station	1
Wind Direction	Campbell Scien.	Outdoor Station	1
Wind Speed	Campbell Scien.	Outdoor Station	1
Temperature	RTD Sensor	Outdoor Station	1
	RTD Sensor	Soil	1
Rel. Humidity	Electronic	Outdoor Station	1
Radon Flux	Wrenn Chamber[a]	Outdoor Station	1
		Side of House	1

[a] Wrenn chamber inside inverted can with temperature/RH sensor and partially controlled air exchange rate

Figure 3.1 Soil Permeameter Schematic



1. #3 Cylinder dry air.
2. Matheson regulator model 8-590.
3. Flow control valve--Circle Seal model MV 92T1-1PP
4. Flowmeters
5. Magnehelic pressure gauges.

4. DIAGNOSTIC PROTOCOLS AND MEASUREMENTS

One of the principal objectives of the Princeton/ORNL research effort is to reduce the costs of, refine, and shorten the diagnostic protocols used in the LBL research effort, with the ultimate goal of creating a procedure more useful to private mitigators. The following section describes our research concerning pre-mitigation, mitigation installation, and post-mitigation diagnostic measures.

4.1 PREMITIGATION DIAGNOSTICS

The initial pre-mitigation diagnostic tests on six of the seven Princeton/ORNL houses (excluding the Control House #2) were performed in November and early December of 1986. Three members of the Princeton team spent a day in November, 1986, with the LBL team observing and participating in LBL pre-mitigation diagnostics in one of the LBL test homes. At that time it was uncertain which measurements were meaningful predictors of the type and configuration of mitigation system needed. This knowledge has evolved during the study as we have evaluated the results from--and usefulness of--each measurement. The preliminary Princeton diagnostic protocol of 11/86 (i.e., Table 4.1) is thus a modified version of LBL's initial protocol, with some measurements deleted or modified, and others added. Additional streamlining of the protocol was made before our diagnostic visit to the control house in April, 1987 (Table 4.2). The preliminary protocol will be discussed first. It differs from the LBL protocol in the following ways:

1. The working assumption in our test homes was that the radon was entering either by soil gas transport or possibly from ground water. Therefore, surface flux measurements to determine if radon was emanating from building materials were not performed.

2. Fewer diagnostic test holes were drilled through the substructure than in the LBL homes. Our procedure iterated towards an optimum minimum number which would give information sufficient to design a mitigation strategy properly.

3. Grab samples of radon were obtained at selected test holes under ambient conditions and under -10 Pa depressurization; these measurements were accompanied by measures of pressure differential across--and air velocity through--each test hole. These combined measures gave an indication of the radon flux at the selected test holes under the ambient versus "enhanced stack effect" conditions, (i.e., -10 Pa depressurization).

4. An infrared scan of each test home was performed to look for leakage points in the building shell and to evaluate the usefulness of this technique as a diagnostic tool.

The data form for the diagnostic protocol used during the initial pre-mitigation diagnostics on Princeton/ORNL test Houses #1, #3, #4, #5, #6 and #7 during 11/86 - 12/86 is given in Table 4.1. The procedure for performing most of these tests have been explained by Turk, et al., in an Interim Report on Diagnostic Procedures for Radon Control,[1] and will not be repeated here.

A brief description of the rationale behind each measurement and evaluation of its usefulness in choosing a mitigation design follows. The discussion follows the protocol given in Table 4.1.

Soil gas radon content determined from grab samples and soil gas permeability were recorded at one location on each side of each house. (See Section 6.2.5 for more on soil characteristics at the test homes and specifics on sampling procedure.) High soil permeability and high radon gas content implies an area where radon transport can be significant. These measurements give information on whether particular sides of the building structure might be favored in the transport of radon-laden soil gas into the building. Mitigation systems such as subslab or wall ventilation could then be designed to exert a greater force on those areas.

Ambiguities in these measurements arise because the soil characteristics at our test home locations are variable on a scale of feet. Backfill (i.e., new, foreign soil) near a building structure can also complicate the interpretation of the soil gas measures. It will be interesting to compare

our data with the more extensive soil gas and permeability mapping done at the LBL seven test homes to determine the number of measurement locations required to generate predictions that are useful for mitigation design. We do not feel these measurements have been characterized or understood well enough to determine successful mitigation design, and do not recommend they be used by private mitigators at this time. The final report on the 14-home study may have more information on the use of soil information in radon diagnostics, but at the moment these measurements are primarily of research interest for understanding radon availability and transport. We are still in the discovery phase of soil characterization and its importance in either designing successful mitigation or understanding the expected severity of a radon problem in a building near or on the spot where the soil measurements were made. It is suggested that such studies could be coupled with other localized geological investigations (e.g., ground penetrating radar) to shed more light on availability and transport.

The visual inspection of each house using a LBL questionnaire[1] was very useful for spotting obvious possible radon entry points such as a sump, perimeter drain, and cracks, and for inspecting the duct system and finding leaks between the substructure and living area. These characteristics affect the design of a mitigation system. The questionnaire is being shortened considerably and will be part of the diagnostic protocol form we will submit in the final report.

The natural (i.e., ambient) condition air grab samples of greatest utility were the comparisons of bathroom air before and after a 10 minute hot shower operation. The only house which showed a significant difference between the two was House #4, which also was the house with the highest well water radon content (see Section 6.1). This is a useful diagnostic tool for quickly getting an indication of whether the ground water is a possible source of indoor radon.

Grab samples of air from various rooms under natural conditions give some indication of the radon distribution throughout the house and may, in special cases, target specific locations in the building as being particularly high in radon concentration. In general, however, one should rely on either

integrated or real-time radon measurements to determine whether a building has a radon problem. We know, from this study and others, that the radon concentration indoors can vary considerably on a daily basis, see Section 6.5.2, so that grab samples of room air should only be used with this caution in mind.

To map the radon concentration distribution under and around the substructure, test holes were drilled in the floor and wall for taking grab samples. These holes should be plugged immediately after drilling (with a removable plug) and allowed to equilibrate for at least 1 hour before grab samples are obtained. Ideally, they should be drilled the day before. The number of test holes needed will be discussed below.

A blower door is used to mechanically depressurize the substructure to -10 Pa to simulate the worst of winter conditions (i.e., the stack effect). Grab samples obtained under these conditions must also be accompanied by measures of pressure differentials across--and air velocities through--the test holes in order to correctly compare with the ambient condition grab samples. These measurements give an estimation of the change in radon flux (i.e., radon concentration times air velocity) through each hole under ambient vs depressurized conditions. Our diagnostic measurements showed that this value usually decreased with time during constant depressurization, presumably due to two mechanisms, depletion and dilution. The reservoir of radon-rich soil gas under the slab may be depleted during substructure depressurization. At the same time, the increased pressure field in the soil draws on more area and thus more soil gas, potentially diluting any concentrated radon source areas (e.g., the reservoir for soil gas under the slab). The blower-door diagnostic technique may prove useful as a research tool for determining the optimum operational flow requirements of a subslab and/or wall ventilation system. We do not recommend this technique as a mitigator's tool at this time.

Infrared scanning of interior surfaces is a diagnostic technique used to uncover air leakage sites and air flow patterns within the building. Outside air is normally a different temperature, colder or hotter, than interior surfaces. When this outside air enters the building it alters the local

surface temperatures and thus can be detected with an infrared scanning device which is sensitive to small changes in surface temperature. Air flowing upward in the home from a cooler or warmer basement environment again results in alteration of interior surface temperatures. If the blower door is used to increase the upward air flow (operating upstairs in the depressurization mode) the air path is made even more evident. Since this is likely to be a pathway for radon transport, the IR technique can prove useful in identifying such radon paths as well as evaluating how well separated the living space is from the basement/crawlspace. This diagnostic technique would be helpful for designing a basement pressurization system by pinpointing areas that should be sealed. The drawback of this technique is that an infrared scanner may not be available, and it is expensive to rent or purchase.

Pressure differentials are measured across the test holes as appliances and air handling systems (i.e., with and without furnace combustion) are cycled on and off. This test helps determine the contribution to basement depressurization (and thus enhanced soil gas entry) attributable to the operation of each device. These measurements are useful for determining whether makeup air supplied to one of the combustion appliances may help alleviate the contribution of the appliance to basement depressurization. These measures also help determine the minimum pressure field that must be maintained by a subslab or wall ventilation (mitigation) system.

The final measurement in our preliminary diagnostic protocol, basement/subslab and basement/wall air communication checks, is one of the most powerful diagnostic tools for determining whether subslab or wall ventilation will work. During subslab depressurization, using a vacuum cleaner attached to a centrally located 1 1/2 inch hole drilled through the slab, pressure differentials and air velocities through the test holes are measured. Large differential pressures across--and large air flows through--the test holes indicate good communication between the suction point and test hole. If the pressure and air flow field is extensive enough across the slab and wall areas (at least +1 Pa Basement-Exterior pressure difference), then subslab ventilation is a viable mitigation choice. If the centrally located hole does not communicate with the entire substructure area, multiple

penetrations may be necessary. We are in the process of quantifying what each of these communication measurements determines.

The Princeton diagnostic protocol for pre-mitigation diagnostics as of April, 1987, is given in Table 4.2. This is a revision and shortening of the previous protocol based on evaluation of which measurements gave us information useful for mitigation selection and design. The April, 1987, version was used in pre-mitigation diagnostics on our control home (i.e., House #2).

The procedure begins by drilling a limited number of test holes in the basement slab and walls, with more being drilled later only if communications are poor and more extensive pressure mapping is necessary to determine whether more suction points will enhance the performance of subslab or wall ventilation. Grab samples in test holes are performed under ambient conditions only, and the -10 Pa depressurization test has been omitted. The communication tests are performed using a variable-speed vacuum cleaner to better simulate pressure/flow characteristics of commonly used duct ventilation fans (e.g., Kanalflakt K6 as installed). This allows for an evaluation of communications under conditions more closely matched to those of a subslab or wall ventilation mitigation system. Please consult the form given in Table 4.2, which is fairly self-explanatory, for further indications of how these procedures have been shortened. Further revisions will come in the final report.

4.2 MITIGATION INSTALLATION DIAGNOSTICS

The permanently installed mitigation systems in the seven Princeton/ORNL homes were subslab, wall, perimeter drain, or drainage tile ventilation systems, all designed to either pressurize or depressurize the air/soil/rock zone immediately outside the below-grade boundary of the basement or crawlspace. See Section 5 for detailed discussion of the mitigation systems employed in the study homes. The discussions on mitigation installation and post-mitigation diagnostics which follow will focus on these four types of mitigation systems.

Diagnostics performed during mitigation installation focused on confirming that the installed system performed adequately. To aid in the refinement of these systems, simple dampers were installed in each independent pipe and variable speed controls were installed on the fans. The following checks were performed after installation was completed.

1. Turn fan on maximum speed.

2. Open all dampers.

3. Record the air velocity at the center of each independent pipe. If there is flow in all pipes, leave the system in this configuration for at least 1 week to check the performance. (In our case, performance is checked by monitoring all the parameters that are being recorded continuously.) If no flow is recorded in any one of the ventilation pipes, adjust dampers until some flow (at least 0.25 m/sec in a 4 in. pipe) can be measured. If adjustment of the dampers does not solve the flow problem, record the pressure differences between the basement or crawlspace and the inside of each independent pipe, and record the performance of the system for one week.

4. Use a tracer gas, (e.g., freon and a standard freon detector available in HVAC contractor supply stores), to check that no exit air is either leaking through any of the joints in the pipe or around the fan, or flowing back from the outside into the basement or crawlspace.

4.3 POST-MITIGATION DIAGNOSTICS

Post-mitigation diagnostics were performed throughout the winter and spring of 1987 for the purpose of optimizing the efficiency of the radon mitigation systems, and, in the cases of Houses #1, 5, and 6, to improve the effectiveness of the radon mitigation system itself. The results of these studies will be given in the final report.

All of the final mitigation systems in the Princeton/ORNL seven homes involved variations on wall or subslab ventilation systems with sealing, in varying degrees, of cracks and sumps and perimeter drains. We found that in many cases the ventilation systems could evacuate sufficient quantities of subslab or wall air to maintain acceptably low levels of indoor radon. In addition, the ventilation systems were exhausting not only air from subslab and wall cavity areas but also conditioned house or basement air, as confirmed by tracer gas measurements. To minimize the energy penalty to the home due to conditioned house air exiting the mitigation system, the fan speed was systematically decreased until the lowest fan speed setting was found that maintained acceptably low levels of radon. Each time the fan setting was changed, the differential pressure and air velocity were recorded at each test hole through the slab or wall in the basement or crawlspace, as well as inside each independent subslab or wall ventilation duct. In addition, grab samples of subslab or inner wall air were taken in selected test holes to monitor the radon concentrations in these areas at each fan speed. Tests were also performed to verify the performance of the mitigation system under simulated adverse weather conditions by depressurizing the basement compartment with a blower door.

Post-mitigation diagnostics performed on the houses that were difficult to mitigate focused on finding where the remaining radon entry points were located. The tests primarily included mapping the air flow and pressure fields around the basement or crawlspace perimeter, monitoring radon concentrations using grab samples, and performing more extensive communication checks.

The final report will contain two diagnostic protocol sheets resulting from our post-mitigation diagnostic studies. One will be a preliminary post-mitigation diagnostic protocol for followup diagnostics to be performed if the installed mitigation system is not reducing the radon levels to acceptable levels. The second will be a preliminary post-mitigation diagnostic protocol for fine tuning a subslab or wall ventilation system.

Table 4.1. Preliminary Princeton Pre-Mitigation Diagnostics Protocol (11/86)

SOILS

1) [ ] Soil gas grab samples

2) [ ] Soil gas permeability

BUILDING STRUCTURE

3) [ ] Visual inspection guided by LBL questionnaire

4) [ ] Natural condition, air grab samples (Lucas cells)

[ ] Level 2
[ ] Level 1
[ ] Basement, each unique zone
[ ] Outside air sample, include: [ ]Temp [ ]Windspeed
[ ] Closed bathroom, 10 min. shower operation

5) [ ] Drill test holes in floor & wall

general guidelines: o Wall holes - 1/2 in. Dia.
o Floor holes - 1/2 in. Dia.

(note: plug immediately after drilling with flagged Mortite)

6) [ ] Lucas cell grab samples of selected test holes under ambient condition. Record pressure differentials and air velocity.

7) [ ] Start Data Logging on one minute interval

[ ] Synchronize all clocks

8) [ ] Mechanical depressurization - 10 PA

Lucas cell grab samples

[ ] Firred wall cavities
[ ] Block walls
[ ] Floors
[ ] Cracks
[ ] Service openings
[ ] Test holes

9) [ ] Blower Door Tests (use ASTM 779 std.)

[ ] Whole house (interior doors open)
[ ] Basement/crawlspace closed off
[ ] Interior breakout (closing doors)
[ ] Basement only (where feasible)

Table 4.1. Preliminary Princeton Pre-Mitigation Diagnostics Protocol (11/86), continued.

10) [ ] IR scan of each room

11) [ ] Appliance cycling - substructure measurements as appliances are cycled ON/OFF

[ ] Clothes dryer _____

[ ] Exhaust fans _____

[ ] Furnace: [ ] Combustion air only _____

[ ] Fan only _____

[ ] Both above _____

12) [ ] Basement/subslab and basement/wall communication using vacuum cleaner. Drill central 1 1/2 in. diameter hole and and attach vacuum cleaner.

[ ] Check pressure differentials in test holes

[ ] Check air velocity through test holes

Table 4.2 Princeton Pre-Mitigation Diagnostics Protocol (April 9, 1987)

Building Structure

1) [ ] Visual inspection of interior and exterior building with questionaire.

Building Dynamics

2) [ ] Drill test holes in floor and wall. One hole into subslab in each corner 1 meter from wall and 1 hole centrally located. One hole into each interior of hollow block walls centrally located on each wall, or 30 feet apart if wall is extensive.

General guidelines: o Wall holes 1/2 in. dia.
o Floor holes 1/2 in. dia.
Drill after test #2 below: o One floor hole 1 1/2 in. dia.

Note: Plug immediately after drilling with flagged Mortite. If possible, drill all holes except the 1 1/2 in. hole at least 1 day before other diagnostic tests to allow substructure air to come to an equilibrium. The 1 1/2 in. diameter floor hole should be drilled in the hottest area of the subslab as determined in the grab sample tests listed next. After drilling the 1 1/2 in. hole, vacuum concrete dust from hole and visually check for gravel or air gap under slab.

3) [ ] Grab samples of test holes under ambient conditions.

Note: If EDA-RDA radon detector is used, count samples 15 minutes after collection for 2 minutes: pCi/L (to within 10%) = counts per 2 minutes counted 15 minutes after collecting. To minimize error in the above approximation, always collect grab samples with filter in line to avoid contaminating flask with particulates, and to assure sample collected is primarily radon gas, with minimum progeny present.

4) [ ] Pressure differential measures across each test hole.

[ ] Determine air flow direction using a smoke bottle and velocity using an appropriate instrument such as a warm wire anemometer.

5) [ ] Blower door tests:

[ ] Whole house with basement/crawlspace door open (all interior doors open)
[ ] Whole house with basement/crawlspace door closed (all interior doors open).
[ ] Basement/crawlspace only (where feasible). Pressurize basement to level over subslab pressure and calculate flow rate of air into basement. This will allow calculation of the amount of air flow into the basement which is necessary for basement pressurization. Seasonal variations in house leakage area should, however, be taken into account.

Table 4.2 Princeton Pre-Mitigation Diagnostics Protocol (April 9, 1987) continued

6) [ ] Appliance cycling - Basement/subslab/wall/upstairs pressure differential measurements as appliances are cycled on/off.

[ ] clothes dryer
[ ] exhaust fan
[ ] furnace - - - -[ ] combustion air only
[ ] fan only
[ ] both above.

7) [ ] Subslab-subslab, subslab-wall, and wall-wall communication using variable-speed, vacuum cleaner or portable fan suction device.

[ ] check pressure differentials
[ ] check air velocities
[ ] check for gravel under slab
[ ] check for hollow areas under the slab

Soil/Water

8) [ ] Grab sample of room air in closed bathroom after 10 minutes of shower operation.

9) Soil gas grab samples.

Note: if soil has a low permeability it is possible to draw a partial vacuum in the soil pipe apparatus. If this happens, make very sure there are no leaks in the grab sample apparatus (to avoid outdoor air intrusion) and let it remain in place, with the air line open to the scintillation cell, until the partial vacuum has disappeared and the cell is presumably full of soil gas.

10) [ ] Soil gas permeability.

5. MITIGATION MEASURES ADOPTED IN STUDY HOUSES

A summary of the Phase I and II mitigation plans for the six ORNL/Princeton homes mitigated during the winter of 1986-1987 is given in Table 5.1. Figures 5.1 - 5.7 show the basement or crawlspace structure drawn to scale with the configuration of the final mitigation system. The mitigation plan for the control home, which will be mitigated in mid-July, is shown in Figure 5.2. The numbers included in the figures are radon concentrations (pCi/L) measured via grab samples of air from the subslab and inner wall cavities under ambient conditions during pre-mitigation diagnostics.

5.1 PHASE I MITIGATION PLANS

Following are the individual mitigation strategies for initial mitigation of six of the seven study homes. (The seventh home is House #2, the control house, that will be mitigated in July.) These are the same descriptions that were circulated to the sponsors and other members of the Piedmont study for their approval before mitigation began last December (1986), along with sketches of the house substructure including the mitigation system (i.e., similar to Figures 5.1 - 5.7). These Phase I choices were also coordinated with the initial mitigation plans for the LBL six homes to increase the variety of systems in the combined study. Homeowners received a condensed version of the mitigation plans in letters that are included in Appendix 9.2. Preceeding the description of the mitigation strategy is a brief account of the findings during our pre-mitigation diagnostic visit which led to each mitigation choice.

5.1.1 House #1

Pre-mitigation diagnostics summary: The substructure (see Figure 5.1) consists of a basement with hollow concrete block walls and a perimeter drain, weep holes on the southern wall, a block drain system (i.e., wall block extending several feet below slab level) on the northern wall, and a sump in the northeast corner. There is a family room and garage on a slab adjacent to

the northwest end of the basement, which intersects the basement wall about six feet above the basement slab. A thick layer of aggregate was found under the basement slab, and good communication (i.e., air flow) was observed between subslab points within the basement. Subslab to wall communications were not observed in the basement because of the intervening perimeter drain. The highest radon concentrations that we found were under the basement floor slab on the side near the garage and family room slab, and in the wall between the garage and family room slab and the basement (see points 3550 and 6800 in Figure 5.1).

Mitigation strategy (initial phase): A combination subslab ventilation and wall ventilation system was installed; this was intended to ventilate the area under the basement slab and the wall between the family room and garage and the north (back) basement wall. This was accomplished by installing two pipes into the block walls, one penetrating the north wall near the basement/family room joint and the other penetrating the block wall which goes between the garage and family room at the point where that wall intersects the west basement wall under the basement stairs. A third pipe for ventilating the basement slab was inserted through the center of the basement, and runs along the center of the basement ceiling between the two existing central air ducts. These pipes were connected to each other and exited the basement through the basement/garage wall and out the back garage roof. All pipes were installed with appropriate slope to maintain a continuous flow back of accumulated condensation water towards the subslab. A Kanalflakt T2 plastic fan was installed in the pipe system in the garage attic which pulled the soil gas from inside the block wall and the gravel bed under the basement slab and vented it to the outside. Standard 4 in. sewer and drain (S & D) pipe was used throughout. At the point where the pipe enters the basement slab, a roughly circular area 1 ft. in diameter was cleared of all existing gravel and other subslab debris to increase the amount of open area to draw air through. Dampers were installed in the pipes which allowed the basement pipe and each of the wall pipes to be closed off completely. The fan was installed so that it could be reversed, with a speed control switch installed in the basement. The perimeter drain was not sealed initially.

5.1.2 House #3

Pre-mitigation diagnostics summary: The substructure (see Figure 5.3) is a basement with hollow concrete block walls, a perimeter drain and a sump in the southeast corner. A garage on a slab on grade is adjacent to the basement on the north side. Good communication was observed between subslab points within the basement, as well as subslab to perimeter drain (i.e. the outer edge of basement floor) and subslab to sump (i.e., point 3180 in Figure 5.3) communication. Subslab to wall communications were not observed because of the intervening perimeter drain. A layer of aggregate was found under the basement slab. The highest radon concentrations were found under the basement floor slab on the side near the basement/garage interface (see starred data in Figure 5.3 taken under -10 Pa depressurized conditions). All the walls showed similar concentrations with slightly higher levels found in the northeast basement wall (see point 270 in Figure 5.3).

Mitigation strategy (initial phase): The excellent air flow characteristics of the subslab (i.e., good communication) were taken advantage of in the design of the mitigation system. A subslab ventilation system was installed with two pipes inserted into the slab 15 ft. 5 in. out from the north and south walls, respectively, along the center of the basement in line with the lolly (i.e., support) columns. The two pipes coming out of the slab connect through one elbow and one tee to a pipe running along the ceiling of the basement between the existing supply and return heater duct system. This pipe exits the basement through the basement/garage wall and out the garage roof on the east side of the center peak of the roof. All pipes were installed with appropriate slopes to maintain a continuous flow back of accumulated condensation water towards the subslab. A Kanalflact T2 plastic duct fan was installed in the garage with a speed control switch installed in the basement. The fan was installed so that it (and therefore the flow) could be reversed to test the effectiveness of pressurizing vs depressurizing the subslab. Standard 4 in. S & D pipe was used throughout. At the point where the pipe enters the basement slab, a roughly circular area 1 ft. in diameter was cleared of all existing gravel and other subslab debris to increase the amount of open area to draw air through. Dampers were installed in the pipes which allow each of the subslab pipes to be closed off completely. A

perimeter drain duct system was installed to test its effectiveness in allowing subslab to wall communication. The duct system was made by stuffing backer rod into the top of the perimeter drain and applying a coating of pourable urethane caulk over the rod to make a seal between the slab and wall. (The backer rod was chosen to match the width of the perimeter drain, which varies from basement to basement and sometimes within a basement.) This configuration allowed free space to be left under the backer rod for air to flow from the hollow block wall to the subslab area (see for example Figure 5.11). In addition, the perimeter drain is still available for use as a drain to any water or moisture that accumulates in the hollow block wall and drips down the inner wall into the drain.

Note: This type of perimeter drain duct was used and evaluated in all the ORNL/Princeton homes which had perimeter drains (Houses #1, #3, #5, and #7), although it was installed in the initial phase of mitigation in Houses #3 and #7 only.

5.1.3 House #4

Pre-mitigation diagnostics summary: The substructure (see Figure 5.4) is a basement with painted hollow cinder block walls, two sumps with drainage tiles visible, and a family room (breezeway) and garage on a slab on grade adjacent to the east end of the basement. The drainage tiles under the basement slab appear to run just inside the perimeter of the foundation all the way around the basement, and spill into the two sumps. Some aggregate was found under the basement slab, although the soil under the aggregate was very wet and contained a lot of clay. We did observe good communication, however, between different points under the basement slab, between the subslab and the basement walls, and between the subslab and the sumps. The highest radon concentrations we found were under the garage slab, in the east basement wall (between the basement and family room slab), and under the east side of the basement slab (see Figure 5.4). Our initial mitigation strategy took advantage of the good communication between the drainage tiles in the sumps and the other subslab points.

Mitigation strategy (initial phase): A subslab ventilation system was installed. This was accomplished by attaching an air suction system to the sump (and therefore the drainage tiles) on the south side of the basement (near the furnace). The sump was covered and a 4 in. S & D pipe exits the sump cover, extending to the ceiling and passes out of the basement through the west wall. A Kanalflakt K6 duct fan was installed in the center of the horizontal pipe before the basement exit point, with a variable speed switch installed in the basement. The pipe was installed to allow a continuous flow back of accumulated water towards the subslab. The basement exit was through a masonry hole in the block wall. The vent pipe on the outside of the home exits the substructure at the west side of the house, where there are no windows, to avoid back flow into the house. The second sump in the NW corner of the basement was covered with a sealed sheet metal cover. Both sumps had a submersible sump pump with a check valve installed.

The north sump, which is not the one we are pulling air through, has a pipe attached to it which is vented to the outside about 100 ft. to the front of the house. Despite this, our measurements have shown that this particular sump communicates well with the adjoining basement walls and subslab, primarily through the drainage tile system under the substructure. The outside vent has been left open during the operation of the mitigation system, which has remained effective in reducing the radon to acceptable levels.

5.1.4 House #5

Pre-mitigation diagnostics summary: The substructure (see Figure 5.5) consists of a basement with hollow concrete block walls, a perimeter drain, and a sump in the northeast corner. There is a garage on a slab on grade adjacent to the basement on the north side. A thick layer of aggregate was found under the basement slab, and good communications were found between subslab points as well as between wall points. The highest radon concentrations we found were in the sump and the large crack in the center of the basement floor (see points 1470 and 280, respectively, Figure 5.5). All the walls showed similar concentrations with slightly higher levels found in the north basement wall (see Figure 5.5.). House #5 was the tightest of the seven houses in the ORNL/Princeton study. (None were very tight; see

discussion on blower-door measurements in Section 6.2.) It was therefore decided to try a basement pressurization system in this house, even though the central air handler system maintained a slight depressurization of the basement. The blower-door measurement showed that, with the air handler off, a flow of 200 cfm would give about a 5 Pa basement pressurization over the outside pressure.

Mitigation strategy (initial phase): A basement pressurization system was installed, with the intention of maintaining a slight positive pressure in the basement to prevent the radon gas from entering the substructure. The sump and perimeter drain were not sealed initially. A Kanalflact K6 fan was installed on the basement side of the block wall between the basement and garage, with a variable speed switch in the basement. At the request of the homeowner, the mount was on the east side of the garage/basement wall as near the corner as possible. The air intake into the basement from the garage was at the point where the pipe comes into the garage through the block wall. (Again, this is at the homeowner's request. They did not want the intake at the ceiling of the garage because they felt it would be too ugly and didn't care about the difference between the quality of air at the bottom of the garage vs. the top.) Construction was with 4 in. S & D pipe throughout, with the ceiling pipe structure installed so that it could be easily converted into a subslab ventilation system (phase 2, see Figure 5.5). Air was piped into three different locations inside the basement to better regulate the pressurization of the basement. Dampers were installed in each independent pipe to better control the air distribution. The ceiling pipe, which extends down the center of the basement, ended between the fourth and fifth lolly column from the basement/garage wall. The pressurization system failed because the metal K6 fan could not maintain sufficient pressure differential between the basement and outdoors locations. (This initial system was followed by extensive sealing and finally a subslab ventilation system with a perimeter drain duct, which was very effective at ventilating both the subslab and hollow block wall air, see Figure 5.11).

5.1.5 House #6

Pre-mitigation diagnostics summary: The substructure (see Figure 5.6) is a basement and crawlspace with hollow cinder-block walls separated by an interior hollow cinder block wall with a small door between the two spaces. A layer of aggregate was found under the crawlspace slab and aggregate with some dry mud silt in it was found under the basement slab. Good communication was observed between different points under the crawlspace slab as well as between most points under the basement slab. No communication between the basement and crawlspace subslab areas was observed. No communication between either the basement subslab and the walls or the crawlspace subslab and the walls was observed. The highest radon concentrations we found were under the basement, the connected workroom, and the crawlspace slabs, with the west side of the crawlspace showing the largest values. The walls all showed similar concentrations with slightly higher values observed in the northeast basement wall next to the garage slab (see Figure 5.6).

Mitigation strategy (initial phase): A subslab ventilation system was installed to ventilate the area under both the basement and crawlspace slabs. The initial installation consisted of two pipe penetrations into the slab in the crawlspace and one pipe penetration into the slab in the basement. The two pipes in the crawlspace were inserted into the slab 19 ft. from the west and east crawlspace walls, and equidistant between the north and south crawlspace walls. An area under the slab at the point where the pipe entered the slab was cleared (approximately 1 ft. cubed, mushroom shaped) to increase the amount of open area for the system to draw on. The two 4 in. S & D pipes which penetrate the crawlspace floor were connected to a 4 in. S & D pipe which exits the crawlspace area through the cinder block on the east wall near the furnace, and extends across the basement ceiling on top of the existing ceiling facade. Schedule 40 PVC pipe was used on the basement side of the manifolded system for support. The hole through the central basement slab was made at the location labeled 4900 in Figure 5.6. These pipes were connected to a common pipe which exits the basement on the north side of the east wall, runs behind the existing duct along the ceiling in the entrance room, and through another wall into the storeroom. It exits the storeroom through the ceiling, into the attic, and out the roof on the north side of the garage.

All pipe was installed to maintain a continuous flow back of accumulated water towards the subslab. A Kanalflakt K6 duct fan was installed in the attic. A variable fan speed control was mounted 6 ft. up in the storeroom next to the garage.

Note: House #6 had two heat recovery ventilators installed before our study began. One was in the basement and the other was in the crawlspace. We have evaluated the system with the HRV's both on and off.

5.1.6 House #7

Pre-mitigation diagnostics summary. The substructure (see Figure 5.7) is a basement and crawlspace combination, connected by a partially opened cinder block wall, with hollow cinder block walls throughout the perimeter of the substructure. The basement has a perimeter drain along all four walls, and one sump located on the east side of the basement/crawlspace wall. The crawlspace has a perimeter drain along the east and part of the south side wall. The rest of the perimeter drain in the crawlspace has previously been sealed by the homeowner. A layer of aggregate was found under both the basement and crawlspace slabs. We observed good communication between subslab points within the basement, but not between the basement and crawlspace zones. Subslab communication was obscured in the crawlspace because of short-circuiting to the perimeter drain. Subslab to wall communications were not observed in either the basement or crawlspace because of the intervening perimeter drain. We observed wall-to-wall communication within walls and around single corners in walls in both the basement and crawlspace zones. The highest radon concentrations were found under the basement floor slab, with slightly lower concentrations under the crawlspace slab. All of the walls showed similar concentrations with slightly higher levels found in the southern crawlspace wall between the crawlspace and garage (see Figure 5.7).

Mitigation strategy (initial phase): A subslab ventilation system was installed to ventilate both the basement and crawlspace subslab and hollow wall areas. This was accomplished by installing a perimeter drain duct system (see, for example, Figure 5.11) for each of the crawlspace and basement drains to allow for air to flow from the hollow wall and the subslab areas to the

perimeter duct drain. Each drain was capped so that they could act as a conduit, or duct system, for the soil gas to flow through. The cap was constructed from backer rod, cut in half to form a half moon shaped rod, and placed in the duct with the flat side up. Note that in basements #3 and #7 we cut the backer rod in half as just described, to make a flat surface over which to pour the urethane. A layer of pourable urethane caulk was used as the sealant. Two suction pipes were installed into the duct system in the basement, one in the center south wall and another into the (covered) sump in the northeast basement corner. One suction pipe was installed in the crawlspace, into the perimeter duct system in the center of the north wall. These duct systems were manifolded to a common pipe that exited the substructure through the garage/crawlspace wall. The pipe exited the garage through the roof on the west side of the house. A Kanalflakt T2 plastic fan was installed in the pipe system in the garage attic to pull the air, or soil gas, from the gravel bed and vent it to the outside. Standard 4 in. S & D pipe was used throughout. All pipes were installed with appropriate slope to maintain a continuous flow back of accumulated water towards the subslab. Dampers were installed in each independent pipe to allow each pipe to be closed off completely. The fan was installed so that it can be reversed, with a speed control switch installed in the basement.

5.2 PHASE II MITIGATION PLANS

The following is a list of the order, with dates, that each step of the mitigation was applied to each test home. Figures 5.8 through 5.13 show the effect on the radon concentrations in the basement and on the first floor due to installation and operation of the initial mitigation system. Test Houses #3 and #4 required the least effort to control radon levels while House #6 required the most. The final report will elaborate on the results at each step in the phased mitigation systems.

5.2.1 House #1

a) Install subslab ventilation through the center of the basement slab and wall ventilation directed on the wall between the basement and family room slab, with no sealing completed. (The

suction on the north outside wall was closed off very soon after installation as no positive effect on reducing the radon levels were observed from using this suction hole. It was installed above grade, and thus pulled more on atmospheric air than inner block air from soil gas.) 1/2/87 (Julian day 2) See Figure 5.8.

b) Seal cracks in wall between basement and family room slab. 1/26/87

c) Convert perimeter drain to a duct, seal sump and weep holes. 2/18/87

d) Cycle fan on/off (several times throughout the winter and spring) and reverse fan for subslab pressurization. (Pressurized on 2/24 - 3/3/87).

e) Tune fan down stepwise to achieve most efficient fan speed.

f) Note: This house was lost as a study house on 5/15/87. (It went on the real estate market.)

5.2.3 House #3

a) Install subslab ventilation with two penetrations into the slab equally spaced along the center lolly column line of the basement. Perimeter drain duct installed and sump sealed. 12/21/86 (Julian day 355) See Figure 5.9.

b) Turn fan off and open dampers to test natural ventilation rate via the stack effect. 1/29/87 - 2/4/87

c) Reverse fan for subslab pressurization. 2/24 - 2/25/87 (Note: the owner complained of fan noise during subslab pressurization, so only 1 day of data obtained).

d) Tune fan down stepwise to achieve most efficient fan speed.

5.2.4 House #4

a) Install weeping tile ventilation. There is only one pipe exiting the basement slab from the weeping tile system accessed through the sump, so there are no dampers to adjust. With the fan on full, acceptable reductions in radon are achieved. Princeton's temporary test system installed 12/15/86 (Julian date 349). A plastic T2 fan was used. See Figure 5.10.

b) Install permanent system (using a metal K6 fan) 1/15/87.

c) Reverse fan for subslab pressurization. 3/5/87 - 3/11/87.

d) Cycle fan on and off throughout the winter and spring seasons.

e) Install plastic T2 fan 6/30/87.

5.3.5 House #5

a) Install basement pressurization. At most only about 1 Pa basement pressurization was achieved, and 40-50% reduction in radon concentrations, due more to dilution than to successful barrier formation from pressurization. 12/29/86

b) Seal basement/first floor openings. Install backer rod in perimeter drain without pourable urethane. Seal sump. 1/7/87

c) Seal perimeter drain with pourable urethane. 1/19/87

d) Install subslab ventilation with a penetration at the sump and another one at the opposite corner through the perimeter drain duct. 2/10/87

e) Cycle fan on/off and measure radon in-growth and decay in the mitigation pipe, under the slab and in the hollow wall cavity. See for example Figure 5.11 where the mitigation fan is turned on mid-day, 2/26/87.

5.3.6 House #6

a) Install basement and crawlspace subslab ventilation manifolded to one system with one central subslab penetration in the basement and two central penetrations in the crawlspace. Acceptable crawlspace levels were achieved, but the basement remained a problem (see Julian days 366 and onward, Figure 5.12).

Figure 5.12 displays the basement, crawlspace and upstairs radon concentrations before mitigation (i.e., Julian days 363-4), during mitigation, and after mitigation (i.e., Julian days 366-8). The figure shows that the upstairs and crawlspace radon concentrations decreased after the installation of the initial mitigation system although the basement concentration remained approximately the same.

b) Install temporary seal on sump on 1/13/87. HRV's off for the last time on 1/15/87 at 1600 h.

c) Add pipe into subslab in workroom and into wall in the basement. 2/2/97

d) Seal cracks in crawlspace and basement and seal sump, with a sump pump installed. 2/11/87, initial sealing in crawlspace. Finish sealing in crawlspace, basement, and install permanant sump pump and cover. 2/20/87

e) Replace metal fan with more efficient plastic fan. 2/5 - 2/11/87.

f) Installed additional 2 in. pipe into subslab in the basement. Install a second fan in line in the entry room on 3/12/87 and remove on 3/27/87. Permanent installation of the first 2 in. SSV pipe on 3/17/87.

g) A second 2 in. pipe into the subslab in the basement was temporarily installed on 3/20/87. The main 4 in. SSV pipe in the center of the basement was disassembled that day.

h) Permanent installation of second 2 in. pipe on 3/24/87, with balancing.

5.3.7 House #7

a) Install perimeter drain duct system in both the basement and crawlspace with two pipe penetrations in the basement and one in the crawlspace, with the exit pipes manifolded together with one fan installed to ventilate the whole system. 12/22/86 (Julian date 356) See Figure 5.13. Subslab ventilation has been analyzed at varying fan speeds.

b) Fan off and dampers open to test natural ventilation rate. 2/18 - 2/25/87.

c) Reverse fan for subslab pressurization. 3/26 - 4/2/87.

In general, we have had success with subslab depressurization using standard widely used fans; in some cases, fan speeds are adequate at as low as 20% of the full speed. We have also seen very effective reductions in radon levels with the fan reversed and the subslab pressurized, but not quite as good as in the depressurization mode. For example, at House #1 we have seen basement radon at an average of 40 pCi/L before mitigation be reduced to about 1 pCi/L with fan in the depressurization mode and to about 3 pCi/L with the fan in the pressurization mode. These numbers are with the basement in its final configuration of subslab ventilation system with perimeter drain duct installed, as noted in the summary above.

Table 5.1. Summary of mitigation plans for the seven ORNL/Princeton homes

I.D.	System 1	System 2
1	Sublab depressurization through the center of the basement slab. Wall ventilation directed on the wall between basement and family room slab.*	Seal perimeter drain sump, weep holes and wall between basement and slab.
2.	Central subslab depressurization system with one penetration. Seal sump.*	Try two point penetration for subslab ventilation.
3	Central subslab depressurization system with two penetrations. Seal perimeter drain and sump.*	Reverse fan for subslab pressurization.
4	Subslab depressurization system by ventingweeping tiles through south sump.†	Reverse fan for subslab pressurization.
5	Basement pressurization. (Seal leaks in basement ceiling.)†	Seal perimeter drain and sump. Subslab ventilation.
6	Basement/crawlspace subslab ventilation. Heat recovery ventilators tested with and without slab ventilation system.*	Additional ventilation penetrations required. Reverse fan flow and pressurize subslab area.
7	Perimeter drain duct system installed to enhance subslab depressurization of both the basement and crawlspace areas, exhause pipes, manifolded together and exit through the garage.*	Reverse fan flow for subslab pressurization

*Fan installed in garage attic.

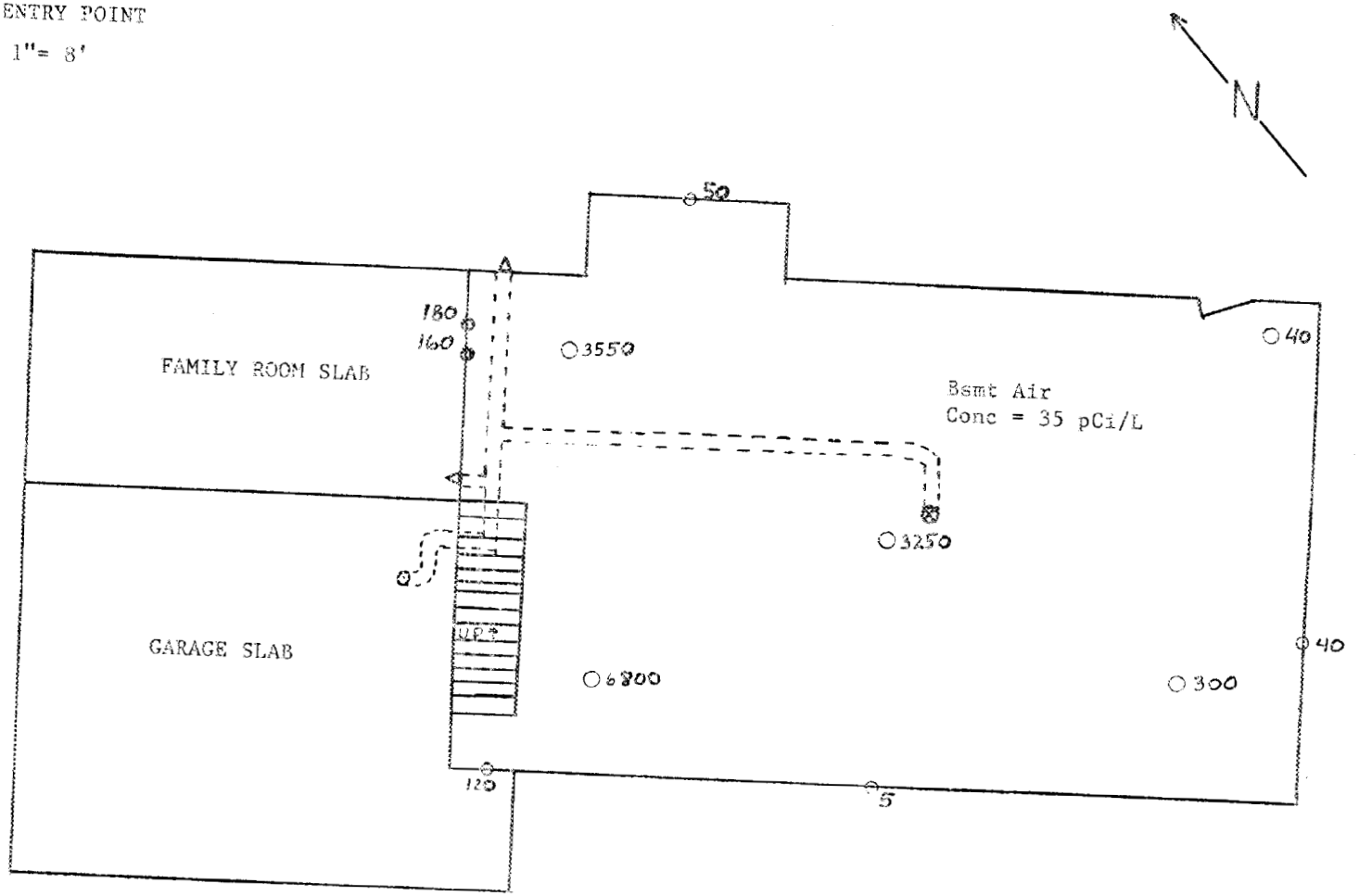
†Fan installed in basement.

⊙ BUILDING EXIT POINT

⊗ SLAB ENTRY POINT

△ WALL ENTRY POINT

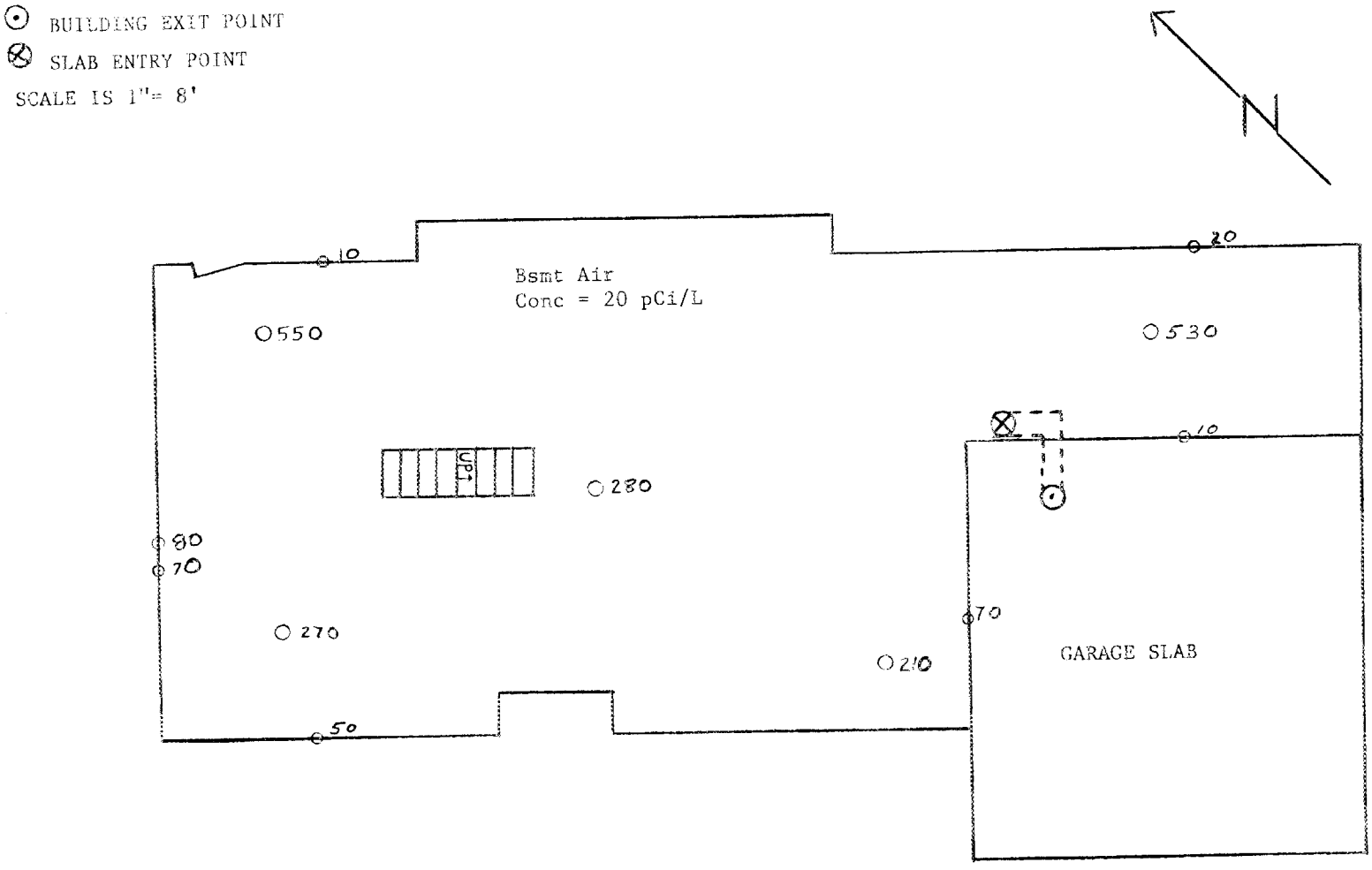
SCALE IS 1"= 8'



HOUSE # 1 BASEMENT FLOOR PLAN

PU/CEES RN8716

Figure 5.1



HOUSE #2 BASEMENT FLOOR PLAN

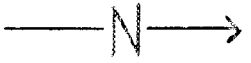
PU/CEES RN8737

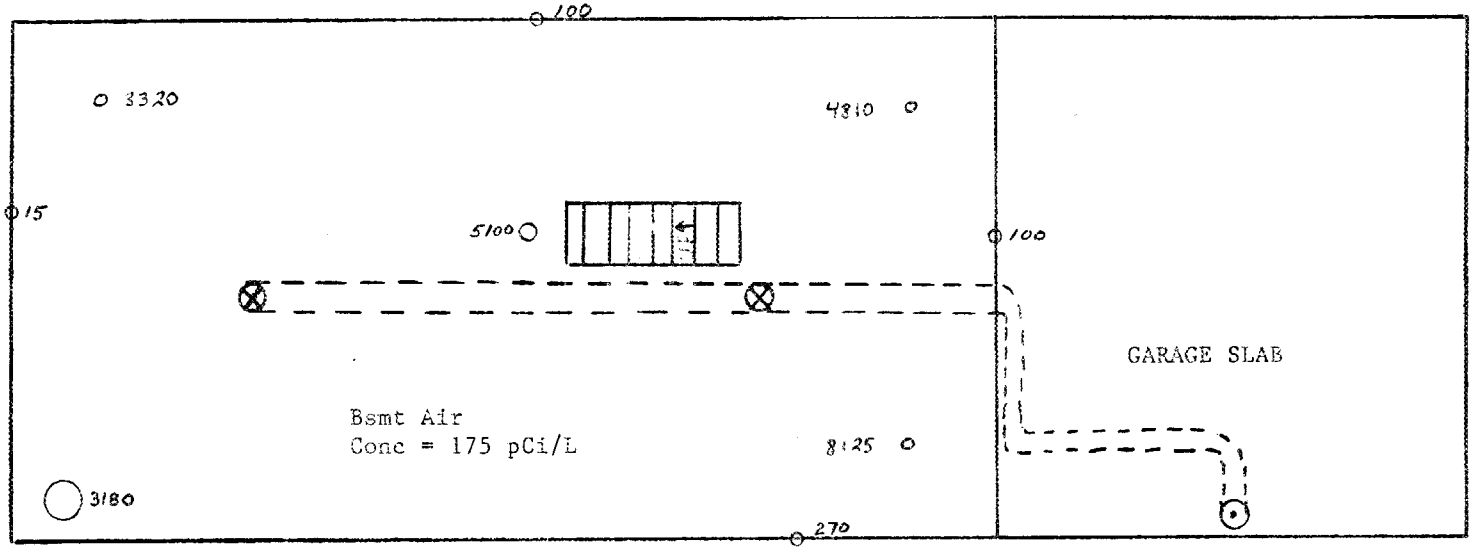
Figure 5.2

⊙ BUILDING EXIT POINT

⊗ SLAB ENTRY POINT

SCALE IS 1"= 8'

