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

C. S. Dudney, L. M. Hubbard,[1] T. G. Matthews,
R. H. Socolow,[1] A. R. Hawthorne, K. J. Gadsby,[1]
D. T. Harrje,[1] D. L. Bohac[1] and D. L. Wilson

[1]Center for Energy and Environmental Studies
Princeton University

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The researchers wish to thank the various sponsors and project officers who made this comprehensive study possible. Without their concerted effort and encouragement, this detailed study of radon entry processes could not have been accomplished.

The authors of this report also wish to thank the occupants of the study houses for their toleration of our experiments so that the scientific understanding of radon transport could be advanced.

ABSTRACT

This report describes the results from a year-long, intensive, instrumented study of radon entry processes and the effectiveness of radon mitigation measures in seven occupied New Jersey houses. All of the houses that were studied are basement houses that had elevated radon levels (i.e., greater than 400 and less than 7,500 Bq m^{-3}) prior to the study. The houses are located within forty km of Clinton, NJ, in the Reading Prong. Various mitigation strategies were evaluated in the houses. The most successful strategy was depressurization of the soil beneath the concrete slab of the basement. To achieve subslab depressurization, one or more slab penetration points were selected for each house. The most important diagnostic measurement in selection of effective slab penetration points was testing of air flows between potential penetrations and points on the slab perimeter. Careful sealing of the wall to the slab was found to increase the effective zone of depressurization beneath the slab.

To augment the information gained in the study, data acquisition systems were installed in each house to record temporal variation of various environmental parameters, averaged and recorded every thirty minutes. Instrumented measurements included: (1) basement and living area radon concentrations; (2) air pressure differences across basement/subslab, basement/living area, and basement/outdoor interfaces; (3) temperatures at basement, living area, and outdoor locations; and (4) central air handler usage. In addition, a weather station was operated at one of the houses during the study. From these data, it is clear that successful reversal of the pressure difference across the basement slab resulted in a rapid decrease in indoor radon levels. It is also clear that occupant manipulation of the central air handler can substantially affect radon entry processes. Preliminary analyses and simple summaries of these data are provided in this report. The data from these systems have been provided to the Lawrence Berkeley Laboratory and to the U.S. Environmental Protection Agency for further analyses.

1. SUMMARY

A detailed radon mitigation study was performed in 14 houses in the New Jersey Piedmont area. Three research teams, one each from Lawrence Berkeley Laboratory (LBL), Oak Ridge National Laboratory (ORNL), and Princeton University (PU) were involved. Seven homes were investigated by LBL and seven homes were investigated by ORNL and Princeton. This intensive, instrumented study was cooperatively funded by the U.S. Environmental Protection Agency (EPA), the U.S. Department of Energy (DOE), and the New Jersey Department of Environmental Protection (NJDEP). The principal goals were 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.

The principal findings of the study were:

1. Reversal of the pressure gradient across the basement slab in these houses resulted in a dramatic, rapid decrease in indoor radon levels.

2. Diagnostic examinations of possible radon reservoirs as well as air flows and pressure gradients resulting from applied depressurization underneath the basement slab were the most important factors in designing a successful subslab depressurization system for radon mitigation.

3. The installation of a subslab depressurization system was uncomplicated for most houses in the study. The presence of both a two-compartment substructure and a water table of temporally varying depth beneath House #6, complicated the installation, evaluation, and operation of a subslab depressurization system.

4. Occupant behavior can substantially perturb the forces driving radon entry. The most important factor in this regard is the operation of the fan in the central air handler.

5. The underlying, interactive, physical forces driving radon entry are very complex. Time series analysis of data from all seven houses for the months of November and December, 1986, failed to reveal consistent cross correlations between radon in the living area and such causative factors as radon in the basement, temperature differences, or pressure differences pressure differences.

6. Sealing of the slab to the wall increased the effective pressure field from subslab depressurization and enhanced the flow of radon-laden gas through the mitigation system. Other

sealing measures, such as barrier paint on the basement walls of House #5, failed to provide much reduction.

Nearly continuous monitoring of radon and related environmental parameters was accomplished before and after mitigation in each house. 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, to monitor: (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 included multizone air infiltration rates that were 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, soil permeability characteristics, and gamma radiation levels were also monitored periodically in all study homes.

Premitigation diagnostic measures have been evaluated and refined in all seven ORNL/Princeton study homes. Procedures were streamlined for measuring and observing air flows within and across building envelopes and for characterizing building structures and soils. In these studies, the principal source of indoor radon was assumed and confirmed to be predominantly pressure-driven transport of soil gas into the house substructure. In the general premitigation diagnostics procedure, several ½-inch-diam 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 conditions or induced depressurization. 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 to a 1½-in.-diam hole through the slab location was observed at the test holes throughout the substructure via measures of differential pressure and air velocity across the basement slab and/or walls. Blower door tests of the whole house and, where feasible, substructure (i.e., basement and/or crawl space) only 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., central air handler, 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 and refined in six of seven ORNL/Princeton study homes in early 1987. Control house mitigation was completed in July 1987, shortly after the end of the continuous data reported here. The principal technique used was depressurization of the region beneath the basement slab with suction points located for enhanced evacuation of radon-containing soil gas. Air flow communication between subslab and wall regions was enhanced via sealing of cracks and closure of perimeter drains via backer-rod-suspended caulk (allowing direct basement-wall communication). Painting (i.e., sealing) of porous walls was evaluated in selected houses and found to be largely unsuccessful in reducing soil gas entry or enhancing mitigation system performance. The sealing of slab cracks and perimeter drains provided improved radon mitigation with a reduced energy penalty due to reduced loss of conditioned basement air. Postmitigation, weekly average radon levels in Houses #1, #3, #4, and #7 were consistently less than 1 to 2 pCi/L in the basement. This corresponds to mitigation efficiencies of typically greater than 95%, considering that the initial basement, weekly average concentrations 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 technique used in this house was to pressurize the basement. House #6 radon levels were reduced to an average of 2 to 4 pCi/L in late spring, after several adjustments in the mitigation system. House #6 posed 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 completed.[1] All continuously acquired data obtained through July 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. The final data set has been transmitted to both LBL and EPA so that a fourteen house data set can be compiled. Field and laboratory calibration data have been summarized. Preliminary data relating radon to selected environmental parameters are presented. For example, heavy rainfall and reduced barometric pressure resulted in temporary twofold to threefold increases in basement radon levels in Houses #1, #6, and #7. Initial results of air exchange experiments using time-averaged PFT and continuous CCTG techniques are discussed. In House #5, for example, the CCTG system quantified a twofold to threefold increase in air infiltration into the basement with operation of the central 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 are tabulated. Effective leakage areas determined in blower door tests ranged from 80 to 300 $in.^2$ and were unchanged by mitigation. Soil permeability measurements ranged from 3×10^{-10} to 1.6×10^{-4} cm^2 with consistent results within a factor of 2 to 3 for individual sites measured at different times but variation as great as an order of magnitude between sites was observed at individual houses. A geological investigation of the region around the test homes and tests for radon in groundwater 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

[1]The units used in this report were chosen to reflect the measurement system most widely used for each type of measurement. Measurements related to mitigation diagnostic tests are generally reported in English units. Most other measurements are reported in metric units.

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 radon in soil gas, gamma radiation, respirable particles, and total working level measures are summarized. Analysis of data from the seven ORNL/Princeton research homes is ongoing. Examples of cross-correlation analyses are presented.

2. INTRODUCTION

This section provides background information, describes the rationale and objectives of this study, and contains an overview of the study's implementation.

2.1 BACKGROUND

The discovery of residences with indoor levels of radon[1] far in excess of those equivalent to federal limits for occupational exposures to short-lived progeny of radon have raised public concern for better understanding of radon entry processes and how best to reduce radon entry. When ^{224}Ra radioactively decays, it gives rise to ^{222}Rn, the only gaseous member of the ^{238}U decay chain. Radon, in turn, gives rise to a series of short-lived progeny, ^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po, two of which are high-energy alpha emitters. Many epidemiological studies have shown that the incidence of fatal lung cancers in underground miners increases according to cumulative exposure to short-lived radon progeny. A thorough review of these studies has been recently completed (BEIR 1988).

Radon has been shown to enter houses by several pathways or mechanisms. The most important pathway for detached, single-family dwellings in most regions of the United States is thought to be pressure-driven flow of soil gas into the substructure. Phenomena that can induce pressure gradients that might drive soil gas entry include:

1. the rising of warm air through the interior volume so that soil gas flows into the substructure to make up for part of the warm air that flows out of the superstructure;

2. the impact of wind on the exterior shell of the building which results in high pressure relative to indoor pressure on one side, and low pressure on the other three sides;

3. falling atmospheric pressure may result in a transient condition in which soil pressures exceed pressures above ground and/or in the house; and

4. heavy rainfall may act as a piston, compressing soil gas beneath a surface water layer in the soil.

There are numerous possible routes of entry for soil gas into basements. In most instances, there is a purposeful gap between the basement slab and the block wall that sits on the footer. Drain lines originating at floor drains or sumps may lead directly to pockets of soil gas with no intervening trap in the line to prevent back flow of soil gas into the basement. There can be cracks that have developed either in the slab or in below grade walls.

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[1] In this report, radon refers to ^{222}Rn unless stated otherwise.

Other radon entry pathways are possible, although these are thought to contribute relatively little to indoor radon in the New Jersey area. Smith et al. (1961) first demonstrated that there were high levels of radon in water that came from groundwater supplies in Maine. Hess et al. (1982) have shown that substantial quantities of radon in the indoor environment can arise from release of waterborne radon into the air. It is widely believed that for every 10,000 pCi of radon in a liter of water, the indoor concentration will be raised one pCi of radon per liter of air. Nazaroff et al. (1988) have recently reviewed this subject. Building materials containing ^{226}Ra can potentially release radon into the indoor environment. Several surveys have been made (e.g., Kahn et al. 1983, Ingersoll 1983, Mustonen 1984), but the contribution from building materials is thought to be small. With the exception of the building materials with the highest radium concentration (i.e., alum shale concrete in Scandinavia), the incremental radon due to building materials is believed to be less than 1 pCi/L.

Little of the previous work on radon mitigation strategies has involved detailed, continuous monitoring over long periods of time in occupied houses. C. D. Hollowell and D. T. Grimsrud and their coworkers at LBL have been studying air flows and radon in detached dwellings for many years. Nero et al. (1983) found little correlation between indoor radon levels and natural infiltration and/or exfiltration in data from multiple house surveys. Fisk et al. (1980,1983) studied the effects of air-to-air heat exchangers on indoor pollutant levels. Nazaroff et al. (1985) monitored radon and related parameters nearly continuously in basement house near Chicago for five months. Nazaroff and Doyle (1985) made similar measurements for 5 to 7 months in two crawl space houses in California and Oregon. Neither of the latter two studies included installation of radon mitigation systems.

The principal approaches to radon mitigation for existing, detached, single-family dwellings with a basement include: sealing to prevent radon entry, house ventilation to increase dilution of radon and plate-out of radon progeny, and subslab ventilation (pressurized or depressurized) to divert radon-laden soil gas away from the living area. EPA (1986) and Scott (1988) have provided recent reviews of the available methodology.

The principal focus of this project was understanding pressure-driven flows of radon-laden soil gas into the substructure of basement houses. The houses enrolled in this study all had basements that were partially or completely below grade on all four sides. The *a priori* radon levels in the study houses were between 20 and 200 pCi/L, levels which were deemed elevated but not excessively so. The owners and occupants of the selected houses graciously agreed to let us study their houses for 7 to 10 months. During this time, radon, temperature, pressure, and weather data were continuously logged, and a variety of experiments were performed to study soil and building dynamics. This report describes the results from all of these measurements and how they relate to pressure-driven flow of soil gas into and through these residential structures. In addition, the report describes design, implementation, and refinement of radon mitigation systems for these houses.

2.2 PROJECT OBJECTIVES AND REPORT OVERVIEW

The primary objectives of this radon mitigation study were:

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

This 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 used in the study homes are described. Results from continuous monitoring packages in premitigation, mitigation, and postmitigation time periods are reported, including extensive summary statistics. Noncontinuous measures including house and site characterizations and laboratory and field calibration data are summarized.

This report serves multiple purposes by reflecting the needs and desires of multiple project sponsors. The principal purpose of this report is to record the methods and results of a major study of radon and related parameters in seven houses before and after successful mitigation. However, two of the sponsors, EPA and NJDEP, desire that Sections 4 and 5 be written such that they can be removed from this document and distributed as a stand-alone report to radon mitigators in the private sector. For this reason, the reader will find that those sections are written in a manner different from the rest of the report.

The units used in this report have also been chosen to facilitate comprehension by practitioners of the science of radon mitigation. Radon concentrations are reported in picocuries per liter (pCi/L)[1] and potential alpha energy concentrations from airborne radon progeny are reported in working levels (WL)[2]. Linear dimensions of holes and pipes used for diagnostic or mitigation purposes are reported in English, rather than metric, units. Otherwise, metric units have been used. Dates are expressed as Julian dates, which are equivalent to the number of days since the beginning of the then current year.

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[1] 1 pCi/L is equivalent to 37 Bq/m^3.
[2] 1 WL is equivalent to 1.3×10^5 MeV (or 20.8 pJ) per liter.

2.3 PROJECT IMPLEMENTATION

2.3.1 House Selection

House screening and final selection were completed by August 1986. LBL and the NJDEP were responsible for developing the data base of homes from which the final study houses were chosen. Table 2.1 provides a copy of the questionnaire that was used in the house selection process.

2.3.2 Development and Installation of Instrumentation Packages

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

2.3.3 Initial (Fall) Premitigation Phase

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

2.3.4 Premitigation Diagnostics

Premitigation diagnostic studies were performed between mid-November and the end of December 1986. These studies included measurements to characterize the entry of radon into structures and potential control measures. Diagnostic measures continued in selected homes through the winter and spring of 1987 to improve mitigation efficiency. A discussion of diagnostic procedures is given in Sections 3, 4, and 5.

2.3.5 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[1]. 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.

2.3.6 Control House Studies

The control house (i.e., House #2) was mitigated in July 1987. The extended premitigation data set provides for interhouse comparisons and the potential for interseason (e.g., fall vs winter vs spring) modeling.

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[1]House #2 was mitigated in July 1987.

2.3.7 Postmitigation Studies

After installation and refinement of the mitigation systems, the performance of the systems was studied in several ways. Subslab ventilation systems were operated in pressurization, depressurization, and passive modes. Tracer gases were used to evaluate the energy penalties associated with the installed subslab depressurization systems. Results from these studies are described in Sections 5, 6, and 7.

2.3.8 Data Analysis

Preliminary analyses of the data have been completed. Much of the analysis to date has been directed toward the creation of a quality data set that can be distributed in whole or in part to scientists and engineers interested in radon entry processes in mitigated and unmitigated houses. Future work will include detailed statistical analysis and model development applied to both the time-series data and the data from noncontinuous measurements.

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Table 2.1. Residential indoor air quality studies

House ID# ____________

Occupant Name ____________
Address ____________
____

Phone: Home ____________
Hours ____________
Work ____________
[ ] OK to call at work

Technician: ____________
____

Date: ____________
Arrival Time: ____________
Departure Time: ____________

HOUSING INFORMATION CHECKLIST
Check as each item is completed and included in notebook

[ ] Master Data Log	[ ] Radon Gas Sampling Log	[ ] Site Floor Plan
[ ] Structure Survey	[ ] Soil Permeability Survey	[ ] Floor Plan
[ ] Housing Questionnaire	[ ] Fan Test Data Sheet	[ ] Site Elevation

House Description

1. Age of house (if known) ____________

2. Basic Building Construction:
   Exterior Materials ____________
   Interior Materials ____________

3. Interior Remodeling: — Date
   New furniture ____________ ______
   Carpeting ____________ ______
   Cabinetry ____________ ______
   Other ____________ ______

   Wall Insulation
   Date ____________
   Type ____________
   Urea Formaldehyde ____________

4. Existing Radon Mitigation Measures:
   Type? ____________
   Where? ____________
   When? ____________

5. Combustion Appliances: — Frequency of use
   kerosene heaters ____________ ____________
   propane heaters ____________ ____________
   wood/coal stove(s) ____________ ____________
   gas/propane stove or oven ____________ ____________
   other ____________ ____________

6. Urban ____________ Rural ____________
   Locale:
   Description: ____________
   ____

7. Unusual outdoor activities: farm ____________
   construction ____________
   factories ____________
   heavy traffic ____________

Occupants

8. Number of occupants ____________ Number of Children ____________

9. Number of smokers ____________ Type of smoking and frequency ____________

Air Quality

10. Complaints about the air (stuffiness, odors, respiratory problems, watery eyes, dampness, etc.)

11. Problems with humidity or condensation? ____________
    Where? ____________
    When? ____________

master.5

Table 2.1 (continued)

INDOOR AIR QUALITY HOUSING STRUCTURE SURVEY

Family Name ______________________ LBL Code __________

Address ______________________

Telephone ______________________ Date __________

GENERAL STRUCTURE CHARACTERISTICS

House Type: ☐ detached ☐ attached ☐ apartment ☐ other (specify) __________

Size: Area (Occupied Only) __________ ft^2 Total Volume __________ ft^3 (occupied) Age: __________

Structure Materials: ☐ wood ☐ concrete block ☐ poured concrete ☐ other (specify) __________

External Cladding: ☐ wood ☐ stucco ☐ brick ☐ metal ☐ vinyl ☐ concrete ☐ other (specify) __________

Number of floors above substructure: ☐ one ☐ two ☐ three ☐ split ☐ other (specify) __________

Attic: ☐ yes ☐ no Use: ☐ storage ☐ residence ☐ other (specify) __________

Vents: ☐ yes ☐ no Windows: ☐ yes ☐ no

Garage: ☐ detached ☐ attached—one wall borders living space ☐ attached—two walls border living space

Door to living space: ☐ yes ☐ no Area: __________ ft^2

INTERIOR SURFACE MATERIALS

Walls: ______ plaster board, ______ wood, ______ plaster, ______ brick, ______ other (specify) __________

Floors: ______ wood, ______ linoleum, ______ carpet, ______ other (specify) __________

Ceilings: ______ wood, ______ plaster board, ______ plaster, ______ other (specify) __________

ENERGY USE ASPECTS

Heating System: ☐ central forced air ☐ hot water/steam ☐ baseboard ☐ wall/space heater ☐ other (specify) __________

Energy: ☐ gas ☐ oil ☐ electric ☐ solar ☐ other (specify) __________

Heat Exchanger: ☐ central ☐ window __________ flow rate % use: __________ (hrs/day

Fire Places: ______ number in house ______ number with dampers ______ number with glass doors ______ wood stove

Air Conditioning: ☐ central ☐ windows ☐ heat pump FUEL TYPE: __________

Infiltration Characteristics: ☐ apparently tight ☐ apparently leaky ☐ uncertain

Weather Stripping: ☐ doors ☐ windows

Exhaust Fans: ☐ kitchen ☐ bathroom ☐ other (specify) __________

Flue Vents: ☐ oven ☐ furnace ☐ other (specify) __________

SUBSTRUCTURE (Complete more than one section, if applicable.)

Basement: floor area __________ ft^2 depth below ground __________ ft. height above ground __________ ft.

Floor Material ☐ open ground ☐ concrete, thickness __________ in. (if known) ☐ other (specify) __________

Floor Finish: ☐ sealant ☐ paint ☐ linoleum ☐ carpet ☐ other (specify) __________

Wall Material: ☐ concrete block ☐ poured concrete ☐ stone ☐ wood ☐ other (specify) __________

Wall Finish: ☐ sealant ☐ paint ☐ plasterboard ☐ other (specify) __________

Doors: ☐ to exterior ☐ to living space ☐ windows __________ ft^2 (total window area)

Drainage: ☐ sump ☐ drain ☐ none ☐ other (specify) __________

Use: ☐ recreation ☐ storage ☐ residence ☐ other (specify): __________

Crawl Space: area __________ ft^2 depth below ground __________ ft. height above ground __________ ft.;

Floor Material: ☐ open ground ☐ concrete, thickness __________ in. (if known) ☐ other (specify) __________

Floor Finish: ☐ sealant ☐ paint ☐ none ☐ other (specify) __________

Wall Material: ☐ concrete block ☐ poured concrete, thickness ______ in. (if known) ☐ stone ☐ wood ☐ other (specify) ______

Vents: ☐ yes ☐ no Door (or other opening): ☐ to exterior ☐ to living space

Slab: area __________ ft^2 thickness __________ in. (if known)

Finish: ☐ sealant ☐ linoleum ☐ carpet ☐ wood ☐ other (specify) __________

Other Substructure Type: Describe. __________

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3. METHODOLOGY

This section summarizes the methods and materials used in this radon mitigation study. Specifically, selection of study sites, monitoring packages, data acquisition systems, radiological measurements, house dynamics measurements, and methods for mitigation system design and implementation are discussed.

3.1 HOUSE DESCRIPTION

The seven study houses are located in Somerset and Morris counties in Northern New Jersey. An outline of a state map with house locations is given in Figure 3.1. Houses with largely unfinished basements were selected for this study The houses also had moderately elevated radon levels in the living area. A summary of the preliminary site characterization data for the study houses is provided in Table 3.1. These data summarize information on house substructures, pertinent modifiers, central air handler systems, ventilation characteristics, and *a priori* radon levels. (Detailed drawings of the substructures are presented in Figures 5.1 to 5.7.) The following is a brief discussion of individual house characteristics.

House #1: This is a single-story house, built in 1981, with a full basement. The basement wall on the northern side varies from about 50 to 100% exposed. There is an attached garage and family room with slab on grade construction. The basement has a perimeter drain, weep holes on the southern side, a block drain system on the northern side, and a drywell. A propane-fired, forced-air heating system and propane water heater are located in the basement. There is a wood stove, used about two days per week in the heating season, in the family room on the main living level. The home is located at the base of a steep hill with numerous trees in the backyard. There are two adult and one teenage occupants; one or more are present most of the time.

House #2: This is a two story house, built in 1980, with a full basement. The basement wall on the northern side is about 50 to 100% exposed. There is an attached garage with slab-on-grade construction. The basement has a perimeter drain and sump. A gas-fired, forced-air heating system with air conditioning plus gas-fired water heater and dryer are located in the basement. The home is built into a moderately steep hillside with few trees. There are two adult and one teenage occupants; one or more are present most of the time.

House #3: This is a two-story house, built in 1985, with a full, below-grade basement. There is an attached garage with slab-on-grade construction. The basement has a perimeter drain and drywell. An oil-fired, forced-air heating system and an electric water heater are located in the basement. The home is built into a steep hillside with many trees. There are three adult and two teenage occupants; two or more are present most of the time.

House #4: This is a single-story house, built in 1972, with a full, below-grade basement. There is an attached garage and enclosed breezeway with slab-on-grade construction. The basement has two sumps and visible, perimeter drain tiles. An oil-fired, forced-air heating system with air conditioning and an electric water heater are located in the basement. The home is built on flat, moist ground with many trees. There are two adult occupants, who were absent during most of the study period.

House #5: This is a single-story house, built in 1983, with a full, below-grade basement. There is an attached two-car garage with slab-on-grade construction. The basement has a perimeter drain and a sump. There is a central, forced-air heating and cooling system composed of an electric heat pump with an oil heat backup. There is an electric water heater in the basement. The home is built on flat ground with few trees. There are three adult occupants; one or more were present most of the time.

House #6: This is a two-story house, built in 1959, with a complex substructure composed of below-grade basement and crawl space (i.e., short basement with cement floor) areas. There is an attached garage and work area with slab-on-grade construction. The basement area has an air-to-air heat exchanger and a sump. An oil-fired, forced-air heating system with air conditioning and an oil-fired water heater are located in the basement. The home is built on a hillside with many trees bordering the home on the west and north sides. During the course of this study, it was observed that the water table below this house rises and falls, perhaps due to the presence of a small stream near the house. There are two adult and two teenage occupants, of whom two or more were home most of the time.

House #7: This is a single-story house, built in 1977, with a substructure composed of below-grade basement and crawl space (i.e., short basement with cement floor) areas. There is an attached garage with slab-on-grade construction. The basement and crawl space areas have perimeter drains; there is a sump in the basement. A gas-fired, forced-air heating system with air conditioning and a gas-fired water heater are located in the basement. The home is built on flat land with few trees. There are two adult occupants, one of whom was home most of the time.

3.2 MONITORING PACKAGES

The development of instrumentation packages for environmental monitoring of seven New Jersey Piedmont houses was initiated in August 1986. Calibration of the instrument packages and installation in the study homes were largely completed by mid-October of 1986. Monitoring packages were maintained in House #1 until sale of the residence in May 1987, in Houses #3, 4, and 7 until July 1987, in House #5 until August 1987, and remained in Houses #2 and 6 after June 1988. The principal elements of the seven indoor and one outdoor/weather monitoring packages are listed in Table 3.2. Information presented on commercially available instruments, monitors, and other products should not be construed as an endorsement of these products by the authors of this report or by any of the sponsors of this project. (Please see the disclaimer on the inside front cover of this report.)

3.2.1 Indoor Monitoring Station

A system was developed to monitor radon levels, temperatures, relative humidity, pressure differences, and operation of the central air handler in each house (Table 3.2). The data acquisition system monitored each parameter 10 times per minute and recorded the average values every 30 minutes.

Continuous radon monitors were fabricated at ORNL for use in this study (see Figure 3.2). The instruments are based on the techniques developed by Wrenn (1975) as modified by Perdue et al. (1984). Room air enters the sensitive volume of the monitor by diffusion through a layer of foam which serves to remove much of the short-lived progeny. Ionic species resulting from decay of ^{222}Rn are accelerated by an approximately 900-V electrostatic field which is generated by a small DC power supply inside the monitor. The accelerated ions become embedded in an aluminized Mylar sheet. Underneath the Mylar is a thin layer of zinc sulphide which is excited by subsequent alpha decay and emits a burst of photons that passes down a Lucite light pipe to a photomultiplier. The electronic pulse from the photomultiplier is amplified, temporally broadened and transmitted via a coaxial cable to the data logger where pulses are counted. Typical background counting rates for the instruments in this study were 0.5 to 1.0 cpm in the presence of aged tank air. Typical counting efficiencies were 0.7 to 1.3 cpm (above background) per pCi/L. Typical limits of detection (defined as signal to noise equal to one) were about 0.5 to 1.0 pCi/L.

Temperature measurements were made at all locations other than the basement using a water-resistant thermistor (Model 107, Campbell Scientific, Inc., P.O. Box 551, Logan, UT 84321). Manufacturer specifications anticipate that systematic errors due to deviations from linearity are less than 0.5°C. Readings from air temperature probes (i.e., basement, living area, and outdoors) were periodically compared to NBS-traceable thermometers to estimate offset errors for each probe. The final data were corrected for offset. As received from the manufacturer, each probe had a 10-ft cable, which was extended using 24-gauge wire and sealed to prevent water from entering the cable.

Temperature and relative humidity (RH) measurements were made at basement locations using a combination of a thermistor and an electronic relative humidity sensor (Model 207, Campbell Scientific, Inc., P.O. Box 551, Logan, UT 84321). The temperature probe is identical to that in the temperature probes described above. Manufacturer specifications anticipate linearization errors in the RH probes to be less than 3% RH. On four occasions, the readings from each RH gauge were compared to the average of three human-hair hygrometers that had been calibrated at ORNL just prior to the trip to the study houses. The final data were corrected for offset.

Pressure differences were measured using variable capacitance monitors (Model 261-1, Setra Systems, Inc., 45 Nagog Park, Acton, MA 01720). Pressure range of the monitors used was 0 to ± 25 Pa (i.e., 0.1 in. of water) for most applications. In some situations, monitors with a range of 0 to ±63 Pa (i.e., 0.25 in. of water) were used. The sensors were mounted on a rigid vertical surface (e.g., floor girder or block wall) located in the basement. The reference port for each sensor was connected to the approximate center of the basement using 3/16-in.-ID flexible tubing. Roughly equal lengths of tubing were connected to the reference and measurement ports on each sensor to balance potential pressure drops across the inputs to the sensors. To monitor the difference in pressure between the basement and the outdoors, a length of 3/16-in.-ID tubing was passed through the exterior wall on each side of the house. The four pieces of tubing were manifolded together and attached to the measurement port of the sensor. To monitor the difference in pressure between the basement and the living area, tubing was routed to two locations in the living area, manifolded together, and attached to the measurement port of the sensor. To monitor the difference in pressure between the basement and the region beneath the basement slab, two pieces of metal tubing penetrated the slab in separate locations and were manifolded together with flexible tubing and attached to the measurement port of the sensor. The readings from each sensor were calibrated against an electronic micromanometer (see Section 3.6.1.1) over the entire dynamic range of the sensor. The final data were corrected for zero offset and sensitivity (i.e, linear slope).

Operation of the central air handler was monitored with a sail switch (Model AF5405, Honeywell, Inc., Minneapolis, MN 55408). The switch was mounted inside a duct near the main plenum of the central heating system so that it was activated by operation of the air handler. The data were recorded as the fraction of time that the switch was activated during each 30-min interval.

3.2.2 Weather Station

A single weather station was operated in a clearing in the backyard of House #5. Monitored parameters included: air and soil temperatures, barometric pressure, wind speed, wind direction, and radon emanation from the soil into inverted trash cans placed at two locations in the yard. The sensors were mounted on or near a tower that was about 30 ft from any tree or the house. Wind sensors were mounted about 12 ft above the ground. As received from the manufacturer, each probe had a 10-ft cable which was extended using 24-gauge wire and sealed to prevent water from entering the cable. The data logger for the weather station was located inside a shielded box attached to the tower. A power cable and the RS-232 cable from the data logger were buried in a shallow trench running to the basement of House #5, where the modem (which was shared with the house data logger) was located.

Wind speed was monitored with a three-cup anemometer (Model 014A, Campbell Scientific, Inc., P.O. Box 551, Logan, UT 84321). Manufacturer's specifications indicated that the minimum detectable wind speed was 0.5 m/s. The factory calibration factors were used without further calibration.

Wind direction was monitored with an air-foil vane with a potentiometer (Model 024A, Campbell Scientific, Inc., P.O. Box 551, Logan, UT 84321). Readings from the sensor were compared to a compass to establish true north, and the data were corrected accordingly.

The barometric pressure sensor consisted of a integrated circuit mounted on a PC board (Model 1521, Sierra-Misco, Inc., 1825 Eastshore Highway, Berkeley, CA 94710). The factory calibration factors were used.

Rainfall was monitored on the ground near the weather station tower with a tipping bucket raingauge (Model RG2501, Campbell Scientific, Inc., P.O. Box 551, Logan, UT 84321). The cumulative bucket tippings were recorded every 30 minutes. Each tipping was equivalent to 0.01 in. of rainfall. No attempt was made to warm the gauge, so data collected during periods of subfreezing temperatures may under-represent total precipitation.

Radon emanation from the soil per unit surface area (i.e., radon flux) was monitored at two locations using an experimental system fabricated at ORNL. One flux monitoring site, at the base of the weather station, was observed from October 1986 until July 1987 and the other site, about 1 to 2 m from the side of the house, was observed until April 1987. At each site, a commercially available plastic garbage can, suitably modified, was inverted and placed over a continuous radon monitor and a small air pump. The juncture between the garbage can and the soil surface was covered with sand to effect a partial seal. The pumps and radon monitors were replaced as needed. During its lifetime, each pump provided a steady flow of outdoor air for continuous dilution of emanating radon within the chamber. In January and April of 1987, the flow from each pump was checked and adjusted as needed. In April 1987, a study was made of air exchange in each monitor as a function of air velocity measured in the immediate vicinity. Flux ($pCi \cdot m\text{-}2 \cdot h^{-1}$) was calculated from the volume and area of the chambers, the radon concentration, and the air exchange rate, which was corrected for wind speed effects (see Section 6.3).

3.3 DATA ACQUISITION SYSTEM

A data acquisition system gathered and recorded information from the instruments described above. The heart of the system was a commercially available data logger with battery backup (Model 21X, Campbell Scientific, Inc., P.O. Box 551, Logan, UT 84321). Readings from the instruments were acquired every 6 s, and average values (or sums for pulse counting channels) were recorded every 30 minutes in long-term storage. The capacity of the data logger memory was 32,000 bytes, or about 17 days worth of records. The data logger programs are included in Appendix A.

A commercially available modem (Model Smartmodem 1200, Hayes Microcomputer Products, Inc., 705 Western Drive, Norcross, GA 30092) provided a direct telecommunications link between each data logger (other than the weather station) and the telephone network. Separate telephone lines were installed at each study house for data transfer to ORNL and Princeton.

Using several software products, transfer of data to ORNL was generally accomplished each weekday but occasionally as much as a week would transpire between transfers. PC-TALK, a public domain telecommunications program, was executed on an personal computer at ORNL to establish a link with data loggers in New Jersey and to capture the transferred data into files. A BASIC program (see Appendix A) was developed at ORNL to remove nonessential characters from the initial files and generate input files for the data base program. A commercially available data base management program, dBaseIII (Ashton-Tate, Inc., 20101 Hamilton Avenue, Torrance, CA 90502), was used to store the data at ORNL. The data base structures and programs used for data storage, data conversion, and error detection are included in Appendix A.

3.4 RADIOLOGICAL AND PARTICULATE MEASUREMENTS

Radiological measurement techniques (other than the previously discussed Wrenn chamber) and particulate measurement techniques will be described in this section. The approximate costs of the instruments and passive samplers are indicated.

3.4.1 Radon Measurements

Nonintegrated, grab-sample measurements of radon at selected sites were made with a field-portable counting system and Lucas cells (counting system: Model RDA-200; cells: Model RDX-113, Rad Tech, Inc., P.O. Box 44172, Pittsburgh, PA 15205). This system was used to measure radon concentrations in soil gas sampled from soil tubes and to map radon concentrations in subslab, hollow block wall, crack, and sump locations. The counting system ($3000) had a linear response for radon levels below about 30,000 pCi/L and was field portable. Samples were collected directly into the Lucas cells ($200), which have a volume of 160 mL and are coated with a zinc sulphide phosphor. The background count rate of each cell was determined daily before sampling. Except for samples collected during mitigation diagnostic sampling (when very high levels were frequently encountered), the cells were typically counted at least 3 h after sample collection to allow establishment of steady state ratios between radon and its short-lived progeny within the sample. Typical counting efficiencies were about 0.50 to 0.75 cpm above background per pCi/L. Each of the sampling cells used for collecting short-term samples of gas for radon analysis was calibrated in the ORNL and EML chambers. Prior to initial use, each cell was filled with radon and counted several times in succession to confirm that there were no operationally significant leaks.

Integrated measurements of radon levels were made using passive monitors (Model F, $20 each, Terradex Corp., 3 Science Road, Glenwood, IL 60425). The alpha track monitors, similar to those described by Alter and

Fleisher (1981), were used to measure radon levels averaged over 2 to 4 month exposure periods. At the end of the study, monitors were left in six houses for 1-year follow-up measurements.[1] Generally, two or more monitors were placed in the living area and two or more in the basement. For long-term soil gas measurements, a monitor that excluded ^{220}Rn was used. Soil monitors were generally placed in the front and back yards, about 1 to 5 m from the foundation and about 0.75 m deep.[2]

3.4.2 Gamma Radiation

Total gamma radiation rates were mapped at each house using a pressurized ionization chamber (Model RSS-111, Reuter-Stokes, Inc., Cleveland, OH 44128) and a portable scintillation counter (Model ??, ??[3]). The pressurized ionization chamber (PIC) was set up at a central location in the basement to record ionizing radiation for at least 1 h. The scintillation counter was then calibrated to the PIC using the average scintillation readings from all four sides of the PIC. Scintillation readings were recorded in the center of most rooms on each level of the house and on the front back and sides of the property. The radiation rate (in μR/h) at each site was calculated from the scintillation rate measured at each site, and the ratio of scintillation reading to PIC reading was determined for that house.

3.4.3 Radioisotopic Analyses of Soil and Water

Samples of soil (and rock) were analyzed for ^{40}K, ^{232}Th, and ^{226}Ra, using standard techniques (Little et. al. 1986). Samples were returned to ORNL where they were dried, ground, and stored in counting bottles for at least 30 days to allow radioactive equilibrium to be established. The gamma emissions from the samples were then detected in germanium/lithium well counters, and the amounts of isotopes (in pCi/g) determined.

Well water samples from the five test homes that obtain their water from wells were analyzed for ^{222}Rn content using the method of R. M. Key (1983).

3.4.4 Working-Level Measurements

Nearly continuous measurements of potential alpha energy from short-lived airborne radon progeny were made with a field portable detector and counting system (Detector: Model WLM-1A; Counting system (reader): Model WLR-1A, Eberline Instrument Corporation, P.O. Box 2108, Santa Fe, NM 87504-2108). Typically, the detector was programmed to collect 168 hourly samples of total airborne alpha activity. Pump flows were checked before each use. Field calibration techniques are described in Section 6.3.

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[1] Results will not be presented in this report.
[2] This has not been verified with the Princeton authors.
[3] The manufacturer has not been contacted yet.

3.4.5 Respirable Particulate Measurements

Levels of airborne respirable particles were occasionally measured in the study houses. A particulate sampling unit developed by the Harvard School of Public Health with an approximate 2½-μm cut was used (Spengler et al. 1985). The pump, which developed a flow rate of 4 L/min, was housed within a box (about 1 ft on each side), which helped to muffle sounds and protect the pump from occupant perturbations. A sampling head was connected to the pump and placed on or near the pump box. Sample filters were weighed before and after approximate 1-week sampling periods. Pump flows were monitored with a rotameter before and after sampling.

3.5 HOUSE DYNAMICS MEASUREMENTS

3.5.1 Intrahouse Airflow Measurements

The CCTG system is used to measure infiltration rates into multiple zones inside buildings. The instrument was fabricated at the Center for Energy and Environmental Studies at Princeton University. The method consists of injecting a required amount of the tracer gas (SF_6) 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 limited only by the length of time needed to read a sample and the capabilities of the sample and injection systems. Although 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-s 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 s to complete (note: the most recent version of the CCTG system operates with the reduced measurement and cycle times of 10 and 30 s). 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) through (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 (1 min) 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-s cycle. This method more closely approximates constant injection. At the end of each hour of operation the average concentration, root-mean-square 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.

3.5.2 Time-Weighted-Average Air Exchange Rate Measurements

The perfluorocarbon tracer (PFT) gas system measures average airflow rates in multizone buildings (Dietz et al. 1984). This technique measures both infiltration and interzone airflow 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 righthand 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:

$$\overline{F} \approx (S/\Delta t) \cdot \int C^{-1}\, dt.$$

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.

$$\int (1/C)dt \approx t/\overline{C}$$

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 consisted of liquid TG contained in a bullet-sized, metal canister that allowed diffusion through the rubber cap in the canister end. The diffusion rate is independent of time but exhibits a strong temperature change of 4 to 5% per °C. 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 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 multizone 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 airflow rates for each zone are computed. For example, the following equations are for airflows in a two-zone building:

$$F_{10} = (S_1C_{22} - S_2C_{12})/D$$
$$F_{12} = S_2C_{12}/D$$
$$F_{20} = (S_2C_{11} - S_1C_{21})/D$$
$$F_{21} = S_1C_{21}/D$$
$$F_{01} = S_1(C_{22} - C_{21})/D$$
$$F_{02} = S_2(C_{11} - C_{12})/D,$$

where:

F_{ij} = airflow 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,
$D = C_{11}C_{22} - C_{12}C_{21}$.

Three perfluorocarbon tracer gases were used: perfluoromethylcyclopentane (PMCP), perfluoromethylcyclohexane (PMCH), and perfluorodimethylcyclohexane (PDCH). Equipment was installed so that each of the seven test houses had an emitter for approximately every 50 m^3 of volume. PMCH was placed in the basement, PDCH on the first floor, and PMCP on the second floor (if there was one). House #6 was the exception to this arrangement. In this house, the basement, crawl space, and above-ground living space were considered to be three separate zones. There was a minimum of two samplers in each zone, and, in addition, each house had one replicate and blank. The sampling was usually performed over 2-week periods.

3.5.3 Blower Door Measurements

Blower door tests (using the ASTM 779 standard) were made of the whole house with all interior doors open, the whole house with the basement or crawl space doors closed (if a door existed between the basement or crawl space and the living level), and of the basement only (where there was an accessible door to the basement). These tests determined the tightness of each zone under the conditions of the day that the test was made. The instruments used are described in Section 4.

3.6 MITIGATION SYSTEM DESIGN AND IMPLEMENTATION

3.6.1 Mitigation Diagnostic Measurements (Except Radon)

This section describes the techniques, instrumentation, and special tools used by Princeton University staff in pre- and postmitigation diagnostic experimentation. The product name, specifications, cost, and a short description of the use of each of the instruments are included.

3.6.1.1 Diagnostic instrumentation

A Dwyer Microtector Electronic Point Gage ($365) was used to calibrate pressure transducers and to measure small pressure differentials in a range of 0 to 2.0 in. water and was accurate to ±0.00025 in. water column. The instrument is accurate but can be difficult to use in the field because of normal pressure fluctuations.

A Neotronics EDM Electronic Digital Micromanometer Model EDM-1 ($1350) was used to measure pressure differences, static pressures, and velocities (with pitot-static tube) and to balance mitigation systems. Its range is 1 to 1999 Pa or 1 to 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.

The Solomat Model MPM 2000/1000/500 with Modumeter 2013 ($1500) 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 was 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.

The Princeton Blower Door ($3000) was used to pressurize and depressurize buildings from 0 to 75 Pa with flows of up to 3000 cfm to determine building leakiness. It was also used to maintain a constant depressurization of the basement (to simulate winter conditions) while other diagnostic measurements are being performed.

3.6.1.2 Soil permeameter

Figure 3.3 displays a simple schematic of the soil permeameter. The following is a list of the components of the soil permeameter:

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.

The following outlines the procedure used in this study for measuring soil permeability. 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. The procedure was as follows:

1. Drill a 47-in. hole using a rotary hammer drill and a 5-ft, modified, ½-in.-diam concrete drill. Check soil characteristics on drill bit at removal.

2. Insert a 47-in.-long, ¼-in.-diam galvanized pipe 41 in. into hole using a 53-in.-long hammer shaft inside pipe. This leaves a 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 ¼-in.-diam 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 to 500-Pa gauge (see schematic).

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

Soil permeability has been calculated for available data using the following expression (Scott et al., 1986):

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

where the constant contains conversion coefficients and the viscosity of air. The results show a dependence of K on applied pressure, which has also been seen in the data taken by LBL scientists. This prompted a re-examination of the mathematical form for K (communication with LBL personnel). The calibration curve of the flowmeter used by the PU/ORNL team was determined a second time, and no significant difference was seen. Soil permeability tests were repeated at all test locations near the seven ORNL/PU houses with good reproducibility (see Table 6.8). The permeability constants reported in Table 6.8 are in the same range as those which have been evaluated by LBL personnel in their Piedmont study homes, i.e., 1.0×10^{-6} to 1.0×10^{-9} (private communication, Brad Turk, LBL).

3.6.1.3 Subslab flow rate measurement

The subslab airflow communication test was the most useful test for determining whether subslab depressurization would work for mitigation. The procedure that was used follows.

One of the test holes through the basement slab was chosen as a suction point. The criteria for choosing which test hole to use were to: (1) choose a test hole located at the point where the subslab depressurization mitigation pipe could be inserted and conveniently configured to exit the building structure, or, if this was not easily decided or there were more than one choice, (2) choose a test hole centrally located in the slab. The size of the hole was increased to 1½-in. diameter. A vacuum cleaner was attached, usually a shop vacuum cleaner, to the hole through a pipe fixture, which was the proper size to fit the vacuum hose on one end and insert into the slab hole on the other. With the vacuum cleaner on, the subslab was depressurized by the vacuum suction. The pressure differentials across and the air velocity through each test hole in the slab was measured with the vacuum cleaner on, using the same procedure described in Section 4.2.5.

3.6.1.4 Special tools

The Skil Model 732 ROTO-set hammer drills ($500) were used to drill test holes in soil, concrete or block walls and concrete slabs or floors. This tool accommodates drill sizes up to 1½-in. diameter and has very fast drilling capabilities.

The Dayton Model 4Z664A industrial vacuum cleaner ($105) was used while drilling holes in basements and crawl spaces. It was also used as a diagnostic tool in combination with pressure and velocity measuring instrumentation to check gas flow beneath slabs and/or within walls.

3.6.2 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. Trademark and price data are provided for information purposes only and should not be construed in any way as constituting an endorsement by the authors or any of the sponsors of this project. Please refer to the disclaimer on the inside front cover of this document.

3.6.2.1 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 nontoxic. 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) is a high-stretch, self-healing caulk. During curing, overexposure to solvent fumes may cause nausea, headache, and fatigue, so adequate ventilation must be supplied. The manufacturer does not recommend it for use in living areas of homes. It has an installed lifetime of 20 years.

3. Geocel SPEC 3000 single-component urethane sealant ($3.00 per 11-oz tube) 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 during application. 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) 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. Hazards are similar to SPEC 3000 and the same cautions should apply.

5. Tremco THC-900 two-part flowable urethane sealant ($49.10 per 1½ gallon) is used in some applications instead of 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% less than quart cartridges, but careful calculations of required material must be done because, once mixed, the material

has only a 2-h pot life. A coloring agent may be mixed with the material, which allows matching surface coloration. Product hazards are probably similar to SPEC 3000.

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

3.6.2.2 Other materials

1. Backer rod is a closed cell foam rod available in diameters from ¼ in. to 2½ in. It is used to fill large cracks or to close off perimeter drains before applying flowable urethanes or other sealing materials.

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

3. Fans used in this study were Kanalflakt 6-in.-diam centrifugal duct fans ($110). 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 airflows in 4-in.-diam pipe than the metal fans.

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(Scott et al., 1986) Soil permeability

3.1. Selection of study houses for mitigation: summary of house parameters and preliminary screening data.

House No.	Sub-Structure	Modifiers	HVAC	Radon[a] (pCi/L)	ACH $(h^{-1})^b$ 50 Pa.	Specific Leakage Area cm^2/m^2	Soil Perm.
1	Basement W/Slab, Att.Gar. W/Slab	Float.Slab, Dry Well	Cent. F.A., Gas	B:73 U:16	18.9	10.2	Mod.
2[c]	Basement, Att.Gar. W/Slab	Sump	Cent. F.A., Gas, W/AC	B:24 U:16 A:15	2.7	1.5	Mod.
3	Basement, Att.Gar. W/Slab	Float.Slab, Dry Well	Cent. F.A., Oil	B:156 U:49 A:60	10.1	4.8	Mod.
4	Basement W/Slab, Att.Gar. W/Slab	2 Sumps	Cent. F.A., Oil, W/AC, Auto Setbak	B:103 B:128 U:31	10.0	4.6	Very Low
5	Basement, Att.Gar. W/Slab		Cent. F.A., ElecHtPump, Oil Back, W/AC	B:60 U:25 U:36	3.6	3.6	High
6	Basement W/Crawl Att.Gar. W/Slab	2 Ht Exc. Sump	Cent. F.A., Oil, W/AC, Auto Setbak	W/HtExc B:25,U:14 W/O HtExc B:30-35	14.6	7.8	High
7	Basement W/Crawl Att.Gar. W/Slab	Float.Slab, Sump with Part. Seal	Cent. F.A., Gas, W/AC,	B:36	10.6	5.2	Very Low

[a] B = basement or crawlspace, U = 1st floor above grade, A = 2nd floor above grade.
[b] preliminary LBL data
[c] preliminary LBL data

Table 3.2. Monitoring packages

Parameter	Monitor	Location(s)	No. Sites
		Typical Indoor Monitoring Packages	
Modem	Hayes 1200	Basement	1
Data logger	CSI 21x	Basement	1
Radon 2-3	Wrenn Chbr.	Upstairs, Basement	(Crawl space)
Total progeny	Eberline WLM-1	Upstairs (intermittent)	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
		Weather Monitoring Package	
Data Logger	CSI 21x	Outdoor Station	1
Rainfall	Tipping Bucket	Outdoor Station	1
Bar. Pressure	Sierra/Misko	Outdoor Station	1
Wind Direction	Campbell Sci.	Outdoor Station	1
Wind Speed	Campbell Sci.	Outdoor Station	1
Temperature	RTD Sensor	Outdoor Station	1
	RTD Sensor	Soil	1
Rel. Humidity	Electronic	Outdoor Station	1
Radon Flux	Enclosed Wrenn Chamber	Outdoor Station	1
		Side of House	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.