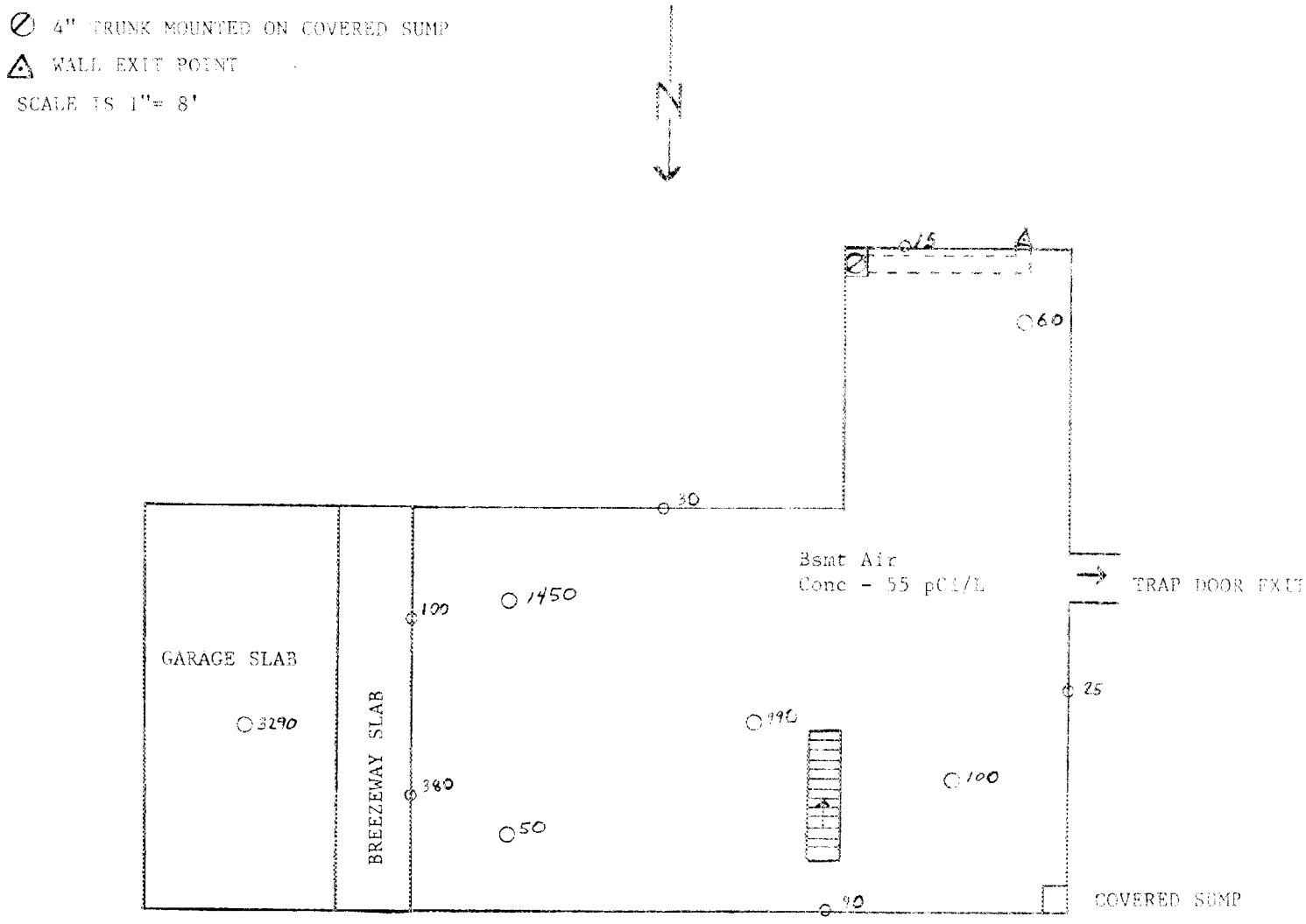




HOUSE#3 BASEMENT FLOOR PLAN

PU/CEES RN8718

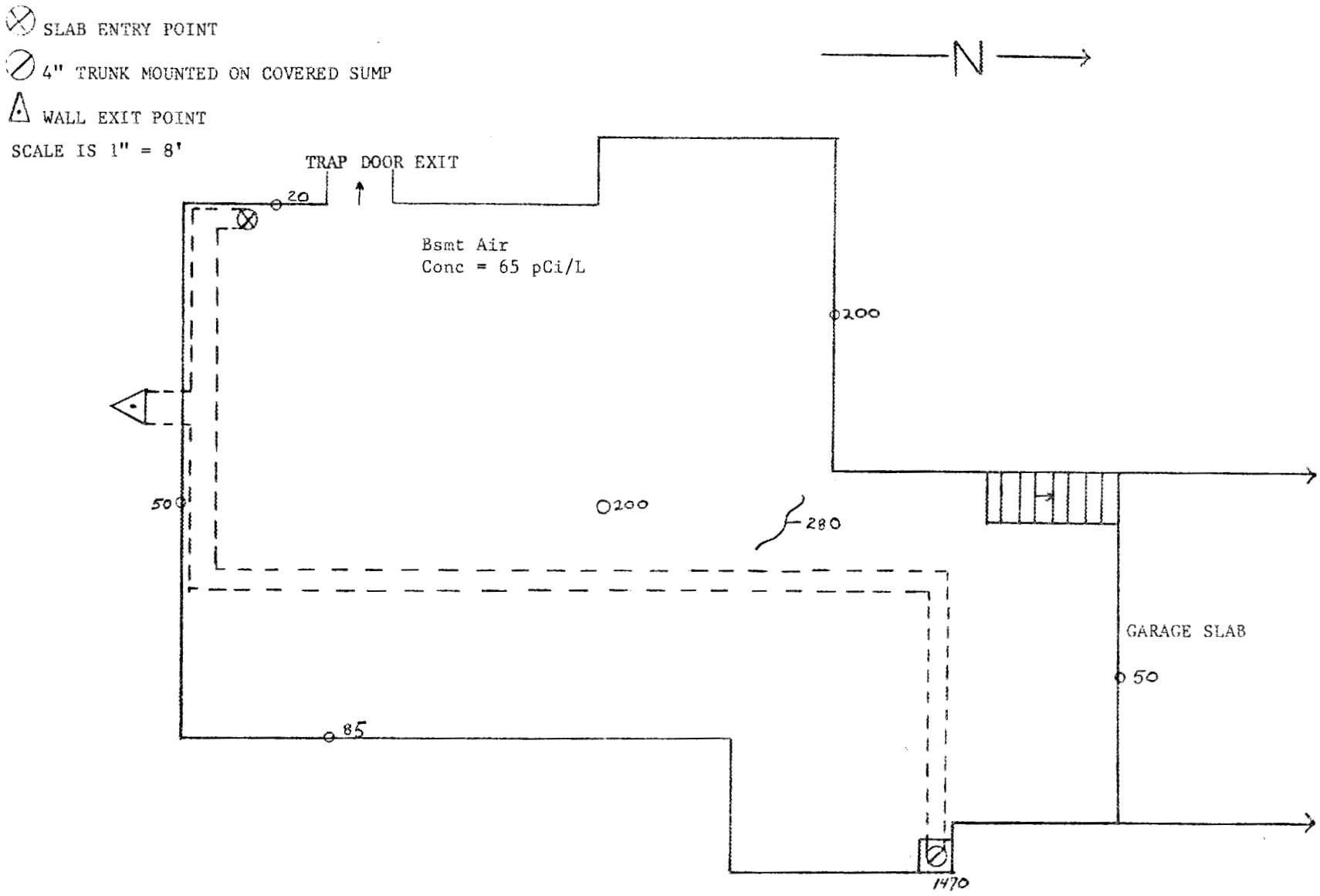
Figure 5.3



HOUSE #4 BASEMENT FLOOR PLAN

PU/CEES RN8719

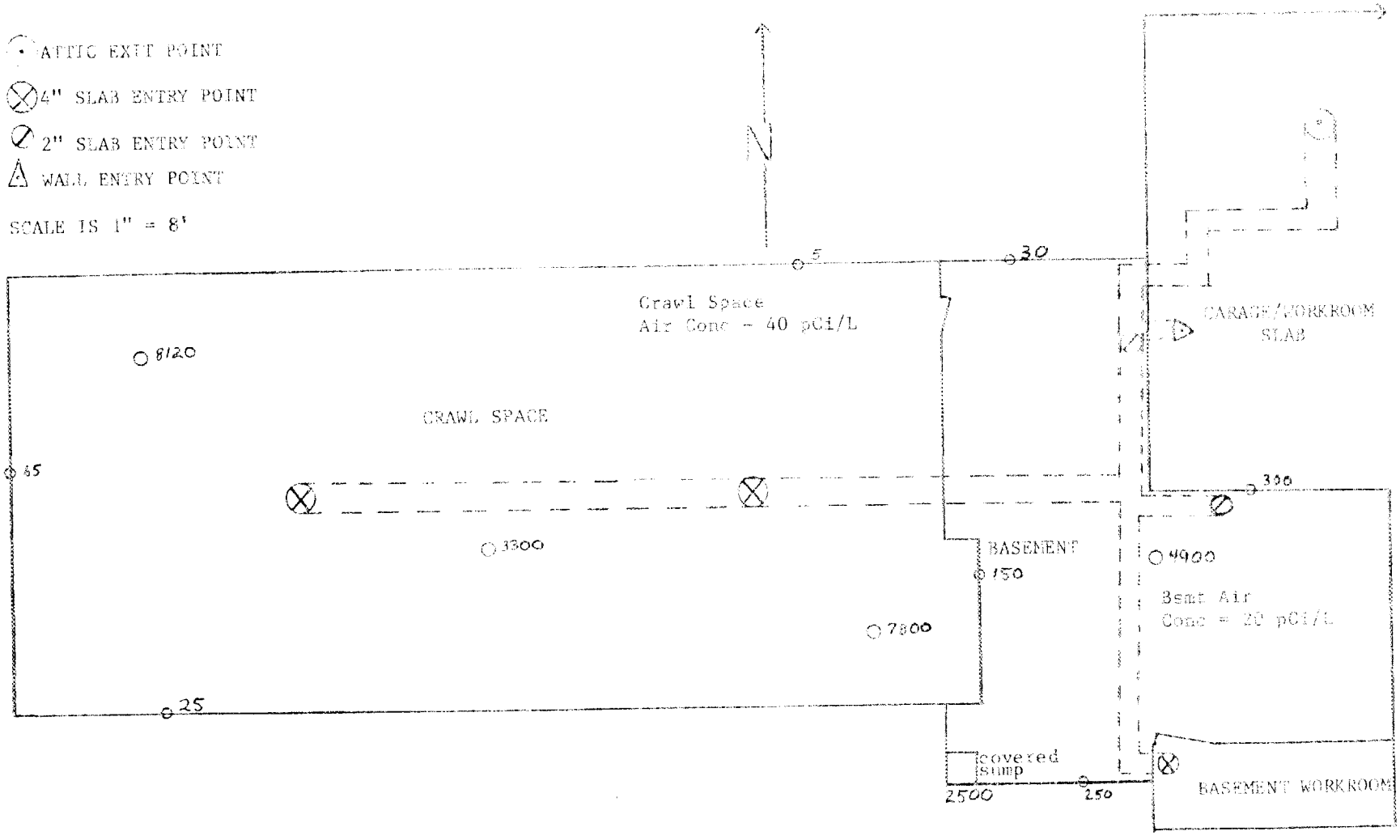
Figure 5.4



HOUSE #5 BASEMENT FLOOR PLAN

PU/CEES RN8720

Figure 5.5



HOUSE #6 BASEMENT/CRAWL SPACE FLOOR PLAN

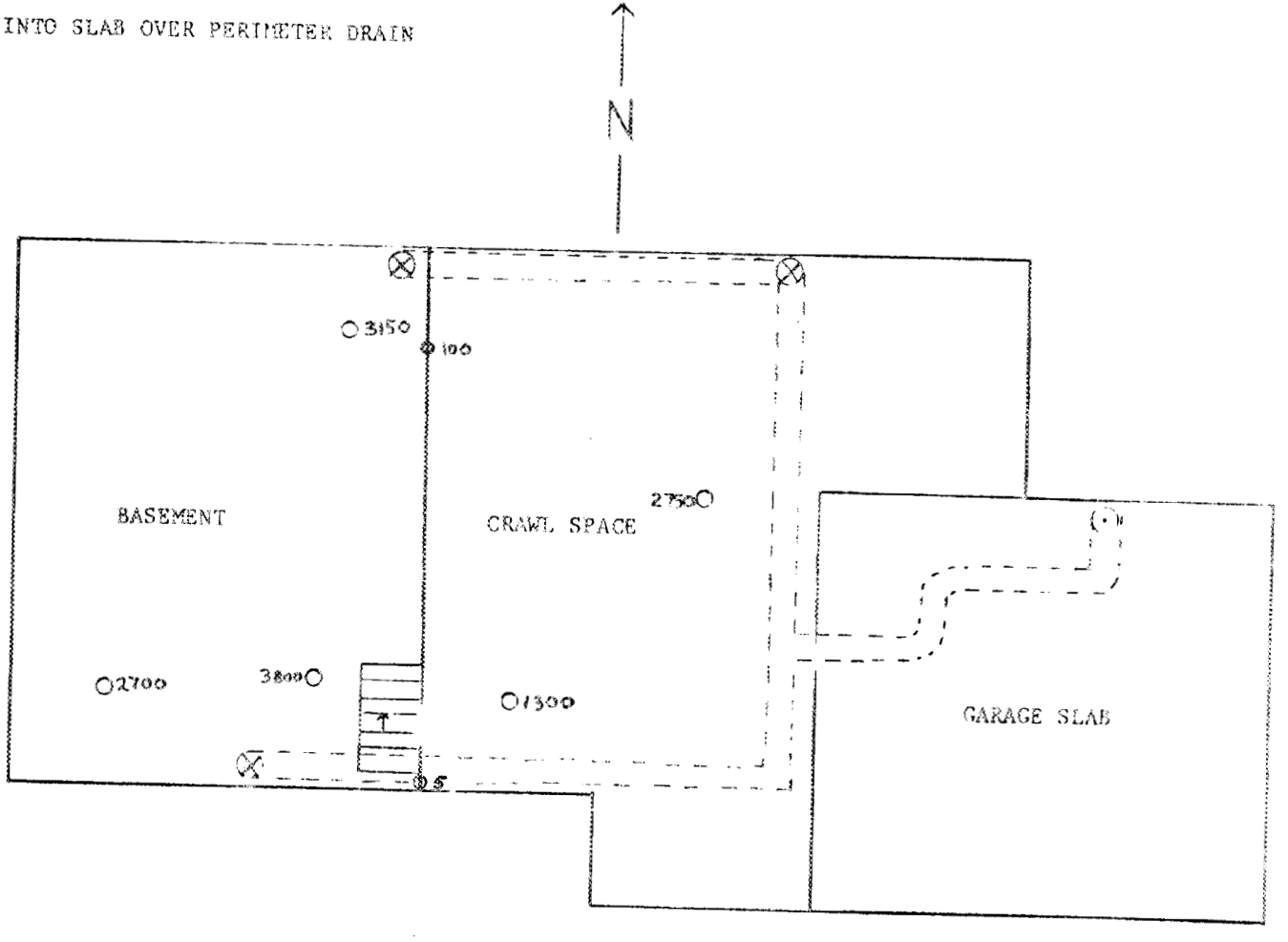
PU/CEES RN8721

Figure 5.6

GARAGE ATTIC EXIT POINT

4" TRUNK MOUNTED INTO SLAB OVER PERIMETER DRAIN

SCALE IS 1" = 8'



HOUSE #7 BASEMENT/CRAWL SPACE FLOOR PLAN

PU/CEES RM8722

Figure 5.7

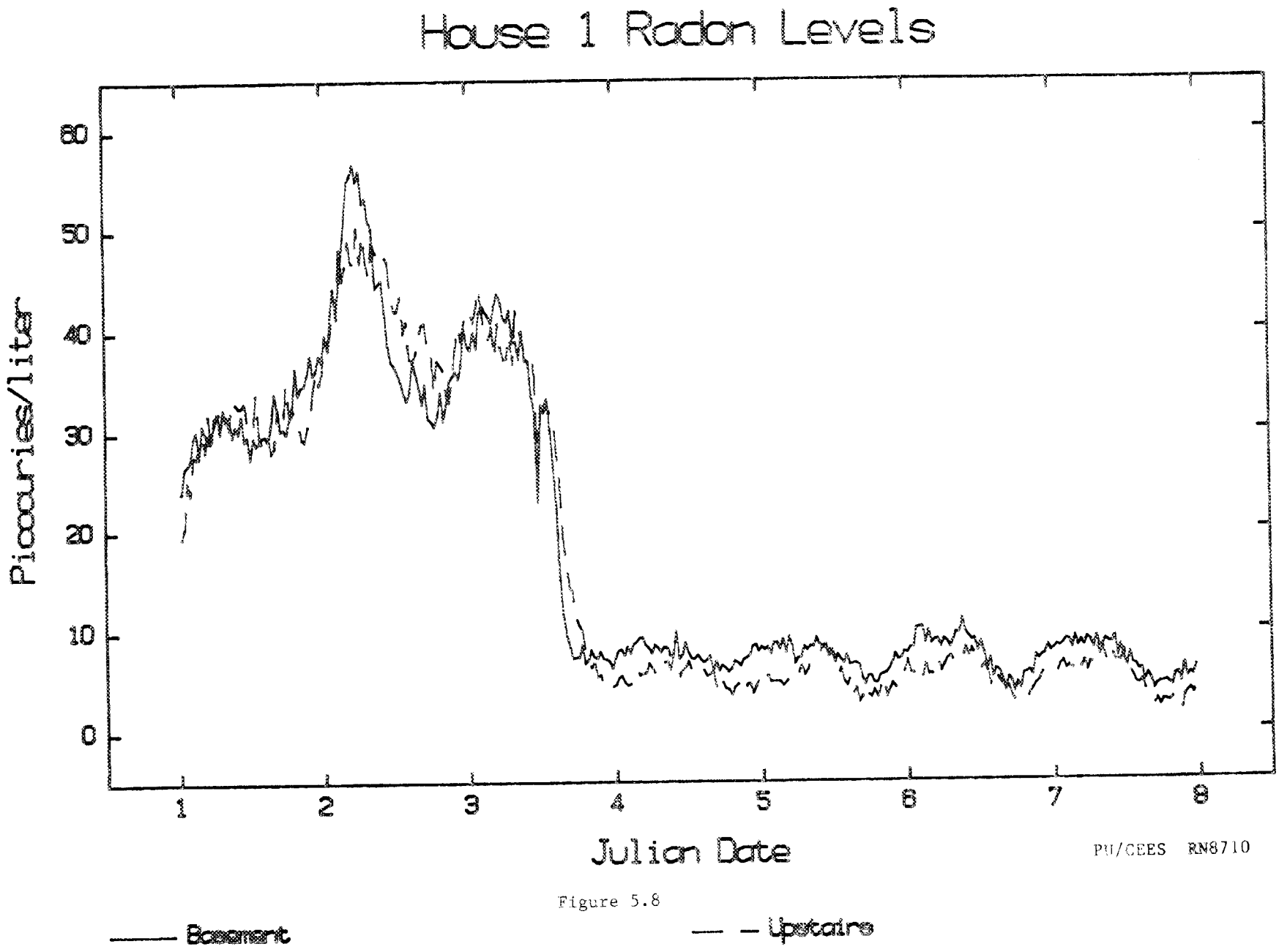

House 1 Radon Levels
Picocuries/liter
0
10
20
30
40
50
60
1
2
3
4
5
6
7
8
Julian Date
PU/CEES RN8710
Basement
Upstairs

Figure 5.8

House 3 Radon Levels
Picocuries/liter
225
200
175
150
125
100
75
50
25
0
360
361
362
363
364
365
366
367
Julian Date
PU/CEES RN8711
Basement
Upstairs

Figure 5.9

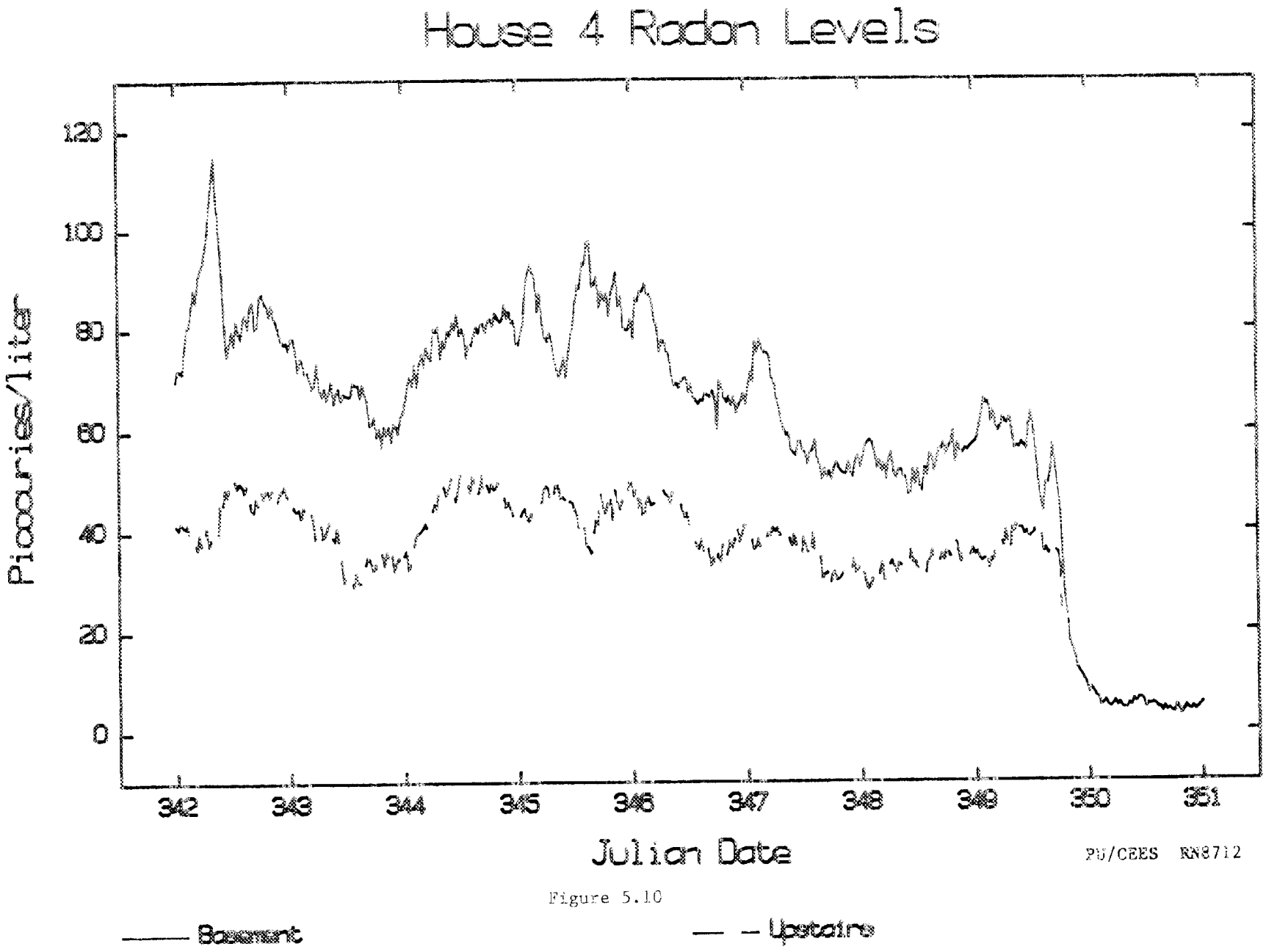
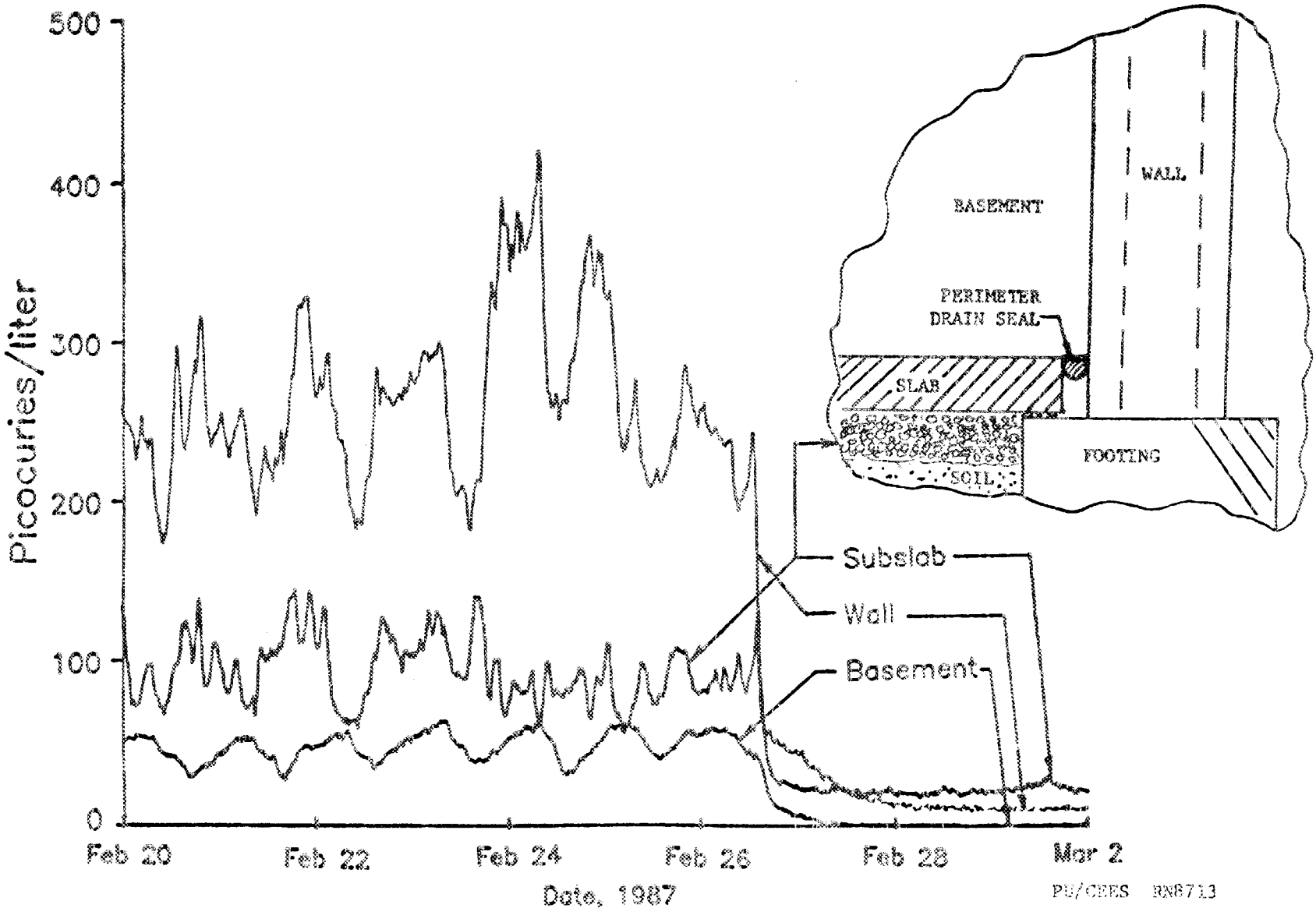

House 4 Radon Levels
Picocuries/liter
120
100
80
60
40
20
0
342
343
344
345
346
347
348
349
350
351
Julian Date
PU/CEES RN8712
Basement
Upstairs

Figure 5.10

House 5 Radon Levels



PU/CEES RN8713

Figure 5.11

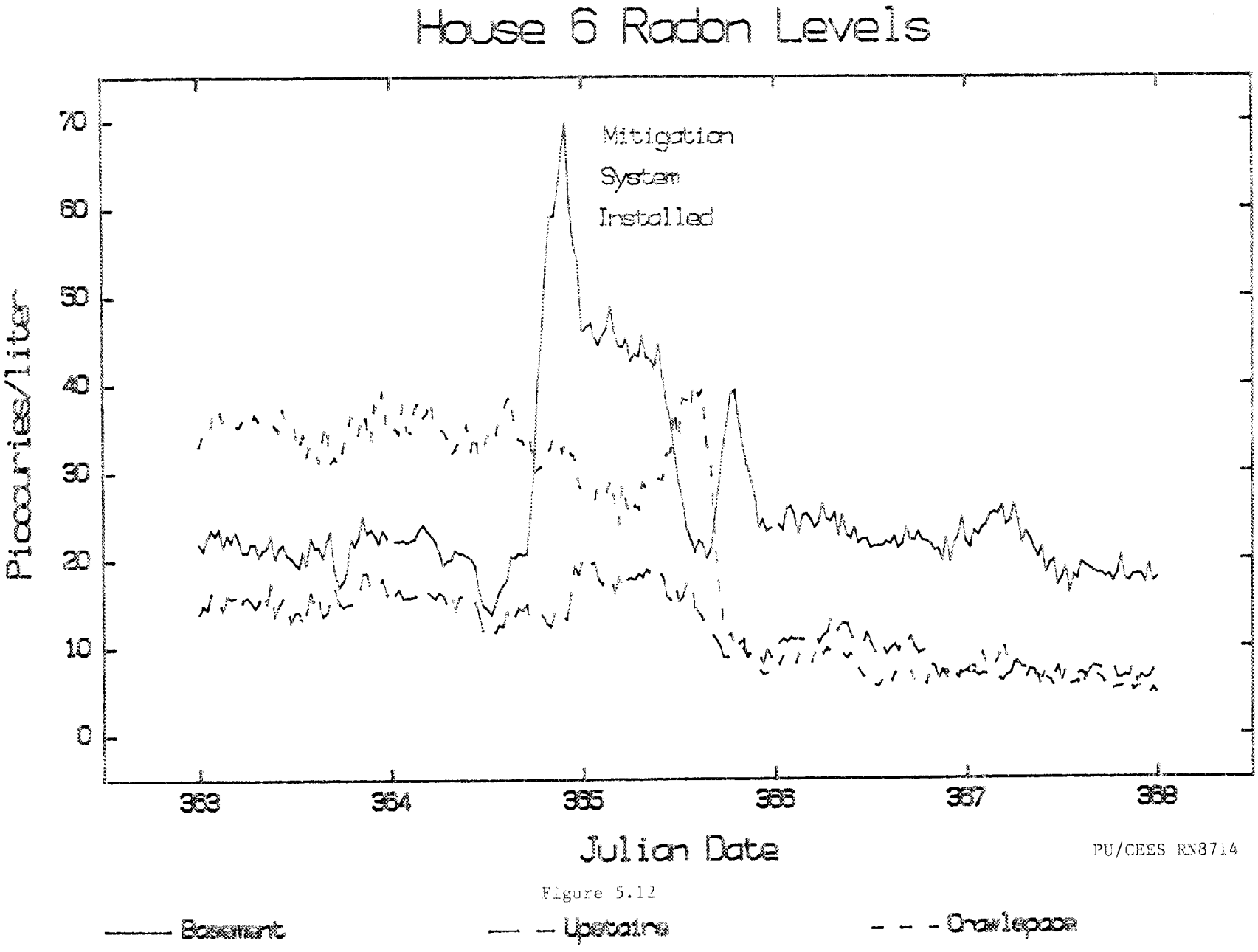

House 6 Radon Levels
Mitigation
System
Installed
Picocuries/liter
70
60
50
40
30
20
10
0
363
364
365
366
367
368
Julian Date
PU/CEES RN8714
Basement
Upstairs
Crawlspace

Figure 5.12

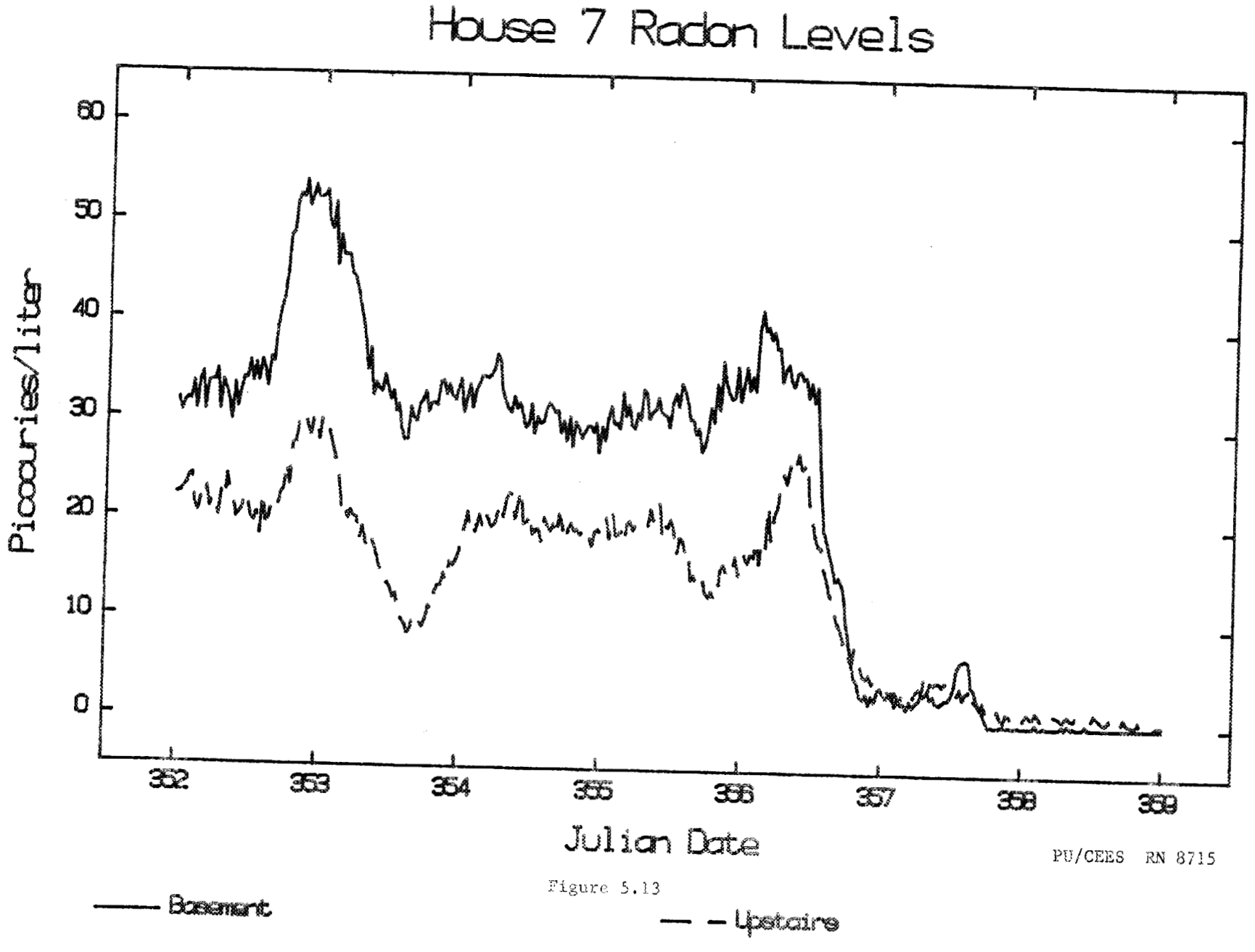

House 7 Radon Levels
Picocuries/liter
60
50
40
30
20
10
0
352
353
354
355
356
357
358
359
Julian Date
PU/CEES RN 8715
Basement
Upstairs

Figure 5.13

6. PRELIMINARY RESULTS OF PRE-MITIGATION AND POST-MITIGATION MEASUREMENTS

This section presents preliminary results obtained from the ORNL/Princeton radon study. These results will be further analyzed and discussed in the final project report and subsequent publications.

6.1 PRELIMINARY HOUSE CHARACTERIZATION DATA

6.1.1 Summary of Preliminary LBL Site Visit

A summary of the preliminary site characterization data for the ORNL/Princeton study houses, including control and alternate homes is summarized in Table 6.1. These data provide a summary of house substructures and pertinent modifiers, HVAC systems, and some preliminary data on house ventilation parameters and radon measurements.

6.1.2 Gamma Spectroscopy Measurements

A combination of pressurized ionization chamber and scintillation counter measurements of total gamma radiation was performed during site characterization studies to semi-quantify gamma levels. A summary of gamma spectroscopy measures made inside the study homes and on the surrounding property are given in Table 6.2.

Slight shielding from terrestrial gamma exposure is provided by the study houses. Assuming (1) a unity conversion of 1 Roentgen = 1 Rem, (2) a 90% occupancy rate indoors (i.e., 7884 h/yr), and (3) a 10% occupancy rate outdoors, annual gamma exposures of approximately 90-125 mrem are anticipated. This is of similar magnitude to Federal Radiation Council (FRC) and International Commission for Radiation Protection (ICRP) estimates of average annual population doses (i.e., <170 mrem).[2]

6.1.3 Geological Data and Report

A brief geological investigation of the test homes in the Clinton, New Jersey, area was conducted as part of our site characterization studies. The goal was a coarse geologic and radiological characterization of the formations underlying the areas surrounding the seven study homes to assess their potential as sources of environmental radon. The complexity of the geology in the Clinton area [3] precludes any definitive remarks about the geological features underlying the study homes from our brief investigation. There is clearly a need for further research.

The seven test homes are located at the southeastern flank of the so-called Reading Prong or New Jersey Highlands. The region is composed of numerous northeasterly trending, alternating ridges and valleys composed of principally metamorphic (metaigneous and metasedimentary) rock. The geologic ages of formations surrounding the study homes range from Triassic to Precambrian (i.e., 180 million to 1 billion plus years old). The exact number and precise identification of geologic formations in close proximity to the test homes has not been determined. The "High Bridge" quadrangle, for example, has not been thoroughly mapped by the U.S. Geological Survey (USGS) due to the complexity of the geology and the amount of overburden covering the outcrops contained within the quadrangle.

Houses #1 and #5 are identified from a geologic overlay of the New Jersey Department of Environment Protection (DEP)[4] as resting on Martinsburg shale of Ordivician age (i.e., about 500 million years old). However, these homes may be resting on a limestone bed within the Martinsburg Shale formation as reported by Banino et al. [3] Additional sampling and analysis is required in this area.

Houses #4 and #6 are identified on the New Jersey DEP geologic overlay[4] as resting on undifferentiated Precambrian gneissoid granites. Rock outcrops surrounding House #4 appear to contain potassium feldspar (orthoclase) as the primary feldspar within the rock. Rock outcrops in the vicinity of House #6 appear to contain plagioclase feldspar as the primary feldspar within the rock. In both cases the rock outcroppings are very heterogeneous with respect

to the total gamma measures. Approximate order of magnitude variation in radionucleides were observed (see Table 6.3). House #3 is located in an area of undifferentiated Precambrian gneisses. The home is in close proximity to an area that has been highly faulted according to a geologic overlay of the New Jersey DEP.[4]

Houses #2 and #7 are identified by the New Jersey State Geological Survey as resting on the Triassic Brunswick formation. Although there were no confirmatory rock outcrops in the area, excavated soils contained pieces of soft red shale similar to the description of the Brunswick formation.[3] It is hypothesized from U.S. Geological Survey data that the Brunswick, Lockatong and Stockton formations lie in order of increasing depth in the area of the study homes.

The results of radiological analysis of soil samples taken from (1) soils excavated for purposes of burial of Track Etch cups at the study homes, or (2) outcropings representative of geological formations are reported in Table 6.3. The data are subdivided geologically by the formations anticipated to underlie the study homes. On-site soil samples (i.e., 0-0.9 m depths) have radium contents ranging from typically 1 to 2.5 pCi/g. Representative samples taken from rock outcrops range as high as 84 pCi/g. For a few samples, radium content exceeds the Uranium Mill Tailings Remedial Action Level (i.e., EPA guideline) of 5 pCi/g for surface contamination and 15 pCi/g for subsurface contamination.[5]

House specific analysis of the soil radiological data in Table 6.3 yields several points of interest. Representative offsite samples from a postulated zone of limestone in the Martinsburg shale formation that is anticipated to underly House #1 yielded 2- to 4-fold higher radium content than soils from nearby zones. At House #4, it can be hypothesized that the sampled rock outcrop on the front/side of the yard extends under the home with increasing depth from the front to back yard. Both the rock/soil radium content (Table 6.3) and gamma counts (Table 6.4) decrease from the outcrop in the front yard to the backyard. Samples taken from Houses #4 and #6 and representative (offsite) gneissoid granites have highly variable radium content. Greater than order of magnitude variation is observed (1) between

onsite-representative and front/back yard soil samples and (2) between various constituents of offsite precambrian gneissoid granites. Radium content of soils taken from Houses #2 and #7 (i.e., presumably the Triassic Brunswick formation) are fairly homogenous, varying from 1.4 to 2.3 pCi/g radium. These results are 2- to 5-fold higher in radium content than offsite samples of Triassic Lockatong and Stockton formations.

Gamma scintillation and portable gamma spectrometer readings were obtained at (1) surface and subsurface locations at the study homes where holes were dug for the placement of Track Etch cups, and (2) locations where on/offsite representative samples were taken. A Victoreen Thyac III gamma scintillator and a Geometrics Exploranium GR410 portable gamma ray spectrometer were used.

The heterogeneity of soils anticipated from previous studies by the Department of Energy[6] are confirmed by the field gamma measurements as well as the soil analyses. Two to three orders of magnitude variation in radium content is observed in samples of soil and representative rock outcrops (Table 6.3). One to two orders of magnitude variation in total gamma counts were also observed for the data set provide in Table 6.4. For House #1, 20-fold variation in total gamma counts were observed between surface measures and measures at 0.8 m. Eight-fold variation in surface gamma counts were observed between front and backyard locations and a nearby offsite location at House #6. Variations of 15-80 K counts and 5-40 K counts were observed at individual outcrops onsite at Houses #4 and #6, respectively (Table 6.4). Including a radium-enriched Epler shale sample from the Clinton quarry, 20-fold variation in radium/thorium ratios are observed.

The complex variability of geological formations in the Clinton, N.J., area likely contributes to signficant home-to-home variations in indoor radon levels. House #6 is a specific example. Neighboring homeowners about 1/4 mile away obtained charcoal canister results of 3 and 10 pCi/L. Even within one set of property lines, 1 to 2 orders of magnitude variations in soil gas radon concentrations have been consistently observed (see Table 6.7, House #2). Many macro--and micro--geological factors could play a role in these observations. For example, there could be structural traps for uranium

concentration (i.e., folds and anticlines), fault zones where uranium has been concentrated, igneous intrusions within rock outcrops, variations in depth to bedrock and underlying formations, pathways with varying transport velocities for radon, and zonal distributions of uranium concentration caused by igneous or metamorphic processes. Further research is proposed in particularly the microgeological analysis of soils and soil/rock near the test houses to better understand point-to-point variation in radon availability and transport into the substructure.

6.1.4 Radon Analyses of Well Water

Well water samples from the five test homes which obtain their water from wells were analyzed for their ^{222}Rn content using the method of R. M. Key.[7] The analyses were performed by J. David Hohmann, under the direction of R. M. Key.[8] A summary of his findings are given in Table 6.5. In several of the homes an interesting relationship is observed between ^{222}Rn concentration and the anticipated, underlying, geologic formation, similar to that described by Hess.[9] Average results of 2800, 5800, and 25900 pCi/L were found in wells of Houses #3, #6, and #4, respectively. These homes are anticipated to lie over geologic formations of pre-Cambrian granitic rock. Houses #1 and #5 are anticipated to lie over a Martinsburg shale formation and had lower concentrations of 1300 and 800-920 pCi/L, respectively. The higher radon concentrations in well water appear to be associated with the granitic rock.

6.2 PERIODIC (NON-LOGGER) MEASUREMENTS

A variety of measurements have been taken periodically. These include measures of total radon progeny, respirable particulates, multi-zone constant concentration tracer gas analyses, additional house dynamics measures, soil characterization data, instrument calibration data and perfluorocarbon tracer data and are highlighted in the following section.

6.2.1 Working Level Measurements

A summary of the total working level data collected from 10/86 to 6/11 are listed in Table 6.6. A discussion of one week of this data compared to other logged parameters in House #5 during December, 1986, can be found in Section 6.5. Further analysis of these data is awaiting final calibration of the response time of the working level monitors as compared to the Wrenn chambers. A single point calibration of the working level monitors is discussed below in the section on instrument calibration data.

6.2.2 Respirable Particulate Samplers

Particulate sampling and analysis in the New Jersey studies consisted of intermittent, week-long sampling experiments for respirable particulates. A particulate sampling unit developed by the Harvard School of Public Health with an approximate 2.5 micron cut was used. The data, which are summarized in Table 6.7, has not as yet been related to available radon and radon progeny data. Evidence of smokers in Houses #2 and #7 is evident; order of magnitude higher particulate concentrations are observed in comparison to non-smoker homes. Comparisons of particulate concentrations in basement and upstairs locations are inconclusive.

6.2.3 Constant Concentration Tracer Gas Measurements

The CCTG measurements have been focused on House #5. Infiltration measurements were recorded hourly in two zones of the basement and seven zones of the living space. The seven zones consist of two bedrooms, the den, living room, dining room, kitchen, and the laundry room. Also, since the mitigation system was installed, the concentration immediately downstream of the mitigation fan has been monitored. This measurement provides information on the movement of basement air into the mitigation system.

The CCTG system was installed in House #5 on October 28, 1986, and began measurements on November 5. It was in place until January 12, 1987. The new version of the CCTG system was installed on February 10, 1987, and began operation on March 1 and has continued to monitor until the present time.

A second CCTG system was recently installed in House #7 on June 2 and began taking measurements. The system measures infiltration in nine zones of the house which consist of the basement, crawlspace, dining room, living room, kitchen, two first floor bedrooms, and two second floor bedrooms. Similar to House #5, the concentration downstream of the mitigation fan is being monitored to study basement air flow into the mitigation system.

Figure 6.1 gives an example of one analysis derived from use of the CCTG system in House #5. The top box plots the radon concentration in the basement (solid line) and upstairs (broken line) for 8 days during December, 1986. The abscissa marks the Julian day. The second box plots the air changes per hour for the basement (solid line) and the upstairs (broken line). The bottom plot shows the frequency of use of the central air heater fan in units of fraction of time on per half hour data point. When the fan comes on the basement, depressurization is induced and an associated increase in basement ACH is evident in the data. Associated with this is a consistent decrease in the basement radon concentration due to dilution from mixing the basement air with the upstairs air as well as increasing the amount of air infiltration into the basement. The amount of increase of air infiltrating the basement from the soil gas versus the outside air is one factor determining the relative change in basement radon concentration and is a subject of future investigations.

6.2.4 Blower Door Measurements

Blower door tests supply useful data on the general tightness of the building envelope. By placing the blower door in different exterior doors and performing the blower-door tests with interior doors open versus closed, information on the distribution of the envelope air leakage can be obtained. There are several ways of expressing the building envelope tightness; air changes per hour (ACH), equivalent leakage area (ELA), or specific leakage area (SLA).

The blower-door test determines the ACH by measuring the rate of air flow through the building envelope over a range of inside-outside pressure differences. A pressure difference of 50 Pascals (Pa), or 0.2 in. of water, has become one standard point of comparing one building to another. This

pressure difference is well beyond average pressure differences generated by the weather. The ELA approach uses the same pressure-flow data but calculates an equivalent leakage area at an indoor-outdoor pressure difference of 4 Pa. The SLA approach divides the leakage area by the building floor area, to give a dimensionless number. A qualitative measure of leakiness in single family detached houses is commonly discussed at a 50 Pa indoor-outdoor pressure difference. Single family detached houses at 50 Pa in the 20 ACH range may be classified as very leaky, 10-15 ACH range as leaky, 6-8 ACH range as desired, and 0-3 ACH as very tight. The blower-door data in Table 6.8 suggest that none of the seven test homes would be classified as tight construction. Only when Houses #3 and #4 are tested with basement doors open (using basement volume in the calculation, which follows Canadian practice) does the house fall in the desired tightness classification, 6-8 ACH.

Looking at all of the seven house data set, the one point that is very apparent is that there is generally good communication between the living space and basements. This is partially true because of the warm air duct systems in each of the houses. When there is good communication between the basement and upstairs, there is typically little change in the ELA when the door to the basement is opened. This is most notable in Houses #3 and #4 and to a lesser degree in Houses #1, #2 and #7 (see Table 6.8). In the calculation of ACH, since the basement is already communicating to the living space, the mathematical addition of the basement volume reduces the ACH number proportionately.

6.2.5 Soil Characterization Studies

Soil characterization measures have consisted primarily of (1) radiological analyses (see Table 6.3), (2) quasi-seasonal exposures of Track Etch cups (see Table 6.9), (3) intermittent grab samples of soil gas (see Table 6.9), and (4) intermittent field measures of soil permeability (see Table 6.10). Much of the data are unfortunately characterized by less than desirable reproducibility between different sampling periods at individual houses for each methodology. Although soil gas concentrations can be variable, some sources of measurement inconsistency are readily identified.

The radon soil-gas grab samples and Track Etch cup results show large intermethod and inter-sampling period discrepancies. For the grab samples, the comparatively low grab sample results taken prior to April, 1987, (see for example sub-100 pCi/L data for Houses #1, #4, and #5) likely resulted from leakage in the sampling apparatus or inadequate sampling periods during the measurement of often highly impermeable soils. Reproducible results from back-to-back grab sampling were achieved in April, 1987, by careful reductions in leaks in the sampling apparatus and extended sampling periods (e.g., 3-30 min to fill the Lucas cell). Grab sample radon concentrations from April vary by approximately 50-fold between study homes, and as much as 18-fold between sites at a single home (see House #5).

The preliminary Track Etch cup results show approximate order of magnitude disparities between fall and winter/spring exposures. Replicate analyses of the Track Etch cups, incorporated in the spring/summer exposures, should provide a better estimate of replicate precision. Soil Track Etch results generally do not compare with those of grab sampling. For example, an approximate 30-fold increase in radon from the front-to-back yard is observed at House #2 determined via grab sampling. Track etch cup data from the front and back yard are very similar. The opposite case is observed for House #6. Front-to-back variation is less than 2-fold for grab sample measures but 14-fold for the Track Etch cups.

Soil permeability has been calculated for available data using the following expression

$$K\ (cm^2) = (2.5 \times 10^{-7}) * \text{flow (L/min)}/[\text{pressure (cm } H_2O) * \text{tube radius (cm)}]$$

where the constant contains conversion coefficients and the viscosity of air. This expression is used by the LBL research team and comes from the research report by Arthur Scott et al.[10] The results show a dependence of K on applied pressure, which has also been seen in the LBL data. This has prompted a re-examination of the mathematical form for K (communication with LBL personnel). Additional uncertainty is also associated with data taken with the highest flow rotometer, reading at a maximum flow of 2.5 L/min. As a result, we are currently redoing the calibration curve of the flowmeter as well as repeating

soil permeability tests at all of those test locations. The permeability constants reported in Table 6.10 are in the same range as those which have been evaluated by LBL in their Piedmont study homes, i.e., 1.0×10^{-6} to 1.0×10^{-9} (private communication, Brad Turk, LBL).

6.2.6 Instrument Calibration Data

Calibration of individual components of the house monitoring packages and supporting instrumentation have been performed in both laboratory and field environments. Calibration checks have received heavy emphasis during installation and QA/QC trips of ORNL personel to the study homes in October, January, and April, as well as during visits to the test homes by Princeton personnel. A summary of quantitation and precision analyses for selected parameters is given in Tables 6.11. and 6.12. Field checks of differential pressure zeros indicate coefficients of variation of typically <1% (i.e., about 0.25 Pa) over the entire study. Calibration (i.e., span) checks performed at the beginning of the study will be repeated when the sensors are removed from the homes. Temperature data show typically $\leq$0.4°C variation on average in multiple checks against NBS calibrated thermometers. Precision (i.e., coefficient of variation) is generally $\leq$0.7°C. Relative humidity data show approximate 1 to 7% RH absolute variation in multiple checks against calibrated hygrometers. Similar levels of precision are observed. Thus far, these calibration data are quite acceptable.

Calibration data for the Wrenn chambers are thus far very encouraging. Wrenn chambers that have not undergone adverse environmental exposures or radical physical/electronic repairs show generally consistent calibration factors (i.e., $\pm$5-15%) between 10/86 (i.e., prior to installation) and selective calibration checks from 1-5/87. These calibrations represent cross comparisons between three laboratories including ORNL, DOE's Environmental Monitoring Laboratory in Manhattan, and EPA's Eastern Environmental Radiation Facility in Montgomery, Alabama. The check source data indicate very small changes in Wrenn response from 10/86 to 4/87. The average ratio of [4/87]/[10/86] data is 0.98 $\pm$ 0.06. Complete zero, span and check source data will be taken following the removal of the Wrenn chambers from the study homes and return to Oak Ridge.

The Eberline working level monitors (WLMs) were calibrated in the DOE Environmental Measurements Laboratory in Manhattan, in January, 1987. The instruments were left overnight in the EML chamber during the worst snowstorm in 10 years. A calibration of radon progeny at a single steady-state concentration was achieved. The counting efficiency for each monitor (i.e., counts per decay event) was determined using a Thorium check source as a standard. This counting efficiency and measured air flow rates are used to calculate a calibration constant, as described in the Eberline manual.

$$\text{Calibration Constant} = [\text{Flow (L/m)} * \text{Efficiency of WLM}]/5.6 \times 10^{-5}$$

The resulting calibration constants (CC), one each for each monitor, were applied to the raw data obtained in the calibration chamber at EML to yield working level data as a function of time. The calibrated data from the WLMs in most cases deviated only slightly from the EML measure of the progeny levels. This deviation was expressed as the ratio of the working level data measured with the WLMs divided by the EML results. This ratio was then applied to the original CC calculated from measured check source and air flow data to refine the calibration for each monitor to more accurately reflect the concentration of radon daughter levels in the EML chamber. Both the original CC and the 'corrected' CC for each WLM, plus the measured air flows and counting efficiencies, are summarized in Table 6.13. As a final step in the calibration process, the flow rate (i.e., L/min) through the WLM recorded at EML was factored out of the corrected CC. As a result, flow rates recorded at past or future measurement sites can be applied to individual data sets. This step is necessary because the performance of the WLM pumps have deviated noticeably during the study. The flow-independent calibration constant [CC' {(cpm/working level)/(L/min)}], summarized in Table 6.13, can be applied using the following equation to convert raw counts from the WLMs into working levels:

$$\text{Working Levels} = \frac{\text{raw counts/min} - \text{background counts/min}}{\text{CC' (counts/(WL*L))} * \text{flow rate (L/min)} * \text{sample interval(min)}}$$

6.2.7 Perfluorocarbon Tracer Analysis

Each of the houses has been monitored with PFT systems since the instrumentation packages were installed at the end of October. The PFT measurements have been made over typically two week periods uninterrupted (except for short time periods during mitigation installation) from the time of installation to the present. The samplers from the tests through May 22 have been analyzed and results of the measured volume recorded. The program to compute the air flow rates from the measured tracer gas concentrations and source rate has been completed. Unfortunately, there is some uncertainty of the makeup of the gas used to calibrate the gas chromatograph, which has prevented the final computation of the air flow rates for the houses. This problem will be solved during the summer of 1987 and the final data will be distributed at a later date.

The method for looking at the PFT data with the other parameters consists of averaging the continuously logged parameters over each time period that the PFT's were active in each house, (which varied slightly between each house). Figures 6.2 - 6.8 show this averaged data for each home, taking into account the specific PFT time periods for each home. The top box in each figure plots the radon concentrations in the basement and upstairs. The second box displays the relative humidity and HVAC use. The third box shows the three logged temperatures at each house, basement, upstairs and outside. The fourth box plots the differential pressures between the basement and the outdoors, subslab, and upstairs. The points on each line represent the average of that parameter during the given PFT time period. The lines across the top of the top box on the page show each PFT time period. Shown on the abscisa of the lowest box are the Julian dates, starting from Julian day 280 (October 7, 1986) to day 155 (June 4, 1987).

The seasonal trends are evident, with the outdoor minimum temperature occuring in late January, lowered humidity in the winter, and increased HVAC usage in the winter. The installation of the mitigation systems in all but the control house (#2) is evident by the decreased levels of radon and larger basement - subslab pressure differences.

Figures 6.9A - 6.9B are similar to those described above except for the second box, which here displays the basement air infiltration rate (solid line) and the radon source strength (broken line). The radon source strength is obtained by assuming the radon gas behaves similarly to the PFT tracer gas. The relationship between the average emission rate (or source strength) of the tracer gas and the average tracer gas concentration is given by:

Source (PFT in basement) = Average Concentration (PFT in basement) * K,

where K = a function of all of the air flows in the building. In the PFT experiments, the source term is known and the average concentration is measured. The value of K can then be computed and used in the same equation, with radon source and average concentration replacing the PFT terms. Knowing the average concentration of radon in the basement from averaging the Wrenn chamber data, i.e., the top box on the figure, the radon source strength can then be estimated.

The results for Houses #1 and #2 are shown in Figures 6.9A and 6.9B, although it should be emphasized again that results from the PFT analysis are preliminary, with final conclusions pending final calibrations. The radon source rate into the basement for House #2 (the control house, which will not be mitigated until July, 1987) shows a seasonal trend with a strong winter peak. However, since both the radon source rate and basement infiltration rate (the major determinant of K) increase during the winter, the radon concentration does not have a large winter peak. In fact, there is not a strong seasonal component in the radon concentration. House #1 shows behavior similar to House #2 for the basement air infiltration rate. Instead of a seasonal dependance, the radon source strength for House #1 decreases and remains low after mitigation. This indicates that the reduced radon levels in the basement are due to decreased source rates brought about by mitigation and not due to increases in infiltration levels.

6.3 INDOOR MONITORING STATION RESULTS

The data acquisition and reduction process has been completed within limits of available calibration data for all seven study houses and the weather station through April of this year. Simple summary statistics (i.e., mean, minimum, maximum, and standard deviation) have been calculated that provide a preliminary view of the status and technical findings of the project. A full quality control review of the data has not been completed at this time. The weekly summary data (i.e., principally mean values) are presented here in graphical form (Figures 6.10 to 6.30), and analyzed on a house-by-house and parameter-by-parameter basis. Complete summary statistics are presented in Tables 9.1 to 9.28 in Appendix 9.B.

The following discussion clarifies the presentation of data in Figures 6.10 to 6.30 and may be applied uniformly to the results from each study home. The mean temperatures (°C), differential pressures (Pa), radon levels (pCi/L), RH (%), and HVAC duty cycle (fraction of time in off condition) all result from single electronic probes placed in specified locations. Positive differential pressures represent elevated pressures in either outdoor, subslab, or upstairs locations relative to basement pressures. Negative differential pressures correspond to elevated pressures in the basement. The minimum, mean, and maximum radon levels are reported for upstairs and basement locations to provide the average and extremes of potential radon exposures before, during, and after mitigation. The reported HVAC probe response represents the fraction of time that the central air handling unit is off during a 30 min period and is thus inversely proportional to duty cycle. Gaps in the data (see for example Week 4 of Houses #1 and #2, i.e. A and B) indicate predominantly an unresolved glitch in the dBASE program for calculating summary statistics.

The temperature data show fairly consistent curves for each study house for basement, upstairs, and outdoor locations. Houses such as #4 and #6 (see Houses D and F in Figures 6.19 and 6.25) have highly conditioned basements with temperatures very similar to upstairs levels. Houses #1 and #2 (see Houses A and B in Figures 6.10 and 6.13) have poorly conditioned basements

during winter periods. Relative humidity and HVAC operation show expected seasonal trends of decreased RH and increased HVAC duty cycle (i.e., decreased off time) during the winter season. However, the peak HVAC duty cycle (i.e., weekly average) varied greatly from about 25% in House #1 (see House A in Figure 6.12) to about 80-90% on in Houses #2 and #4 (see Houses B and D in Figures 6.15 and 6.21).

The differential pressure data show the impact of both seasonal processes and active mitigation measures depressurizing the subslab regions. The control House #2 (i.e., House B with mitigation delayed until 7/87) shows winter/seasonal basement depressurization relative to outdoor locations averaging about 4.5 $\pm$ 1 Pa (Figure 6.13). The impact of on/off operation and adjustment of depressurization measures is obvious for the rest of the study homes as negative basement-subslab pressure differentials. A range of weekly-average subslab depressurization levels (at the sensor tube locations) from 1-4 Pa in Houses #3, #4, and #7 (see Houses C, D, and G in Figures 6.16, 6.19, 6.28, respectively) were generally effective in reducing basement radon levels to sub 4 pCi/L levels, whereas 10-17 Pa subslab depressurization was required at House #6 (see House F in Figure 6.25) with more complex pumping and exhaust systems.

A broad range of downstairs and upstairs pre-mitigation radon levels are observed in most of the study houses. For example, in House #3 half hour averages (i.e., plotted minimum and maximum half-hour average values, House C, Figure 6.17) range from about 20 to 180 and 10 to 90 pCi/L in the basement and upstairs levels, respectively. Pre-mitigation radon levels in the control House #2 are among the least variant and consistent between basement and upstairs levels (see House B, Figure 6.14). Weekly average radon levels of approximately 2 to 24 pCi/L are observed in both basement and upstairs locations.

The most effective radon mitigation systems are observed in Houses #1, #3, #4, and #7 (see Houses A, C, D and G in Figures 6.11, 6.17, 6.20, and 6.29, respectively), particularly towards the end of the weekly summary data. Weekly mean and (half hourly) maximum basement and upstairs radon levels are typically maintained below 1-2 pCi/L with the mitigation systems in operation

(see Tables 6.3, 9.11, and 9.15). At such low levels, the incomplete calibration and zero data used for calculation of the radon levels become a potentially large source of error.

6.4 WEATHER STATION RESULTS

The following discussion clarifies the presentation of the weekly summary data in Figures 6.31 - 6.34 for the weather station located in the backyard of House #5. The mean temperatures (°C), RH (%), precipitation (0.01 in./30 min), barometric pressure (bars), wind speed (m/s), and radon levels (pCi/L) inside the outdoor instrumented flux monitors all result from single electonic probes in specified locations. The outdoor flux monitors are an experimental technique to measure radon emanation from the soil as a function of weather parameters in a location decoupled from the test home. Analogous to the treatment of the weekly radon data for the houses, the minimum, mean, and maximum radon levels are plotted for the outdoor flux monitors for comparison purposes.

Seasonal effects in the available weather data are most clearly observed in the dip in the soil temperature, and in the temperature and RH data both outdoors and inside the outdoor flux monitors during the winter months. No analogous, clearly discernable seasonal affects are observed in the outdoor flux monitors. However, with the current design of the outdoor flux monitors, the data needs to be grossly corrected for wind speed effects on the air exchange rate of the chambers. The weekly-average wind speed typically varies over a limited range from about 1.1 to 2.5 m/sec. At House #5, the dip in precipitation during the winter months is believed to be caused in part by the freezing of the tipping bucket with snow and ice.

6.5 RELATING RADON LEVELS TO ENVIRONMENTAL PARAMETERS

The continuous monitoring of radon levels and other physical parameters at half-hour intervals provides an opportunity to investigate various relationships. The four figures we have chosen to display here each plot radon levels across one week; each figure also shows the time-dependence of other physical variables, averaged again over half-hours, for the same week.

The variables displayed are ones which could plausibly be considered to have a causal relationship to radon concentration. We want to emphasize, however, the anecdotal character of these observations. Only a few time-series analyses have been performed, and the full data set has not yet been searched systematically to see how frequently these suggestive patterns are observed.

Figure 6.35 shows a diurnal variation in basement radon concentration in a single house (Figure 6.35a) in cold weather (February 1987). The peak and valley concentrations differ by a factor of two (60 pCi/l vs 30 pCi/l), with the peak concentration occurring at 7:30 a.m. (weekly average). Figure 6.35b shows the fraction of time that the HVAC fan is running each half hour; the HVAC fan is associated with an electric heat pump and powers a forced air distribution system. The HVAC fan is off during the night (this family sets back the thermostat setting manually but regularly at bedtime), and between 7:30 and 8:30 a.m., after the thermostat setting is raised, the HVAC fan is on nearly continuously (about 90% of the time, averaged over the week). One can plausibly imagine that the basement radon concentration increases during the night by inflow from the subsoil, with reduced removal mechanisms, and that when the forced air distribution system comes on, the basement radon is redistributed upstairs. In fact (not shown) the radon concentration upstairs does rise in the morning.

Figure 6.35 also shows two of the pressure differences which have been continuously monitored in the Piedmont study. The air below the slab is seen to have a pressure greater than the basement air throughout the week (Figure 6.35c); this pressure difference is the principal mechanism in cold weather for driving radon into the house. This pressure difference displays spikes synchronous with the HVAC fan operation, a plausible effect reflecting the additional basement depressurization which accompanies the operation of the distribution system (e.g. leaky return ducts). Figure 6.35d shows the pressure difference between the outdoor air and the basement air. The same spikes are seen when, presumably, the basement air pressure drops during HVAC operation, but there is an additional prominent large-scale pattern during February 23-25, presumably weather related, which has no obvious effect on the radon variable. More detailed analyses will be performed and presented in the final project report.

Figure 6.36 shows the apparent impact of "rain spikes" on radon levels in three houses (Figures 6.36a, 6.36b, 6.36c). Here, outdoor weather does have a pronounced effect on basement radon levels. Figure 6.36d shows two of the weather channels (barometric pressure and amount of rain). The rainstorms of November 18 and 20, 1986, precede the rain spikes by a few hours and are accompanied by a fall in atmospheric pressure. There are several possible conjectures about the cause and effect here. Further work will be needed to clarify this mechanism of radon inflow, starting with a more systematic analysis of the data already in hand.

Figure 6.37 shows very recent data in the post-mitigation period for House #5, shown previously in Figure 6.35. During a five-day stretch in the middle of the week displayed here, the owners went on vacation and agreed to allow us to shut off their mitigation system, a subslab ventilation (SSV) system. Figure 6.37a shows the basement and living area radon concentrations and demonstrates the success of the mitigation system: levels in both basement and living area are close to zero when the mitigation system is running. Figure 6.37b shows the subslab-basement pressure difference during the same week. It is about -12 Pa when the SSV is running, and between +1 and +2 Pa when the SSV is off. Throughout this period (not shown) the HVAC is off, and the difference in pressure between subslab and basement shows almost none of the diurnal behavior seen in Figure 6.35c. The basement radon concentration, however, develops a diurnal pattern reminiscent of Figure 6.35a, although of reduced amplitude, still peaking in the morning. Something other than HVAC operation, evidently, is responsible for a portion of the cyclic character of the driving mechanism for this house. One can only conjecture that the daily outdoor temperature (Figure 6.37c) couples to this driving mechanism, in view of its close tracking with the basement radon concentration. Note in particular April 18, 1987, when the typical daily temperature cycle was suppressed and the basement radon level was suppressed as well.

Figure 6.38 shows radon (Figure 6.38a) and radon progeny (Figure 6.38b) concentrations in the basement air of House #3. The equilibrium ratio is plotted in Figure 6.38c (i.e., normalized to 0.01 WL/(pCi/l), the ratio at secular equilibrium). Figure 6.38c shows that the equilibrium ratio exhibits

considerable structure over a week, and Figures 6.38a and 6.38b show that this phenomenon is the result of somewhat uncorrelated time dependences of the concentrations of radon gas and radon progeny. Figure 6.38d shows the time dependence of the run time of the furnace fan (percent on each half hour), which is a strong candidate for an important explanatory variable, in that it appears to have a definite effect on both the radon gas concentration and the radon progeny concentration. Specifically, (1) the radon gas concentration in the basement increases when the furnace is running (the opposite of what was seen in the house with a heat pump, whose data are shown in Figures 6.35 and 6.37, perhaps because furnace operation decreases the basement pressure, permitting further inflow of soil gas, and (2) the radon progeny concentration in the basement decreases when the furnace is running, perhaps because the progeny plate out on the ducts, filters, and other components of the forced air distribution system. Careful time series analysis of the extensive data sets now in hand will address this issue.

Table 6.1. Selection of study, control, and backup houses for mitigation: summary of house parameters and preliminary screening data.

House No.[a]	Sub-Structure	Modifiers	HVAC	Radon[b] (pCi/L)	ACH (h^{-1})[c] 50 Pa.	Surface Leakage Area[c] (cm^2/m^2)	Soil Perm.
I	Basement W/Slab, Att.Gar. W/Slab	Float.Slab, Dry Well	Cent. F.A., Gas	B:73 U:16	18.9	10.2	Mod.
II[d]	Basement, Att.Gar. W/Slab	Sump	Cent. F.A., Gas, W/AC	B:24 U:16 A:15	2.7	1.5	Mod.
III	Basement, Att.Gar. W/Slab	Float.Slab, Dry Well	Cent. F.A., Oil	B:156 U:49 A:60	10.1	4.8	Mod.
IV	Basement W/Slab, Att.Gar. W/Slab	2 Sumps	Cent. F.A., Oil, W/AC, Auto Setback	B:103 B:128 U:31	10.0	4.6	Very Low
V	Basement, Att.Gar. W/Slab		Cent. F.A., Elec. Ht Pump, Oil Back, W/AC	B:60 U:25 U:36	3.6	3.6	High
VI	Basement W/Crawl Att.Gar. W/Slab	2 Ht Exc. Sump	Cent. F.A., Oil, W/AC, Auto Setback	W Ht Exc B:25, U:14 W/O Ht Exc B:30-35	14.6	7.8	High
VII	Basement W/Crawl Att.Gar. W/Slab	Float.Slab, Sump (Part. Seal)	Cent. F.A., Gas, W/AC,	B:36	10.6	5.2	Very Low
VIII[e]	Basement W/Crawl	Flr. Drains Sealed	Hot Water	B:57 U:54 U:21	31.3	17.9	Low

[a] house numbering convention is I - VIII, 1 - 8, or A - H.
[b] B = basement or crawlspace, U = 1st floor above grade, A = 2nd floor above grade
[c] preliminary LBL data
[d] control house
[e] alternate house

Table 6.2. Results of total gamma measurements during site characterization

House	PIC (uR/h)[a]	Ave Indoor (uR/h)[b]	Ave Outdoor (uR/h)[c]
1	12.0	12.6 ± 0.8	13.7 ± 0.4
2	8.9	9.9 ± 1.2	15.3 ± 1.0
3	15.5	14.0 ± 2.1	15.3 ± 1.6
4	12.0	13.4 ± 2.0	22.0 ± 1.3
5	12.0	12.7 ± 1.8	15.2 ± 1.3
6	12.8	14.2 ± 3.8	15.6 ± 3.9
7	9.8	10.2 ± 1.5	13.8 ± 1.1

[a] 1-4 hour pressurized ionization chamber measurements in center of basement

[b] ≥8 scintillation counter measurements in basement and upper level(s)

[c] ≥4 scintillation counter measurements outdoors

Table 6.3. Average Radium-226, Potassium-40, Thorium-232 (pCi/g) measured in soil samples taken from the property of study homes[a] and representative rock formations in both onsite and offsite locations.

House, Sample	Location	Soil Type	Radium	Potassium	Thorium
	A. Homes Tentatively Identified as Overlaying Martinsburg Shale				
1 S1	backyard		1.73	59.70	1.16
1 S2	frontyard		1.15	61.80	0.92
1 R1	rep. offsite	Limestone Bedb	0.64	14.75	0.79
1 R2	rep. offsite	Limestone Bedb,c	2.41	7.37	0.66
1 R3	rep. offsite	Limestone Bedb	1.04	75.50	1.14
1 Q5	rep. offsite	Martinsburg Shale	0.95	31.40	1.24
5 S1	backyard		0.77	50.70	1.07
5 S2	frontyard		0.68	49.10	1.18
	B. Homes Tentatively Identified as Overlaying Undifferentiated Precambrian Gneissoid Granites				
3 S1	backyard		0.73	38.65	0.96
3 S2	frontyard		1.13	33.70	1.43
3 R1	rep. onsite		0.98	30.60	0.24
4 S1	frontyard		7.37[d]	27.95	2.17
4 S2	backyard		3.33	22.05	1.84
4 R1	rep. onsite	Undiff. Precam. Gneiss	84.30[d,e]	43.50	18.70
6 S1	frontyard		1.57	28.85	0.67
6 S2	backyard		4.10	28.85	2.04
6 R1	rep. onsite	Undiff. Precam. Gneiss	40.95[d,e]	12.55	1.17
Q6	rep. offsite	Quartzo-Feldspathic Gneiss	0.82	83.35	1.18
Q7	rep. offsite	Amphibolite	10.30[d]	34.30	9.94
Q8	rep. offsite	Albite-oligoclase gran.	0.16	39.65	0.26
Q9	rep. offsite	Albite-oligoclase quartz gneiss	0.78	34.50	2.48
Q10	rep. offsite	migmatite	1.45	41.35	2.24
	C. Homes Tentatively Identified as Overlaying a Triassic Brunswick Formation				
2 S1	backyard		1.52	28.55	1.84
2 S2	frontyard		1.70	22.75	1.58
7 S1	backyard		1.43	42.40	1.85
7 S2	frontyard		2.26	43.35	1.88
Q1	rep. offsite	Triassic Stockton form.	0.91	22.85	1.39
Q2	rep. offsite	Triassic Lockatong form.	0.49	20.20	0.43

Table 6.3. Average Radium-226, Potassium-40, Thorium-232 (pCi/g) measured in soil samples taken from the property of study homes[a] and representative rock formations in both onsite and offsite locations, continued.

House, Sample	Location	Soil Type	Radium	Potassium	Thorium
		D. Samples Taken From Clinton Quarry			
Q3	Clinton Quarry	Epler Shale	28.70[d,e,f]	5.43	0.71
Q4	Clinton Quarry	Epler Limestone	0.45	2.19	0.36

[a] Soil samples taken from depths of typically 0-0.9 m.

[b] Tentative identification of limestone bed in Martinsburg shale formation.

[c] Tentative zone of limestone bed underlying House #1.

[d] Radium exceed Uranium Mill Tailings Remedial Action level of 5 pCi/g for surface contamination[4].

[e] Radium exceed Uranium Mill Tailings Remedial Action level of 15 pCi/g for subsurface contamination[4].

[f] Uranium ore has been found in Mulligan (i.e., Clinton) quarry according to the Clinton Historical Society.

Table 6 - Summary of total, radium-226 and thorium-232 gamma counts at surface and hole locations plus radium/thorium ratios.

House Samp	Location	Total Counts Surface	Total Counts Hole	Radium Cts Surf.	Radium Cts Hole	Thorium Cts Surf.	Thorium Cts Hole	Rad/Thor Surf.	Rad/Thor Hole
A. Homes Tentatively Identified as Overlaying Martinsburg Shale									
1 S1	backyard	6860	17800	164	335	74	171	1.41	1.96
1 S2	frontyard	6290	11280	76	295	62	108	1.23	1.90
1 R1	rep. offsite	3963		101		63		1.60	
1 R2	rep. offsite	5207		196		67		2.94	
1 R3	rep. offsite	7755		131		79		1.66	
Q5	rep. offsite	7390		161		134		1.20	
5 S1	backyard	11120		170		134		1.27	
B. Homes Tentatively Identified as Overlaying Undifferentiated Precambrian Gneissoid Granites									
3 S1	backyard	10443		208		150		1.39	
3 S2	frontyard	5170	10067	125	211	92	193	1.36	1.09
4 S1	frontyard	8030	20367	268	916	168	346	1.59	2.64
4 S2	backyard	6910	15773	236	621	145	340	1.63	1.83
4 R1	rep. onsite	54930 (15-80K)		3037		193		3.90	
6 S1	frontyard	12030		383		259		1.48	
6 R1	rep. onsite	19223 (5-40K)		643		764		0.84	
Q6	rep. offsite	7783		133		91		1.47	
Q8	rep. offsite	6957		123		110		1.12	
Q9	rep. offsite	8157		198		201		0.98	
C. Homes Tentatively Identified as Overlaying a Triassic Brunswick Formation									
2 S1	backyard	10493		320		198		1.61	
2 S2	frontyard	5170	10067	125	211	92	193	1.36	1.09
7 S1	backyard	5030	11037	121	319	111	205	1.09	1.52
7 S2	frontyard	5070	11180	127	301	111	221	1.14	1.36
Q1	rep. offsite	8050		217		159		1.37	
Q2	rep. offsite	4910		88		55		1.61	
D. Samples Taken From Clinton Quarry									
Q3		59140		3413		206		16.57	

Table 6.5. Radon activity of well water samples from study homes.

House	Sample Collection Point	Surface Geological Formation[a]	Activity (pCi/L)
1	outside faucet	Martinsburg shale	1300 ± 200
3	outside faucet	undifferentiated precambrian gneissoid granites	2800 ± 400
4	bathtub	undifferentiated precambrian gneissoid granites	25900 ± 3100
5	laundry room[b] outside faucet	Martinsburg shale	800 ± 80 920 ± 90
6	bathtub	undifferentiated precambrian gneissoid granites	5800 ± 780

[a] Mapped by Markewicz, (1964) NJ Bureau of Geology (in Harper, 1977).

[b] Aerator removed from tap.

Table 6.6. Working Level Monitor Data Files as of 5/22/87

Julian Start Date	House #	Location	Filename*	Duration (days)
295	7	Basement	WLM295.318	168
295	4	Basement	WLM295.343	168
295	5	Basement	WLM295.348	168
309	6	Basement	WLM316.317	168
309	3	Basement	WLM316.318	168
309	1	Basement	WLM316.343	168
317	4	Basement	WLM323.317	168
317	2	Basement	WLM323.318	168
317	7	Basement	WLM323.343	168
316	5	Basement	WLM323.348	168
344	6	Basement	WLM353.317	144
344	4	Basement	WLM353.318	144
345	1	Basement	WLM353.343	144
345	3	Basement	WLM353.348	144
9	2	Basement	WLM019.317	168
8	6	Basement	WLM019.318	168
8	3	Basement	WLM019.343	168
24	3	Basement	WLM024.317	168
24	4	Basement	WLM024.318	168
24	5	Basement	WLM024.343	168
24	1	Basement	WLM024.348	168
35	6	Basement	WLM044.317	168
35	3	Basement	WLM044.343	168
35	3	Basement	WLM044.348	168
35	3	Upstairs	WLM051.348	168
47	6	Upstairs	WLM055.317	168
55	5	Upstairs	WLM062.343	144
55	5	Basement	WLM062.348	144
64	4	Basement	WLM071.317	144
63	7	Basement	WLM072.343	168
63	2	Basement	WLM072.348	168
78	5	Upstairs	WLM086.343	168
78	5	Basement	WLM086.348	168
105	5	Upstairs	WLM112.317	168
105	5	Basement	WLM112.343	168
127	6	Upstairs	WLM138.317	168
127	5	Basement	WLM138.343	168
127	5	Upstairs	WLM138.348	168
141	6	Basement	WLM154.317	168
141	2	Basement	WLM161.343	168
142	5	Basement	WLM161.348	168
162	6	Basement	WLM170.317	168
162	7	Basement	WLM170.343	168
162	5	Basement	WLM170.348	168

* wlm # is last three digits of file name

Table 6.7. Summary of weekly-averaged respirable particulate data

House	Location	Date Sampling	Concentration (ug/m3)
1	dining room	11/05/86	20.0
1	basement	03/10/87	11.3
1	upstairs den	01/24/87	24.4
Average			18.7 ± 6.7
2	upstairs Wrenn	10/30/86	115.5
3	upstairs Wrenn	10/29/86	11.0
3	upstairs Wrenn	11/12/86	16.2
3	basement	03/10/87	13.1
3	upstairs	03/10/87	8.9
3	upstairs Wrenn	01/24/87	14.3
Average			12.7 ± 2.8
4	upstairs Wrenn	11/05/86	4.0
4	upstairs Wrenn	01/24/87	11.0
Average			7.5 ± 5.0
5	upstairs Wrenn	11/12/86	9.0
5	upstairs Wrenn	01/24/87	8.3
Average			8.6 ± 0.5
6	living room	11/05/86	9.9
7	upstairs	11/13/86	124.2

Table 6.8. Blower Door Data (depressurization only)

Use #	Test Condition[a]	Date	Fan Location	ACH (-50 Pa)	ELA (in2)	SLA in^2/ft^2
1	bc	12/ 1/86	main entrance	16.2	181	0.124
	bo	12/ 1/86	main entrance	10.9	270	0.102
2	bo	10/13/86	main entrance	10.5	170	0.075
	--	4/11/87	basement/outside	25.8	238	0.186[b]
	bc	5/14/87	main entrance	12.3	159	0.07
	bo	5/14/87	main entrance	9.0	207	0.058[c]
3	bc	10/15/86	main entrance	11.9	203	0.098[d]
	bo	11/24/86	main entrance	6.7	84	0.026
	bc	11/24/86	main entrance	9.3	83	0.039
4	bc	10/15/86	main entrance	9.9	169	0.074
	bc	11/19/86	main entrance	8.7	98	0.043
	bo	11/19/86	main entrance	6.2	98	0.03
	--	6/09/87	basement/outside	17.8	100	0.11[b]
5	nd	10/14/86	main entrance	8.2	102	0.055
	nd	11/21/86	main entrance	8.8	103	0.055
	--	11/21/86	basement door	10.1	82	0.053[b]
6	nd	10/15/86	front door	19.8	353	0.14
	nd	11/25/86	front door	20.9	323	0.13
	nd	6/04/87	front door	18.8	352	0.14
	cc	6/04/87	basement door	16.8	202	0.09[b]
	co	6/04/87	basement door	24.2	267	0.12[b]
7	bc	11/17/86	front door	11.0	116	0.067
	bo	11/17/86	front door	9.0	152	0.051

[a] bc = basement door closed
bo = basement door open
cc = crawlspace door closed
co = crawlspace door open
nd = no door between basement and house

[b] = basement volume only

[c] = all volume

[d] = fireplace damper partially open

Table 6.9. Results of Soil Characterization Measures (pCi/L)

House	Date	Method	Yard Location Front	Side-Garage	Side	Back
1	10/15/86	Grab	6354	--	6618	--
	12/01/86	Grab	60, 87	--	30, 410	382
	10/86-1/87	Trk Etch	646	--	--	--
	1/20/87	Grab	56	--	59	305
	2-4/87	Trk Etch	237	--	--	2414
	4/08/87	Grab	945	--	3078	409
2	10/13/86	Grab	149	--	1090	3081
	10/86-1/87	Trk Etch	539	--	--	598
	2-4/87	Trk Etch	359	--	--	428
	4/11/87	Grab	84, 74	--	965, 873	3457, 3056
3	10/14/86	Grab	--	--	1184	--
	11/24/86	Grab	127	--	1474	983
	10/86-1/87	Trk Etch	--	--	--	1066
	2-4/87	Trk Etch	30	--	--	135
	4/07/87	Grab	65, 71, 56	--	525, 514	196, 138
4	10/15/86	Grab	--	--	35	--
	11/19/86	Grab	48, 604	300	10654	6, 13, 10, 60
	10/86-1/87	Trk Etch	1835	--	--	2343
	2-4/87	Trk Etch	2927	--	--	1455
	4/07/87	Grab	10794	--	9637	--
5	10/14/86	Grab	189	--	1024	721
	11/21/86	Grab	885	--	335	30
	10/86-1/87	Trk Etch	1151	--	--	121
	1/20/87	Grab	64	--	391	30
	2-4/87	Trk Etch	138	--	--	71
	4/08/87	Grab	19, 20	--	350, 354	41, 58
6	10/15/86	Grab	3987	--	--	975
	11/25/86	Grab	1600	--	2010	2320
	10/86-1/87	Trk Etch	312	--	--	4275
	2-4/87	Trk Etch	130	--	--	--
	4/07/87	Grab	7336, 8493	--	--	11041, 10492
7	10/16/86	Grab	--	--	4464	1476
	10/86-1/87	Trk Etch	839	--	--	2222
	2-4/87	Trk Etch	106	--	--	221
	4/09/87	Grab	469, 405	1463, 1337	2492, 2224	685, 1040

Table 6.10. Soil Permeability Data

Hse #	Date	Location	Pressure (Pa)	K (cm^2)	Avg.K (cm^2)	Comments
1	12/1/86	SE,2m,Front	7.5	2.1×10^{-5}*	2.1×10^{-5}	pipe loose
1	12/1/86	N,3m,Side	10	7.6×10^{-6}	6.7×10^{-6}	pipe loose
			28	5.7×10^{-6}*		pipe loose
1	12/1/86	W,1m,Back	10	1.6×10^{-5}*	1.6×10^{-5}	
2	4/11/87	S,1.5m,Front	10	1.7×10^{-6}	1.1×10^{-6}	
			50	1.1×10^{-6}		
			250	6.4×10^{-7}		
2	4/11/87	W,1.5m,Side	10	3.2×10^{-6}	2.3×10^{-6}	
			50	2.1×10^{-6}		
			100	1.5×10^{-6}		
2	4/11/87	N,1.5m, back	10	6.1×10^{-10}		10 Pa data not
			50	6.1×10^{-9}	6.0×10^{-9}	incl. in avg.
			250	5.9×10^{-9}		
3	11/24/86	E,1.2m,Rear	10	1.3×10^{-6}	1.2×10^{-6}	
			50	1.3×10^{-6}		
			150	1.0×10^{-6}*		
3	11/24/86	S,2m,Side	10	9.8×10^{-7}	8.2×10^{-7}	
			50	8.2×10^{-7}		
			200	6.6×10^{-7}		
3	11/24/86	W,1.5m,Front	1	1.6×10^{-4}*	1.6×10^{-4}	
4	6/9/87	N,1.5m, Front	10	7.7×10^{-9}	6.9×10^{-9}	flowmeter P1
			50	7.4×10^{-9}		
			250	5.6×10^{-9}		
4	11/19/87	W,3m,Side	250	No flow		No measureable flow on
		S,1.5m,Back	250	No flow		permeameter.
		E, 2m,Side		No flow		" "
		N, 1.5m,Front		No flow		" "
4	12/3/86	E,2m,Side	250	1.5×10^{-10}		Wet clay
			250	No flow		meter P1

Table 6.10. Soil Permeability Data, continued

Hse #	Date	Location	Pressure (Pa)	K (cm^2)	Avg.K (cm^2)	Comments
4	12/3/86	Bsmt Subslab		No flow		Clay soil under slab
4	1/5/87	NW,2m,Front	250	No flow		Clay
5	11/21/86	S,2m, Side	10	3.7×10^{-7}	3.6×10^{-7}	
			50	4.3×10^{-7}		
			250	2.9×10^{-7}		
5	11/21/86	E,2m, Front	3	5.4×10^{-5}*	5.4×10^{-5}	
5	11/21/86	W,3m, Back	2	8.1×10^{-5}*	8.1×10^{-5}	
6	11/25/86	S,1.5m,Front	250	3.1×10^{-10}	3.1×10^{-10}	meter P1
6	11/25/86	W,1m,Side	10	1.2×10^{-6}	8.4×10^{-7}	
			50	8.2×10^{-7}		
			250	5.0×10^{-7}		
6	11/25/86	N,2m,Back	250	No flow		
7	12/3/86	E,2m,Back	10,50	No flow		Wet clay
7	12/3/86	N,2m,Side	10	6.7×10^{-8}	6.1×10^{-8}	Wet clay
			50	6.2×10^{-8}		
			50	6.1×10^{-8}		
			250	5.4×10^{-8}		
7	11/17/86	E,2m,Back	250	No flow		Clay
7	11/17/86	N,2m,Side	10	2.3×10^{-7}	1.9×10^{-7}	Clay
			50	1.8×10^{-7}		
			100	1.8×10^{-7}		
			250	1.5×10^{-7}		
7	11/17/86	W,1.5m,Front	10	2.8×10^{-9}	4.2×10^{-9}	Clay (meter P1)
			50	4.3×10^{-9}		meter P1
			250	5.4×10^{-9}		meter P2
7	11/17/86	S,1m,Side	10	No flow		meter P1
			50	No flow		meter P1
			250	7.4×10^{-11}		meter P1
			250	No flow		meter P1

* Uncertain data taken with the highest flow rotometer, reading at a maximum flow of 2.5 L/min.

Table 6.11. Summary of field calibration data for selected sensors between 10/86 and 4/87.

	Differential Pressure			Temperature		Basement RH
House	Sensor	Response Pa/volt	Zero Off Mean ± SD	Location	Delta Span[a] Mean ± SD	Delta Span[a] Mean ± S.D.
1	Bsmt-Out	10.49	2565 ± 35	Bsmt	0.4 ± 0.3	-4.7 ± 5.3
	Bsmt-Sub	9.99	2583 ± 8	Upstairs	-0.3 ± 0.3	
	Bsmt-Ups	10.02	2586 ± 11	Outdoors	-0.3 ± 0.5	
2	Bsmt-Out	9.98	2470 ± 4	Bsmt	0.4 ± 0.5	-0.7 ± 3.4
	Bsmt-Sub	9.99	2532 ± 24	Upstairs	-0.3 ± 0.3	
	Bsmt-Ups	9.97	2497 ± 24	Outdoors	-0.9 ± 0.7	
3	Bsmt-Out	9.98	2527 ± 5	Bsmt	0.3 ± 0.4	3.0 ± 1.4
	Bsmt-Sub	10.06[b]	2548 ± 6	Upstairs	0.3 ± 0.4	
	Bsmt-Sub	24.70[c]	2529 ± 6	Outdoors	0.1 ± 0.5	
	Bsmt-Ups	9.98	2533 ± 7			
4	Bsmt-Out	10.33	2493 ± 17	Bsmt	0.1 ± 0.7	-0.4 ± 2.2
	Bsmt-Sub	10.32	2526 ± 13	Upstairs	-0.2 ± 0.1	
	Bsmt-Ups	10.07	2555 ± 9	Outdoors	-0.2 ± 0.2	
5	Bsmt-Out	9.97	2503 ± 6	Bsmt	0.3 ± 0.3	-6.3 ± 1.7
	Bsmt-Sub	10.02	2477 ± 5	Upstairs	-0.8 ± 0.5	
	Bsmt-Ups	9.99	2513 ± 5	Outdoors	-1.6 ± 0.7	
6	Bsmt-Out	9.91	2338 ± 62	Bsmt	-0.1 ± 0.5	7.3 ± 8.3
	Bsmt-Sub	10.03	2463 ± 7	Upstairs	-0.3 ± 0.7	
	Bsmt-Ups	9.85	2509 ± 11	Outdoors	-0.2 ± 0.2	
	Crwl-Sub	24.62	2505 ± 28			
7	Bsmt-Out	10.31	2498 ± 8	Bsmt	0.2 ± 0.4	4.4 ± 2.8
	Bsmt-Sub	10.24	2512 ± 8	Upstairs	0.1 ± 0.4	
	Bsmt-Ups	10.43	2517 ± 10	Outdoors	-0.4 ± 0.2	

[a] Delta values represent the difference between the field probe and reference device.
[b] Probe used from 10/86 to 12/29/86.
[c] Probe used from 12/29/86 to present.

Table 6.12. Summary of laboratory and field calibration data for Wrenn chambers (cpm) from 10/86 to 4/87.

	Zero Values		Laboratory Calibration Data					Check Source Lab	Check Source Field		
Wrenn	10/86	1/87[a]	10/86[b]	12/86	1/87[c]	2/87[b]	5/87[b]	10/86	10/86	1/87	4/87
1	0.67	0.39	0.82	----	1.21	----	1.44	787	765	741	868
2	0.49	0.35	0.72	----	0.65	----	----	515	503	477	516
3	0.50	----	0.83	----	----	----	1.12[d]	840	840	574	---
4	0.48	0.31	0.90	0.90[c]	0.88	0.91	----	679	676	661	---
5	0.59	0.68	0.92	----	0.83	----	----	1053	949	897	953
6	0.44	0.33	0.84	----	0.83	----	----	953	978	896	1032
7	0.81	0.54	0.91	----	0.82	----	----	1098	---	1022	1032
8	0.43	0.36[d]	0.86	0.93[b]	1.00[d]	----	----	1121	---	1019[d]	1089
9	0.75	0.41	0.81	----	0.74	----	----	983	1035	833	951
10	0.38	----	0.82	----	----	----	----	932	941	873	912
11	0.80	0.39	0.81	----	0.94	----	----	787	748	670	742
12	0.00	----	1.11	----	----	----	1.32[d]	1016	1016	885	---
13	0.61	0.38	0.84	----	0.97	----	----	1282	1268	1199	1241
14	0.53	0.39	0.86	0.71[c]	0.79	0.81	----	783	736	704	719
15	0.63	----	0.89	0.78[c]	----	----	----	1013	1028	998	1033
16	0.69	----	0.76	----	----	----	----	839	793	842	---
17	0.59	----	0.64	----	----	----	----	640	---	588	615
18	0.85	----	0.72	0.64[c]	----	----	----	1008	---	---	---
19	0.47	0.48[d]	0.65	0.67[b,d]	0.67	----	----	363	---	397[d]	(543)
20	----	----	----	----	----	1.80	1.84	---	---	---	---

[a] Zero values taken at 5 °C, and therefore may be somewhat lower than under normal indoor conditions.

[b] Calibrations performed in the ORNL walkin chamber

[c] Calibrations performed at the EML radon chamber, Manhattan, N.Y.

[d] Adverse environmental exposures or repairs performed to the Wrenn chamber since the previous calibration period could change the zero and calibration factors.

Table 6.13. Calibration of the Eberline Working Level Monitors (WLMs)

WLM	Measured Air Flow (L/min)	Counting Efficiency[a]	Calib. Constant[b]	WLM/EML[c]	Corrected Calib. Constant[d]	Air Flow Independent Calibration Constant[e]
WLM317	0.155	0.212	586.5	0.984	577.2	3724
WLM343	0.154	0.210	576.7	1.091	628.9	4084
WLM348	0.190	0.218	739.6	1.045	772.8	4067
WLM318[f]	0.160	0.232	663.7	3.460	2296.5	14353

[a] counting efficiency measured with Thorium check source

[b] Calibration Constant (cpm/WL) = (Flow (L/m) * Efficiency) / 5.6×10^{-5}

[c] ratio of working level data measured by WLMs (using calibration constant[b])

[d] calibration constant corrected for WLM/EML ratio.

[e] units of (counts/[Working Level * L])

[f] mechanical problems with the pump of WLM318 have been recurrent

House 5

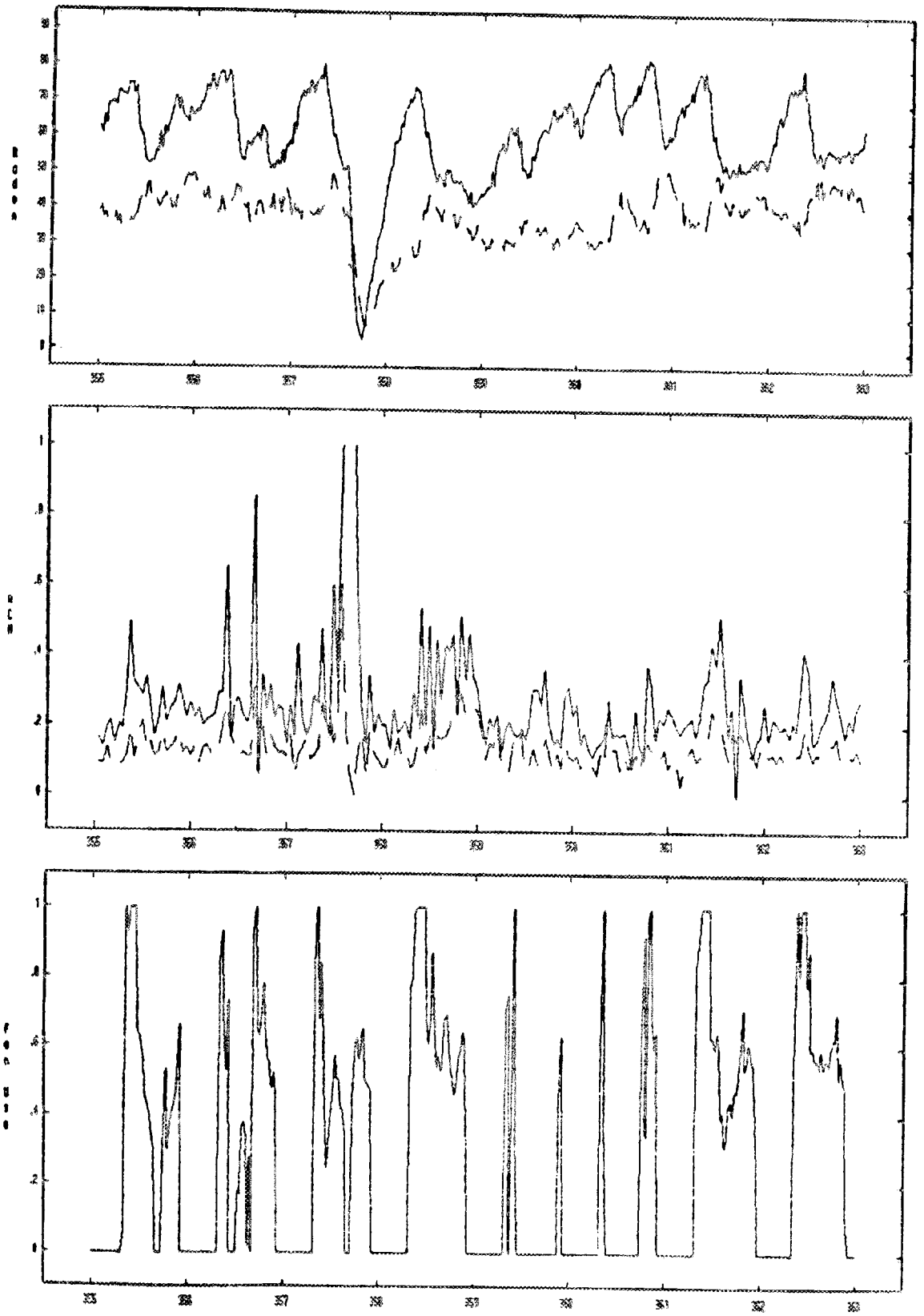


Figure 6.1

PU/CEES 8740

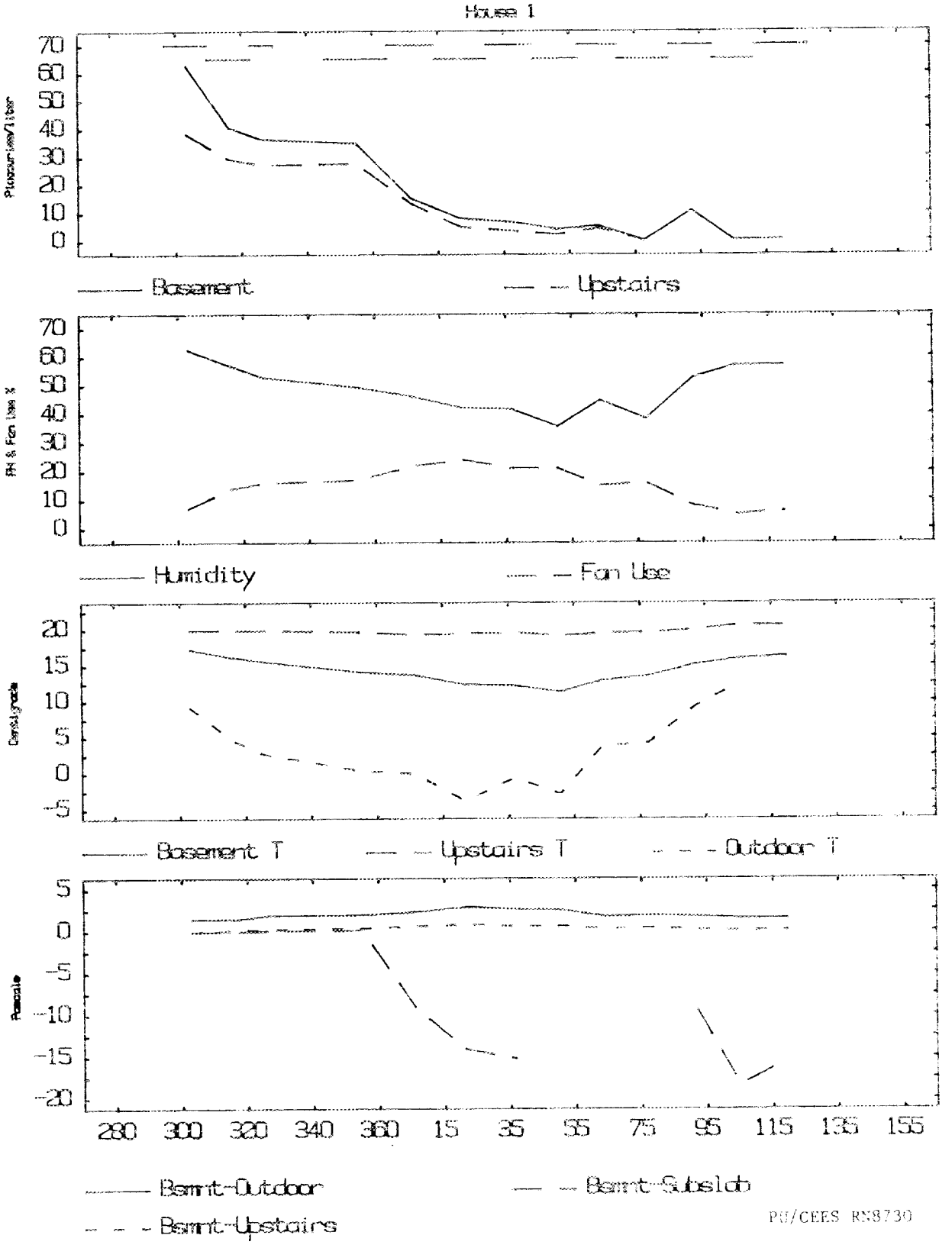

House 1
70
60
50
40
30
20
10
0
Basement
Upstairs
70
60
50
40
30
20
10
0
Humidity
Fan Use
20
15
10
5
0
-5
Basement T
Upstairs T
Outdoor T
5
0
-5
-10
-15
-20
280
300
320
340
360
15
35
55
75
95
115
135
155
Bsmnt-Outdoor
Bsmnt-Subslab
Bsmnt-Upstairs
PU/CEES RN8730

Figure 6.2

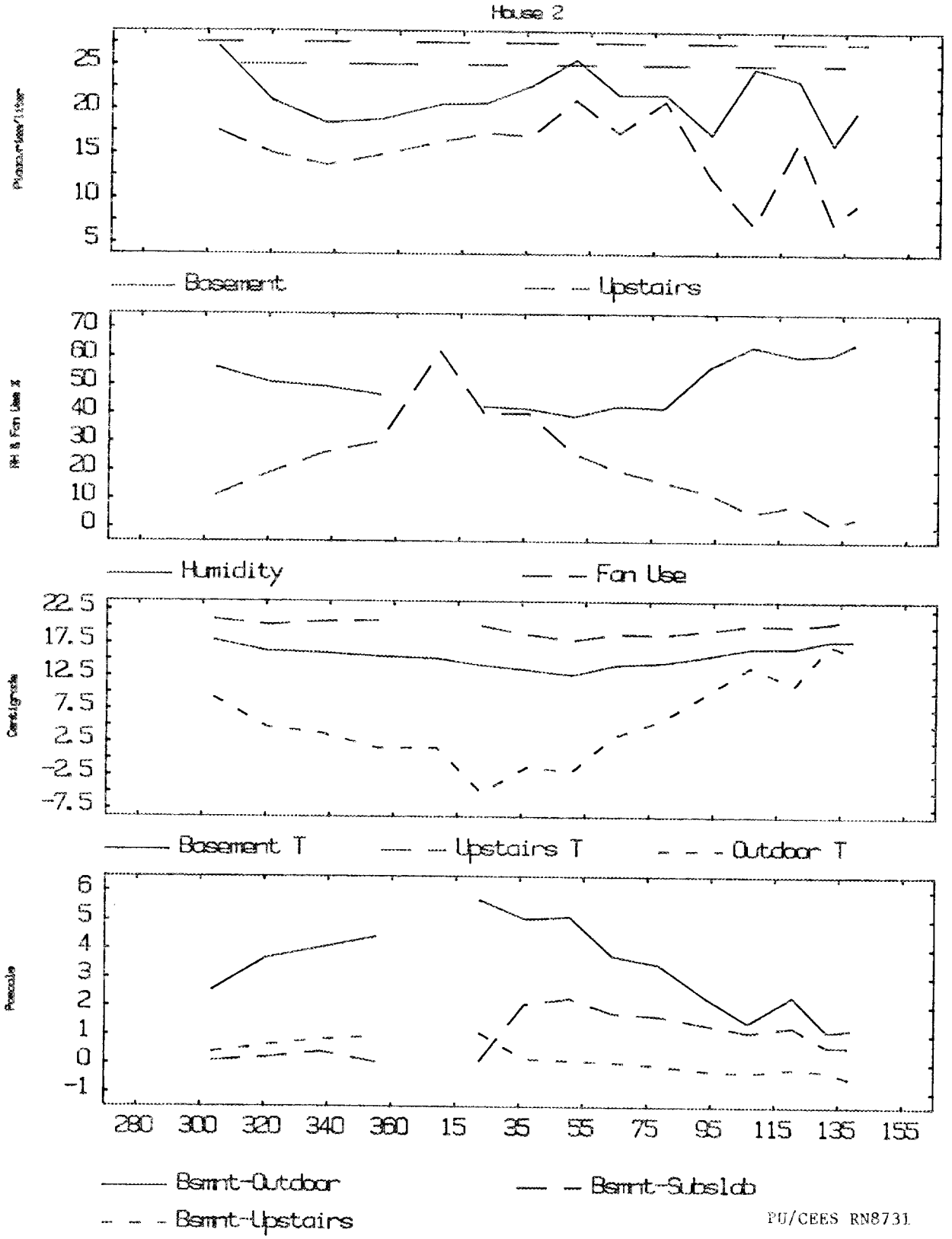

House 2
25
20
15
10
5
Basement
Upstairs
70
60
50
40
30
20
10
0
Humidity
Fan Use
22.5
17.5
12.5
7.5
2.5
-2.5
-7.5
Basement T
Upstairs T
Outdoor T
6
5
4
3
2
1
0
-1
280 300 320 340 360 15 35 55 75 95 115 135 155
Bsmnt-Outdoor
Bsmnt-Subslab
Bsmnt-Upstairs
PU/CEES RN8731

Figure 6.3

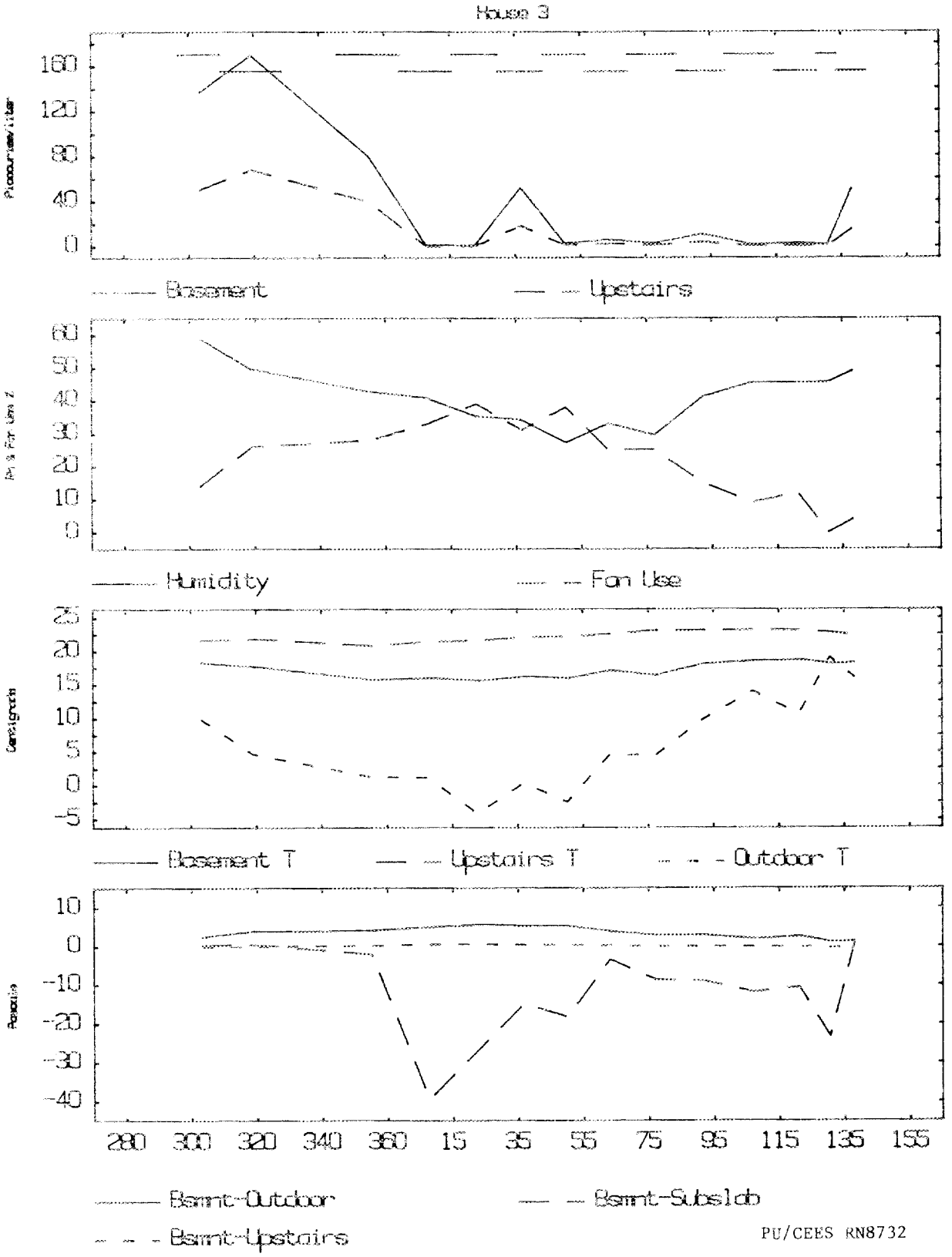

House 3
160
120
80
40
0
Basement
Upstairs
60
50
40
30
20
10
0
Humidity
Fan Use
25
20
15
10
5
0
-5
Basement T
Upstairs T
Outdoor T
10
0
-10
-20
-30
-40
280
300
320
340
360
15
35
55
75
95
115
135
155
Bsmnt-Outdoor
Bsmnt-Subslab
Bsmnt-Upstairs
PU/CEES RN8732

Figure 6.4

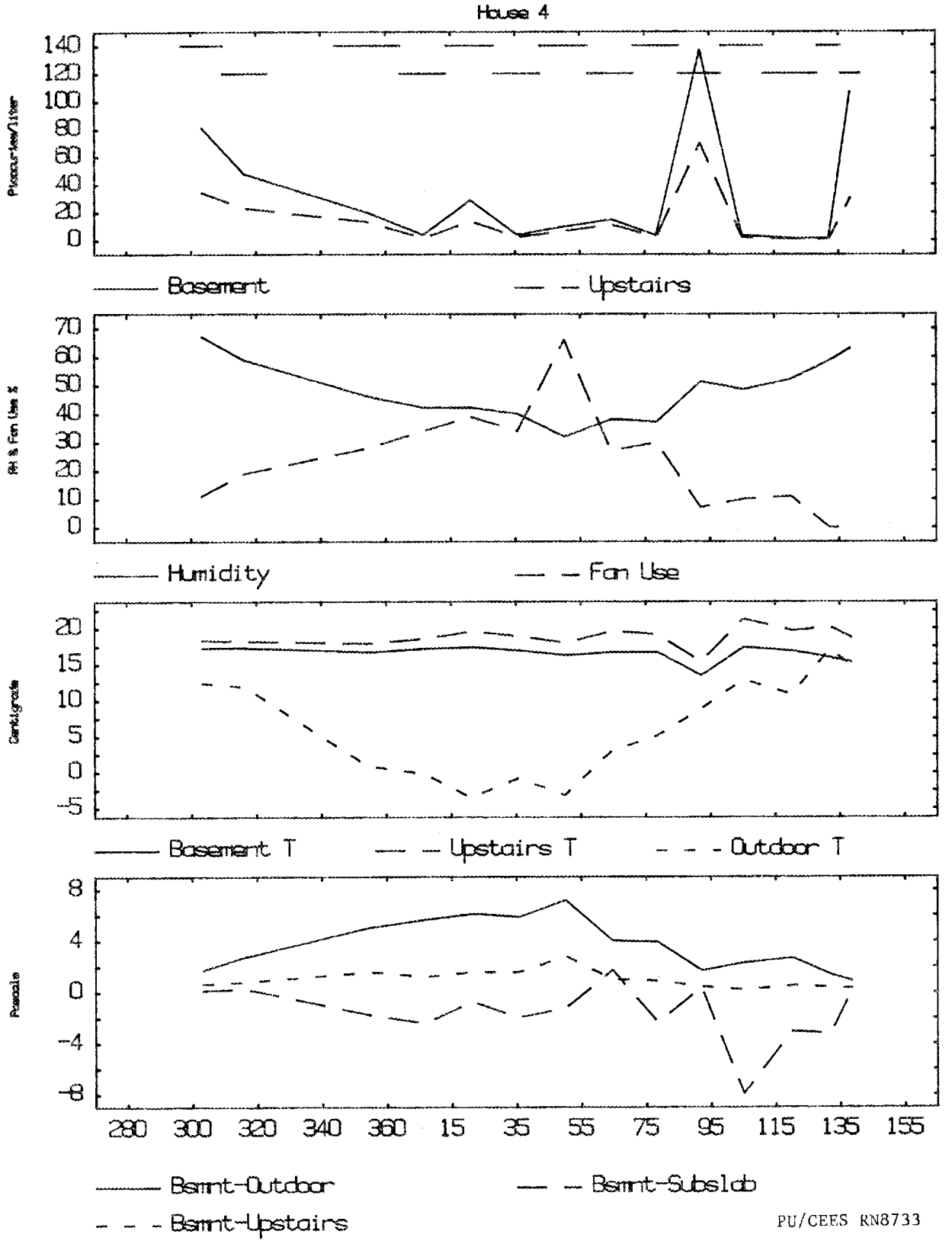

House 4
Picocuries/liter
140
120
100
80
60
40
20
0
Basement
Upstairs
RH % Fan Use %
70
60
50
40
30
20
10
0
Humidity
Fan Use
Centigrade
20
15
10
5
0
-5
Basement T
Upstairs T
Outdoor T
Pascals
8
4
0
-4
-8
280
300
320
340
360
15
35
55
75
95
115
135
155
Bsmnt-Outdoor
Bsmnt-Subslab
Bsmnt-Upstairs
PU/CEES RN8733

Figure 6.5

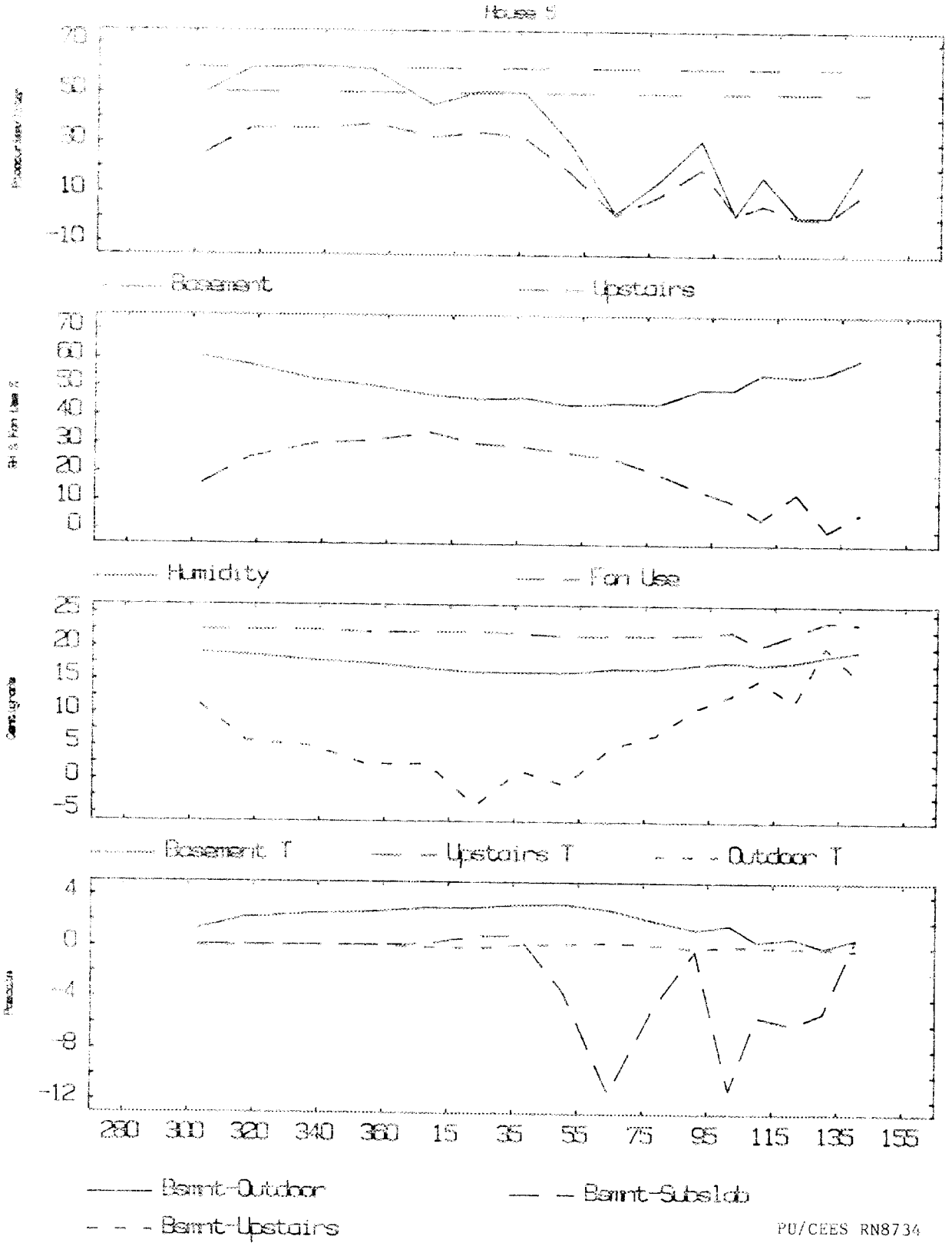

House 5
70
50
30
10
-10
Basement
Upstairs
70
60
50
40
30
20
10
0
Humidity
Fan Use
25
20
15
10
5
0
-5
Basement T
Upstairs T
Outdoor T
4
0
-4
-8
-12
280
300
320
340
360
15
35
55
75
95
115
135
155
Bsmt-Outdoor
Bsmt-Subslab
Bsmt-Upstairs
PU/CEES RN8734