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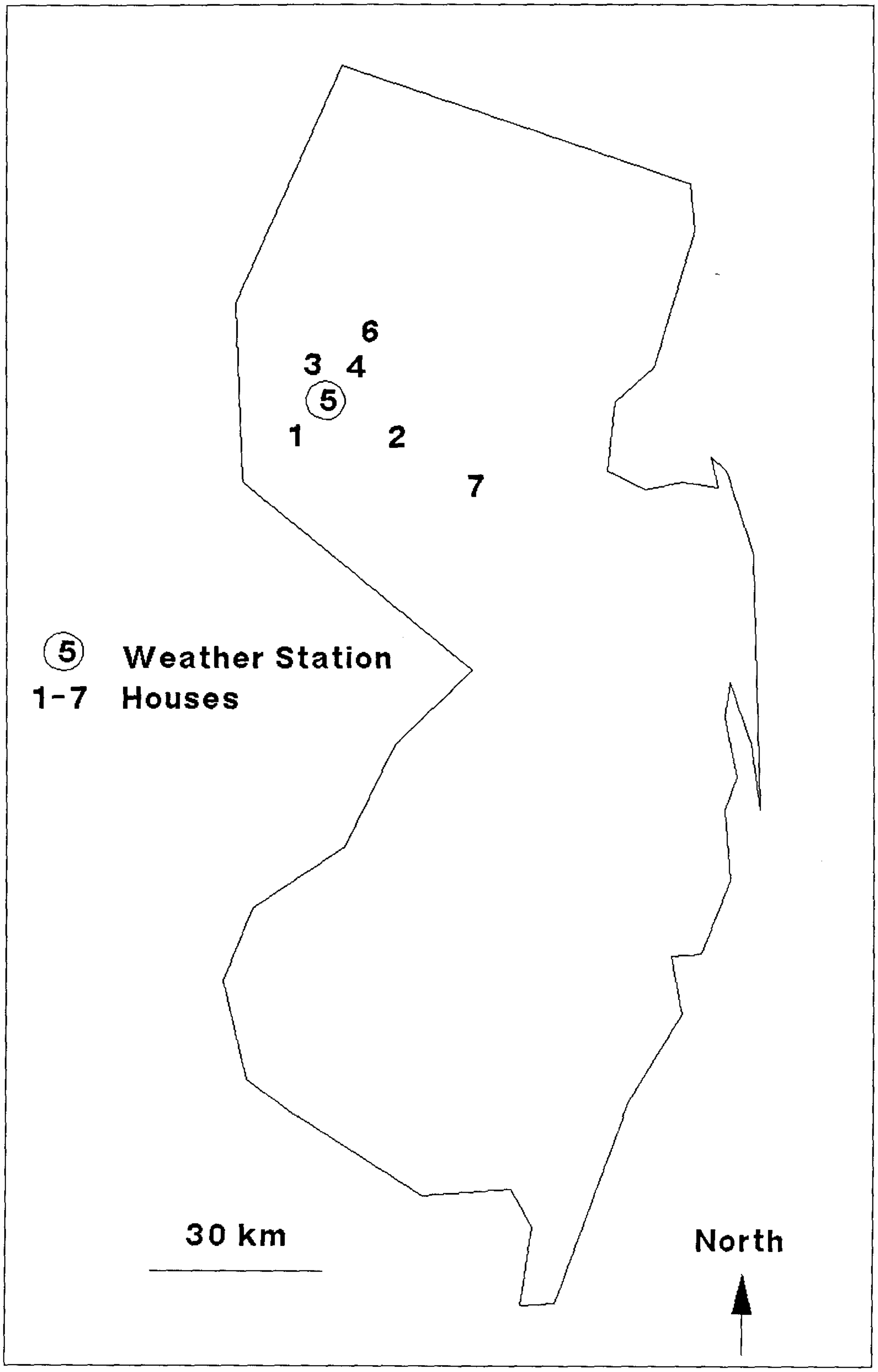

Fig. 3.1. Map of New Jersey and study home locations.

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Fig. 3.2. Picture of Wrenn chamber.

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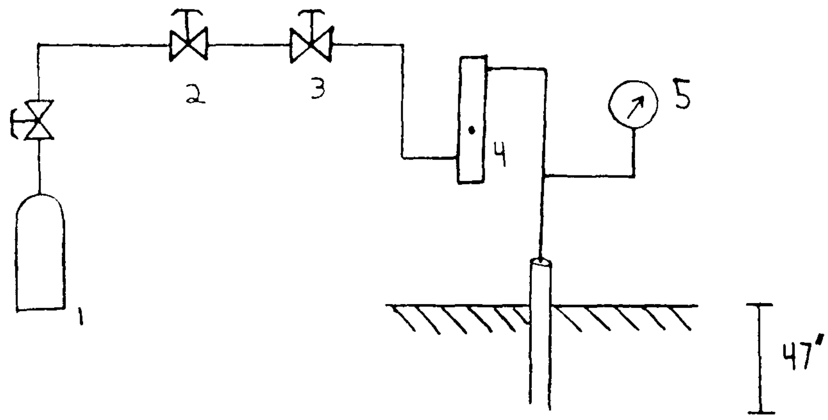

1. #3 Cylinder dry air.

2. Matheson regulator model 8-590.

3. Flow control valve--Circle Seal model MV 92T1-1PP

4. Flowmeters

5. Magnehelic pressure gauges.

Fig. 3.3. Soil parameter schematic.

4. DIAGNOSTIC PROTOCOLS AND MEASUREMENTS

4.1 INTRODUCTION

One goal of the New Jersey Piedmont Radon Project was to develop and evaluate diagnostic measurement procedures and mitigation techniques. This work was performed in 14 research houses split between three research groups; a group from LBL studied 7 houses and groups from ORNL and the Center for Energy and Environmental Studies (CEES) at Princeton University (PU) studied a companion set of 7 houses. A variety of parameters were logged continuously, including radon concentrations, temperatures, pressure differences, heating and air-conditioning use, and outdoor weather parameters. According to the study design, the LBL team maintained a similar instrument package as the ORNL/PU team for the continuous measurements, with the exception that the LBL group measured the various parameters at a larger number of locations. In addition, the LBL team concentrated on soil science, while the PU/ORNL team concentrated on air infiltration and interzone airflow in the buildings.

In addition to the continuously logged parameters, an initial set of premitigation diagnostic measurements were made in each research house. Some of these initial measurements were repeated periodically throughout the study year after mitigation installation and are referred to as postmitigation diagnostic measurements. The periodic diagnostic measurements at the LBL research houses were also designed to be more extensive and detailed than those at the ORNL/PU hoouses. The combination of the continuous and periodic data sets was designed to give information on the detailed physical mechanisms of radon entry and the usefulness and relevance of diagnostic measurement techniques. Many of the periodic diagnostic measurements were designed to answer basic research questions related to the physics of radon gas entry into buildings. In addition, it was hoped that the plethora of measurements would answer more practical questions, such as which parameters are key for proper diagnosis of a radon problem and which of the variety of diagnostic measurements in the initial LBL protocol can be neglected in a protocol used by private radon mitigators or diagnosticians. The intent of the study design was to allow the PU/ORNL team to learn from the detailed diagnostic measurements made by the LBL team and to evaluate the usefulness of each of the measurements and to suggest improvements as needed. However, the reality of the scheduling of the two projects allowed a preparation time only on the order of days between the LBL and the PU diagnostic visits, and thus no time was available for initial evaluation of the LBL protocol. Improvements to the diagnostic techniques have been identified during the course of the study as the results from each measurement have been evaluated.

Section 4.2 discusses the usefulness of and the procedure for performing the initial premitigation diagnostic protocol, patterned after the LBL protocol. That section ends with a revised premitigation diagnostic protocol, which is shortened considerably from the initial protocol. The diagnostic measurements performed during mitigation installation and postmitigation are discussed in Sections 4.3 and 4.4, respectively. Section 4.5 provides a discussion of airflow through hollow block walls. Results of the mitigation techniques used in the seven PU/ORNL houses are discussed in the Section 5.

It is important to keep in mind that the research houses were chosen to be of similar building type (descriptions are provided in Table 3.1) and that the development and testing of the diagnostic tools in this study were influenced by the building type. Also, subslab or wall depressurization was the most successful mitigation choice in this study. Thus, the refinement of the initial premitigation diagnostic protocol and the development of mitigation installation and postmitigation diagnostic techniques have been performed considering subslab or wall depressurization as the most likely mitigation approach.

4.2 PREMITIGATION DIAGNOSTICS

The initial premitigation diagnostic tests on six of the seven PU/ORNL houses (excluding the control, House #2) were performed in November and early December of 1986. Three members of the PU team spent a day in November 1986 with the LBL team observing and participating in LBL premitigation diagnostics in one of the LBL test houses. Table 4.1 is the LBL diagnostic protocol that was used in the initial visits by LBL personnel for premitigation diagnostic testing. Table 4.2 is the LBL house questionnaire, completed at the beginning of each premitigation diagnostic visit. The preliminary PU diagnostic protocol of November 1986, shown in Table 4.3, is patterned after the LBL protocol, with some measurements either deleted or modified and others added. These changes are based on observation and evaluation of the LBL protocol made during the LBL house diagnostic visit of November 1986. Additional streamlining of the protocol was made before the diagnostic visit to the control house (House #2) in April 1987.

The initial protocol, used in all houses except House #2, differs from the LBL protocol in the following ways:

1. The initial house screening tests indicated high radon concentrations in the soil gas entering the substructure of the houses selected for research by the PU/ORNL team. Thus, the working assumption in this project was that pressure-driven flow of radon-laden soil gas into the substructures of the test houses caused the elevated indoor radon levels. Contributions from groundwater were also evaluated. The initial protocol omitted surface radon flux measurements included in the LBL protocol for the purpose of determining if radon emanates from building materials. Laboratory and field experiments designed to characterize and quantify flow through hollow block walls were later performed and are discussed in Section 4.5.

2. Fewer diagnostic test holes were drilled through the substructure floor and walls in our test houses than in the LBL test houses. These test holes served to measure: (1) subslab and hollow block wall cavity radon concentrations and (2) the pressure field extension from a central suction hole for subslab depressurization mitigation design. The motivation for fewer holes was to determine the minimum number of holes needed to successfully design a mitigation system, as the use

of fewer holes reduces the time needed for the diagnostic measurements.

3. The LBL protocol specified collecting grab samples of radon from the test holes both under ambient conditions and during a -10-Pa depressurization of the substructure, induced with a blower door. The -10-Pa depressurization simulates an enhanced stack effect. (Normal winter conditions yield between 2 and 5 Pa depressurization of the substructure due to the stack effect.) These measurements are accompanied by measures of pressure differentials across each test hole. Measurement of the air velocity through each test hole was added to the protocol as a first step towards quantifying the amount of subslab airflow induced by a given subslab-basement pressure difference.

4. An infrared scan of each test house was done to evaluate the usefulness of this technique as a diagnostic tool for locating air leakage points in the building shell.

A description of the rationale for each measurement and an evaluation of its usefulness in choosing a mitigation design is discussed next. The discussion follows the order of the measurements in the protocol shown in Table 4.3. Details on performing each measurement have been described by Turk et al. (1987).

4.2.1 Soil Radon Content and Soil Permeability

Soil gas permeability and soil gas radon content determined from grab samples were recorded at one location outside between 1 and 2 m from each side of each house. The procedure and instrumentation for making these measurements are described in the Section 3 of this report. See Section 3.4.1 for radon grab sampling and Section 3.6.1.2 for soil permeability methodologies.

These measurements were intended to give information on the variability of the radon content in soil gas and the soil permeability around a building structure. In addition, we looked for the presence of both high soil permeability and high soil gas radon content at any single site outside the building structure to see if there was any correlation with the subslab or hollow wall cavity radon concentrations on that side of the building substructure. Mitigation systems such as subslab or wall depressurization could then be designed to exert a greater pressure field on those sites. However, weather variables such as rainfall and snowfall affect the permeability and, in addition, diurnal temperature and pressure variables affect the soil gas radon content. How much the soil gas radon content and soil permeability vary as a function of the weather variables has not been well characterized in previous studies. Thus, it is still too early to say whether or not such measurements will be helpful in determining successful mitigation design, and we do not recommend they be used by private mitigators at this time. Results of the seasonal soil permeability measurements and soil gas radon concentrations at each location at each research house are given in Section 6.

The airflow communication diagnostic which tests subslab and wall cavity airflow connectivity, described in Section 4.2.10, was found to be a more useful predictor of proper design of a subslab or wall depressurization system. That test, similar to the outdoor soil permeability tests, is a measure of the amount of airflow induced by a given applied suction (or pressure). However, the sampled air is in the subslab and the hollow block wall cavities around the substructure. Knowledge of the airflow characteristics of that air is relevant to successful design of a subslab depressurization mitigation system, because it is the same air that needs to be ventilated.

4.2.2 Visual Inspection of the Building

Visual inspection of the building aids in understanding the layout and construction of a house and in spotting possible radon entry points. The visual inspection of these study houses was completed using the LBL questionnaire given in Table 4.2. Visual inspection is also useful for locating leaks in the air handler duct system and between the substructure and living area. These observations affect the type and location of diagnostic measurements performed and ultimately the design of a mitigation system in the following ways:

1. Understanding the layout and construction of the house aids the diagnostician in developing a tentative design for a mitigation system. For example, in designing a subslab depressurization mitigation system, convenient spots for suction holes and exhaust locations for mitigation pipe and fan locations can be identified during the house inspection.

2. Suspected radon entry points such as the sump(s), a perimeter drain or crack, and cracks in the slab or walls identified during the house inspection can be tested for radon source strength.

3. Leakage points in the air handler return duct system identified during the house inspection can be sealed to help minimize the amount of basement depressurization during air handler use. Examples were found where previous contractors had run wiring and plumbing from the basement to the living area through cutouts in the air handler return duct. These cutouts are often as large as 2 in. x 3 in. If a subslab depressurization system were the chosen mitigation system, then sealing these leakage points need be done only if it is found that air handler use causes a depressurization of the basement which cannot be overcome by the subslab depressurization system.

4. Leakage points between the basement and living area identified during the house inspection, such as around plumbing and wiring penetrations, need to be sealed if basement pressurization is the method chosen for mitigation. A basement pressurization system will not work in a building with large leakage paths between the basement and living area. An expanding foam sealant (described in Section 3.6.2.1) was used in this study for filling openings between the basement and living area in House #5, where the initial system chosen for mitigation was basement pressurization.

We recommend use of a building questionnaire during a premitigation diagnostic visit to any building that needs radon mitigation.

4.2.3 Samples of Room Air

Samples of air from various rooms under natural house conditions, when analyzed for radon content, give some indication of the radon distribution throughout the house. In general, however, one should rely on either integrated or real-time radon measurements over at least 3 days to determine the extent of a radon problem in any particular building. This study and others have shown that the indoor radon concentration can change considerably within hours, so that a sample of radon at any particular time will give only an indication of whether a radon problem exists. The report by Harrje et al. (1987) provides a discussion of the error associated with a 2-day vs 4-day measurement of the average radon concentration.

The air samples of greatest utility in this protocol were the comparisons of bathroom air radon concentration before and after operating a hot shower for 10 min. Because it was not known at the beginning of this study whether any of the research houses had significant contributions to indoor radon content from groundwater, the hot-shower diagnostic tool gave a quick indication of whether the groundwater was a possible source of indoor radon. The only house that showed a significant difference in radon concentration in the bathroom before and after the shower operation was House #4, which turned out to be the house with the highest well water radon content. (Section 6 gives the results of tests performed at Princeton to determine the radon content in the water at the research houses that had wells.)

4.2.4 Wall and Floor Test Holes

Test holes (½-in.-diam) drilled through the slab and through the inside layer of the block walls are used to map the variation in the radon concentration under the slab and in the hollow cavities of block walls in the substructure, discussed in Section 4.2.5. Holes should be plugged with a removable plug immediately after drilling; we used a ball of rope caulk molded into the hole for a plug, with a piece of colored tape tacked to the rope caulk (to make the hole more visible). Care must be taken to achieve a good seal. The holes should be drilled at least 1 h before grab samples are collected to allow the soil gas to equilibrate, although drilling the holes 1 day in advance of the tests is recommended to ensure equilibration. We drilled fewer test holes than were used in the LBL test houses. Our current recommendation on how many test holes should be drilled during initial premitigation diagnostics is discussed in Section 4.2.11.

4.2.5 Examination of Test Holes and Possible Radon Entry Points

After the test holes come to equilibrium, the radon concentrations in samples of air in the test holes should be measured and recorded, along with the pressure difference across the hole and the airflow direction through each test hole. The same measurements should be made in any large cracks or holes in the slab or walls and in sumps or other possible radon entry points identified during the building inspection. In the following discussion, these possible radon entry points will also be called test holes. These measurements give an initial indication of the variability of the radon gas content in the subslab and hollow block wall cavities and the airflow direction through and pressure difference across various points in the basement shell.

The measurement of the pressure difference across the test holes is compared with the same measurements made under a depressurization (-10 Pa) of the substructure and with measurements made during the appliance and air handler cycling discussed below. The comparison indicates how much the pressure difference across the substructure shell changes under these various conditions, which in turn determines the amount of pressure difference that must be overcome for a subslab depressurization mitigation system to work properly.

The simplest way to determine airflow direction is with a smoke bottle; inject smoke into the hole and observe whether it flows into or out of the substructure. A heated-wire anemometer can make a more detailed measurement by measuring the air speed, with smoke used to determine the direction.

If an anemometer is used, an additional attachment to the hole must be fabricated in order to provide reproducible readings. The attachment we used is a metal pipe inserted (and sealed) through the center of a metal disc, which can be placed over the test hole. A seal must be made between the disc and the slab floor. The metal pipe should have a hole drilled through its side the size of the anemometer probe, allowing the probe to sit inside the pipe with the heated wire in the center of the air stream. The anemometer probe must be sealed at the hole where it enters the metal tube to prevent leakage into the pipe. The volume of air flowing over time is the product of the average air speed and the cross-sectional area of the inside of the pipe.

4.2.6 Mechanical Depressurization of the Substructure

A blower door used to mechanically depressurize the substructure to -10 Pa simulates an extreme winter-condition stack effect. To compare with the ambient measurements described above, samples of air from the test holes are analyzed for radon and pressure differences across and air velocities through the test holes are measured. These measurements indicate changes in the radon concentration at each of the test holes during depressurization. During the diagnostic measurements on the research houses, the radon content in the hole usually decreased with time during constant depressurization due to depletion and dilution. Substructure depressurization depletes the reservoir of radon-rich soil gas under the slab because of the increased flow into the substructure. At the same time, the increased pressure field in the soil would be expected to draw on more area, and thus on more soil gas and outdoor air. The increased flow from outdoor air will dilute the radon in the soil gas. Increased flow from soil gas could either increase or decrease the radon concentration in subslab air, depending on the availability of radon in the soil gas. Because the radon concentration in subslab air can change rapidly during changes in the basement-subslab pressure difference, continuous monitoring of the radon would be much more useful. Continuous measurements give an indication of the radon availability to the subslab air, and the technique is useful as a research tool for study of radon availability and transport. Better characterization of the subslab gas under various conditions is needed before a useful diagnostic measurement of this quantity can be formulated. We do not recommend this technique for use by mitigators at this time.

4.2.7 Blower Door Tests

A blower door test (using the ASTM 779 standard) is performed on the whole house with all interior doors open, on the whole house with the basement or crawl space doors closed (if a door exists between the basement or crawl space and the living area), and on the basement only (where a door to the basement is accessible). These tests determine the tightness of each zone during the weather conditions on the day that the test is made. The blower door test generates data on the flow into or out of each zone tested as a function of applied pressure across the zone shell. This curve can be used to determine how much airflow into a basement is needed to maintain an overpressurization sufficient for basement pressurization. If the airflow needed to maintain 5 Pa is less than 250 cfm, basement pressurization is a viable mitigation choice.

4.2.8 Infrared Scan of Each Room

Infrared scanning of interior surfaces is a diagnostic technique used to uncover air leakage sites and airflow patterns within the building. It has been used extensively in improving building energy conservation by locating building leakage sites which can be sealed. Outside air is normally colder or hotter than interior air. When this outside air enters the building, it causes large temperature gradients to develop on interior surfaces and can be detected with an infrared scanning device, which is sensitive to small changes in surface temperature. Air flowing into the house from the cooler or warmer basement or outside environment results in alteration of interior surface temperatures. If the blower door is used to depressurize the indoors and thus increase the air infiltration, these air paths are made more evident. The technique can help evaluate how well separated the living space is from the basement or crawl space. 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 infrared scanners are currently expensive to rent or purchase.

4.2.9 Appliance Cycling

Pressure differentials are measured across the test holes as major appliances and the air-handling system with and without furnace combustion are cycled on and off. These measurements help determine appliance contributions to basement depressurization, and thus enhanced soil gas entry attributable to the operation of each device. They are useful for determining whether makeup air supplied to one of the combustion appliances will alleviate the contribution that operation of the appliance makes to the basement depressurization. These measurements also help determine the minimum pressure field needed by a subslab or wall depressurization mitigation system.

4.2.10 Basement-to-Subslab and Basement-to-Wall Communication Test

The final diagnostic test in the preliminary diagnostic protocol is the basement-to-subslab and basement-to-wall airflow communication test. This is the most useful test for determining whether subslab or wall depressurization will be successful in mitigating a radon problem. The procedure for the test follows.

One of the test holes through the basement slab is chosen as a suction point. The method for choosing which test hole to use is locate a point where the subslab depressurization mitigation pipe can be inserted and conveniently configured to exit the building structure. If this is not easily decided or there is more than one choice, use a central location in the slab, such as one of the centrally located test holes. Drill a 1½-in.-diam hole through the slab. Attach a vacuum cleaner, usually an industrial vacuum cleaner, to the hole through a pipe fixture that is the proper size to fit the vacuum hose on one end and insert into the slab hole on the other. Vent the vacuum cleaner to the outside. With the vacuum cleaner on, the subslab will be depressurized from the vacuum suction. Measure the pressure differentials across and the air velocity through each test hole in the slab and in the walls with the vacuum cleaner on, using the same procedure described in Section 4.2.5. If an anemometer is not available, record the direction of airflow using smoke.

A pressure difference across the hole of 1 Pa or greater, with air flowing into the subslab, indicates the vacuum cleaner is pulling air through the test hole. If the first suction hole does not communicate with the other test holes, another suction hole needs to be drilled in the area of the noncommunicating test holes and the communication test repeated.

If the basement has a perimeter drain, there is no point in checking the communication between the subslab and the hollow block walls. After such a drain was capped and sealed, in most cases subslab depressurization resulted in depressurization of the hollow wall cavities. When no drain exists, subslab-to-wall communications should be checked using the procedure described above. If no communication is found, two alternative solutions can be tried. The first is to seal any large cracks or holes in the slab, in the walls, or along the floor-wall joint. This will minimize the amount of air flowing from the basement into the subslab suction through these paths and may extend the distance under the slab or in the walls from which air was pulled by the subslab depressurization system. After sealing, determine whether the subslab-to-wall communication has improved using the same procedure described above. The second solution is to test for wall-to-wall communication, using the vacuum cleaner on one of the wall test holes, and determine how far a wall depressurization field extends by measuring the pressure differences across the other wall test holes with the vacuum cleaner turned on and off. If turning the vacuum cleaner on or off causes a change in pressure difference, wall-to-wall communication is likely to exist between the two points being tested. If the radon concentration in the wall cavity is high, and subslab suction does not reach that point, wall suction can be used along with subslab suction, providing both subslab and wall depressurization.

4.2.11 Revised Princeton Premitigation Diagnostic Protocol

During the diagnostic visit to the control houses during April 1987, a revised protocol for premitigation diagnostics was used. Revisions were based on what we did and did not find useful in the original protocol for designing mitigation systems. The initial diagnostic tests described above made it clear that a protocol that quantifies the communication diagnostic test for subslab depressurization mitigation systems is needed. Research is currently being done (in 1988) to further quantify these diagnostic tests for optimum design of subslab depressurization systems.

The Princeton premitigation diagnostics protocol is shown in Table 4.4. This protocol has been developed for basements that are well suited for subslab and/or wall depressurization and specifically for basements with slabs and hollow block walls. Several diagnostic tests have been eliminated from the preliminary protocol in Table 4.3, and the order of tests has been changed. The protocol still begins with the useful building inspection questionnaire. The diagnostic tests remaining in the protocol are explained in the protocol itself, Table 4.4, or in the description of the mitigation diagnostic evaluation of House #2 which follows.

Figures 4.1 and 4.2 show how the pressures across selected test holes in the slab varied during the premitigation diagnostics and after the subslab depressurization system was installed. Figure 4.1 is the basement floor plan for House #2, with floor (or slab) test holes labeled with an F prefix and wall test holes labeled with a W prefix. (The basement construction is described in more detail in Sectiob 5.1.7.)

Figure 4.2 shows the pressure difference across three floor test holes during premitigation diagnostics and after mitigation. The basement is the reference pressure. The ordinate is the difference between the subslab pressure minus the basement pressure; a negative pressure means the subslab is depressurized relative to the basement. Five different tests are presented, as shown in the key on the figure. During the premitigation diagnostics, airflow communications were tested by suction on both the sump and the floor hole F6, shown in Figure 4.1. Both of these are convenient locations for placement of the subslab suction, as determined during the building inspection. The first two bars above each floor hole in Figure 4.2 are the pressure differences in the three test holes with: (1) the variable-speed vacuum on F6, labeled F6=-290, and (2) the variable speed vacuum on the sump, labeled sump=-290. Both suctions were through a 1½-in.-diam hole, drilled through the slab at F6 and drilled into a temporary sump cover at the sump. A 1½-in.-diam pipe was connected to the hole, and the vacuum cleaner suction tube connected to the pipe, as discussed in Section 4.2.10. The number -290 refers to the pressure difference at the suction hole between the inside of the 1½-in.-diam pipe and the basement. All test holes other than the suction holes are

½-in.-diam. Suction at F6 gave a measurable pressure difference at each floor hole, but suction at the sump gave no measurable pressure difference at test hole F5. Thus the installed mitigation system used F6 as the suction hole, as shown in Figure 4.1.

The other three columns above each test hole in Figure 4.2 show the pressure differences measured under different conditions after the mitigation system was installed. The positive pressure difference measured with the mitigation system off and the air conditioner (AC) running means the basement is depressurized relative to the subslab soil gas. When the mitigation system is running and the air conditioner is on vs off, the effect of the basement depressurization caused by the air-conditioner air handler is evident. In both cases, however, the subslab remains depressurized relative to the basement. The pressure difference between the inside of the 4-in. mitigation pipe and the basement is shown in the key (as F6=-276). Note that the premitigation pressures at the suction point are taken between the basement and the inside of a 1½-in.-diam pipe, and, after mitigation is installed, the measurements are between the inside of a 4-in.-diam pipe and the basement. Also note from Figure 4.1 that F3 is the farthest hole from F6, so that the decrease in magnitude of the pressure differences between holes is consistent with the distance each hole is from the suction.

4.3 MITIGATION INSTALLATION DIAGNOSTICS

The permanently installed mitigation systems in the seven PU/ORNL houses were subslab, wall, perimeter drain, or drainage tile depressurization systems. The discussions on mitigation installation and postmitigation diagnostics which follow focus on these types of mitigation systems.

Diagnostics performed during mitigation installation focused on confirming that the installed system was working. To aid in the refinement of these systems, simple rubber-edged 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 and record the radon concentration in the basement and living area(s). (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 can be measured. If adjustment of the dampers does not solve the flow problem, record the pressure differences between the basement or crawl space and the inside of each independent pipe, and record the performance of the system for 1 week.

4. Use a tracer gas and detector [e.g., freon and a standard freon detector which are available in heating, ventilating, and air conditioning (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. This can be done by squirting the freon into the subslab at a point where the subslab air is being drawn out the mitigation system; use the freon detector to locate freon leaking out any joints or other possible leakage points. Also test the room air near windows or building joints to check for reentrainment.

4.4 POSTMITIGATION DIAGNOSTICS

Postmitigation diagnostics were performed throughout the winter and spring of 1987 in order to maximize 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.

All of the final mitigation systems in the seven PU/ORNL houses involved variations on wall or subslab depressurization systems with sealing, in varying degrees, of cracks, sumps and perimeter drains. In the case of House #5, tracer gas measurements during subslab depressurization indicated conditioned indoor air was being exhausted in the mitigation pipe with the subslab air. This will be discussed in more detail in Section 4.5.

To minimize the energy penalty to the houses due to conditioned indoor air exiting the mitigation system, the lowest fan speed that maintained acceptably low radon levels was found for Houses #1, #3, #5, and #7. Table 4.6 shows the amount of airflow for these different fan settings. Section 6 discusses the radon concentration in the basement as a function of the different fan settings for House #3.

Postmitigation 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 airflow and pressure fields around the basement or crawlspace shell, monitoring radon concentrations using grab samples, and performing more extensive communication checks. The degree of mitigation achieved at each stage is discussed in Section 5.

4.5 AIRFLOW THROUGH HOLLOW BLOCK WALLS[1]

Research on radon movement across the below-ground boundary of a building reveals complex effects which must be taken into account in optimizing radon mitigation. Both of the examples presented show the following two consequences of the high porosity of hollow-block basement walls. (1) Before mitigation, these walls are a major avenue of radon entry into the basement, accounting for roughly 20% of total radon entry in one house as estimated by combining several field and laboratory experiments. (2) After mitigation, these walls are pathways for the entrainment of basement air with subslab air removed by the subslab depressurization system; another experiment with tracer gas yields an estimate that 50% of the air in the exit pipe is from the basement, with evident energy penalties. By exploiting the wall-to-subslab coupling, the mitigation system is able to make the basement walls an insignificant radon source, even without direct wall penetrations.

4.5.1 Motivation

The task of identifying good strategies to save energy in buildings has multiple parallels with the newer task of identifying good strategies to reduce the radon concentrations in buildings: (1) cleverly chosen diagnostic equipment greatly improves the productivity of a short visit by a professional (i.e., a "house doctor"), (2) airflows are a central concern, (3) potentially adverse side effects to the buildings or the occupant must be taken into account, and (4) quantitative modeling rooted in conservation laws disciplines the analysis. Our research, designed to develop diagnostic procedures that will allow a professional visiting a house for a limited period of time to prescribe optimal radon mitigation strategies, is at an early stage, but it is clear that, when the method of mitigation is subslab depressurization, a substantial investment of time at the front end in carefully characterizing the subslab geometry and connectivity by pressure difference measurements pays off in better design of the mitigation system itself (optimizing the fan power, minimizing the number of subslab penetrations, enhancing the wall-to-subslab coupling, etc.). Given that a service industry is now emerging that provides complete house checkups, addressing building structural integrity, energy use, radon, and other indoor air quality issues, an overall optimization of the house doctor visit across these subtasks should be developed. Such an optimization requires research on the precise mechanisms of radon flow, documented quantitatively in a few buildings.

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[1]Much of the text in this subsection is taken from a paper written for the American Council for an Energy Efficient Economy, Summer Study on Energy Efficiency in Buildings, held at the Asilomar Conference Center, Pacific Grove, CA, in August 1988. The title of the paper is "Research on Radon Movement in Buildings in Pursuit of Optimal Mitigation," by L.M. Hubbard, D.L. Bohac, K.J. Gadsby, D.T. Harrje, A.M. Lovell, and R.H. Socolow, all of the Center for Energy and Environmental Studies, Princeton University.

The primary cause for the occurrence of radon gas in indoor air in U.S. houses is entry of radon-rich soil gas through the substructure of buildings. The soil gas enters through diffusion and pressure-driven flow, although it is now commonly accepted that pressure-driven flow is the dominant mechanism (Nazaroff et al. 1988). The stack effect, furnace operation, whole-house air distribution systems for heating and cooling, and outdoor wind cause fluctuations in pressure differences across the shell of the building's substructure, which is in contact with the soil, creating the driving force for radon entry. A complete understanding of these dynamics is essential to ensure that appropriate diagnostic measurements are made and effective mitigation is applied. An assessment of the effect on energy consumption of any particular mitigation choice would be included in the design of the mitigation system; such an assessment would include: (1) direct energy use of the mitigation system itself and (2) the amount of indoor conditioned air lost through the mitigation system.

Currently the most popular mitigation choices for radon reduction are procedures which attempt at least one of the following strategies:

1. to prevent the soil gas from entering the building substructure by pressurizing or, more commonly, depressurizing (by ventilation) the soil gas beyond the substructure shell, using subslab or wall ventilation,

2. to seal the building substructure shell against radon entry, and

3. to dilute the indoor radon concentration by increasing the air exchange rate, while minimizing heat loss by using a heat recovery ventilator (HRV).

HRVs and substructure sealing have been found to be useful only where a modest reduction in indoor radon levels is desired. HRVs have the additional obvious disadvantage of an energy penalty associated with the increased air exchange rate and the associated loss of conditioned indoor air. Some amount of sealing is often a necessary accompaniment to subslab depressurization (SSD) or wall depressurization (WD) mitigation systems to better isolate the conditioned indoor air from the soil gas which is being ventilated.

SSD and/or WD systems have met with considerable success in radon reduction in the northeastern United States, due to the ease of installation, acceptable initial cost, low maintenance requirements, and effectiveness in reducing radon levels by large factors. The data presented below show that SSD and WD systems also can incur an energy penalty associated with removal of conditioned indoor air through openings in the substructure, and that properly tuned and optimized mitigation systems can reduce this penalty.

The initial diagnostic measurements to evaluate the suitability of a building for SSD or WD are likely to be of four kinds:

1. House questionnaire: A brief worksheet completed during a house inspection, which evaluates building size, construction of the substructure, obvious candidates for soil gas entry points in the substructure, and convenient locations for the mitigation ducts, mitigation fan, penetrations through the substructure, and mitigation exhaust.

2. Radon source locations: Grab samples of soil gas in several locations, to identify possible dominant radon entry points or "hot spots".

3. Airflow Connectivity: Measurements of the degree of airflow communication within the subslab and hollow block wall air spaces.

4. Pressure differences: Measurements of pressure differentials across the basement shell under various house conditions.

The discussion in this subsection will address research on the development of the last two kinds of measurements.

Standardized diagnostic protocols for the selection of appropriate mitigation systems for existing single-family buildings are being developed (Matthews et al. 1987, Sextro et al. 1987, Turk et al. 1987, Harrje et al. 1987). The research described in this paper is directed at identifying, quantifying, and optimizing the diagnostic procedures that could be incorporated in such protocols. In particular, we are developing ways to characterize the suitability of a structure for SSD or WD mitigation systems. The ultimate goal is to develop a rapid diagnostic procedure for subslab or wall depressurization systems which a professional visiting a house can use to design the optimal mitigation system.

A general description of an SSD or WD mitigation system is presented. We then discuss the characteristics of airflow within the subslab volume and (when present) within the hollow block wall air spaces. We conclude with a description of results of detailed studies of one house with hollow block basement walls, suggesting some of the ways in which ventilating the soil gas close to the substructure shell changes these airflows and indoor radon levels.

4.5.2 Subslab Depressurization Mitigation Systems

In a typical subslab depressurization mitigation system, PVC pipe is connected to one or several penetrations through the slab floor of the substructure, forming a duct system which exits the building, preferably through the roof. Air is pulled through those penetrations using a fan installed in the duct system. Subslab depressurization can also be achieved by drilling and inserting a pipe through a block wall to the area beneath the adjoining slab and depressurizing that area using fan suction. Although 4-in.-diam pipe is commonly used because of its low cost and availability, other pipe diameters may be preferable depending on the flow of soil gas needed for sufficient ventilation of the soil. If a roof exit is not possible, a wall exit is chosen that minimizes the possibility of reentry of the exiting soil gas through windows or other leakage points. A hollow block wall depressurization system is similar, except the penetration goes into one of the hollow spaces in a block wall (Matthews et al. 1987).

A duct fan is placed in the pipe system near the building exit point. When the fan is in operation, soil gas flows through the mitigation system as indicated in Figure 4.3. This soil ventilation causes depressurization (minus signs in Figure 4.3) in the subslab and soil areas surrounding the basement shell. In the absence of a SSD or WD mitigation system, the basement in winter is usually depressurized relative to the subslab and surrounding soil gas due to the warm basement (stack effect), the furnace operation, and the effect of wind on the building shell (so that the plus and minus signs in Figure 4.3 would be reversed).

Figure 4.4 shows, among other things, a schematic of one particular mitigation system, installed in House #5. There are two slab suction points, one below the slab in the southwest corner and the other in the sump. A 6-in. duct fan rated at 340 mm^3/h (200 cfm) is installed near the wall exit point, although due to pressure losses in the mitigation ducting the actual flow in this system is only 110 m^3/h (65 cfm).

Figure 4.4 also shows pressure differences between the basement and the subslab across the sump and 7 ½-in.-diam test holes (two through the basement slab and five into the hollow portion of the block walls). Pressure differences relative to the basement are given both under ambient conditions and with the mitigation system operating. Also shown are radon levels in the various test holes (except F2) before mitigation, obtained by grab sampling. The values in the various wall locations vary between 20 and 450 pCi/L, with more values measured towards the low side.

At floor location F1 and wall location W1, continuous radon measurements were made. Figure 4.5 shows these readings for a 10-day period starting five days before the mitigation system was turned on. Before mitigation and (not shown) during times after mitigation when the mitigation system was turned off, the wall concentration consistently remained higher than the floor concentration in these two specific locations. Also, wall location W1 consistently had the highest radon concentration of all the wall test locations. The wall radon shows some of the diurnal variation displayed by the basement radon concentration and, to a lesser extent, so does the subslab radon concentration. The wall has better airflow communication than the subslab with the basement air due to the very porous nature of the hollow block walls. This points out the role of porous walls in soil gas entry.

4.5.3 Subslab Airflow Communication and Pressure Differentials

A successful SSD or WD mitigation system requires soil gas to flow through the porous soil or rock medium surrounding the basement substructure towards individual suction points in the mitigation system. We call this the "airflow communication," and we and others are developing premitigation diagnostic measurements to characterize this property.

When there are hollow block walls and the radon concentrations in the wall spaces are high, the basement walls may be a significant radon entry route. In that case communication between the subslab air and the air within the walls must be evaluated and a choice made between adding wall suction points or using the subslab suction alone. Figure 4.5, discussed in more detail below, illustrates that subslab suction alone can pull air from the hollow blocks.

In the test house we have estimated that roughly 20% of the air entering the basement from beyond the house boundary enters through the basement walls. This estimate required:

1. the field measurement of an 80-m^3/h outdoor air infiltration rate into the 400-m^3 basement, based on three-gas/three-zone perfluorocarbon tracer gas (PFT) diagnostics (Matthews et al. 1987; Bohac et al. 1987) averaging over four consecutive roughly 10-day average values in winter,

2. the laboratory measurement of airflows per unit area through block walls for a variety of pressure differences, and

3. field measurements of actual pressure differences across the inner portion of the block walls, on three separate winter days, averaging 1.0 Pa.

For a pressure difference of 1.0 Pa between the basement and inner block wall cavity, the airflow determined in the laboratory measurements was 0.10 m^3/h per m^2 of wall. The flow varied according to pressure difference raised to the eight-tenths power (Marynowski 1988). Therefore, for a basement wall area of 150 m^2, this is 15 m^3/h flow of air through the basement walls, roughly 20% of the total.

An estimate of the radon source strength through the walls can also be made. If we assume an average (over time and over basement wall void volume) hollow block void radon concentration of 100 pCi/L (see Figures 4.4 and 4.5), then the radon source strength through the walls is 1.5 μCi/h. Our PFT measurements, moreover, determine a total source strength for radon in the basement, under the assumption that the ratio of the strength of the basement PFT source to the average basement PFT concentration is the same as the corresponding ratio for radon. This method yields a total radon source strength into this basement in the winter averaging 5 μCi/h. Thus 30% of the radon in soil gas flowing into this basement enters through the walls.

Clearly, soil gas flow through hollow block walls should not be ignored in designing subslab or wall depressurization systems.

In Figure 4.5, observe the rapid drop in radon levels in both wall and subslab when the SSD is turned on, illustrating the good communication that exists between the subslab and the interiors of the blocks. A perimeter drain between the slab and the block wall, a feature that is common in basements in the northeastern United States, had to be capped and sealed to achieve this reduction (see insert in Figure 4.5). If these drains are not sealed or capped, subslab ventilation will be shunted through the perimeter drain, a low-resistance air path from the basement air to the subslab and thus fail to reach the radon-containing soil gas in the walls. Figure 4.5 (see insert) illustrates an easy way to cap the drain using backer rod and a flowable urethane seal, so that the drain becomes a conduit for airflow from the hollow inner wall to the subslab ventilation system. Moreover, with the design shown, the perimeter drain still allows water filtering down the inside of the hollow blocks to be drained away.

4.5.4 Loss of Indoor Air to SSD or WD Systems

In attempting to achieve an adequate reversal of flow between the basement and the subslab soil for proper exhaust of the soil gas, it is important to avoid excessive flow of indoor air into the mitigation system. In one experiment we found that 50% of the air exiting the mitigation system originated indoors. The experiment proceeded as follows: A CCTG system installed in House #5 (Matthews et al. 1987; Bohac et al. 1987) maintained a constant concentration (100 ppb) of a single tracer gas (SF_6) in each of nine interior zones. A tenth probe was used in the mitigation pipe to monitor the concentration of tracer gas in the exiting air. From the rate at which tracer gas was needed in each zone to maintain a constant concentration, the outdoor air exchange rate in each zone was recorded hourly. Figure 4.6 shows the concentration of SF_6 in the air exiting the mitigation pipe during the hours before and after the mitigation system was turned on; the tracer gas concentration in the mitigation pipe remains zero while the mitigation fan is off. During operation of the mitigation system, the concentration stabilizes at 50 ppb. Thus, about half of the exiting air must be coming from conditioned indoor air. Several repetitions of this measurement led to an estimate that, of the average flow of 108 m^3/h (64 cfm) through the exit pipe when the mitigation system was running, 50 m^3/h (30 cfm), or roughly 45%, was indoor air. Integrity checks on the mitigation system itself indicated no leakage points, so that the indoor air must be following various flow paths (such as through the porous block walls) into the soil gas on its way to the mitigation system.

The amount of indoor (conditioned) air lost through the mitigation system can be compared to the changes in the infiltration rates in various zones indoors with the mitigation fan on versus off. Table 4.5, based on the same data set obtained by the CCTG unit and averaged over a two day period in late March 1987, shows that the increase in the air infiltration into the basement when the mitigation fan is running is 50 m^3/h (30 cfm) and into the whole house is 79 m^3/h (47 cfm). The increased basement infiltration is seen to match exactly the flow of indoor air exiting the mitigation system. To review, the mitigation system depressurizes the soil gas both below the slab and in the soil beyond the basement walls, and the resulting basement airflow outward is balanced by increased air infiltration into both the basement and upstairs.

We have discussed the implications of airflow through block walls under two conditions. The first discussion focused on airflow into a building substructure through the block walls under ambient conditions. We showed that approximately 30% of the total air infiltration into one basement comes through the walls.

The second discussion addressed the loss of indoor air to SSD or WD radon mitigation systems. Can anything be done to reduce the loss of conditioned air? One possibility is to paint the walls. The walls in this house received two coats of paint after the measurements reported above were made, yet no significant change in the fraction of indoor air in the air exiting the mitigation pipe was observed. (The tops of the blocks were capped, but not painted.) Another possibility is to reduce the fan flow rate. Results from four houses in which the SSD fan was operated at two different speeds are presented in Table 4.6. In House #5, the fan flow was reduced by one-third (to 70 m^3/h or 42 cfm), and no increase in radon concentrations in the basement was observed. The amount of entrained indoor air remained about 50% of the total flow and was therefore also reduced by one-third. This lower fan setting should therefore be considered superior.

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Table 4.1. Radon diagnostic checklist

NAME ______________________ HOUSE ID ______________________
DATE ______________________

NON-SOILS: [] Water Sample From Outside Faucet ______________________
[] Surface Flux Measurements: [] Wall ______________________
[] Floor ______________________

SOILS: [] Soil Air Permeability ______________________
[] Soil Gas Grab Samples ______________________
[] Core Sample ______________________

BUILDING STRUCTURE: [] Visual Inspection, Complete Survey Form

[] Natural Condition Scintillation Cell Grab Samples
- [] Level 2 ______________________
- [] Level 1 ______________________
- [] Level 0; Each Unique Zone ______________________

[] Ambient Air Sample; Outside Air Temp ______________________
Wind Speed ______________________
Inside Air Temp ______________________
[] Closed Bathroom, 15 Min. Shower Operation ______________________

[] Drill Test Holes in Floors/Walls
[] Start Data Logging on 1 Min. Interval:
- [] Synchronize All Clocks

[] Shut Off Combustion Appliances
[] Mechanical Depressurization
- [] Scintillation Cell Grab Samples (to - 10Pa)
  - [] Substructure Firred Wall Cavities ______________________
  - [] Substructure Block Wall Cells ______________________
  - [] Substructure Wall, Floor Cracks ______________________
  - [] Substructure Service Penetrations ______________________
  - [] Substructure Test Holes ______________________
  - [] Natural Condition Sample Locations ______________________
- [] Air Movement Smoke Tube (to - 30 PA)
  - [] Substructure Cracks, Holes (Particularly Walls)
  - [] Tops of Block Walls ______________________
  - [] Test Holes
  - [] Exterior Soil Line ______________________
  - [] Between Floors
  - [] Other
- [] ELA Tests:
  - [] Whole House (Open to Substructure)
  - [] Substructure Only ______________________
  - [] Super Structure Only ______________________
  - [] 2 Blower Test ______________________

[] Depressurize Attic: With [] Calibrated Blower
[] Whole House Attic Fan
- [] Cycle Fan and Measure Basement ΔP ______________________

[] Appliance Cycling - Substructure ΔP Measurements as Appliances are Cycled On/Off 5 Times
- [] Clothes Dryer ______________________
- [] Exhaust Fans ______________________
- [] Furnace: [] Combustion Air Only ______________________
  [] Fan Only ______________________
  [] Both of Above ______________________
- [] Whole House Vacuum Cleaner ______________________
- [] Jenn-Air

OTHER MEASUREMENTS: [] Sub-Slab ΔP Mapping With Industrial Vacuum
[] Through Floor ______________________
[] Through Walls ______________________

Optional [] Soil Line SF6 Injection While Depressurized:
Use Miran to Sample: [] Substructure Room Air ______________________
[] Block Wall Cells ______________________

OTHER TASKS: ______________________

Table 4.2. Radon source diagnosis building survey

RADON SOURCE DIAGNOSIS
BUILDING SURVEY

NAME: ______________________ HOUSE INSPECTED ________

ADDRESS: ______________________ DATE ________

____

______________________ ARRIVAL TIME ________

PHONE NO: ______________________ DEPARTURE TIME ________

SURVEY TECHNICIANS: ______________________

____

____

____

I. BASIC CHARACTERIZATION OF BUILDING AND SUBSTRUCTURE

<u>Site</u>

1 Age of house ________

2. Basic Building Construction:
   Exterior Materials ______________________

   ____

   Interior Materials ______________________

   ____

3. Earth-based building materials in the building - describe:

   ____

   ____

4. Domestic water source:
   a. municipal surface
   b. municipal well
   c. on-site well
   d. other ______________________

5. Building infiltration or mechanical ventilation rate:
   a. building shell - leaky, moderate, tight
   b. weatherization - caulk, weatherstrip, etc.
   c building exposure a. heavy forest ______________________
   b. lightly-wooded or other nearby buildings ______________________
   c. open terrain, no buildings nearby ______________________
   - exhaust fans: a. whole house attic fans ______________________
   b. kitchen fans ______________________
   c. bath fans ______________________
   d. other ______________________
   e. frequency of use ______________________
   - other mechanical ventilation ______________________

Table 4.2 (continued)

6. Existing Radon Mitigation Measures
   Type ______
   Where ______
   When ______

7. Locale - Description: ______
   ______

8. Unusual outdoor activities: farm ______
   construction ______
   factories ______
   heavy traffic ______

Substructure

1. Full basement (basement extends beneath entire house)
2. Full crawlspace (crawlspace extends beneath entire house)
3. Full slab on grade (slab extends beneath entire house)
4. House elevated above ground on piers
5. Combination basement and crawlspace (% of each)
6. Combination basement and slab on grade (% of each)
7. Combination crawlspace and slab on grade (% of each)
8. Combination crawlspace, basement, and slab on grade (% of each)
9. Other -- specify

Occupants

1. Number of occupants ______ Number of Children ______
2. Number of smokers ______ Type of smoking and frequency ______

Air Quality

1. Complaints about the air (stuffiness, odors, respiratory problems, watery eyes, dampness, etc.)

2. Are there any indications of moisture problems, humidity or condensation (water marks, molds, condensation, etc.)?
   ______
   When ______
   ______

Note: complete floorplan with approximate dimensions and attach.