Figure 6.6

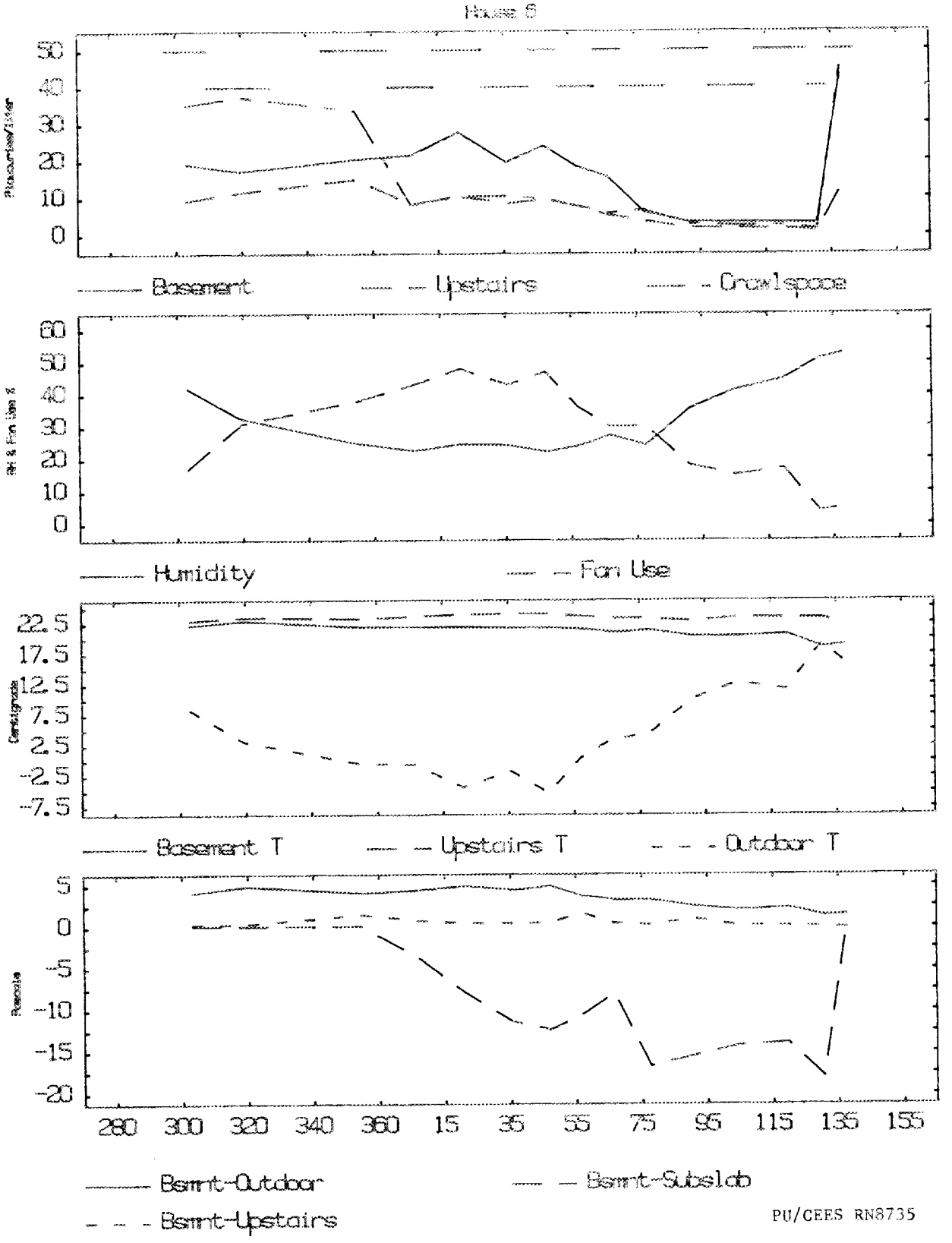
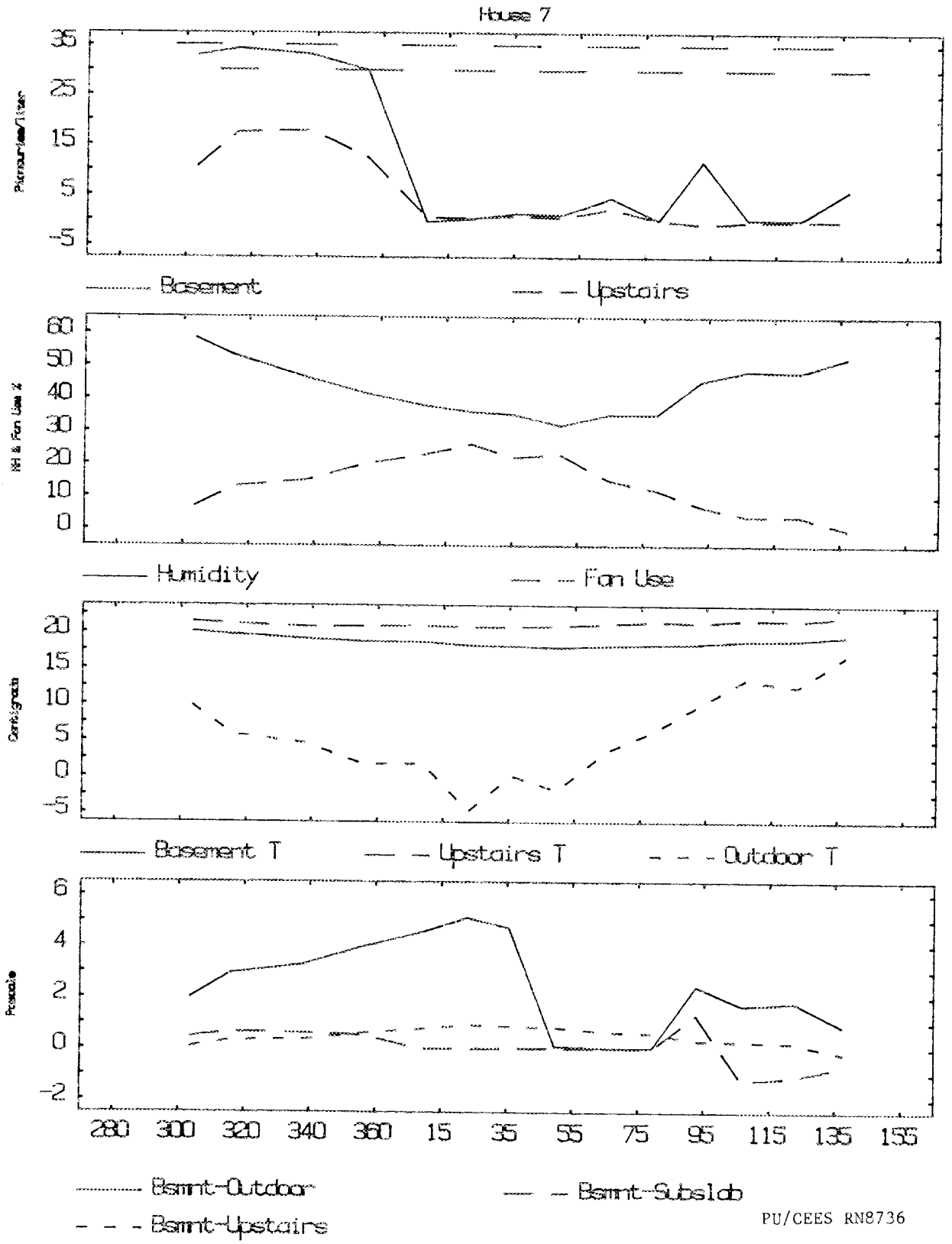

House 6
50
40
30
20
10
0
Basement
Upstairs
Crawlspace
60
50
40
30
20
10
0
Humidity
Fan Use
22.5
17.5
12.5
7.5
2.5
-2.5
-7.5
Basement T
Upstairs T
Outdoor T
5
0
-5
-10
-15
-20
280
300
320
340
360
15
35
55
75
95
115
135
155
Bsmt-Outdoor
Bsmt-Subslab
Bsmt-Upstairs
PU/CEES RN8735

Figure 6.7



PU/CEES RN8736

Figure 6.8

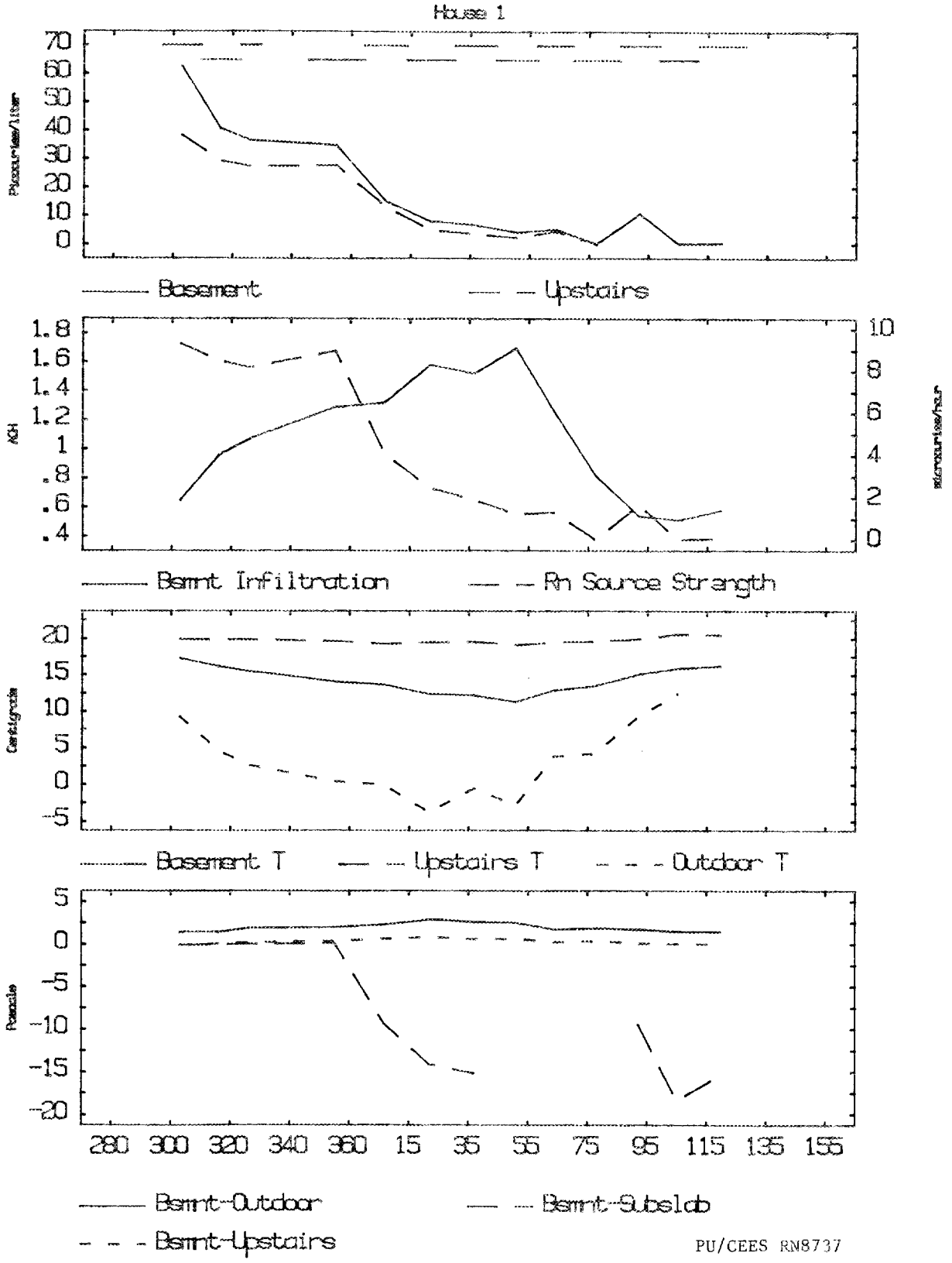

House 1
Basement
Upstairs
AOH
Bsmnt Infiltration
Rn Source Strength
Centigrade
Basement T
Upstairs T
Outdoor T
Pascals
280 300 320 340 360 15 35 55 75 95 115 135 155
Bsmnt-Outdoor
Bsmnt-Subslab
Bsmnt-Upstairs
PU/CEES RN8737

Figure 6.9 A

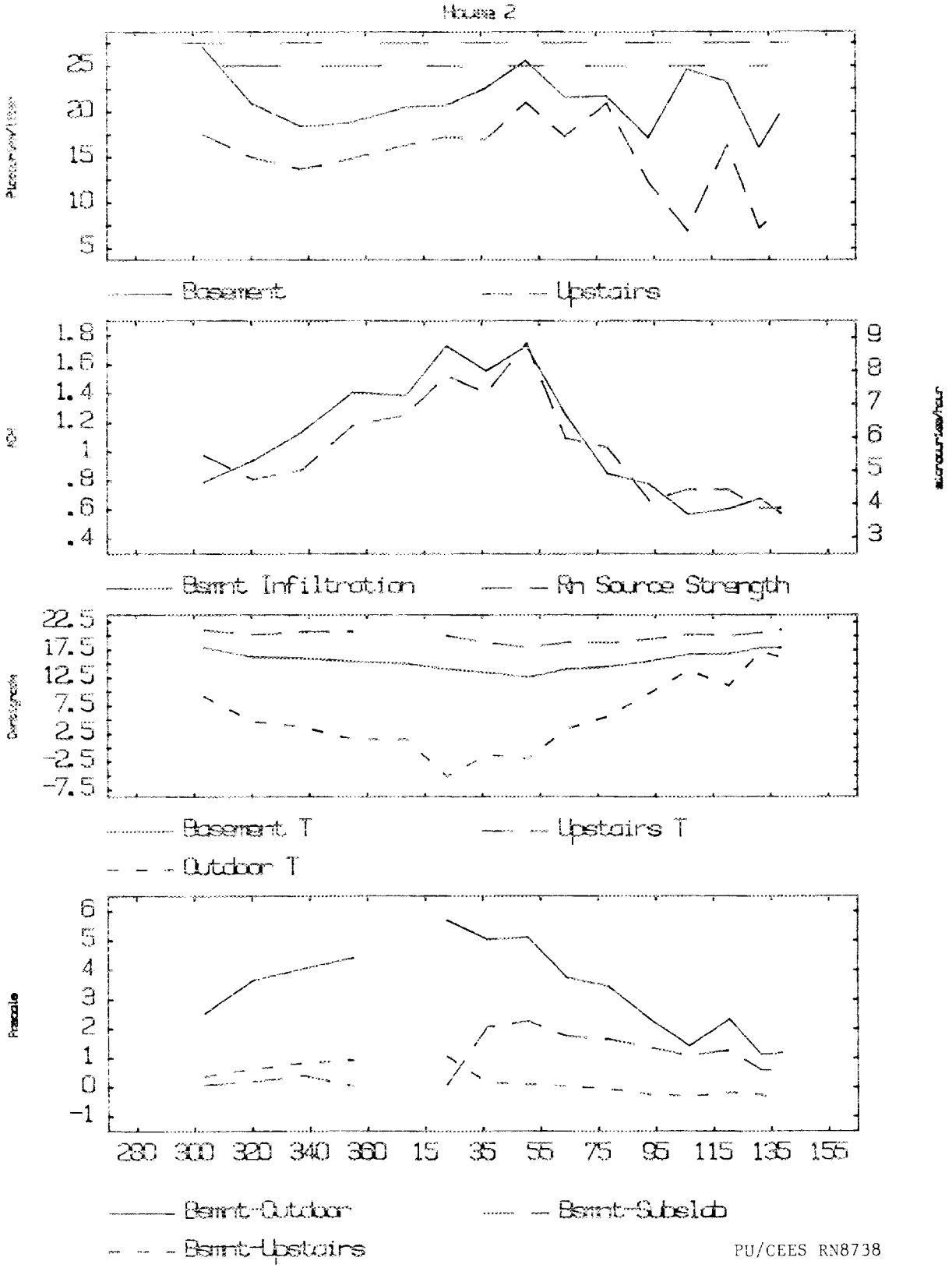
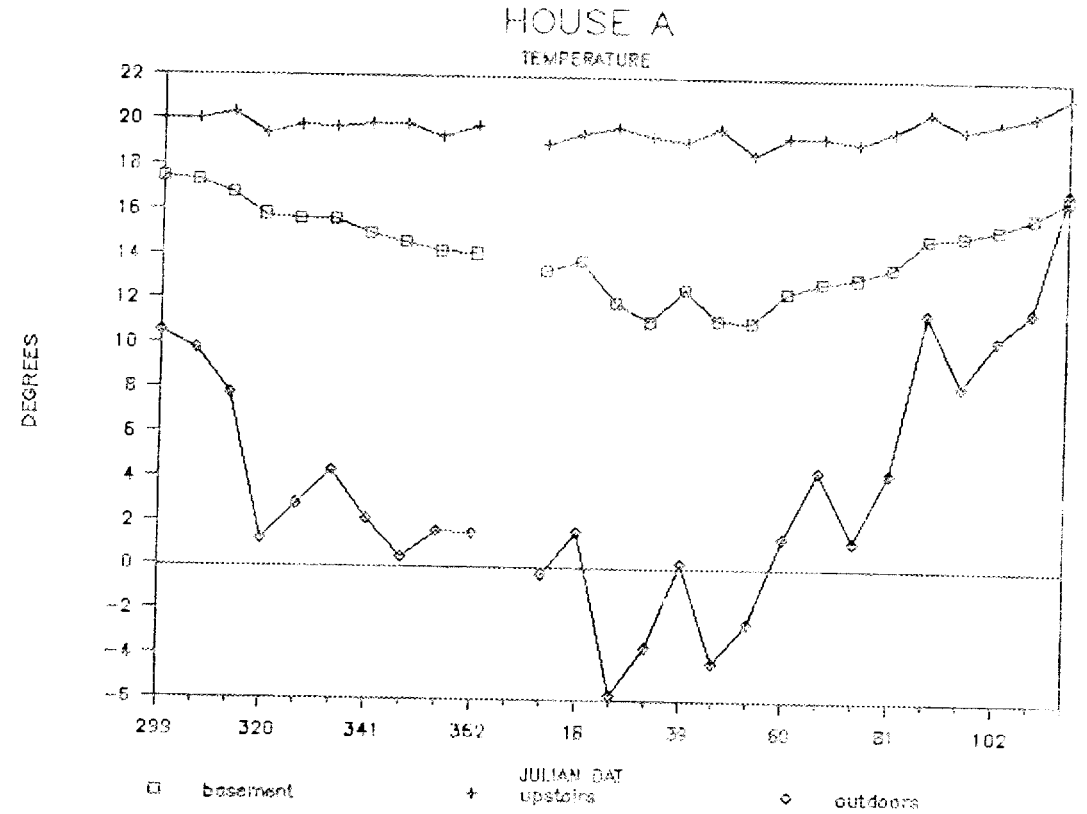

House 2
25
20
15
10
5
Basement
Upstairs
1.8
1.6
1.4
1.2
1
.8
.6
.4
9
8
7
6
5
4
3
Bsmt Infiltration
Rn Source Strength
22.5
17.5
12.5
7.5
2.5
-2.5
-7.5
Basement T
Upstairs T
Outdoor T
6
5
4
3
2
1
0
-1
280 300 320 340 360 15 35 55 75 95 115 135 155
Bsmt-Outdoor
Bsmt-Subslab
Bsmt-Upstairs
PU/CEES RN8738

Figure 6.9B


HOUSE A
TEMPERATURE
DEGREES
22
20
18
16
14
12
10
8
6
4
2
0
-2
-4
-6
299
320
341
362
18
39
60
81
102
JULIAN DAT
basement
upstairs
outdoors

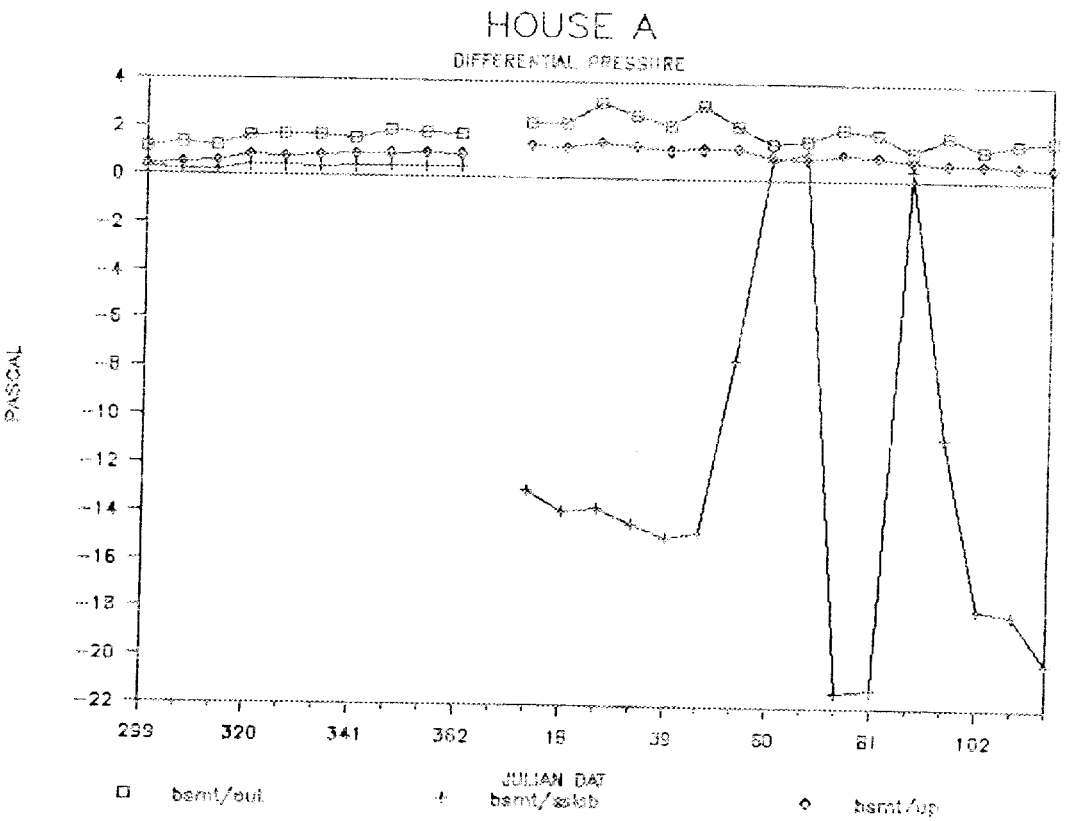
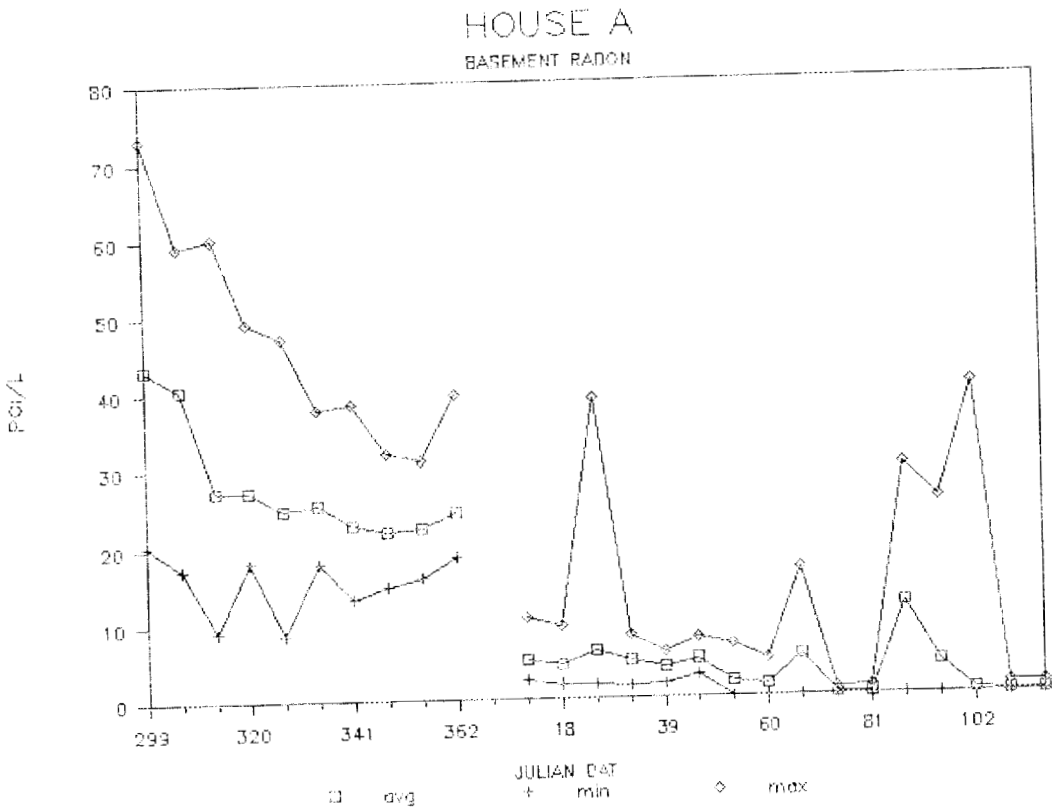

HOUSE A
DIFFERENTIAL PRESSURE
PASCAL
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
299
320
341
362
18
39
60
81
102
JULIAN DAT
bsmt/out
bsmt/sklb
bsmt/up

Figure 6.10


HOUSE A
BASEMENT RADON
PCI/L
80
70
60
50
40
30
20
10
0
299
320
341
362
18
39
60
81
102
JULIAN DAT
avg
min
max

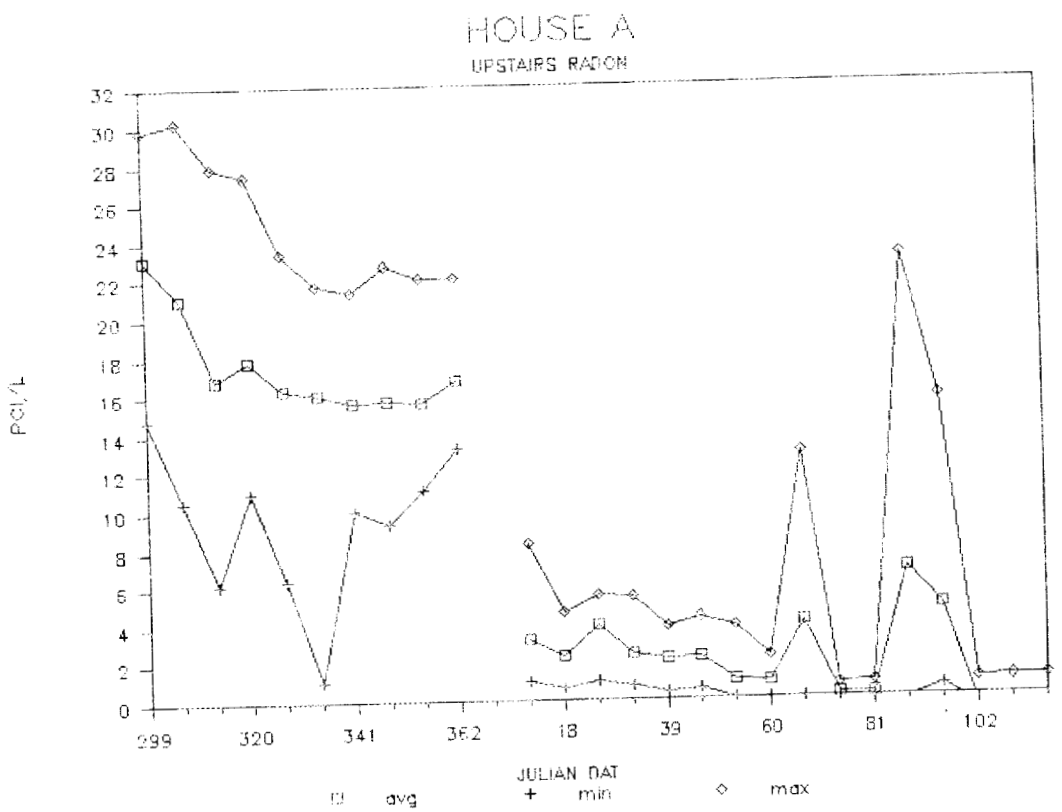
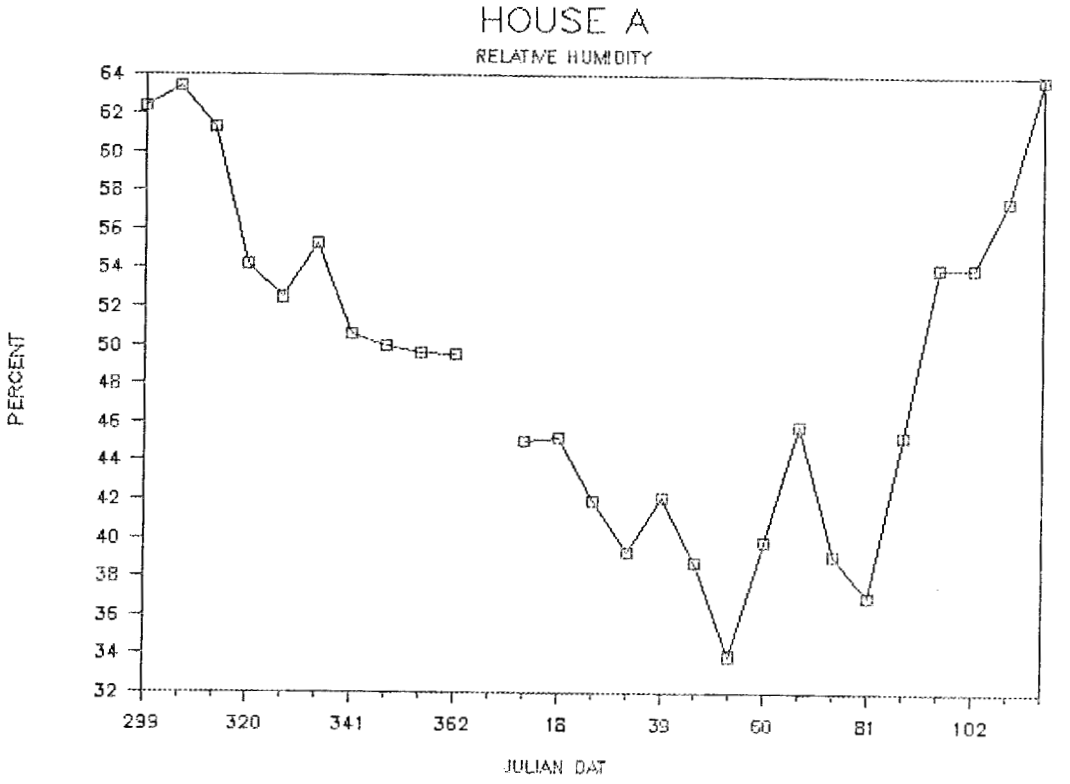

HOUSE A
UPSTAIRS RADON
PCI/L
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
299
320
341
362
18
39
60
81
102
JULIAN DAT
avg
min
max

Figure 6.11


HOUSE A
RELATIVE HUMIDITY
PERCENT
64
62
60
58
56
54
52
50
48
46
44
42
40
38
36
34
32
299
320
341
362
18
39
60
81
102
JULIAN DAT

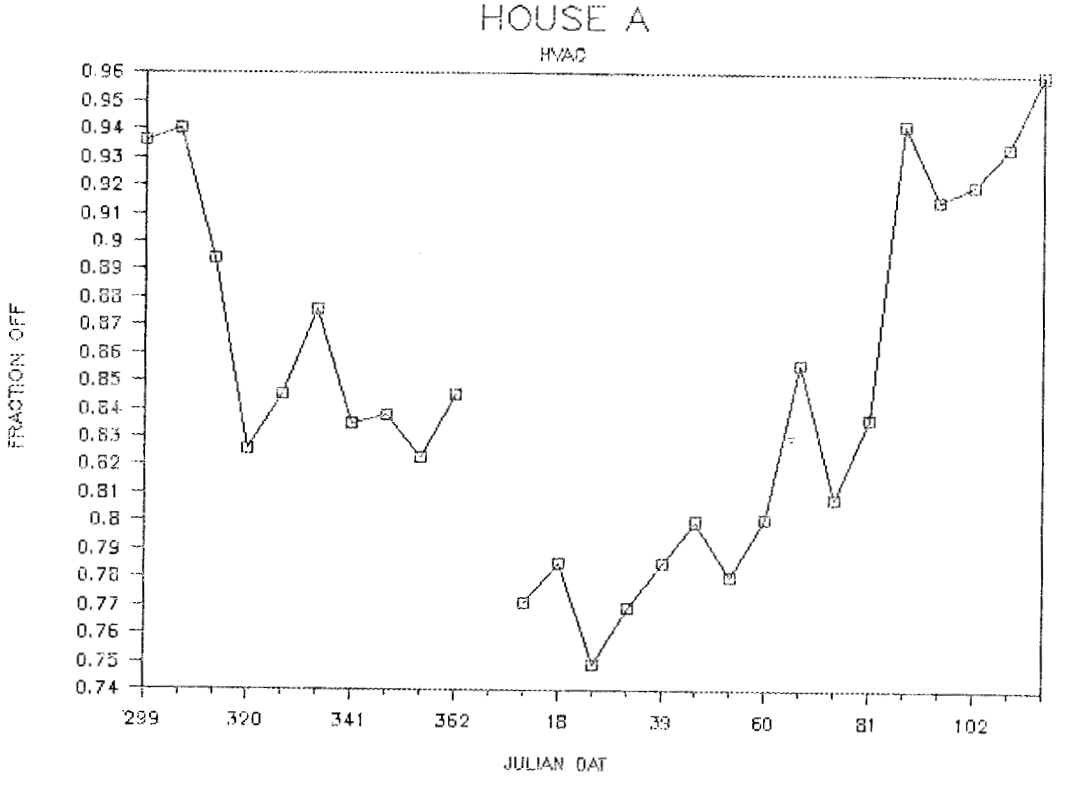

HOUSE A
HVAC
FRACTION OFF
0.96
0.95
0.94
0.93
0.92
0.91
0.9
0.89
0.88
0.87
0.86
0.85
0.84
0.83
0.82
0.81
0.8
0.79
0.78
0.77
0.76
0.75
0.74
299
320
341
362
18
39
60
81
102
JULIAN DAT

Figure 6.12

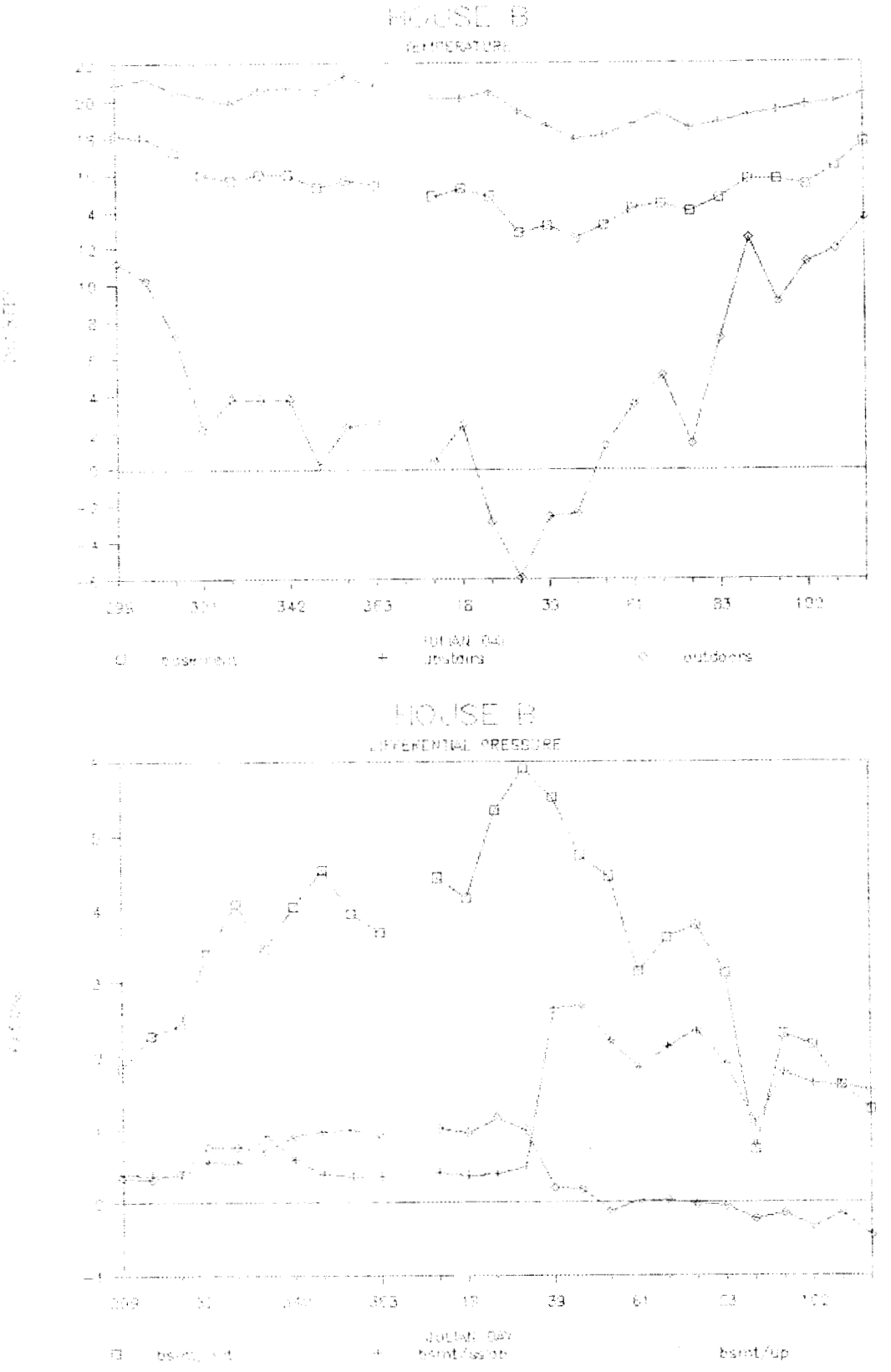
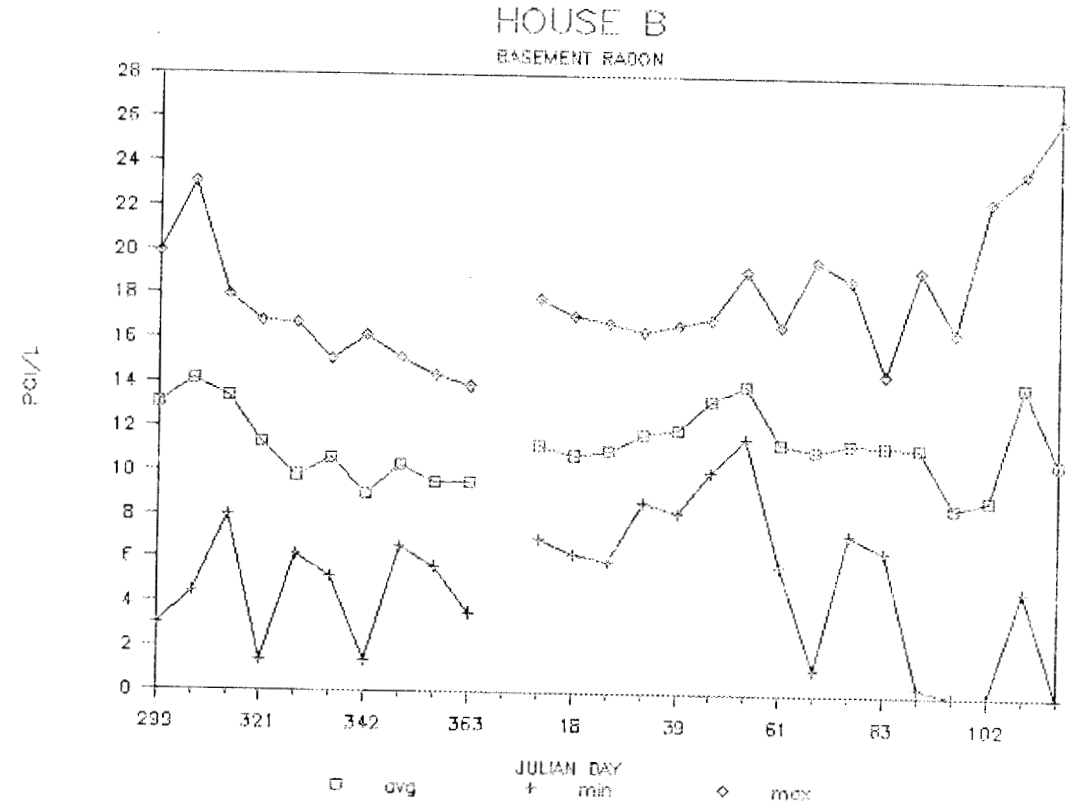

HOUSE B
TEMPERATURE
JULIAN DAY
basement
outdoors
HOUSE B
DIFFERENTIAL PRESSURE
JULIAN DAY
bsmt/up

Figure 6.15


HOUSE B
BASEMENT RADON
PCI/L
JULIAN DAY
avg
min
max

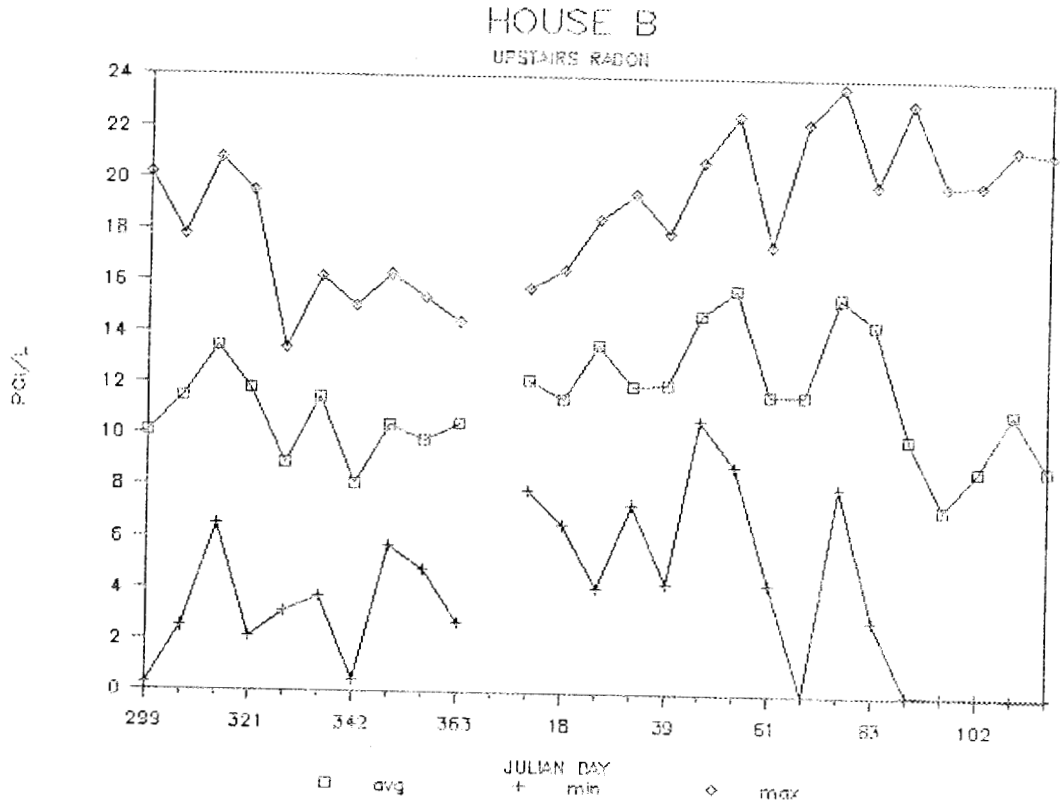
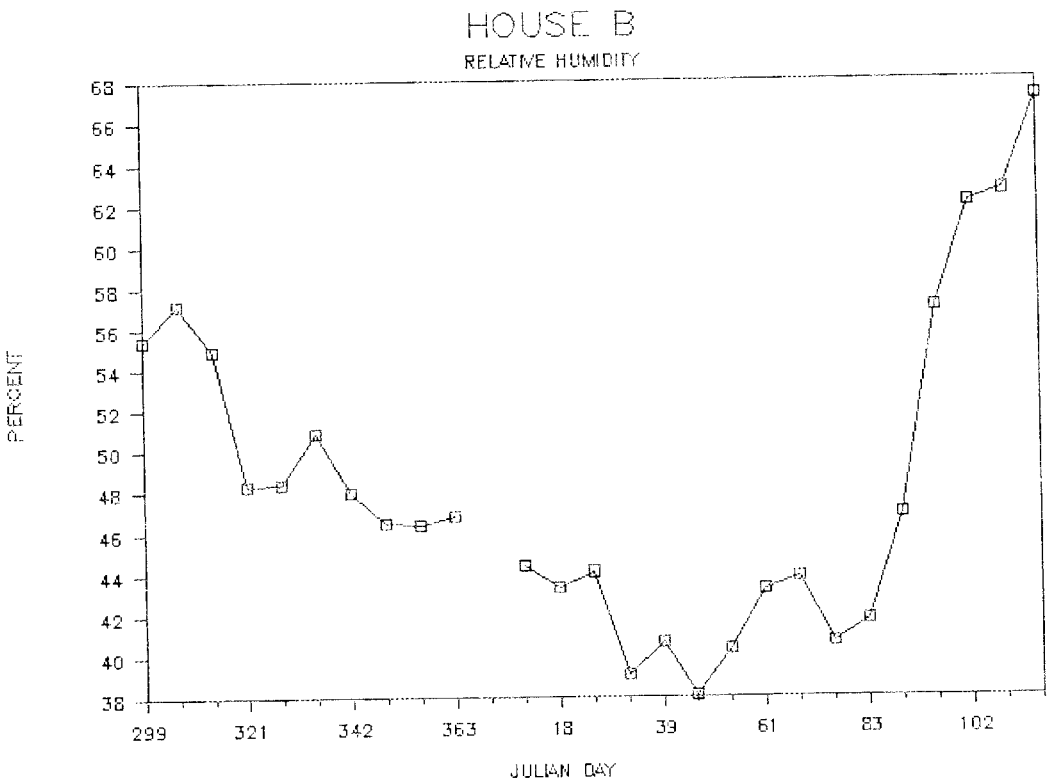

HOUSE B
UPSTAIRS RADON
PCI/L
JULIAN DAY
avg
min
max

Figure 6.14


HOUSE B
RELATIVE HUMIDITY
PERCENT
68
66
64
62
60
58
56
54
52
50
48
46
44
42
40
38
299
321
342
363
18
39
61
83
102
JULIAN DAY

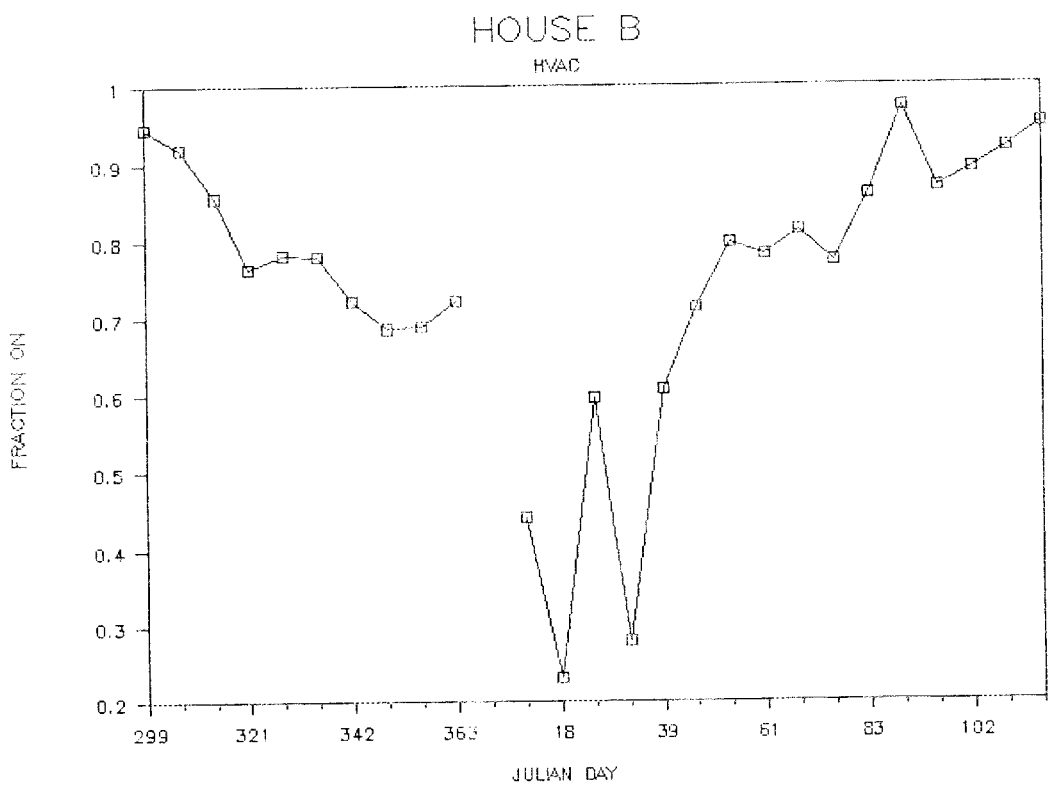
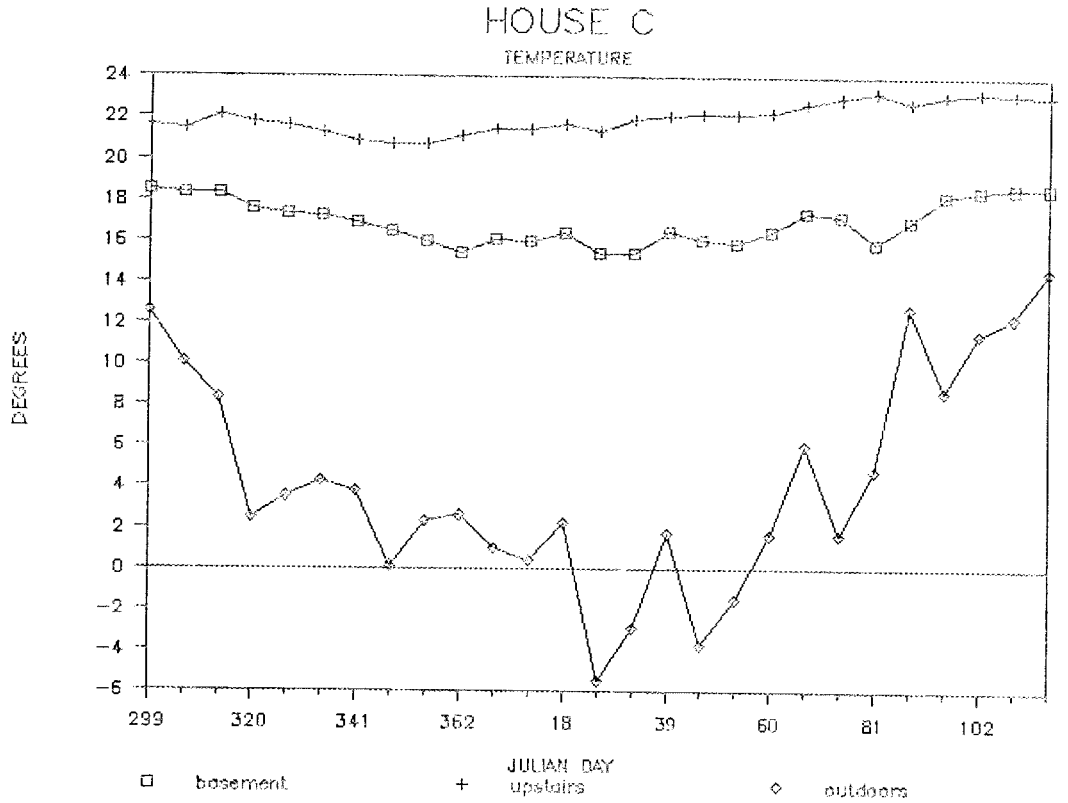

HOUSE B
HVAC
FRACTION ON
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
299
321
342
363
18
39
61
83
102
JULIAN DAY

Figure 6.15


HOUSE C
TEMPERATURE
DEGREES
24
22
20
18
16
14
12
10
8
6
4
2
0
-2
-4
-6
299
320
341
362
18
39
60
81
102
JULIAN DAY
basement
upstairs
outdoors

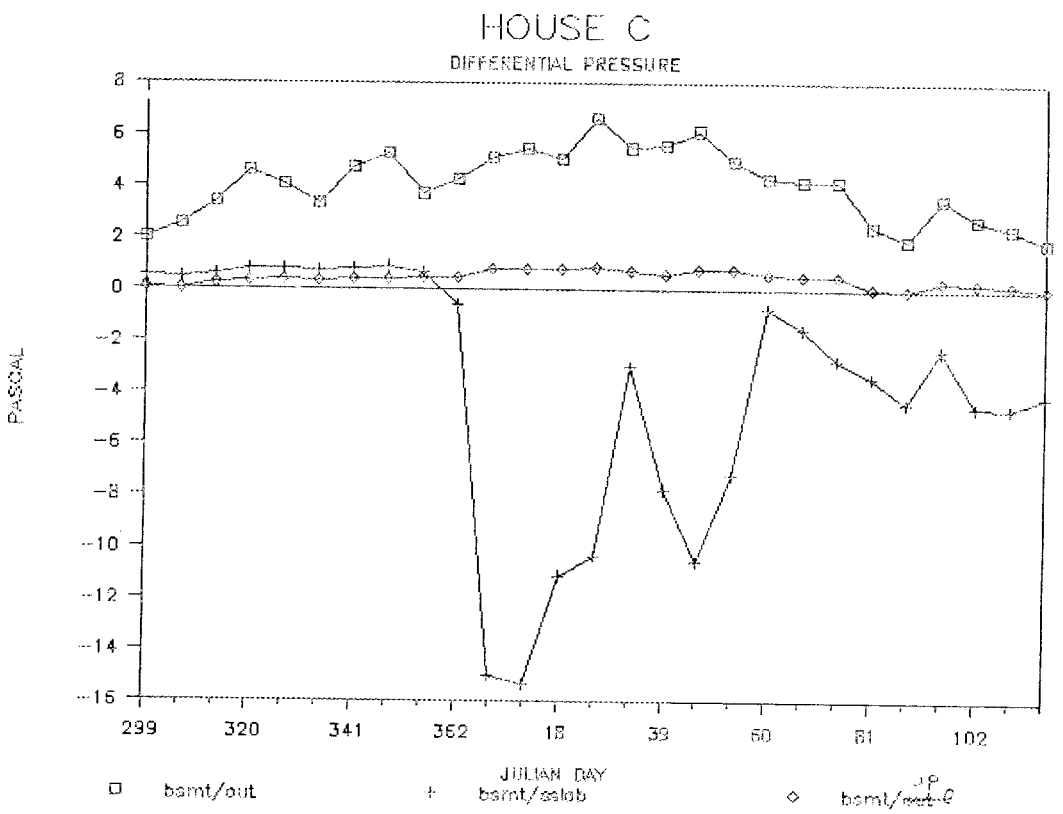
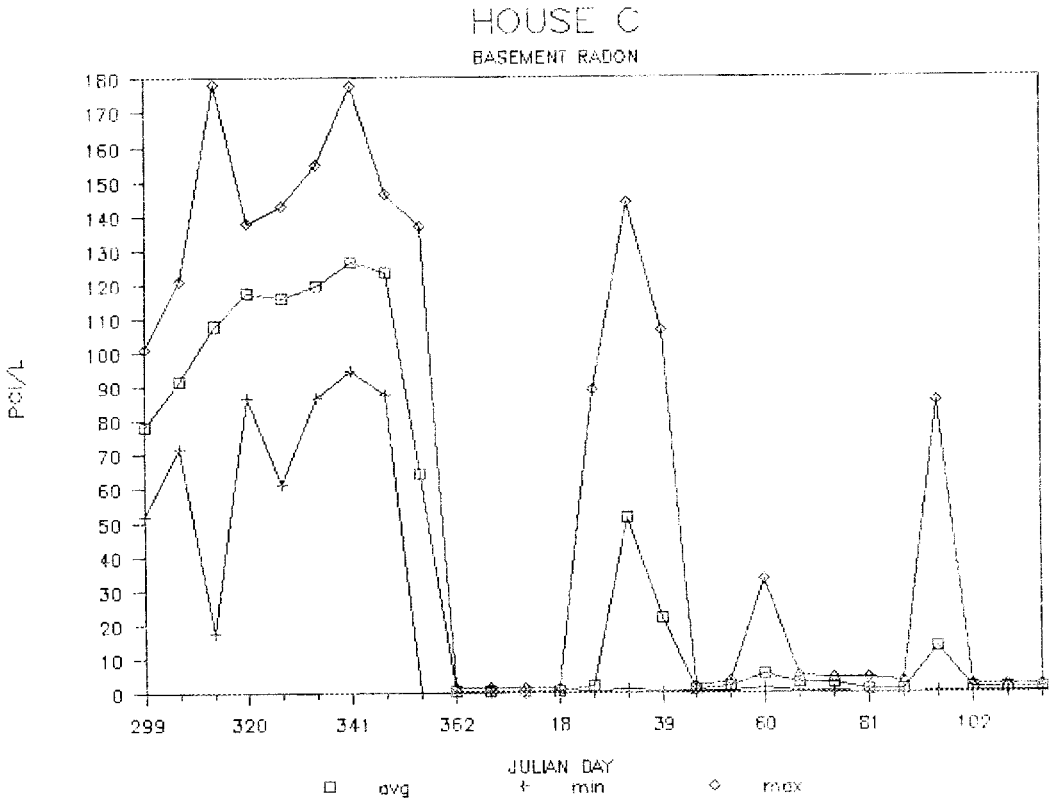

HOUSE C
DIFFERENTIAL PRESSURE
PASCAL
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
299
320
341
362
18
39
60
81
102
JULIAN DAY
bsmt/out
bsmt/sslab
bsmt/out

Figure 6.16


HOUSE C
BASEMENT RADON
PCI/L
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
299
320
341
362
18
39
60
81
102
JULIAN DAY
avg
min
max

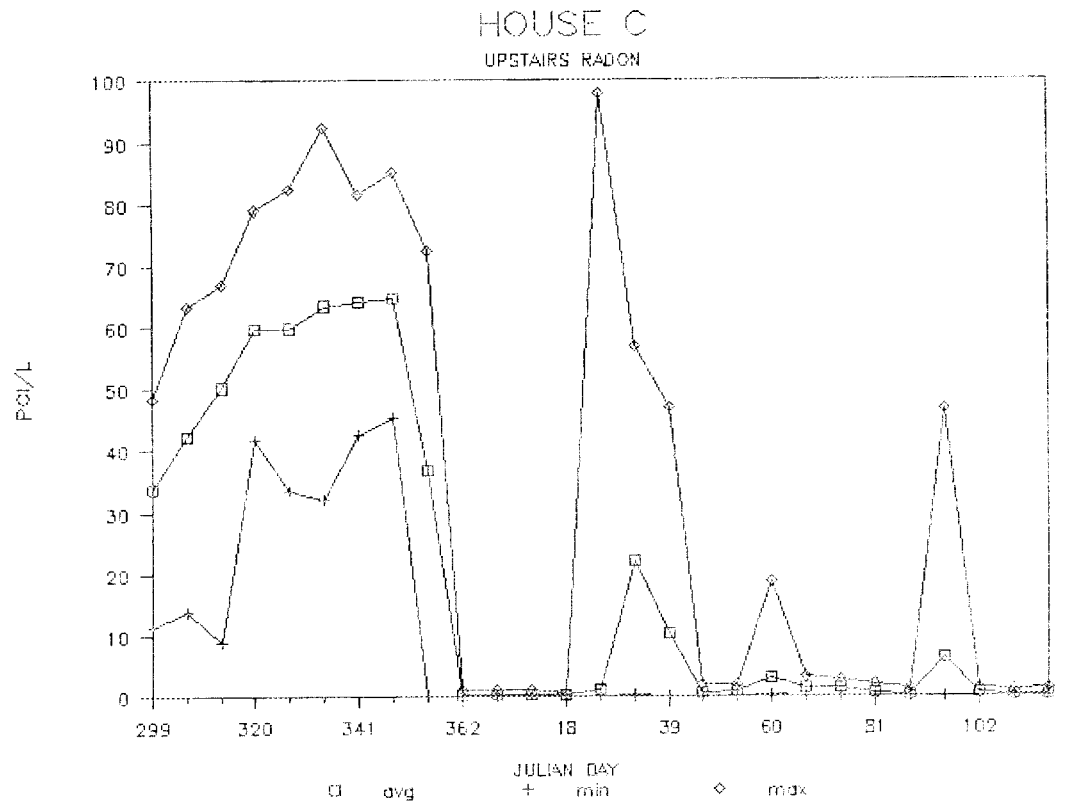
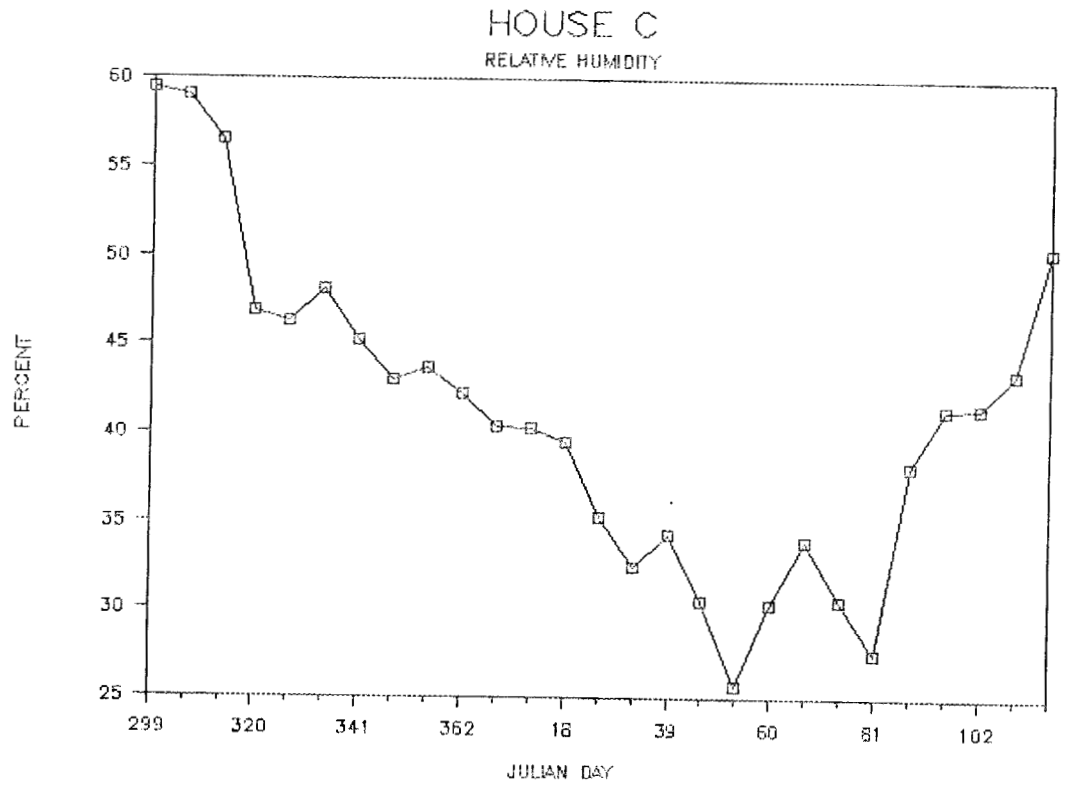

HOUSE C
UPSTAIRS RADON
PCI/L
100
90
80
70
60
50
40
30
20
10
0
299
320
341
362
18
39
60
81
102
JULIAN DAY
avg
min
max

Figure 6.17


HOUSE C
RELATIVE HUMIDITY
PERCENT
60
55
50
45
40
35
30
25
299
320
341
362
18
39
60
81
102
JULIAN DAY

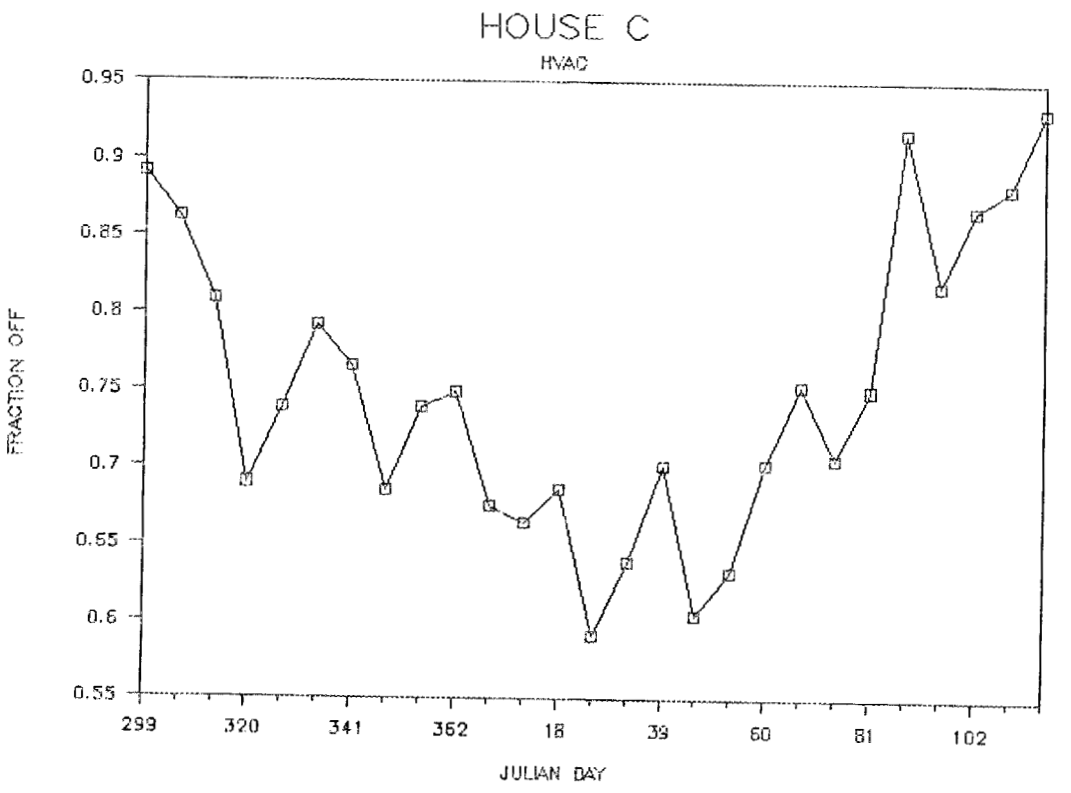
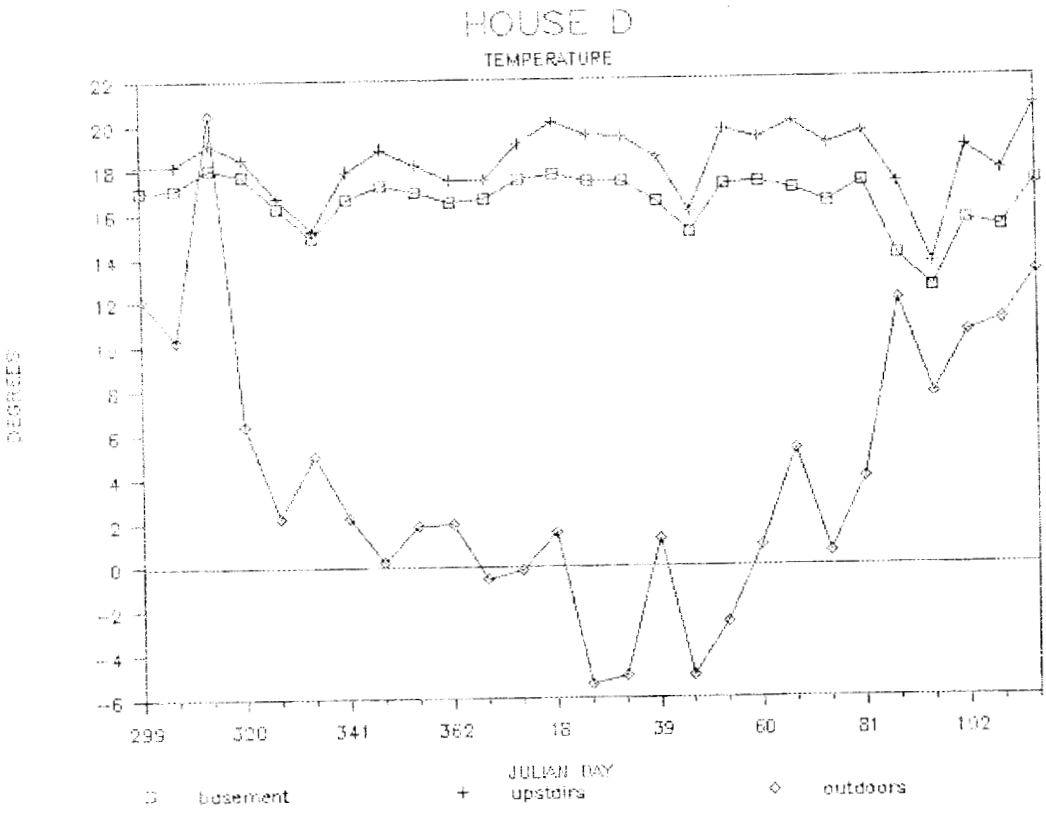

HOUSE C
HVAC
FRACTION OFF
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
299
320
341
362
18
39
60
81
102
JULIAN DAY

Figure 6.18


HOUSE D
TEMPERATURE
DEGREES
22
20
18
16
14
12
10
8
6
4
2
0
-2
-4
-6
299
320
341
362
18
39
60
81
102
JULIAN DAY
basement
upstairs
outdoors

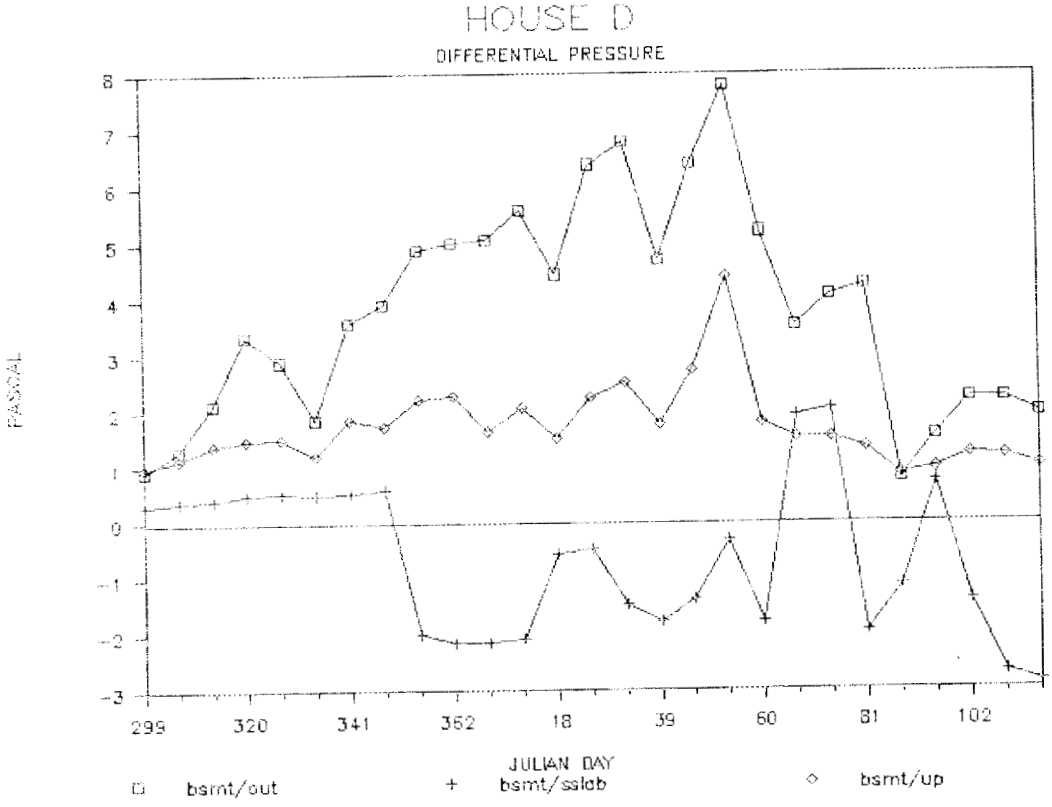
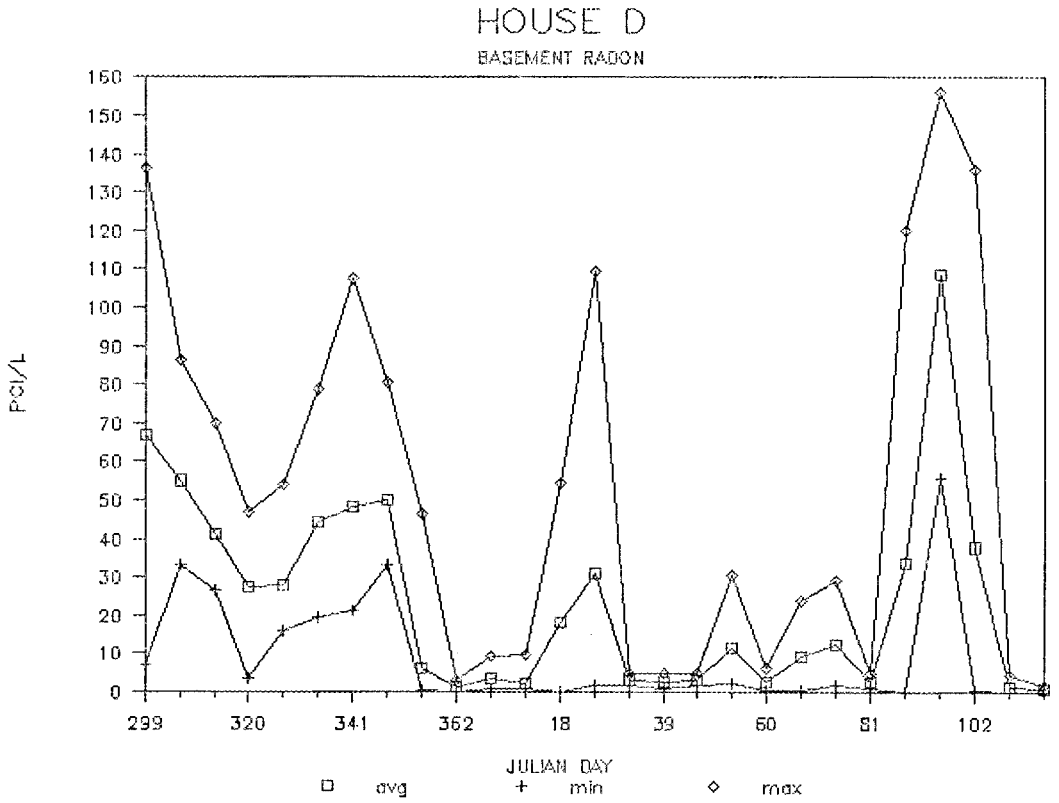

HOUSE D
DIFFERENTIAL PRESSURE
PASCAL
8
7
6
5
4
3
2
1
0
-1
-2
-3
299
320
341
362
18
39
60
81
102
JULIAN DAY
bsmt/out
bsmt/sslab
bsmt/up

Figure 6.19


HOUSE D
BASEMENT RADON
PCI/L
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
299
320
341
362
18
39
60
81
102
JULIAN DAY
avg
min
max

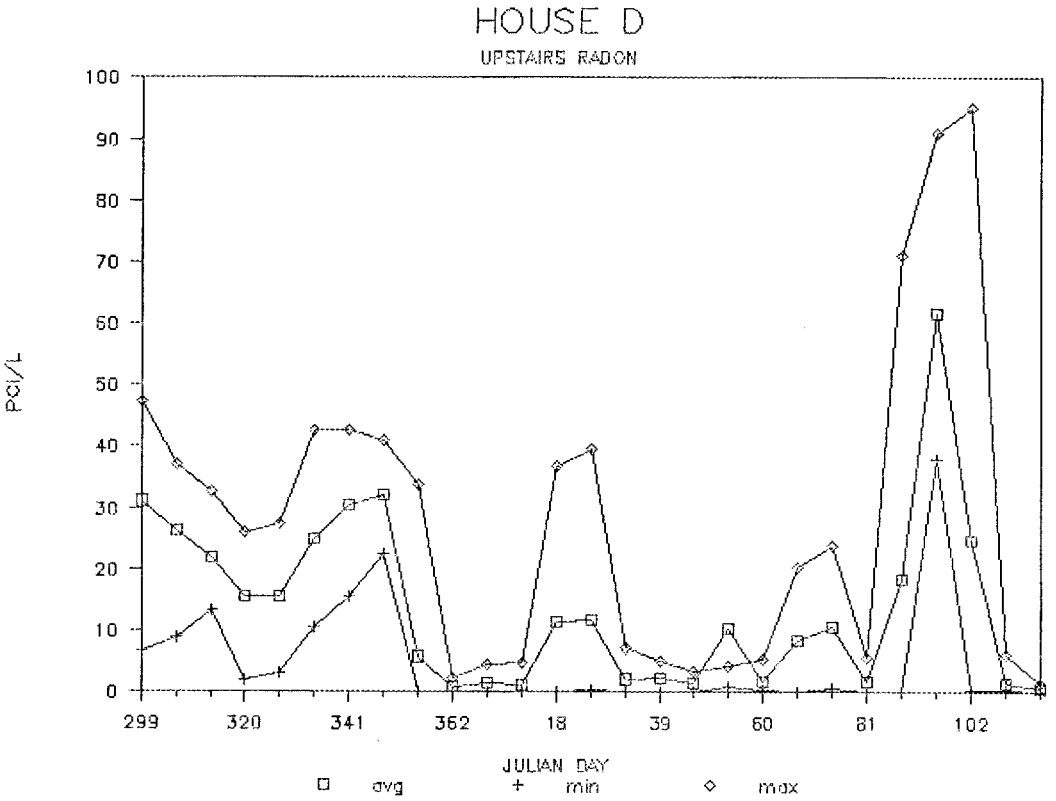
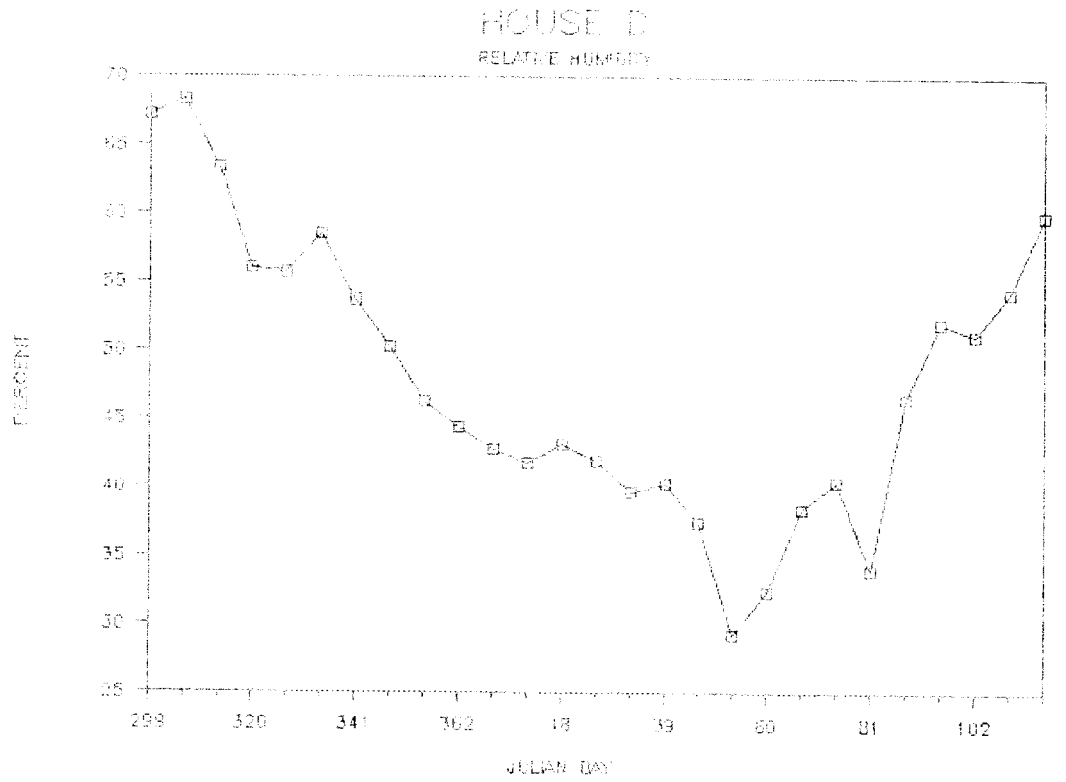

HOUSE D
UPSTAIRS RADON
PCI/L
100
90
80
70
60
50
40
30
20
10
0
299
320
341
362
18
39
60
81
102
JULIAN DAY
avg
min
max

Figure 6.20


HOUSE D
RELATIVE HUMIDITY
PERCENT
70
65
60
55
50
45
40
35
30
25
299
320
341
362
18
39
60
81
102
JULIAN DAY

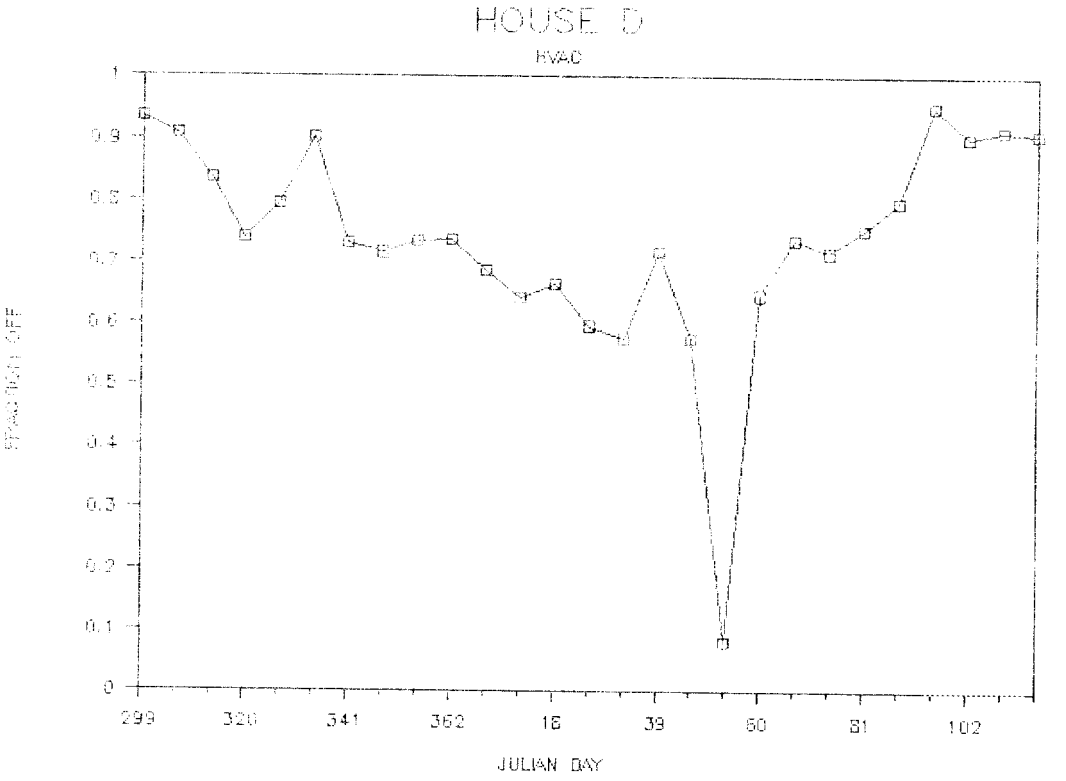
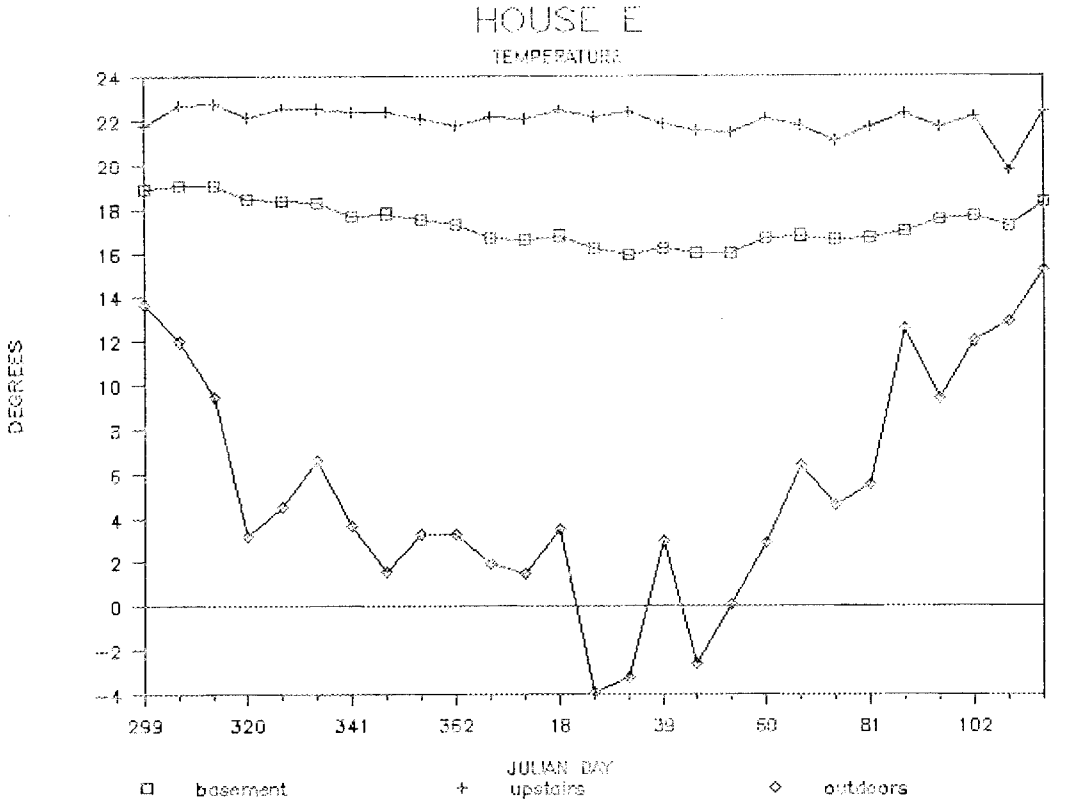

HOUSE D
HVAC
EFFECTIVENESS
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
299
320
341
362
18
39
60
81
102
JULIAN DAY

Figure 6.21


HOUSE E
TEMPERATURE
DEGREES
24
22
20
18
16
14
12
10
8
6
4
2
0
-2
-4
299
320
341
362
18
39
60
81
102
JULIAN DAY
basement
upstairs
outdoors

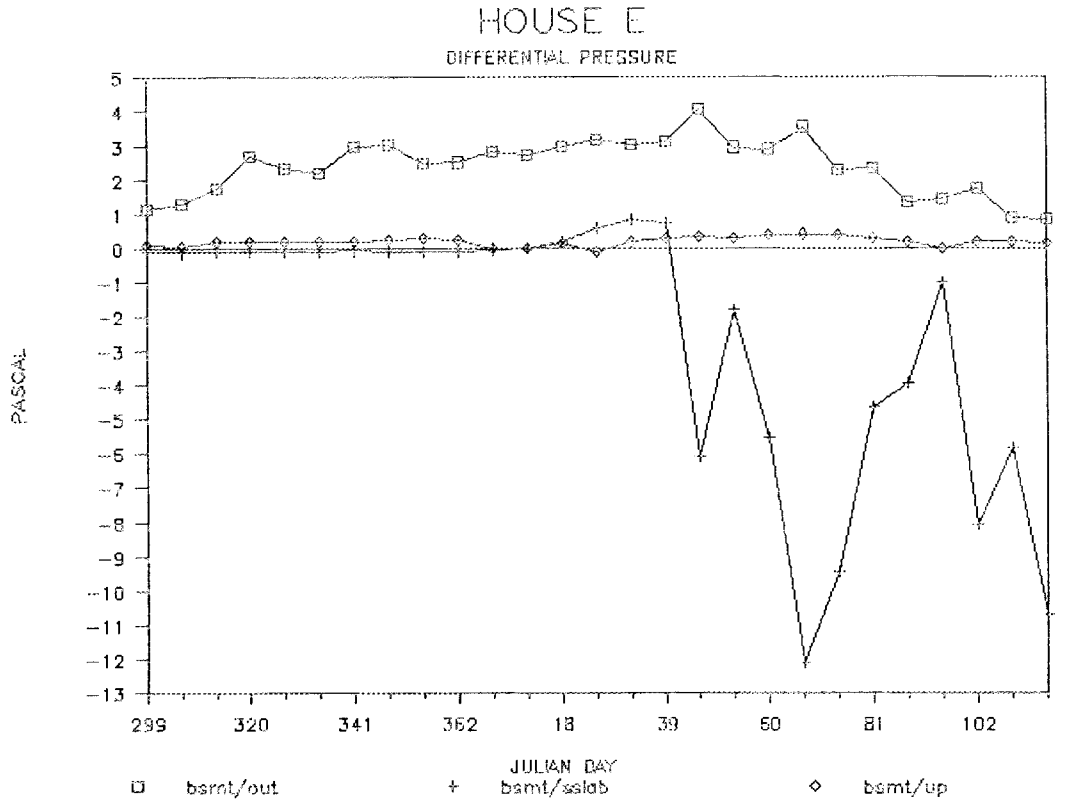
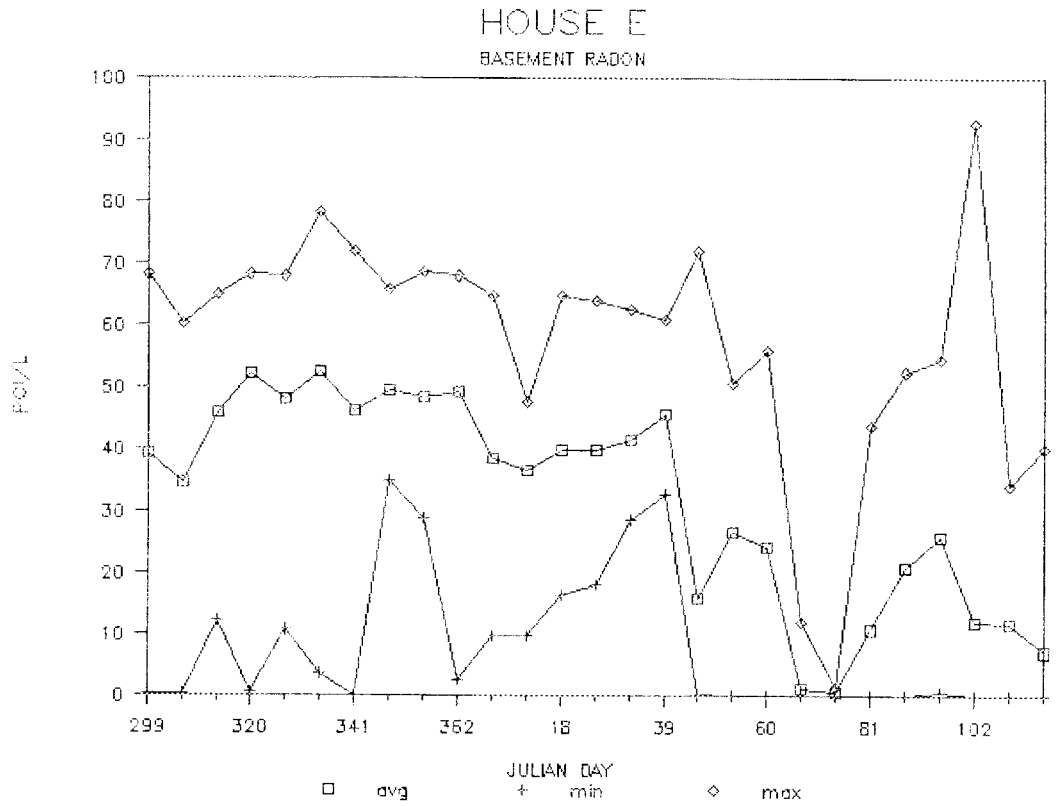

HOUSE E
DIFFERENTIAL PRESSURE
PASCAL
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
299
320
341
362
18
39
60
81
102
JULIAN DAY
bsmt/out
bsmt/sslab
bsmt/up

Figure 6.22


HOUSE E
BASEMENT RADON
PCI/L
100
90
80
70
60
50
40
30
20
10
0
299
320
341
362
18
39
60
81
102
JULIAN DAY
avg
min
max

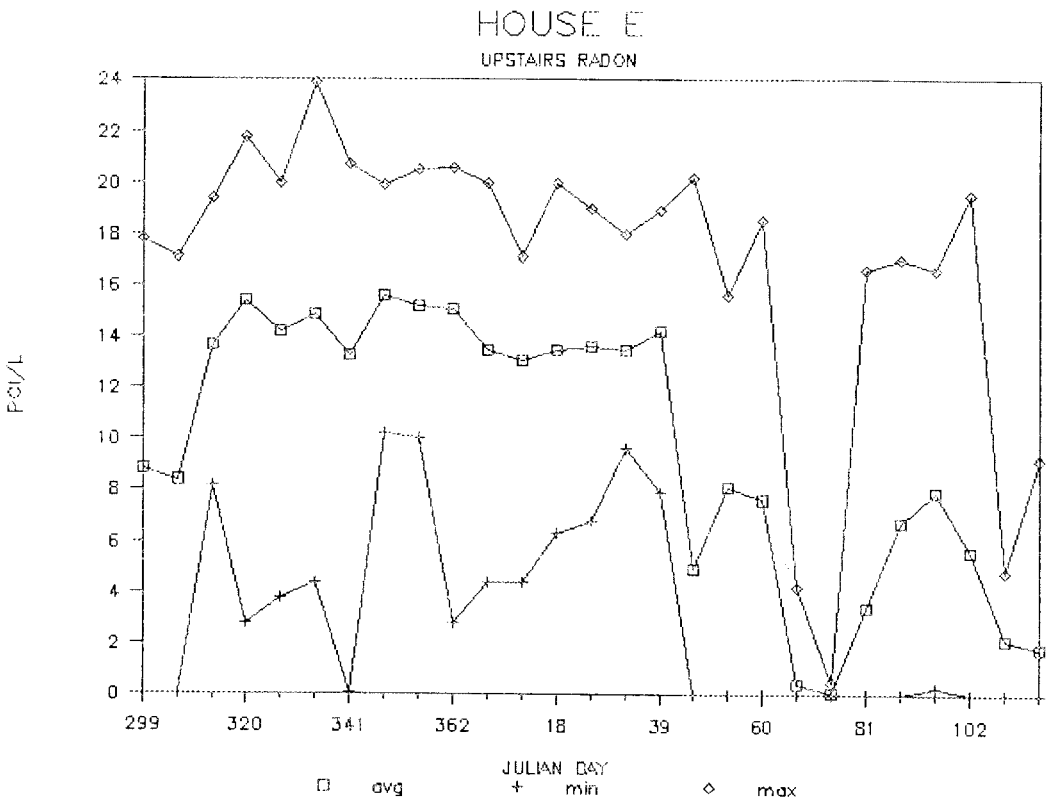
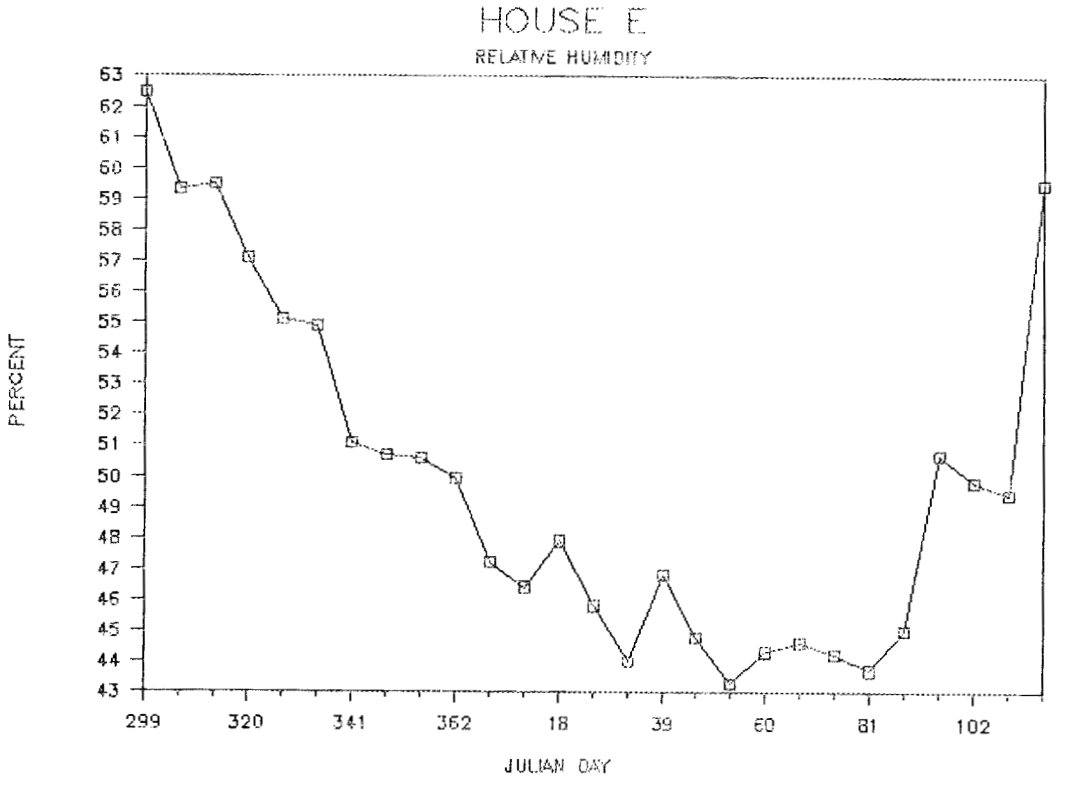

HOUSE E
UPSTAIRS RADON
PCI/L
24
22
20
18
16
14
12
10
8
6
4
2
0
299
320
341
362
18
39
60
81
102
JULIAN DAY
avg
min
max

Figure 6.23


HOUSE E
RELATIVE HUMIDITY
PERCENT
63
62
61
60
59
58
57
56
55
54
53
52
51
50
49
48
47
46
45
44
43
299
320
341
362
18
39
60
81
102
JULIAN DAY

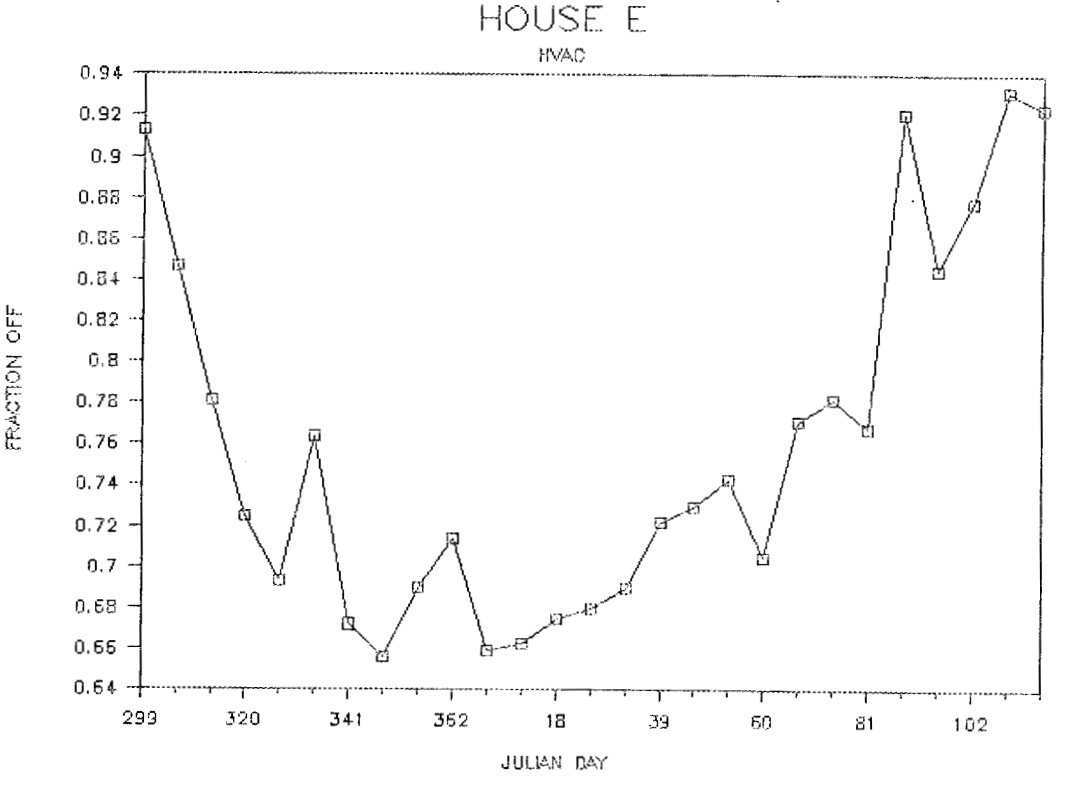
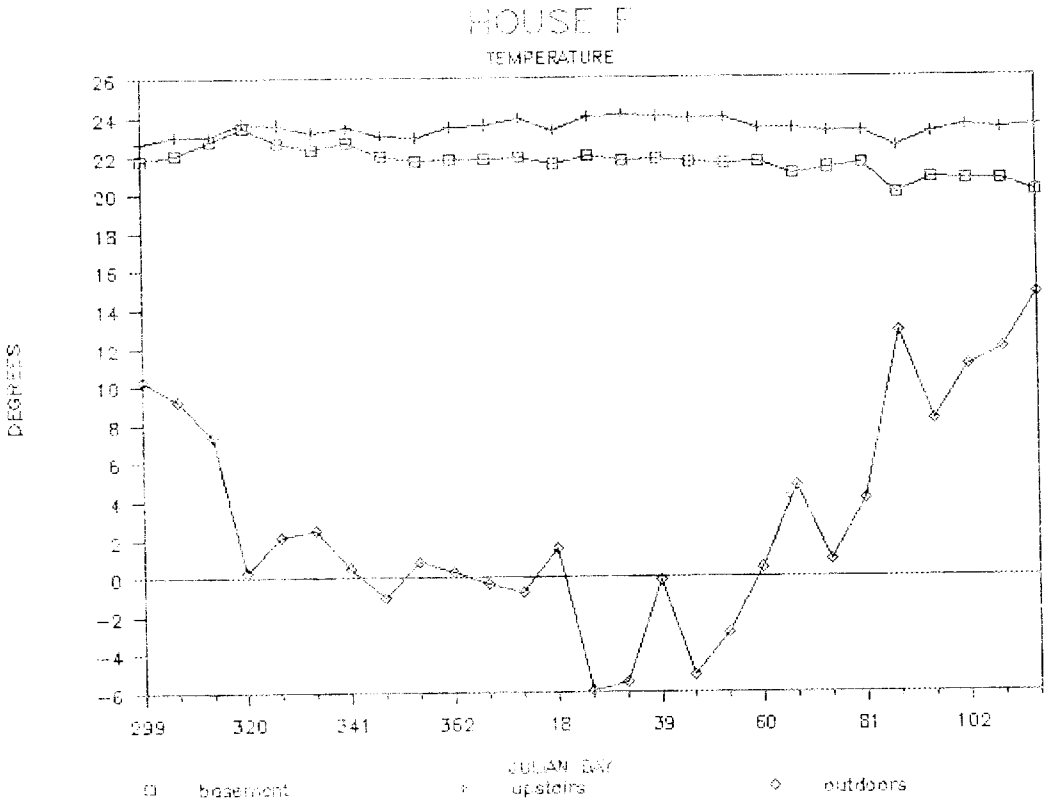

HOUSE E
HVAC
FRACTION OFF
0.94
0.92
0.9
0.88
0.86
0.84
0.82
0.8
0.78
0.76
0.74
0.72
0.7
0.68
0.66
0.64
299
320
341
362
18
39
60
81
102
JULIAN DAY

Figure 6.24


HOUSE F
TEMPERATURE
DEGREES
26
24
22
20
18
16
14
12
10
8
6
4
2
0
-2
-4
-6
299
320
341
362
18
39
60
81
102
JULIAN DAY
basement
upstairs
outdoors

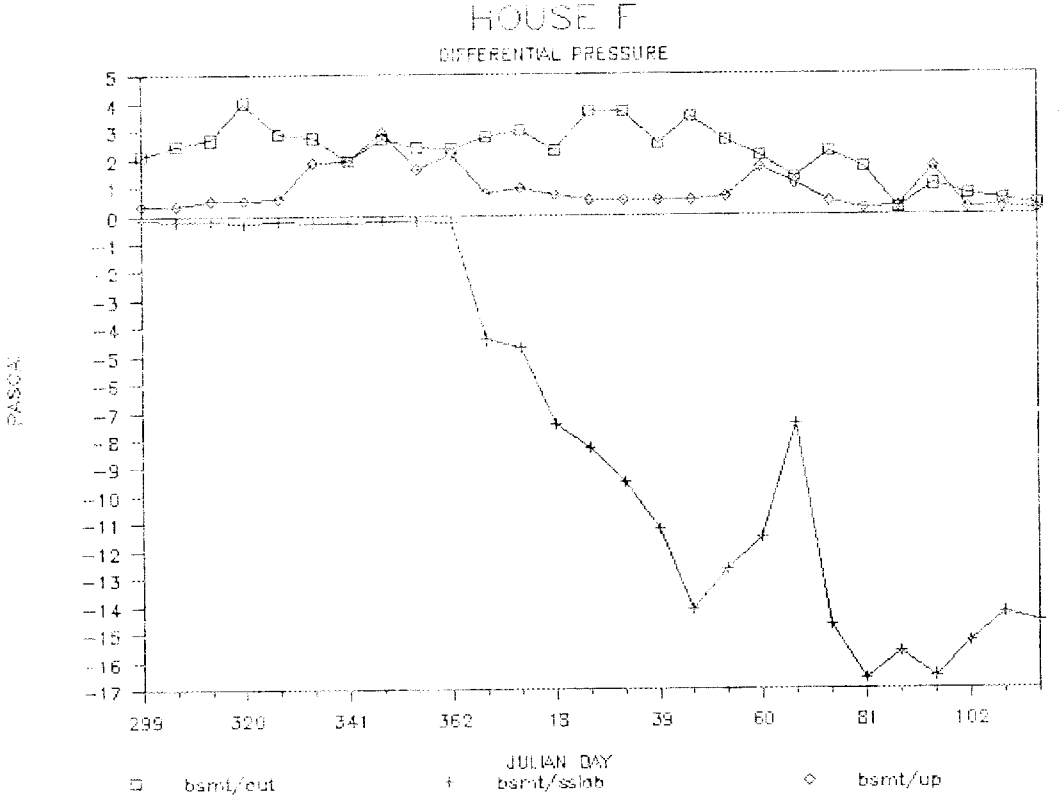
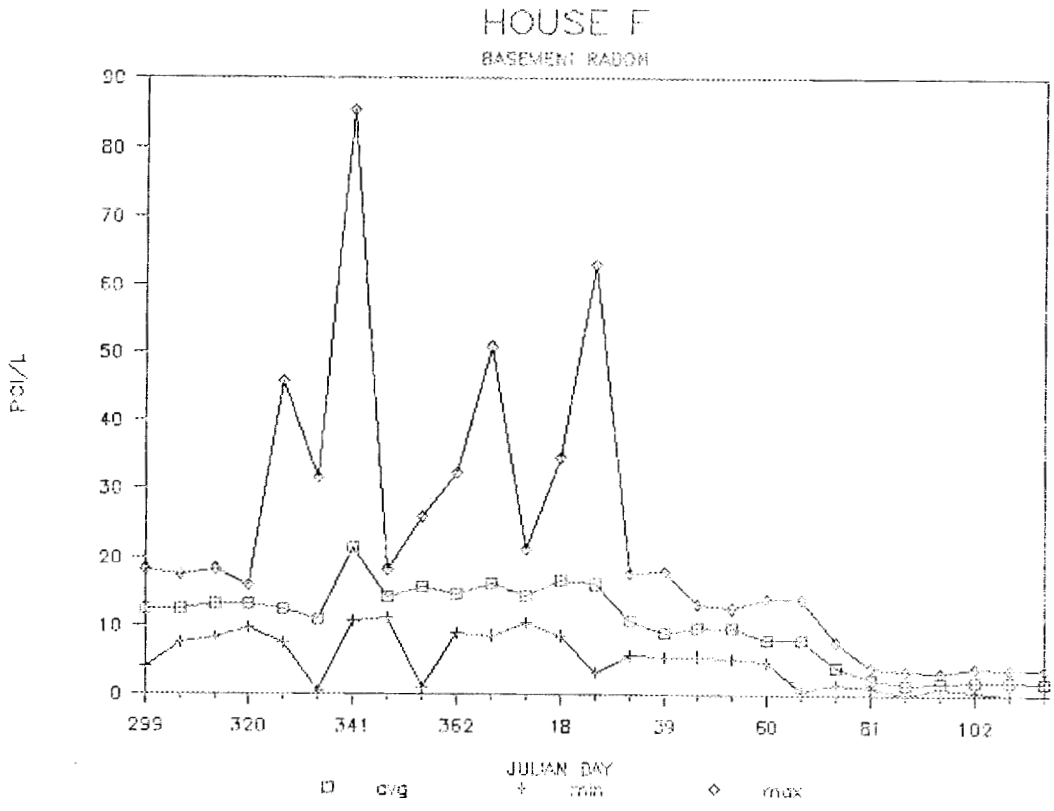

HOUSE F
DIFFERENTIAL PRESSURE
PASCAL
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
-16
-17
299
320
341
362
18
39
60
81
102
JULIAN DAY
bsmt/out
bsmt/sslab
bsmt/up

Figure 6.25


HOUSE F
BASEMENT RADON
PCI/L
90
80
70
60
50
40
30
20
10
0
299
320
341
362
18
39
60
81
102
JULIAN DAY
avg
min
max