Table 4.2 (continued)

II. BUILDINGS WITH FULL OR PARTIAL BASEMENTS

1. Basement usage: occupied, recreation, storage, other ____________________

2. Basement walls constructed of:
   a. hollow block (concrete, cinder)
   b. block plenums: filled, unfilled
      top block filled or solid: yes, no
   c. solid block (concrete, cinder)
   d. condition of block mortar joints: (good, medium, poor)
   e. poured concrete
   f. other materials -- specify: ____
   g. estimate length and width of unplanned cracks: ____________________
   h. interior wall coatings: paint, sealant, other: ____________________
   i. exterior wall coating: parget, sealant, insulation (type ___________________________________)

3. Basement finish:
   a. completely unfinished basement, walls and floor have not been covered with paneling, carpet, tile, etc.:
      ____
   b. fully finished basement - specify finish materials:
      ____
   c. partially finished basement -- specify:
      ____

4. Basement floor materials:
   a. contains unpaved section (i.e., exposed soil) -- specify site and location of unpaved area(s):
      ____
   b. poured concrete gravel layer underneath
   c. block, brick, or stone - specify ____
   d. other materials - specify ____
   e. describe floor cracks and holes through basement floor
      ____
   f. floor covering - specify ____

5. Basement floor depth below grade - front ________ rear__________ side 1 _________side 2__________

6. Basement access:
   a. door to first floor of house
   b. door to garage
   c. door to outside
   d. other - specify ____

7. Door between basement and first floor is:
   a. normally or frequently open
   b. normally closed

8. Condition of door seal between basement and first floor - describe (leaky, tight, etc.):
   ____

Table 4.2 (continued)

9. Basement window(s) -- specify:
   a. number of windows ____________________
   b. type: ____________________
   c. condition: ____________________
   d. total area: ____________________

10. Basement wall-to-floor joint
    a. estimate total length and average width of joint: ____________________
    b. indicate if filled or sealed with a gasket of rubber, styrofoam, or other materials - specify materials: ____________________
    c. accessibility - describe: ____________________

11. Basement floor drain:
    a. standard drain(s) - location: ____________________
    b. french drain - describe length, width, depth
    ____
    c. other specify: ____________________
    d. connects to a weeping (drainage) tile system beneath floor - specify source of information (visual inspection, homeowner comment, building plan, other):
    ____
    e. connects to a sump
    f. connects to a sanitary sewer
    g. contains a water trap
    h. floor drain water trap is full of water:
       a. at time of inspection
       b. always
       c. usually
       d. infrequently
       e. insufficient information for answer
       f. specify source of information:
       ____

12. Basement sump(s) (other than above): location: ____________________
    a. connected to weeping (drainage) tile system beneath basement floor -- specify source of information:
    ____
    b. water trap is present between sump and weeping (drainage) tile system -- specify source of information:
    ____
    c. wall or floor of sump contains no bottom, cracks or other penetrations to soil -- describe:
    ____
    d. joint or other leakage path is present at junction between sump and basement floor - describe
    ____
    e. sump contains water:
       a. at time of inspection
       b. always
       c. usually
       d. infrequently
       e. insufficient information for answer
       f. specify source of information:
       ____

Table 4.2 (continued)

g. pipe or opening through which water enters sump is occluded by water:
- a. at time of inspection
- b. always
- c. usually
- d. infrequently
- e. insufficient information for answer
- f. specify source of information: ____________________

f. Contains functioning sump pump: ____________________

13. Forced air heating system ductwork: condition or seal - describe: supply air: __________
- basement heated: a. intentionally return air: __________
  b. incidentally

14. Basement electrical service:
a. electrical outlets -- number __________ (surface or recessed)
b. breaker/fuse box -- location ____________________

15. Penetrations between basement and first floor:
a. plumbing: ____________________
b. electrical: ____________________
c. ductwork: ____________________
d. other: ____________________

16. Bypasses or ‹ .ses to attic (describe location and size):
____

17. Floor material type, accessibility to flooring, etc.
____

18. Is caulking or sealing of holes and openings between substructure and upper floors possible from:
a. basement
b. living area

Table 4.2 (continued)

III. BUILDINGS WITH FULL OR PARTIAL CRAWLSPACES

1. Crawlspace usage: storage, other ______

2. Crawlspace walls constructed of:
   a. hollow block (concrete, cinder)
      block plenums: filled, unfilled
      top blocks filled: yes, no
   b. solid block (concrete, cinder)
   c. condition of mortar joints: (good, medium, poor)
   d. poured concrete
   e. other ______
   f. estimate length and width of unplanned cracks ______
   g. interior wall coatings: paint, sealant, other ______
   h. exterior wall coating: parget, sealant, insulation (type ______)

3. Crawlspace floor materials
   a. open soil
   b. poured concrete
      gravel layer underneath
   c. block, brick, or stone - specify ______
   d. plastic sheet
      condition: ______
   e. other materials - specify: ______
   f. describe floor cracks a... holes through crawlspace floor ______
   g. floor covering - specify: ______

4. Crawlspace floor depth below grade ______

5. Describe crawlspace access ______
   condition ______

6. Crawlspace vents:
   a. number ______
   b. location ______
   c. cross-sectional area ______
   d. obstruction of vents (soil, plants, snow, intentional) ______

7. Crawlspace wall-to-floor joint:
   a. estimate length and width of crack ______
   b. indicate if sealed with gases of rubber, styrofoam, other - specify ______
   c. accessibility - describe ______

8. Crawlspace contains:
   a. standard drain(s) - location ______
   b. french drain - describe length, width, depth ______
   c. sump
   d. connect to: weeping tile system ______
      a. sanitary sewer
      b. water trap (trap filled, empty)

Table 4.2 (continued)

9. Forced air heating system ductwork: condition and seal - describe ______________________

10. Crawlspace heated: a. intentionally
b. incidentally

11. Crawlspace electrical service:
a. electrical outlets - number ______________________
b. breaker/fuse box - location ______________________

12. Describe the interface between crawlspace, basement, and slab.
____
____

13. Penetrations between crawlspace and first floor:
a. plumbing: ______________________
b. electrical: ______________________
c. ductwork: ______________________
d. other: ______________________

14. Bypasses or chases to attic:
____

15. Caulking feasible from: a. basement
b. living room

Table 4.2 (continued)

IV. BUILDINGS WITH FULL OR PARTIAL SLAB FLOORS

1. Slab usage: occupied, recreation, storage, other: ____________________

2. Slab room(s) finish:
   a. completely unfinished, walls and floor have not been covered with paneling, carpet, tile, etc.
   ____
   b. fully finished - specify finish materials ____________________
   c. partially finished - specify ____________________

3. Slab floor materials:
   a. poured concrete
   b. block, brick, or stone - specify ____________________
   c. other materials - specify ____________________
   d. fill materials under slab: sand, gravel, packed soil, unknown ____________________
      - source of information ____________________
   e. describe floor cracks and holes through slab floor: ____________________
   f. floor covering - specify ____________________

4. Elevation of slab relative to surrounding soil (e.g., on grade, 6" above grade, etc.):
   ____
   - Is slab perimeter insulated or covered: yes, no

5. Slab area access to remainder of house - describe ____________________
   - normally: open, closed

6. Slab wall-to-floor joint:
   a. estimate length and width if crack ____________________
   b. indicate if sealed with gasket of rubber, styrofoam, other - specify ____________________
   c. accessibility - describe ____________________

7. Slab drainage:
   a. floor drain - describe ____________________
   b. drain tile system beneath slab or around perimeter - describe ____________________
   c. source of information ____________________

8. Forced air heating system ductwork:
   a. above slab condition and seal - describe ____________________
   b. below slab: ____________________
      a. length and location ____________________
      b. materials ____________________

9. Slab area electrical service:
   a. electrical outlets - number ____________________
   b. breaker/fuse box - location ____________________

10. Describe the interface between slab, basement, and crawlspace:
    ____

Table 4.2 (continued)

11. Penetrations between slab area and occupied zones:
    a. plumbing __________
    b. electrical __________
    c. ductwork __________
    d. other __________

12. Bypasses or chases to attic: __________

Table 4.2 (continued)

V. SUBSTRUCTURE SERVICE HOLES AND PENETRATIONS

(Note on floor plan)

Complete table to describe all service penetrations (i.e., pipes on conduit for water, gas electricity, or sewer) through substructure floors and walls. Indicate on floor plan.

Description of service, size location, accessibility	Size of crack or gap around service and type and condition of seal
Example: water, 3/4" copper pipe, through floor, accessible.	Example: Approx. 1/8" gap around circumference of pipe with sealing styrofoam gasket.

Table 4.2 (continued)

VI. Appliances

Major appliances located in substructure (crawlspace, slab-on-grade, basement)

Appliance	Location (Crawl, Slab, Base)	Description (Fuel type, style, operation)
Furnace		
Water Heater		
Air Conditioner		
Clothes Dryer		
Exhaust Fans		
Other:		

Forced air duct/plenum seals - describe

Combustion Appliances: combustion air supplied (yes, no)

Table 4.3 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, before and after 10 min. shower operation

5) [ ] Drill test holes in floor & wall

general guidelines: o Wall holes - 1/2 inch diameter
o Floor holes - 1/2 inch diameter

(note: plug immediately after drilling with flaggea Mortite)

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

7) [ ] Mechanical depressurization - 10 PA

Lucas cell grab samples

[ ] Block walls
[ ] Floors
[ ] Cracks
[ ] Service openings
[ ] Test holes

Pressure differentials across and air velocity through each test hole.

[ ] Floor test holes
[ ] Block wall test holes

Table 4.3 (continued)

8) Blower Door Tests (use ASTM 779 std.)

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

9) [ ] IR scan of each room

10) [ ] Appliance cycling - substructure measurements of pressure differentials in testholes as appliances are cycled on and off.

[ ] Clothes dryer ____________________

[ ] Exhaust fans ____________________

[ ] Furnace: [ ] Combustion air only ________________
[ ] Fan only __________________________
[ ] Both above _________________________

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

[ ] Check pressure differentials in test holes

[ ] Check air velocity through test holes

Table 4.4 Princeton Pre-Mitigation Diagnostics Protocol

Building Structure

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

During the building inspection decide on a convenient location or locations to place the mitigation pipe and the penetration(s) into the slab. Criteria for this decision include the following.

1) Look for a slab penetration point which is near a convenient basement (or crawlspace) exit point. Convenient exit points are, for example, through a band joist to an adjoining garage which allows venting through the roof.
2) Look for a slab penetration point which allows access to the complete subslab area without blockage from footers, piping, or duct work under the slab.
3) Look for a slab penetration point which places the duct work in the most unobtrusive position in the substructure as possible.

Building Dynamics

2) [ ] Drill test holes in floor and wall. Drill one hole into subslab in each corner 1 foot from wall and one hole centrally located in the slab. Drill two holes through first layer of hollow block walls, evenly spaced on each wall, or 30 feet apart if wall is extensive.

General guidelines:
- o Wall holes 1/2 inch diameter
- o Floor holes 1/2 inch diameter

Note: Plug immediately after drilling with flagged rope caulk. If possible, drill all holes except the 1 1/2 inch hole 1 day before other diagnostic tests to allow subslab air to come to an equilibrium. At a minimum, drill one hour before performing the following tests.

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

Note: Count Lucas cell samples 15 minutes after collection for 2 minutes: pCi/L ($\pm$ 15%) = counts per <u>2</u> 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.

Table 4.4 (continued)

4) [ ] Drill a 1 1/2 inch diameter floor hole in the area of the subslab that appears to be the logical mitigation pipe exit point. After drilling the 1 1/2 in. hole, vacuum concrete dust from holes and visually check for gravel or air gap under slab. Plug hole with backer rod and rope caulk.

5) [ ] Measure pressure difference across each test hole.

[ ] Determine airflow direction using a smoke bottle and speed using an appropriate instrument such as a warm wire anemometer.

6) [ ] Appliance cycling - Pressure differential measurements across the test holes 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.

Water

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

Perform only if subslab depressurization is not a viable mitigation choice.

9) [ ] 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 which is necessary for basement pressurization.

Table 4.5 Average Air Exchange Rate Relative to the Enclosed Space With and Without the Mitigation Fan Operating

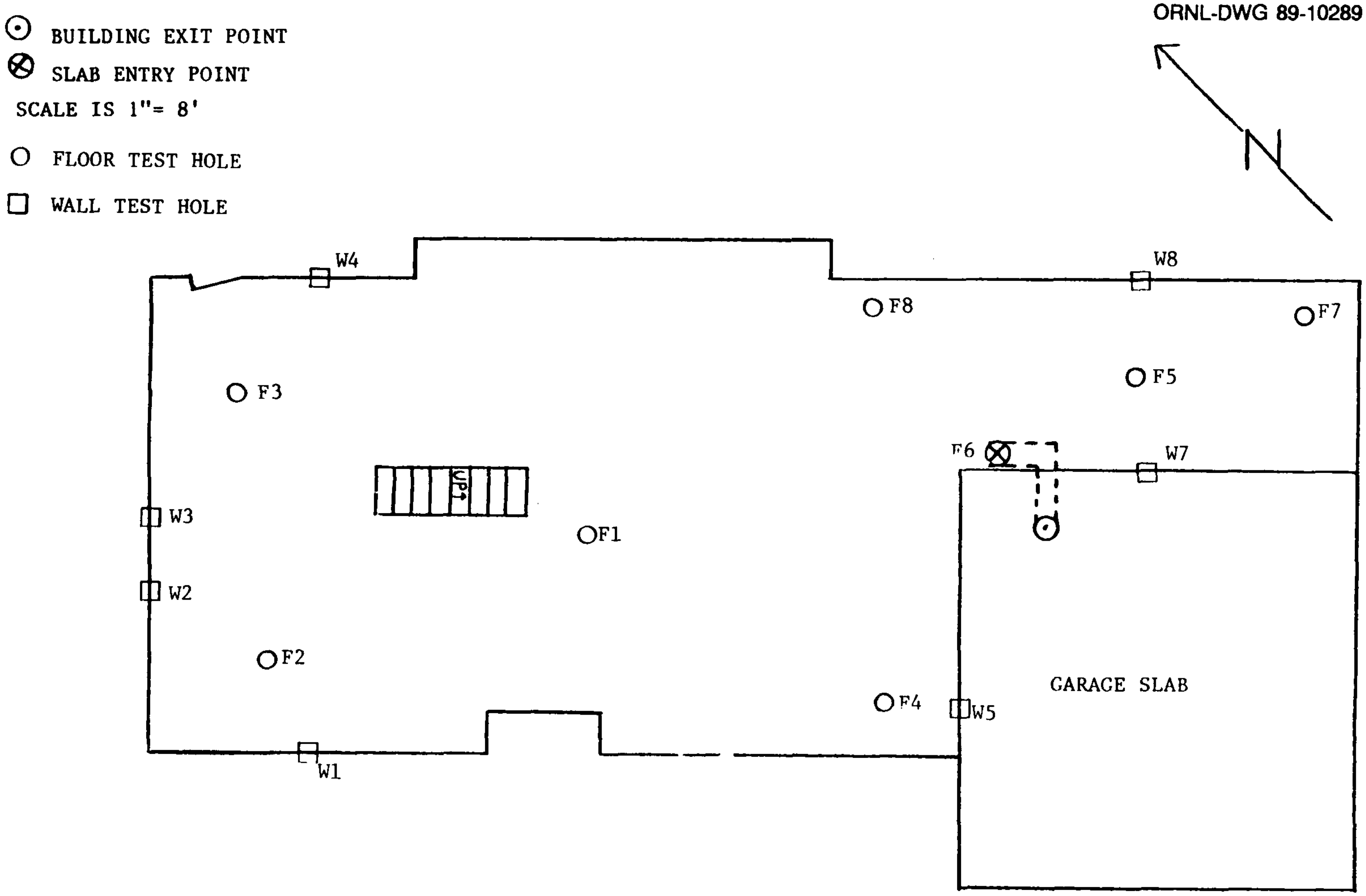
Air Flow	Mitigation Fan Off	Mitigation Fan On	Increased Infiltration m^3/hr m)
Outdoors to Basement	0.24 ACH	0.37 ACH	50. (30)
Outdoors to Upstairs	0.07 ACH	0.13 ACH	29. (17)
Sum (Whole House)	0.16 ACH	0.25 ACH	79. (47)

(Basement volume = 400 m^3, Upstairs volume = 475 m^3.)

Table 4.6 Average Total Flow (cfm) Out the Mitigation Pipe for Two Different Fan Settings: 1) Fan on Highest Setting and 2) Fan on Lowest Setting Which Maintained the Radon Levels Indoors Below 4 pCi/L.

	House			
	1	3	5	7
Fan Setting 1)	143 cfm	128	65	113
Fan Setting 2)	94	69	42	31

ORNL-DWG 89-10289



PU/CEES RN688

Fig. 4.1. House #2 basement floor plan.

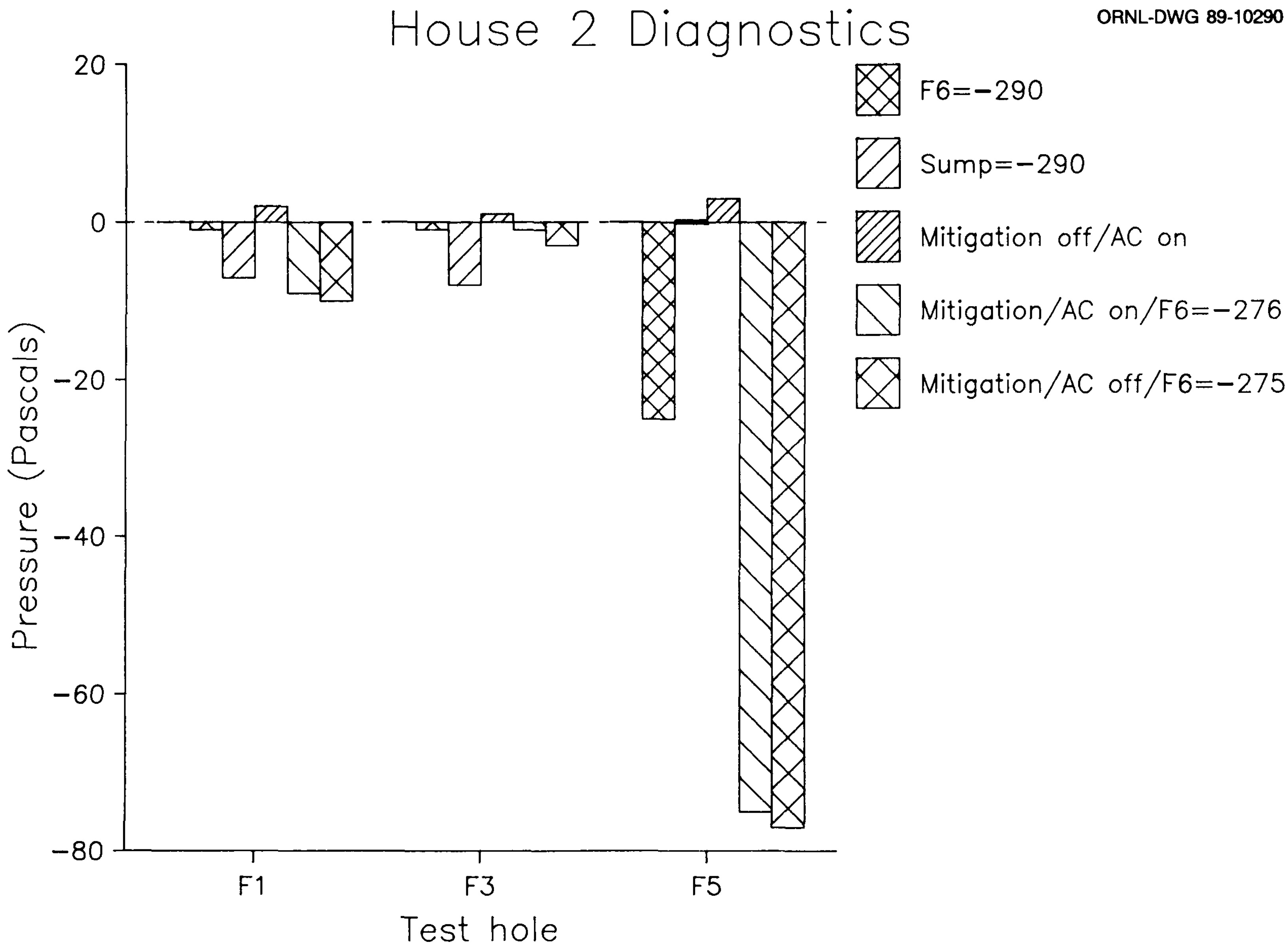


Fig. 4.2. House #2 diagnostics.

ORNL-DWG 89-10291

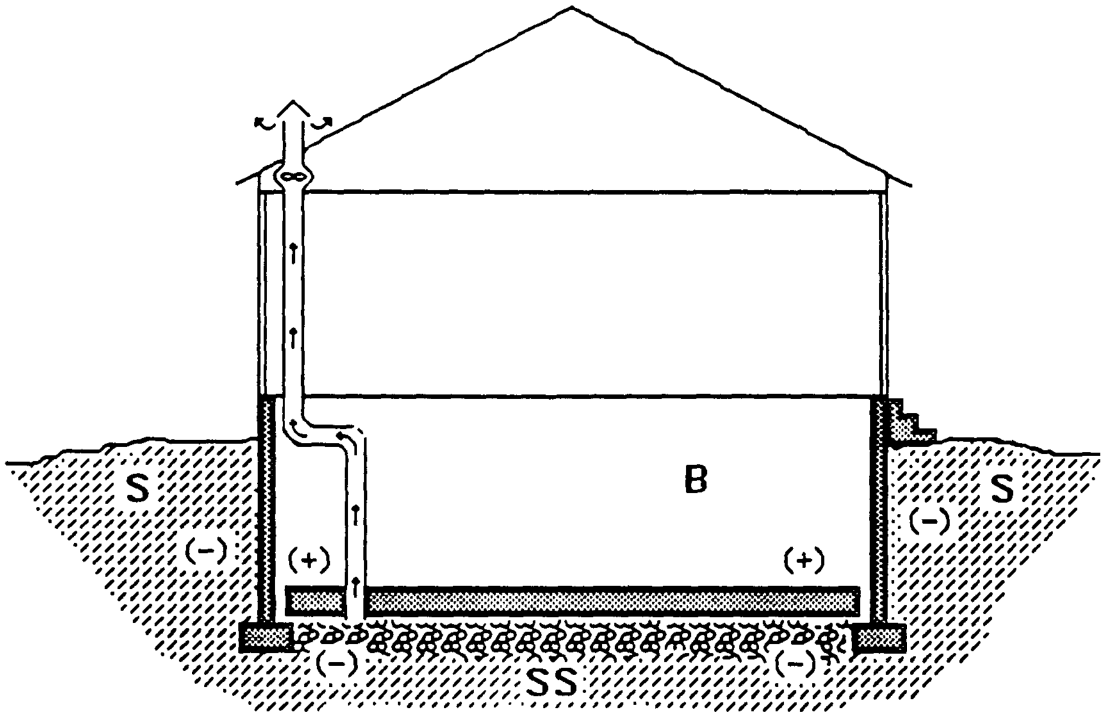


Fig. 4.3. Cross section of a house with a subslab (SS) depressurization system penetrating the basement (B) slab in one location. (SS) and (S) label the subslab and surrounding soil, respectively. When the mitigation system is running, the air flow out the system is in the direction of the arrows, depressurizing the subslab and soil relative to the basement. This pressure difference is represented by the (+) and (-) signs.

ORNL-DWG 89-10292

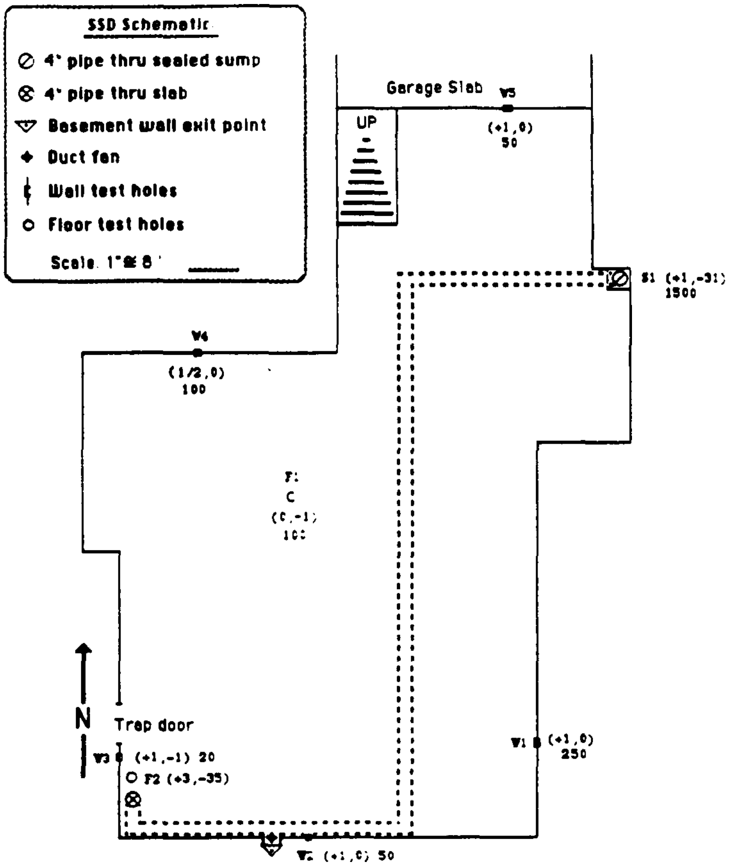


Fig. 4.4. Basement floor plan with SSD mitigation system and test holes. The floor plan represents two elevations; the basement slab is six feet below grade and the garage slab is at grade level. The mitigation duct system is outlined with dashed lines, with a penetration into the subslab in the southwest corner and one another in the sump. The sump was covered and a submersible sump pump installed. The duct system exits the building through the basement wall. There are eight test locations: five wall test holes connecting the basement to the inner block walls labeled W1 and W5, two slab test holes connecting the basement to the subslab labeled F1 and F2, and the sump. All wall holes are 3 1/2-4' above the slab. Each hole is labeled with two pressure differences, in Pascals, given in parenthesis. The first pressure difference across the test hole is recorded under ambient conditions, and the second one is recorded during operation of the mitigation system. Radon concentrations (in pCi/L) obtained by grab sampling are printed under the pressures.

ORNL-DWG 89-10293

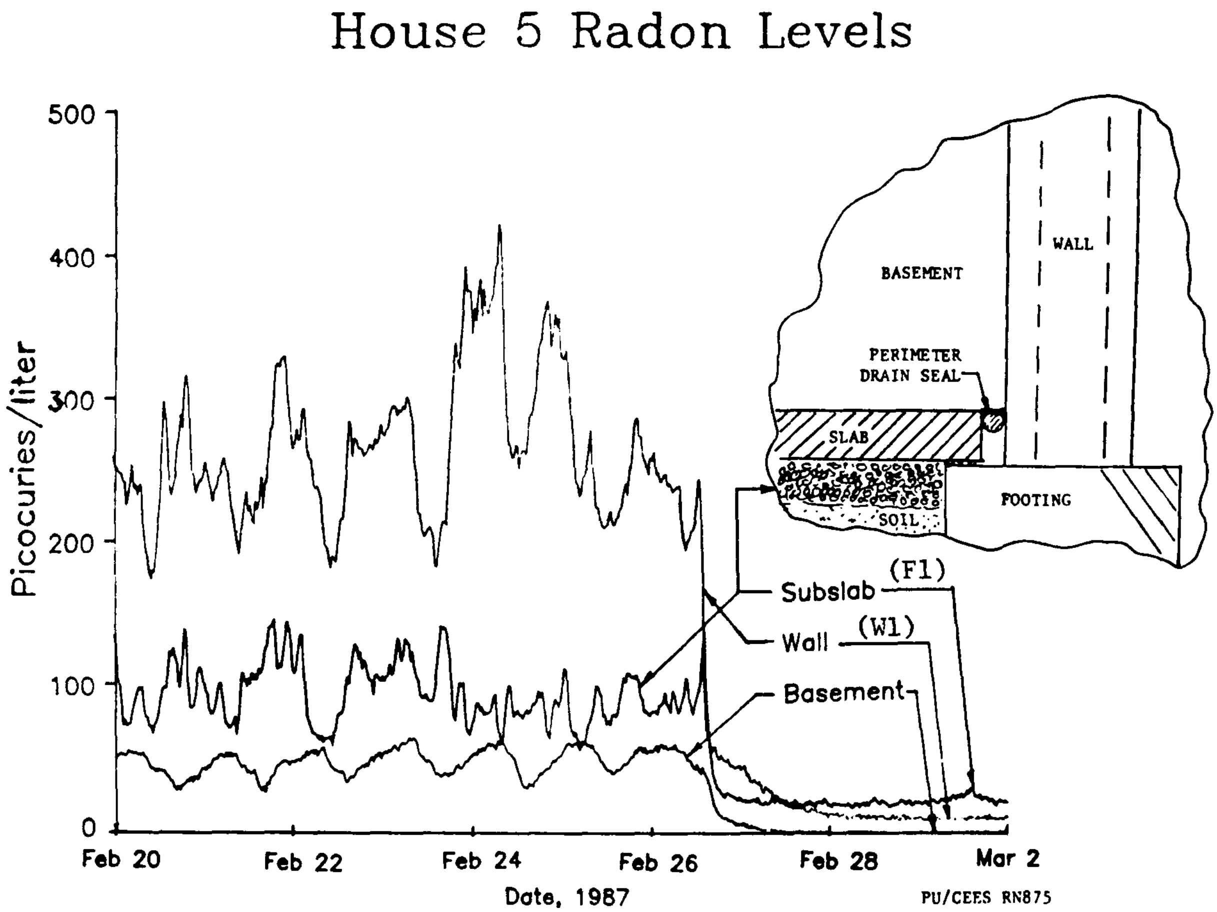


Fig. 4.5. Daily fluctuations in radon concentrations before and after the mitigation is turned on. The concentrations are located in the basement air, in the wall at position W1 in Fig. 2, and in the subslab at position F1 in Fig. 2. The inset shows details of the perimeter drain seal which channels air flow from the hollow block wall to the subslab suction point.

ORNL-DWG 89-10294

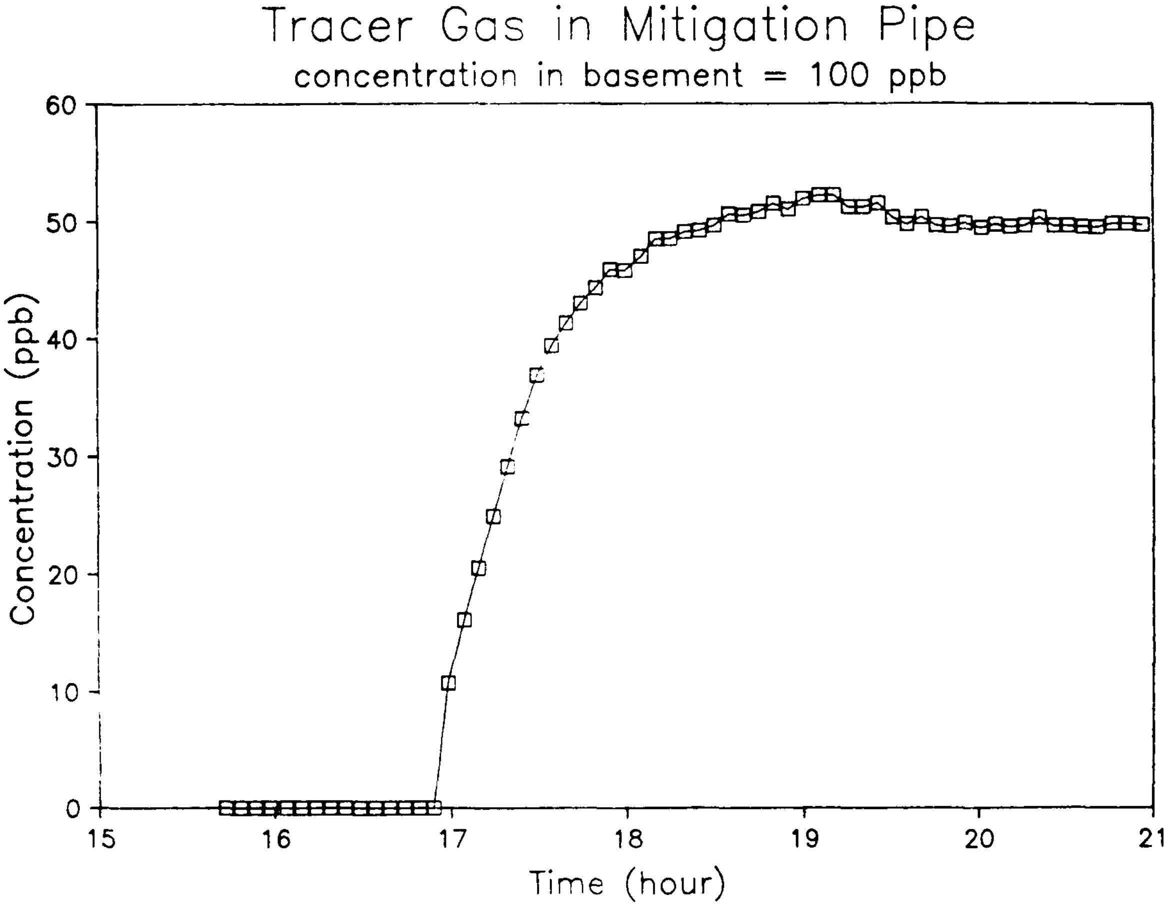


Fig. 4.6. Tracer gas concentration in air exiting the mitigation system. The concentration of a tracer gas sulfur hexafluoride (SF_6) is shown, in parts per billion (ppb), before and after the mitigation system is turned on. Because the basement concentration of tracer gas is kept constant at 100 ppb, the vertical scale is also the percent of air exiting the system which is indoor air. After the mitigation system is turned on at hour 17, 50% of the exit air is indoor air.

5. MITIGATION OF STUDY HOUSES

Mitigation of the study houses in phases allowed evaluation of the effectiveness of different types of mitigation, including subslab and wall depressurization with and without sealing, subslab pressurization, basement pressurization, heat recovery ventilators, and basement sealing. Figures 5.1 to 5.7 show the basement or crawl space structure drawn to scale with the configuration of the final mitigation system in each house. Most of the houses were mitigated during the winter of 1986-1987, except the control house, House #2, which was mitigated in mid-July, 1987. The numbers included in these seven figures are radon concentrations (pCi/L) measured via grab samples of air from the subslab and inner wall cavities under ambient conditions during premitigation diagnostics.

5.1 Mitigation Plans

Presented in this section are the individual mitigation strategies for initial mitigation of six of the seven study houses, excluding the control house. The initial mitigation strategy for each house is explained in light of the premitigation diagnostic results. The mitigation choices were coordinated with the initial mitigation plans for the six LBL houses to increase the variety of systems in the combined study. Homeowners received a condensed version of the mitigation plans in letters that were included in Appendix 9.2 of the midproject report (Matthews et al. 1987).

5.1.1 House #1

Premitigation diagnostics summary: The substructure of this house is shown in Figure 5.1. It consists of a basement with hollow concrete block walls (with capped tops) and a perimeter drain. There are weep holes in 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 6 ft above the basement slab. We found a thick layer of aggregate under the basement slab with good communication (i.e., airflow connectivity) between subslab points under the basement slab. There were no subslab to wall communications in the basement due to the intervening perimeter drain. The highest radon concentrations under the basement floor slab were 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): We installed a combination subslab and wall depressurization system in order to ventilate the areas under the basement slab and within 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 that 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 ran along the center of the basement ceiling between the two existing central air ducts. These pipes are connected to each other and exit the basement through the basement/garage wall and out the back garage roof. All the pipes are sloped to allow condensed water to flow back towards the subslab. A reversible Kanalflakt T2 plastic fan equipped with a speed control switch was installed in the pipe system in the garage attic to pull the soil gas from inside the block wall and the gravel bed under the basement slab and vent it to the outside. All plumbing was of standard 4-in.-diam sewer and drain (S & D) pipe. At the point where the pipe enters the basement slab, a roughly circular area 1 ft in diameter was cleared of gravel and other subslab debris to increase the open area to draw air through. Dampers were installed in the pipes to allow the basement pipe and each of the wall pipes to be closed off completely. The perimeter drain was not sealed initially.

Mitigation refinement and experimentation: The initial wall and subslab depressurization system pulled radon concentrations down substantially, but after a month of operation the basement still had an average level of over 7 pCi/L (down from a premitigation value of over 35 pCi/L). We sealed cracks in the walls, but after three weeks in this configuration only slight improvement was observed.

On February 18, 1987, we converted the perimeter drain into a duct system and sealed the sump. Using the fan system in a pressurization mode, we were able to reduce the average radon levels in the basement by more than one-half. Switching the fan back to depressurization, the gas concentrations fell well below 4 pCi/L, averaging less than 1 pCi/L. The average radon levels in the basement and upstairs during these different mitigation configurations are shown in Figure 5.8.

5.1.2 House #3

Premitigation diagnostics summary: The substructure (see Figure 5.3) is a basement with hollow concrete block walls with the tops capped, 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. We found good communication between subslab points, as well as between the subslab and sump (i.e., point 3180 in Figure 5.3). The perimeter drain disrupted the subslab-to-wall communications. There was a layer of aggregate under the basement slab. The radon concentrations were highest over 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 northeast basement wall (see point 270 in Figure 5.3).

Mitigation strategy (initial phase): We installed a subslab depressurization system 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 columns. The two pipes coming out of the slab connect through an elbow and tee to a pipe which runs along the basement ceiling between two heater ducts before exiting the basement through the basement/garage wall. The exit pipe is then directed upward, exiting the house through the garage roof on the east side of the center peak of the roof. The pipes were sloped to allow condensation to flow back towards the subslab. A Kanalflakt T2 plastic duct fan equipped with a speed control was installed in the garage. The fan was installed so that it (and therefore the flow) could be reversed to test the effectiveness of pressurizing vs depressurizing the subslab. The plumbing was standard 4-in.-diam S&D pipe throughout. At the point where the pipe enters the basement slab, an area 1 ft in diameter was cleared of gravel and other subslab debris to increase the amount of open area to draw through. Dampers were installed in the pipes to allow each of the subslab pipes to be closed 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. The perimeter drain can still function as a drain for water or moisture that accumulates in the hollow block wall and drips down the inner wall of the blocks into the drain. We used this type of perimeter drain duct in all the ORNL/PU houses that 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.

Mitigation refinement and experimentation: The initial system was able to bring basement radon concentrations down to under 2 pCi/L, with the perimeter drain duct allowing excellent communication between the wall and subslab spaces. We turned the depressurization fan off for five days to measure the effectiveness of sealing alone in keeping out the radon gas. Reversing the fan for 1 week to evaluate the efficacy of a pressurization scheme showed that the levels would still be far below the premitigation radon levels, but over 5 times as high as those seen while the subslab was depressurized. For the remainder of the study, we experimented with fan speeds in House #3 to determine the most efficient degree of depressurization. The average radon levels in the basement and upstairs during these different mitigation configurations are shown in Figure 5.9.

The three fan settings referred to in Figure 5.9 correspond to the following flow out the mitigation pipe: (1) flow at fan setting 1 was 92 cfm, (2) flow at fan setting 2 was 69 cfm, and (3) flow at fan setting 3 was 90 cfm, with the damper in the mitigation pipe into the slab farthest from the garage shown in Figure 5.3 closed off. The average radon both in the basement and upstairs was lowest at fan setting 1 and highest at fan setting 3, but remained below 4 pCi/L on the average in all configurations. Figure 5.10 shows the 24-h average radon concentration in the basement vs the subslab-basement pressure difference. The different fan settings correspond to different subslab-basement pressure differences, with fan setting 1 having clustered around the more negative pressure differences and fan setting 3 clustered at the lower end of the same scale. At a pressure difference of about -10 Pa between the subslab and the basement (which was measured at two locations in the center of the basement slab), the subslab depressurization mitigation system begins to manifest occasional daily basement average radon concentrations above 4 pCi/L.

5.1.3 House #4

Premitigation diagnostics summary: The substructure (see Figure 5.4) is a basement with painted hollow cinder block walls with tops capped, 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. We found some aggregate under the basement slab, although the soil beneath it was very wet and clay-laden. We did observe good communication, however, between 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 depressurization 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.-diam S&D pipe was inserted through the cover. The pipe extends to the ceiling and passes out of the basement through the west wall. A Kanalflakt K6 metal duct fan with a speed control is located in the center of the horizontal pipe before the basement exit point. An adequate slope in the pipe allows condensed water to drain back to the sump. The exit pipe passes through a hole in the block wall. The vent pipe on the outside of the house 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 northwest corner of the basement was covered with a sealed sheet metal cover. Both sumps were equipped with a submersible pump with a check valve.

The north sump, through which air was not pulled, has a pipe attached to it which vents to the outside about 100 ft to the front of the house. Despite this, our measurements show that this 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.

Mitigation refinement and experimentation: After 2 weeks of operation, a metal fan was substituted for the plastic mitigation fan. Radon levels increased slightly; we found the metal fan pulled less flow than the plastic fan. Subslab pressurization was applied for 5 days in early March. This experiment showed that the system was relatively poorly adapted to this mode, with basement radon levels reduced just 50% from their unmitigated state and upstairs levels reduced even less. We replaced the metal fan with the plastic one which had performed better. The average radon levels in the basement and upstairs during these different mitigation configurations are shown in Figure 5.11.

5.1.4 House #5

Premitigation diagnostics summary: The substructure (see Figure 5.5) consists of a basement with hollow concrete block walls with capped tops, 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. There was a thick layer of aggregate under the basement slab which allowed good communications between subslab points. Communication between subslab and walls was prevented by the perimeter drain. We found the highest radon concentrations in the sump and near a large crack in the center of the basement floor (see points 1500 and 280, respectively, Figure 5.5). The walls showed similar concentrations with slightly higher levels found in the north basement wall. The basement at House #5 was the tightest of the seven houses in the ORNL/PU study. (None was very tight; see discussion on blower-door measurements in Section 6). It was therefore decided to employ 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 establish basement pressurization of about 5 Pa greater than the outside pressure.

Mitigation strategy (initial phase): A basement pressurization system was installed, with the intention of maintaining a slight pressure in the basement to prevent the radon gas from entering the substructure. The sump and perimeter drain were not sealed initially. A Kanalflakt K6 metal fan with a speed switch was installed on the basement side of the block wall between the basement and garage. 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. (This was a temporary system. The homeowners assured us that they would not run their cars in the garage during the 2-week trial of this system. We do not recommend that air from a garage be used as supply air for a basement pressurization system under any circumstances.) Construction was 4-in.-diam S&D pipe throughout, with the ceiling pipe structure installed so that it could be easily converted into a subslab depressurization system. Air was piped into three different locations inside the basement to better regulate the pressurization of the basement. Dampers were installed in each pipe to regulate the air distribution. The ceiling pipe, which extends down the center of the basement, ends between the fourth and fifth lolly columns from the basement/garage wall. The pressurization system failed because the metal K6 fan did not maintain sufficient flow to establish adequate pressurization of the basement. This initial system was followed by extensive sealing. Still, at most only a 0.5 Pa pressurization of the basement was obtained. Any reduction in radon achieved during this phase of mitigation was due to the increased ventilation of the basement from the pressurization system.

Mitigation refinement and experimentation: The unorthodox approach of basement pressurization in House #5 seemed to be fundamentally flawed. The initial system reduced radon concentrations only by about 20% in the basement, and almost no reduction was observed in the living spaces. Incremental variations on the scheme included sealing the perimeter drain and wall and floor cracks. This did not fix the problem. The perimeter drain was sealed to form a perimeter drain duct, and application of subslab depressurization through the sump and a single slab penetration on the opposite side of the basement (shown in Figure 5.5) immediately decreased the radon concentration to an acceptable level. The average radon levels in the basement and upstairs during these different mitigation configurations are shown in Figure 5.12.

5.1.5 House #6

Premitigation diagnostics summary: The substructure (see Figure 5.6) is a basement and crawl space with hollow cinder block walls with the tops capped, separated by an interior hollow cinder block wall with a small door between the two spaces. We found a layer of aggregate under both the crawl space and basement slab, with good communication observed between points under the crawl space slab. Communication under the basement slab was less certain. There was no communication between the basement and crawl space subslab areas, or between either subslab area and its adjoining walls. We found the highest radon concentrations under the basement, the connected workroom, and the crawl space slabs, with the west side of the crawl space showing the highest levels. We measured fairly uniform concentrations in the walls, with slightly higher levels in the northeast basement wall next to the garage slab (see Figure 5.6).

Mitigation strategy (initial phase): A subslab depressurization system was installed to ventilate the area under both basement and crawl space slabs. The initial installation consisted of two pipe penetrations into the slab in the crawl space and one pipe penetration into the center of the slab in the basement. The pipes in the crawl space were inserted into the slab 19 ft from the west and east crawl space walls and equidistant between the north and south crawl space walls. An area under the slab at the point where the pipe entered the slab was cleared (approximately 1 ft^3, mushroom shaped) to increase the amount of open area for the fan to draw upon. The two 4-in.-diam S&D pipes which penetrate the crawl space floor connected to a 4-in.-diam S&D pipe which exits the crawl space through the east wall and runs along the basement ceiling behind the existing facade. Schedule 40 PVC pipe on the basement side of the manifolded system provided support. The hole in the basement slab was made at the location labeled 4900 in Figure 5.6. These pipes were connected to a common pipe that exited the basement on the north side of the east wall and ran behind the existing duct along the ceiling in the entrance room and through another wall into the storeroom. It exited upward through the storeroom ceiling, into the attic and out the roof on the north side of the garage. A slope in the pipe was designed to allow condensation to flow back towards the subslab. A Kanalflakt T2 plastic fan with speed control was installed in the attic.

House #6 had two HRVs installed before our study began, one in the basement and the other in the crawl space. We evaluated the mitigation system with the HRVs both on and off before turning the HRVs off for the last time on January 15, 1987.