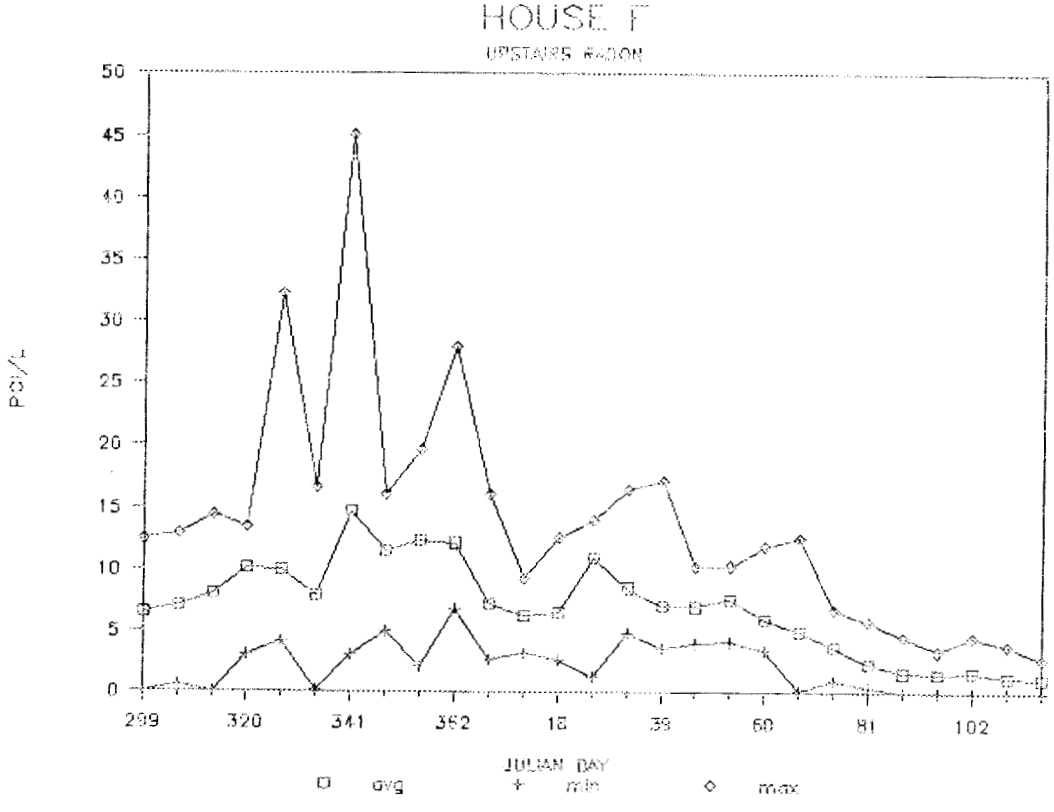
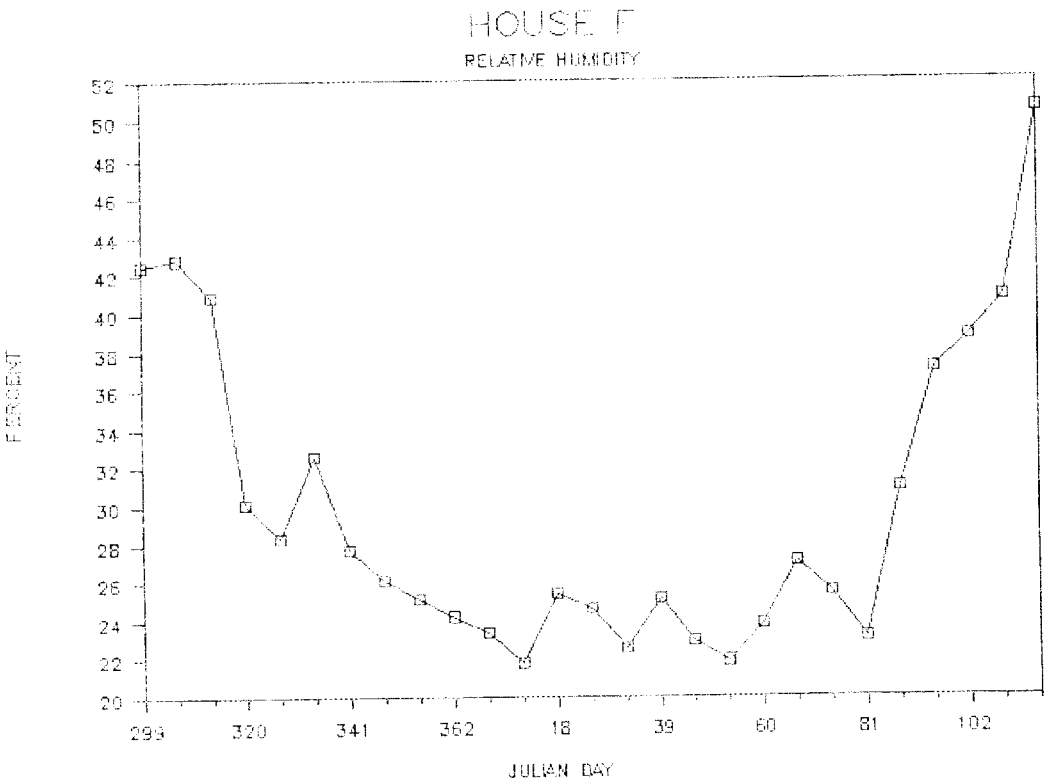

HOUSE F
UPSTAIRS RADON
PCI/L
50
45
40
35
30
25
20
15
10
5
0
299
320
341
362
18
39
60
81
102
JULIAN DAY
avg
min
max

Figure 6.26


HOUSE F
RELATIVE HUMIDITY
PERCENT
52
50
48
46
44
42
40
38
36
34
32
30
28
26
24
22
20
299
320
341
362
18
39
60
81
102
JULIAN DAY

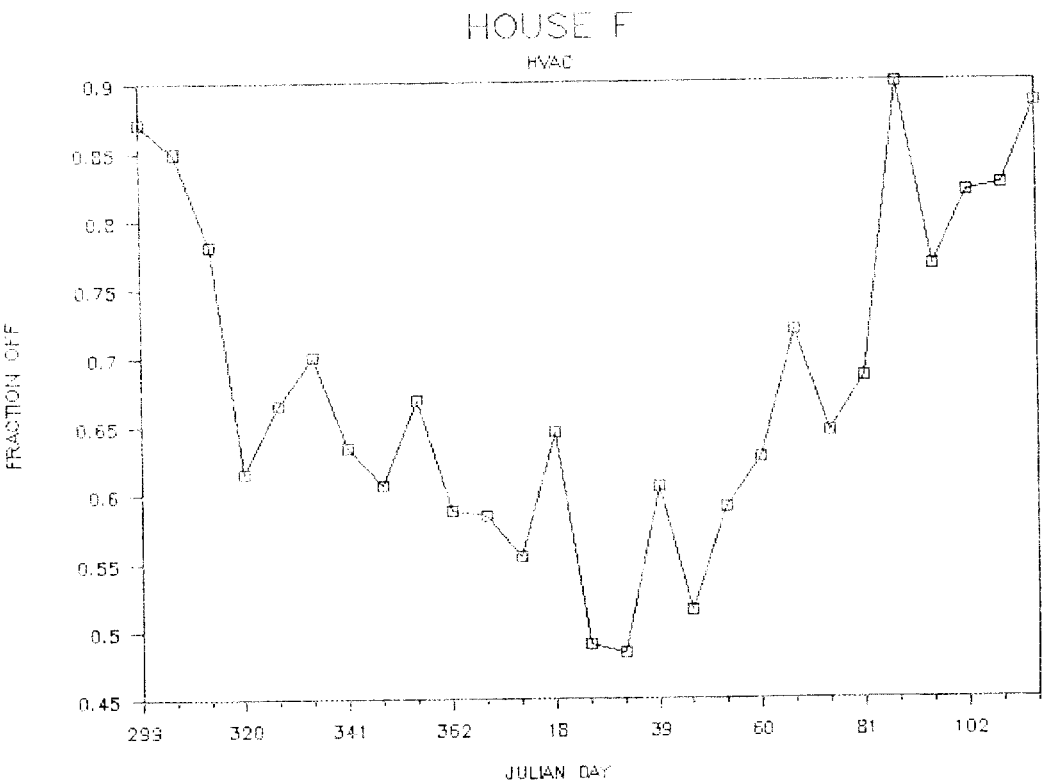
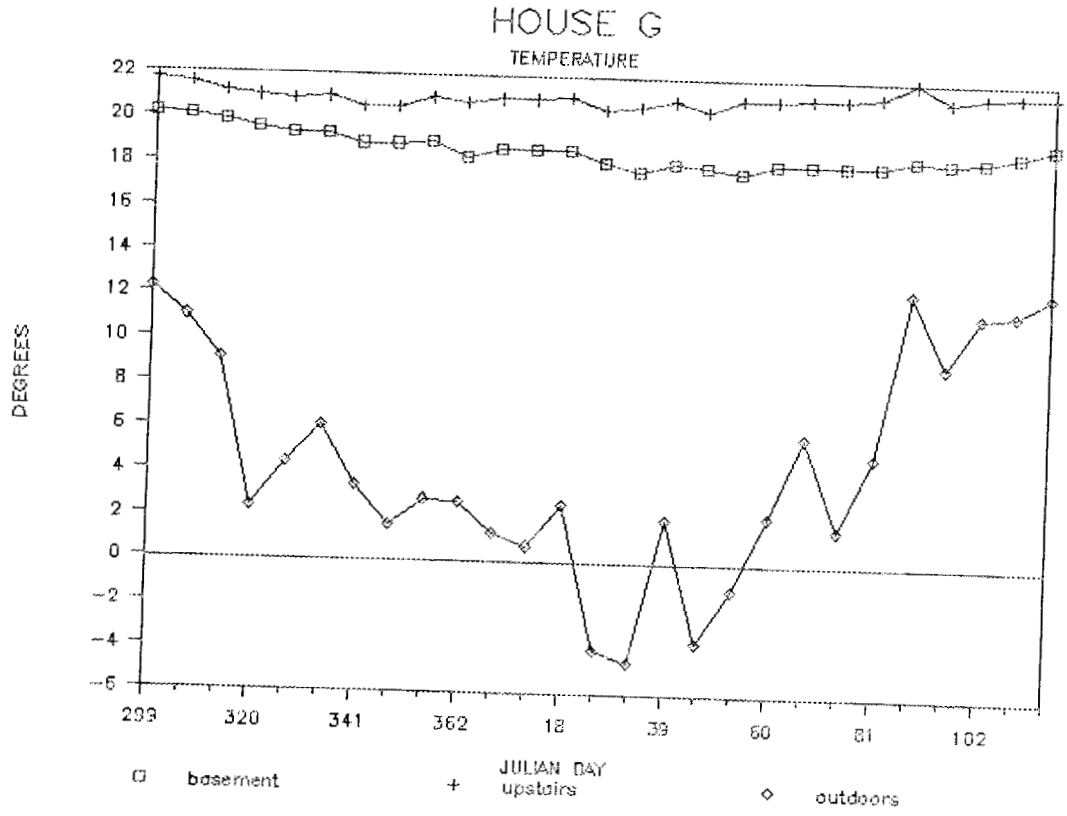

HOUSE F
HVAC
FRACTION OFF
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
299
320
341
362
18
39
60
81
102
JULIAN DAY

Figure 6.27


HOUSE G
TEMPERATURE
DEGREES
22
20
18
16
14
12
10
8
6
4
2
0
-2
-4
-6
299
320
341
362
18
39
60
81
102
JULIAN DAY
basement
upstairs
outdoors

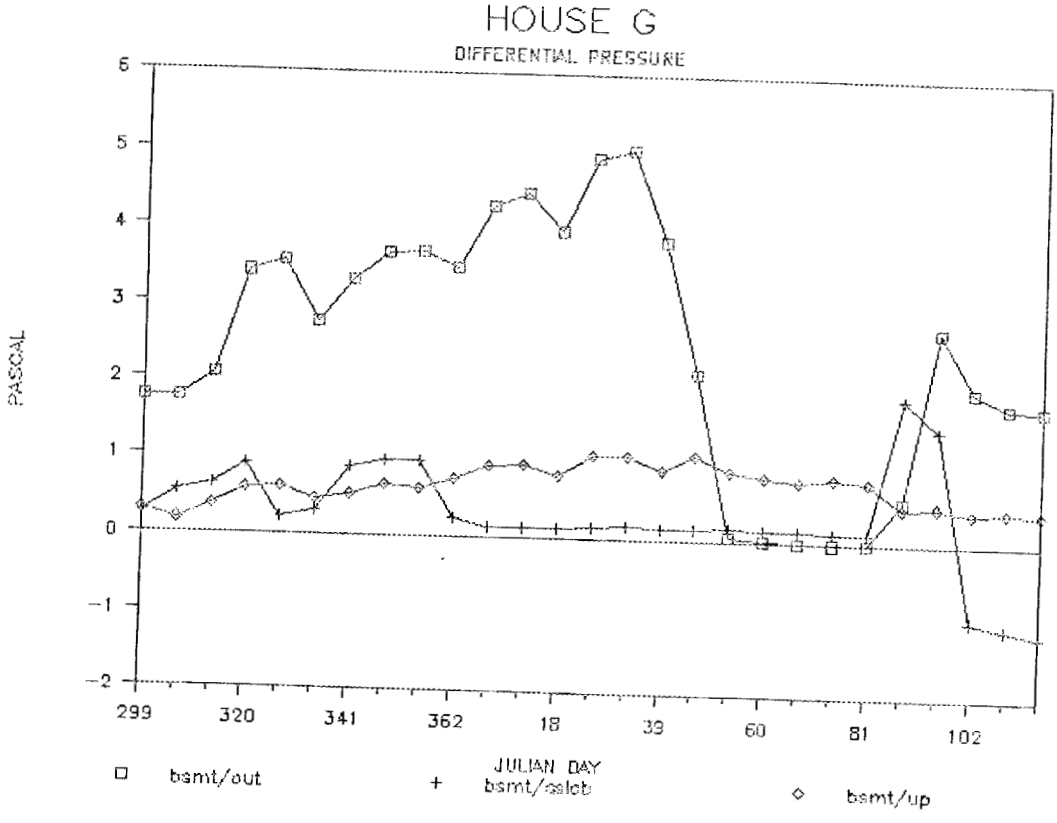
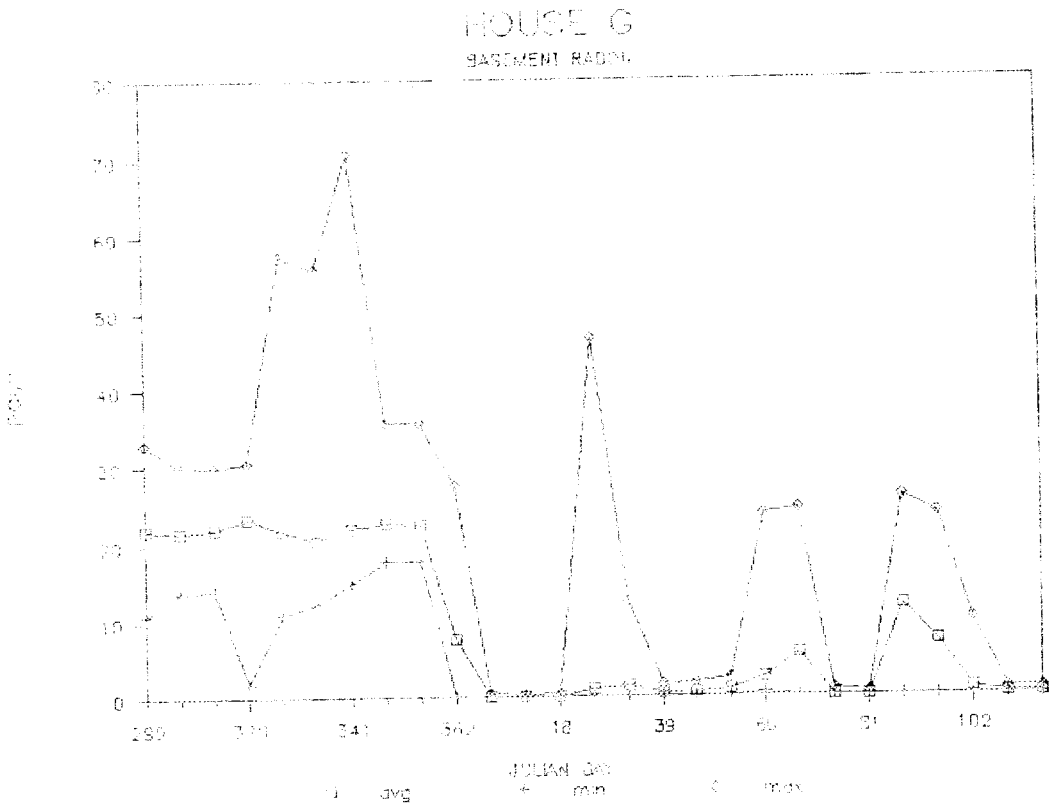

HOUSE G
DIFFERENTIAL PRESSURE
PASCAL
6
5
4
3
2
1
0
-1
-2
299
320
341
362
18
39
60
81
102
JULIAN DAY
bsmt/out
bsmt/up

Figure 6.28


HOUSE G
BASEMENT RADON
0
10
20
30
40
50
60
70
80
90
12
38
102
JULIAN DAY

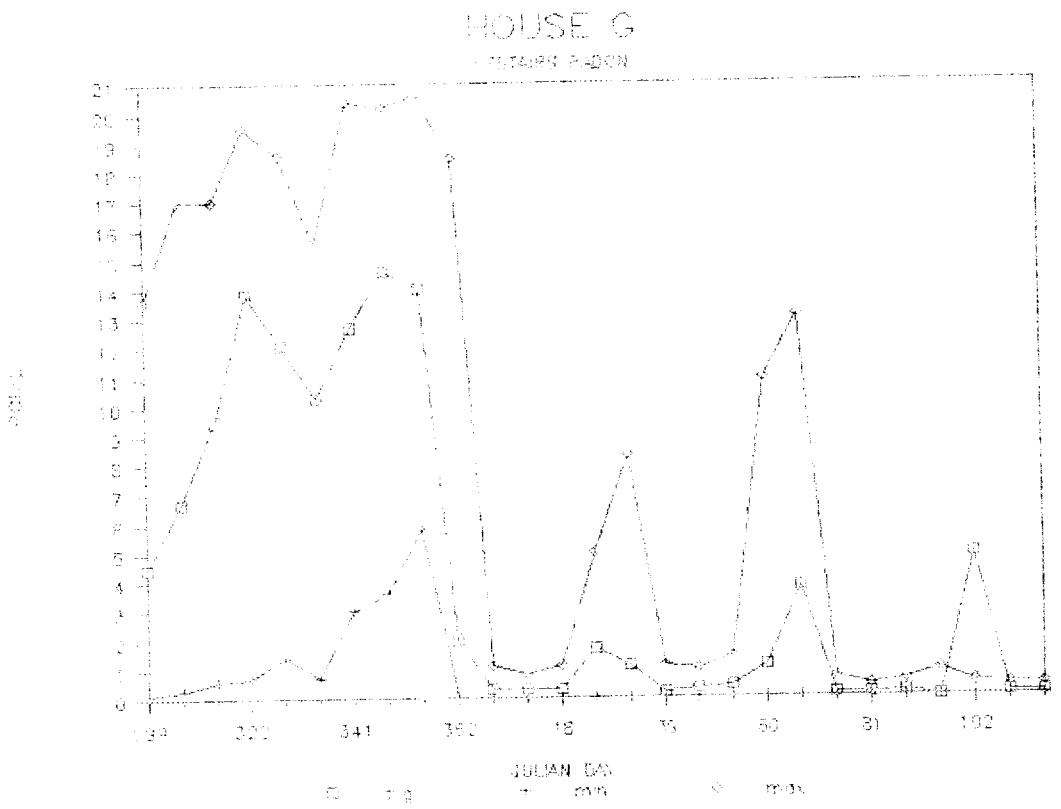

HOUSE G
STAIRS RADON
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
341
18
50
81
102
JULIAN DAY

Figure 6.29

HOUSE G
RELATIVE HUMIDITY
PERCENT
60
58
56
54
52
50
48
46
44
42
40
38
36
34
32
30
299
320
341
362
18
39
60
81
102
JULIAN DAY

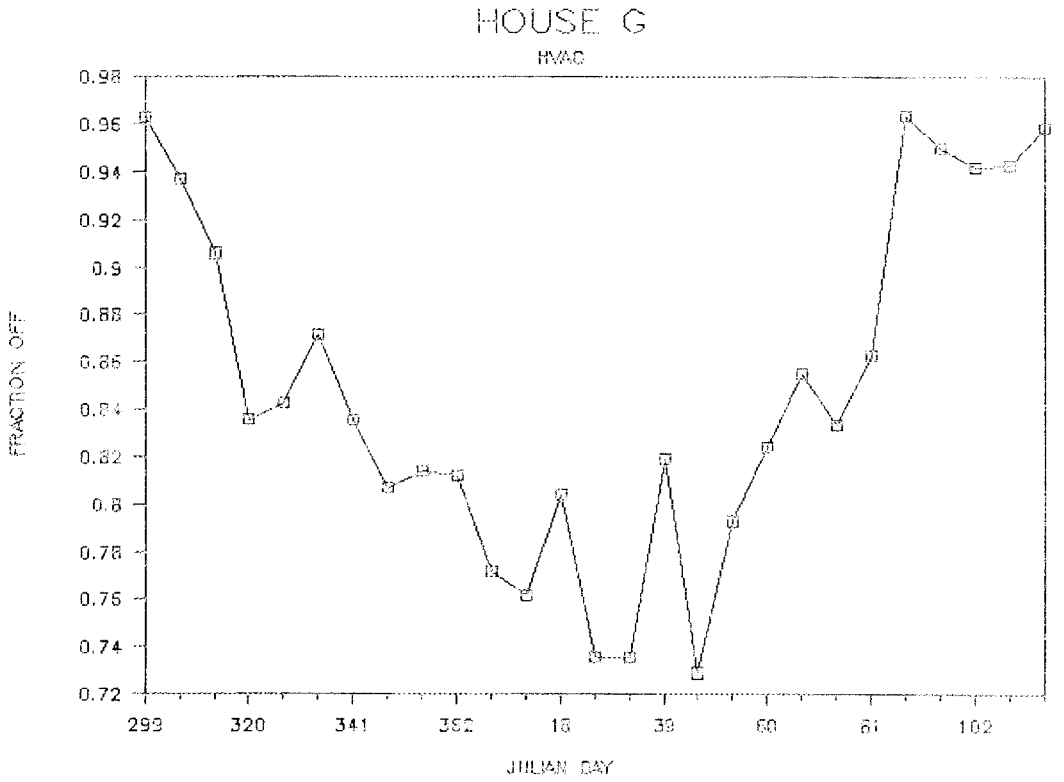
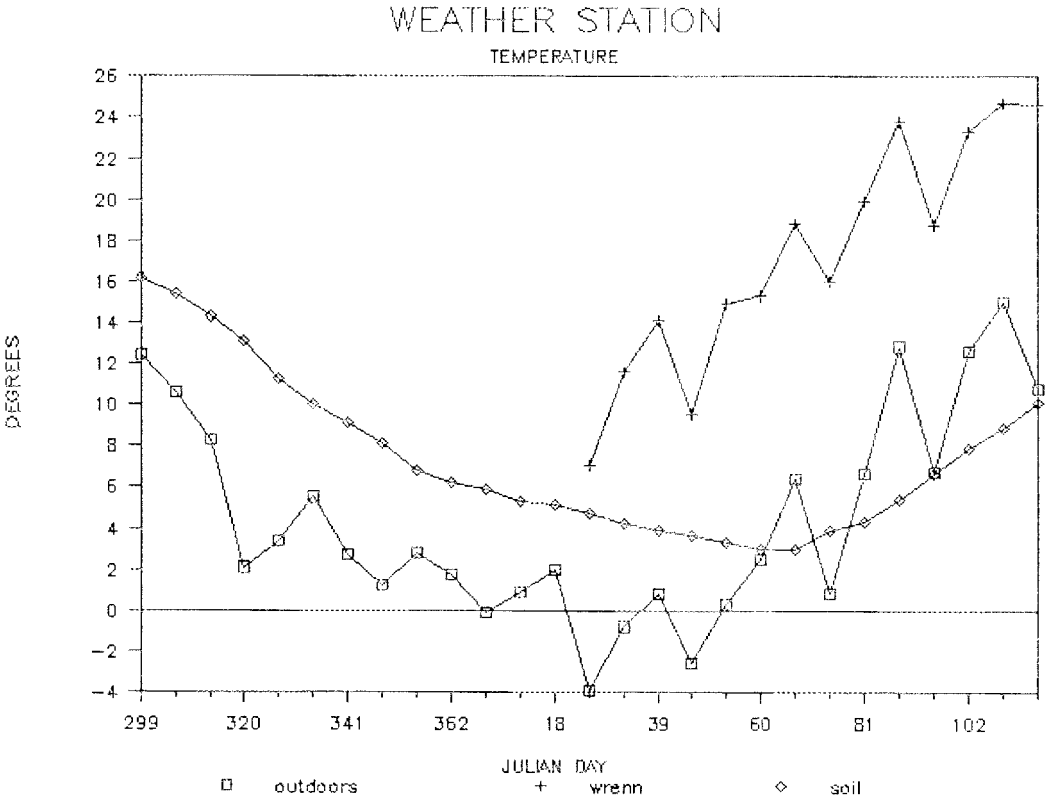

HOUSE G
HVAC
FRACTION OFF
0.98
0.96
0.94
0.92
0.9
0.88
0.86
0.84
0.82
0.8
0.78
0.76
0.74
0.72
299
320
341
362
18
39
60
81
102
JULIAN DAY

Figure 6.30


WEATHER STATION
TEMPERATURE
DEGREES
26
24
22
20
18
16
14
12
10
8
6
4
2
0
-2
-4
299
320
341
362
18
39
60
81
102
JULIAN DAY
outdoors
wrenn
soil

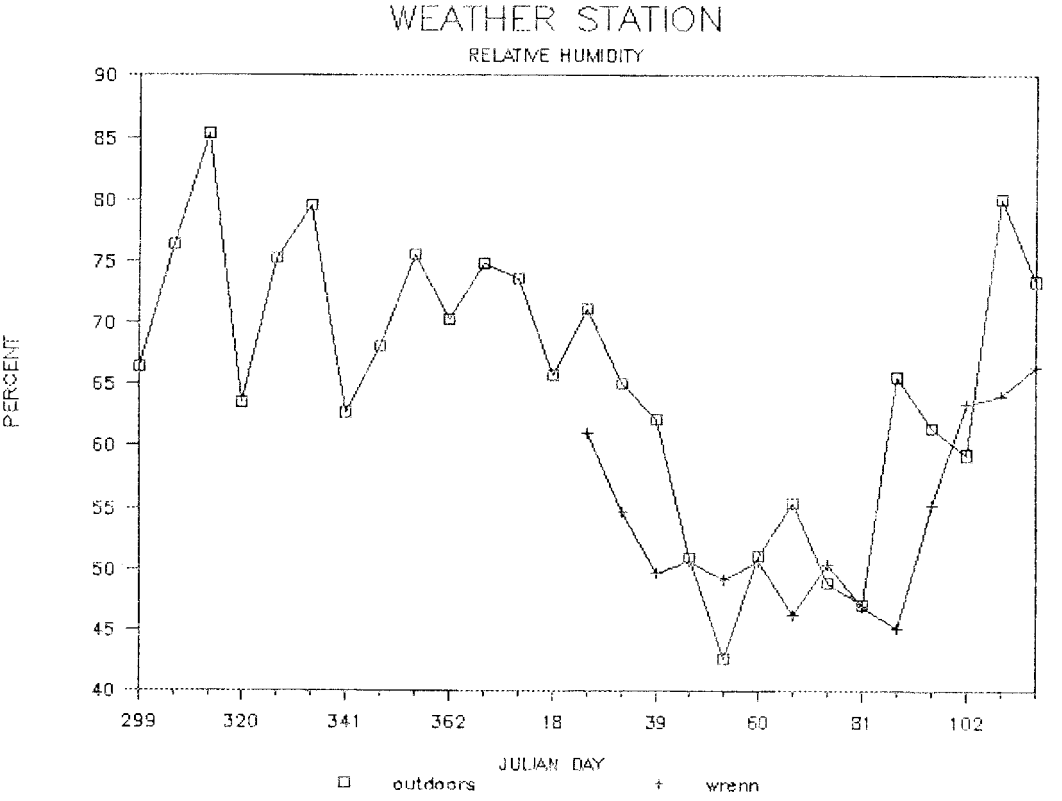
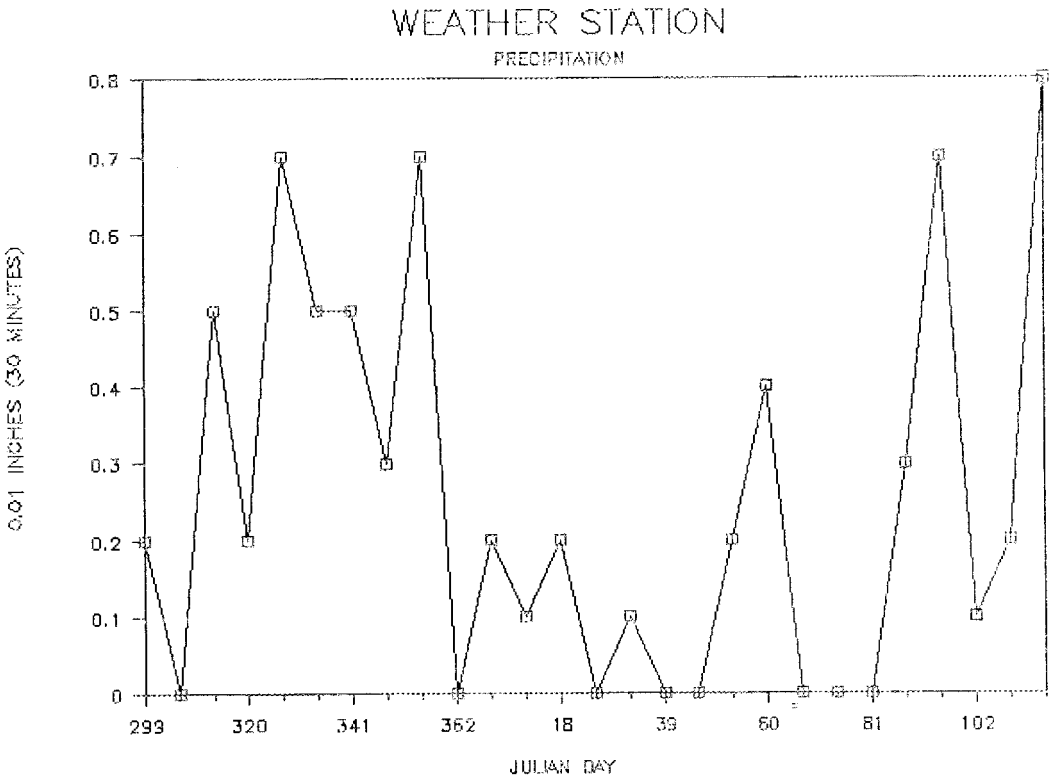

WEATHER STATION
RELATIVE HUMIDITY
PERCENT
90
85
80
75
70
65
60
55
50
45
40
299
320
341
362
18
39
60
81
102
JULIAN DAY
outdoors
wrenn

Figure 6.31


WEATHER STATION
PRECIPITATION
0.01 INCHES (30 MINUTES)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
299
320
341
362
18
39
60
81
102
JULIAN DAY

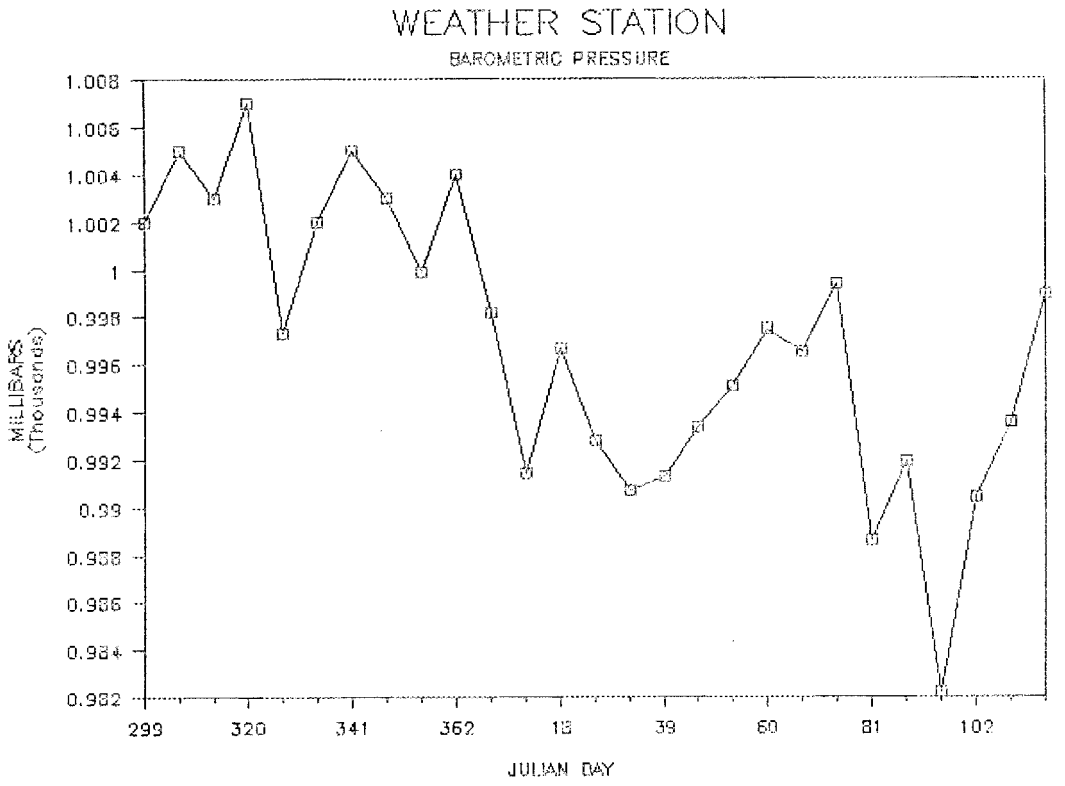
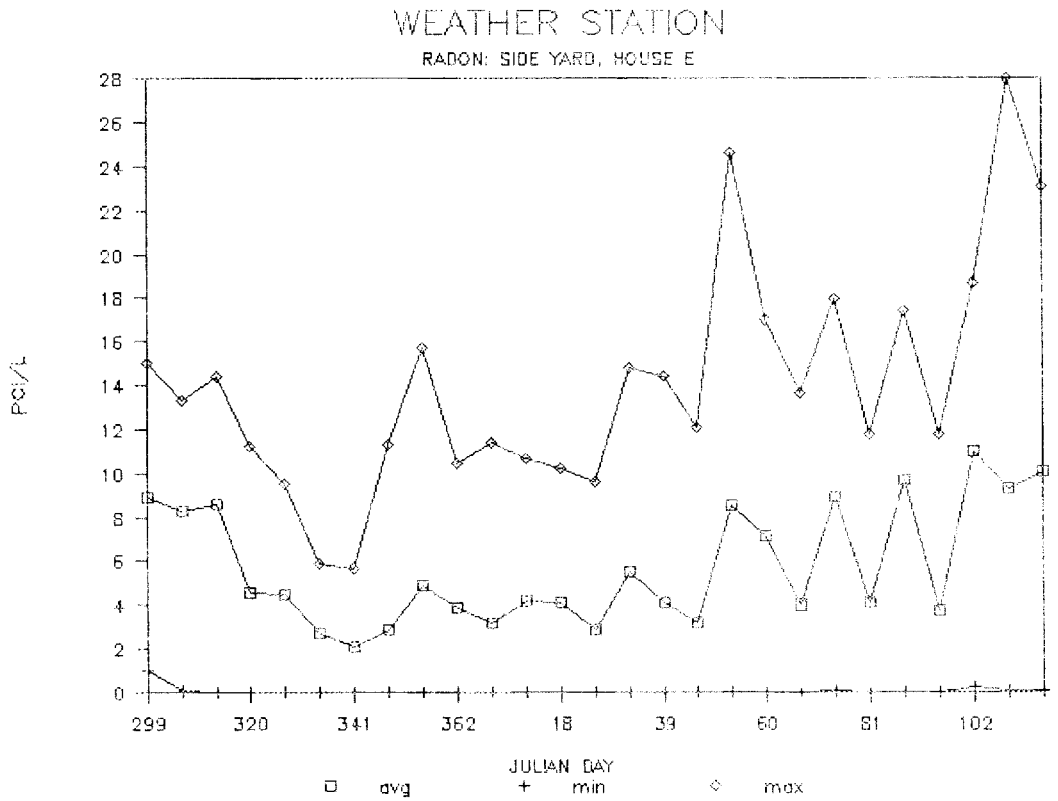

WEATHER STATION
BAROMETRIC PRESSURE
MILLIBARS
(Thousands)
1.008
1.006
1.004
1.002
1
0.998
0.996
0.994
0.992
0.99
0.988
0.986
0.984
0.982
299
320
341
362
18
39
60
81
102
JULIAN DAY

Figure 6.32


WEATHER STATION
RADON: SIDE YARD, HOUSE E
PCI/L
JULIAN DAY
avg
min
max

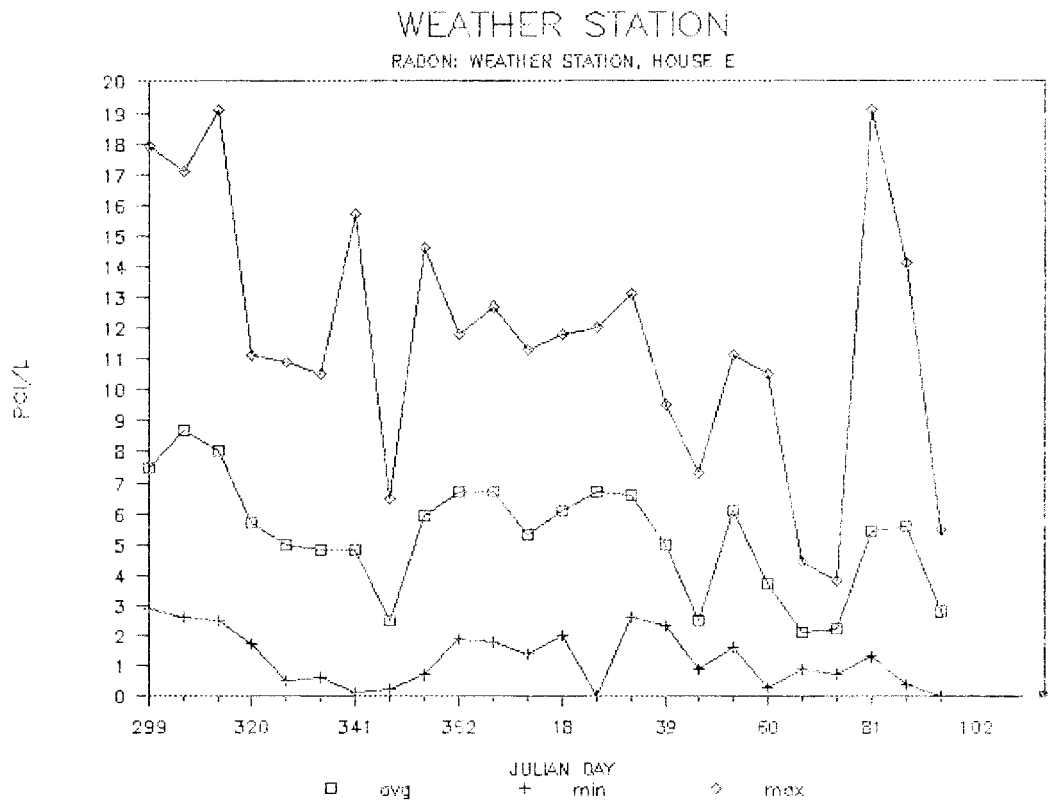

WEATHER STATION
RADON: WEATHER STATION, HOUSE E
PCI/L
JULIAN DAY
avg
min
max

Figure 6.33

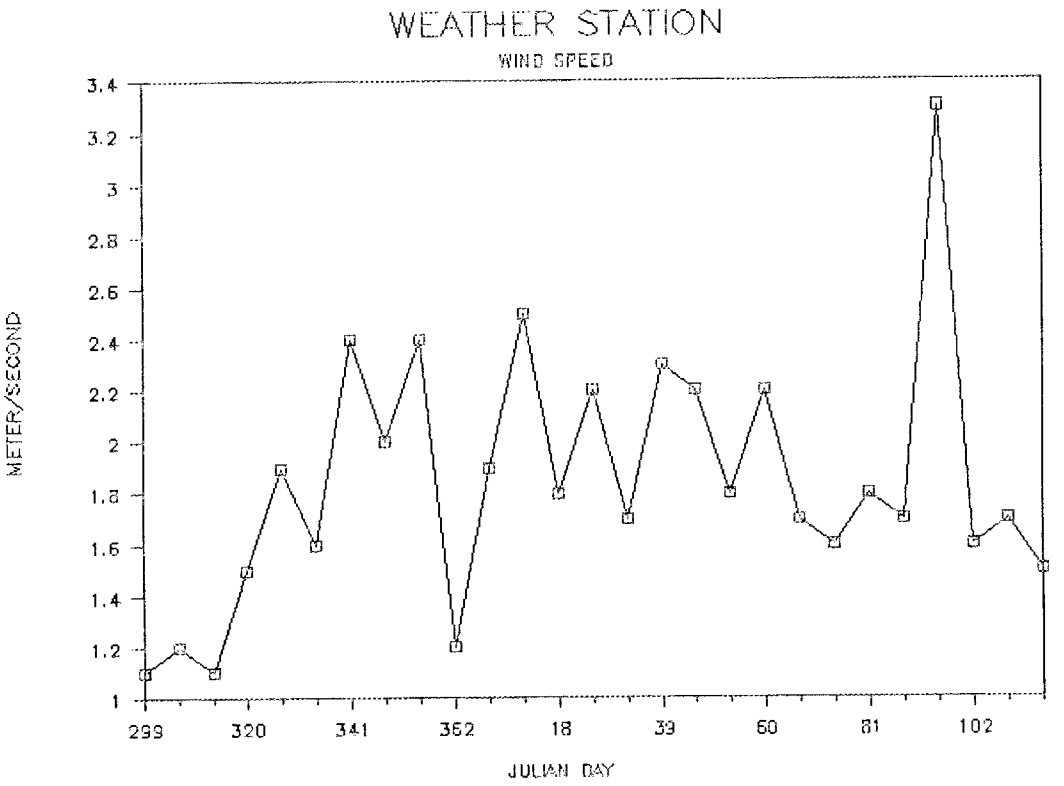

WEATHER STATION
WIND SPEED
METER/SECOND
3.4
3.2
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
299
320
341
362
18
39
60
81
102
JULIAN DAY

Figure 6.34

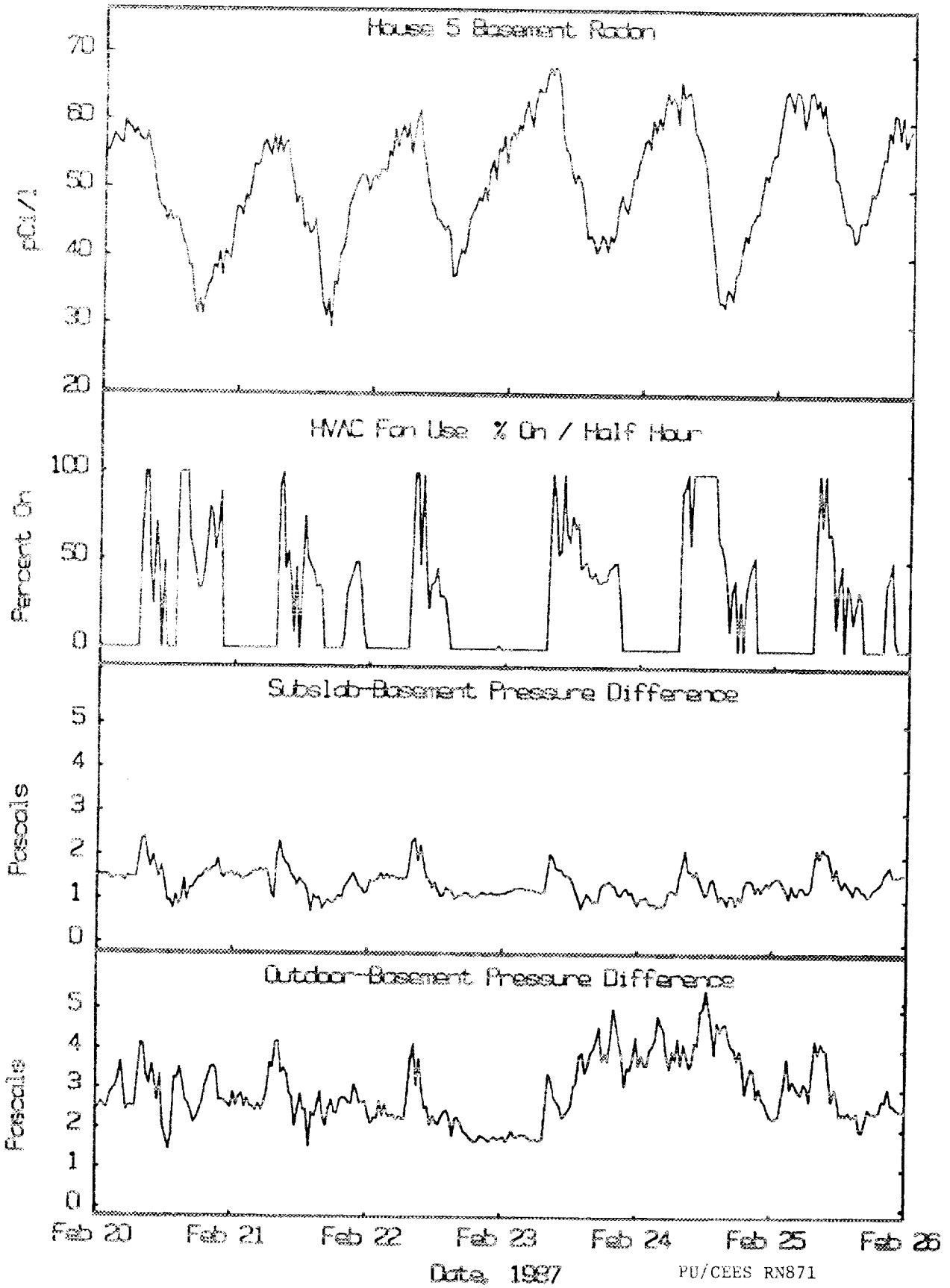

House 5 Basement Radon
pCi/l
70
60
50
40
30
20
HVAC Fan Use % On / Half Hour
Percent On
100
50
0
Subslab-Basement Pressure Difference
Pascals
5
4
3
2
1
0
Outdoor-Basement Pressure Difference
Pascals
5
4
3
2
1
0
Feb 20
Feb 21
Feb 22
Feb 23
Feb 24
Feb 25
Feb 26
Date, 1987
PU/CEES RN871

Figure 6.35

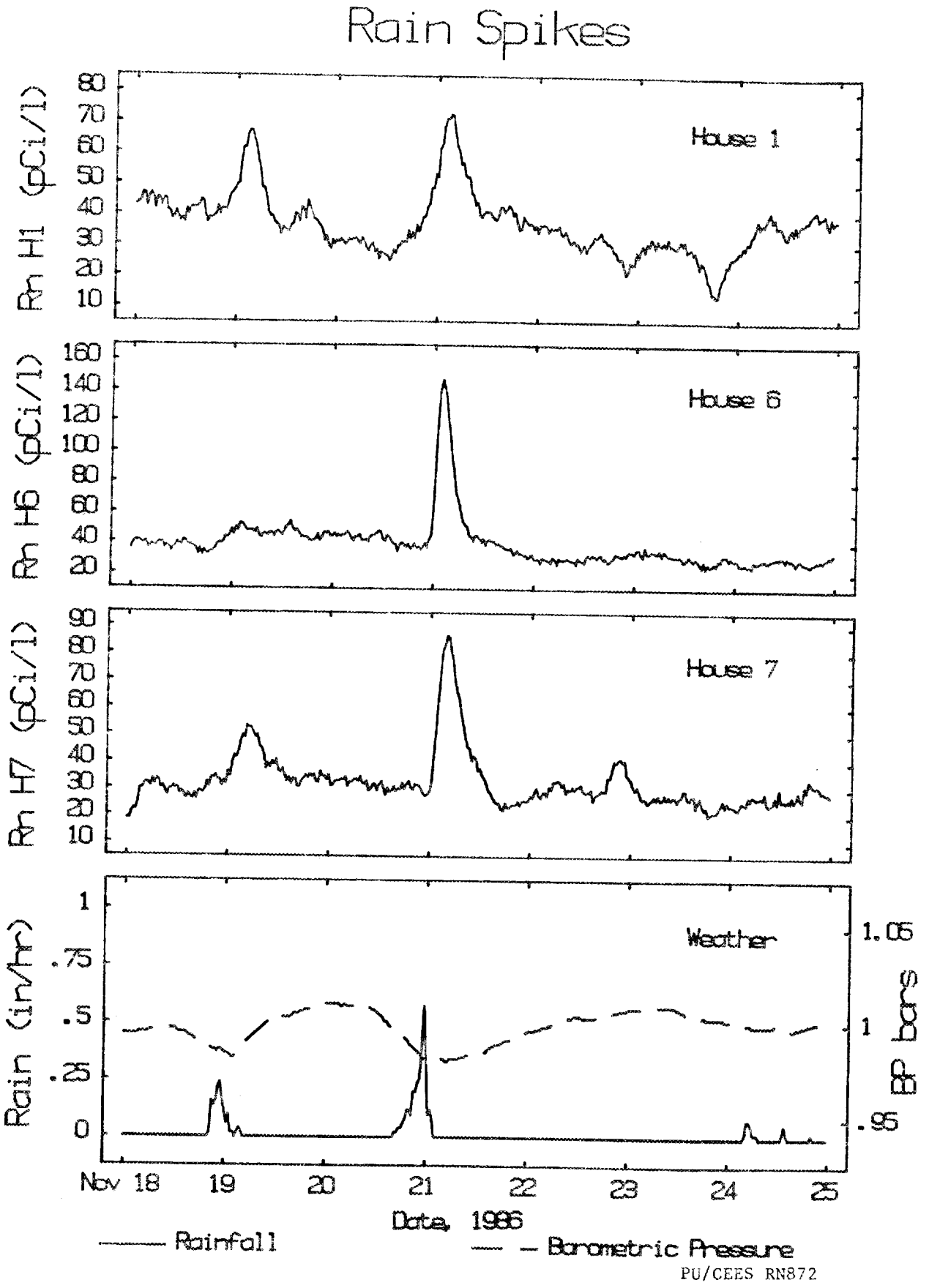

Rain Spikes
House 1
Rn H1 (pCi/l)
House 6
Rn H6 (pCi/l)
House 7
Rn H7 (pCi/l)
Weather
Rain (in/hr)
BP bars
Nov 18
19
20
21
22
23
24
25
Date, 1986
Rainfall
Barometric Pressure
PU/CEES RN872

Figure 6.36

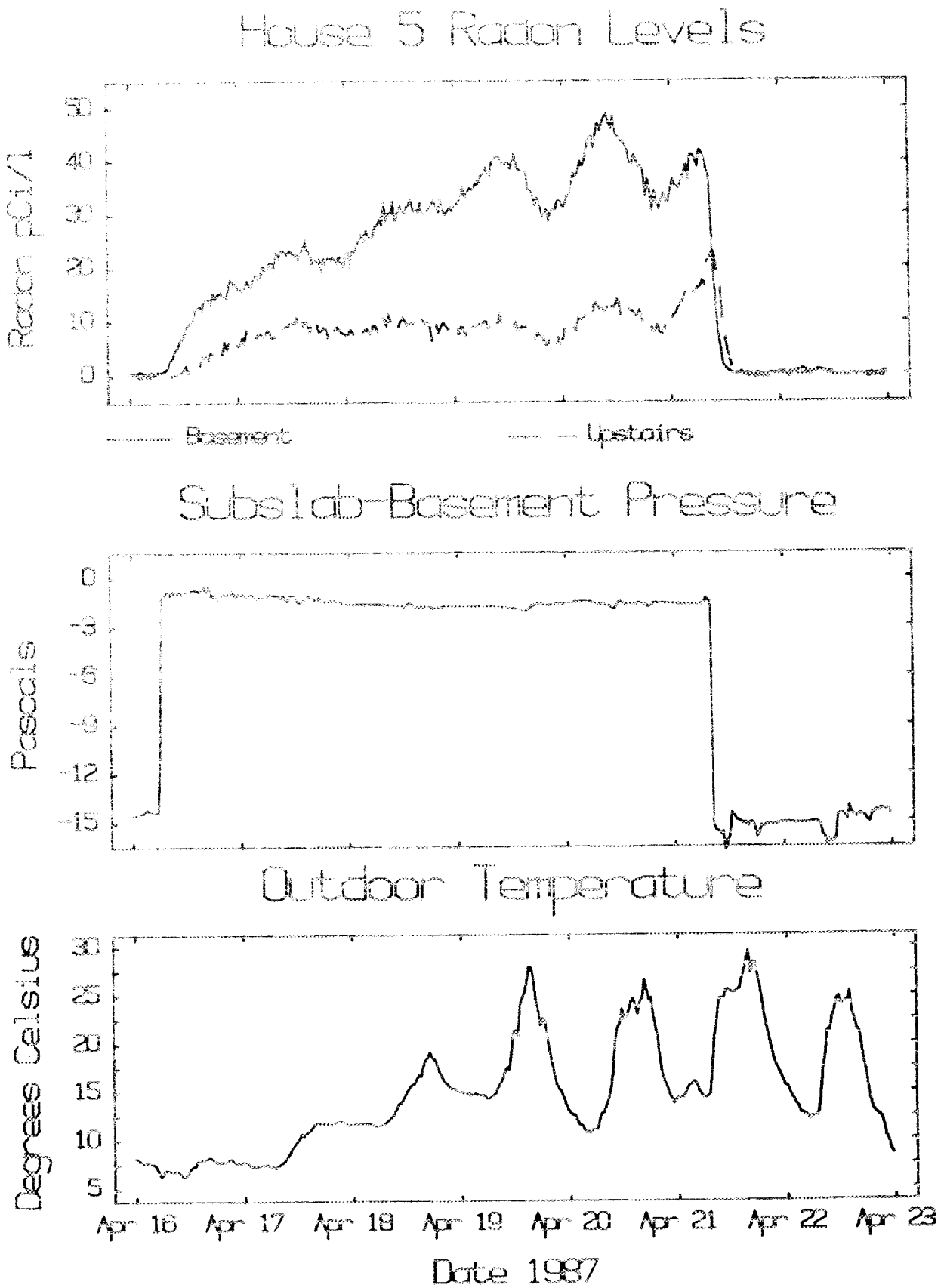

House 5 Radon Levels
Radon pCi/l
50
40
30
20
10
0
Basement
Upstairs
Subslab-Basement Pressure
Pascals
0
-3
-6
-9
-12
-15
Outdoor Temperature
Degrees Celsius
30
25
20
15
10
5
Apr 16
Apr 17
Apr 18
Apr 19
Apr 20
Apr 21
Apr 22
Apr 23
Date 1987

Figure 6.37

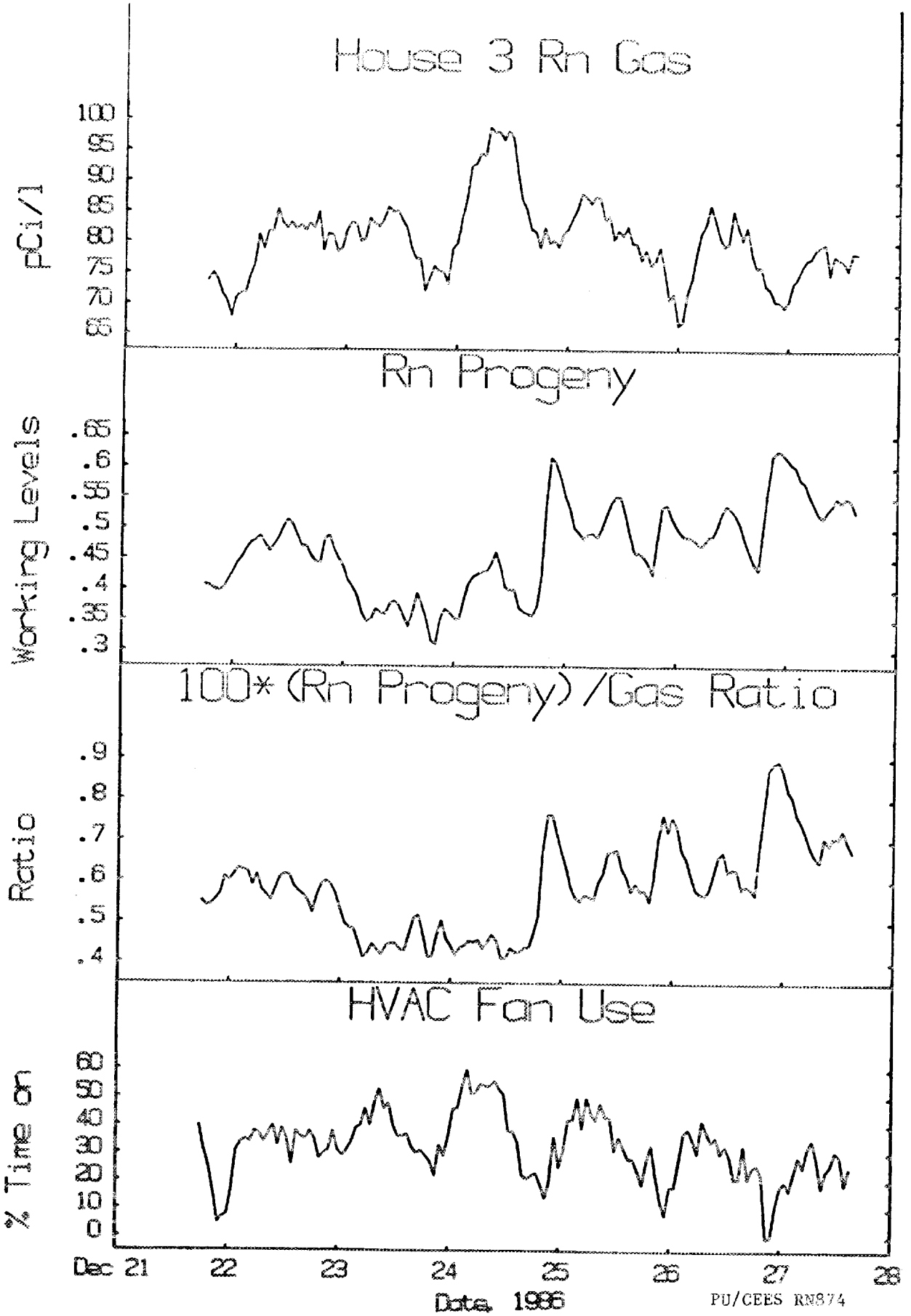

House 3 Rn Gas
pCi/l
100
95
90
85
80
75
70
65
Rn Progeny
Working Levels
.65
.6
.55
.5
.45
.4
.35
.3
100* (Rn Progeny) /Gas Ratio
Ratio
.9
.8
.7
.6
.5
.4
HVAC Fan Use
% Time on
60
50
40
30
20
10
0
Dec 21
22
23
24
25
26
27
28
Date, 1986
PU/CEES RN874

Figure 6.38

7. INTERACTION WITH LBL, DATA TRANSFER

Interaction with LBL has been multifaceted, beginning with ORNL/Princeton participation in the screening of potential study homes in August, 1986. There has been a cooperative exchange of technology throughout the study. The ORNL/Princeton team is appreciative of the loan of Continuous Radon Monitors from LBL for detailed studies in House #5. The ORNL/Princeton team included LBL monitors in a January calibration trip to DOE's Environmental Monitoring Laboratory in Manhattan.