Mitigation refinement and experimentation: Figure 5.13 shows the average basement, upstairs, and crawl space radon concentrations during the different mitigation configurations. The first two sets of bars in Figure 5.13 show days prior to our mitigation when we had the HRVs either running or turned off. The increased ventilation resulting from the HRVs gave about a 50% reduction in radon in the basement and upstairs and about a 35% reduction in the crawl space. The initial subslab depressurization system we installed worked adequately in the crawl space, but resulted in only marginal reduction in radon in the basement. This was due to poor communication between our basement suction point and the rest of the basement subslab space, because of water accumulation under the basement suction point. Addition of a subslab penetration in the workroom adjoining the basement and another one through one of the basement walls which pulled on soil under the entry room slab still reduced the basement radon level only by 50% from the original. (These days are 34-40 in Figure 5.13.) Sealing holes, cracks, and the sump, which was provided with a submersible sump pump, did not improve the radon problem significantly. Finally, two 2-in.-diam pipe penetrations were put into the basement subslab near the edges of the slab. These points were chosen because diagnostic tests showed the communications on the edge of the slab were slightly better than in the center of the slab, and the water problem under the slab appeared less severe on the edge of the slab (at least on the day that we looked). This final configuration reduced the radon to acceptable levels.

5.1.6 House #7

Premitigation diagnostics summary: The substructure (see Figure 5.7) is a basement and crawl space combination, connected by a partially opened cinder block wall, with capped hollow cinder block walls throughout. The basement has a perimeter drain along all four walls and a sump on the east side of the basement/crawl space wall. The crawl space has a perimeter drain along the east and part of the south side wall. The rest of the perimeter drain in the crawl space had been sealed by the homeowner before the study began. Both the basement and crawl space slabs had a good aggregate underneath them. We found good communication between subslab points within the basement, but not between the basement and crawl space zones. Subslab communication was reduced in the crawl space due to short-circuiting to the perimeter drain. The perimeter drain blocked all subslab-to-wall communication in the basement and crawl space. We achieved wall-to-wall communication within walls and around single corners in walls in both the basement and crawl space zones. We found high radon concentrations under the basement slab and slightly lower concentrations under the crawl space slab. The walls showed similar concentrations with slightly higher levels in the southern crawl space wall between the crawl space and garage (see Figure 5.7).

Mitigation strategy (initial phase): A subslab depressurization system was installed. This was accomplished by applying suction to a perimeter drain duct system, which depressurized both the hollow walls and the basement and crawl space subslab. 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 crawl space duct system in the center of the north wall. These ducts were connected through a manifold to a pipe which exited the substructure through the garage/crawl space wall before running up through the roof on the west side of the house. A Kanalflakt T2 plastic fan with a speed control located in the garage attic provided the necessary depressurization of the duct system. Standard 4-in.-diam S&D pipe was used throughout, with proper sloping to permit condensation to flow back towards the subslab. Dampers in each pipe allow individual pipes to be closed off completely.

Mitigation refinement and experimentation: Subslab depressurization through the perimeter drain duct successfully reduced the radon concentration to below 4 pCi/L both in the basement/crawl space and upstairs. The depressurization fan was turned off to test the effect of sealing alone, which resulted in almost 50% reduction in indoor radon levels in this house. Reversing the fan to test subslab pressurization through the perimeter drain duct resulted in only about a 25% reduction in radon below the premitigation concentrations. The average radon levels in the basement and upstairs during these different mitigation configurations are shown in Figure 5.14. During days 86-92 the upstairs radon monitor was inoperable.

5.1.7 House #2, the Control House

Figure 5.15 shows the averaged fall, winter, and spring premitigation radon concentrations in the basement and upstairs. The seasonal variation in the basement radon levels is much less than that observed in the upstairs levels, partially if not totally accounted for by the family's airing the upstairs by window opening during warmer weather, while the basement remains closed throughout the year.

The substructure of House #2 consists of a basement with hollow-block walls with capped tops. A sump is located near the center of the northeast wall. A garage on a slab is located on the southeast corner of the house and intersects the basement wall about 5 ft above the basement slab. The northwest corner of the basement slab is at grade level.

A simply designed subslab depressurization system was installed in this house. A single pipe penetration enters the basement slab near the basement/garage wall. The pipe exits the basement through that same wall into the garage, passes into the garage attic, and leaves the structure through the garage roof. A Kanalflakt T2 plastic duct fan was installed in the attic with a variable speed switch. The last two sets of bars in Figure 5.15 show the average radon concentration in the basement and upstairs during days 205-250 of 1987 (late summer) and during 112-134 (spring) of 1988. The fan setting was the same during these two time periods. Although differences in the two time periods are evident, the average is below 4 pCi/L in both cases.

Figure 5.16 summarizes some of the data collected during successful operation of the SSD system in House #2. The figure provides a scatter plot of the 24-h averages of pressure difference between the outdoor and the basement versus radon in the basement. A relationship between higher radon and higher outdoor-basement pressure difference is evident. The period between days 205 and 250, shown in Figure 5.15, was a period of generally small pressure differences. In contrast, the period between days 112 and 134 was a period of comparatively larger pressure differences. The pressure difference between the basement and the subslab versus radon concentration in the basement shows no similar correlation, as seen in Figure 5.17. These observations can be compared with premitigation data plotted in Figures 5.18 and 5.19. No relationship between radon concentration in the basement and the pressure difference between the basement and the outdoors or the subslab, respectively, is evident although it should be noted that the average basement radon in much higher than in the postmitigation plots. The mechanism which explains this interesting observation is currently being explored in our physical modeling studies.

5.2 Radon Entry Into Detached Dwellings: House Dynamics and Mitigation Techniques[1]

Mitigation and PFT airflow measurements made at Houses #1 and #5 are discussed in this section. In addition, Table 5.1 shows the basement average radon, infiltration, and radon source strength for all seven research houses, during the pre- and postmitigation phases of the study. Basements #1 and #2 are the leakiest, and basement #5 is the tightest. The smallest premitigation radon source strength is at House #7, and the largest is at House #3.

The Piedmont study was a detailed radon mitigation and diagnostic study conducted in 14 houses in northern New Jersey. From September 1986 to September 1987, PU and ORNL studied seven houses while LBL studied seven other houses in this region (Matthews et al. 1987; Sextro et al. 1987). This subsection discusses data from two of the PU/ORNL houses.

Diagnostic measurements, confirming earlier work in this field (Nazaroff et al. 1988), indicated that the prime source of radon was soil gas entering through the substructure. One goal of the research was to determine the effectiveness of alternative mitigation techniques. This evaluation was aided by continuous measurements of: (1) basement and upstairs radon concentrations; (2) pressure differences across the basement/subslab, basement/upstairs, and basement/outdoor interfaces; (3) temperatures in basement, upstairs and outdoors; and (4) central air handler usage. A weather station located at House #5 monitored wind speed

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[1]Much of the text from this subsection is drawn largely from a paper delivered at the Fourth International Symposium on the Natural Radiation Environment, Lisbon, December 1987, and accepted for publication in *Radiation Protection Dosimetry*. The authors are L.M. Hubbard, K.J. Gadsby, D.L. Bohac, A.M. Lovell, D.T. Harrje, R.H. Socolow, from the Center for Energy and Environmental Studies, Princeton University, and T.G. Matthews, and C.S. Dudney, from the Oak Ridge National Laboratory, and D.C. Sanchez, from the Air and Energy Engineering Research Laboratory, United States Environmental Protection Agency. Radon concentrations are reported in Bq/m^3. 1 pCi/L equals 37 Bq/m^3.

and direction, barometric pressure, precipitation, soil temperature, outdoor temperature, and relative humidity. A time-averaged value of the above parameters was recorded every 30 min. Several additional parameters were monitored on an intermittent basis in the test houses. These parameters included multizone air infiltration rates using passive PFT samplers in all houses, and using a CCTG in one house (Bohac et al. 1987).

Both of the test houses discussed here are large ranch houses, built less than 10 years ago, with a full basement and an attached garage built on a slab. House #1 has a gas furnace with forced air distribution, and House #5 has an electric heat pump with oil combustion backup and forced air distribution. Both basements have hollow cinder block walls, a perimeter drain around a floating slab, and a sump (a collection pit for water, cut into the basement floor). The soil gas below House #1 has a much higher radon content than below House #5 -- 15 times higher (111,000 vs 7400 Bq/m^3) as measured by grab samples taken below the two slabs in the premitigation period. Nonetheless, the average premitigation basement radon concentrations are similar in the two houses, with house 5 actually higher (2220 vs 1369 Bq/m^3) for two reasons: (1) the soil around House #5 is more permeable, so more soil gas can enter the basement for the same pressure difference between subslab and basement, and (2) House #5 has a much tighter basement, with roughly 4 times smaller air exchange rate with outside air (0.8 vs 0.2 basement air exchanges per hour for Houses #1 and #5, respectively, averaged over 2 months premitigation). Despite such important differences in radon environments, the mitigation results in the two houses will be seen below to be quite similar.

5.2.1 Mitigation Techniques

Subslab and/or wall depressurization was particularly successful in mitigating the Piedmont study houses. The ease of installation, relatively low costs of installation and initial maintenance, unobtrusiveness, and efficacy in reducing radon levels made it the most desirable mitigation system. Previous studies (Ericson et al. 1984, Cliff et al. 1987) have drawn similar conclusions. The Piedmont study was nearly unique, however, in implementing several mitigation systems serially in the same house. Figures 5.20 and 5.21 show the average radon concentrations in the basement and upstairs before and during different phases of mitigation in Houses #1 and #5. In both cases, the final mitigation configuration was subslab (and wall for House #1) depressurization, with the perimeter drains sealed to form perimeter drain ducts.

The initial mitigation system in house 1 consisted of two penetrations through the substructure: a single penetration into the center of the basement slab for subslab depressurization and another into the center of the hollow block wall between the basement slab and the garage slab for wall depressurization. Neither the perimeter drain nor any cracks were sealed. Figure 5.20 shows that three-fourths of the eventual radon reduction was already achieved by this system. During the second phase of mitigation, cracks and holes in the penetrated hollow block wall were sealed, but no significant improvement in radon reduction occurred.

The final two phases consisted of sealing the perimeter drain to form a perimeter drain duct, sealing the sump, and either pressurizing or depressurizing the subslab and hollow wall by reversing the fan. Figure 5.20 shows that subslab (plus wall) depressurization was the most successful mitigation configuration.

Figure 5.21 shows the average basement and upstairs radon concentrations for the mitigation systems tested at house 5. The two initial mitigation systems were basement pressurization, with and without sealing of cracks and the sump, the perimeter drain, and the largest leaks between the basement and the upstairs. The basement radon concentration decreased by 25%, and the upstairs radon concentration remained about the same. Our tracer gas measurements show that the flow of air from the basement to the upstairs increased from a 2-month premitigation average of 95 m^3/h to 170 m^3/h during the pressurization time period. Thus, the radon source strength to the upstairs, which is the product of the radon concentration in the basement and the airflow from the basement to the upstairs, remained about the same before and during the basement pressurization test.

The third mitigation system tested at House #5, basement sealing without pressurization, did not significantly reduce radon. The sealing was the same as in the second mitigation system. The fourth and final mitigation system involved subslab depressurization, using two penetrations into the subslab in opposite corners of the basement. One of these penetrations was through the sump, which was sealed and provided with a submersible pump. Figure 5.21 shows that this system was very effective in reducing the indoor radon concentration.

The final subslab depressurization mitigation systems in Houses #1 and #5 used 6-in. duct fans, installed in a duct system of 4-in.-diam plastic pipe. The exhaust was directed through the garage roof at House #1 and through the basement wall at House #5. After the fan was tuned to maximum efficiency (i.e., minimum flow necessary for keeping soil gas out of the building) the mitigation system exhaust airflows were 0.04 m^3/s and 0.02 m^3/s at Houses #1 and #5, respectively.

5.2.2 Air Infiltration and Radon Source Strength

Simultaneous PFT measurements provide information on the airflow patterns before and after mitigation in these houses (Dietz et al. 1986). The PFT system uses passive sources and samplers to measure interzone airflow rates as well as outdoor infiltration in multizone buildings, averaged over periods of roughly 2 weeks. PFT monitoring in all test houses began when the instrumentation packages were installed at the end of October 1986 and was continuous except for brief gaps during mitigation installation.

To combine the PFT data with the other measurements, the continuously logged parameters were averaged over the intervals between replacement of the PFT samplers. Figures 5.22 and 5.23 show these averaged data for Houses #1 and #5.

The radon source strength, displayed in the second box of Figures 5.22 and 5.23, is obtained by assuming that radon enters the house through the basement and that the radon and the tracer gas behave similarly in the basement:

$$\frac{\text{Source(PFT)}}{\text{Concentration(PFT)}} = \frac{\text{Source(Radon)}}{\text{Concentration(Radon)}} \qquad (1)$$

PFT source strength and PFT concentration refer to the tracer gas emitted and measured in the basement. Basement radon concentrations recorded from the continuous monitors are averaged over the entire PFT placement period. Knowing these three quantities gives the radon source strength.

Figures 5.22 and 5.23 describe some interesting differences between the two basements. The initial, premitigation radon concentration in House #1 is 62% of the radon concentration in House #5, while the House #1 basement infiltration is about 4 times greater (compare the second box of Figure 5.22 and 5.23). It follows that the radon source strength is about 2 times larger in House #1 than in House #5.

Two terms make up the total basement inriltration -- the infiltration from the soil gas and the infiltration from the outdoor air. During subslab depressurization, the entry of soil gas into the basement should go to zero, the basement pressure should exceed the subslab pressure, and the radon source strengths and radon concentrations should drop dramatically in both houses. Figures 5.22 and 5.23 confirm these expectations.

We can estimate the soil gas flow into the basement if we assume the source strength is equal to the product of the flow from the soil gas and the radon concentration in the soil gas and also assume that other sources of basement radon, such as from upstairs air, are negligible. Measured soil gas concentrations before mitigation (grab samples under the slab at House #1 and continuous measurements under the slab at House #5) are 111,000 and 7400 Bq/m^3, respectively. The volume of basement #1 is 265 m^3 and the volume of basement #5 is 371 m^3. Using the average premitigation radon source strength obtained from the tracer gas measurements, 320 and 180 kBq/h, we estimate the contribution to the basement air infiltration which comes from flow from the soil gas for House #1 is 3 m^3/h or 0.01 air changes per h (ACH) and for House #5 is 25 m^3/h or 0.07 ACH. Comparing with Figures 5.22 and 5.23, we see that in House #1 soil gas is 1% of the total air infiltration into the basement and in House #5 it is 40% of the total. These numbers are obtained assuming that the radon concentration in the soil gas flowing into the basement and the amount of flow into the basement are uniform.

The comparison of interzone flows during premitigation and after subslab depressurization is consistent with this analysis. In House #5 the postmitigation basement infiltration is down by about 40% and in House #1 it remains about the same. The total airflow into the basement (which includes flow from the upstairs) decreased in House #5 by about 25% and increased slightly in House #1.[2] The mitigation system in the depressurized mode can pull air from the basement into the system, and thus increase the flow from the upstairs to the basement. This could be happening in both houses, with House #5 showing a decrease in total flow into the basement because of the loss of the comparatively large contribution from the soil gas flow. In fact, the upstairs-to-basement flow does increase slightly in both houses during subslab depressurization.

5.2.3 New Questions

Ongoing analysis of these data and those from the other five Piedmont houses will provide more details on the changes in airflow patterns indoors due to depressurization of the subslab and hollow wall cavities, including interactive effects with the heating and cooling systems. It would be interesting to see if, when the mitigation systems are turned off for research purposes, the total flow into the basement from the soil gas increases; this could happen if subslab depressurization were to dry out the soil.

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[2]This estimate was obtained using the basement infiltration data from PFT time periods pre- and postmitigation when the difference between the indoor and outdoor temperatures was similar, to minimize error associateds with the change in air infiltration with variation in the stack effect. The 40% decrease in air filtration pre- and postmitigation is not obvious from Figure 5.23: the average basement infiltration rate from days 330 through 364 was 88 m^3/h and from days 59 through 71 it was 55 m^3/h.

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Table 5.1 Basement averages, pre- and postmitigation (from PFT data)

	House						
	1	2	3	4	5	6	7
Premitigation							
N (number of points)	4	3	2	2	3	2	3
Days (Julian date)	296-364	296-330	296-328	296-323	296-344	296-309	296-330
Radon (pCi/L)	43.64	22.09	152.7	64.43	56.7	18.47	33.38
Infiltration (ACH)	0.767	0.793	0.65	0.50	0.190	3.74*	0.37
Rn source (μCi/h)	8.89	5.28	26.2	7.70	4.83	13.8	3.39
Postmitigation							
N	2	+	3	1	5	**	2
Days	69-85 98-111		56-69 84-114	72-86	57-71 97-105 114-133 156-170		72-85 99-113
Radon	0.17		4.41	3.42	0.59		0.049
Infiltration	0.67		0.17	0.33	0.49		0.085
Rn source	0.03		0.74	0.26	0.06		0.007

* Heat recovery ventilator (HRV) running.
** Zones changed; no comparable data.
\+ House 2 was not mitigated until after PFT measurements ended.

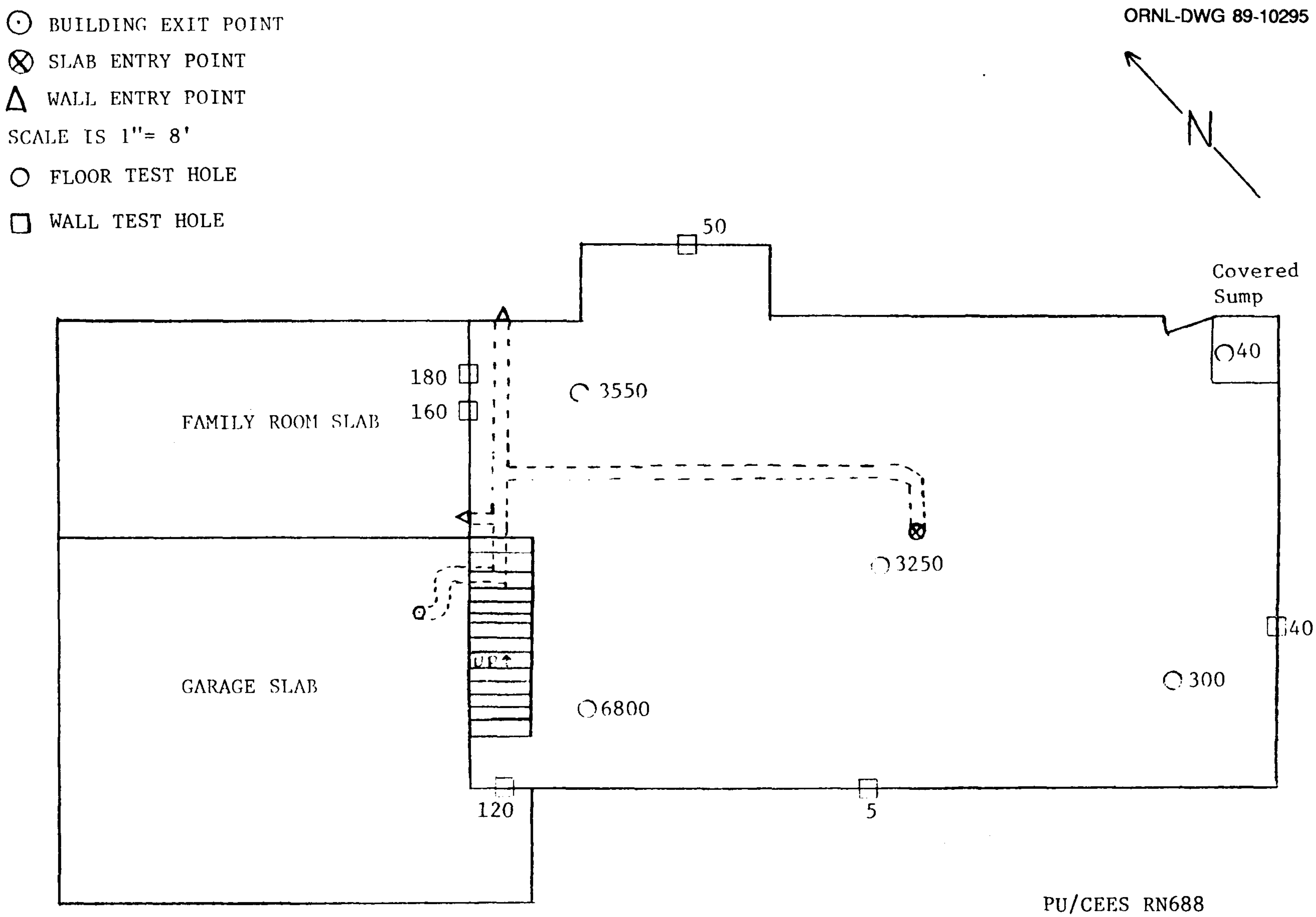
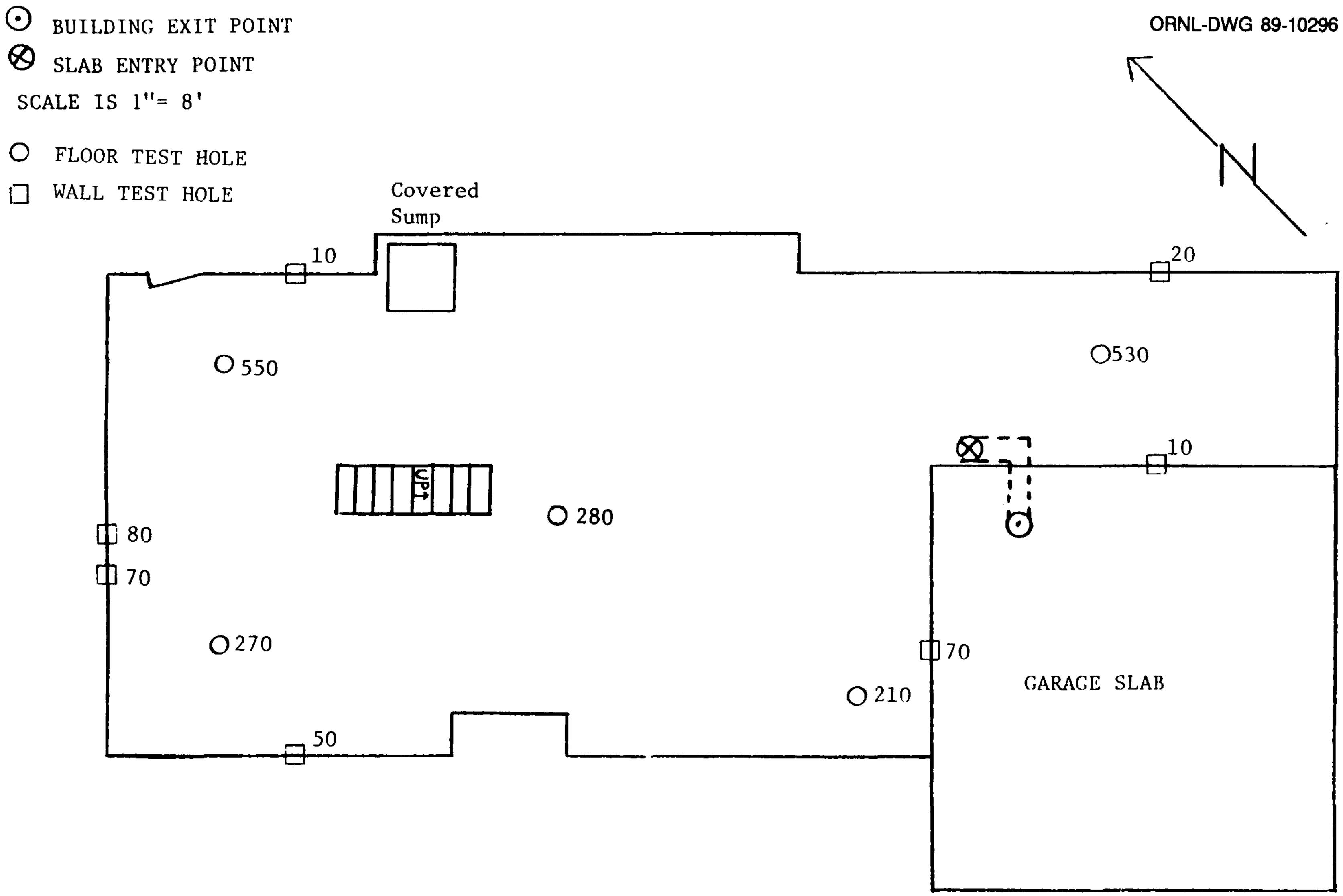


Fig. 5.1. House #1 basement floor plan.

ORNL-DWG 89-10296



PU/CEES RN688

Fig. 5.2. House #2 basement floor plan.

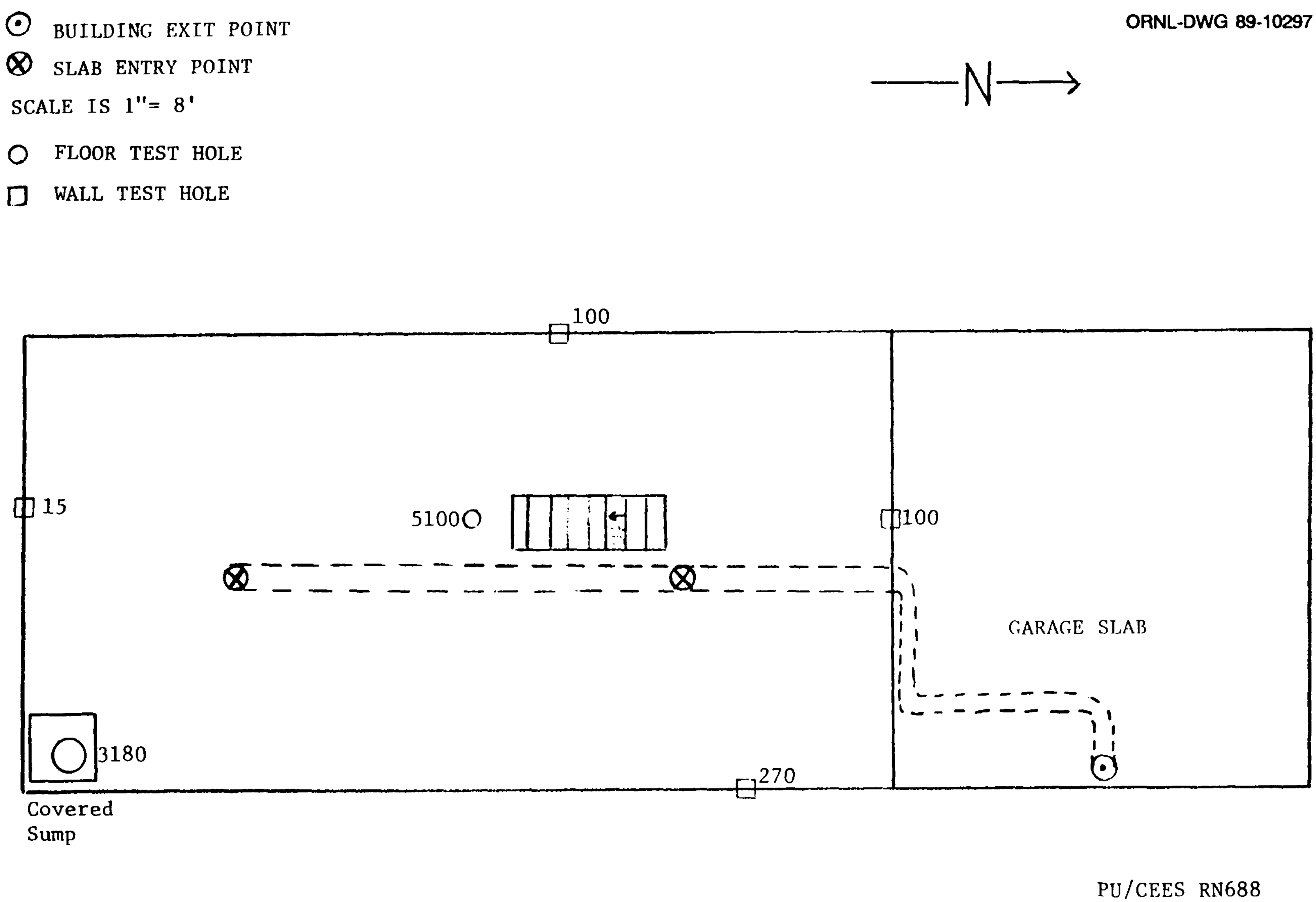


Fig. 5.3. House #3 basement floor plan.

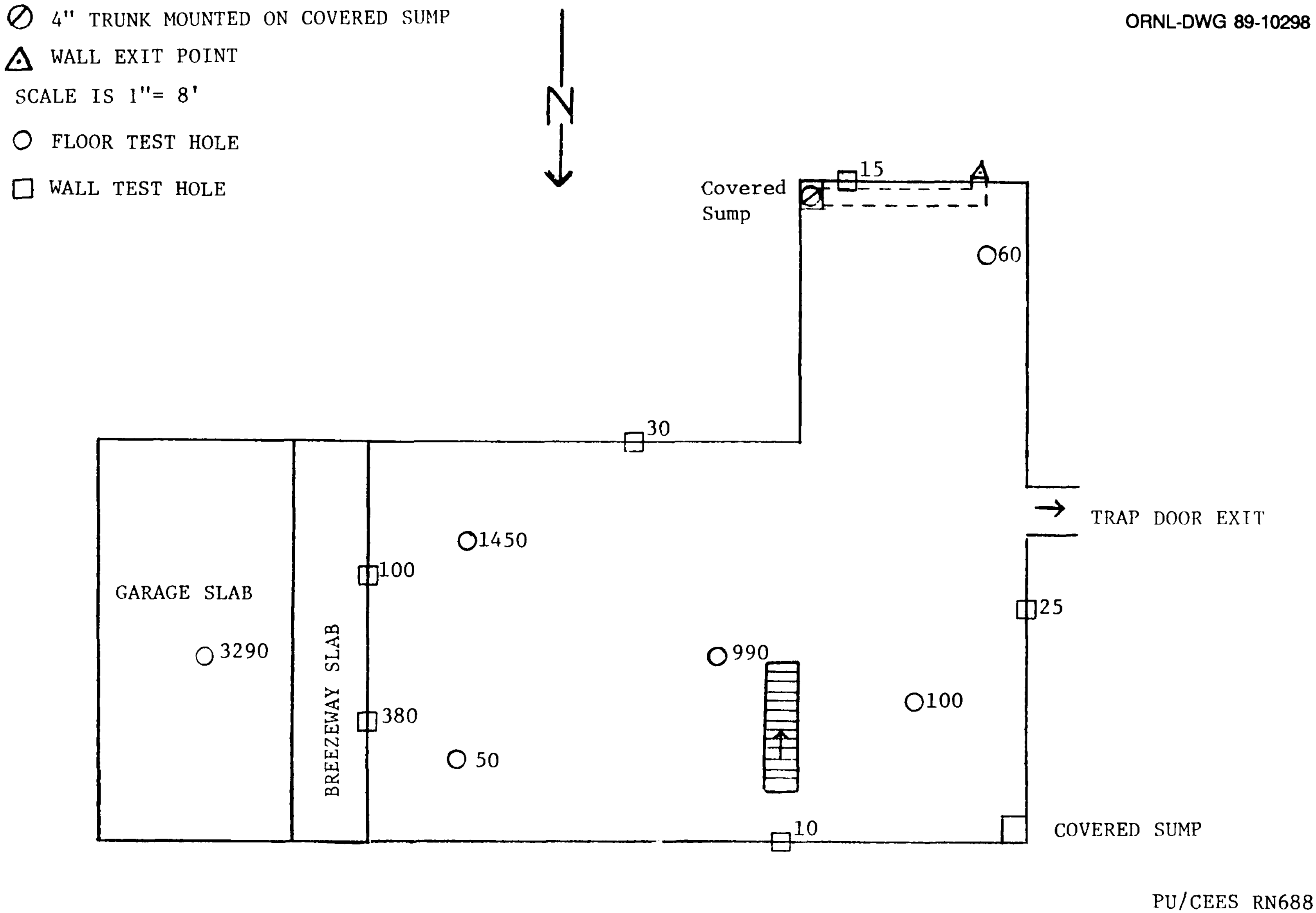


Fig. 5.4. House #4 basement floor plan.

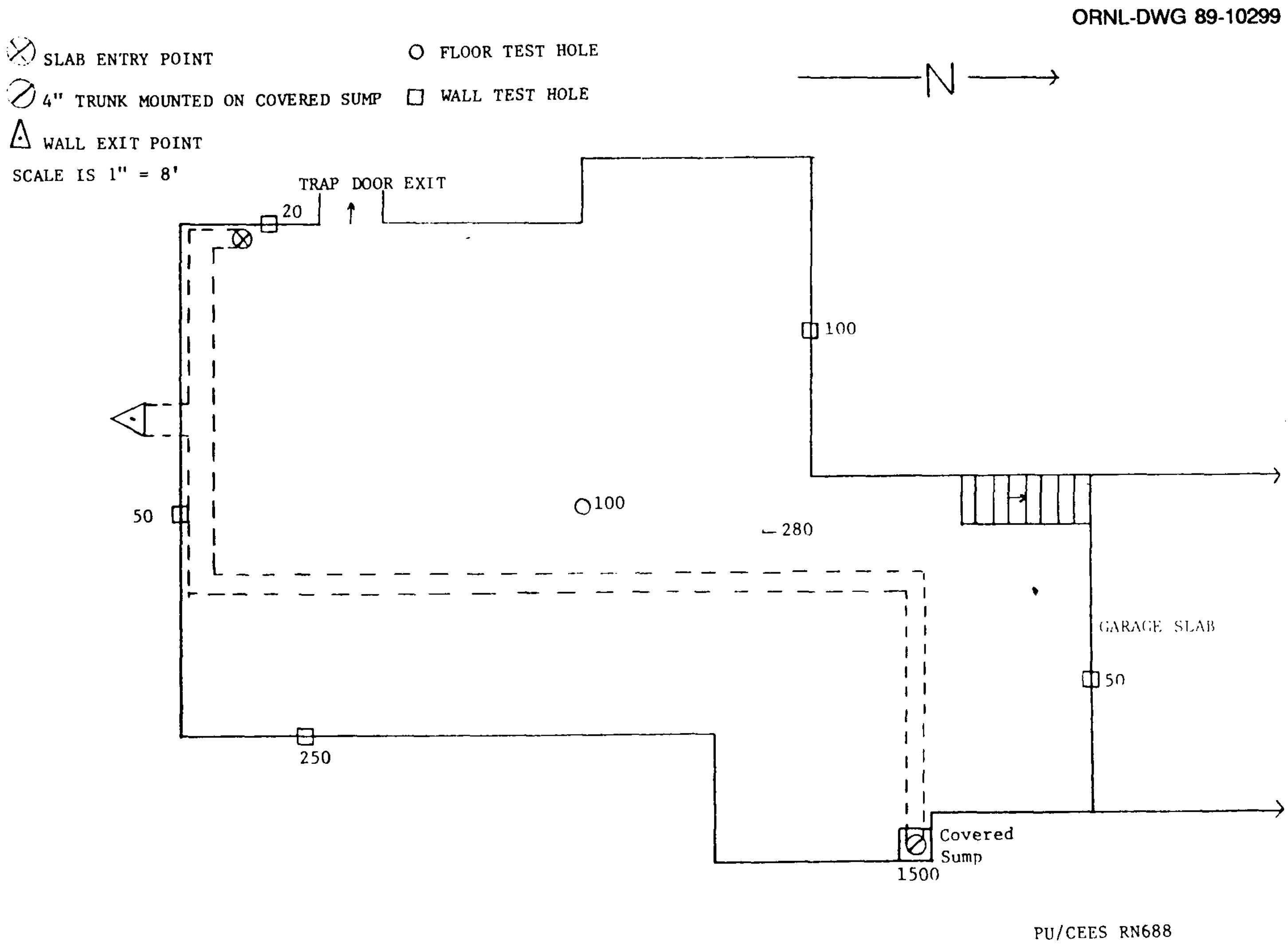


Fig. 5.5. House #5 basement floor plan.

ORNL-DWG 89-10300

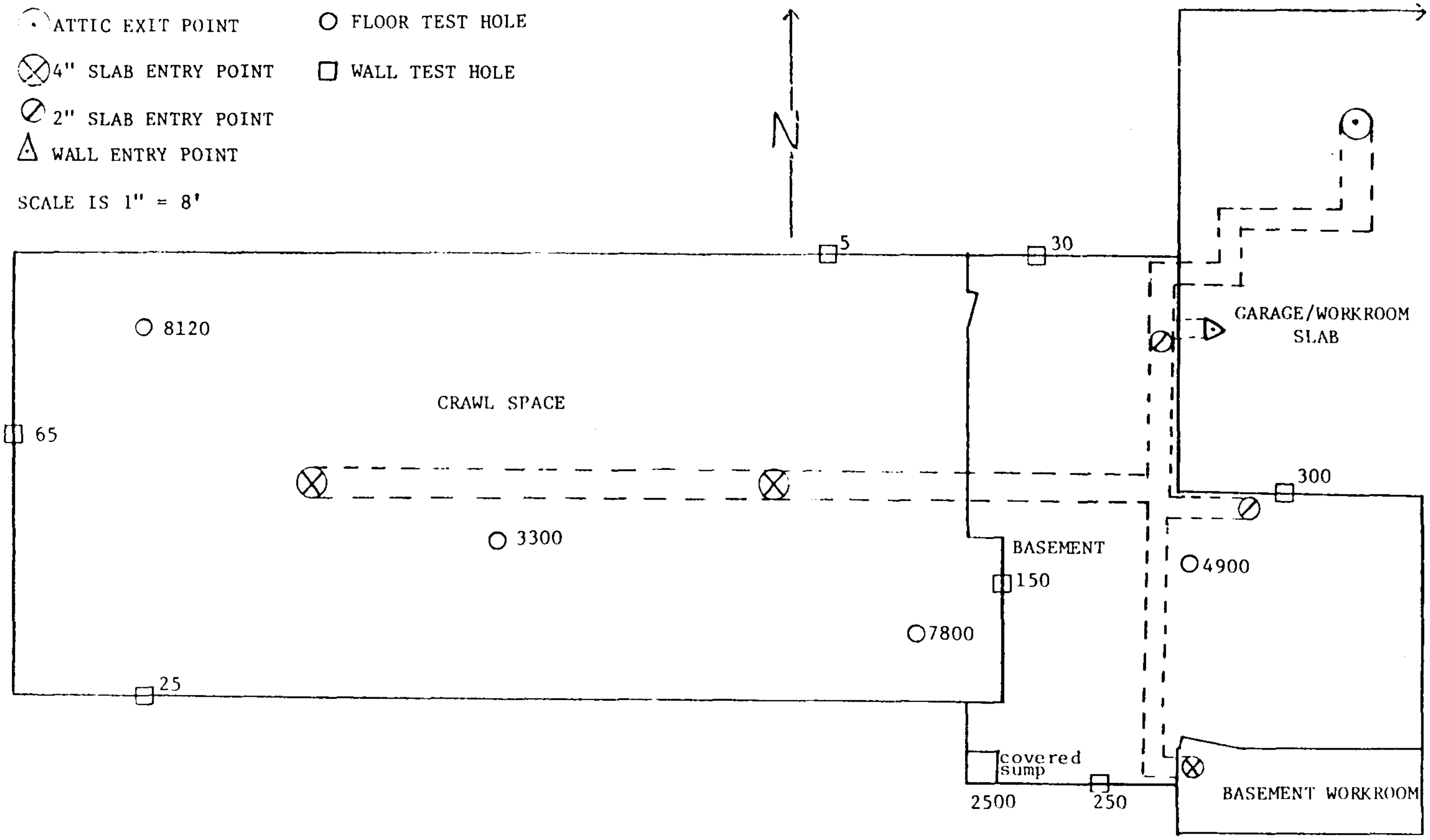


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Fig. 5.6. House #6 basement/crawl space floor plan.

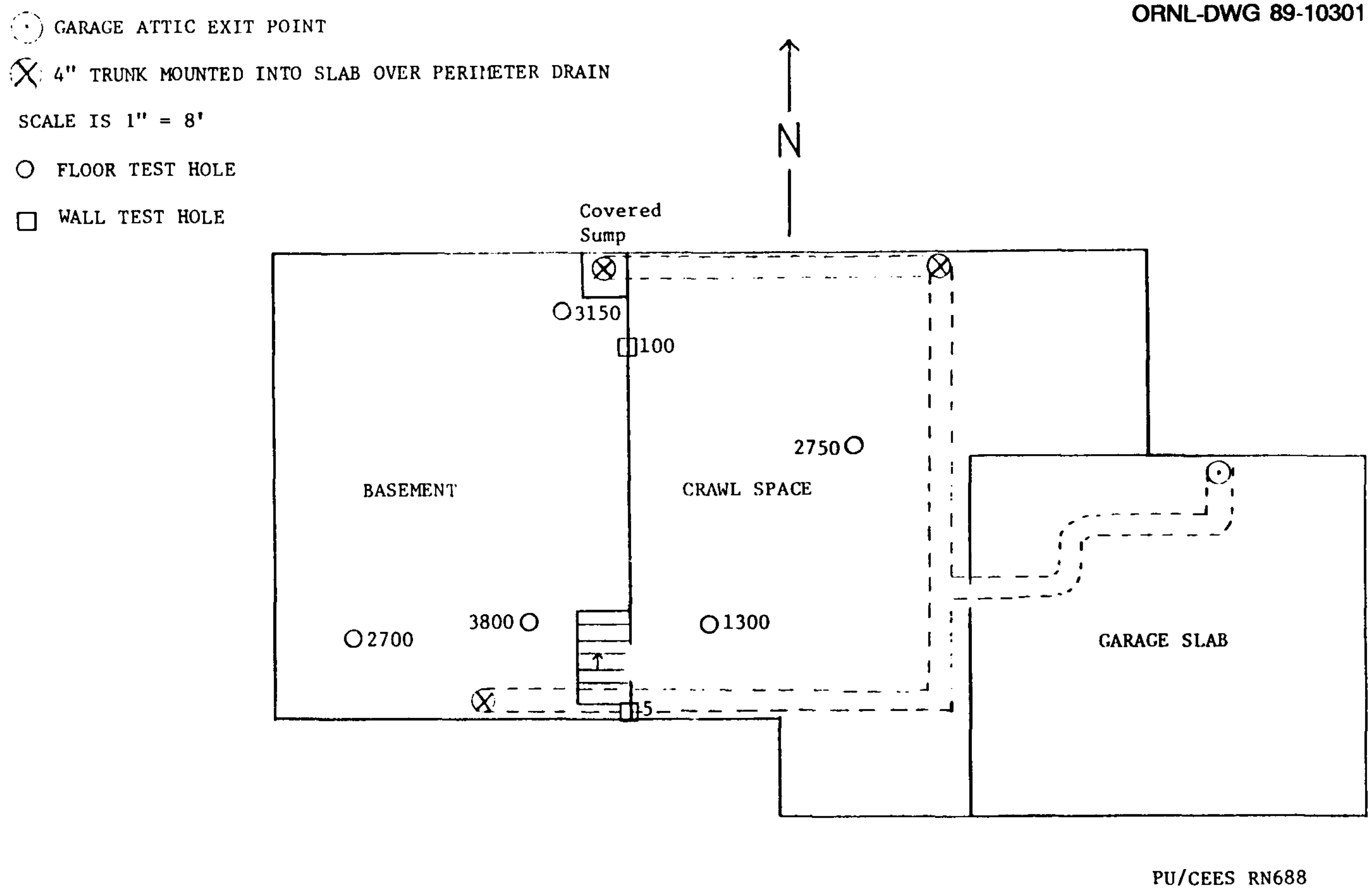

Fig. 5.7. House #7 basement/crawl space floor plan.

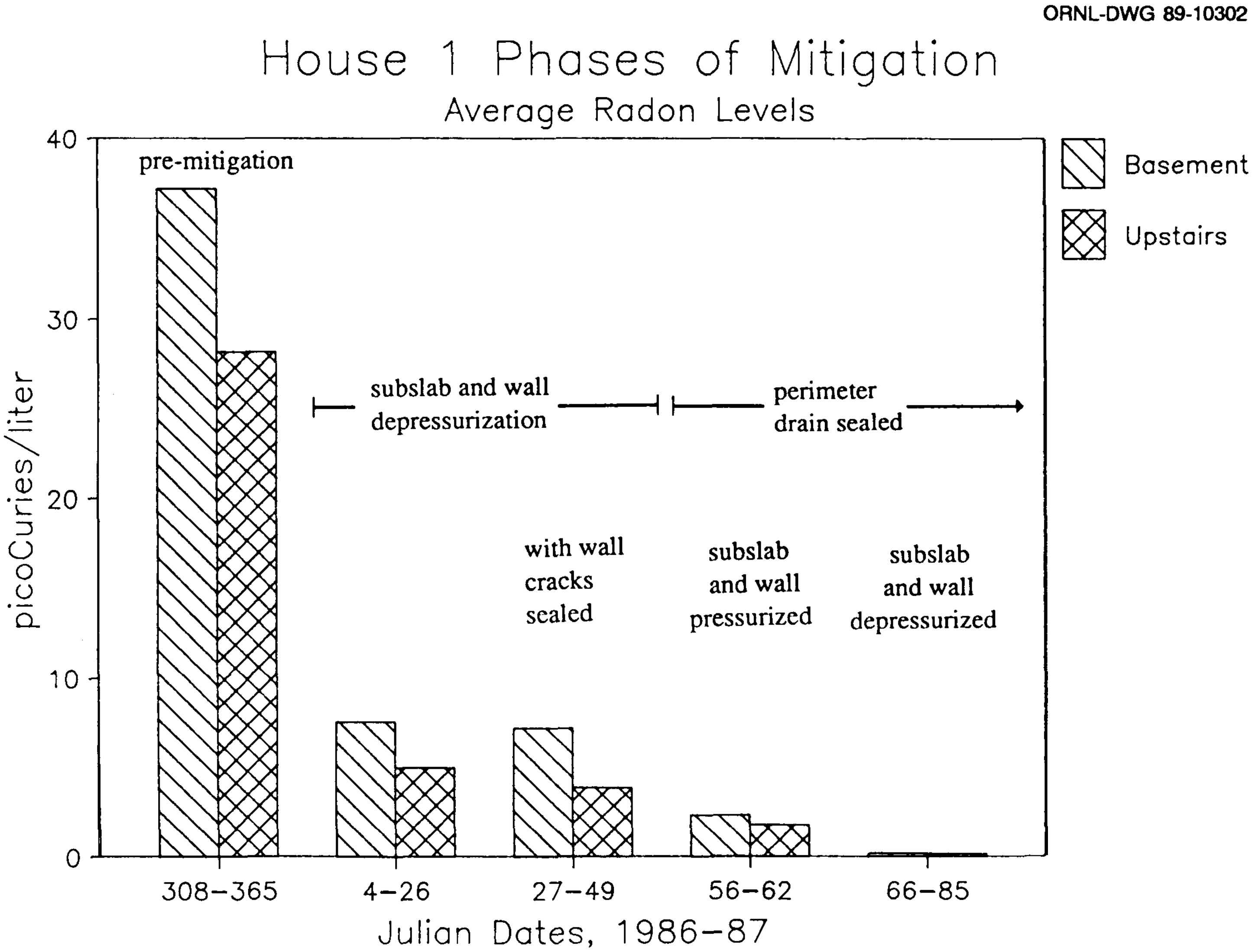

Fig. 5.8. House #1 phases of mitigation.

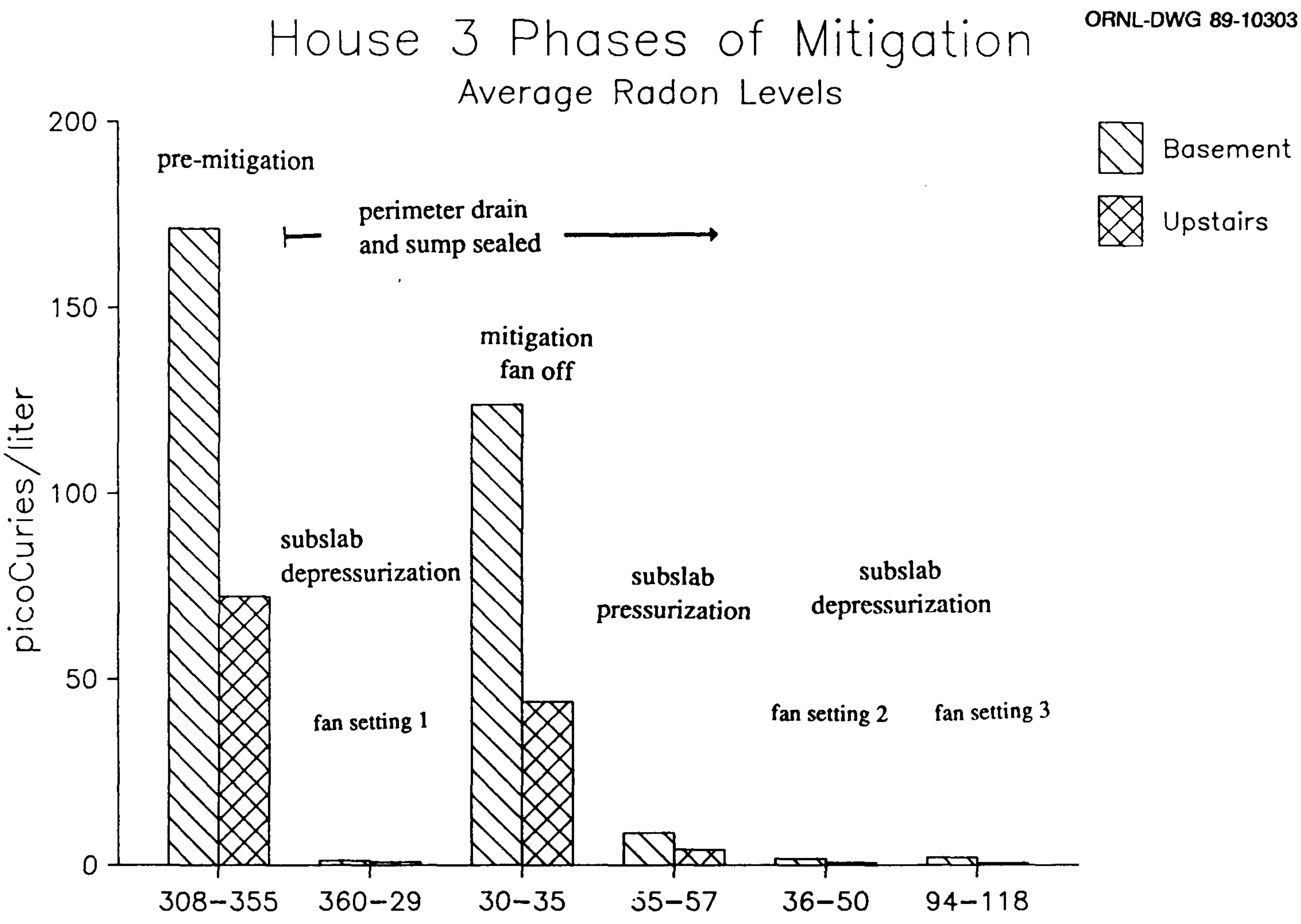

Fig. 5.9. House #3 phases of mitigation.

Fig. 5.9. House #3 phases of mitigation.

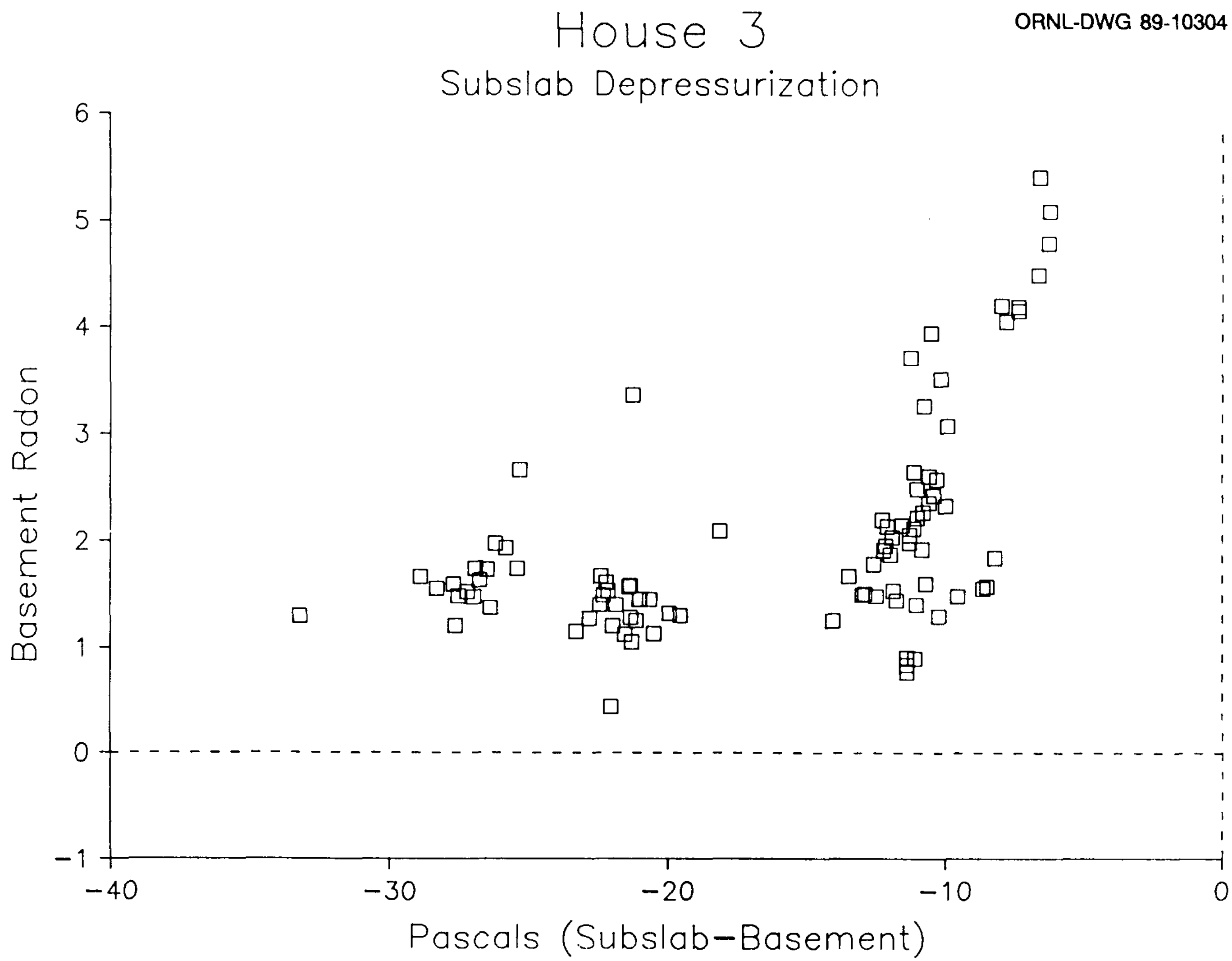

Fig. 5.10. House #3: radon concentration vs. subslab/basement pressure difference.

ORNL-DWG 89-10305

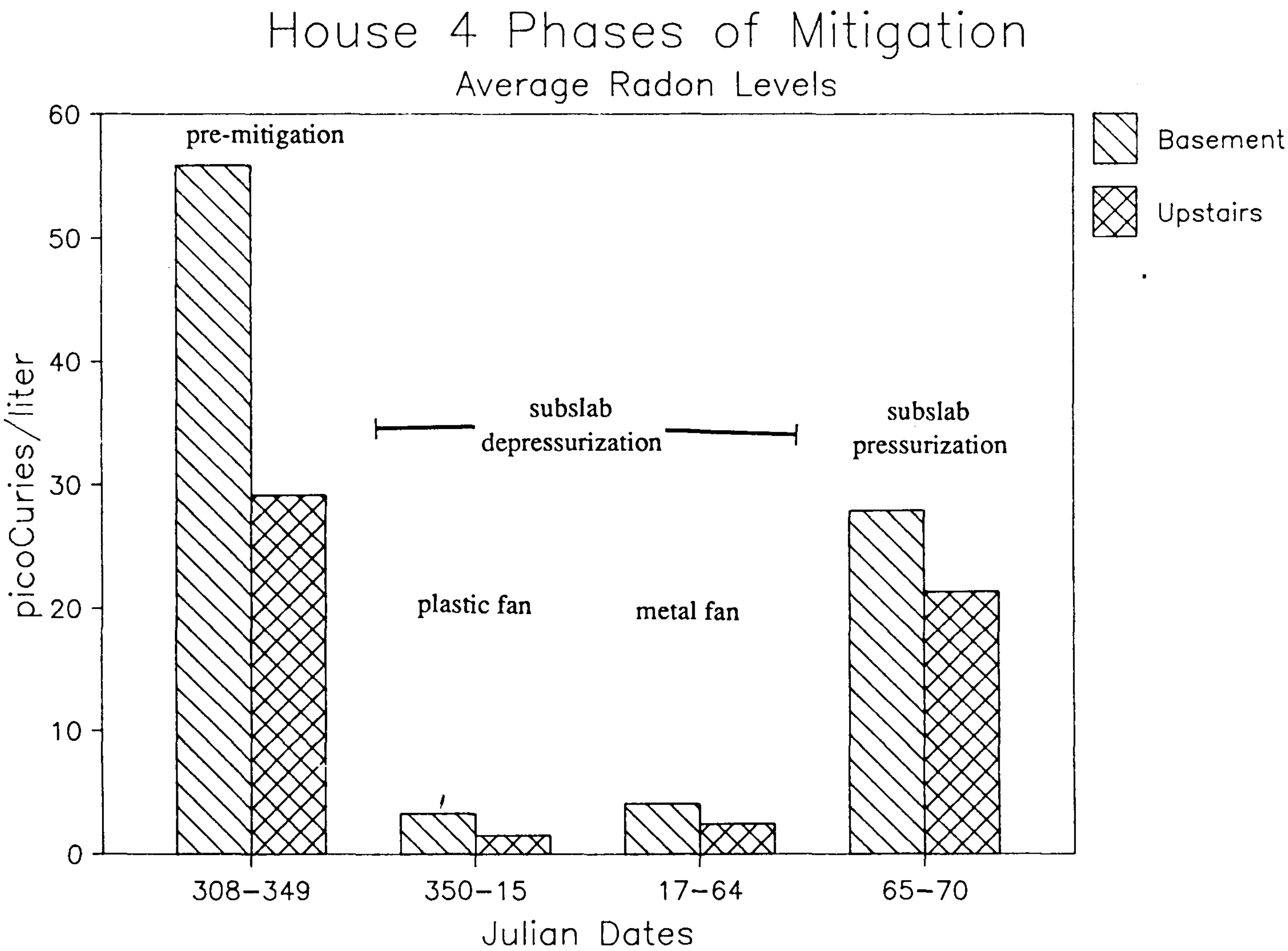

Fig. 5.11. House #4 phases of mitigation.

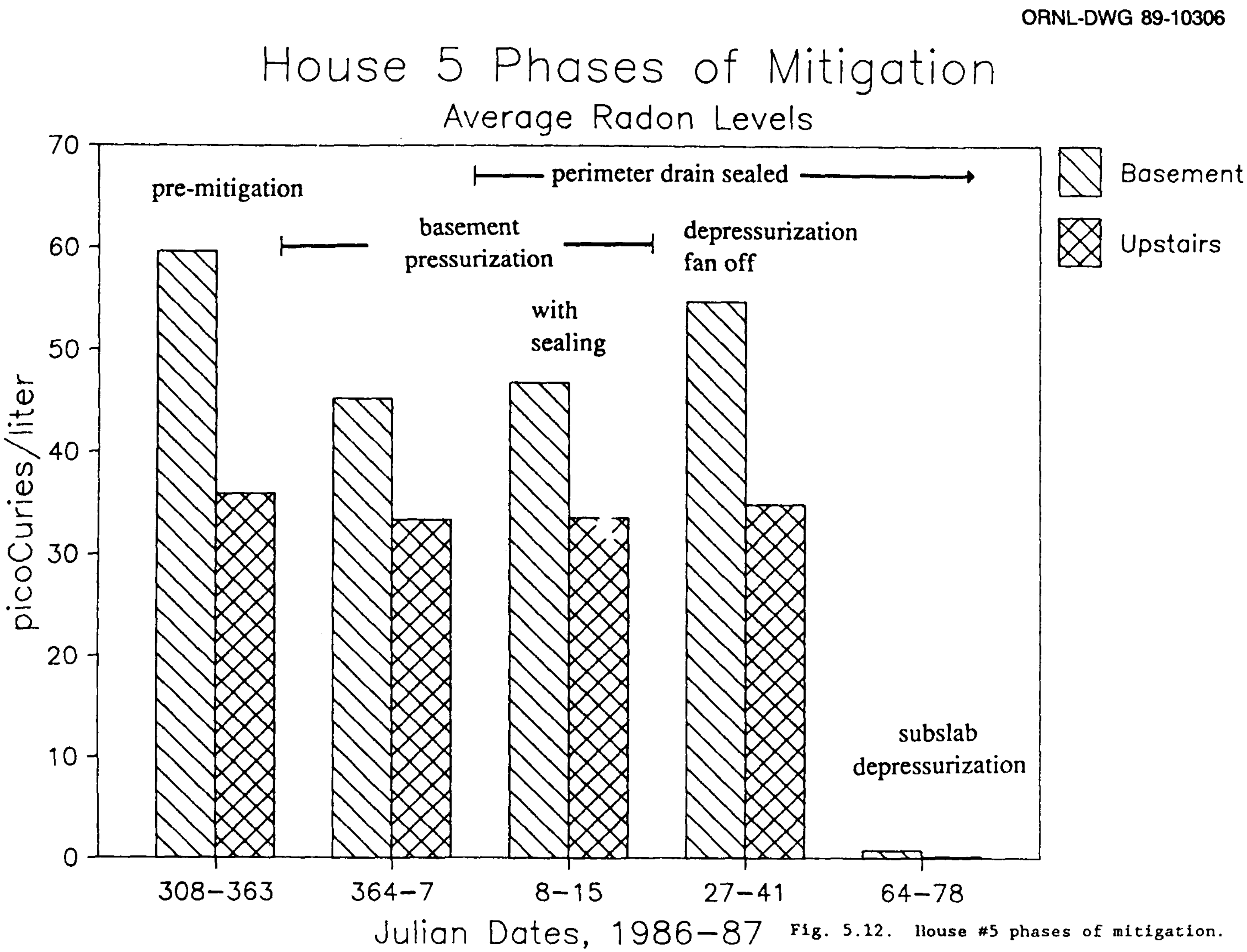

Fig. 5.12. House #5 phases of mitigation.

Fig. 5.12. House #5 phases of mitigation.

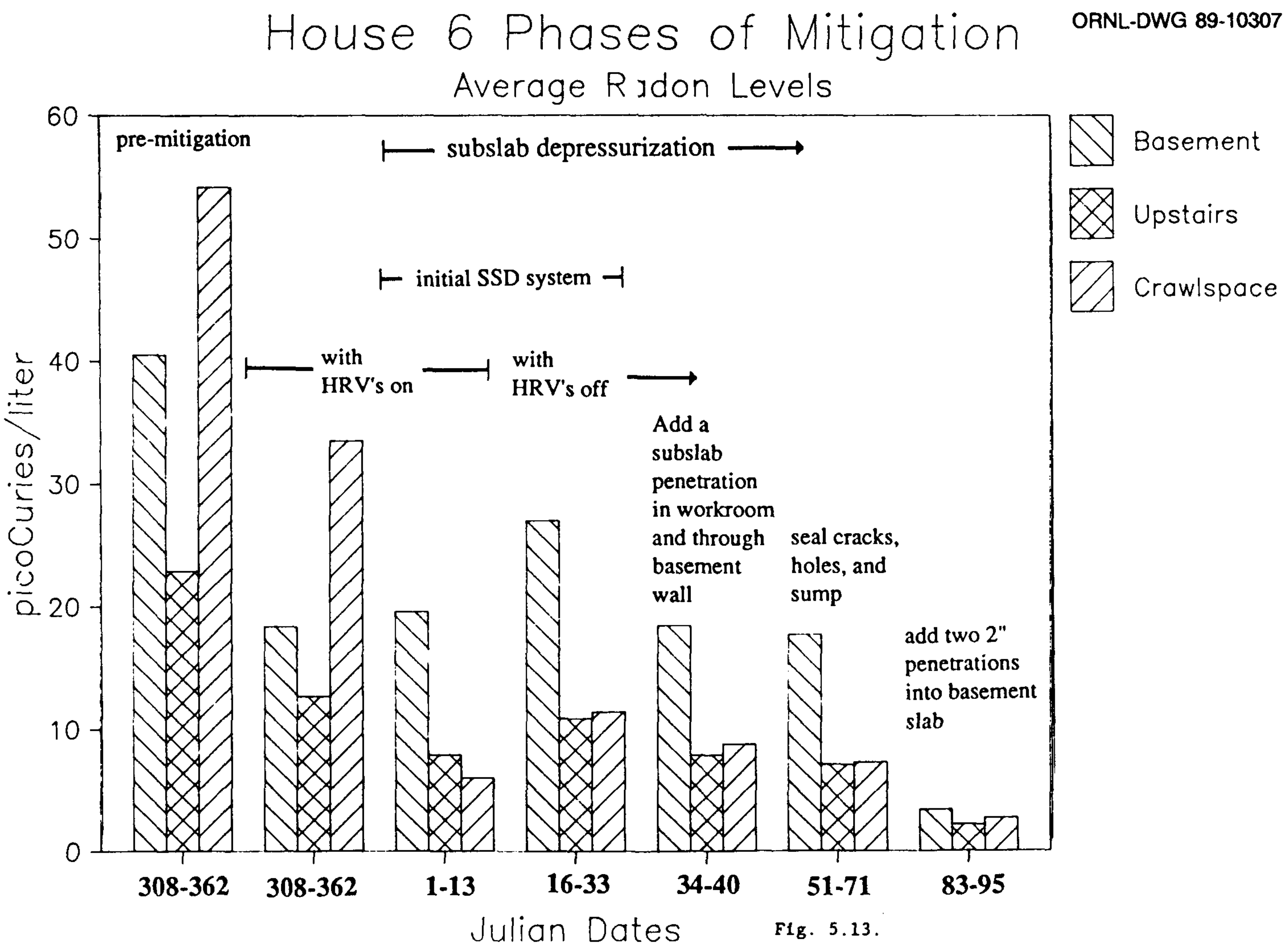

Fig. 5.13. House #6 phases of mitigation.

ORNL-DWG 89-10308

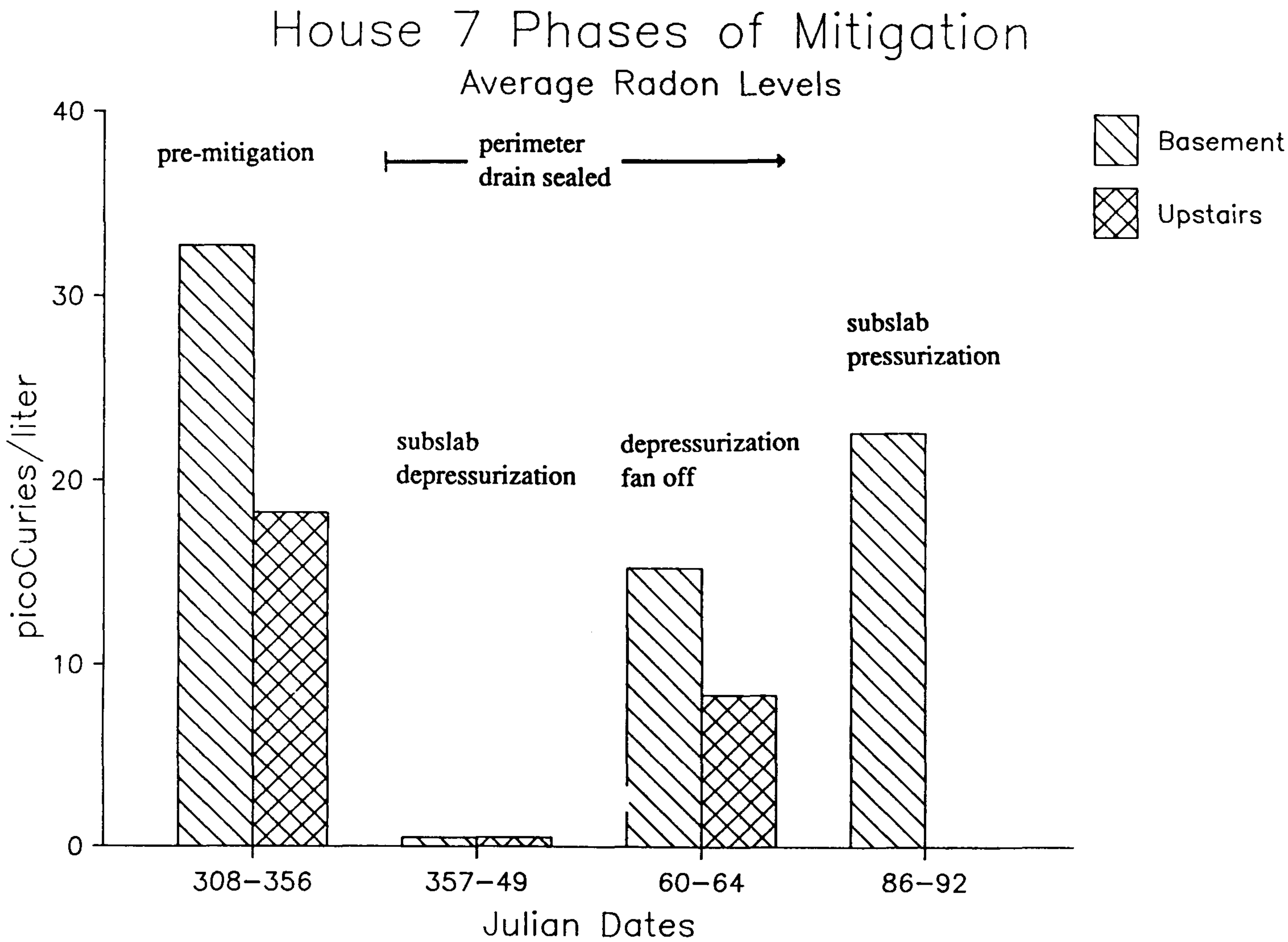

Fig. 5.14. House #7 phases of mitigation.

ORNL-DWG 89-10309

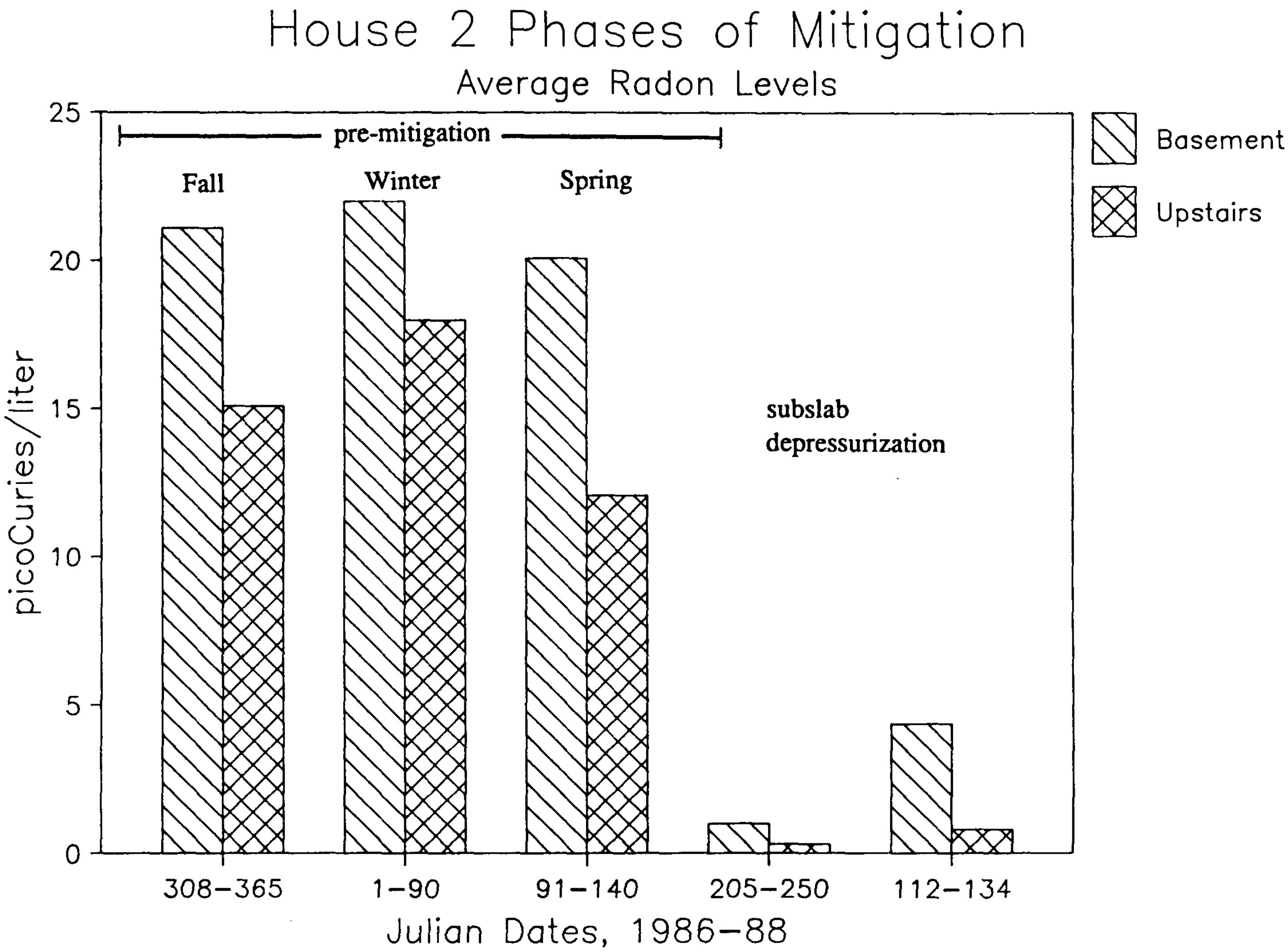

Fig. 5.15. House #2 phases of mitigation.

ORNL-DWG 89-10310

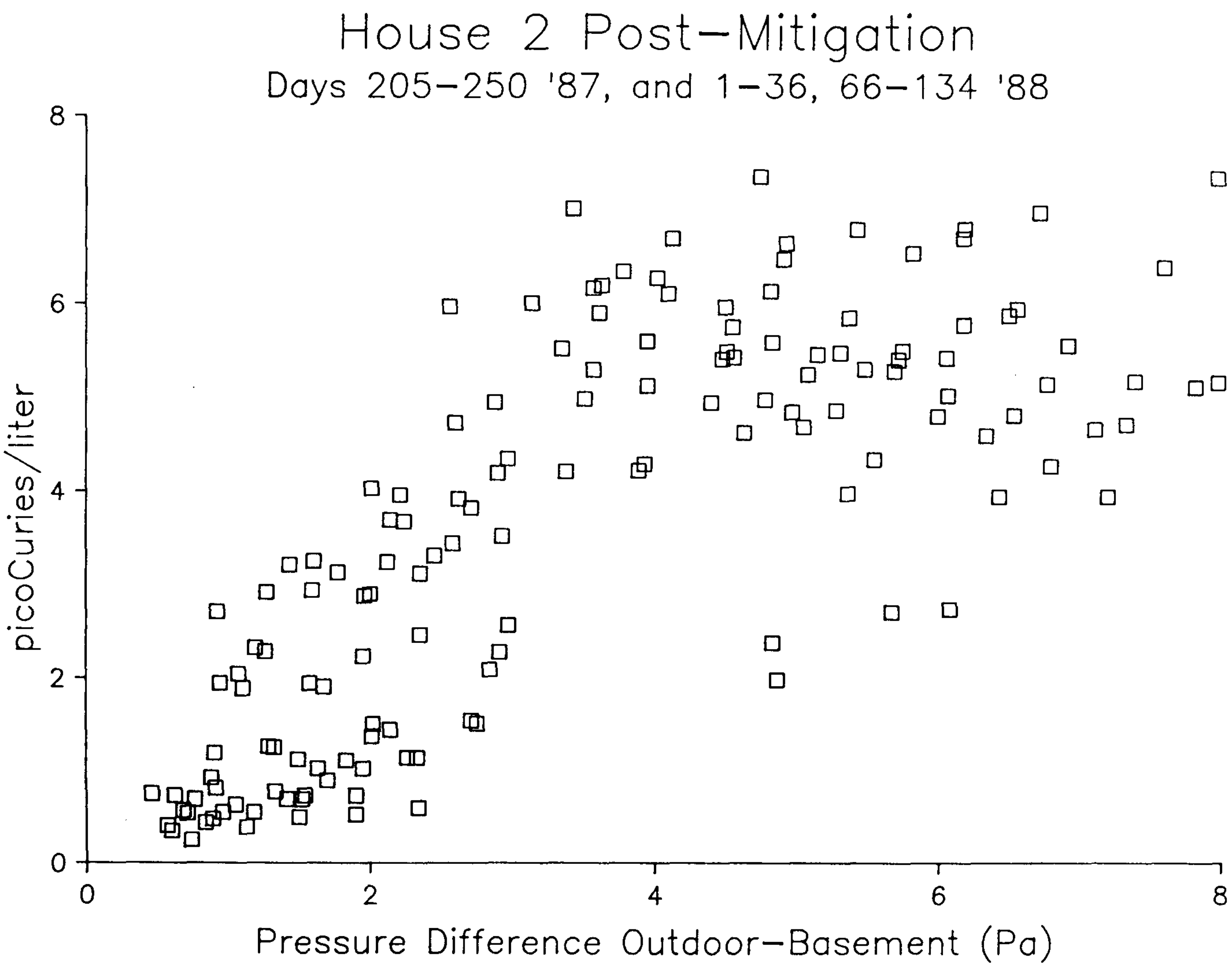

Fig. 5.16. House #2 (pre-mitigation): radon concentrations vs. outdoor/basement pressure difference.

ORNL-DWG 89-10311

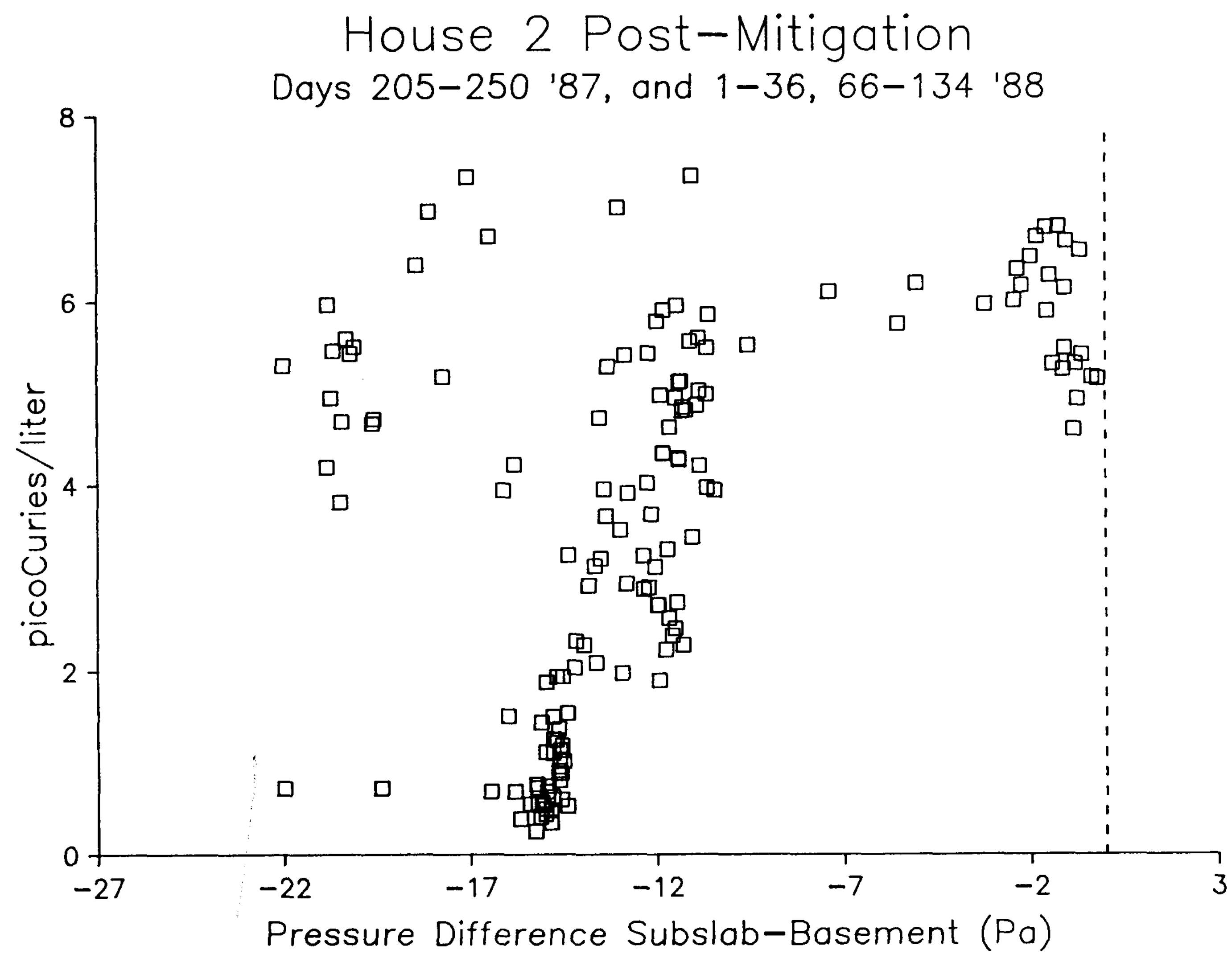

Fig. 5.17. House #2 (post-mitigation): radon concentration vs. subslab/basement pressure difference.

ORNL-DWG 89-10312

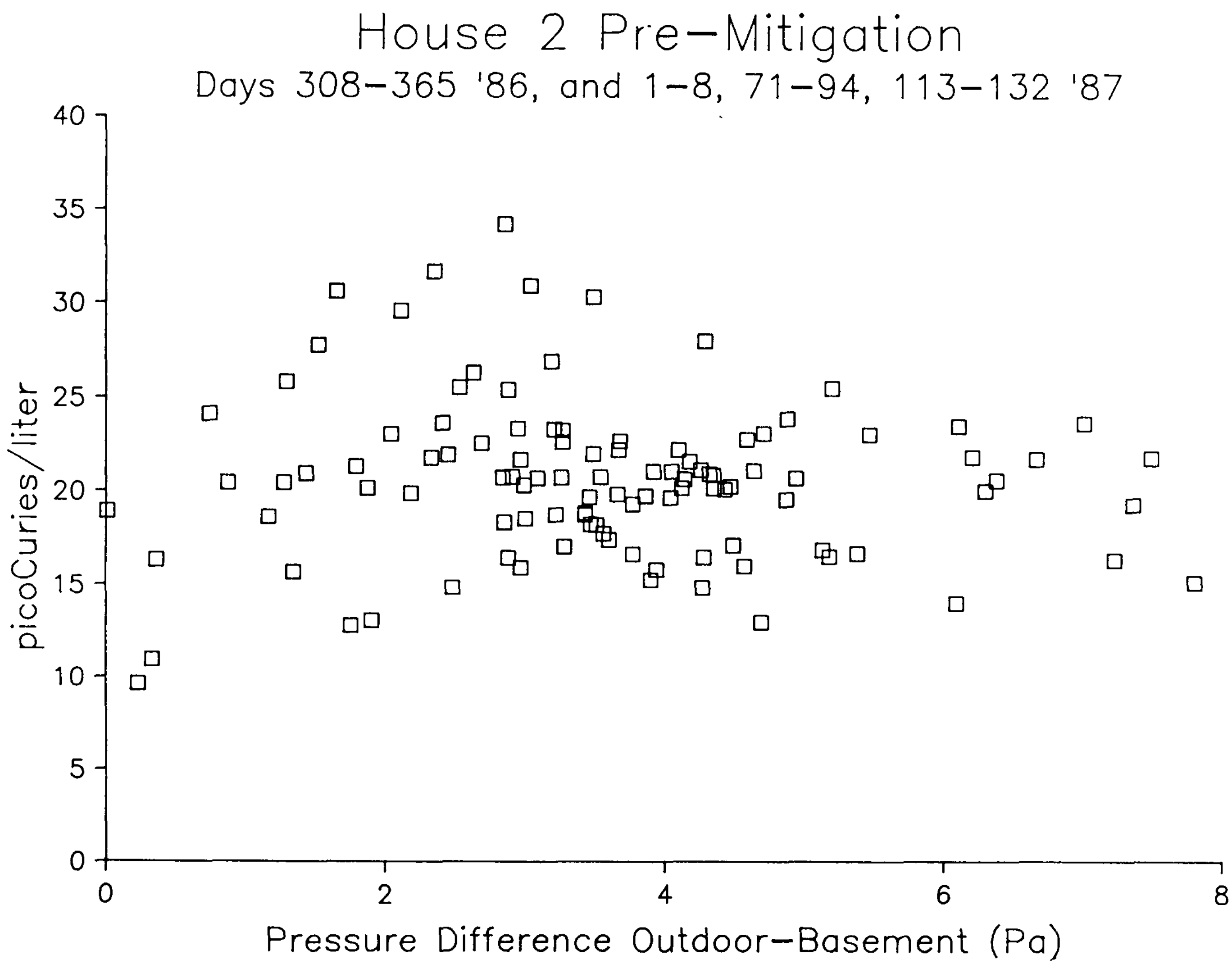

Fig. 5.18. House #2 (pre-mitigation): pre-mitigation radon concentration vs. subslab/basement pressure difference.

ORNL-DWG 89-10313

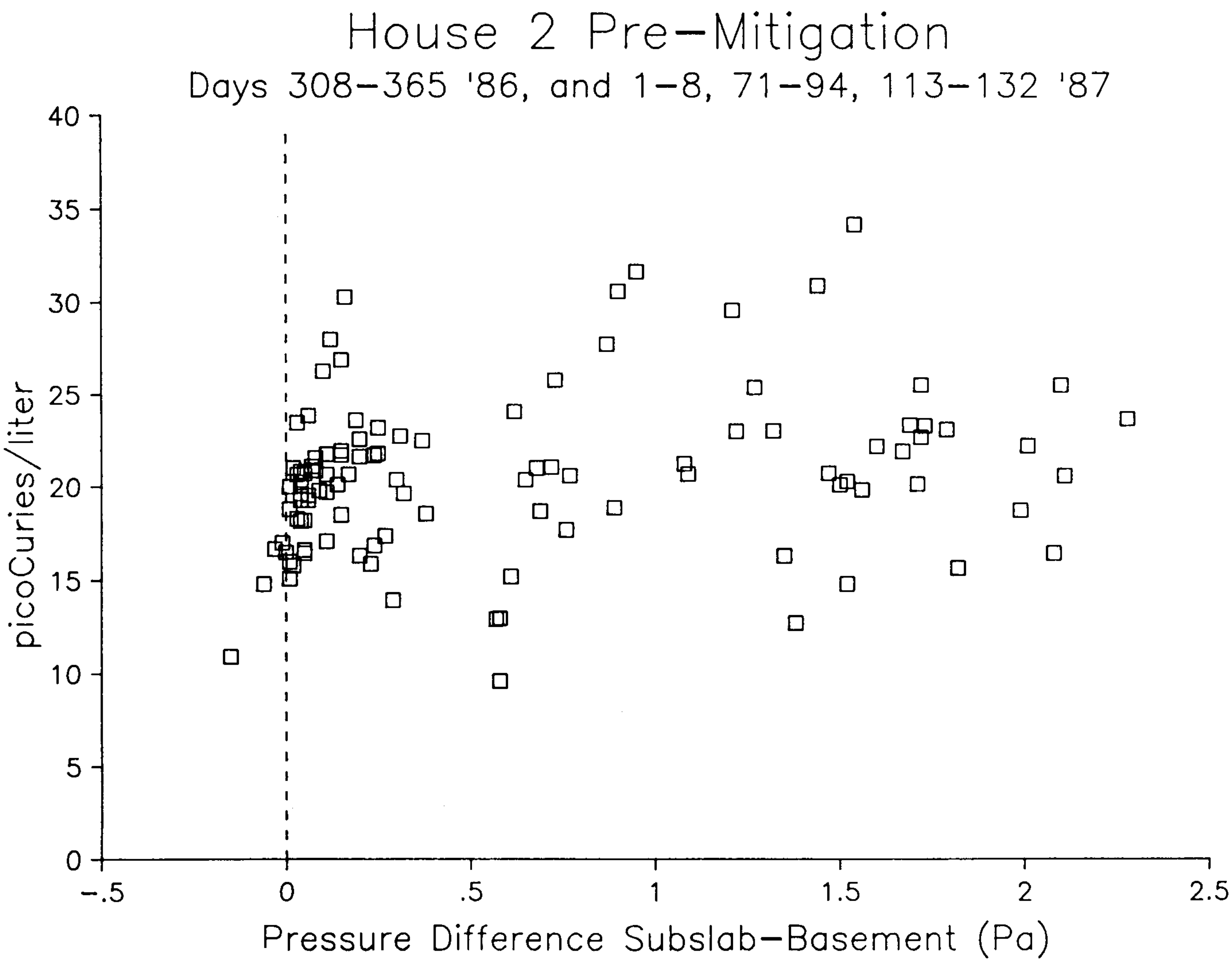

Fig. 5.19. House #2 (pre-mitigation): radon concentration vs. subslab/basement pressure difference.

ORNL-DWG 89-11517

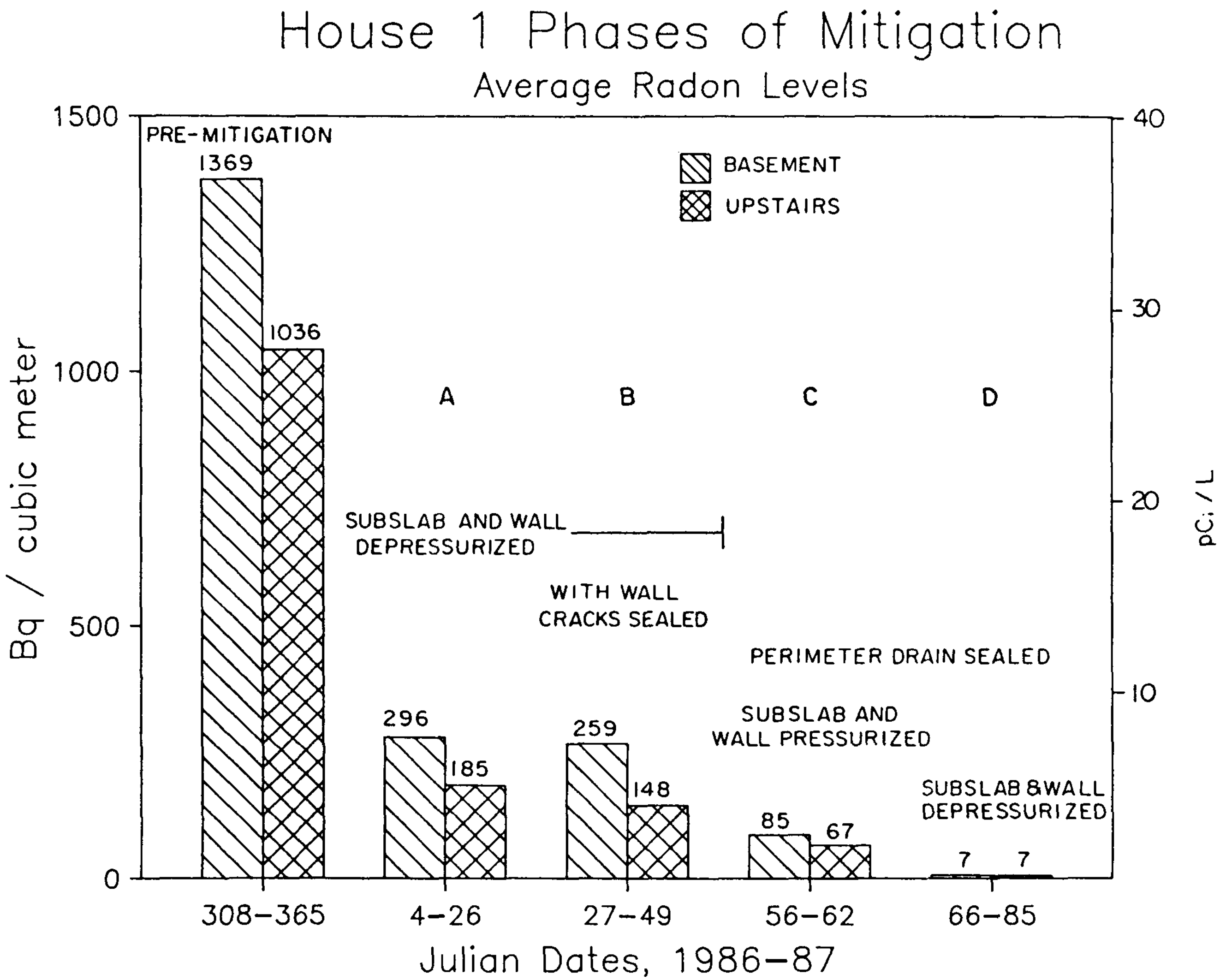

Fig. 5.20. Average basement and upstairs radon levels in house #1 at each phase of mitigation. The number on top of each rectangle is the average radon concentration for that time period.

ORNL-DWG 89-11518

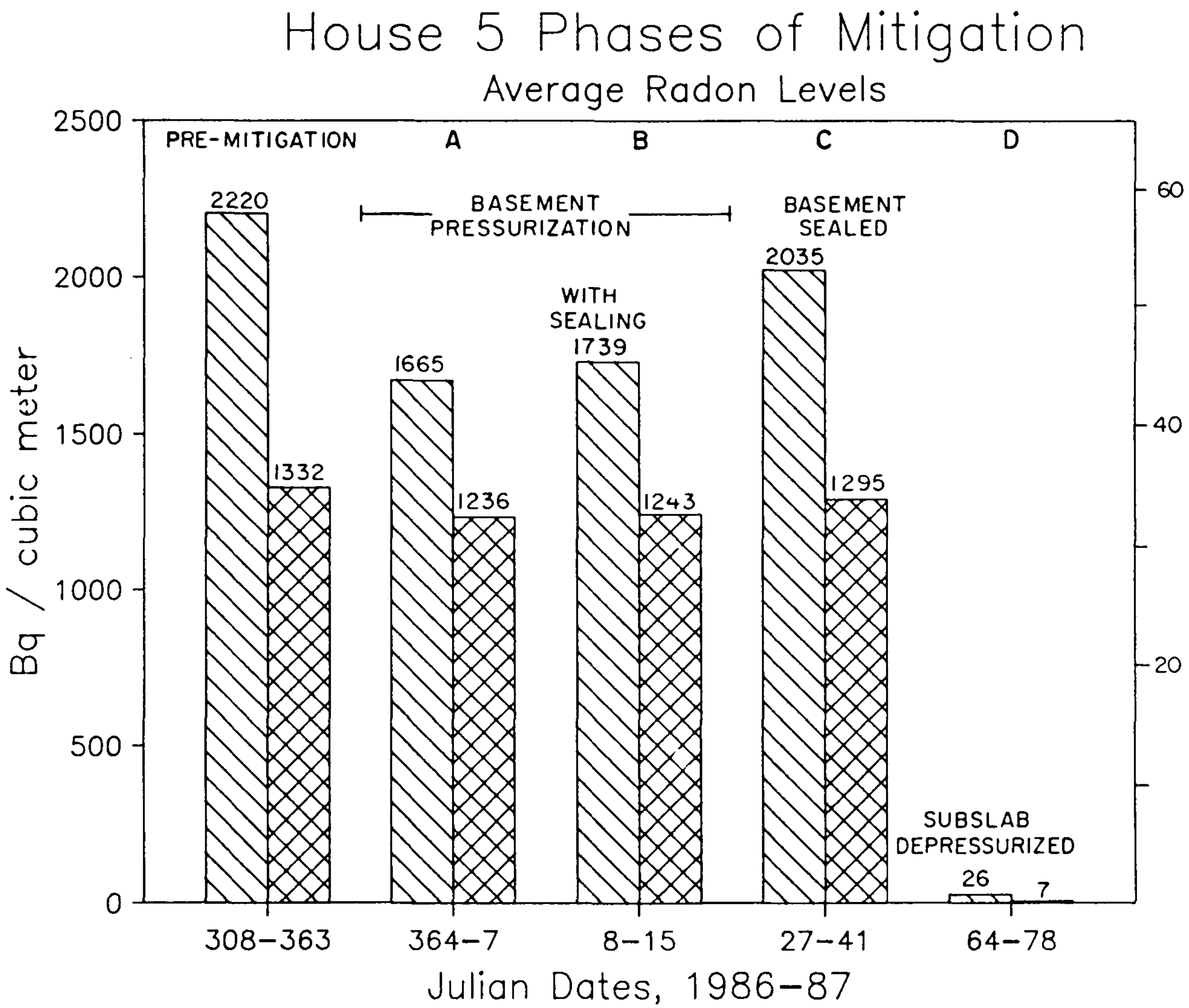

Fig. 5.21. Average basement and upstairs radon levels in House #5 at each phase of mitigation. The number on top of each rectangle is the average radon concentration for that time period.