7.1 TRANSFER OF LOGGER DATA WITH TENTATIVE CALIBRATION FACTORS

ORNL transferred an initial batch of data covering from 10/20/86 to 1/18/87 for all seven study homes in March, 1987. The data were presented in engineering units, but left uncorrected for changes in calibration factors and zeros throughout the study. Further transmissions of data will be performed after final calibration factors are determined. This is anticipated to occur during September-November, 1987.

7.2 INTERACTION IN SELECTION AND IMPLEMENTATION OF MITIGATION SYSTEM

Princeton researchers spent one day interacting with LBL researchers during the initial LBL diagnostic visits to their seven homes in November, 1986. The information obtained from LBL at that time was used in Princeton's diagnostic studies that focused on shortening the diagnostic protocol. Brad Turk of LBL and Lynn Hubbard of Princeton exchanged information on the homes after our intensive initial pre-mitigation diagnostic visits, and the ORNL/Princeton mitigation systems were chosen to complement the LBL set. There have been continued interactions between the three research teams throughout the winter and spring seasons. Both the LBL and ORNL/Princeton teams have had one or two research homes which have proven somewhat difficult to mitigate. Brad Turk, Ken Gadsby, and Lynn Hubbard have visited these difficult homes and interacted in followup diagnostics to try and solve the problems.

8. REFERENCES

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[3] G. M. Banino, F. J. Markewicz, J. W. Miller. "Geologic, Hydrologic and Well Drilling Characterization of the Rocks of Northern and Central New Jersey". State of New Jersey Bureau of Geology and Topography, P.O. Box 1889, Trenton, N.J. 08625, 1970.

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[5] Federal Register Vol. 46, No. 9 1/5/83, Rules and Regulations "The Standards for Cleanup of Tailings"

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[7] Key, Robert M., 1983. Transeint tracers in the ocean: Collection and analysis of samples for Radium-228 and Radium-226; Princeton University. Ocean Tracer Laboratory Technical Report #2.

[8] Hohmann J. David and R.M. Key, 1987. Junior Paper JP-II, Department of Geological and Geophysical Sciences, Princeton University.

[9] Hess, C.T., Weiffenbach, C.V., Norton, S.A., Brutsaert, W.F., and Hess, A.L., 1981. Radon-222 in potable water supplies in Maine: The geology, physics and health effects. Text of talk received from author, March, 1981.

[10] Authur Scott and Associates, "Review of Existing Instrumentation and Evaluation of Possibilities for Research and Development of Instrumentation to Determine Future Levels of Radon at a Proposed Building Site", INFO-0096.

9. APPENDICES

A. WEEKLY DATA SUMMARIES

B. INFORMATION TO SOLLEAGUES AND LETTERS TO HOMEOWNERS REGARDING MITIGATION SYSTEMS CHOSEN FOR THE HOMES

9.A WEEKLY DATA SUMMARIES

Weekly summary statistics are provided for each study house in Tables 9.1 to 9.28, and for the weather station in Tables 9.29 to 9.32. Unless otherwise noted, the clarification of each parameter provided in the following discussion can be applied uniformly for each house and the weather station.

Date (Julian): Each date refers to a one week period preceeding and including the listed day.

Temperatures (°C): uncorrected for available calibration data.

Pressure Differentials (pa): uncorrected for available calibration data.

Radon Concentration (pCi/L): corrected for ORNL zero and span calibration data taken inside a walk-in radon chamber in October, 1986. No corrections for temperature and relative humidity have been applied.

Relative Humidity (%): uncorrected for available calibration data. The RH sensor inside the outdoor radon flux monitor was added 1/20/87.

Wind Speed (m/sec): factory calibration is assumed.

Barometric Pressure (mbars): factory calibration is assumed.

Precipitation (0.01 in./30 min): factory calibration is assumed.

"****": This notation indicates predominantly an unresolved glitch in the dBASE program for calculating summary statistics. See for example Week 4 of Houses #1 and #2.

±6999: This notation indicates predominantly an unresolved logic error in the dBASE program for calculating summary statistics. It is seen occasionally as a minimum or maximum value. In the raw data set, it indicates an unused or saturated data channel.

Table 9.1. Weekly summary statistics of temperatures for House #1.

	Basement Temp. (°C)				Upstairs Temp. (°C)				Outdoor Temp. (°C)			
Date	Mean	Min	Max	S.D.	Mean	Min	Max	S.D.	Mean	Min	Max	S.D.
299	17.5	16.1	18.4	0.5	20.0	16.7	22.3	1.3	10.6	-0.6	23.0	5.8
306	17.3	15.5	18.1	0.6	20.0	17.6	21.5	0.9	9.8	-2.1	21.0	5.4
313	16.8	14.8	18.1	0.6	20.3	18.1	22.1	0.9	7.8	-2.8	20.4	5.4
320	15.8	13.9	17.2	0.8	19.4	16.4	20.8	0.9	1.2	-8.9	11.4	4.8
327	15.6	13.1	16.9	0.7	19.8	18.2	22.7	0.8	2.8	-6.8	12.8	4.6
334	15.6	14.4	16.7	0.5	19.7	17.3	21.6	1.0	4.3	-4.8	17.5	4.6
341	15.0	13.3	16.6	0.7	19.9	17.4	23.0	1.0	2.1	-8.1	12.0	5.0
348	14.6	10.5	16.1	1.2	19.9	17.3	22.4	0.9	0.4	-13.6	12.0	5.3
355	14.2	11.8	15.5	0.7	19.3	17.7	20.8	0.8	1.6	-8.5	6.8	3.6
362	14.1	11.8	15.7	0.8	19.8	17.5	23.7	1.2	1.5	-8.0	10.0	4.5
4	****	****	****	****	****	****	****	****	****	****	****	****
11	13.4	12.0	15.0	0.7	19.0	16.8	21.6	1.1	-0.3	-9.4	5.8	3.6
18	13.8	11.9	15.5	0.8	19.5	17.4	21.2	0.9	1.6	-7.4	12.2	4.5
25	12.0	9.3	14.1	1.1	19.8	17.6	23.6	1.4	-5.8	-17.3	2.2	4.7
32	11.1	7.5	13.4	1.3	19.4	16.1	23.4	1.4	-3.6	-19.9	10.1	6.0
39	12.6	11.3	14.0	0.6	19.2	17.6	23.8	1.1	0.2	-7.8	10.2	4.7
46	11.2	7.6	13.9	1.3	19.8	17.1	23.6	1.3	-4.3	-17.4	7.9	4.8
53	11.1	7.3	13.2	1.0	18.6	16.9	21.0	1.1	-2.5	-15.3	10.5	5.4
60	12.4	11.0	14.1	0.8	19.4	17.1	23.0	1.1	1.4	-5.8	9.7	4.0
67	12.9	11.4	15.1	0.9	19.4	16.5	22.5	1.2	4.4	-7.9	24.8	7.3
74	13.1	11.1	15.5	1.0	19.2	16.6	21.6	1.1	1.2	-11.0	16.4	5.8
81	13.6	12.1	15.1	0.7	19.7	17.1	21.4	1.0	4.3	-5.8	18.3	5.4
88	14.9	12.8	16.2	0.7	20.6	17.8	23.0	1.1	11.6	-1.9	25.8	6.9
95	15.1	13.9	16.8	0.6	19.8	17.7	22.6	0.9	8.3	-3.0	18.0	5.2
102	15.4	14.1	17.1	0.6	20.1	17.7	22.4	1.1	10.4	1.0	27.1	6.1
109	15.9	14.7	17.9	0.6	20.5	18.2	24.4	1.4	11.7	0.6	28.4	5.2
116	16.8	15.6	18.6	0.7	21.3	18.8	25.1	1.6	17.1	9.3	28.1	5.1

Table 9.2. Weekly summary statistics of differential pressures for House #1.

	Bsmt-Out Pres. (pa)				Bsmt-Subslab Pres. (pa)				Bsmt-Upst Pres. (pa)			
Date	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	1.17	0.13	2.42	0.46	0.31	0.04	0.71	0.18	0.43	-22.5	1.40	1.27
306	1.34	0.00	2.70	0.54	0.21	0.10	0.42	0.08	0.51	0.22	1.33	0.18
313	1.23	0.29	2.69	0.54	0.25	0.09	0.41	0.08	0.60	0.11	1.44	0.17
320	1.69	0.30	3.65	0.72	0.41	0.24	0.63	0.09	0.84	0.35	1.61	0.21
327	1.72	-0.15	3.93	0.72	0.40	0.25	0.58	0.08	0.81	0.45	1.73	0.22
334	1.75	-0.52	2.80	0.51	0.37	0.20	0.55	0.08	0.87	0.42	2.16	0.26
341	1.59	0.20	2.81	0.52	0.41	0.22	0.60	0.10	0.95	0.55	2.10	0.29
348	1.92	0.63	4.26	0.60	0.45	0.25	0.75	0.09	0.97	0.56	2.22	0.26
355	1.89	0.36	5.05	0.80	0.45	0.35	0.61	0.06	1.01	0.57	2.32	0.29
362	1.78	0.19	3.07	0.53	0.46	0.30	0.62	0.08	0.97	0.46	2.25	0.30
4	****	****	****	****	****	****	****	****	****	****	****	****
11	2.32	0.23	4.30	0.65	-13.00	-22.32	0.31	3.74	1.36	0.72	1.48	0.39
18	2.32	0.38	4.65	0.76	-13.89	-14.25	-13.02	0.17	1.30	0.35	0.88	0.41
25	3.17	1.26	4.98	0.67	-13.70	-13.99	-13.34	0.14	1.53	0.88	0.90	0.43
32	2.64	0.58	5.02	0.92	-14.40	-15.10	-7.49	0.72	1.36	0.75	1.11	0.47
39	2.26	0.50	4.82	0.70	-14.95	-15.20	-14.59	0.11	1.19	0.69	0.75	0.38
46	3.11	1.14	7.23	1.21	-14.76	-15.10	-12.27	0.27	1.27	0.77	2.86	0.41
53	2.23	0.38	4.84	0.79	-7.56	-24.80	0.48	7.67	1.29	0.51	2.69	0.39
60	1.52	0.41	5.07	0.71	0.81	0.34	24.56	2.94	0.97	0.20	2.42	0.34
67	1.63	-0.53	3.35	0.73	1.16	-4.43	*****	0.53	0.90	0.50	2.39	0.35
74	2.17	0.68	5.21	0.97	-21.34	-24.46	*****	4.41	1.06	0.40	2.42	0.35
81	1.94	0.64	3.42	0.53	-21.24	-21.24	*****	****	1.04	0.61	2.22	0.30
88	1.19	-0.15	2.97	0.55	0.45	-5.20	*****	0.52	0.77	-0.15	2.31	0.28
95	1.89	-0.79	4.02	0.89	-10.72	-22.49	0.96	8.63	0.76	0.45	1.97	0.25
102	1.28	-1.09	2.68	0.63	-17.85	-19.22	-16.44	0.55	0.75	-0.04	2.18	0.28
109	1.61	0.16	3.42	0.44	-18.04	-19.37	-16.59	0.59	0.69	-1.45	1.80	0.26
116	1.72	-0.22	4.00	0.61	-20.06	-22.52	-16.81	1.33	0.56	0.31	1.85	0.20

Table 9.3. Weekly summary statistics of radon concentrations for House #1

	Basement Radon (pCi/L)				Upstairs Radon (pCi/L)			
Date	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	43.1	20.4	73.1	8.3	23.1	14.8	29.8	3.7
306	40.6	17.2	59.1	9.4	21.1	10.5	30.3	3.9
313	27.2	9.1	60.1	12.6	16.8	6.2	27.9	5.2
320	27.3	18.2	49.1	5.7	17.8	11.0	27.4	3.4
327	24.8	8.7	47.1	6.7	16.3	6.4	23.4	3.6
334	25.4	18.0	37.9	3.7	16.0	1.1	21.7	3.3
341	22.8	13.3	38.5	5.1	15.6	10.0	21.3	2.2
348	21.9	14.8	32.1	3.7	15.7	9.3	22.7	2.8
355	22.4	15.9	31.1	2.7	15.6	11.1	22.0	1.8
362	24.3	18.7	39.6	3.2	16.7	13.2	22.0	1.5
4	****	****	****	****	****	****	****	****
11	5.1	2.5	10.6	1.7	3.2	1.0	8.2	1.5
18	4.5	1.9	9.6	1.1	2.3	0.6	4.6	0.7
25	6.3	1.8	39.0	3.3	3.9	1.0	214.8	11.8
32	4.9	1.6	8.2	1.3	2.4	0.7	5.4	1.0
39	4.1	1.7	6.0	1.0	2.1	0.4	3.8	0.8
46	5.0	2.9	7.8	1.1	2.2	0.5	4.3	0.8
53	2.0	0.0	6.8	2.0	1.0	0.0	3.8	1.1
60	1.5	0.1	4.8	0.8	0.9	0.0	2.2	0.5
67	5.3	0.0	16.6	5.6	4.0	0.0	12.8	4.2
74	0.2	0.0	0.9	0.2	0.2	0.0	0.7	0.2
81	0.2	0.0	1.1	0.2	0.2	0.0	0.8	0.2
88	12.0	0.0	29.9	11.0	6.7	-0.1	23.0	7.6
95	4.2	0.0	25.4	6.0	4.8	0.5	15.7	3.7
102	0.5	-0.1	40.3	2.6	***	-0.5	-0.5	***
109	0.2	0.0	1.3	0.2	***	-0.5	-0.5	***
116	0.3	0.0	1.4	0.3	***	-0.5	-0.5	***

Table 9.4. Weekly summaries of basement RH and HVAC duty cycle for House #1

	Basement RH (%)				Fraction HVAC OFF			
Date	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	62.4	59.2	65.6	1.6	0.936	0.000	1.000	0.129
306	63.4	56.6	67.0	3.0	0.940	0.163	1.000	0.128
313	61.3	55.1	69.8	4.2	0.894	0.163	1.000	0.139
320	54.2	46.8	65.8	5.1	0.826	0.140	1.000	0.158
327	52.5	48.3	55.8	2.2	0.845	0.127	1.000	0.155
334	55.3	50.1	60.6	2.3	0.876	0.137	1.000	0.132
341	50.6	46.3	59.0	3.8	0.835	0.173	1.000	0.153
348	50.0	44.7	56.4	2.9	0.838	0.073	1.000	0.156
355	49.6	45.3	54.2	2.2	0.823	0.000	1.000	0.174
362	49.5	45.8	55.5	2.8	0.845	0.050	1.000	0.174
4	****	****	****	****	*****	*****	*****	*****
11	45.0	43.0	48.0	1.2	0.771	0.000	1.000	0.194
18	45.2	41.2	51.1	2.4	0.785	0.000	1.000	0.207
25	41.9	35.0	45.8	3.6	0.749	0.083	1.000	0.206
32	39.3	32.2	44.6	3.7	0.769	0.000	1.000	0.251
39	42.1	39.4	44.8	1.5	0.785	0.007	1.000	0.202
46	38.7	31.0	43.6	3.1	0.800	0.000	1.000	0.228
53	33.9	30.7	37.0	1.4	0.780	0.000	1.000	0.209
60	39.8	35.4	52.1	3.8	0.801	0.000	1.000	0.191
67	45.8	42.2	52.0	2.3	0.856	0.000	1.000	0.208
74	39.1	31.6	49.7	4.6	0.808	0.000	1.000	0.203
81	37.0	33.4	41.1	2.1	0.837	0.000	1.000	0.174
88	45.3	40.6	53.0	3.4	0.942	0.083	1.000	0.136
95	54.0	46.5	71.8	5.9	0.915	0.183	1.000	0.137
102	54.0	50.2	58.3	1.9	0.919	0.120	1.000	0.144
109	57.5	50.1	68.5	5.2	0.940	0.293	1.000	0.111
116	63.9	47.2	70.4	5.2	0.964	0.387	1.000	0.079

Table 9.5. Weekly summary statistics of temperatures for House #2.

	Basement Temp. (°C)				Upstairs Temp. (°C)				Outdoor Temp. (°C)			
Date	Mean	Min	Max	S.D.	Mean	Min	Max	S.D.	Mean	Min	Max	S.D.
299	18.1	16.4	19.1	0.6	20.9	18.0	23.4	1.0	11.2	-0.5	23.5	5.8
306	18.0	15.7	19.4	0.7	21.2	18.3	23.6	1.0	10.3	-1.5	20.6	5.4
313	17.2	0.0	18.4	1.1	20.6	0.0	22.8	1.4	7.2	-2.2	15.7	4.5
321	16.0	13.2	18.2	1.0	20.2	15.9	24.1	1.6	2.1	-9.1	13.2	5.2
328	15.7	13.4	18.2	1.0	19.9	16.3	23.6	1.6	3.8	-5.6	13.9	4.7
335	16.0	13.4	18.5	0.8	20.6	16.4	24.3	1.4	3.8	-4.8	18.4	5.1
342	16.0	13.0	17.6	0.9	20.7	16.2	23.3	1.3	3.8	-8.0	12.5	4.8
349	15.3	11.7	16.9	1.1	20.6	15.1	24.2	1.5	0.2	-12.6	12.1	5.0
356	15.7	14.8	16.7	0.4	21.3	20.1	23.4	0.4	2.3	-6.9	7.8	3.3
363	15.4	13.1	16.6	0.7	20.7	16.9	23.0	1.1	2.5	-6.2	10.0	4.0
4	****	****	****	***	****	****	****	***	***	****	****	***
11	14.8	12.7	16.1	0.9	20.1	17.5	23.8	1.3	0.4	-9.2	6.4	3.5
18	15.2	13.4	17.2	0.8	20.1	****	22.5	0.7	2.4	-7.2	12.8	4.8
25	14.8	11.3	16.4	1.1	20.5	15.5	23.7	1.6	-2.9	-14.2	1.8	4.1
32	12.8	9.8	14.9	1.2	19.4	14.3	24.2	2.1	-5.9	-19.9	3.9	5.6
39	13.2	10.0	15.2	1.2	18.6	****	23.3	1.6	-2.6	-16.0	7.9	4.4
46	12.5	9.4	14.4	1.1	17.9	14.6	19.9	1.3	-2.4	-15.3	6.4	4.9
53	13.2	2.9	14.7	1.0	18.1	8.4	20.0	1.3	1.3	-7.4	9.1	3.7
61	14.1	11.3	15.7	1.0	18.7	15.4	20.7	1.3	3.5	-5.5	9.8	4.1
69	14.4	11.6	16.5	1.1	19.3	15.7	22.9	1.4	5.1	-7.7	23.4	8.7
76	14.0	11.7	15.7	0.9	18.5	15.7	20.1	1.2	1.4	-9.9	9.3	4.1
83	14.7	12.5	16.2	0.9	18.8	15.9	20.2	1.0	7.1	-5.0	20.9	6.0
90	15.7	13.7	17.2	0.9	19.2	16.7	22.2	1.2	12.5	-0.5	21.8	5.8
95	15.7	13.1	17.8	1.0	19.4	16.4	21.3	0.9	9.0	-2.9	18.9	5.2
102	15.4	10.2	19.0	1.3	19.7	17.4	22.6	1.0	11.2	2.2	24.9	5.8
109	16.4	14.6	18.8	0.8	19.9	14.2	22.5	1.5	11.9	0.1	24.8	4.7
116	17.7	14.9	20.6	1.0	20.3	17.5	23.6	1.2	13.6	0.1	25.8	5.6

Table 9.6. Weekly summary statistics of differential pressures for House #2.

	Bsmt-Out Pres. (pa)				Bsmt-Subslab Pres. (pa)				Bsmt-Upst Pres. (pa)			
Date	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	1.82	0.17	5.05	0.86	0.39	0.31	0.56	0.04	0.34	-0.14	2.19	0.35
306	2.27	0.35	7.68	1.39	0.38	0.28	0.56	0.05	0.31	-0.63	2.65	0.50
313	2.42	-25.00	7.22	1.96	0.38	-25.00	0.61	1.38	0.42	-25.00	2.38	1.48
321	3.40	1.20	12.64	1.70	0.56	0.43	0.79	0.08	0.76	-0.15	3.47	0.76
328	4.08	-0.21	12.09	2.23	0.55	0.40	0.70	0.05	0.76	-0.09	3.15	0.75
335	3.46	-1.49	10.09	1.43	0.92	0.47	1.22	0.21	0.71	-0.13	3.39	0.72
342	4.04	0.84	11.77	1.98	0.58	0.26	1.20	0.32	0.91	-0.12	3.33	0.68
349	4.54	1.05	13.18	1.91	0.39	0.27	0.59	0.06	0.97	-0.16	3.13	0.72
356	3.93	1.93	10.86	1.48	0.35	0.23	0.44	0.04	0.99	0.06	1.59	0.30
363	3.68	1.36	9.06	1.12	0.36	0.20	0.58	0.06	0.90	-0.06	3.10	0.65
4	****	****	****	****	****	****	****	****	****	****	****	****
11	4.43	2.40	8.13	1.29	0.41	0.32	0.59	0.06	1.02	-0.10	2.95	0.64
18	4.16	-94.99	7.30	0.84	0.37	-94.99	0.51	0.06	0.95	-94.99	2.38	0.47
25	5.35	2.21	15.58	2.54	0.39	0.23	0.62	0.09	1.16	-0.15	3.34	0.78
32	5.91	2.41	10.37	1.62	0.50	0.31	0.73	0.10	1.00	-0.48	2.92	0.84
39	5.52	-94.99	12.80	2.45	2.65	-94.99	5.85	0.88	0.20	-94.99	2.22	0.68
46	4.73	1.99	11.08	1.76	2.68	1.58	4.18	0.53	0.18	-0.78	2.06	0.67
53	4.45	0.90	10.16	1.88	2.19	-25.00	3.38	1.80	-0.11	-25.00	2.19	1.75
61	3.15	0.21	10.04	1.80	1.83	0.71	3.31	0.58	0.02	-22.49	2.41	1.61
69	3.60	-1.36	11.06	2.38	2.11	0.15	5.22	1.02	0.02	-0.61	2.12	0.57
76	3.79	0.84	9.99	1.96	2.35	1.54	3.59	0.40	-0.02	-0.66	1.78	0.53
83	3.12	-0.54	10.22	1.65	1.89	0.79	3.54	0.46	-0.05	-0.73	2.17	0.57
90	0.73	-5.17	3.42	1.56	1.07	-0.42	2.18	0.48	-0.22	-0.73	2.05	0.36
95	2.30	-5.22	11.75	2.94	1.76	-23.77	3.79	2.38	-0.15	-1.22	1.96	0.57
102	2.13	-2.22	6.56	1.46	1.61	-2.95	3.04	0.81	-0.32	-8.23	3.94	1.42
109	1.60	-1.06	5.51	0.91	1.60	0.16	2.99	0.48	-0.14	-0.78	2.00	0.40
116	1.27	-5.78	5.34	1.49	1.52	-2.09	3.31	0.64	-0.45	-4.57	2.02	0.86

Table 9. Weekly summary statistics of radon concentrations for House #2

	Basement Radon (pCi/L)				Upstairs Radon (pCi/L)			
Date	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	13.1	3.0	19.9	3.2	10.1	0.3	20.2	4.1
306	14.2	4.5	23.1	2.8	11.5	2.5	17.8	2.8
313	13.6	8.0	18.0	2.2	13.5	6.5	20.8	3.5
321	11.3	1.4	16.8	1.7	11.8	2.1	19.5	1.9
328	9.8	6.2	16.7	2.6	8.9	3.1	13.4	2.3
335	10.6	5.2	15.1	1.7	11.5	3.7	16.2	2.1
342	9.0	1.4	16.2	2.8	8.1	0.5	15.1	3.2
349	10.3	6.6	15.2	1.6	10.4	5.7	16.3	2.1
356	9.5	5.7	14.4	1.5	9.8	4.8	15.4	2.0
363	9.5	3.6	13.9	1.9	10.5	2.7	14.5	2.8
4	****	****	****	***	****	****	****	****
11	11.2	7.0	17.9	1.8	12.2	7.9	15.8	1.5
18	10.8	6.3	17.1	2.1	11.5	6.6	16.5	2.4
25	11.0	6.0	64.2	4.5	13.6	4.1	138.8	11.9
32	11.8	8.7	16.4	1.6	12.0	7.4	19.5	2.2
39	12.0	8.2	16.7	1.5	12.1	4.3	18.0	2.4
46	13.3	10.1	17.0	1.4	14.8	10.7	20.8	1.9
53	14.0	11.6	19.2	1.4	15.8	8.9	22.6	2.4
61	11.4	5.8	16.7	2.3	11.7	4.3	17.5	3.1
69	11.1	1.2	19.7	3.6	11.7	0.0	22.3	5.2
76	11.4	7.3	18.8	2.0	15.5	8.1	23.7	3.0
83	11.3	6.5	14.6	1.4	14.5	2.9	19.9	3.5
90	11.2	0.4	19.3	5.7	10.0	0.0	23.1	7.3
95	8.5	0.0	16.5	4.1	7.3	0.0	19.9	5.4
102	8.9	0.0	88.3	7.2	8.8	0.0	20.0	5.6
109	14.1	4.8	23.8	3.3	11.1	0.1	21.4	6.2
116	10.6	0.0	26.2	6.4	8.9	-0.5	21.2	5.0

Table 9.8. Weekly summaries of basement RH and HVAC duty cycle for House #2

	Basement RH (%)				Fraction HVAC OFF			
Date	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	55.4	51.7	59.7	2.1	0.946	0.313	1.000	0.111
306	57.2	50.0	60.9	2.9	0.919	0.087	1.000	0.158
313	54.9	0.0	63.5	4.1	0.856	0.000	1.000	0.177
321	48.3	42.9	54.9	4.1	0.764	0.000	1.000	0.248
328	48.4	44.7	53.0	2.0	0.781	0.000	1.000	0.234
335	50.9	45.3	57.9	3.4	0.779	0.000	1.000	0.234
342	48.0	44.8	54.9	2.9	0.722	0.000	1.000	0.215
349	46.5	42.3	51.0	2.2	0.686	0.000	1.000	0.249
356	46.4	44.3	49.3	1.2	0.689	0.450	1.000	0.101
363	46.8	44.1	51.0	1.9	0.722	0.000	1.000	0.216
4	****	****	****	***	*****	*****	*****	*****
11	44.4	43.5	45.2	0.5	0.442	0.000	1.000	0.366
18	43.3	****	45.0	0.8	0.230	0.000	1.000	0.332
25	44.1	39.1	45.7	1.8	0.596	0.000	1.000	0.268
32	39.1	35.8	40.6	1.2	0.279	0.000	1.000	0.351
39	40.7	****	43.8	1.6	0.607	0.000	1.000	0.341
46	38.1	34.7	40.0	1.1	0.713	0.000	1.000	0.274
53	40.3	38.3	42.5	1.0	0.798	0.000	1.000	0.267
61	43.2	39.6	47.0	2.2	0.782	0.000	1.000	0.255
69	43.8	37.3	48.0	2.7	0.814	0.000	1.000	0.264
76	40.7	37.0	43.0	1.6	0.774	0.000	1.000	0.259
83	41.7	38.1	44.7	1.7	0.859	0.000	1.000	0.232
90	46.9	42.9	52.6	2.5	0.973	0.083	1.000	0.113
95	57.0	48.8	74.3	7.2	0.868	0.000	1.000	0.217
102	62.1	44.6	68.8	5.9	0.893	0.000	1.000	0.209
109	62.6	56.7	69.8	3.1	0.919	0.107	1.000	0.144
116	67.2	58.5	73.3	3.4	0.949	0.197	1.000	0.122

Table 9.9. Weekly summary statistics of temperatures for House #3.

	Basement Temp. (°C)				Upstairs Temp. (°C)				Outdoor Temp. (°C)			
Date	Mean	Min	Max	S.D.	Mean	Min	Max	S.D.	Mean	Min	Max	S.D.
299	18.5	17.6	19.0	0.3	21.6	20.7	22.6	0.3	12.6	2.1	23.0	4.9
306	18.3	0.0	19.0	1.0	21.5	0.0	22.7	1.2	10.1	-1.2	21.6	5.1
313	18.3	17.6	19.1	0.3	22.1	21.0	23.2	0.4	8.4	-0.3	20.1	5.0
320	17.6	16.7	18.4	0.5	21.8	20.7	22.8	0.4	2.5	-7.5	12.3	4.7
327	17.3	15.7	18.8	0.5	21.6	20.8	22.5	0.4	3.5	-6.3	11.6	4.3
334	17.2	15.8	18.1	0.5	21.3	19.6	23.1	0.6	4.3	-5.8	17.8	4.5
341	16.9	15.6	17.7	0.4	20.9	20.2	21.6	0.3	3.8	-5.7	12.1	4.0
348	16.5	15.3	17.5	0.6	20.7	19.7	21.6	0.4	0.1	-11.7	11.8	4.8
355	16.0	13.9	17.0	0.7	20.7	18.1	21.7	0.5	2.3	-5.5	7.3	2.8
362	15.4	12.1	16.8	1.2	21.1	20.1	22.3	0.4	2.6	-4.2	10.0	3.3
4	16.1	13.8	17.8	0.4	21.5	20.2	22.6	0.4	1.0	-7.9	12.1	3.6
11	16.0	15.2	16.5	0.2	21.5	21.0	22.2	0.3	0.4	-6.5	4.9	2.7
18	16.4	15.7	17.8	0.4	21.7	20.9	22.4	0.4	2.2	-7.9	12.1	4.6
25	15.4	14.3	16.3	0.6	21.4	20.0	22.8	0.6	-5.5	-14.7	1.7	4.3
32	15.4	13.5	16.4	0.6	22.0	19.5	23.2	0.6	-2.9	-15.9	12.5	5.7
39	16.5	14.3	18.0	0.5	22.1	20.3	23.3	0.5	1.7	-6.1	12.2	3.9
46	16.1	14.1	17.2	0.7	22.2	21.3	23.1	0.4	-3.8	-17.2	5.6	4.7
53	15.9	14.2	16.8	0.5	22.2	21.2	23.1	0.5	-1.5	-15.0	11.9	5.3
60	16.5	15.5	17.4	0.5	22.3	1.0	23.4	1.2	1.6	-5.3	8.7	3.5
67	17.4	16.7	19.5	0.5	22.7	21.3	24.6	0.5	6.0	-5.4	26.0	7.7
74	17.2	16.3	18.0	0.4	23.0	21.5	24.1	0.6	1.6	-10.8	17.3	6.0
81	15.9	14.8	17.8	0.7	23.3	22.3	24.3	0.4	4.8	-3.5	15.2	4.7
88	17.0	14.8	18.4	0.9	22.8	21.4	24.9	0.6	12.8	1.6	23.8	5.9
95	18.2	16.6	19.2	0.5	23.1	21.7	24.7	0.6	8.7	-1.7	18.8	5.0
102	18.5	17.3	19.2	0.3	23.3	21.2	25.5	0.7	11.5	4.2	28.3	5.7
109	18.6	17.4	19.3	0.4	23.2	22.2	25.7	0.6	12.3	3.3	28.9	4.9
116	18.6	17.5	19.5	0.5	23.1	21.3	26.5	0.9	14.6	3.5	30.7	6.4

Table 9.10. Weekly summary statistics of differential pressures for House #3.

	Bsmt-Out Pres. (pa)				Bsmt-Subslab Pres. (pa)				Bsmt-Upst Pres. (pa)			
Date	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	2.02	0.31	4.30	0.69	0.50	0.36	0.67	0.07	0.10	-0.40	0.61	0.23
306	2.53	-25.00	4.62	1.67	0.47	-25.00	0.72	1.36	0.03	-25.00	0.73	1.90
313	3.38	1.19	5.80	1.04	0.61	0.43	0.76	0.08	0.24	-0.36	1.02	0.24
320	4.57	2.15	8.12	1.11	0.77	0.60	0.95	0.09	0.34	-0.44	0.76	0.24
327	4.06	1.96	8.17	1.34	0.77	0.63	0.96	0.09	0.42	-0.50	0.87	0.24
334	3.29	-1.69	5.87	0.78	0.75	0.61	0.93	0.07	0.34	-0.34	0.97	0.26
341	4.69	1.93	10.40	1.39	0.83	0.62	1.06	0.08	0.39	-0.27	0.77	0.21
348	5.26	2.65	9.16	1.31	0.90	0.70	1.13	0.09	0.42	-0.16	0.89	0.16
355	3.68	0.29	8.78	1.29	0.68	0.55	0.89	0.11	0.48	-0.49	2.42	0.39
362	4.28	0.49	7.80	1.62	-0.61	-19.39	0.66	4.64	0.49	-1.13	1.23	0.55
4	5.10	2.79	12.74	1.31	-14.97	-21.15	-8.86	3.99	0.82	-0.13	1.33	0.21
11	5.42	3.58	12.74	1.40	-15.31	-20.22	-8.86	3.87	0.83	0.01	0.83	0.20
18	5.06	2.79	10.96	1.56	-11.12	-13.17	-9.15	0.80	0.79	0.28	0.83	0.18
25	6.65	3.60	15.62	2.21	-10.35	-12.23	-8.26	0.89	0.84	0.21	0.81	0.22
32	5.48	3.15	8.14	1.03	-2.98	-11.34	1.94	5.45	0.73	-0.21	0.88	0.30
39	5.60	3.50	10.16	1.42	-7.73	-12.79	1.55	5.21	0.63	-0.26	0.59	0.26
46	6.14	3.67	10.62	1.41	-10.52	-12.63	-8.69	0.87	0.82	-0.08	1.28	0.20
53	4.97	3.29	8.14	0.93	-7.15	-12.07	-2.60	3.31	0.80	0.20	1.25	0.22
60	4.32	-25.00	8.97	1.88	-0.71	-25.00	0.39	2.25	0.57	-25.00	1.08	1.43
67	4.19	-2.81	11.57	1.87	-1.50	-5.96	0.32	1.99	0.53	-0.20	1.17	0.27
74	4.21	1.37	6.17	1.05	-2.74	-5.15	-1.24	0.80	0.53	-0.16	0.95	0.24
81	2.45	1.03	5.34	0.81	-3.37	-5.06	-1.39	0.70	0.05	-0.66	0.86	0.30
88	1.95	0.07	5.73	0.81	-4.35	-5.55	-2.86	0.59	0.02	-0.84	0.80	0.30
95	3.51	0.18	9.02	1.48	-2.36	-13.69	1.35	2.55	0.33	-0.26	0.74	0.23
102	2.72	0.18	5.50	0.85	-4.52	-6.18	-2.92	0.64	0.27	-0.41	0.76	0.26
109	2.36	0.26	4.26	0.84	-4.55	-6.44	-3.10	0.68	0.19	-0.32	0.63	0.23
116	1.88	0.07	3.90	0.93	-4.12	-5.49	-2.87	0.55	0.05	-0.43	0.72	0.25

Table 9.11. Weekly summary statistics of radon concentrations for House #3

	Basement Radon (pCi/L)				Upstairs Radon (pCi/L)			
Date	Mean	Min.	Max	S.D.	Mean	Min.	Max.	S.D.
299	78.3	51.8	101.1	12.1	33.8	11.3	48.5	8.0
306	91.6	71.7	120.8	11.9	42.4	13.9	63.4	9.5
313	107.8	17.4	178.3	17.5	50.2	9.0	66.9	9.2
320	117.4	86.9	138.0	10.6	59.7	41.8	79.0	8.4
327	116.2	61.2	142.9	14.5	59.9	33.6	82.4	9.8
334	119.6	86.8	155.0	14.6	63.5	32.1	92.3	12.6
341	126.4	94.8	177.9	15.4	64.2	42.5	81.5	9.0
348	123.6	87.5	146.3	10.9	64.7	45.4	85.2	7.6
355	64.1	0.2	136.7	53.7	36.8	0.0	72.5	28.4
362	0.5	0.0	1.4	0.2	0.2	0.0	1.1	0.2
4	0.6	0.0	1.5	0.3	0.2	0.0	1.0	0.2
11	0.6	0.0	1.4	0.3	0.2	-0.2	1.0	0.2
18	0.7	0.2	1.5	0.3	0.2	0.0	0.6	0.2
25	2.0	0.3	89.1	6.9	1.2	0.0	97.8	7.3
32	51.4	0.8	143.8	47.6	22.2	0.2	56.9	20.6
39	21.7	0.6	106.6	34.5	10.2	0.0	47.0	16.1
46	1.1	0.3	2.0	0.3	0.5	0.0	1.9	0.3
53	1.8	0.5	3.6	0.8	0.8	0.0	2.0	0.5
60	5.6	1.6	33.3	6.2	3.1	0.4	18.7	3.5
67	2.8	0.5	4.9	1.1	1.5	0.0	3.2	0.7
74	2.8	0.6	4.6	0.8	1.4	0.0	2.8	0.6
81	1.2	0.2	4.3	0.8	0.6	0.0	2.1	0.5
88	1.0	0.1	3.4	0.6	0.4	0.0	1.4	0.3
95	13.7	0.5	85.8	21.5	6.4	0.0	46.8	10.7
102	1.3	0.4	2.3	0.4	0.5	0.0	1.3	0.3
109	1.3	0.3	2.5	0.4	0.4	0.0	1.2	0.3
116	1.4	0.4	2.6	0.5	0.4	-0.1	1.3	0.3

Table 9.12. Weekly summaries of basement RH and HVAC duty cycle for House #3

	Basement RH (%)				Fraction HVAC OFF			
Date	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	59.5	55.8	62.4	1.6	0.891	0.593	1.000	0.100
306	59.1	0.0	63.0	4.3	0.862	0.000	1.000	0.122
313	56.6	51.7	63.5	3.3	0.809	0.475	1.000	0.122
320	46.9	41.5	53.1	3.9	0.690	0.363	1.000	0.152
327	46.3	43.2	50.0	1.8	0.739	0.493	1.000	0.114
334	48.1	43.2	52.0	2.1	0.792	0.477	1.000	0.114
341	45.2	42.8	50.4	2.1	0.765	0.543	1.000	0.102
348	43.0	37.3	47.5	2.5	0.685	0.370	0.953	0.110
355	43.7	40.4	51.8	2.4	0.739	0.073	1.000	0.114
362	42.2	39.8	46.4	1.9	0.749	0.460	1.000	0.132
4	40.4	35.7	43.7	1.5	0.675	0.457	1.000	0.093
11	40.3	39.2	41.7	0.7	0.664	0.457	0.993	0.085
18	39.5	35.7	42.8	1.8	0.686	0.470	0.943	0.099
25	35.3	28.4	40.1	4.5	0.591	0.253	0.897	0.133
32	32.5	26.3	38.5	3.7	0.638	0.293	1.000	0.150
39	34.3	30.4	39.0	2.8	0.702	0.340	1.000	0.136
46	30.5	23.4	35.2	3.0	0.604	0.297	0.957	0.124
53	25.7	22.5	28.1	1.1	0.632	0.240	0.963	0.143
60	30.3	27.9	37.9	2.2	0.703	0.000	1.000	0.126
67	33.9	30.0	37.8	2.1	0.754	0.443	1.000	0.137
74	30.5	25.6	38.3	3.2	0.706	0.317	1.000	0.154
81	27.5	23.2	34.6	3.0	0.751	0.427	1.000	0.132
88	38.2	32.4	43.6	3.0	0.917	0.000	1.000	0.105
95	41.4	37.8	47.3	2.2	0.819	0.483	1.000	0.132
102	41.5	40.0	43.0	0.7	0.867	0.530	1.000	0.104
109	43.4	39.9	52.5	2.9	0.882	0.620	1.000	0.102
116	50.4	43.8	54.8	2.6	0.932	0.607	1.000	0.090

Table 9.13. Weekly summary statistics of temperatures for House #4.

	Basement Temp. (°C)				Upstairs Temp. (°C)				Outdoor Temp. (°C)			
Date	Mean	Min	Max	S.D.	Mean	Min	Max	S.D.	Mean	Min	Max	S.D.
299	17.0	16.1	18.3	0.5	18.2	17.1	19.3	0.4	12.1	3.8	25.9	4.5
306	17.1	14.1	19.2	1.2	18.2	12.9	20.8	1.8	10.3	0.0	21.8	4.4
313	18.0	16.5	19.3	0.7	19.2	17.8	20.1	0.6	20.5	-1.2	32.8	5.7
320	17.7	15.4	18.8	0.8	18.5	16.8	19.6	0.7	6.4	-8.6	22.2	7.1
327	16.2	11.3	19.9	2.2	16.7	8.2	20.6	3.6	2.2	-6.0	12.1	4.4
334	14.9	13.2	18.9	1.9	15.2	12.8	20.6	2.9	5.0	-2.3	16.8	3.6
341	16.6	13.0	20.6	2.0	17.9	12.8	22.1	2.9	2.2	-6.1	11.5	4.2
348	17.2	14.6	19.4	1.0	18.9	16.8	21.2	1.0	0.2	-11.6	10.1	4.9
355	16.9	12.7	19.3	1.5	18.2	13.3	20.7	1.8	1.8	-4.8	6.2	2.5
362	16.5	13.9	17.7	1.1	17.5	15.2	18.7	1.0	1.9	-5.9	8.6	3.1
4	16.6	13.5	18.1	1.2	17.5	14.1	19.1	1.6	-0.6	-6.3	4.6	2.2
11	17.5	13.3	20.8	1.8	19.1	14.5	21.5	1.8	-0.2	-6.3	4.6	2.6
18	17.7	13.3	19.6	1.7	20.1	15.1	21.6	1.5	1.5	-7.9	10.9	4.6
25	17.4	12.6	19.7	2.0	19.5	14.3	21.5	1.9	-5.4	-15.7	1.1	4.8
32	17.4	12.8	19.8	2.1	19.4	14.4	21.4	2.0	-5.0	-14.5	2.5	4.4
39	16.5	13.0	19.4	1.7	18.5	14.4	21.4	1.6	1.2	-7.2	8.4	3.6
46	15.1	7.2	21.1	4.1	16.0	3.8	23.4	5.7	-5.0	-18.2	3.9	4.8
53	17.2	11.1	20.2	1.8	19.7	11.4	22.7	2.0	-2.6	-16.1	10.2	5.2
60	17.3	13.2	19.1	1.0	19.3	14.6	21.1	0.9	0.9	-5.6	7.5	3.6
67	17.0	13.9	20.6	1.8	20.0	16.8	22.9	1.6	5.2	-4.8	24.7	7.2
74	16.4	13.9	18.3	1.2	19.0	18.1	21.1	0.8	0.6	-10.3	16.3	5.8
81	17.3	15.4	18.4	0.6	19.6	-6999	20.4	0.3	3.9	-3.3	14.7	4.5
88	14.0	12.5	18.0	1.3	17.2	14.5	20.9	1.8	12.0	2.6	23.8	5.1
95	12.5	10.3	19.2	2.0	13.6	9.6	22.4	3.1	7.7	-2.7	16.0	4.7
102	15.5	13.6	19.3	1.6	18.9	15.9	22.3	1.6	10.5	4.3	26.2	5.1
109	15.2	13.1	20.0	1.8	17.8	15.0	22.1	2.0	11.0	2.9	24.9	4.5
116	17.3	15.3	19.8	1.0	20.7	16.9	23.7	1.3	13.2	3.5	26.9	5.4

Table 9.14. Weekly summary statistics of differential pressures for House #4.

	Bsmt-Out Pres. (pa)				Bsmt-Subslab Pres. (pa)				Bsmt-Upst Pres. (pa)			
Date	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	0.93	-0.88	3.65	0.95	0.33	0.25	0.42	0.03	0.98	0.68	3.74	0.62
306	1.29	-0.10	6.48	1.10	0.37	0.30	0.56	0.04	1.15	0.68	5.89	0.90
313	2.11	-0.18	6.36	1.42	0.41	0.30	0.53	0.05	1.38	-9.87	22.38	2.21
320	3.33	1.24	8.66	1.43	0.51	0.37	0.70	0.06	1.48	0.43	5.19	1.05
327	2.89	0.68	6.70	1.49	0.53	0.44	0.64	0.05	1.49	0.47	6.06	1.26
334	1.84	-0.38	5.04	1.13	0.50	0.43	0.59	0.03	1.21	0.51	3.32	0.81
341	3.57	0.27	7.57	1.40	0.53	-2.10	0.68	0.20	1.84	0.37	5.65	1.16
348	3.91	1.17	8.77	1.47	0.58	0.43	0.80	0.07	1.73	0.41	5.06	1.11
355	4.89	1.21	10.18	1.63	-1.99	-2.97	0.74	0.91	2.20	0.27	6.95	1.51
362	4.99	2.55	9.97	1.56	-2.15	-2.82	0.18	0.29	2.26	0.62	6.81	1.43
4	5.06	0.98	9.27	1.30	-2.15	-2.50	-0.62	0.18	1.63	0.52	6.57	1.31
11	5.57	3.07	10.38	1.74	-2.07	-2.54	1.24	0.42	2.04	0.47	6.51	1.72
18	4.44	-1.32	9.45	1.79	-0.56	-2.67	1.96	1.75	1.52	0.32	6.38	1.32
25	6.39	2.21	11.68	2.48	-0.47	-2.00	1.85	1.39	2.24	0.30	6.24	1.80
32	6.79	3.38	11.38	2.04	-1.48	-2.04	-0.74	0.29	2.52	0.44	6.04	1.84
39	4.69	2.46	10.10	1.63	-1.78	-2.19	-1.03	0.24	1.75	0.48	6.31	1.58
46	6.40	1.53	13.12	3.24	-1.40	-2.01	-0.52	0.38	2.72	0.50	6.65	2.30
53	7.81	3.44	12.20	1.94	-0.31	-1.97	2.03	1.49	4.40	0.43	5.86	1.52
60	5.20	2.11	8.41	1.36	-1.78	-2.56	-1.28	0.26	1.79	0.45	5.32	1.29
67	3.52	-0.69	9.43	2.74	1.89	-2.34	6.28	3.68	1.49	0.23	5.87	1.37
74	4.05	-0.02	7.55	1.77	2.02	-2.21	6.67	3.87	1.50	0.31	4.24	1.05
81	4.24	2.02	6.60	1.20	-1.96	-2.36	-1.61	0.18	1.33	0.36	3.52	1.03
88	0.77	-0.83	5.58	0.95	-1.14	-2.97	0.72	1.55	0.85	0.11	3.19	0.72
95	1.55	0.24	6.81	1.13	0.71	-1.45	1.46	0.21	0.94	0.60	5.22	0.71
102	2.20	-0.38	8.48	1.52	-1.41	-3.13	1.44	1.74	1.20	0.60	6.39	1.14
109	2.19	0.39	8.19	1.38	-2.69	-3.06	-1.88	0.21	1.16	0.66	7.11	1.17
116	1.94	0.57	7.11	0.86	-2.87	-3.19	-2.21	0.16	0.98	0.71	5.92	0.42

Table 9.10 Weekly summary statistics of radon concentrations for House #4

Date	Basement Radon (pCi/L) Mean	Min.	Max.	S.D.	Upstairs Radon (pCi/L) Mean	Min.	Max.	S.D.
2-9	67.0	7.2	136.5	21.6	31.1	6.6	47.2	7.7
300	58.1	33.9	86.3	17.0	26.4	8.9	37.1	5.6
313	41.2	36.3	69.8	8.6	21.9	13.2	32.7	3.9
320	21.3	3.6	46.8	5.3	15.6	2.0	26.0	2.8
327	28.0	16.1	54.0	10.1	15.4	3.1	27.4	4.6
334	44.1	19.5	78.7	15.8	25.0	10.6	42.6	9.5
341	69.4	21.1	107.7	19.9	30.4	15.5	42.6	5.9
348	50.2	33.1	80.7	9.2	32.0	22.4	41.0	4.9
355	6.6	0.5	46.1	11.9	5.7	0.0	33.9	11.0
362	1.5	0.2	3.2	0.7	0.8	0.0	2.3	0.5
6	3.4	1.0	8.3	2.5	1.5	0.0	4.4	1.1
11	2.1	0.7	9.4	1.0	1.1	0.0	4.8	0.7
18	14.1	0.4	74.1	19.5	11.4	0.0	36.9	12.8
25	30.9	1.7	109.3	25.0	11.6	0.2	39.6	12.3
32	3.8	1.3	4.5	0.6	2.1	0.0	7.1	1.1
39	3.5	0.8	4.8	0.7	2.2	0.1	82.8	5.3
46	3.1	1.4	4.7	0.6	1.3	0.0	3.3	0.9
53	11.4	2.3	16.7	16.9	10.3	0.8	219.7	15.2
60	2.9	0.4	6.1	1.0	1.8	0.3	5.4	0.9
67	8.3	0.3	27.8	8.4	8.3	0.0	20.1	7.7
74	13.7	1.2	29.5	9.5	10.5	0.6	23.8	8.3
81	2.5	1.0	3.7	0.6	1.6	0.1	5.5	0.8
88	33.5	0.6	153.1	45.9	18.0	0.0	71.0	23.9
95	108.5	55.8	156.3	31.2	61.6	37.8	90.9	12.8
102	37.4	0.1	135.8	47.8	24.6	0.3	95.2	30.4
109	1.5	0.1	4.3	0.7	1.4	0.3	6.1	0.9
116	0.7	0.0	1.6	0.3	0.6	0.0	1.4	0.2

Table 9.16. Weekly summaries of basement RH and HVAC duty cycle for House #4

	Basement RH (%)				Fraction HVAC OFF			
Date	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	67.2	62.0	70.1	1.6	0.936	0.443	1.000	0.137
306	68.3	63.1	70.4	1.9	0.908	0.000	1.000	0.192
313	63.3	59.6	69.3	2.6	0.835	0.123	1.000	0.218
320	56.0	48.1	67.0	5.1	0.738	0.000	1.000	0.242
327	55.7	51.5	59.4	2.1	0.794	0.000	1.000	0.256
334	58.5	54.3	61.5	1.9	0.901	0.430	1.000	0.166
341	53.7	48.8	60.6	3.3	0.730	0.000	1.000	0.246
348	50.3	43.7	56.2	3.2	0.715	0.000	1.000	0.240
355	46.3	43.5	49.4	1.4	0.733	0.000	1.000	0.254
362	44.4	42.4	48.0	1.5	0.736	0.000	1.000	0.242
4	42.8	41.0	44.8	0.7	0.687	0.000	1.000	0.212
11	41.8	40.7	43.8	0.6	0.641	0.000	1.000	0.286
18	43.2	40.7	53.9	2.6	0.665	0.000	1.000	0.309
25	42.0	38.1	44.8	1.4	0.596	0.000	1.000	0.345
32	39.7	37.1	41.8	0.7	0.575	0.000	1.000	0.347
39	40.3	38.8	42.1	0.8	0.717	0.000	1.000	0.298
46	37.5	26.8	41.5	3.5	0.575	0.000	1.000	0.443
53	29.2	24.4	33.4	2.0	0.080	0.000	1.000	0.270
60	32.3	28.8	40.5	2.6	0.646	0.000	1.000	0.252
67	38.4	31.7	46.2	3.8	0.735	0.000	1.000	0.259
74	40.4	33.8	48.9	3.9	0.715	0.313	1.000	0.219
81	34.0	30.7	38.6	1.6	0.752	0.137	1.000	0.215
88	46.5	37.5	64.5	6.0	0.798	0.000	1.000	0.385
95	52.0	49.3	55.1	1.1	0.952	0.000	1.000	0.181
102	51.2	45.7	55.6	2.0	0.902	0.000	1.000	0.240
109	54.3	47.6	62.8	3.2	0.913	0.000	1.000	0.238
116	59.9	43.5	67.9	6.7	0.907	0.000	1.000	0.221

Table 9.17. Weekly summary statistics of temperatures for House #5.

	Basement Temp. (°C)				Upstairs Temp. (°C)				Outdoor Temp. (°C)			
Date	Mean	Min	Max	S.D.	Mean	Min	Max	S.D.	Mean	Min	Max	S.D.
299	18.9	18.2	19.7	0.4	21.8	18.9	25.0	1.4	13.7	2.7	27.3	6.2
306	19.1	15.8	20.3	0.7	22.7	19.5	24.8	1.2	12.0	-0.8	25.9	5.7
313	19.1	18.2	19.7	0.3	22.8	20.1	24.9	1.2	9.5	-0.7	21.2	5.5
320	18.5	17.0	19.4	0.5	22.2	16.9	26.5	1.9	3.2	-7.2	16.4	5.2
327	18.4	17.0	19.8	0.5	22.6	18.3	26.1	1.6	4.5	-5.5	16.9	4.8
334	18.3	16.1	19.2	0.5	22.6	18.9	26.9	1.5	6.6	-1.8	18.6	4.7
341	17.7	13.9	18.9	0.9	22.4	18.1	25.5	1.7	3.7	-5.8	13.2	4.7
348	17.8	16.1	18.8	0.5	22.4	17.0	25.9	1.8	1.6	-11.8	13.8	5.1
355	17.5	16.2	19.1	0.6	22.1	18.2	26.8	1.9	3.3	-5.3	11.5	3.4
362	17.3	15.6	18.1	0.5	21.8	17.8	26.2	2.0	3.3	-5.0	14.2	4.2
4	16.7	0.0	18.5	***	22.2	0.0	26.1	***	2.0	-6.3	15.2	***
11	16.6	15.3	18.0	0.6	22.1	17.2	25.8	2.1	1.5	-6.1	11.7	3.3
18	16.8	15.4	17.7	0.6	22.5	17.3	26.1	2.1	3.5	-6.3	15.2	4.8
25	16.2	14.0	18.1	0.8	22.2	15.3	26.1	2.4	-3.9	-15.5	4.0	4.9
32	15.9	14.1	17.0	0.7	22.4	15.8	26.4	2.4	-3.2	-15.8	10.2	5.4
39	16.2	14.8	17.0	0.6	21.9	17.5	25.6	2.0	3.0	-5.3	14.5	5.0
46	16.0	13.2	17.9	0.9	21.6	16.6	25.5	2.1	-2.6	-16.7	11.0	5.2
53	16.0	13.8	17.2	0.7	21.5	15.5	25.8	2.1	0.1	-14.7	14.4	6.6
60	16.7	15.5	17.6	0.6	22.1	17.4	25.5	2.0	2.9	-4.5	14.3	4.4
67	16.8	15.6	17.9	0.5	21.8	17.5	25.7	1.7	6.4	-5.8	25.1	7.7
74	16.6	15.2	17.6	0.5	21.1	16.2	25.1	2.0	4.6	-10.2	31.9	8.5
81	16.7	15.4	17.5	0.5	21.7	17.2	25.6	2.0	5.5	-2.5	19.1	5.5
88	17.0	16.2	17.9	0.3	22.3	18.8	25.7	1.5	12.6	1.2	29.5	7.6
95	17.5	16.3	18.6	0.5	21.7	17.4	24.7	1.6	9.4	-1.3	19.1	5.2
102	17.7	16.8	19.6	0.4	22.2	19.0	25.5	1.3	12.0	4.8	27.4	5.8
109	17.2	15.9	19.1	1.0	19.8	15.7	26.1	3.1	12.9	3.0	30.3	5.1
116	18.3	16.5	20.5	0.9	22.4	18.4	26.3	1.7	15.2	3.8	31.8	6.3

Table 9.18. Weekly summary statistics of differential pressures for House #5.