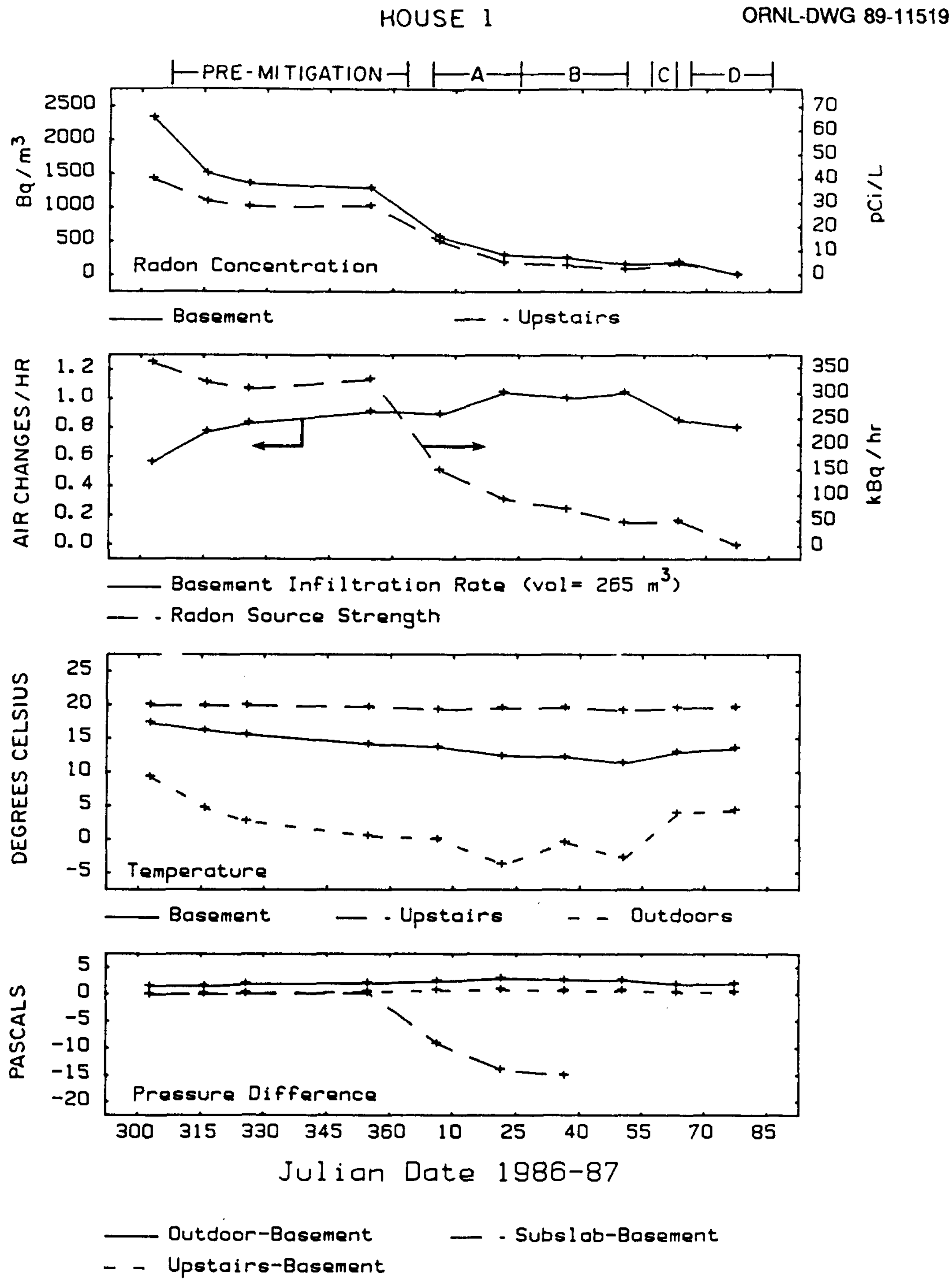

Fig. 5.22. Pre- and post-mitigation data for House #1. The top box in each figure shows the radon concentrations in the basement and upstairs. The second box shows the basement air infiltration rate (solid line) and the radon source strength (broken line). The third box shows the basement, upstairs, and outdoor temperatures. The fourth box shows the difference between the outdoor, subslab, and upstairs pressure and the basement pressure. The more positive these differences are, the greater the relative depressurization of the basement. The points on each line represent the parameter average during the PFT time period. Each time period is 10 to 14 days long. The time periods marked A through D correspond to the mitigation time periods in Fig. 5.20.

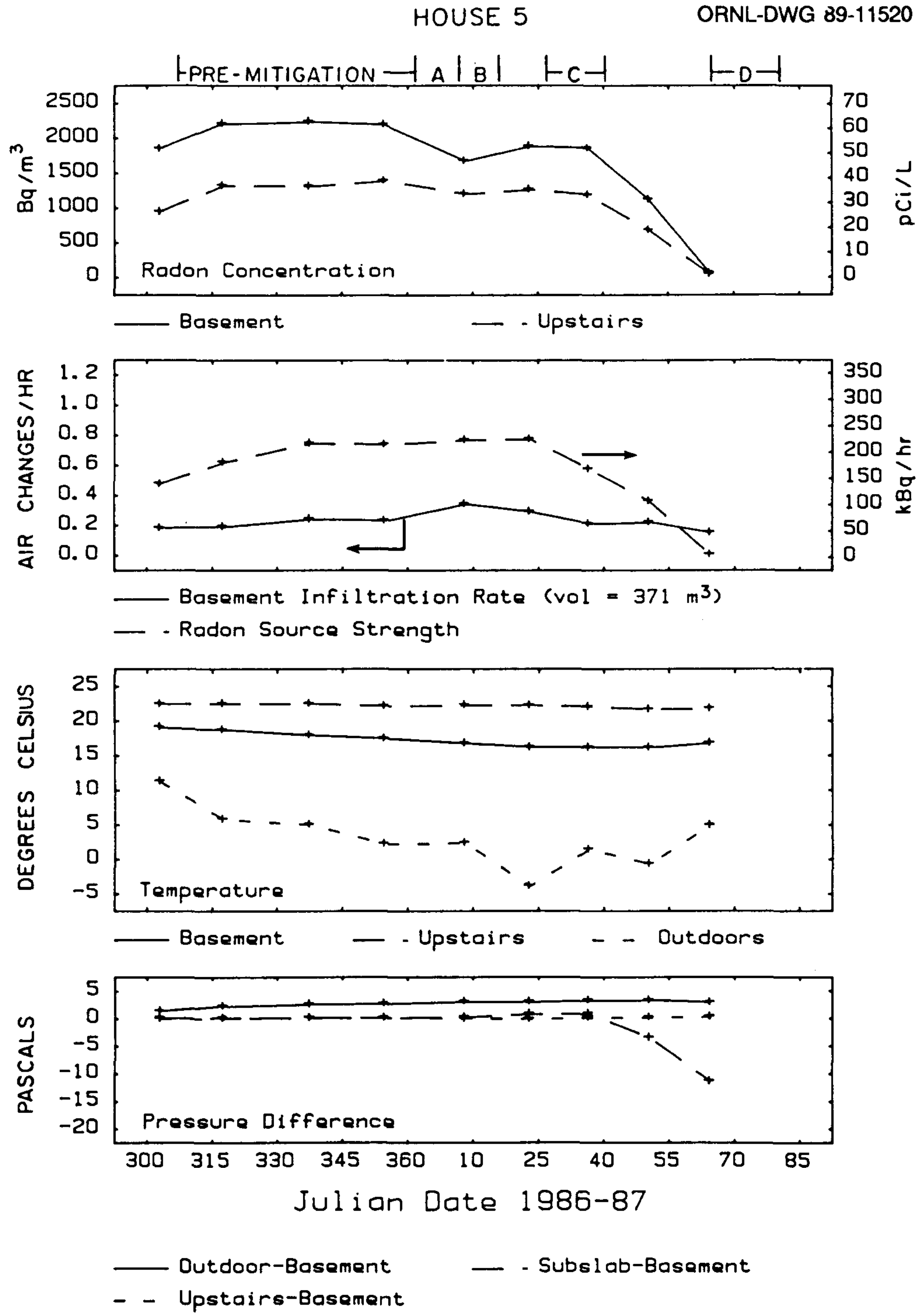

Fig. 5.23. Pre- and post-mitigation data for House #5. Data are organized as in Fig. 5.22.

6. RESULTS OF NONCONTINUOUS MEASUREMENTS AND SPECIAL STUDIES

A variety of routine and special studies that were independent of the continuous data acquisition system have been undertaken in the course of this project. These studies involved the characterization of radiologic and geologic parameters concerning indoor radon and its progeny, the investigation of gaseous transport processes both within and across the building envelope, and calibration activities. Some of the specific measurements highlighted in the following section include measures of total radon progeny and respirable particles, multizone constant concentration tracer gas analyses, soil characterization data, and air exchange data.

6.1 CHARACTERIZATION OF RADIOLOGIC AND GEOLOGIC PARAMETERS

The concentration of radon and radon progeny in indoor air depends on generation and transport of radon from radium-bearing materials to the indoor environment and the characteristics of indoor aerosols. Data related to the investigation of indoor radon and radon progeny that are discussed below include: gamma radiation surveys, geological survey results, radon in well water, radon progeny measurements, and time-weighted-average radon measurements.

6.1.1 Gamma Spectroscopy

At the beginning and end of the study, a combination of PIC and scintillation counter measurements of total gamma radiation was performed during site characterization studies to semiquantify gamma radiation levels. A summary of gamma spectroscopy measures made inside the study homes and on the surrounding property are given in Table 6.1. The data from October 1986 generally agree with the data from July 1987.

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/y), and (3) a 10% occupancy rate outdoors, annual gamma exposures of approximately 90 to 125 mrem are anticipated. This is of similar magnitude to Federal Radiation Council and International Commission for Radiation Protection estimates of average annual population doses (i.e., <170 mrem).

6.1.2 Geological Characterization

A brief geological investigation of the test homes in the Clinton, New Jersey, area was conducted as part of our preliminary 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 (Banino et al. 1970) 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 7 study 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 more than 1 billion years old). The exact number and precise identification of geologic formations in close proximity to the test homes have 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) (Harper 1977) 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. (1970). Additional sampling and analysis are required in this area.

Houses #4 and #6 are identified on the New Jersey DEP geologic overlay (Harper 1977) 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 concentrations of radionuclides were observed (see Table 6.2). 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.

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 (Banino et al. 1970). It is hypothesized from USGS 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 alpha track radon monitors at the study homes, or (2) outcroppings representative of geological formations are reported in Table 6.2. The data are subdivided geologically by the formations anticipated to underlie the study homes. On-site soil samples (i.e., 0 to 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.

House-specific analysis of the soil radiological data in Table 6.2 yields several points of interest. Representative off-site samples from a postulated zone of limestone in the Martinsburg shale formation that is anticipated to underlie House #1 yielded twofold to fourfold 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 6.2) and gamma radiation count rates (Table 6.3) decrease from the outcrop in the front yard to the backyard. Samples taken from Houses #4 and #6 and representative (off-site) gneissoid granites have highly variable radium content. Greater than order of magnitude variation is observed (1) between on-site-representative and front/backyard soil samples and (2) between various constituents of off-site 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 twofold to fivefold higher in radium content than off-site 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 alpha track radon monitors, and (2) locations where on-/off-site 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 DOE (1985) are confirmed by the field gamma measurements as well as the soil analyses. Two to three orders of magnitude variation in radium content was observed in samples of soil and representative rock outcrops (Table 6.2). One to two orders of magnitude variation in total gamma counts was also observed for the data set provide in Table 6.3. For House #1, a 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 was observed between front yard and backyard locations and a nearby off-site location at House #6. Variations of 15-80 x 10^3 counts and 5-40 x 10^3 counts were observed at individual outcrops on-site at Houses #4 and #6, respectively (Table 6.3). 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 area probably contributes to significant home-to-home variations in indoor radon levels. House #6 is a specific example. Neighboring homeowners about ¼ 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 microgeological 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, particularly in 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.

6.1.3 Radon in Well Water Samples

Well water samples from the five test homes which obtain their water from wells were analyzed for their ^{222}Rn content by Hohmann and Key (1987) using the method of Key (1983). A summary of the findings is given in Table 6.4. 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 et al. (1981). Average results of 2800, 5800, and 25,900 pCi/L were found in wells of Houses #3, #6, and #4, respectively. These homes are anticipated to lie over geologic formations of Precambrian granitic rock. Houses #1 and #5 are anticipated to lie over a Martinsburg shale formation and had lower concentrations of 1300 and 800 to 920 pCi/L, respectively. The higher radon concentrations in well water appear to be associated with the granitic rock.

6.1.4 Radon Progeny

At various times during this study, potential alpha energy concentrations (PAEC) from short-lived airborne radon progeny were measured. Pumped samplers were left near either the basement or upstairs radon monitor for approximate one-week intervals, during which hourly readings were recorded. A summary of the time-weighted-average radon progeny data and simultaneous time-weighted-average radon data collected during the study is provided in Table 6.5. The basement data do not indicate that there was a substantial effect on the working level ratio (i.e., 100 times radon, in pCi/L, divided by PAEC, in WL) resulting from installation of radon mitigation systems. It should be noted that after mitigation, the levels of both radon and radon progeny are very low compared to the limits of detection. There does appear to be a substantial difference between basement and upstairs working level ratios. Figures 6.1 and 6.2 summarize regression analyses of the PAEC data measured at basement and living area sites, respectively. In the opinion of the authors, one pair of data, measured at House #2, appears to be an outlier compared to the rest of the basement data. Therefore, the regression was computed both for all of the data and for all except the indicated outlier. The results from both regressions are shown in Figure 6.1. Although there were not as many living area measurements as basement measurements, it is clear that per unit radon gas there are lower levels of PAEC at basement sites compared to living area sites. This suggests that the points of entry for radon into these houses are in the basements.

6.1.5 Integrated Radon Measurements

Integrated measures of radon levels were performed in all of the houses with passive alpha track monitors during the course of the study. A comparison of the integrated radon data with the average of simultaneous instrumented (i.e., real time) data is provided in Table 6.6. The agreement between the two measurement techniques was reasonably good as seen in Figure 6.3.

6.1.6 Soil Characterization: Radon and Permeability

Soil characterization measures consisted primarily of (1) radiological analyses (see Table 6.2), (2) quasi-seasonal exposures of alpha track radon monitors (see Table 6.7), (3) intermittent grab samples of soil gas (see Table 6.7), and (4) intermittent field measures of soil permeability (see Table 6.8). Unfortunately, much of the data for each methodology is characterized by less than desirable reproducibility between different sampling periods at individual houses. Although soil gas concentrations can be variable, some sources of measurement inconsistency are readily identified.

The radon soil-gas grab samples and alpha track monitor radon monitor results show large intermethod and inter-sampling period discrepancies. For the grab samples, the comparatively low grab sample results taken prior to April 1987, (e.g., see 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 to 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 alpha track radon monitor results show approximate order of magnitude discrepancies between fall and winter/spring exposures. Soil alpha track monitor results generally do not compare with those of grab sampling. For example, an approximate 30-fold increase in radon from the front yard to backyard was determined at House #2 via grab sampling. Alpha track monitor data from the front yard and backyard were very similar. The opposite case was observed for House #6. Front yard to backyard variation was less than twofold for grab sample measures but 14-fold for the alpha track radon monitors.

Soil permeability was measured at selected sites near the houses throughout the study, and the results are presented in Table 6.8. Measurements made in November 1986 and in June 1987 agree within a factor of 2 to 3 for most measurement sites. At Houses #3, #5, #6, and #7, the June measurements were made with the mitigation system fan operating and not operating. Very little difference in apparent permeability was observed. At House #4, there were occasions when there was no measurable flow in the permeameter, and it is believed that those are times when the water table was very near the surface.

6.1.7 Respirable Particulate Measurements

Particulate sampling and analysis in the New Jersey studies consisted of intermittent, week-long sampling experiments for respirable particles. A particulate sampling unit developed by the Harvard School of Public Health with an approximate 2.5-μm cut was used (Spengler et al. 1985). The data, are summarized in Table 6.9. The presence of smokers in Houses #2 and #7 is evident; order of magnitude higher particulate concentrations are observed in comparison to nonsmoker homes. Comparisons of particulate concentrations in basement and upstairs locations are inconclusive.

6.2 AIRFLOWS INTO AND WITHIN HOUSES

The rates at which air moves among the various compartments of a house strongly affect the spatial and temporal distribution of radon. Data discussed in this section include measurements of building leakage using blower doors and measurements of air exchange using active and passive multicompartment systems.

6.2.1 Building Leakage

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 vs 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 air exchange rate, in ACH, by measuring the rate of airflow through the building envelope over a range of inside-outside pressure differences. A pressure difference of 50 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 to 15 ACH range as leaky, 6 to 8 ACH range as desired, and 0 to 3 ACH as very tight. The blower-door data in Table 6.10 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 to 8 ACH.

Looking at all of the 7-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 true partially 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 6.10). 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.

6.2.2 Building Air Exchange

6.2.2.1 Continuous measurements with CCTG system

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, den, living room, dining room, kitchen, and laundry room. Also, after the mitigation system was installed, the concentration immediately downstream of the mitigation fan was monitored. This measurement provided information on the movement of basement air into the mitigation system.

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

A second CCTG system was installed in House #7 on June 2, 1987, and began taking measurements. The system measures infiltration in nine zones of the house which consist of the basement, crawl space, 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 airflow into the mitigation system.

Figure 6.4 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 vs the outside air is one factor determining the relative change in basement radon concentration and is a subject of future investigations.

6.2.2.2 Time-weighted-average measurements using the PFT system

Each of the houses has been monitored with PFT systems since the instrumentation packages were installed at the start of the study (October 1986). 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 airflow rates from the measured tracer gas concentrations and source rate has been completed.

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 PFTs were active in each house (which varied slightly between each house). Figures 6.5 to 6.11 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 abscissa 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 occurring 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 6.12a and 6.12b 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 airflows 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 be estimated.

The results for Houses #1 and #2 are shown in Figures 6.12a and 6.12b. The radon source rate into the basement for House #2 (the control house, which was not 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 dependence, the radon source strength for House #1 decreases and remains low after mitigation. This indicates that the reduced radon levels in the basement are caused by decreased source rates brought about by mitigation and not caused by increases in infiltration levels.

6.3 CALIBRATION ACTIVITIES

Calibration of individual components of the house monitoring packages and supporting instrumentation has been performed in both laboratory and field environments. Calibration checks have received heavy emphasis during instrument installation (i.e., October 1986) and during QA/QC trips of ORNL personnel to the study homes in October 1986, January 1987, and April 1987, as well as during visits to the test homes by PU personnel.

6.3.1 Instruments Attached to Indoor Data Logger

A summary of quantitation and precision analyses for selected parameters is given in Tables 6.11 to 6.13. Field checks of differential pressure zeros indicate coefficients of variation typically <1% (i.e., about 0.25 Pa) over the entire study (Table 6.11). The average of two calibration (i.e., span) checks, performed at the beginning and at the end of the study, are reported in Table 6.11. The calibration data varied by typically <1 to 2% between the beginning and end of the study. Temperature data show typically ≤1.5°C variation in multiple checks against NBS-calibrated thermometers. Estimates of precision are generally ≤1.5°C. Relative humidity data show approximate 1 to 5% RH absolute variation in multiple checks against calibrated hygrometers.

Calibration data for the Wrenn chambers are summarized in Table 6.12. Wrenn chambers that have not undergone adverse environmental exposures or radical physical/electronic repairs show generally consistent calibration factors (i.e., ±5 to 15%) between October 1986 (i.e., prior to installation) and January 1987. These calibrations represent cross-comparisons between three laboratories including ORNL, DOE's Environmental Monitoring Laboratory (EML) in Manhattan, and EPA's Eastern Environmental Radiation Facility in Montgomery, Alabama. For most Wrenn chambers there was an increase in efficiency (cpm per pCi/L) between January 1987, and the summer of 1987. In converting the observed cpm values to equivalent pCi/L values, it was assumed that the conversion efficiency increased linearly with time between January 20, 1987, and July 10, 1987. The conversion efficiency was assumed to be constant prior to January 20, 1987. The data on instrumental counting efficiency from exposure to a check source (Table 6.13) indicate very small changes in Wrenn response from October 1986 to April 1987. The average ratio of April 1987 data to October 1986 data is 0.98 ± 0.06.

6.3.2 Weather Station Instruments

A special study of wind speed effects on air exchange into and out of the radon flux monitors was made during April 1987. Aliquots of a tracer gas, carbon monoxide, were released within each chamber, and the rate of decay of the tracer gas was determined in conjunction with the velocity of air striking the outer surfaces of the chambers. The basic experiment was done three times under conditions of ambient, reduced, and increased air velocity. Reduced air velocity occurred when a heavy tarpaulin was draped over each chamber and the velocity was measured underneath the cover. Increased air velocity occurred when a 20-in. window fan was operated to create an airflow toward each chamber. At the weather station site, the experiment under ambient conditions was repeated once. Data from the experiments were reduced to exchange rate and air velocity values. The summary data from the seven experiments are plotted along with a regression line in Figure 6.13.

6.3.3 Other Instruments

The Eberline working level monitors (WLMs) were calibrated in the radon daughter chamber at EML in January 1987. 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 ^{232}Th check source as a standard. This counting efficiency and measured airflow 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 airflow data to refine the calibration for each monitor to more accurately reflect the concentration of radon progeny levels in the EML chamber. Both the original CC and the "corrected" CC for each WLM, plus the measured airflows and counting efficiencies, are summarized in Table 6.14. 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:

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

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Table 6.1. Results of total gamma measurements during site characterization.

House	Date	PIC (μR/h)[a]	Ave. Indoor (μR/h)[b]	Ave. Outdoor (μR/h)[c]
1	(10/86)	12.0	12.6 ± 0.8	13.7 ± 0.4
2	(10/86)	8.9	9.9 ± 1.2	15.3 ± 1.0
2	(7/87)	8.7	10.9 ± 1.8	14.1 ± 2.4
3	(10/86)	15.5	14.0 ± 2.1	15.3 ± 1.6
3	(7/87)	13.2	13.1 ± 2.7	14.2 ± 1.3
4	(10/86)	12.0	13.4 ± 2.0	22.0 ± 1.3
4	(7/87)	11.3	15.7 ± 3.9	20.7 ± 4.7
5	(10/86)	12.0	12.7 ± 1.8	15.2 ± 1.3
5	(7/87)	9.3	10.4 ± 1.5	14.0 ± 1.2
6	(10/86)	12.8	14.2 ± 3.8	15.6 ± 3.9
6	(7/87)	11.1	13.9 ± 3.4	17.2 ± 1.7
7	(10/86)	9.8	10.2 ± 1.5	13.8 ± 1.1
7	(7/87)	8.7	10.1 ± 1.2	15.2 ± 1.7

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[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 6.2. Average ^{226}Ra, ^{40}K, ^{232}Th (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 Bed[b]	0.64	14.75	0.79
1 R2	rep. offsite	Limestone Bed[b,c]	2.41	7.37	0.66
1 R3	rep. offsite	Limestone Bed[b]	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[7]	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

[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 (Federal Register, 1983).
[e] Radium exceed Uranium Mill Tailings Remedial Action level of 15 pCi/g for subsurface contamination (Federal Register, 1983).

Table 6.2 (continued)

Average ^{226}Ra, ^{40}K, ^{232}Th (pCi/g) measured in soil samples taken from the property of study homes[a] and representative rock formations in both onsite and offsite locations (cont.)

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

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

b Radium exceed Uranium Mill Tailings Remedial Action level of 5 pCi/g for surface contamination (Federal Register, 1983).

c Radium exceed Uranium Mill Tailings Remedial Action level of 15 pCi/g for subsurface contamination (Federal Register, 1983).

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

Table 6.3. Summary of total, ^{226}Ra and ^{232}Th gamma counts at surface and hole locations plus radium/thorium ratios.

House, Sample	Location	Total Counts Surface	Total Counts Hole	Radium Cts Surface	Radium Cts Hole	Thorium Cts Surface	Thorium Cts Hole	Rad/Thor Surface	Rad/Thor Hole
A. Homes Tentatively Identified as Overlaying Martinsburg Shale									
1 S1	backyard	6860	147800	104	335	74	171	1.41	1.96
1 S2	frontyard	6290	11980	76	205	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	7753		131		79		1.66	
Q5	rep. offsite	7290		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 6.4. 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]	Martinsburg shale	800 ± 80
	outside faucet		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 6.5. Comparison of Radon and Radon Progeny Levels for Selected Times and Houses.

Start Date	End Date	House ID	Mitigation Status	PAEC (WL)	Radon (pCi/L) Bsmt	Radon (pCi/L) Up	Working Level Ratio
Basement Measurements							
86309	86316	1	None	0.169	41.6	----	0.408
86345	86351	1	None	0.094	32.0	----	0.296
87024	87031	1	Complete	0.019	8.9	----	0.223
87009	87016	2	None	0.054	20.3	----	0.271
87063	87069	2	None	0.063	21.5	----	0.295
87141	87148	2	None	0.038	95.4	----	0.040
86345	86351	3	None	0.463	185.4	----	0.250
87035	87042	3	Complete	0.004	2.0	----	0.247
87008	87015	3	Complete	0.003	1.1	----	0.330
87024	87031	3	Complete	0.054	29.9	----	0.181
86295	86302	4	None	0.186	92.9	----	0.201
87064	87070	4	Partial	0.077	28.2	----	0.275
87024	87031	5	None	0.113	49.8	----	0.229
86295	86302	5	None	0.145	51.6	----	0.281
87055	87061	5	Partial	0.052	20.2	----	0.260
87105	87112	5	Partial	0.071	21.2	----	0.337
87142	87149	5	Complete	0.010	1.7	----	0.622
87127	87134	5	Complete	0.005	0.4	----	1.435
87162	87169	5	Complete	0.005	0.4	----	1.407
86309	86316	6	None	0.039	17.5	----	0.228
86344	86350	6	None	0.044	20.0	----	0.222
87162	87169	6	Partial	0.024	14.1	----	0.176
87141	87148	6	Partial	0.031	6.0	----	0.522
87035	87042	6	Partial	0.030	21.6	----	0.143
87063	87069	7	None	0.005	0.5	----	1.012
87162	87169	7	Complete	0.002	0.0	----	---
Living Area Measurements							
87044	87051	3	Complete	0.010	----	0.7	1.487
87035	87042	3	Complete	0.006	----	0.7	0.817
86317	86324	4	None	0.078	----	18.4	0.426
86316	86323	5	None	0.186	----	36.8	0.505
87055	87061	5	Partial	0.031	----	13.1	0.235
87105	87112	5	Partial	0.023	----	6.6	0.353
87078	87085	5	Partial	0.043	----	16.8	0.255
87127	87134	5	Complete	0.003	----	0.0	---
86317	86324	7		0.071	----	18.1	0.390

Table 6.6. Comparison of Average Radon Levels Measured Actively and Passively During the Study.

Start Date	Finish Date	Location	Passive Mean (pCi/L)	Active Mean (pCi/L)
** House: 1				
10/10/86	01/20/87	Bsmt WC[a]	48.30	41.67
10/10/86	01/20/87	Bsmt	53.70	41.67
10/10/86	01/20/87	Up BR	28.00	26.12
10/10/86	01/20/87	Up K	31.80	26.12
01/20/87	04/08/87	Bsmt WC	ND[b]	7.00
01/20/87	04/08/87	Bsmt	ND	7.00
01/20/87	04/08/87	Bsmt WC (blank)	ND	----
01/20/87	04/08/87	Bsmt WC (blank)	ND	----
01/20/87	04/08/87	Up BR	ND	4.22
01/20/87	04/08/87	Up WC	ND	4.22
04/08/87	07/11/87	Up WC	1.30	NA[c]
04/08/87	07/11/87	Up BR	1.80	NA
** House: 2				
10/10/86	01/24/87	Bsmt WC	20.40	24.60
10/10/86	01/24/87	Bsmt	22.60	24.60
10/10/86	01/24/87	Up BR	10.50	14.45
10/10/86	01/24/87	Up K	8.60	14.45
01/24/87	04/11/87	Bsmt WC	ND	22.66
01/24/87	04/11/87	Bsmt	ND	22.66
01/24/87	04/11/87	Up K	ND	16.47
01/24/87	04/11/87	Up WC	ND	16.47
04/11/87	07/09/87	Bsmt WC	11.90	19.23
04/11/87	07/09/87	Bsmt WC	15.70	19.23
04/11/87	07/09/87	Bsmt	13.10	19.23
04/11/87	07/09/87	Up WC	9.40	10.50
04/11/87	07/09/87	Up	10.30	10.50
07/09/87	/ /	Bsmt WC		
07/09/87	/ /	Bsmt WC		
07/09/87	/ /	Bsmt		
07/09/87	/ /	Up FamR		
07/09/87	/ /	Up K		

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[a]WC indicates that measurement was made near the continuous radon monitor.

[b]Data not returned by vendor yet.

[c]Data not available because house changed ownership.

Table 6.6. Comparison of Average Radon Levels Measured Actively and Passively During the Study (cont'd.)

Start Date	Finish Date	Location	Passive Mean (pCi/L)	Active Mean (pCi/L)
** House: 3				
10/10/86	01/20/87	Bsmt WC[a]	80.50	118.20
10/10/86	01/20/87	Up WC	46.30	45.84
10/10/86	01/20/87	Up WC	44.40	45.84
01/20/87	04/07/87	Bsmt WC	ND[b]	13.85
01/20/87	04/07/87	Bsmt WC blank	ND	-----
01/20/87	04/07/87	Bsmt WC blank	ND	-----
01/20/87	04/07/87	Bsmt B	ND	13.85
01/20/87	04/07/87	Up BR	ND	5.63
01/20/87	04/07/87	Up WC	ND	5.63
04/07/87	07/10/87	Bsmt WC	4.20	5.77
04/07/87	07/10/87	Bsmt WC	4.50	5.77
04/07/87	07/10/87	Bsmt	4.90	5.77
04/07/87	07/10/87	Up K	2.20	1.92
04/07/87	07/10/87	Up WC	2.20	1.92
07/10/87	/ /	Bsmt WC		
07/10/87	/ /	Bsmt		
07/10/87	/ /	Bsmt		
07/10/87	/ /	Up BR		
07/10/87	/ /	Up WC		
07/10/87	/ /	Up WC		
** House: 4				
10/10/86	01/24/87	Bsmt WC	33.20	46.00
10/10/86	01/24/87	Bsmt	30.70	46.00
10/10/86	01/24/87	Up BR	17.40	22.44
10/10/86	01/24/87	Up K	18.50	22.44
01/24/87	04/07/87	Bsmt WC	ND	30.18
01/24/87	04/07/87	Bsmt WC blank	ND	-----
01/24/87	04/07/87	Bsmt WC blank	ND	-----
01/24/87	04/07/87	Bsmt	ND	30.18
01/24/87	04/07/87	Up BR(2nd Flr)	ND	-----
01/24/87	04/07/87	Up WC	ND	14.48
04/07/87	07/08/87	Bsmt WC	8.60	12.49
04/07/87	07/08/87	Bsmt WC	9.40	12.49
04/07/87	07/08/87	Bsmt WC	9.10	12.49
04/07/87	07/08/87	Up BR(2nd Flr)	2.60	-----
04/07/87	07/08/87	Up WC	4.30	5.49
07/08/87	/ /	Bsmt WC		
07/08/87	/ /	Bsmt WC		
07/08/87	/ /	Bsmt Frezr		

[a]WC indicates that measurement was made near the continuous radon monitor.
[b]Data not returned by vendor yet.

Table 6.6. Comparison of Average Radon Levels Measured Actively and Passively During the Study (cont'd.)

Start Date	Finish Date	Location	Passive Mean (pCi/L)	Active Mean (pCi/L)
** House: 5				
10/10/86	01/19/87	Bsmt WC[a]	44.70	61.15
10/10/86	01/19/87	Bsmt	54.70	61.15
10/10/86	01/19/87	Up Den	31.80	33.05
10/10/86	01/19/87	Up WC	24.40	33.05
01/19/87	04/08/87	Bsmt WC	ND[b]	31.98
01/19/87	04/08/87	Bsmt WC blank	ND	-----
01/19/87	04/08/87	Bsmt	ND	31.98
01/19/87	04/08/87	Bsmt Blank	ND	31.98
01/19/87	04/08/87	Up LR	ND	17.53
01/19/87	04/08/87	Up WC	ND	17.53
04/08/87	07/08/87	Bsmt WC	2.80	4.34
04/08/87	07/08/87	Bsmt WC	2.30	4.34
04/08/87	07/08/87	Bsmt	3.50	4.34
04/08/87	07/08/87	Up	1.20	2.46
04/08/87	07/08/87	Up	0.90	2.46
07/08/87	/ /	Bsmt WC		
07/08/87	/ /	Bsmt WC		
07/08/87	/ /	Bsmt WC		
07/08/87	/ /	Up LR		
07/08/87	/ /	Up WC		
** House: 6				
10/10/86	01/24/87	Bsmt WC	19.70	23.58
10/10/86	01/24/87	crawlspace	38.50	-----
10/10/86	01/24/87	Up den	9.80	11.58
10/10/86	01/24/87	Up den	11.00	11.58
01/24/87	04/07/87	Bsmt WC	ND	18.09
01/24/87	04/07/87	Crawlspace	ND	-----
01/24/87	04/07/87	Up LR	ND	7.04
01/24/87	04/07/87	Up WC	ND	7.04
04/07/87	07/09/87	blank	5.10	-----
04/07/87	07/09/87	blank	5.20	-----
04/07/87	07/09/87	crawlspace	11.60	-----
04/07/87	07/09/87	Bsmt	18.70	8.71
04/07/87	07/09/87	Bsmt	6.70	8.71
04/07/87	07/09/87	Up	2.80	3.08
04/07/87	07/09/87	Up	3.30	3.08
07/09/87	/ /	Bsmt WC		
07/09/87	/ /	Bsmt WC		
07/09/87	/ /	Crawlspace		

[a]WC indicates that measurement was made near the continuous radon monitor.
[b]Data not returned by vendor yet.

Table 6.6. Comparison of Average Radon Levels Measured Actively and Passively During the Study (cont'd.)

Start Date	Finish Date	Location	Passive Mean (pCi/L)	Active Mean (pCi/L)
** House: 7				
10/10/86	01/24/87	Crawlspace	29.40	-----
10/10/86	01/24/87	Bsmt WC[a]	26.30	22.98
10/10/86	01/24/87	Up BR	9.40	9.39
10/10/86	01/24/87	Up WC	13.70	9.39
01/24/87	04/09/87	Bsmt WC	ND[b]	3.99
01/24/87	04/09/87	Bsmt Lndry	ND	3.99
01/24/87	04/09/87	Up BR	ND	1.10
01/24/87	04/09/87	Up WC	ND	1.10
04/09/87	07/08/87	Bsmt	3.40	2.81
04/09/87	07/08/87	Bsmt	2.70	2.81
04/09/87	07/08/87	Bsmt	1.80	2.81
04/09/87	07/08/87	Up	0.30	0.18
04/09/87	07/08/87	Up	0.30	0.18
07/08/87	/ /	Bsmt WC		
07/08/87	/ /	Bsmt WC		
07/08/87	/ /	Bsmt B		
07/08/87	/ /	Up BR		
07/08/87	/ /	Up WC		

[a]WC indicates that measurement was made near the continuous radon monitor.
[b]Data not returned by vendor yet.

Table 6.7. Results of Soil Characterization Measures (pCi/L)

House	Date	Method	Front	Side-Garage	Side	Back
			- - - - - - - Yard Location			- - - - - - -
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 6.8. Soil Permeability Data

House	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}[a]	2.1 x 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}[a]		pipe loose
1	12/1/86	W,1m,Back	10	1.6×10^{-5}[a]	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
			50	6.1×10^{-9}	6.0×10^{-9}	not incl.
			250	5.9×10^{-9}		in avg.
3	11/24/86	W,1.5m,Front	1	1.6×10^{-4}[a]	1.6×10^{-4}	
3	6/16/87	W,1.5m,Front	2	7.4×10^{-5}	7.4×10^{-5}	Fan ON
3	6/16/87	W,1.5m,Front	2	5.0×10^{-5}	5.1×10^{-5}	Fan OFF
			3	5.1×10^{-5}		Fan OFF
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	6/16/87	S,2m,Side	10	2.1×10^{-6}	1.6×10^{-6}	Fan ON
			50	1.5×10^{-6}		Fan ON
			130	1.2×10^{-6}		Fan ON
3	6/16/87	S,2m,Side	10	2.0×10^{-6}	1.5×10^{-6}	Fan OFF
			50	1.5×10^{-6}		Fan OFF
			130	1.1×10^{-6}		Fan OFF
3	11/24/86	E,1.2m,Rear	10	1.3×10^{-6}	1.2×10^{-6}	
			50	$1.3 \times 10^{-6}{}_2$		
			150	1.0×10^{-6}[a]		
3	6/16/87	E,1.2m,Rear	10	2.8×10^{-6}	2.0×10^{-6}	Fan ON
			50	1.3×10^{-6}		Fan ON
			87	1.8×10^{-6}		Fan ON
3	6/16/87	E,1.2m,Rear	10	2.6×10^{-6}	2.1×10^{-6}	Fan OFF
			50	2.0×10^{-6}		Fan OFF
			87	1.7×10^{-6}		Fan OFF

[a] Uncertain data taken with the highest flow rotameter, reading at a maximum flow of 2.5 L/min.

Table 6.8. Soil Permeability Data, continued

House	Date	Location	Pressure (Pa)	K (cm^2)	Avg. K (cm^2)	Comments
4	11/19/86	N,1.5m,Front		No flow[a]		
4	6/9/87	N,1.5m,Front	10	7.7×10^{-9}	6.9×10^{-9}	meter P1
			50	7.4×10^{-9}		meter P2
			250	5.6×10^{-9}		meter P2
4	1/5/87	NW,2m,Front	250	No flow		Clay
4	11/19/86	W,3m,Side	250	No flow		
4	11/19/86	E,2m,Side		No flow		
4	12/3/86	E,2m,Side	250	1.5×10^{-10}		Wet clay
			250	No flow		meter P1
4	11/19/86	S,1.5m,Back	250	No flow		
4	12/3/86	Bsmt Subslab		No flow		Clay soil under slab
5	11/21/86	E,2m, Front	3	5.4×10^{-5}[b]	5.4×10^{-5}	
5	6/16/87	E,2m, Front	2	4.3×10^{-5}	3.8×10^{-5}	Fan ON
			4	3.3×10^{-5}		Fan ON
5	6/16/87	E,2m, Front	4	2.4×10^{-5}	2.4×10^{-5}	Fan OFF
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	6/16/87	S,2m, Side	10	8.6×10^{-7}	6.2×10^{-7}	Fan ON
			50	5.9×10^{-7}		Fan ON
			250	4.0×10^{-7}		Fan ON
5	6/16/87	S,2m, Side	10	8.0×10^{-7}	6.0×10^{-7}	Fan OFF
			50	5.8×10^{-7}		Fan OFF
			250	4.2×10^{-7}		Fan OFF
5	11/21/86	W,3m, Back	2	8.1×10^{-5}[b]	8.1×10^{-5}	
5	6/16/87	W,3m, Back	2	2.1×10^{-5}	2.5×10^{-5}	Fan ON
			4	2.9×10^{-5}		Fan ON
5	6/16/87	W,3m, Back	2	3.3×10^{-5}	3.3×10^{-5}	Fan OFF
			4	3.2×10^{-5}		Fan OFF

[a] No measurable flow on permeameter.

[b] Uncertain data taken with the highest flow rotameter, reading at a maximum flow of 2.5 L/min.

Table 6.8. Soil Permeability Data, continued

House	Date	Location	Pressure (Pa)	K (cm^2)	Avg. K (cm^2)	Comments
6	11/25/86	S,1.5m,Front	250	3.1×10^{-10}	3.1×10^{-10}	meter P1
6	6/17/87	S,1.5m,Front	10	1.0×10^{-7}	8.3×10^{-8}	Fan ON
			50	8.6×10^{-8}		Fan ON
			250	6.4×10^{-8}		Fan ON
6	6/17/87	S,1.5m,Front	10	7.4×10^{-8}	6.5×10^{-8}	Fan OFF
			50	6.1×10^{-8}		Fan OFF
			250	5.9×10^{-8}		Fan OFF
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	6/17/87	W,1m,Side	10	2.9×10^{-6}	1.8×10^{-6}	Fan ON
			50	1.5×10^{-6}		Fan ON
			250	1.0×10^{-6}		Fan ON
6	6/17/87	W,1m,Side	10	2.8×10^{-6}	1.7×10^{-6}	Fan OFF
			50	1.5×10^{-6}		Fan OFF
			250	9.1×10^{-7}		Fan OFF
6	11/25/86	N,2m,Back	250	No flow[a]		
6	6/17/87	N,2m,Back	10	1.1×10^{-7}	8.7×10^{-8}	Fan ON
			50	8.6×10^{-8}		Fan ON
			250	6.6×10^{-8}		Fan ON
6	6/17/87	N,2m,Back	10	3.2×10^{-7}	1.6×10^{-7}	Fan OFF
			50	8.6×10^{-8}		Fan OFF
			250	6.4×10^{-8}		Fan OFF
7	11/17/86	W,1.5m,Front	10	2.8×10^{-9}	4.2×10^{-9}	(meter P1)
			50	4.3×10^{-9}		meter P1
			250	5.4×10^{-9}		meter P2
7	6/17/87	W,1.5m,Front	10	3.1×10^{-7}	1.9×10^{-7}	Fan ON
			50	1.6×10^{-7}		Fan ON
			250	9.8×10^{-8}		Fan ON
7	6/17/87	W,1.5m,Front	10	2.5×10^{-7}	1.7×10^{-7}	Fan OFF
			50	1.6×10^{-7}		Fan OFF
			250	9.8×10^{-8}		Fan OFF

[a] No measurable flow on permeameter.

Table 6.8. Soil Permeability Data, continued

House	Date	Location	Pressure (Pa)	K (cm^2)	Avg. K (cm^2)	Comments
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	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	6/17/87	N,2m,Side	10	3.7×10^{-7}	2.7×10^{-7}	Fan ON
			50	2.7×10^{-7}		Fan ON
			250	1.8×10^{-7}		Fan ON
7	6/17/87	N,2m,Side	10	3.7×10^{-7}	2.6×10^{-7}	Fan OFF
			50	2.6×10^{-7}		Fan OFF
			250	1.6×10^{-7}		Fan OFF
7	6/23/87[a]	N,2m,Side	10	2.3×10^{-7}	2.0×10^{-7}	Fan ON
			50	2.1×10^{-7}		Fan ON
			100	2.0×10^{-7}		Fan ON
			250	1.5×10^{-7}		Fan ON
7	11/17/86	S,1m,Side	10	No flow[b]		meter P1
			50	No flow		meter P1
			250	7.4×10^{-11}		meter P1
			250	No flow		meter P1
7	6/17/87	S,1m,Side	10	No flow		Fan ON
			50	5.5×10^{-9}	4.9×10^{-9}	Fan ON
			250	4.2×10^{-9}		Fan ON
7	6/17/87	S,1m,Side	10	No flow		Fan OFF
			50	4.9×10^{-9}	4.6×10^{-9}	Fan OFF
			250	4.2×10^{-9}		Fan OFF
7	11/17/86	E,2m,Back	250	No flow		Clay
7	12/3/86	E,2m,Back	10,50	No flow		Wet clay
7	6/17/87	E,2m,Back	10	1.8×10^{-7}	1.2×10^{-7}	Fan ON
			50	1.1×10^{-7}		Fan ON
			250	6.9×10^{-8}		Fan ON
7	6/17/87	E,2m,Back	10	1.8×10^{-7}	1.1×10^{-7}	Fan OFF
			50	9.8×10^{-8}		Fan OFF
			250	6.4×10^{-8}		Fan OFF

[a]A number of measurements were done this day, while varying the indoor pressure of the house by use of the blower door. No large variation in the permeability constant was observed.

[b] No measurable flow on permeameter.

Table 6.9. Summary of weekly-averaged respirable particulate data

House	Location	Beginning Date	Concentration ($\mu g/m^3$)
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
2	upstairs	06/18/87	159.3
2	basement	06/18/87	57.6
Average			110.8 ± 51.0
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
4	upstairs	06/18/87	23.7
4	basement	06/18/87	15.7
Average			13.6 ± 8.3
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 6.10. Blower Door Data (depressurization only)

House	Test Condition[a]	Date	Fan Location	ACH (@ 50 Pa)	ELA (in^2)	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[14]
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[14]
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[14]
	co	6/04/87	basement door	24.2	267	0.12[14]
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; co = crawlspace door open; bo = basement door open; nd = no door between basement; cc = crawlspace door closed and house.

[b] Basement volume only.

[c] Whole volume.

[d] Fireplace damper partially open.

Table 6.11. Summary of field calibration data for selected sensors between 10/86 and 7/87.

		Differential Pressure		Temperature		Rel. Hum.
		Response	Zero (mv)		Delta[a]	Delta[a]
House	Sensor	Pa/volt	Mean ± SD	Location	Mean ± SD	Mean ± SD
1	Bsmt-Out	10.49	2476 ± 45	Bsmt	0.40 ± 0.41	-4.7 ± 5.3
	Bsmt-Sub	9.99	2528 ± 13	Upstairs	-0.27 ± 0.31	
	Bsmt-Ups	10.02	2561 ± 14	Outdoors	-0.28 ± 0.45	
2	Bsmt-Out	10.09	2475 ± 11	Bsmt	0.33 ± 0.45	-3.3 ± 4.4
	Bsmt-Sub	10.11	2536 ± 13	Upstairs	-0.30 ± 0.27	
	Bsmt-Ups	10.04	2490 ± 25	Outdoors	-2.00 ± 2.21	
3	Bsmt-Out	9.99	2522 ± 12	Bsmt	0.15 ± 0.52	0.8 ± 2.9
	Bsmt-Sub	10.06[b]	2548 ± 6	Upstairs	-0.82 ± 1.04	
	Bsmt-Sub	24.71[c]	2529 ± 14	Outdoors	-0.25 ± 0.75	
	Bsmt-Ups	9.96	2528 ± 12.1			
4	Bsmt-Out	10.19	2500 ± 24	Bsmt	-0.04 ± 0.62	-3.5 ± 4.4
	Bsmt-Sub	10.17	2524 ± 13	Upstairs	-0.28 ± 0.09	
	Bsmt-Ups	9.92	2565 ± 18	Outdoors	-0.15 ± 0.19	
5	Bsmt-Out	9.95	2499 ± 10	Bsmt	0.33 ± 0.33	-4.4 ± 3.0
	Bsmt-Sub	9.99	2476 ± 5	Upstairs	-0.58 ± 0.56	
	Bsmt-Ups	9.94	2509 ± 11	Outdoors	-1.46 ± 0.66	
6	Bsmt-Out	9.93	2347 ± 52	Bsmt	-0.10 ± 0.39	2.9 ± 8.0
	Bsmt-Sub	10.10	2467 ± 10	Upstairs	-1.17 ± 1.58	
	Bsmt-Ups	10.00	2503 ± 16	Outdoors	-0.53 ± 0.68	
	Crwl-Sub	24.73	2499 ± 28			
7	Bsmt-Out	10.22	2491 ± 17	Bsmt	0.10 ± 0.59	4.4 ± 2.2
	Bsmt-Sub	10.06	2507 ± 13	Upstairs	-0.20 ± 0.36	
	Bsmt-Ups	10.29	2511 ± 17	Outdoors	-0.83 ± 0.85	
Weather Station (5)				Outdoors	2.40	-1.7 ± 1.2

---

[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 calibration data for Wrenn chambers from 10/86 to 7/87.

Wrenn	Zero Values (cpm)		Laboratory Calibration Data (cpm per pCi/L)					
Date:	10/86	1/87[a]	10/86[b]	12/86	1/87[c]	2/87[b]	5/87[b]	6-10/87[d]
1	0.67	0.39	0.82	----	1.21	----	1.44	1.18±0.04
2	0.49	0.35	0.72	----	0.65	----	----	----
3	0.50	----	0.83	----	----	----	1.12[e]	0.95±0.03
4	0.48	0.31	0.90	0.90[c]	0.88	0.91	----	1.20±0.04
5	0.59	0.68	0.92	----	0.83	----	----	1.07±0.05
6	0.44	0.33	0.84	----	0.83	----	----	1.03±0.04
7	0.81	0.54	0.91	----	0.82	----	----	1.05±0.01
8	0.43	0.36[e]	0.86	0.93[b]	1.00[e]	----	----	----
9	0.75	0.41	0.81	----	0.74	----	----	----
10	0.38	----	0.82	----	----	----	----	1.05±0.02
11	0.80	0.39	0.81	----	0.94	----	----	1.00±0.01
12	0.00	----	1.11	----	----	----	1.32[e]	1.04±0.06
13	0.61	0.38	0.84	----	0.97	----	----	----
14	0.53	0.39	0.86	0.71[c]	0.79	0.81	----	1.07±0.04
15	0.63	----	0.89	0.78[c]	----	----	----	1.09±0.05
16	0.69	----	0.76	----	----	----	----	1.00±0.03
17	0.59	----	0.64	----	----	----	----	0.81±0.04
18	0.85	----	0.72	0.64[c]	----	----	----	0.90±0.02
19	0.47	0.48[e]	0.65	0.67[b,e]	0.67	----	----	0.86±0.01
20	----	----	----	----	----	1.80	1.84	1.43±0.06

[a]Zero values taken at 5 °C, and therefore may be somewhat lower than under normal indoor conditions.
[b]Calibrations performed in the chamber at ORNL.
[c]Calibrations performed in the chamber at EML in New York City.
[d]Average (± SD) of 2-6 calibrations at ORNL, EERF, or Mounds.
[e]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. Counting Efficiency Data (cpm)[a]

Wrenn	Laboratory	Field		
Date:	10/86	10/86	1/87	4/87
1	787	765	741	868
2	515	503	477	516
3	840	840	574[b]	---
4	679	676	661	---
5	1053	949	897	953
6	953	978	896	1032
7	1098	---	1022	1032
8	1121	---	1019	1089
9	983	1035	833	951
10	932	941	873	912
11	787	748	670	742
12	1016	1016	885[b]	---
13	1282	1268	1199	1241
14	783	736	704	719
15	1013	1028	998	1033
16	839	793	842	---
17	640	---	588	615
18	1008	---	---	---
19	363	---	397[b]	(543)
20	---	---	---	---

[a] A small amount of ^{239}Pu was placed near the phosphor and the resulting count rate recorded.

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

Table 6.14. Calibration of the Eberline Working Level Monitors (WLMs)

WLM	Measured Air Flow (L/min)	Counting Efficiency[a]	Calib. Constant[b]	WLM/EML[c]	Corr'd 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

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[a] Counting efficiency measured with Thorium check source.
[b] Calibration Constant (cpm/WL) = {Flow (L/m) * Efficiency} / $5.6x10^{-5}$.
[c] Ratio of working level data measured by WLMs (using calibration constant[b]) to potential alpha energy concentration determined by EML.
[d] Calibration constant corrected for WLM/EML ratio.
[e] Units of {counts/[Working Level * L]}.
[f] Mechanical problems with the pump of WLM318 have recurred often.

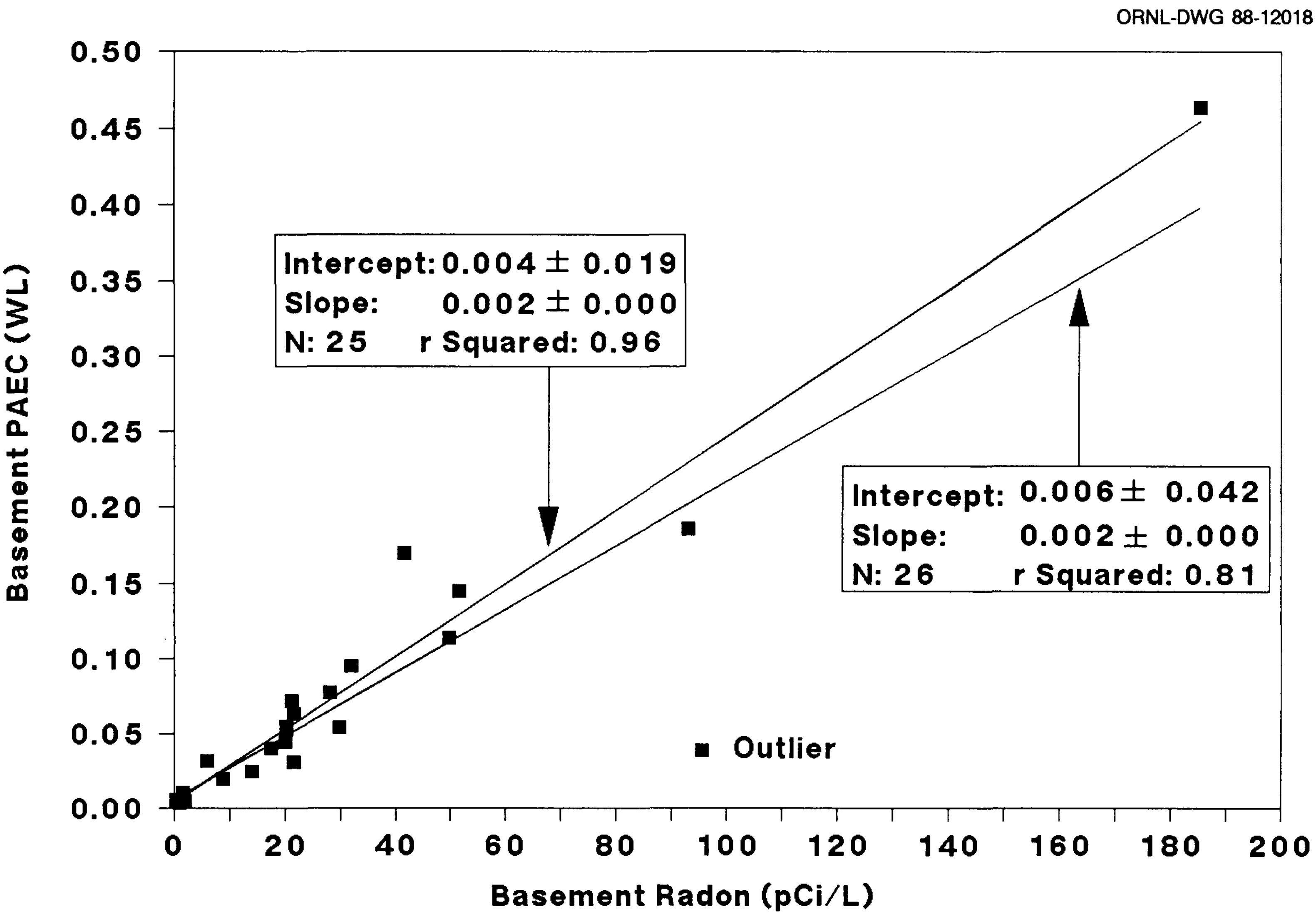


Fig. 6.1. Comparison of radon and PAEC for basement measurements.

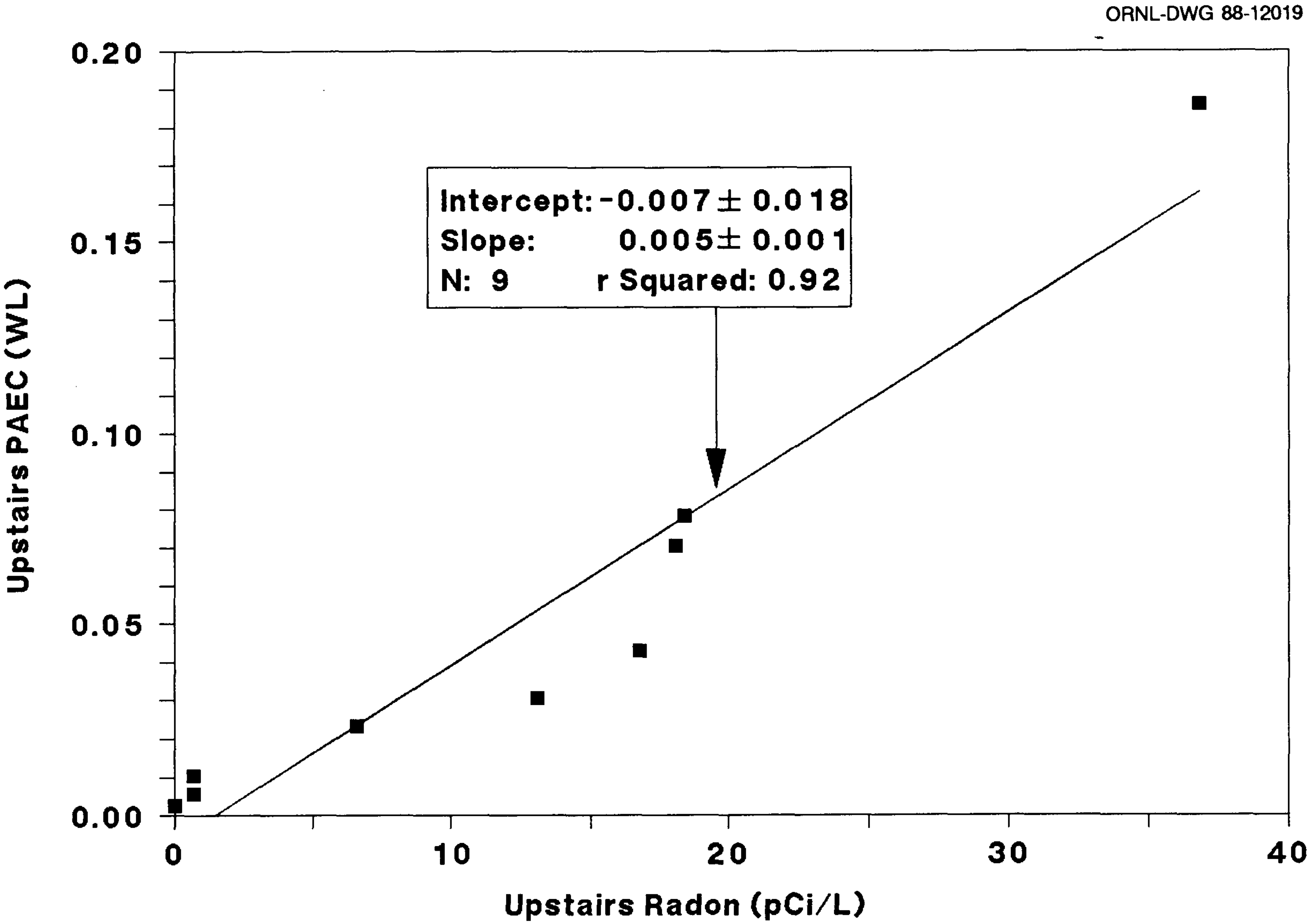


Fig. 6.2. Comparison of radon and PAEC for living-area measurements.

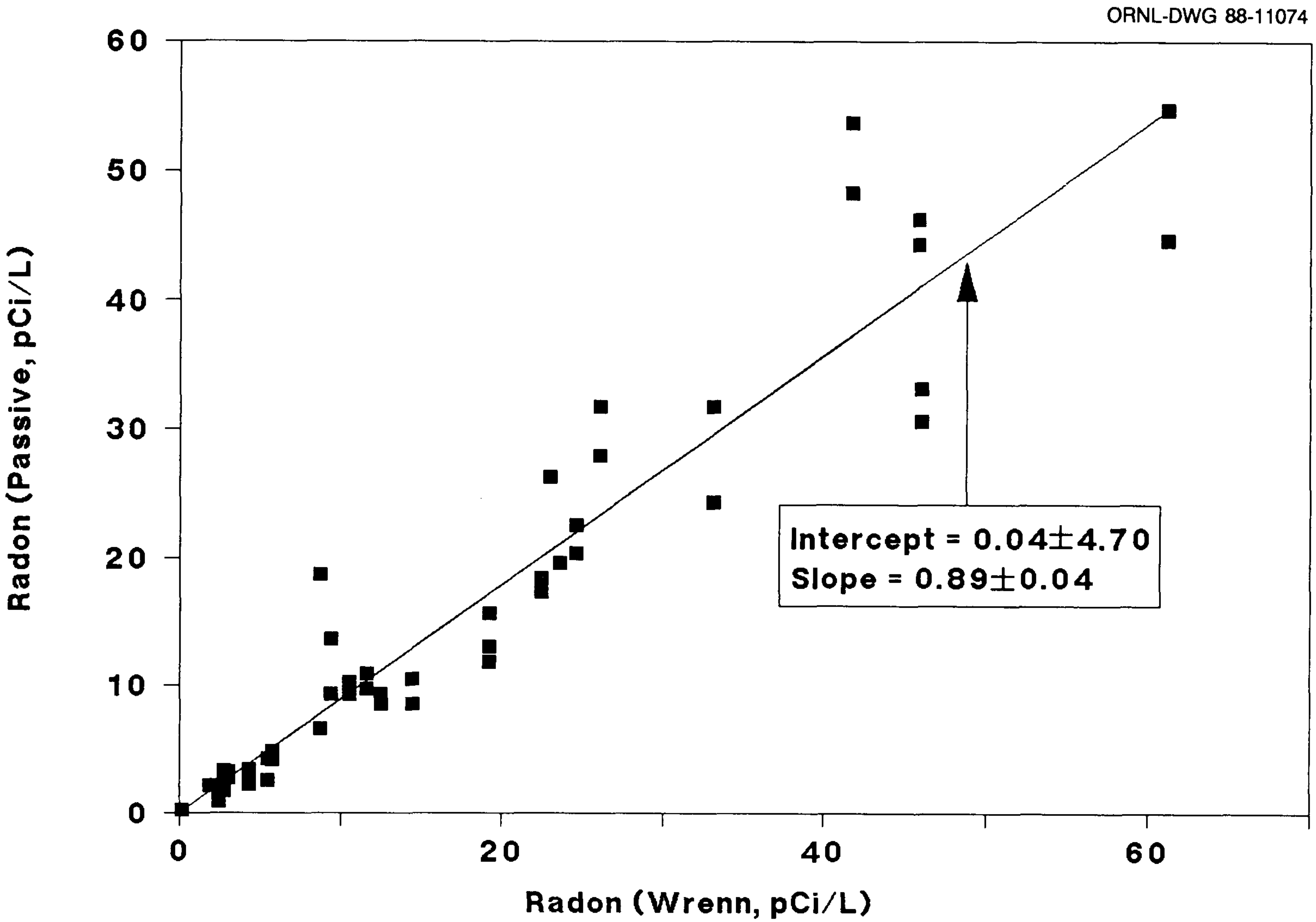


Fig. 6.3. Comparison of continuous and passive radon measurements.

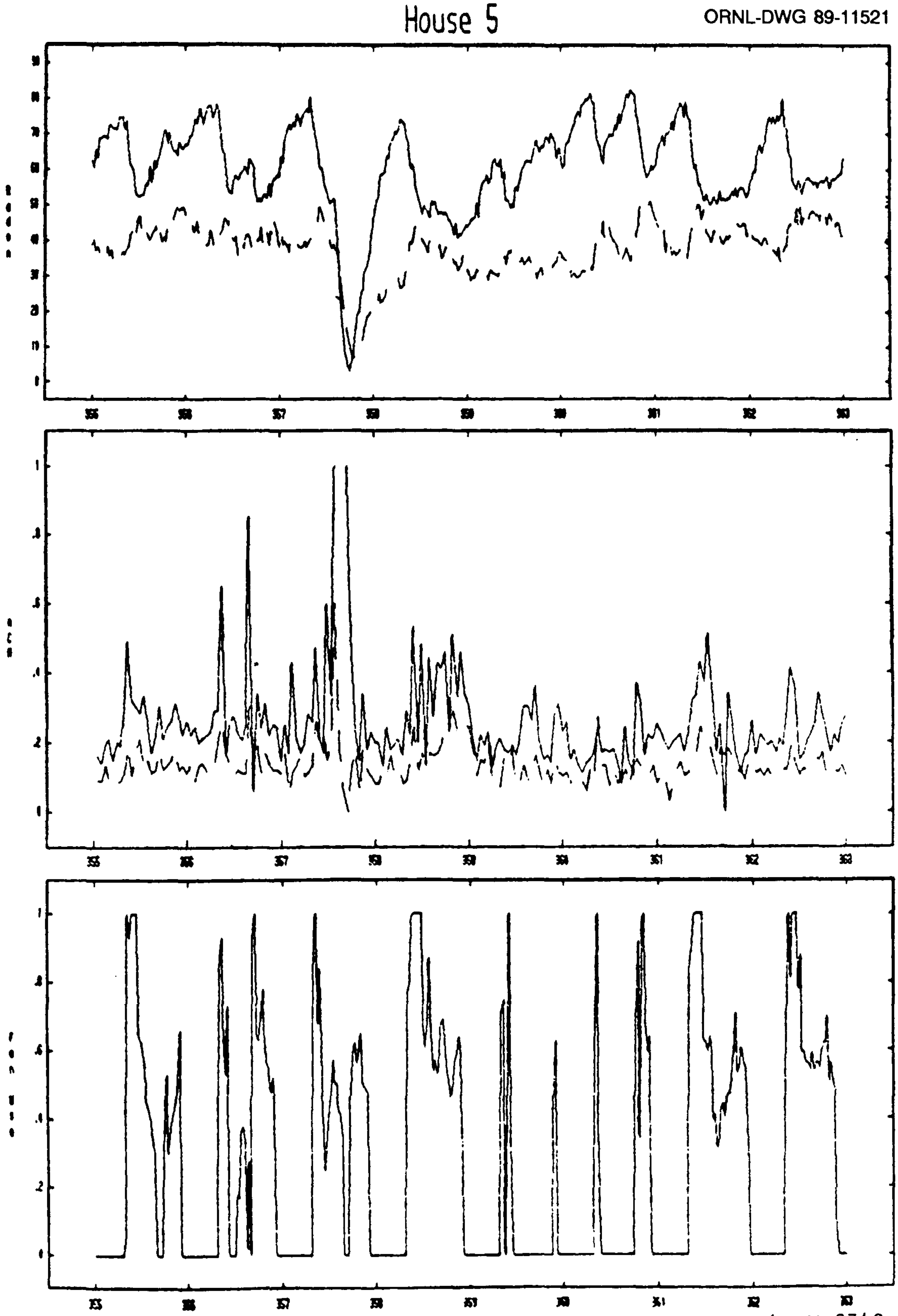


Fig. 6.4. Comparison of radon, air exchange, and fan usage in House #5 for eight days in December, 1986.

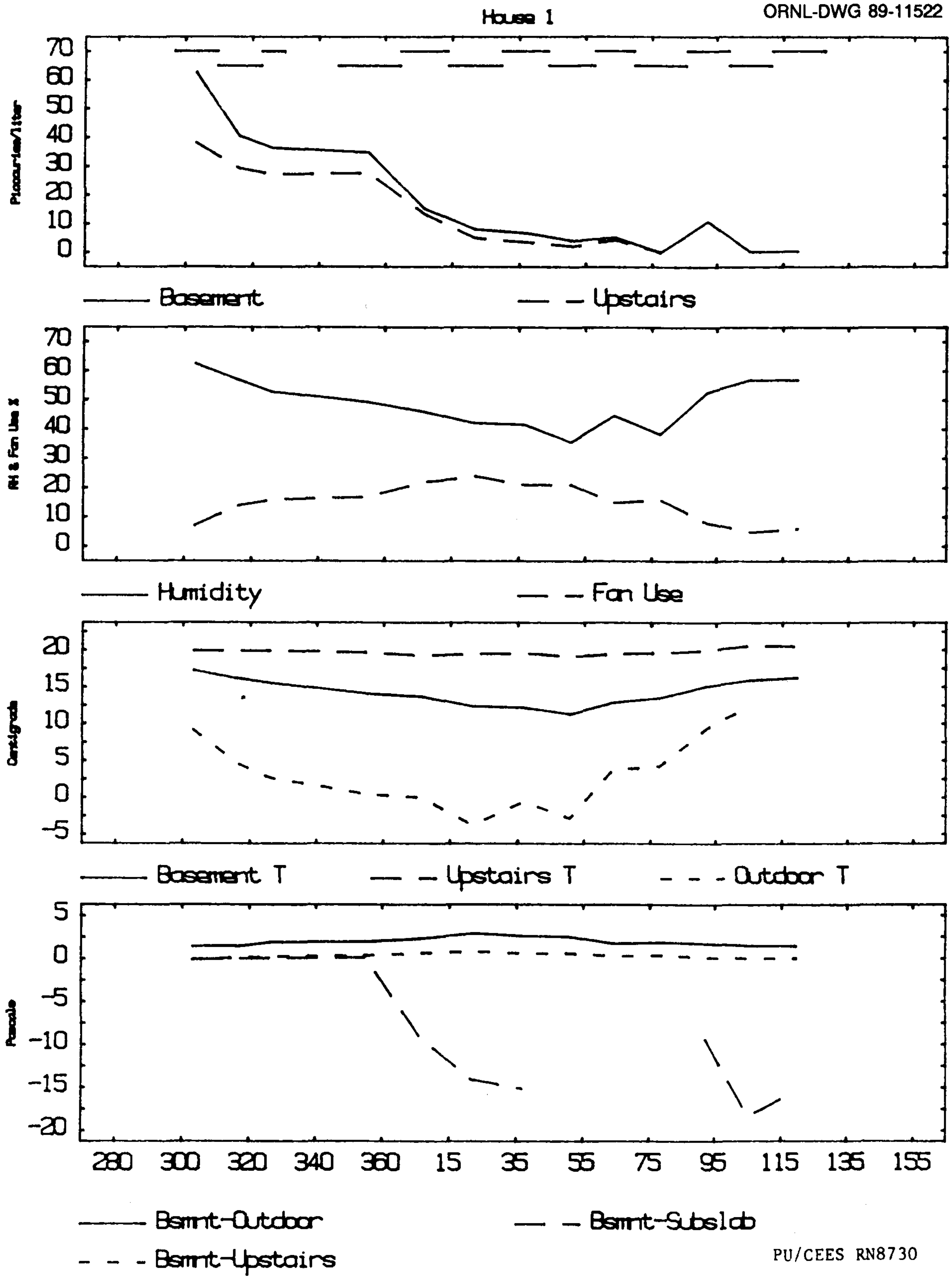


Fig. 6.5. House #1: Comparison of radon, humidity, fan usage, temperature, and pressure differences during PFT experiments.

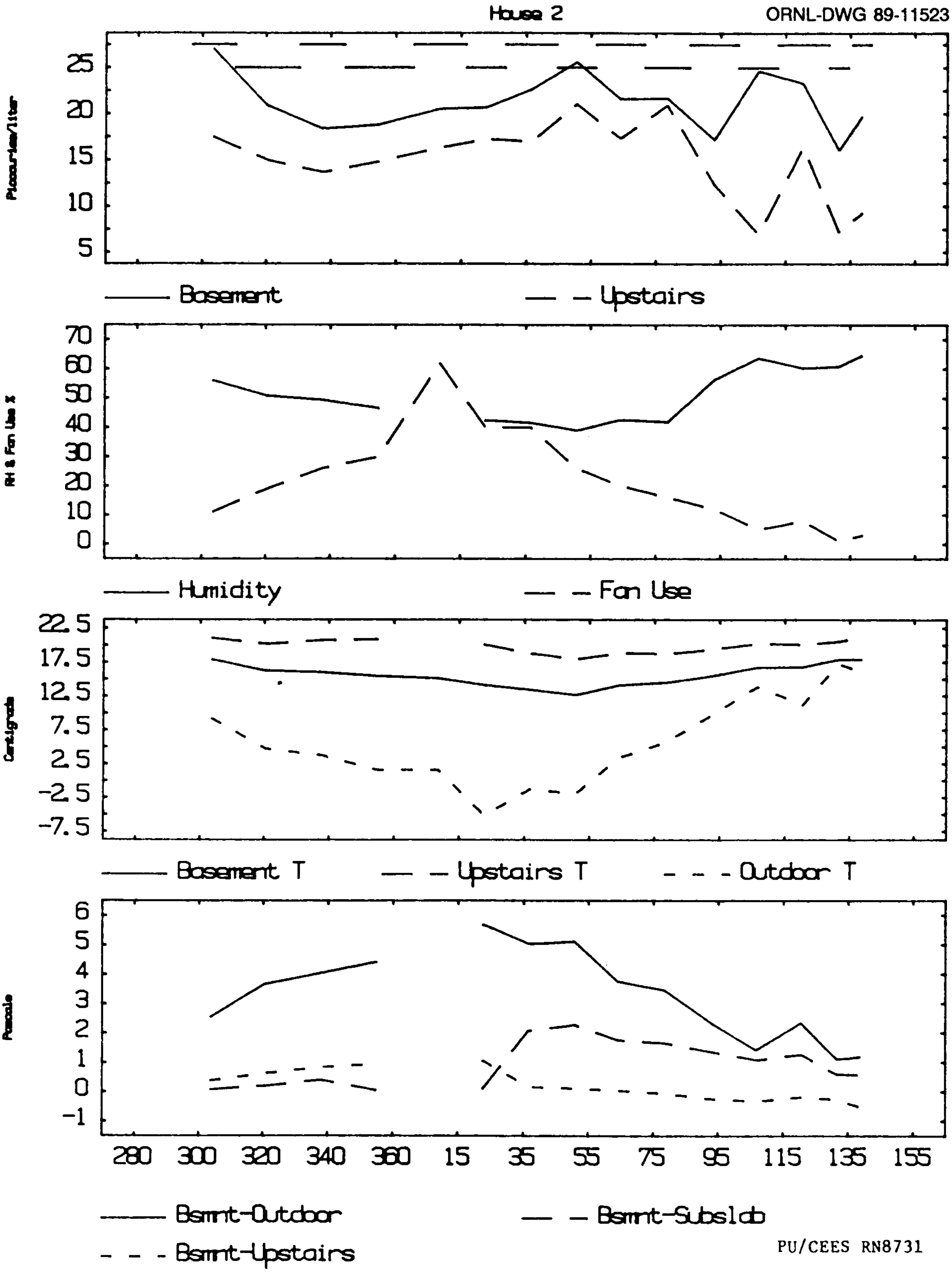
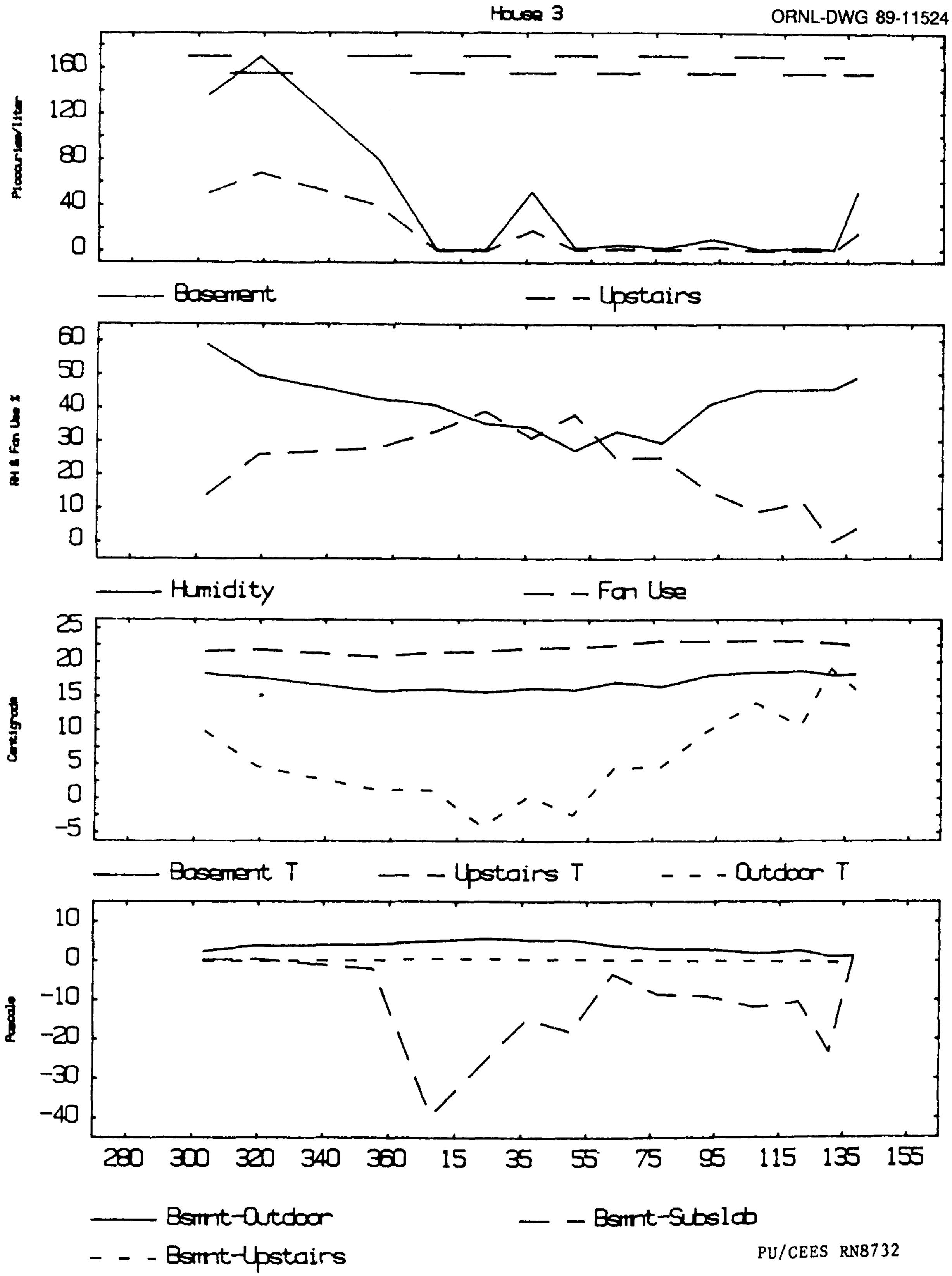


Fig. 6.6. House #2: Comparison of radon, humidity, fan usage, temperature, and pressure differences during PFT experiments.



PU/CEES RN8732

Fig. 6.7. House #3: Comparison of radon, humidity, fan usage, temperature, and pressure differences during PFT experiments.

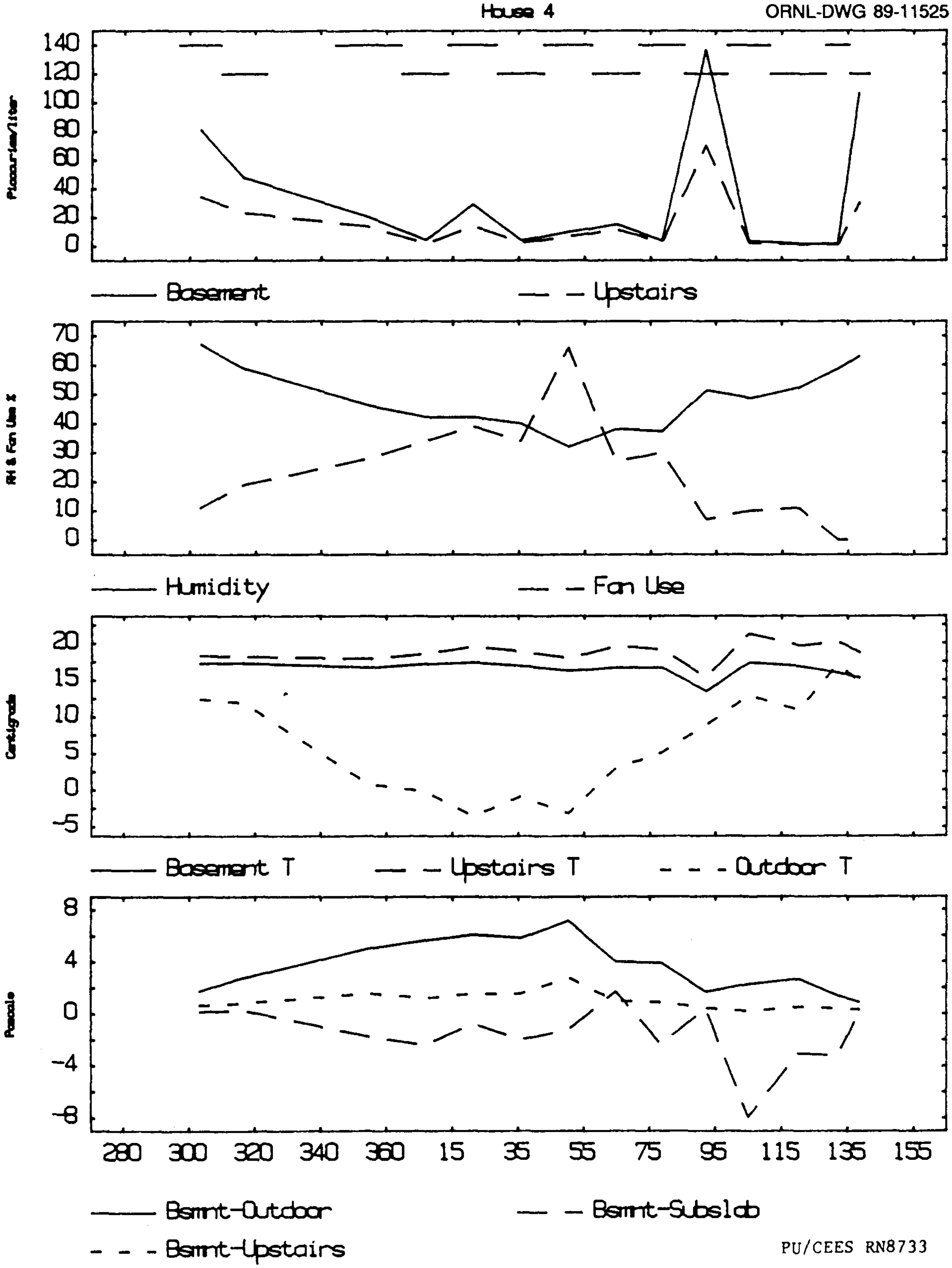


Fig. 6.8. House #4: Comparison of radon, humidity, fan usage, temperature, and pressure differences during PFT experiments.

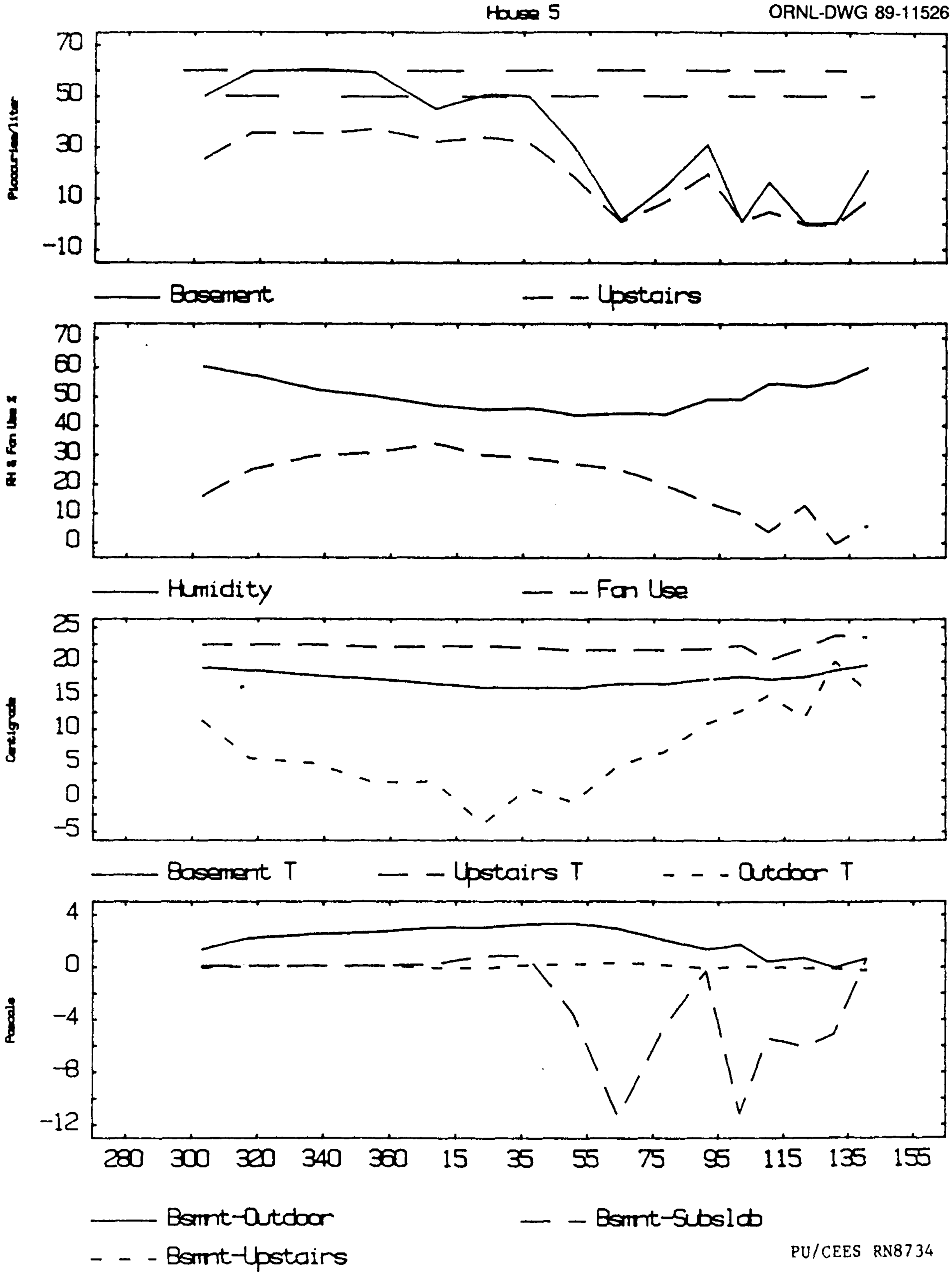
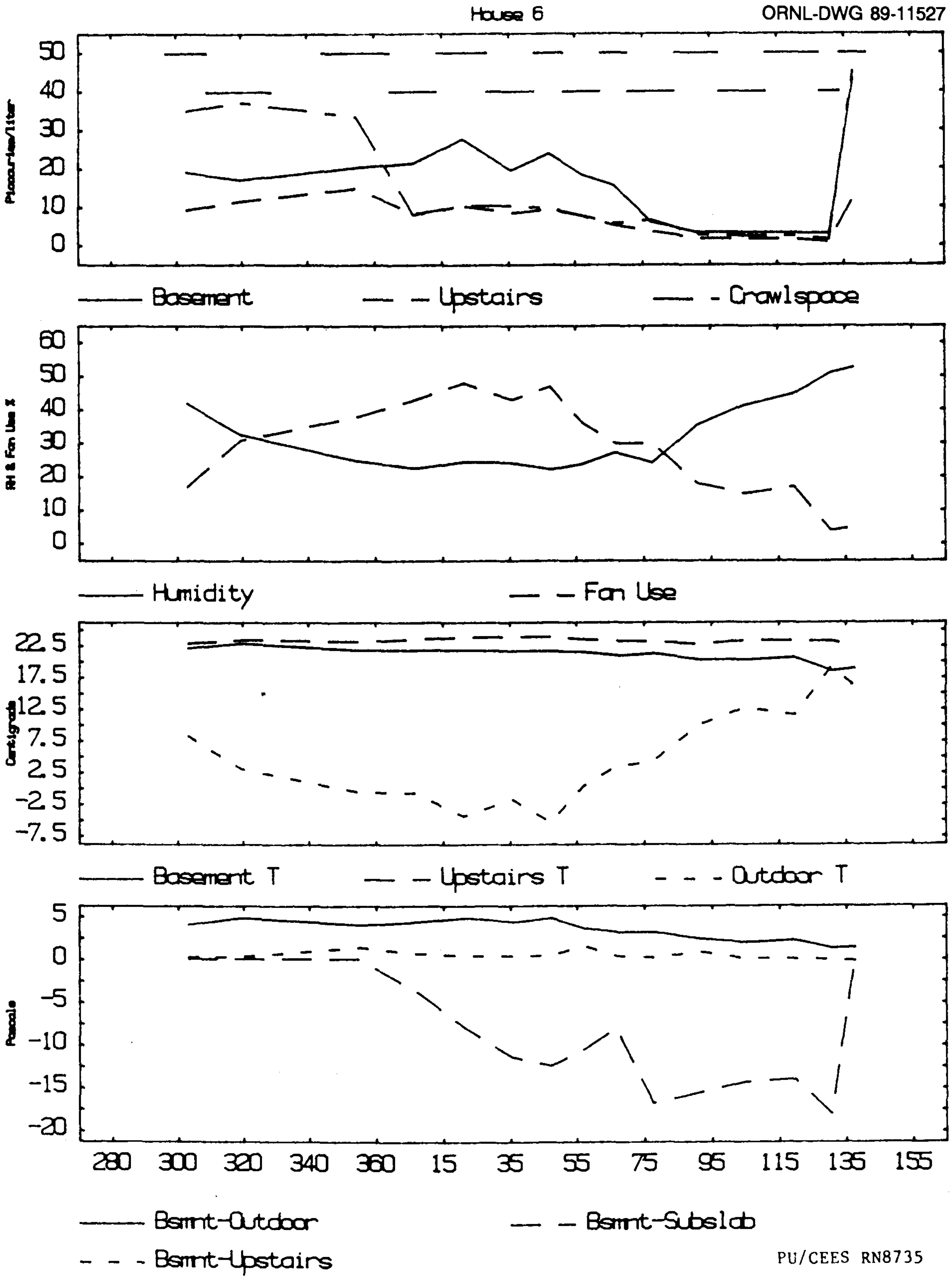
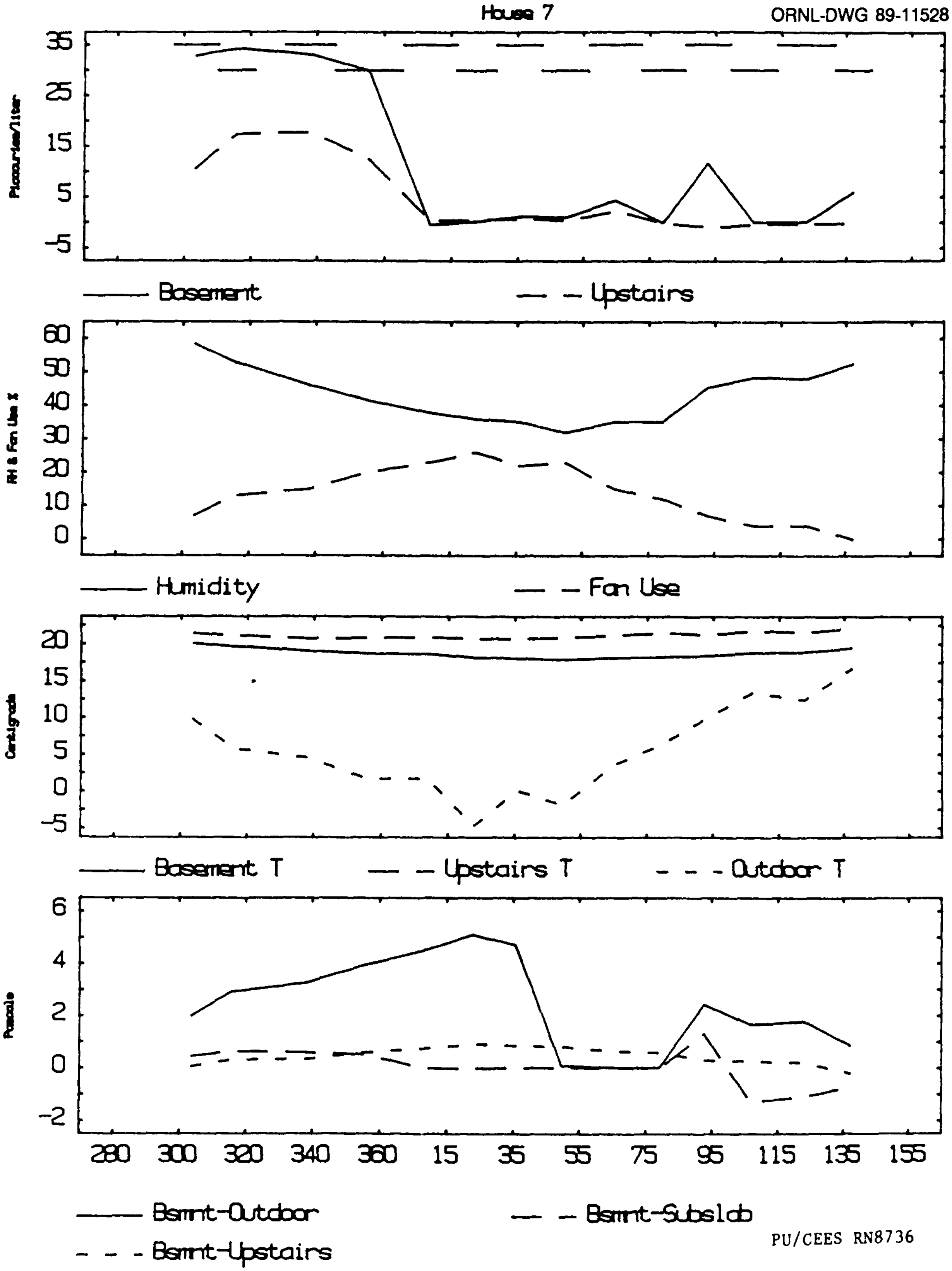


Fig. 6.9. House #5: Comparison of radon, humidity, fan usage, temperature, and pressure differences during PFT experiments.



PU/CEES RN8735

Fig. 6.10. House #6: Comparison of radon, humidity, fan usage, temperature, and pressure differences during PFT experiments.



PU/CEES RN8736

Fig. 6.11. House #7: Comparison of radon, humidity, fan usage, temperature, and pressure differences during PFT experiments.