	Bsmt-Out Pres. (pa)				Bsmt-Subslab Pres. (pa)				Bsmt-Upst Pres. (pa)			
Date	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	1.15	-0.94	2.13	0.42	-0.12	-0.17	-0.08	0.01	0.11	-1.89	0.73	0.19
306	1.27	-1.85	2.99	0.68	-0.13	-0.17	-0.05	0.02	0.02	-3.06	0.85	0.42
313	1.74	0.11	6.69	0.82	-0.12	-0.16	-0.07	0.02	0.18	-0.39	0.88	0.22
320	2.69	0.03	6.94	1.03	-0.10	-0.14	-0.02	0.02	0.21	-0.62	1.00	0.26
327	2.32	-3.51	5.27	1.00	-0.11	-0.16	-0.02	0.02	0.22	-0.90	0.91	0.26
334	2.20	0.19	7.17	0.79	-0.10	-0.16	-0.04	0.02	0.20	-0.45	1.01	0.23
341	2.98	-3.05	11.07	1.97	-0.08	-0.14	0.01	0.03	0.21	-2.05	1.02	0.43
348	3.03	0.49	10.25	1.22	-0.10	-0.19	-0.01	0.02	0.27	-0.11	1.01	0.23
355	2.49	0.13	5.60	0.84	-0.10	-0.15	-0.03	0.02	0.28	-0.19	0.98	0.25
362	2.51	-0.35	7.44	0.91	-0.10	-0.14	-0.02	0.02	0.25	-1.07	0.99	0.27
4	2.83	-25.0	8.78	2.16	-0.05	-25.00	0.64	****	0.01	-25.0	1.42	****
11	2.74	-0.01	8.40	1.45	0.01	-0.17	0.31	0.13	-0.01	-0.78	-0.06	0.26
18	2.97	0.66	8.49	1.47	0.18	-0.10	0.64	0.16	0.13	-0.43	-0.40	0.35
25	3.20	0.43	11.46	1.70	0.60	0.19	1.46	0.26	-0.10	-0.82	-0.04	0.38
32	3.03	1.39	5.02	0.73	0.84	-1.43	1.58	0.27	0.20	-0.56	-0.48	0.41
39	3.13	1.51	11.74	1.38	0.72	0.44	1.30	0.18	0.28	-0.18	-0.03	0.36
46	4.06	2.02	9.12	1.21	-6.09	-13.05	1.43	6.38	0.33	-0.70	1.98	0.43
53	2.96	1.50	5.82	0.77	-1.81	-13.01	2.20	5.66	0.31	-0.18	1.92	0.43
60	2.91	-0.57	5.55	0.89	-5.53	-14.10	2.16	6.88	0.41	-1.03	2.09	0.45
67	3.55	1.37	13.37	1.69	-12.09	-13.50	1.25	2.84	0.42	-0.47	1.96	0.38
74	2.30	-0.29	5.43	0.86	-9.48	-14.08	-5.98	2.82	0.39	-0.12	1.82	0.38
81	2.35	1.04	4.13	0.59	-4.66	-8.51	1.50	4.03	0.30	-0.11	1.58	0.35
88	1.32	-0.55	3.83	0.70	-3.94	-9.13	1.41	4.32	0.19	-0.27	1.23	0.22
95	1.43	-5.42	10.97	2.20	-1.02	-13.32	2.71	4.51	0.01	-0.56	1.10	0.21
102	1.73	-3.10	5.74	0.88	-8.08	-15.26	1.37	5.33	0.18	-2.15	1.38	0.33
109	0.91	-0.79	5.14	0.98	-5.84	-14.06	1.11	6.52	0.18	-0.74	1.65	0.26
116	0.83	-5.63	2.64	1.02	-10.71	-15.05	0.36	5.25	0.16	-1.40	2.59	0.39

Table 9.19. Weekly summary statistics of radon concentrations for House #5

	Basement Radon (pCi/L)				Upstairs Radon (pCi/L)			
Date	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	39.2	0.4	68.2	17.7	8.8	0.0	17.8	4.8
306	34.5	0.2	60.2	17.1	8.4	0.0	17.1	4.6
313	46.0	12.1	65.0	9.0	13.7	8.2	19.4	2.5
320	52.3	0.5	68.2	11.7	15.4	2.8	21.8	3.8
327	48.2	10.7	67.9	10.7	14.2	3.8	20.0	3.1
334	52.6	3.6	78.2	14.2	14.9	4.4	23.9	3.7
341	46.2	0.1	71.9	14.7	13.3	0.1	20.7	4.6
348	49.6	34.8	65.8	7.1	15.6	10.2	19.9	2.2
355	48.3	28.8	68.7	9.5	15.2	10.0	20.5	2.3
362	49.2	2.6	67.9	11.3	15.1	2.8	20.6	3.2
4	38.5	9.8	64.8	7.8	13.5	4.4	20.0	2.4
11	36.6	9.8	47.7	6.2	13.1	4.4	17.1	2.1
18	39.9	16.3	64.8	9.4	13.5	6.3	20.0	2.9
25	39.8	18.0	155.9	13.5	13.6	6.8	77.0	5.3
32	41.6	28.5	62.6	6.5	13.5	9.6	18.0	1.7
39	45.7	32.5	60.8	5.1	14.2	7.9	18.9	2.2
46	15.8	0.3	71.8	22.5	4.9	0.0	20.2	6.7
53	26.7	0.0	50.6	17.1	8.1	0.0	15.6	5.4
60	24.0	0.0	55.9	21.9	7.6	0.0	18.5	6.5
67	1.0	0.0	11.9	1.8	0.4	-0.1	4.2	0.8
74	0.6	0.0	1.3	0.3	0.1	0.0	0.5	0.1
81	10.7	0.0	43.6	15.1	3.4	0.0	16.6	5.3
88	20.8	0.1	52.4	19.0	6.7	0.0	17.0	5.7
95	25.6	0.7	54.4	13.8	7.9	0.3	16.6	4.3
102	11.8	0.0	92.6	19.3	5.6	0.0	19.5	7.1
109	11.5	0.0	34.0	11.6	2.1	0.0	4.8	1.7
116	7.1	0.0	40.1	13.0	1.8	0.0	9.2	2.5

Table 9.20. Weekly summaries of basement RH and HVAC duty cycle for House #5

	Basement RH (%)				Fraction HVAC OFF			
Date	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	62.5	48.3	65.8	2.5	0.913	0.000	1.000	0.213
306	59.3	37.7	64.9	5.6	0.847	0.000	1.000	0.271
313	59.5	55.2	62.5	1.3	0.781	0.000	1.000	0.299
320	57.1	46.4	61.8	2.8	0.725	0.000	1.000	0.313
327	55.1	45.7	57.2	1.7	0.693	0.000	1.000	0.341
334	54.9	45.3	56.6	1.7	0.764	0.000	1.000	0.287
341	51.1	39.1	55.7	3.6	0.672	0.000	1.000	0.347
348	50.7	47.8	52.3	0.9	0.656	0.000	1.000	0.327
355	50.6	47.9	52.2	1.0	0.690	0.000	1.000	0.345
362	49.9	39.1	51.4	1.9	0.714	0.000	1.000	0.342
4	47.2	0.0	51.0	***	0.659	0.000	1.000	*****
11	46.4	43.5	47.8	0.7	0.662	0.000	1.000	0.345
18	47.9	46.0	50.2	1.1	0.675	0.000	1.000	0.336
25	45.8	42.2	48.8	1.9	0.680	0.000	1.000	0.324
32	44.0	40.9	46.4	1.3	0.690	0.000	1.000	0.319
39	46.8	45.6	47.9	0.6	0.722	0.000	1.000	0.327
46	44.8	41.7	47.4	1.4	0.730	0.000	1.000	0.305
53	43.3	41.3	44.1	0.6	0.743	0.000	1.000	0.318
60	44.3	42.2	45.7	0.5	0.705	0.000	1.000	0.325
67	44.6	43.2	46.0	0.5	0.771	0.000	1.000	0.310
74	44.2	42.8	46.2	1.1	0.782	0.000	1.000	0.334
81	43.7	42.8	45.0	0.4	0.768	0.000	1.000	0.347
88	45.0	44.4	45.5	0.2	0.921	0.000	1.000	0.215
95	50.7	48.3	57.3	1.8	0.845	0.000	1.000	0.260
102	49.8	38.5	52.4	2.4	0.878	0.000	1.000	0.232
109	49.4	47.6	51.1	0.7	0.932	0.000	1.000	0.179
116	59.5	51.2	67.5	4.7	0.924	0.000	1.000	0.193

Table 9.21. Weekly summary statistics of temperatures for House #6.

	Basement Temp. (°C)				Upstairs Temp. (°C)				Outdoor Temp. (°C)			
Date	Mean	Min	Max	S.D.	Mean	Min	Max	S.D.	Mean	Min	Max	S.D.
299	21.8	20.2	24.0	0.9	22.7	21.3	24.0	0.6	10.3	-2.0	26.8	6.3
306	22.1	20.4	24.3	0.8	23.0	21.5	24.9	0.6	9.2	-4.2	23.1	5.7
313	22.8	20.9	24.7	0.8	23.0	22.2	24.4	0.5	7.4	-5.2	19.5	5.8
320	23.5	21.3	24.9	0.7	23.7	22.1	25.2	0.6	0.3	-11.6	11.3	5.0
327	22.7	20.6	24.1	0.6	23.6	22.5	24.8	0.6	2.1	-8.9	13.8	5.4
334	22.3	20.3	24.7	0.7	23.2	20.2	25.9	0.9	2.5	-6.4	11.5	4.6
341	22.7	20.9	25.4	0.7	23.5	21.9	24.9	0.6	0.5	-9.9	12.4	4.8
348	22.0	20.5	23.6	0.6	23.0	21.7	24.6	0.6	-1.0	-14.7	11.7	5.3
355	21.7	20.2	23.4	0.5	22.9	21.8	24.2	0.6	0.8	-7.7	8.9	3.9
362	21.8	19.8	23.2	0.7	23.5	21.8	25.6	0.7	0.3	-10.1	8.0	4.3
4	21.8	17.9	25.4	1.1	23.6	18.1	27.7	1.4	-0.3	-10.4	13.3	4.2
11	21.9	20.5	23.2	0.5	23.9	22.9	25.2	0.6	-0.8	-9.4	5.6	3.3
18	21.5	19.0	25.4	1.6	23.3	21.1	27.7	2.0	1.5	-10.4	13.3	5.3
25	22.0	20.6	23.1	0.5	24.0	22.8	25.6	0.5	-5.9	-19.6	1.1	5.3
32	21.7	18.8	23.0	0.7	24.1	23.0	25.5	0.5	-5.5	-19.9	2.4	5.4
39	21.8	20.1	23.1	0.6	24.0	22.7	25.4	0.6	-0.2	-9.2	10.9	4.9
46	21.6	20.1	23.1	0.6	23.9	22.6	25.3	0.6	-5.1	-18.6	8.5	5.2
53	21.5	17.1	23.3	1.0	23.9	20.7	25.9	0.7	-2.9	-16.6	19.7	6.6
60	21.6	2.0	23.0	1.2	23.4	0.0	25.1	1.4	0.5	-7.9	16.2	5.3
67	21.0	****	22.5	0.9	23.4	22.3	24.6	0.5	4.8	****	34.8	8.9
74	21.3	18.0	23.7	1.0	23.2	20.1	25.9	0.8	0.9	-12.7	21.2	7.2
81	21.5	19.5	23.0	0.6	23.2	22.2	24.7	0.5	4.1	-6.6	23.1	7.2
88	19.9	17.7	22.5	1.1	22.4	20.1	24.3	0.9	12.8	-2.8	33.9	9.8
95	20.7	18.1	22.9	0.8	23.1	21.8	24.6	0.5	8.2	-4.6	22.5	6.6
102	20.6	17.9	22.9	1.2	23.5	22.6	24.6	0.4	11.0	0.2	34.8	8.6
109	20.6	18.1	23.0	1.0	23.3	22.2	24.9	0.5	11.9	-2.1	37.1	7.1
116	20.0	17.8	22.6	1.2	23.5	22.1	25.4	0.7	14.7	-2.0	38.1	8.8

Table 9.22. Weekly summary statistics of differential pressures for House #6.

	Bsmt-Out Pres. (pa)				Bsmt-Subslab Pres. (pa)				Bsmt-Upst Pres. (pa)			
Date	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	2.09	-0.18	5.70	1.18	-0.12	-0.43	0.34	0.24	0.36	-0.16	2.42	0.50
306	2.45	0.31	6.10	1.16	-0.22	-0.41	-0.01	0.09	0.36	-0.20	2.16	0.52
313	2.69	-0.35	5.92	1.32	-0.22	-0.38	-0.01	0.08	0.50	-0.17	2.08	0.54
320	4.02	1.42	6.17	1.00	-0.25	-0.40	-0.10	0.06	0.50	-0.26	1.86	0.50
327	2.91	-22.36	6.28	3.71	-0.22	-0.37	0.03	0.06	0.56	-0.30	5.05	0.65
334	2.75	-13.71	10.94	1.85	-0.26	-2.00	-0.03	0.11	1.85	-1.81	23.37	5.14
341	1.94	-19.68	4.87	2.32	-0.28	-0.48	-0.14	0.06	1.91	-0.47	23.02	4.48
348	2.70	-0.51	5.87	1.22	-0.22	-0.33	-0.09	0.05	2.95	-0.06	23.36	5.99
355	2.39	0.02	4.86	0.89	-0.22	-0.34	-0.12	0.05	1.61	-0.04	22.18	3.60
362	2.33	-2.41	4.52	0.93	-0.26	-0.44	-0.12	0.06	2.20	-0.22	23.31	5.01
4	2.77	-0.30	5.52	1.18	-4.43	-7.94	0.05	2.88	0.80	-0.67	2.18	0.56
11	3.01	0.67	5.52	0.92	-4.71	-7.94	-2.15	2.57	0.93	-0.11	1.96	0.52
18	2.27	-0.30	5.41	1.47	-7.45	-7.89	-3.38	0.35	0.69	-0.46	2.06	0.52
25	3.66	1.59	6.54	1.09	-8.27	-9.98	-7.06	0.80	0.54	-0.35	1.45	0.42
32	3.68	1.53	6.96	1.21	-9.52	-10.25	0.32	1.36	0.55	-0.77	1.39	0.44
39	2.52	0.13	4.67	0.98	-11.19	-21.26	14.70	9.87	0.53	-0.25	1.60	0.45
46	3.53	0.90	6.82	1.27	-14.13	-19.38	-10.59	2.53	0.55	-0.28	1.41	0.42
53	2.68	-0.19	7.04	1.26	-12.69	-13.95	-6.06	0.96	0.66	-0.97	1.95	0.49
60	2.12	-25.00	4.19	1.71	-11.53	-25.00	-7.81	0.96	1.66	-25.0	23.16	4.31
67	1.34	-94.99	3.99	1.39	-7.46	-11.27	-2.34	1.73	1.11	-0.16	23.27	3.08
74	2.22	-0.33	4.61	1.00	-14.68	-20.19	-3.75	4.50	0.44	-0.29	1.64	0.39
81	1.70	-0.04	3.27	0.72	-16.64	-24.70	-8.78	3.17	0.24	-21.0	1.28	1.68
88	0.24	-2.13	2.76	1.01	-15.66	-20.79	-4.59	2.31	0.28	-0.09	1.30	0.28
95	1.05	-24.70	9.02	2.96	-16.54	-19.95	-14.93	0.72	1.66	-0.30	23.11	4.52
102	0.70	-2.84	2.36	0.93	-15.28	-17.57	-13.87	0.64	0.23	-0.28	1.17	0.33
109	0.50	-2.53	3.13	1.01	-14.26	-15.79	-12.62	0.55	0.26	-0.22	1.26	0.36
116	0.37	-2.60	2.85	1.00	-14.55	-15.89	-12.13	0.45	0.17	-0.34	1.15	0.33

Table 9.7). Weekly summary statistics of radon concentrations for House #6

Week	Basement Radon (pCi/L) Mean	Min.	Max.	S.D	Upstairs Radon (pCi/L) Mean	Min.	Max.	S.D.
299	12.5	3.9	18.3	2.8	6.5	0.0	12.4	3.0
306	12.4	7.5	17.4	2.1	7.1	0.5	12.9	2.7
313	13.2	8.3	18.3	1.8	8.0	0.0	14.4	3.1
320	13.1	9.8	15.9	1.2	10.1	3.1	13.4	1.7
327	12.6	7.6	45.8	4.8	10.0	4.2	32.2	3.7
334	16.8	0.5	31.3	5.1	7.3	0.1	16.6	3.5
341	21.5	10.8	85.4	13.6	14.6	3.0	45.1	7.3
348	14.3	11.2	18.3	1.3	11.5	5.0	16.0	1.9
355	15.6	0.9	26.0	2.9	12.3	2.1	19.7	2.2
362	14.6	8.9	32.4	3.3	12.1	6.8	27.9	3.4
4	16.2	8.6	50.9	5.5	7.2	2.6	16.1	2.6
11	14.4	10.4	21.1	1.9	6.2	3.2	9.2	1.1
18	16.7	8.6	34.7	6.3	6.5	2.6	12.6	2.0
25	16.1	3.3	63.1	4.0	10.9	1.3	184.1	17.5
32	10.6	5.7	17.8	3.3	8.5	4.9	16.4	2.8
39	8.9	5.5	17.9	3.0	7.1	3.6	17.2	3.0
46	9.8	5.6	13.2	1.9	7.0	4.0	10.2	1.2
53	9.8	5.2	12.6	1.4	7.6	4.2	10.3	1.2
60	7.9	4.8	14.0	1.6	6.0	3.5	11.9	1.3
67	8.1	0.4	13.9	4.0	5.0	0.1	12.6	1.7
74	4.0	1.6	7.7	1.0	3.8	1.0	6.8	1.1
81	2.2	1.1	4.0	0.5	2.3	0.4	5.8	1.1
88	1.6	0.0	3.5	0.7	1.6	0.0	4.6	1.2
95	1.8	0.9	3.2	0.6	1.5	0.0	3.4	0.7
102	2.0	0.5	3.9	0.6	1.7	0.0	4.6	0.9
109	1.9	0.0	3.7	0.8	1.3	0.0	3.9	0.8
116	1.7	0.1	3.7	0.7	1.1	0.0	2.8	0.6

Table 9.24. Weekly summaries of basement RH and HVAC duty cycle for House #6

	Basement RH (%)				Fraction HVAC OFF			
Date	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	42.5	38.1	49.8	2.8	0.871	0.093	1.000	0.221
306	42.8	35.2	48.4	3.6	0.849	0.000	1.000	0.234
313	40.9	33.7	59.9	6.3	0.781	0.067	1.000	0.249
320	30.1	21.7	43.5	5.4	0.615	0.000	1.000	0.281
327	28.3	22.1	34.4	2.9	0.665	0.000	1.000	0.272
334	32.6	24.9	40.0	2.7	0.700	0.000	1.000	0.312
341	27.7	22.3	38.2	4.3	0.634	0.000	1.000	0.281
348	26.1	19.2	38.0	3.9	0.607	0.000	1.000	0.289
355	25.1	20.0	30.4	2.4	0.669	0.037	1.000	0.249
362	24.2	21.0	32.7	2.7	0.588	0.000	1.000	0.271
4	23.4	18.8	33.0	2.7	0.585	0.000	1.000	0.277
11	21.8	18.8	25.4	1.7	0.555	0.000	1.000	0.246
18	25.4	22.2	33.0	3.3	0.646	0.000	1.000	0.306
25	24.6	21.1	29.4	1.5	0.490	0.000	1.000	0.233
32	22.6	20.7	24.9	1.2	0.484	0.000	1.000	0.234
39	25.1	23.1	27.4	1.1	0.606	0.020	1.000	0.251
46	22.9	20.7	25.8	1.2	0.515	0.003	1.000	0.246
53	21.9	19.7	23.9	0.7	0.591	0.003	1.000	0.275
60	23.8	22.4	26.7	0.9	0.627	0.000	1.000	0.242
67	27.1	24.1	****	2.0	0.719	0.000	1.000	0.263
74	25.5	21.8	34.8	3.5	0.646	0.000	1.000	0.267
81	23.1	21.7	25.9	1.1	0.685	0.137	1.000	0.240
88	30.9	25.7	39.3	3.7	0.899	0.203	1.000	0.183
95	37.1	32.3	43.2	2.4	0.766	0.000	1.000	0.245
102	38.8	36.9	42.3	1.0	0.820	0.327	1.000	0.206
109	40.8	36.6	51.7	3.4	0.825	0.170	1.000	0.203
116	50.5	40.6	59.0	4.8	0.884	0.237	1.000	0.185

Table 9.25. Weekly summary statistics of temperatures for House #7.

	Basement Temp. (°C)				Upstairs Temp. (°C)				Outdoor Temp. (°C)			
Date	Mean	Min	Max	S.D.	Mean	Min	Max	S.D.	Mean	Min	Max	S.D.
299	20.2	19.6	21.1	0.3	21.7	20.0	24.4	0.9	12.3	1.3	23.7	5.2
306	20.1	19.4	20.9	0.2	21.6	19.7	24.1	0.8	11.0	-0.7	20.8	5.0
313	19.9	19.4	20.4	0.2	21.2	19.9	22.3	0.5	9.1	-0.4	22.5	5.2
320	19.6	18.8	20.6	0.4	21.0	19.6	22.8	0.5	2.4	-8.3	11.6	4.6
327	19.3	18.3	19.9	0.3	20.9	18.7	21.8	0.6	4.4	-5.5	14.3	4.9
334	19.3	18.3	20.2	0.3	21.0	18.9	22.4	0.5	6.1	-2.7	18.4	4.6
341	18.9	17.6	20.0	0.4	20.6	18.8	21.4	0.5	3.4	-6.5	12.8	4.9
348	18.9	18.2	19.3	0.2	20.6	19.4	21.9	0.4	1.6	-11.6	12.6	4.9
355	19.0	18.4	19.4	0.2	21.0	19.6	21.9	0.4	2.8	-5.0	8.0	3.3
362	18.3	16.2	18.9	0.6	20.8	19.1	22.0	0.5	2.7	-6.5	11.1	4.1
4	18.7	18.0	19.4	***	21.0	18.2	22.7	0.5	1.3	-7.7	12.8	***
11	18.7	18.0	19.1	0.2	21.0	19.7	21.9	0.4	0.7	-7.3	6.9	3.3
18	18.7	18.2	19.4	0.2	21.1	18.2	22.7	0.6	2.6	-7.7	12.8	4.8
25	18.2	17.1	19.3	0.5	20.6	19.2	22.7	0.7	-4.0	-16.1	2.4	4.8
32	17.8	16.9	18.6	0.4	20.7	19.7	22.2	0.5	-4.5	-19.5	3.6	5.6
39	18.2	17.6	19.3	0.2	21.0	11.9	22.0	0.7	2.0	-5.5	10.4	4.0
46	18.0	17.1	18.6	0.3	20.6	19.0	21.9	0.5	-3.6	-15.8	5.8	4.4
53	17.8	17.1	18.6	0.3	21.1	19.6	22.6	0.6	-1.2	-14.8	9.6	5.1
60	18.2	17.6	18.8	0.2	21.1	19.9	22.4	0.5	2.1	-6.4	13.4	4.3
67	18.2	17.5	18.9	0.3	21.2	19.6	24.0	0.8	5.8	-5.5	24.0	7.3
74	18.2	17.6	18.8	0.2	21.2	19.8	23.8	0.7	1.6	-9.4	19.8	6.0
81	18.2	17.6	18.9	0.2	21.3	19.8	23.8	0.8	4.9	-2.9	14.1	4.6
88	18.5	17.9	19.3	0.3	22.0	18.9	24.1	0.9	12.4	-0.7	22.2	5.8
95	18.4	17.7	19.0	0.3	21.2	19.6	24.1	0.7	9.1	-1.6	18.4	5.1
102	18.5	17.8	19.6	0.3	21.4	19.5	25.0	1.0	11.4	3.0	24.9	5.8
109	18.8	18.1	19.8	0.3	21.5	20.2	24.4	0.8	11.6	0.9	24.9	4.7
116	19.2	18.6	20.1	0.3	21.5	20.1	23.8	0.8	12.4	0.8	24.3	5.0

Table 9.26. Weekly summary statistics of differential pressures for House #7.

	Bsmt-Out Pres. (pa)				Bsmt-Subslab Pres. (pa)				Bsmt-Upst Pres. (pa)			
Date	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	1.77	-0.76	7.01	0.97	0.25	-0.11	0.98	0.29	0.29	-0.21	1.61	0.35
306	1.76	-0.13	4.10	0.79	0.55	0.25	1.08	0.17	0.18	-0.11	2.99	0.40
313	2.07	-0.20	5.49	0.92	0.64	0.24	1.33	0.19	0.36	-0.57	2.46	0.40
320	3.41	1.92	7.39	1.08	0.89	-0.93	1.80	0.33	0.59	-0.05	1.43	0.33
327	3.56	1.13	10.72	1.57	0.21	-2.40	2.82	0.88	0.62	0.06	2.11	0.35
334	2.75	0.25	5.36	0.77	0.30	-2.22	3.19	0.84	0.46	-0.36	2.03	0.30
341	3.31	1.10	7.38	1.09	0.88	0.43	2.08	0.24	0.52	-0.56	1.27	0.21
348	3.67	1.74	9.51	1.24	0.97	0.55	2.22	0.27	0.65	0.18	1.48	0.21
355	3.68	2.03	10.31	1.32	0.96	0.62	2.40	0.29	0.62	0.20	1.22	0.17
362	3.48	-0.05	9.76	1.50	0.23	0.15	1.05	0.21	0.74	-1.22	1.99	0.67
4	4.29	1.43	8.68	1.10	0.13	-0.44	0.17	0.02	0.92	0.23	1.83	0.22
11	4.46	3.01	8.68	1.13	0.13	0.11	0.15	0.01	0.94	0.44	1.53	0.17
18	3.97	1.43	8.59	1.35	0.13	0.11	0.16	0.01	0.81	0.28	1.54	0.25
25	4.93	2.74	11.29	1.48	0.14	0.10	0.17	0.01	1.07	0.29	2.08	0.30
32	5.04	3.05	8.52	1.19	0.16	0.13	0.18	0.01	1.07	0.37	1.85	0.25
39	3.86	1.97	8.71	1.12	0.15	0.12	0.17	0.01	0.89	0.36	4.07	0.32
46	2.17	-0.02	10.42	3.08	0.15	0.12	0.17	0.01	1.09	0.29	2.04	0.28
53	0.06	0.02	0.11	0.02	0.16	0.14	0.19	0.01	0.89	0.34	1.54	0.25
60	0.02	-0.02	0.06	0.02	0.15	0.13	0.17	0.01	0.83	0.30	1.34	0.22
67	-0.01	-0.05	0.05	0.02	0.14	0.11	0.16	0.01	0.78	0.20	2.59	0.32
74	-0.02	-0.07	0.02	0.02	0.13	0.11	0.15	0.01	0.83	0.26	2.60	0.32
81	-0.01	-0.06	0.03	0.02	0.13	0.11	0.16	0.01	0.78	0.31	1.67	0.27
88	0.54	-4.13	2.38	0.87	1.87	0.11	4.59	1.84	0.45	-0.41	5.22	0.50
95	2.76	-0.56	6.65	1.18	1.48	-7.42	5.55	2.90	0.49	0.10	3.07	0.37
102	1.98	-1.59	4.82	0.92	-0.97	-1.90	-0.02	0.28	0.41	-0.71	2.31	0.40
109	1.79	-1.76	4.59	0.81	-1.08	-2.20	-0.41	0.24	0.44	-0.03	3.53	0.35
116	1.77	-0.46	3.55	0.81	-1.15	-2.22	-0.58	0.25	0.42	0.06	2.82	0.37

Table 9.27 Weekly summary statistics of radon concentrations for House #7

	Basement Radon (pCi/L)				Upstairs Radon (pCi/L)			
Date	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	22.0	10.8	33.1	4.0	4.5	0.1	13.6	3.3
306	21.4	13.8	30.1	3.0	6.7	0.3	17.0	3.7
313	22.0	14.0	29.9	2.6	9.5	0.6	17.0	4.2
320	23.2	1.7	30.6	2.2	13.8	0.7	19.5	2.7
327	21.7	10.9	57.2	6.8	12.1	1.4	18.6	3.5
334	20.3	12.2	55.5	6.7	10.3	0.7	15.6	2.9
341	22.0	14.8	70.6	9.3	12.7	3.0	20.4	3.2
348	22.6	17.6	35.6	2.9	14.6	3.6	20.2	2.8
355	22.4	17.8	35.7	3.3	14.0	5.8	20.6	2.9
362	7.5	0.0	27.5	9.5	2.0	0.0	18.5	4.0
4	0.1	-0.3	0.4	0.1	0.3	0.0	1.1	0.2
11	0.1	-0.3	0.2	0.1	0.3	0.0	0.8	0.2
18	0.1	-0.4	0.4	0.1	0.3	0.0	1.1	0.2
25	0.8	0.0	46.4	4.3	1.7	0.0	128.7	11.6
32	1.3	0.0	12.5	2.5	1.1	0.0	8.3	1.9
39	0.4	0.0	1.5	0.3	0.2	0.0	1.1	0.2
46	0.4	0.0	1.7	0.4	0.3	0.0	1.0	0.2
53	0.9	0.0	2.5	0.6	0.4	0.0	1.4	0.3
60	2.5	0.4	23.6	3.7	1.1	0.0	10.9	1.6
67	5.6	0.0	24.4	7.0	3.8	0.0	13.1	4.4
74	0.1	0.0	0.8	0.1	0.1	-0.4	0.7	0.1
81	0.1	0.0	0.4	0.1	0.1	0.0	0.4	0.1
88	11.7	0.0	25.8	9.9	0.2	-0.1	0.6	0.2
95	7.2	0.0	23.7	6.7	****	-0.6	-0.6	****
102	0.9	-0.2	160.4	10.3	4.9	-0.6	178.3	29.3
109	0.2	0.0	0.8	0.1	0.1	-0.1	0.4	0.1
116	0.2	0.0	1.0	0.2	0.1	-0.3	0.4	0.1

Table 9.28. Weekly summaries of basement RH and HVAC duty cycle for House #7

	Basement RH (%)				Fraction HVAC OFF			
Date	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	59.8	57.4	62.3	1.1	0.963	0.410	1.000	0.085
306	58.9	54.4	60.8	1.5	0.937	0.000	1.000	0.137
313	56.7	53.3	61.4	1.9	0.906	0.037	1.000	0.126
320	50.9	44.6	60.3	4.3	0.836	0.543	1.000	0.115
327	46.8	44.2	51.2	1.6	0.843	0.357	1.000	0.115
334	48.1	46.0	51.9	1.3	0.872	0.000	1.000	0.138
341	45.2	42.6	50.3	2.1	0.836	0.580	1.000	0.090
348	43.9	40.7	47.4	1.5	0.807	0.190	1.000	0.103
355	42.5	40.8	43.6	0.7	0.814	0.373	1.000	0.084
362	40.4	34.3	43.8	2.3	0.812	0.507	1.000	0.095
4	37.9	35.5	40.9	1.1	0.772	0.000	1.000	*****
11	37.2	36.1	38.6	0.7	0.762	0.577	1.000	0.090
18	37.8	35.5	40.9	1.3	0.804	0.493	1.000	0.110
25	36.4	32.3	38.7	2.0	0.736	0.347	1.000	0.110
32	33.9	30.6	37.4	1.7	0.736	0.343	1.000	0.103
39	35.9	33.9	38.0	1.0	0.819	0.000	1.000	0.112
46	33.5	29.2	37.4	1.8	0.729	0.000	1.000	0.113
53	31.1	28.0	33.7	1.2	0.793	0.470	1.000	0.118
60	33.0	30.8	37.4	1.4	0.824	0.000	1.000	0.103
67	36.1	33.4	40.6	1.6	0.855	0.000	1.000	0.136
74	35.3	32.0	41.1	2.4	0.834	0.000	1.000	0.135
81	34.0	32.2	37.2	1.0	0.863	0.513	1.000	0.108
88	39.8	35.5	47.0	2.9	0.964	0.713	1.000	0.073
95	46.9	43.8	53.2	2.0	0.914	0.000	1.000	0.123
102	45.5	44.0	46.8	0.6	0.942	0.510	1.000	0.086
109	46.3	43.7	54.1	2.4	0.943	0.670	1.000	0.078
116	53.6	47.2	58.7	2.8	0.959	0.720	1.000	0.072

Table 9.29. Weekly summary statistics of temperatures (°C) logged at the weather Station.

	Outdoor Temp. (°C)				Wrenn Temp. (°C)				Soil Temp. (°C)			
Date	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
292	11.0	1.5	23.5	4.9	10.8	1.6	22.9	4.8	17.4	16.8	17.8	0.3
299	12.4	1.9	23.6	5.4	12.1	1.8	23.1	5.2	16.2	15.8	16.8	0.3
306	10.6	-1.6	22.2	5.1	10.4	-1.6	21.7	5.0	15.4	14.9	15.8	0.2
313	8.3	-1.5	20.0	5.2	8.0	-1.6	19.8	5.2	14.3	13.6	14.9	0.4
320	2.1	-7.8	11.7	4.7	1.9	-7.9	11.4	4.6	13.1	12.0	13.7	0.5
327	3.4	-6.5	14.7	4.6	3.2	-6.5	14.0	4.5	11.3	10.4	12.0	0.5
334	5.5	-3.0	17.9	4.1	5.3	-3.3	17.2	4.1	10.0	9.7	10.4	0.2
341	2.7	-7.1	12.1	4.5	2.5	-7.3	11.5	4.4	9.1	8.5	9.7	0.3
348	1.2	-10.0	11.1	4.4	1.0	-9.7	10.8	4.3	8.1	7.3	8.5	0.2
355	2.8	-5.8	9.3	3.6	2.6	-5.9	9.3	3.5	6.8	6.1	7.3	0.3
362	1.7	-3.5	6.8	2.6	1.6	-3.5	6.5	2.5	6.2	6.1	6.2	0.0
4	-0.1	-6.1	9.9	3.2	-0.3	-6.0	9.0	3.0	5.9	5.6	6.2	0.2
11	0.9	-7.0	6.7	2.6	0.7	-7.2	5.6	2.5	5.3	5.1	5.6	0.1
18	2.0	-8.0	13.3	4.8	1.8	-8.0	13.0	4.8	5.1	5.0	5.2	0.1
25	-3.9	-9.8	2.2	3.0	7.0	-4.6	21.1	6.2	4.7	4.4	5.0	0.2
32	-0.8	-9.8	99.0	4.2	11.6	-1.3	33.6	7.3	4.2	4.1	4.4	0.1
39	0.8	-9.1	10.0	4.4	14.1	0.5	30.6	6.5	3.9	3.8	4.1	0.1
46	-2.6	-10.0	5.8	3.8	9.5	-5.5	29.1	7.4	3.6	3.4	3.8	0.1
53	0.3	-9.4	12.0	5.0	14.9	3.2	34.6	8.7	3.3	3.1	3.4	0.1
60	2.5	-5.1	10.2	4.2	15.3	4.9	31.7	6.6	3.0	2.8	3.1	0.1
67	6.4	-6.7	26.4	8.1	18.8	6.1	34.8	8.0	3.0	2.8	3.5	0.2
74	0.8	-9.8	11.0	4.8	16.0	2.6	32.3	7.8	3.9	3.5	4.0	0.1
81	6.6	-1.9	23.1	5.8	19.9	8.2	35.0	7.7	4.3	4.0	4.6	0.2
88	12.8	0.5	26.0	5.7	23.8	14.4	34.9	4.8	5.4	4.6	6.3	0.5
95	6.7	-2.2	17.1	6.1	18.7	8.7	25.2	5.4	6.6	6.4	7.5	0.2
102	12.6	2.3	25.5	5.6	23.3	16.2	34.8	4.6	7.9	7.5	8.5	0.3
109	15.0	6.4	29.6	5.9	24.7	16.5	35.0	5.0	8.9	8.5	9.7	0.3
116	10.8	2.9	21.1	4.4	24.6	16.4	35.0	4.9	10.1	9.7	10.4	0.2

Table 9.30. Weekly summary statistics of windspeed, barometric pressure and precipitation at the Weather Station.

	Wind Speed (m/sec)				Barometeric Pres. (mbars)				(0.01 In/30 min)			
Date	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
292	1.0	0.4	2.8	0.5	1001.0	986.0	1014.0	7.2	0.1	0.0	9.0	0.8
299	1.1	0.4	2.4	0.5	1002.0	994.0	1009.0	3.4	0.2	0.0	8.0	0.9
306	1.2	0.4	3.5	0.7	1005.0	990.0	1023.0	9.7	0.0	0.0	2.0	0.2
313	1.1	0.1	3.9	0.8	1003.0	993.0	1015.0	5.7	0.5	0.0	9.0	1.3
320	1.5	0.4	5.0	0.9	1007.0	992.0	1021.0	7.1	0.2	0.0	7.0	1.0
327	1.9	0.4	7.1	1.3	997.3	980.0	1010.0	8.5	0.7	0.0	29.0	2.8
334	1.6	0.4	4.9	0.8	1002.0	985.0	1014.0	5.5	0.5	0.0	21.0	2.5
341	2.4	0.5	5.7	1.3	1005.0	980.0	1020.0	11.0	0.5	0.0	22.0	2.0
348	2.0	0.5	5.3	1.2	1003.0	990.0	1023.0	8.7	0.3	0.0	7.0	1.1
355	2.4	0.5	9.5	1.6	999.9	982.0	1013.0	8.4	0.7	0.0	18.0	2.3
362	1.2	0.4	3.5	0.6	1004.0	996.0	1008.0	2.7	0.0	0.0	0.0	0.0
4	1.9	0.5	5.8	1.1	998.2	979.0	1009.0	9.2	0.2	0.0	4.0	0.7
11	2.5	0.4	7.2	1.6	991.4	973.0	1008.0	10.0	0.1	0.0	7.0	0.6
18	1.8	0.5	5.4	1.1	996.7	978.0	1011.0	8.1	0.2	0.0	9.0	1.1
25	2.2	0.4	6.7	1.5	992.8	962.0	1007.0	10.9	0.0	0.0	2.0	0.2
32	1.7	0.4	5.4	1.1	990.7	977.0	1003.0	7.8	0.1	0.0	4.0	0.4
39	2.3	0.4	6.1	1.2	991.3	973.0	1011.0	10.7	0.0	0.0	1.0	0.1
46	2.2	0.4	5.9	1.1	993.4	981.0	1004.0	5.1	0.0	0.0	3.0	0.2
53	1.8	0.4	5.1	1.0	995.1	978.0	1007.0	6.5	0.2	0.0	13.0	1.4
60	2.2	0.4	6.4	1.4	997.5	971.0	1012.0	11.7	0.4	0.0	11.0	1.4
67	1.7	0.4	4.3	0.8	996.5	978.0	1010.0	9.5	0.0	0.0	1.0	0.1
74	1.6	0.4	3.9	0.7	999.4	989.0	1010.0	4.8	0.0	0.0	0.0	0.0
81	1.8	0.5	3.7	0.7	988.6	981.0	996.0	4.4	0.0	0.0	0.0	0.0
88	1.7	0.4	4.7	1.1	991.9	982.0	1001.0	3.7	0.3	0.0	9.0	1.0
95	3.3	0.5	6.4	1.1	982.2	967.0	991.0	7.4	0.7	0.0	25.0	2.8
102	1.6	0.4	4.2	0.8	990.4	982.0	1004.0	6.6	0.1	0.0	6.0	0.4
109	1.7	0.4	3.8	0.9	993.6	986.0	1002.0	4.1	0.2	0.0	6.0	0.7
116	1.5	0.4	3.6	0.8	999.0	992.0	1004.0	3.5	0.8	0.0	12.0	2.3

Table 9.31. Weekly summary statistics of radon concentrations (pCi/L) in outdoor radon flux monitors logged at the Weather Station.

	Glue Seed Monitor				Precipitation Weather Station Monitor			
Date	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
292	8.9	0.5	15.8	3.3	7.2	1.7	20.1	
299	8.9	1.0	15.0	2.9	7.5	2.9	17.9	2.5
306	8.5	0.1	13.3	3.2	8.7	2.6	17.1	3.2
313	8.6	0.0	14.4	3.1	8.0	2.5	19.1	3.2
320	4.6	0.0	11.2	3.0	5.7	1.7	11.1	2.0
327	4.5	0.0	9.5	2.4	5.0	0.5	10.9	2.9
334	2.7	0.0	5.9	1.8	4.8	0.6	10.5	2.8
341	2.1	0.0	5.7	1.6	4.8	0.1	15.7	3.5
348	2.9	0.0	11.3	2.0	2.5	0.2	6.5	1.5
355	4.9	0.0	15.7	4.1	5.9	0.7	14.6	3.5
362	3.9	0.0	10.5	2.8	6.7	1.9	11.8	2.0
4	3.2	0.0	11.5	3.0	6.7	1.8	12.7	2.7
11	4.2	0.0	10.7	3.7	5.3	1.4	11.3	2.9
18	4.1	0.0	10.2	2.8	6.1	2.0	11.8	2.3
25	2.9	0.0	4.6	2.9	6.7	0.0	87.8	5.6
32	5.1	0.0	14.8	4.1	6.6	2.6	13.1	2.6
39	4.1	0.0	14.4	4.5	5.0	2.3	9.5	1.7
46	3.2	0.0	12.1	3.0	2.5	0.9	7.3	1.1
53	8.5	0.0	24.6	7.6	6.1	1.6	11.1	1.8
60	7.1	0.0	17.0	5.1	3.7	0.3	10.5	2.4
67	4.0	0.1	11.4	3.3	2.1	0.9	4.4	0.6
74	5.5	0.1	14.0	4.7	2.2	0.7	3.6	0.7
81	5.1	0.0	15.8	4.4	5.4	1.3	19.1	3.8
88	9.7	0.0	14.4	3.3	5.6	0.4	14.1	3.2
95	3.7	0.0	13.8	4.2	2.3	0.0	5.5	1.6
102	11.0	0.2	28.7	4.5	0.0	0.0	0.0	0.0
109	9.2	0.1	25.0	7.4	0.0	0.0	0.0	0.0
116	10.3	0.1	29.1	6.7	0.0	0.0	0.0	0.0

Table 9.32. Weekly summary statistics of relative humidities (%) outdoors and inside an outdoor radon flux monitor logged at the Weather Station.

	Outdoor				Radon Flux Monitor			
Date	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
292	77.0	22.7	99.6	20.1	****	****	****	****
299	66.4	24.3	100.0	19.3	****	****	****	****
306	76.4	37.2	*****	19.2	****	****	****	****
313	85.4	42.5	100.0	15.8	****	****	****	****
320	63.5	39.4	100.0	15.8	****	****	****	****
327	75.3	48.9	100.0	13.4	****	****	****	****
334	79.6	33.7	100.0	17.8	****	****	****	****
341	62.7	38.1	100.0	15.0	****	****	****	****
348	68.1	37.7	100.0	17.1	****	****	****	****
355	75.6	37.8	100.0	14.9	****	****	****	****
362	70.3	52.2	97.8	9.9	****	****	****	****
4	74.9	37.5	100.0	17.7	****	****	****	****
11	73.6	46.9	100.0	14.4	****	****	****	****
18	65.7	27.9	100.0	17.9	****	****	****	****
25	71.1	34.3	100.0	19.8	61.0	43.0	100.3	12.0
32	65.0	22.3	100.0	20.0	54.7	34.3	79.3	6.6
39	62.1	34.9	99.3	17.1	49.7	26.5	71.2	7.6
46	50.9	23.3	98.3	16.7	50.7	35.4	77.4	5.6
53	42.6	20.4	99.8	16.4	49.1	32.8	76.1	7.4
60	51.0	23.1	99.9	17.6	50.7	29.0	62.9	7.9
67	55.4	22.0	97.5	16.7	46.3	18.9	65.0	9.9
74	48.9	18.4	96.5	22.9	50.4	37.5	60.9	4.5
81	47.1	17.6	90.3	20.2	46.9	25.4	60.5	8.1
88	65.6	13.6	100.0	27.0	45.1	21.0	62.9	11.0
95	61.4	41.5	*****	15.4	55.2	44.3	71.6	6.2
102	59.3	14.2	99.2	24.7	63.4	46.8	75.0	6.4
109	80.1	40.1	100.0	19.3	64.1	42.9	73.7	8.1
116	73.4	15.9	100.0	29.3	66.4	61.6	70.9	2.2

9.B INFORMATION TO COLLEAGUES AND LETTERS TO HOMEOWNERS REGARDING SYSTEMS CHOSEN FOR THE HOMES

The following is a memo regarding information sent on the mitigation plans for six of the seven ORNL/Princeton study homes. The mitigation plans are now included in Section 5.1.1. Following the memo is a complete copy of the letter sent to Homeowner #1 and pertinent portions from analogous letters sent to the rest of the homeowners.

Date: December 19, 1986

To: David Sanchez, Alan Hawthorne, Tom Matthews, Charlie Dudney, Brad Turk, Mary Cahill

From: Lynn Hubbard

Re: Mitigation plans for 6 of the 7 Princeton/ORNL homes.

Enclosed are mitigation plans for the 6 Princeton/ORNL homes scheduled for mitigation between December 15th and January 8th. You will find:

1) A summary of the mitigation plans for the six homes.

2) A one page description of the mitigation strategy followed by a basement floor plan.

3) A legend which explains what the numbers on the floor plan mean.

4) A copy of the letters sent to each of the homeowners.

Each letter contains a brief summary of some of the information we obtained during the diagnostics as well as a summary of the mitigation strategy for each home. (More detailed information from our diagnostics such as flow rate, source strength, and pressure differential measurements which we made under various conditions will be summarized in a future report.) Some of those mitigation strategies have changed slightly during the last 2 weeks, and those changes are reflected on the one page descriptions of mitigation plans for each house. The homeowners have been informed of all changes, and have walked through the plans with us in their basements. All six homeowners have given us their permission to proceed.

Ron Simon and Bill Brodhead are doing the work in our homes, as in the LBL homes. Ron will be doing houses #4, 5, and 6 and Bill is doing houses #1, 3, and 7.

Contact me with any questions, and have some very HAPPY HOLIDAYS.

Sincerely,

Lynn M. Hubbard

Mr. and Mrs. Homeowner #1
104 Homeowner Drive
Clinton, New Jersey

Dear Mr. and Mrs. Homeowner #1:

We have just completed a set of diagnostic measurements on your home which have helped us understand better how your house interacts with its environment. In general, the way in which radon is able to enter any home involves the following three factors.

First, the amount of radon in the soil surrounding the foundation of your home and the porosity of the soil itself determines how much radon is available for transport into your home. Second, the construction of the lower portion of the house determines how easily the radon can enter. Perimeter drains and sumps provide easy entry points for radon gas. Unfortunately, even tiny cracks provide leakage sites which makes sealing against radon usually difficult and ineffective. The third major factor is the weather. The colder the temperature, the more buoyant the indoor heated air becomes. Much like a hot air balloon, the heated air rises in the house and tends to exit at the upper locations while sucking in outdoor air and radon from the soil at the lower part of the house.

Keeping these three factors in mind, we have arrived at a strategy which should make progress towards relieving the radon problem in your house. The following is a summary of what we have found.

Substructure type: Basement with perimeter drain, weep holes on southern wall, and sump in NE corner. Family room and garage on slab adjacent to basement.

Subslab type: Good aggregate was found under the basement slab.

Radon entry points: The highest radon concentrations we found were under the basement floor slab on the side near the garage and family room slab. All the walls showed similar concentrations with slightly higher levels found in the wall between the family room slab and the basement. (See attached basement floor map.)

Subslab communication: We observed good communication (i.e., air flow) between subslab points within the basement. Subslab to wall communications were not observed in the basement because of the intervening perimeter drain.

Mitigation strategy: A ventilation system will be installed which will ventilate the area under your basement slab and the wall between the garage and family room and the north (back) basement wall. This will be accomplished by installing two pipes into the block walls, one penetrating the north wall near the basement/family room joint and the other penetrating the block wall which goes between the garage and family room at the point where that wall intersects the west basement wall under the basement stairs. A third pipe for ventilating the basement slab will be inserted through the center of the basement floor. These pipes will be manifolded to each other and exit the basement through the basement/garage wall and out the garage roof. A fan will be

installed in the pipe system in the garage and will pull the air, or soil gas (including the radon), from the gravel bed and vent it to the outside.

To achieve our goals of better understanding the way in which radon enters and moves through the house, and how radon concentrations can be lowered using long term economical solutions, requires information gathering on our part. The monitoring system installed in your home plus additional detailed diagnostics are being used to supply the necessary information for successful radon mitigation. Questions of radon levels, effect of the weather, conditions under basement floors (and behind basement walls) and the soil conditions on your property are all important pieces necessary to solve the radon puzzle. With your help we look forward to lowering the radon concentrations in your home and achieving an improved understanding of the problem, and its solutions, so that other homes facing similar situations can also be remedied.

I will be visiting your home during the week of December 8th to discuss the details of our mitigation plans with you.

Sincerely yours,

Lynn M. Hubbard, Ph.D.
Radon Project Coordinator

Dear Mr. and Mrs. Homeowner #3:

Introductory Remarks

Keeping these three factors in mind, we have arrived at a strategy which should make progress towards relieving the radon problem in your house. The following is a summary of what we have found.

Substructure type: Basement with perimeter drain and sump in SE corner. Garage on slab adjacent to basement on north side.

Subslab type: Good aggregate was found under the basement slab.

Radon entry points: The highest radon concentrations we found were under the basement floor slab on the side near the basement/garage interface. All the walls showed similar concentrations with slightly higher levels found in the NE basement wall. (See attached basement floor ma

Subslab communication: We observed good communication (i.e., air flow) between subslab points within the basement, as well as subslab to perimeter drain and subslab to sump communication. Subslab to wall communications were not observed in the basement because of the intervening perimeter drain.

Mitigation strategy: A subslab ventilation system will be installed which will ventilate the area under your basement slab. This will be accomplished by installing two pipes into the slab, one at 15'5" from each of the north and south walls. These pipes will be manifolded together and exit the basement through the basement/garage wall and out the garage roof on the east side of the roof peak. A fan will be installed in the pipe system in the garage and will pull the air, or soil gas (including the radon), from the gravel bed and vent it to the outside.

Concluding Remarks

I will be visiting your home during the week of December 8th to discuss the details of our mitigation plans with you.

Sincerely yours,

Lynn M. Hubbard, Ph.D.
Radon Project Coordinator

Dear Mr. and Mrs. Homeowner #4,

Introductory Remarks

Keeping these three factors in mind, we have arrived at a strategy which should make progress towards relieving the radon problem in your house. The following is a summary of what we have found.

Substructure type: Basement with painted hollow cinder block walls, 2 sumps with weeping tiles visible, family room and garage on slab adjacent to basement.

Subslab type. Some aggregate was found under the basement slab. The soil 2 ft. under the slab was very wet clay.

Radon entry points: The highest radon concentrations we found were under the garage slab, in the east basement wall (between the basement and family room slab), and under the east side of the basement. (See attached basement floor map.)

Subslab communication: We observed good communication (i.e., air flow) between different points under the basement slab, between the subslab and the basement walls, and between the subslab and the sumps.

Mitigation strategy: A subslab/basement wall ventilation system will be installed. This will be accomplished by attaching an air suction system to the sump on the south side of the basement (near the furnace). This sump will be covered and a 4" S. & D. pipe will exit the sump cover, extend to the ceiling and pass out of the basement through the west wall. A Kanalflakt K6 duct fan will be installed in the pipe at the basement exit point, with a variable speed switch installed in the basement. We may use the small basement window on the west wall near the furnace for the pipe exit point, subject to your approval.

Concluding Remarks

I will be visiting your home during the week of December 15th to discuss the details of our mitigation plans with you.

Sincerely yours,

Lynn M. Hubbard, Ph.D.
Radon Project Coordinator

Dear Mr. and Mrs. Homeowner #5:

Introductory Remarks

Keeping these three factors in mind, we have arrived at a strategy which should make progress towards relieving the radon problem in your house. The following is a summary of what we have found.

Substructure type: Basement with perimeter drain and sump in NE corner. Garage on slab adjacent to basement on north side.

Subslab type: Good aggregate was found under the basement slab.

Radon entry points: The highest radon concentrations we found were in the sump and in the crack in the center of the basement floor. All the walls showed similar concentrations with slightly higher levels found in the north basement wall between the basement and garage. (See attached basement floor).

Subslab communication: We did not observe good communication (i.e., air flow) between the center of the subslab and the sump, the perimeter drain, or the crack through the center of the basement floor. Subslab to wall communications were not observed in the basement because of the intervening perimeter drain.

Mitigation strategy: A basement pressurization system will be installed, which will maintain a slight positive pressure in the basement. This acts as a cap to keep the radon gas from entering your substructure. The sump and most of the perimeter drain will not be sealed initially. A Kanalflakt K6 fan will be installed in the garage-basement wall, which will blow air to maintain a slight pressurization into a pipe system installed in the basement.

Concluding Remarks

I will be visiting your home during the week of December 15th to discuss the details of our mitigation plans with you.

Sincerely yours,

Lynn M. Hubbard, Ph.D.
Radon Project Coordinator

Dear Mr. and Mrs. Homeowner #6:

Introductory Remarks

Keeping these three factors in mind, we have arrived at a strategy which should make progress towards relieving the radon problem in your house. The following is a summary of what we have found.

Substructure type: Basement and crawlspace with hollow cinder block walls, 1 sump in the basement, garage on slab adjacent to basement.

Subslab type: Good aggregate was found under the basement and the crawlspace slab.

Radon entry points: The highest radon concentrations we found were under the basement and crawlspace slab with the west side of the crawlspace showing the largest values. The walls all showed similar concentrations with slightly higher values observed in the NE basement wall next to the garage slab. (See attached basement/crawlspace floor map.)

Subslab communication: We observed good communication (i.e., air flow) between different points under the crawlspace slab as well as between most points under the basement slab, but not between the basement and crawlspace subslab points. There was not good communication between either the crawlspace or the basement subslab and the walls. There was some wall to wall communication in the basement.

Mitigation strategy: A subslab ventilation system will be installed to ventilate the area under both the basement and crawlspace slabs. This will be accomplished by installing two pipes into the slab in the crawlspace and one pipe into the slab in the basement. The pipes will be manifolded together and exit the structure through the garage roof after passing through the wall between the basement and workroom and the wall between the workroom and garage. A Kanalflakt K6 duct fan will be installed in the duct system in the garage, with a variable speed switch installed in the workroom.

Concluding Remarks

I will be visiting your home during the week of December 15th to discuss the details of our mitigation plans with you.

Sincerely yours,

Lynn M. Hubbard, Ph.D.
Radon Project Coordinator

Dear Mr. and Mrs. Homeowner #7:

Introductory Remarks

Keeping these three factors in mind, we have arrived at a strategy which should make progress towards relieving the radon problem in your house. The following is a summary of what we have found.

Substructure type: Basement and crawlspace, with garage on slab adjacent to crawlspace. The basement has a perimeter drain along the three basement/outdoor walls and one sump located on the basement side of the basement/crawlspace wall. The crawlspace has a perimeter drain along the east and part of the south side wall.

Subslab: Good aggregate was found under both the basement and crawlspace subslab.

Radon entry points: The highest radon concentrations were found under the basement floor slab, with slightly lower concentrations under the crawlspace slab. All the walls showed similar concentrations with slightly higher levels found in the southern crawlspace wall between the crawlspace and garage. (See attached basement/crawlspace floor map.)

Subslab and wall communications: We observed good communication (i.e., air flow) between subslab points within the basement, but not between the two (basement and crawlspace) zones. Subslab communication was obscured in the crawlspace because of short-circuiting to the perimeter drain. Subslab to wall communications were not observed in either the basement or crawlspace because of the intervening perimeter drain. We observed wall-to-wall communication within walls and around single corners in walls in both the basement and crawlspace zones.

Mitigation strategy: A subslab ventilation system will be installed which will ventilate both your basement and crawlspace subslab. This will be accomplished by a perimeter drain duct system for each of the crawlspace and basement drains. Each drain will be capped so that it can act as a conduit, or duct system, for the soil gas from under the slab to flow through. These duct systems along with a cover for the sump will be manifolded to a common pipe which will exit the substructure through the garage/crawlspace wall. The pipe will exit the garage through the ceiling on the west side of the house. A fan will be installed in the pipe in the garage which will pull the air, or soil gas (including the radon), from the gravel bed under the basement and crawlspace slabs and vent it to the outside.

Concluding Remarks

I will be visiting your home during the week of December 8th to discuss the details of our mitigation plans with you.

Sincerely yours,

Lynn M. Hubbard, Ph.D.
Radon Project Coordinator

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