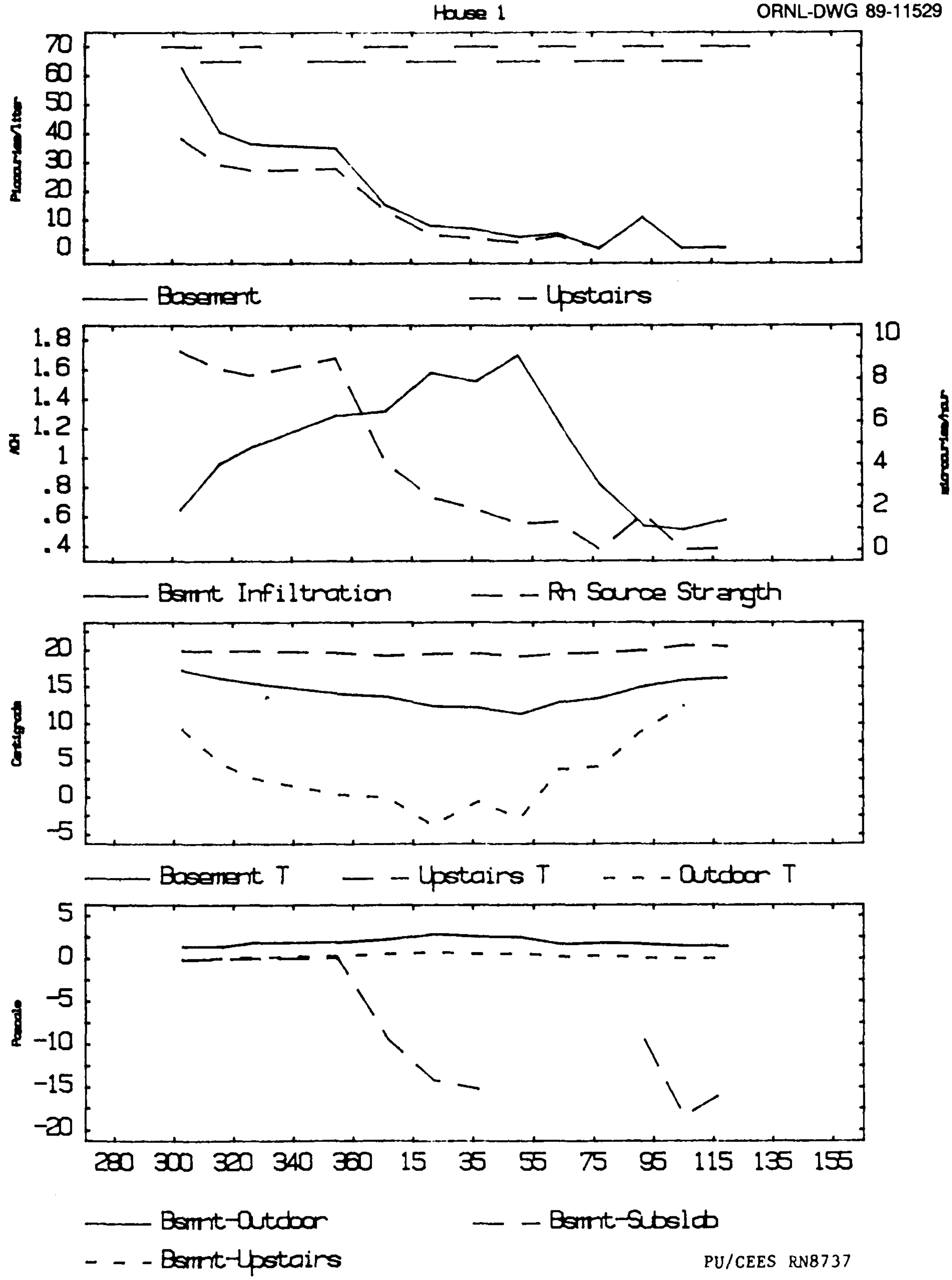


Fig. 6.12A. House #1: Comparison of source strength with environmental conditions.

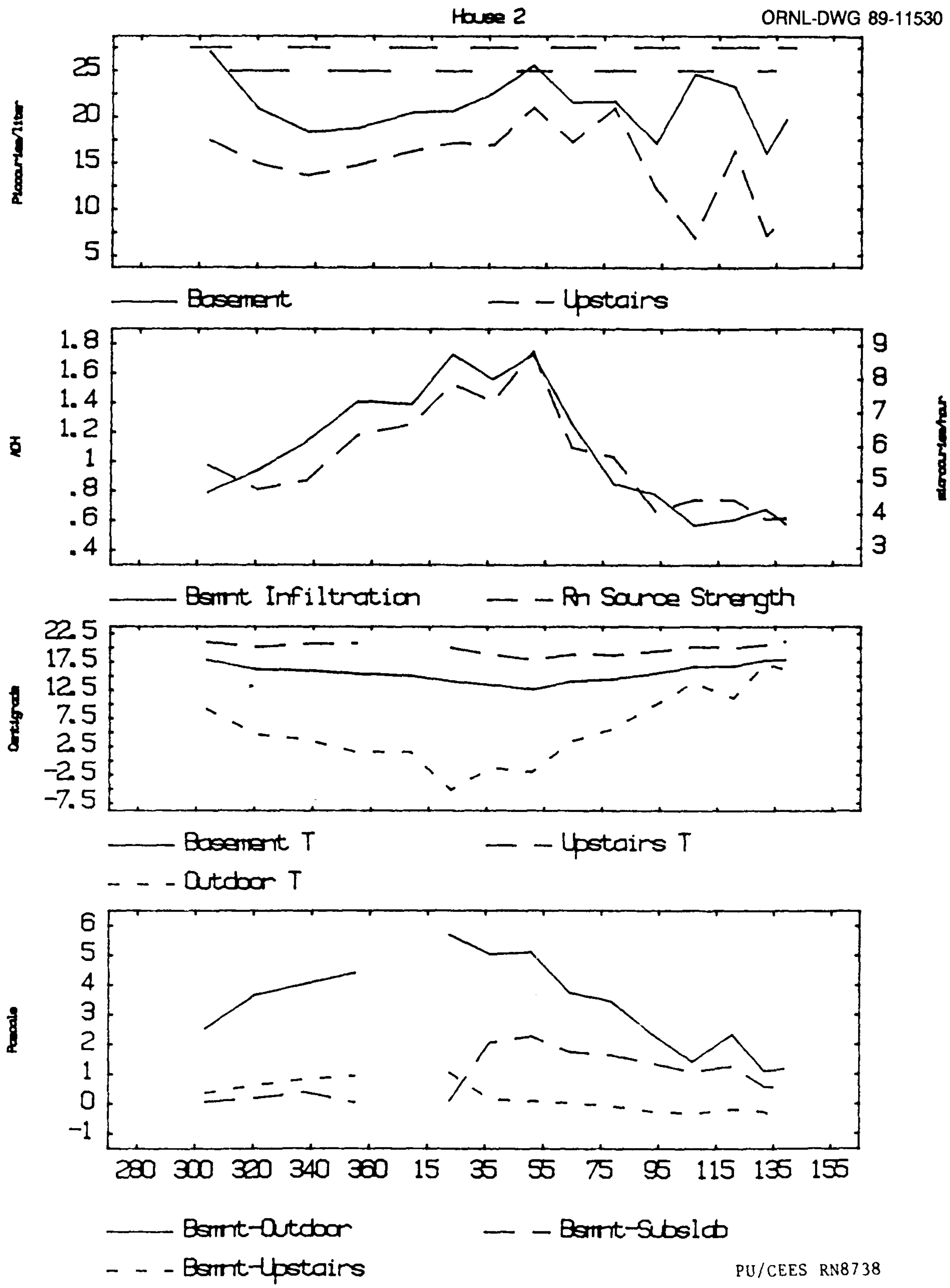


Fig. 6.12B. House #2: Comparison of source strength with environmental conditions.

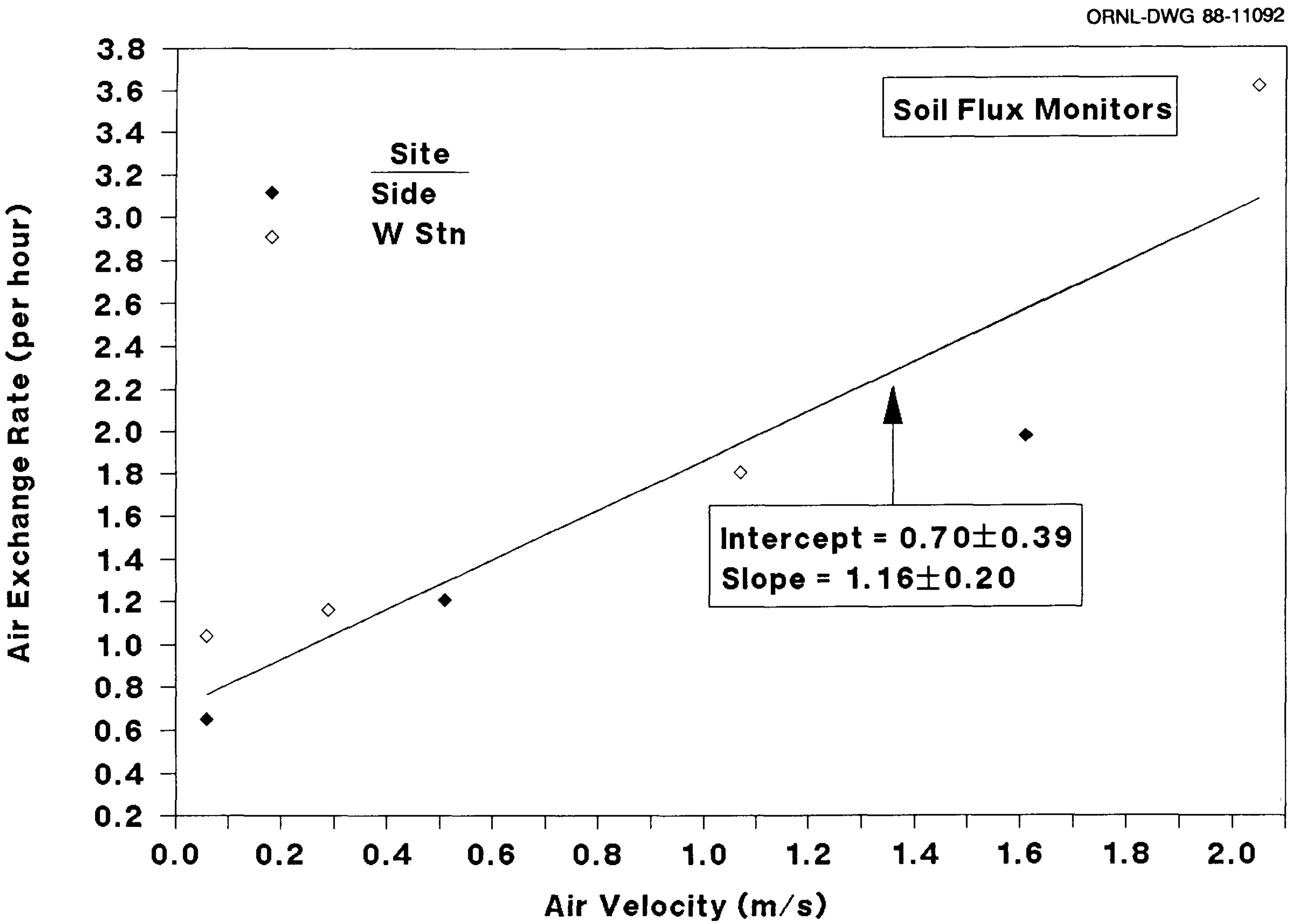


Fig. 6.13. Comparison of air velocity at surface of soil flux monitor with air exchange rate.

7. RESULTS OF CONTINUOUS MEASUREMENTS

7.1 INSTRUMENTS ATTACHED TO INDOOR DATA LOGGER

Data from each of the indoor data loggers and the weather station data logger were transferred to ORNL and stored until final calibration data were obtained for each instrument used in the study. The data were systematically reviewed for completeness and for nonrealistic values using the programs listed in the appendix. The reliability of the data loggers and data transfer process was quite good, as indicated by the high numbers of successful measurements made each week (Tables 7.1 to 7.8). Radon measurements made after mitigation frequently resulted in fewer counts being observed than was the background count rate and these events were recorded as "unsuccessful." This accounts for many of the missing radon measurements in the tables. During the spring, the owner of House #1 began to prepare to sell the house; the upstairs radon monitor was removed during the week ending on Julian date 95, and the outdoor temperature probe was removed during the week ending on Julian date 116. All remaining monitors were removed during the week ending on Julian date 137. The basement-subslab pressure transducer in House #2 was faulty from Julian date 341 until its repair on Julian date 38. Most of the data from House #2 for the week ending on Julian date 39 was lost when power to the data logger was lost for an extended period. Power to the weather station data logger was lost for an extended period prior to Julian date 99 and resulted in data losses for the two-week period ending on Julian date 102. Most other data losses were due to removal of the instruments for calibration, repair, or temporary experimentation.

The results of these measurements will be given to interested scientists and engineers. Readers who send a brief description of their intended use of the data to the senior author of this report will receive 1.2 MB floppy diskettes, readable on an IBM AT, with dBaseIII files appropriate for their purposes. The approximate size of the data base is 2 MB per house.

For each of the instruments attached to the indoor data loggers, simple summary statistics (i.e., mean, minimum, maximum, and standard deviation) for each one-week period, beginning at midnight of Monday morning, have been calculated and provide a preliminary view of the technical findings from the continuous data sets. Examples of the programs used are listed in the appendix. The weekly summary data (principally mean values) are presented here in graphical form (Figures 7.1 to 7.44), and analyzed on a house-by-house and parameter-by-parameter basis. Complete summary statistics are presented in tables in the Appendix.

The following discussion clarifies the presentation of data in Figures 7.1 to 7.44 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 furnace fan duty cycle (fraction of time in "on" 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 during each week of the study. The reported furnace fan duty cycle represents the fraction of time that the central air handling unit is on during a 30-minute sampling interval.

The temperature data show fairly consistent curves for each study house for basement, upstairs, and outdoor locations. Houses such as #4 and #6 (see Figures 7.20 and 7.33) have highly conditioned basements with temperatures very similar to upstairs levels. The transient decreases in indoor temperatures at House #4 correspond to periods when the occupants went on vacation. The other houses (see Figures 7.2, 7.8, 7.14, 7.26, and 7.40) have poorly conditioned basements during winter periods. Relative humidity data show expected seasonal trends with very narrow weekly ranges during the study. Furnace fan duty cycle data show expected seasonal trends with very broad weekly ranges during the study. For most of the houses there was at least one half-hour period during each week when the fan was off the entire period. The houses varied widely with regard to the maximum duty cycle recorded each week. In House #5 (see Figure 7.28), the weekly maxima were always 1.0 except for the week they were on vacation. This reflects the family's diurnal pattern of adjusting the heating and cooling system every morning and evening. In contrast, the weekly maxima at House #3 (see Figure 7.16) were generally less than 0.8 even in the coldest weeks of the winter.

The differential pressure data show the impact of both seasonal processes and active mitigation measures depressurizing, or occasionally pressurizing, the subslab regions. The impact of on/off operation and adjustment of depressurization measures is obvious for most 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 to 4 Pa in Houses #3, #4, and #7 (see Figures 7.13, 7.19, and 7.39, respectively) were generally effective in reducing basement radon levels to less than 4 pCi/L, whereas 10 to 17 Pa subslab depressurization was required at Houses #1, #5, and #6 (see Figures 7.1, 7.25, and 7.32), which generally had more complex pumping and exhaust systems. The subslab pressure transducer was not operative between Julian dates 343 and 39 in House #2 at which mitigation was delayed until July 1987.

A broad range of basement and living area premitigation radon levels were observed in most of the study houses. For example, in House #3 30-min averages (see Figures 7.17 and 7.18) range from about 80 to 240 and 15 to 110 pCi/L in the basement and living area, respectively. Premitigation radon levels in the control house (i.e., #2) are among the least variant and consistent between basement and upstairs levels (see Figures 7.11 and 7.12). Weekly average radon levels of approximately 10 to 30 pCi/L are observed in both basement and living area locations.

The most effective radon mitigation systems are observed in Houses #1, #3, #4, and #7 (see Figures 7.5, 7.17, 7.23, and 7.43, respectively). Weekly mean and maximum radon levels at basement and upstairs monitoring sites are typically maintained below 1 to 2 pCi/L with the mitigation systems in operation. The initial mitigation strategy in House #5 was basement pressurization (see Figures 7.25 and 7.29, weeks ending on Julian dates 18 to 39), which did not maintain levels below 4 pCi/L. The induced pressure was of the order of 1 Pa. We now believe that with a different fan, a larger pressure field could have been induced which would have better controlled radon ingress. Subslab depressurization of about 15 Pa did control radon levels satisfactorily in House #5. Successful mitigation of House #6 required many adjustments to the subslab depressurization system. Reasons for the needed adjustments included: (1) two-compartment substructure (i.e., basement and crawl space) and (2) preexisting, partially successful mitigation system (i.e., heat recovery ventilation system in basement). In the period from Julian dates 81 to 123, a pressure difference of about 15 Pa kept weekly average radon levels below 4 pCi/L (see Figures 7.32 and 7.36).

7.2 WEATHER STATION

The following discussion clarifies the presentation of the weekly summary data in Figures 7.45 to 7.53 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 fluxes ($pCi \cdot m^{-2} \cdot h^{-1}$) inside the outdoor instrumented flux monitors all result from single electronic 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 fluxes are plotted for the outdoor flux monitors for comparison.

Radon flux was calculated from the data as follows:[1]

$$\mathrm{Flux}(pCi \cdot m^{-2} \cdot h^{-1}) = \frac{\mathrm{Concentration}(pCi/L) * \mathrm{Volume}(L) * \mathrm{Air\ Exchange}(h^{-1})}{\mathrm{Area}\ (m^2)},$$

where: Concentration was measured by the Wrenn chamber
Volume of the flux monitor was 528 L
Area of the monitor opening was 0.223 m^2
Air exchange was estimated from the wind speed[2] according to:

$$\mathrm{Air\ exchange}(h^{-1}) = 0.699 + 1.16 * \mathrm{wind\ speed}(m/s).$$

Seasonal effects in the available weather data are most clearly observed in the dips in the air and soil temperatures, Figures 7.45 and 7.46. Outdoor relative humidity (Figure 7.47), rainfall (Figure 7.48), and barometric pressure (Figure 7.49) do not show clearly discernible seasonal effects. The dip in rainfall during the winter months is believed to be caused in part by the freezing of the tipping bucket with snow and ice. Average wind speed (Figure 7.50) appears to be somewhat elevated in the coldest part of the winter. In every week there was at least one half hour

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[1]Radioactive decay of radon was assumed to account for very little of the disappearance of radon within the chamber.
[2] See section 6.3.2 for description of wind speed effects on air exchange.

interval during which the wind speed failed to exceed the minimum necessary for rotation of the anemometer. Radon concentrations in the flux monitors (Figures 7.51 and 7.52) were relatively constant prior to April 1987. After April 1987, the radon concentration in the monitor at the weather station site began to trend upward until the end of the study. The flux data (Figures 7.53 and 7.54) exhibit the same trends as the radon concentration data.

7.3 Impact on Indoor Radon from Stages of Mitigation

Mitigation systems were installed and subsequently adjusted or modified in each house. For varying lengths of time, different mitigation options were investigated, including subslab pressurization, basement pressurization, passive subslab ventilation, and various sealing measures. At the end of the study all houses were mitigated with subslab depressurization systems operating at the minimum fan speed that reliably held radon levels below 4 pCi/L. The impact on indoor radon levels from each change to the mitigation system was evaluated and is described in this section.

Table 7.9 summarizes the mean radon level at the basement and living area sites for various periods of time at each house, except the control house (#2). In addition, the frequency of 30-min sampling intervals for which the mean radon level is above 4 pCi/L is indicated. The periods were chosen to facilitate comparisons among the phases of the mitigation process. One phase for each house is the period just prior to the beginning of mitigation. Another phase common to all houses is a one-week period in late May 1987, representing the final mitigation system.

The initial mitigation strategies chosen for Houses #3, #4, and #7 were subslab depressurization, and the installed systems were immediately successful. For Houses #1, #5, and #6, the effects of numerous interventions can be seen in Table 7.9. In none of the houses was subslab pressurization as effective as subslab depressurization. When the fan was not operated and the dampers were open in the subslab ventilation system in each of Houses #3, #4, and #5, it was observed that passive ventilation of the subslab was insufficient to control radon entry. In contrast, passive ventilation of the subslab in House #7 may be sufficient, but the system was not operated in this mode long enough to be sure.

7.4 RELATING RADON TO ENVIRONMENTAL PARAMETERS

The continuous monitoring of radon levels and other physical parameters and recording of 30-min average values 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 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 7.55 shows a diurnal variation in basement radon concentration in a House #5 (Figure 7.55a) 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 7.55b shows the fraction of time that the fan in the central air handler is running for each 30-min interval; the fan is associated with an electric heat pump and powers a forced-air distribution system. The central 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 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 soil, 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 7.55 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 7.55c); this pressure difference is the principal mechanism in cold weather for driving radon into the house. This pressure difference displays spikes synchronous with the operation of the central fan, a plausible effect reflecting the additional basement depressurization which accompanies the operation of the distribution system (e.g. leaky return ducts). Figure 7.55d 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 fan 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.

Figure 7.56 shows the apparent impact of heavy rainfall on radon levels in three houses (Figures 7.56a, 7.56b, 7.56c). Here, outdoor weather does have a pronounced effect on basement radon levels. Figure 7.56d shows time series for two meteorological factors, barometric pressure and amount of rain, for a week in November 1986. 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.

A preliminary investigation was made of the consistency of rainstorm-induced transient increases in indoor radon. The investigation was limited to Houses #1, #5, and #6. Figure 7.57 summarizes the magnitudes of rainstorms and the associated transient increases in radon at the basement and living area sites. Substantial rain spikes were only observed for storms greater than 0.75 in. of rainfall. There are not enough data to infer whether the magnitude of the rain spike increases according to the magnitude of the storm event.

Figure 7.58 shows data in the postmitigation period for House #5, shown previously in Figure 7.55. During a five-day stretch in the middle of the week displayed here, the occupants went on vacation and agreed to allow us to shut off their mitigation system, a subslab ventilation (SSV) system. Figure 7.58a 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 7.58b 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 air handler fan is off, and the difference in pressure between subslab and basement shows almost none of the diurnal behavior seen in Figure 7.55c. The basement radon concentration, however, develops a diurnal pattern reminiscent of Figure 7.55a, although of reduced amplitude, still peaking in the morning. Something other than fan 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 7.58c) 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.

The concentrations of radon and radon progeny and the equilibrium ratio in the basement air of House #3 are compared in Figures 7.59.a, 7.59.b, and 7.59.c, respectively. The equilibrium ratio is normalized to 0.01 WL/(pCi/L), which is the ratio at secular equilibrium. The equilibrium ratio exhibits considerable structure over a week period. This phenomenon is likely to be the result of uncorrelated time dependencies between the concentrations of radon gas and radon progeny (see Figures 7.59a, 7.59b). The time dependence of the run time of the furnace fan (percentage on each 30-min interval) is illustrated in Figure 7.59d. The operation of the central air handler 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, the concentrations of radon gas and radon progeny in the basement increase and decrease, respectively, with the operation of the furnace. The increase in radon gas may be caused by decreases in basement pressure, permitting further inflow of soil gas. The decrease in radon progeny may be caused by 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. Further analysis of these data is awaiting final calibration of the response time of the working level monitors as compared to the Wrenn chambers.

When the subslab depressurization systems are cycled on and off (see Figures 5.8 to 5.14), two things are clear: (1) indoor radon levels are dramatically and quickly reduced after startup, and (2) of all the parameters measured, the pressure difference across the basement slab is the most strongly affected. These observations, along with theoretical considerations, have led us to begin systematic evaluations of the correlations between radon levels and subslab pressure differences.

Darcy's law suggests that the source strength for radon entry into the basement depends on both radon concentration in the soil gas and the pressure difference across the slab. Between March 23, 1987, and April 26, 1987, there were three extended periods when radon was monitored in subslab gas and the mitigation system was not operating. Figure 7.60 shows the time series for radon in the basement and in the subslab region and the pressure difference across the slab during this period. The extended periods when the mitigation system was not perturbed are also indicated. Probable loss mechanisms, such as flow of radon-laden gas from the basement via the central air handler, were not included in this preliminary analysis.

Using commercially available software (SAS 1984), the data from the three indicated periods were examined for cross-correlations (Box and Jenkins 1970) between radon in the basement and radon in the subslab region. Cross-correlations between the first-order change in basement radon (i.e., analogous to the first derivative) and subslab radon were also calculated. The results are presented in Figure 7.61. For all three periods of data, the cross-correlation function for radon shows a strong peak at zero lag, whereas the function for the change in radon does not show a peak. Cross-correlation functions for radon and change in radon were also calculated with pressure across the slab as the independent variable and the results are shown in Figure 7.62. As seen in Figure 7.61, the change in radon does not exhibit a strong peak in the cross-correlation function for any of the three periods. The cross-correlation function for radon from the first period fails to show a strong peak. From the second period, there is a strong positive correlation at zero lag, and from the third period, there is a strong negative correlation at zero lag. Examination of the time series data from the third period reveals a decreasing trend in the pressure difference and an increasing trend in the radon in the basement, which account for the negative correlation. Cross-correlation functions for radon and change in radon were also calculated with the independent variable being the source strength (i.e., the product of pressure across the slab and radon concentration in the subslab gas), and the results are shown in Figure 7.63. With the possible exception of the cross-correlation between radon and source strength during the second period, there are no strong peaks in any of the cross-correlation functions.

It was decided to see if this preliminary indication of noncorrelation between radon and subslab pressure difference extended to House #3. Four one-week periods in November 1986 were analyzed in the same way, and Figure 7.64 describes the cross-correlation functions between either radon or change in radon and pressure across the slab for each of the periods. In addition, cross-correlation functions for House #3 for three periods in February 1987, when the mitigation system was not operating, are presented in Figure 7.65. There is no consistent correlation with pressure across the slab for the seven periods of time covered by Figures 7.64 and 7.65. Future work will further examine the available data by using this and other techniques and by applying them to other blocks of data. Until that work is done, the tentative conclusion is that, for House #5, the major factor controlling the source term for radon in the basement is the concentration in the soil gas and not the pressure difference across the slab. In other words, mitigation strategy for House #5 should emphasize diluting or removing the radon in the subslab reservoir.

Efforts to develop physical models of radon entry processes have shown so far that many forces are involved interactively. For an example of the complex models being developed, the reader is referred to the recent article by Mowris and Fisk (1988). Preliminary efforts to develop statistical models have begun with the goal of identifying the relative importance of various driving forces for different houses and/or seasons. The available data from House #5 for four weeks in December 1986 were examined for cross-correlations, and a summary of the results is shown in Table 7.10. The pressure differences exhibiting the most impact on basement radon levels were found to be across the slab and across the floor. The important temperature difference was found to be that between the living area and the basement.

The finding of no significant correlation of upstairs radon with basement radon in House #5 in December was unexpected and led us to examine other houses and other times. Cross-correlations between upstairs radon (dependent variable) and basement radon (independent variable) were computed for all houses for four weeks in November and for four weeks in December. A summary of the results is shown in Table 7.11. For five houses, cross-correlation functions were computed from the December data and none of the functions showed a significant peak. In contrast, five of seven functions computed from the November data showed a substantial peak in the cross-correlation function.

The variation seen in cross-correlation functions computed from data from different times in a single house, or from data from different houses during a single period, strongly illustrate the complex nature of the processes underlying radon entry into houses.

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Mowris, R. J., and Fisk, W. J. 1988. "Modeling the Effects of Exhaust Ventilation on ^{222}Rn Entry Rates and Indoor ^{222}Rn Concentrations," Health Physics 54:491-501.

SAS. 1984. *SAS/ETS User's Guide, Version 5 Edition*, SAS Institute, Cary, NC.

Table 7.1. Numbers of Successful Measurements per Week for House #1.

Ending Julian Date	Relative Humidity	Temperature			Diff. Pressure			Radon	
		Bsmt	Upst.	Out	Out	Sslab	Upst.	Bsmt	Upst.
299	336	336	336	336	336	336	336	336	336
306	336	336	336	336	336	336	336	336	336
313	336	336	336	336	336	336	336	336	336
320	336	336	336	336	336	336	336	336	336
327	336	336	336	336	336	336	336	336	336
334	336	336	336	336	336	336	336	336	336
341	336	336	336	336	336	336	336	336	336
348	336	336	336	336	336	336	336	336	336
355	336	336	336	336	336	336	336	336	336
362	336	336	336	336	336	336	336	336	336
4	336	336	336	336	336	336	336	336	336
11	336	336	336	336	336	336	336	336	336
18	336	336	336	336	336	336	336	336	336
25	336	336	336	336	336	336	336	226	336
32	336	336	336	322	336	336	336	336	336
39	336	336	336	336	336	336	336	336	336
46	336	336	336	336	336	336	336	336	336
53	336	336	336	336	336	232	336	331	286
60	336	336	336	336	336	75	336	336	328
67	335	335	335	335	335	141	335	329	324
74	336	336	336	336	336	2	336	261	159
81	336	336	336	336	336	1	336	270	152
88	336	336	336	336	336	168	336	303	286
95	336	336	336	336	336	336	336	300	162
102	336	336	336	336	336	336	336	303	0
109	336	336	336	336	336	336	336	291	0
116	336	336	335	71	336	336	336	260	0
123	336	336	336	0	336	336	336	311	0
130	336	336	336	0	336	218	336	335	0
137	192	193	193	1	192	29	192	191	0

Table 7.2. Numbers of Successful Measurements per Week for House #2.

Ending Julian Date	Relative Humidity	Temperature			Diff. Pressure			Radon	
		Bsmt	Upst.	Out	Out	Sslab	Upst.	Bsmt	Upst.
299	335	335	335	335	335	335	335	335	336
306	336	336	336	336	336	336	336	336	336
313	336	336	336	336	336	336	336	336	336
320	336	336	336	336	325	336	336	336	336
327	336	336	336	336	320	336	336	336	336
334	332	336	332	336	330	332	332	332	336
341	336	336	336	336	328	336	336	334	334
348	336	336	336	336	320	0	336	336	336
355	334	334	336	334	307	0	336	334	336
362	288	288	288	288	288	0	288	288	288
4	336	336	336	336	335	0	336	336	336
11	220	335	220	335	220	0	220	220	336
18	113	336	113	336	113	0	113	113	336
25	336	336	336	336	308	0	336	210	211
32	121	331	121	307	121	0	119	121	336
39	48	48	48	48	34	48	48	48	48
46	336	336	336	336	315	336	336	336	336
53	306	306	306	306	306	306	306	306	306
60	336	336	336	336	334	335	336	335	335
67	336	336	336	336	321	336	336	334	334
74	336	336	336	336	334	336	336	336	336
81	336	336	336	336	334	336	336	335	335
88	336	336	336	336	336	336	336	336	334
95	330	336	330	336	330	329	330	323	336
102	216	336	216	336	208	214	215	214	326
109	336	336	336	336	336	336	336	336	173
116	336	336	336	336	336	336	336	336	256
123	336	336	336	336	329	336	336	336	336
130	336	336	336	336	336	336	336	335	309
137	336	336	336	336	331	336	336	330	308
144	336	336	336	336	336	336	336	314	240
151	336	336	336	336	336	336	336	335	329
158	336	336	336	336	336	336	336	336	328
165	336	336	336	336	335	336	336	336	231
172	336	336	336	336	336	336	336	336	327
179	336	336	336	336	336	336	336	336	274
186	336	336	336	317	336	336	336	332	295

Table 7.3. Numbers of Successful Measurements per Week for House #3.

Ending Julian Date	Relative Humidity	Temperature Bsmt	Temperature Upst.	Temperature Out	Diff. Pressure Out	Diff. Pressure Sslab	Diff. Pressure Upst.	Radon Bsmt	Radon Upst.
299	336	336	336	336	336	336	336	336	336
306	336	336	336	336	336	336	335	335	335
313	335	335	335	335	335	335	335	335	335
320	336	336	336	336	336	336	336	336	336
327	336	336	336	336	330	336	336	336	336
334	327	327	327	327	327	327	327	327	327
341	336	336	336	336	333	336	336	336	336
348	336	336	336	336	335	336	336	336	336
355	336	336	336	336	332	336	336	336	335
362	335	336	335	336	335	335	335	335	201
4	334	336	335	336	335	335	335	334	175
11	336	336	336	336	327	336	336	335	215
18	336	336	336	336	333	336	336	336	203
25	336	336	336	336	322	336	336	184	324
32	336	336	336	336	335	336	336	336	336
39	336	336	336	336	334	336	336	336	336
46	336	336	336	336	333	336	336	336	336
53	336	336	336	336	336	336	336	336	336
60	336	336	336	336	336	335	336	335	335
67	336	336	336	336	327	336	336	336	322
74	336	336	336	336	336	336	336	336	335
81	336	336	336	336	336	336	336	333	333
88	336	336	336	336	336	336	336	328	318
95	336	336	336	336	335	336	336	336	336
102	336	336	336	336	336	336	336	336	313
109	336	336	336	336	336	336	336	336	325
116	336	336	336	336	336	336	336	336	316
123	336	336	336	336	336	336	336	336	330
130	336	336	336	336	336	336	336	334	304
137	336	336	336	336	336	336	336	326	307
144	336	336	336	336	336	336	336	312	333
151	336	336	336	336	336	336	336	292	318
158	336	336	336	336	336	336	336	336	316
165	336	336	336	336	336	336	336	336	292
172	336	336	336	336	336	336	336	336	293
179	334	334	336	334	331	336	336	334	311
186	336	336	336	336	336	336	336	336	306

Table 7.4. Numbers of Successful Measurements per Week for House #4.

Ending Julian Date	Relative Humidity	Temperature			Diff. Pressure			Radon	
		Bsmt	Upst.	Out	Out	Sslab	Upst.	Bsmt	Upst.
299	336	336	336	336	336	336	336	336	336
306	336	336	336	336	336	336	336	336	336
313	336	336	336	336	336	336	333	336	336
320	336	336	336	336	336	336	335	336	336
327	335	335	335	222	336	336	336	335	336
334	336	336	336	336	336	336	336	336	336
341	336	336	336	336	336	336	336	336	336
348	336	336	336	336	336	336	336	336	336
355	336	336	336	336	336	335	336	336	195
362	336	336	336	336	336	336	336	336	326
4	336	336	336	336	336	336	336	336	336
11	336	336	336	336	336	336	336	336	330
18	336	336	336	336	336	336	336	335	334
25	336	336	336	336	335	336	336	191	335
32	336	336	336	336	336	336	336	336	335
39	336	336	336	336	336	336	336	336	336
46	336	336	336	336	336	336	336	336	333
53	336	336	336	336	336	336	336	336	336
60	336	336	336	336	336	336	336	335	335
67	336	336	336	336	336	336	336	336	334
74	336	336	169	336	336	336	336	336	336
81	336	336	213	336	336	336	336	335	335
88	336	336	336	336	336	336	336	333	325
95	336	336	336	336	336	336	336	336	336
102	336	336	336	336	336	336	336	336	336
109	335	335	335	335	335	335	335	335	335
116	336	336	336	336	336	336	336	336	335
123	336	336	336	336	336	335	336	336	336
130	336	336	336	336	336	336	336	336	335
137	336	336	336	336	336	336	336	336	336
144	336	336	336	336	336	336	336	336	336
151	336	336	336	336	336	336	336	336	336
158	336	336	336	336	336	336	336	336	336
165	335	335	335	335	331	335	335	335	336
172	335	335	336	335	335	336	336	335	336
179	336	336	336	336	336	336	336	336	336
186	336	336	336	336	336	336	336	336	336

Table 7.5. Numbers of Successful Measurements per Week for House #5.

Ending Julian Date	Relative Humidity	Temperature			Diff. Pressure			Radon	
		Bsmt	Upst.	Out	Out	Sslab	Upst.	Bsmt	Upst.
299	336	336	336	336	336	336	336	336	331
306	336	336	336	336	336	336	336	336	325
313	336	336	336	336	336	336	336	336	336
320	336	336	336	336	336	336	336	336	335
327	335	335	336	335	335	336	336	334	335
334	336	336	336	336	333	336	336	336	336
341	336	336	336	336	331	336	336	336	336
348	336	336	336	336	336	336	336	336	336
355	336	336	336	336	336	336	336	336	336
362	336	336	336	336	336	336	336	336	336
4	336	336	336	336	336	336	336	336	336
11	335	335	335	335	333	335	335	335	335
18	336	336	336	336	336	336	336	336	336
25	336	336	336	336	331	336	336	230	336
32	336	336	336	336	336	336	336	336	336
39	336	336	336	336	335	336	336	336	336
46	336	336	336	335	336	336	336	336	318
53	336	336	336	336	336	336	336	336	330
60	336	336	336	336	336	336	336	334	311
67	336	336	336	336	327	336	336	335	191
74	336	336	336	336	336	336	336	336	233
81	336	336	336	336	336	336	336	335	303
88	336	336	336	336	336	336	336	336	309
95	336	336	336	336	331	336	336	336	336
102	336	336	336	336	336	336	336	326	231
109	336	336	336	336	336	336	336	331	235
116	336	336	336	336	336	336	336	322	171
123	336	336	336	336	336	336	336	328	154
130	336	336	336	336	336	336	336	310	165
137	336	336	336	336	336	336	336	311	71
144	336	336	336	336	335	336	336	334	229
151	336	336	336	336	336	336	336	314	135
158	336	336	336	336	336	336	336	327	98
165	336	336	336	336	336	336	336	317	48
172	336	336	336	336	336	336	336	315	133
179	334	334	336	334	333	336	333	304	67
186	144	144	144	144	144	144	144	138	49

Table 7.6. Numbers of Successful Measurements per Week for House #6

Ending Julian Date	Relative Humidity	Temperature Bsmt	Temperature Upst.	Temperature Out	Diff. Pressure Out	Diff. Pressure Sslab	Diff. Pressure Upst.	Radon Bsmt	Radon Upst.	Radon Crawl.
299	336	336	336	336	336	336	336	336	332	336
306	336	336	336	336	336	336	336	336	336	336
313	336	336	336	336	336	336	336	336	333	336
320	336	336	336	336	336	336	336	336	336	336
327	316	316	336	316	309	336	336	316	336	336
334	307	307	336	307	306	336	336	305	336	334
341	304	304	336	303	300	336	336	304	336	336
348	294	294	336	294	294	336	336	294	336	336
355	312	312	336	312	310	336	336	178	201	202
362	302	302	336	302	300	336	336	302	336	336
4	336	336	336	336	336	336	336	336	336	336
11	336	336	336	336	336	336	336	336	336	336
18	336	336	336	336	335	336	336	336	336	336
25	336	336	336	332	335	336	336	193	193	336
32	336	336	336	321	336	336	336	336	336	336
39	336	336	336	336	336	336	336	336	336	336
46	336	336	336	336	335	336	336	336	336	330
53	336	336	336	336	336	336	336	336	336	336
60	310	309	334	309	309	334	334	309	334	334
67	320	320	335	320	320	335	335	320	331	333
74	336	336	336	336	336	336	336	335	335	335
81	336	336	336	336	336	336	336	336	336	336
88	335	335	336	335	336	336	336	334	316	290
95	284	284	336	284	272	336	336	284	336	336
102	335	335	336	336	336	336	336	334	327	334
109	336	336	336	336	336	336	336	336	326	327
116	336	336	336	335	336	336	336	336	316	323
123	336	336	336	336	336	336	336	335	332	336
130	336	336	336	336	336	336	336	162	316	281
137	336	336	336	336	336	336	336	313	311	324
144	48	48	48	48	48	48	48	48	41	46
151	336	336	336	335	336	336	336	336	328	335
158	334	335	335	335	332	335	334	334	333	332
165	336	336	336	336	336	336	336	336	334	335
172	336	336	336	336	336	336	336	336	336	336
179	335	335	336	334	334	336	336	332	320	328
186	247	247	247	247	247	247	247	247	247	247

Table 7.7. Numbers of Successful Measurements per Week for House #7.

Ending Julian Date	Relative Humidity	Temperature			Diff. Pressure			Radon	
		Bsmt	Upst.	Out	Out	Sslab	Upst.	Bsmt	Upst.
299	336	336	335	336	336	335	336	336	336
306	336	336	336	336	336	336	336	336	336
313	336	336	336	336	336	336	336	336	336
320	336	336	336	336	336	336	336	336	336
327	334	334	334	334	334	334	334	334	334
334	336	336	336	336	335	335	336	336	336
341	336	336	336	336	335	336	335	336	336
348	336	336	336	336	336	336	336	336	336
355	336	336	336	336	336	336	336	336	336
362	336	336	336	336	334	336	336	142	335
4	329	336	329	336	329	329	329	58	333
11	336	336	336	336	336	336	336	82	335
18	336	336	336	336	336	336	336	209	336
25	336	336	336	336	336	336	336	200	207
32	336	336	336	333	336	336	336	336	241
39	336	336	336	336	336	336	336	331	297
46	336	336	336	336	336	336	336	328	311
53	336	336	336	336	336	336	336	336	331
60	336	336	336	336	336	336	336	335	335
67	336	336	336	336	336	336	336	317	276
74	336	336	336	336	336	336	336	304	226
81	336	336	336	336	336	336	336	293	215
88	336	336	336	336	336	336	336	285	90
95	336	336	336	336	335	336	336	324	0
102	336	336	336	336	336	336	336	300	59
109	336	336	336	336	336	336	336	293	145
116	298	298	298	298	298	298	298	249	104
123	336	336	336	336	336	336	336	307	133
130	336	336	336	336	336	336	336	313	176
137	336	336	336	336	336	336	336	323	133
144	336	336	336	336	336	336	336	310	49
151	336	336	336	336	336	336	336	336	172
158	336	336	336	336	336	336	336	307	124
165	288	288	288	288	288	287	288	155	52
172	336	336	336	336	336	336	336	151	37
179	336	336	336	336	332	336	335	164	16
186	336	336	336	336	336	336	336	226	56

Table 7.8. Numbers of Successful Measurements per Week for Weather Station.

Ending Julian Date	Relative Humidity	Temperature		Barometric Pressure	Radon		Rain	Wind Speed
		Air	Soil		Side	W-Stn		
292	330	336	336	336	336	336	336	336
299	300	336	336	336	336	336	336	336
306	284	336	336	336	336	336	336	336
313	279	336	336	336	336	336	336	336
320	305	336	336	336	336	336	336	336
327	293	336	336	336	336	336	336	336
334	315	336	336	336	336	336	336	336
341	299	336	336	336	336	336	336	336
348	271	322	336	336	336	336	336	336
355	303	336	336	336	336	336	336	336
362	320	336	336	336	336	336	336	336
4	296	309	309	309	309	309	309	309
11	313	336	336	336	336	336	336	336
18	316	336	336	336	336	336	336	336
25	294	276	336	336	336	334	336	336
32	310	291	336	336	336	336	336	336
39	336	336	336	336	336	336	336	336
46	336	299	336	336	336	336	336	336
53	336	318	336	336	336	336	336	336
60	294	336	336	336	336	336	336	336
67	325	336	336	336	336	336	336	336
74	336	331	336	336	336	336	336	336
81	336	336	336	336	336	336	336	336
88	336	336	336	336	336	336	336	336
95	121	144	144	144	144	144	144	144
102	192	192	192	192	192	192	192	192
109	327	336	336	336	336	336	336	336
116	336	336	336	336	336	336	336	336
123	336	336	336	336	336	336	336	336
130	336	336	336	336	336	336	336	336
137	336	336	336	336	336	336	336	336
144	336	333	336	336	336	336	336	336
151	336	306	336	336	336	336	336	336
158	333	330	336	336	336	336	336	336
165	336	336	336	336	336	336	336	336
172	336	301	336	336	336	336	336	336
179	336	325	336	336	336	336	336	336
186	316	332	336	336	336	336	336	336

Table 7.9. Radon Response to Stages of Mitigation.

Mitigation[a] Status	From date	til date	Radon(pCi/L) Bsmt	Radon(pCi/L) Living Area	% > 4 pCi/l[b] Bsmt	% > 4 pCi/l[b] Living Area
*** House 1						
Original	360	365	35.7	29.7	100	100
SSD & Wall D	4	8	7.4	5.4	98	81
No Change	19	25	7.4	5.0	98	69
Sealed Wall and slab	28	32	7.4	4.5	97	60
Tuned SSD	44	48	8.2	4.0	100	47
Per Dr sealed	50	54	0.8	0.3	0	0
SSP	56	62	2.3	1.8	5	0
SSD 100%	68	75	0.1	0.0	0	0
Final SSD	124	127	0.7	---	0	-
*** House 3						
Original	342	349	179.6	74.7	100	100
SSD 100%	356	362	0.8	0.2	0	0
SSD 75%	364	6	0.7	0.1	0	0
SSD 75%	22	28	2.3	0.7	2	0
No power to open SSV	30	35	123.8	44.2	100	100
SSD 75%	36	42	1.8	0.6	0	0
SSD 50%	51	54	3.7	1.4	38	0
SSP	55.5	56.5	8.0	4.2	96	58
SSD 50%	58	63	4.6	1.9	63	0
Final SSD	124	130	1.0	0.1	0	0
*** House 4						
Original	339	345	75.9	43.4	100	100
Temporary SSD 100%	350	356	2.9	0.8	27	0
No change	8	14	2.9	1.3	12	0
No power to open SSV	16	21	59.2	32.3	100	98
SSD 100%	23	30	5.0	2.7	92	14
SSD 100%	57	63	2.9	1.6	35	0
SSP	65	70	27.7	21.5	100	100
SSD 100%	72	78	3.7	2.0	34	4
Final SSD	124	130	1.5	1.2	2	3

[a]Abreviations used are: SS=subslab V=ventilation D=depresurization P=pressurization nn%=% power applied to SSV fan PerDr=perimeter drain BkrRod=backer rod Urethn=urethane.
[b]Frequency (in %) of 30-minute intervals during which radon levels are above 4 pCi/L.

Table 7.9. Radon Response to Stages of Mitigation (cont'd.)

Mitigation[a] Status	From date	til date	Radon(pCi/L) Bsmt	Radon(pCi/L) Living Area	% > 4 pCi/l[b] Bsmt	% > 4 pCi/l[b] Living Area
*** House 5						
Original	358	363	61.5	37.7	100	100
Bsmnt P	364	6	46.5	34.3	100	100
PerDr sealed wBkrRod	8	18	47.6	33.0	100	100
PerDr sealed w/Urethane	20	26	46.2	31.9	100	100
no pwer to to Bsmnt	34	40	56.0	34.9	100	100
SSD 100%	44	48	1.2	0.6	1	0
no power to open SSV	50	56	49.3	29.7	100	100
SSD 100%	58	61	1.1	0.9	6	6
Final SSD	124	130	0.4	0.0	0	0
*** House 6						
Original	360	364	19.0	13.3	100	100
SSD 100%	1	7	21.1	8.1	100	100
Tuned SSD	9	12	17.7	7.0	100	99
Bal Ps (SSD), w/HRV off	16	21	29.8	10.2	100	100
HRV on	31	32	20.9	7.8	100	100
Add wrkrm pipe	34	35	16.2	7.4	100	100
rvrse plast fan	37	42	19.4	8.0	100	100
Mtl fan, sealed CrawlSpace	43	48	25.0	9.6	100	100
Sealed sump	52	58	19.6	7.9	100	100
WallD, BalS SD, 2nd fan	72	76	7.2	4.9	100	83
added SSV pipe	77	79	5.2	3.1	81	21
add another one	80	83	4.5	2.4	73	5
Perm SSD balanc	84	86	4.0	1.9	34	20
SSD 100%	87	94	3.0	1.9	16	3
Final SSD	126	133	2.1	1.2	11	2

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[a]Abreviations used are: SS=subslab V=ventilation D=depresurization P=pressurization nn%=% power applied to SSV fan PerDr=perimeter drain BkrRod=backer rod Urethn=urethane.
[b]Frequency (in %) of 30-minute intervals during which radon levels are above 4 pCi/L.

Table 7.9. Radon Response to Stages of Mitigation (cont'd.)

Mitigation[a] Status	From date	til date	Radon(pCi/L) Bsmt	Radon(pCi/L) Living Area	% > 4 pCi/l[b] Bsmt	% > 4 pCi/l[b] Living Area
*** House 7						
Original	349	355	34.3	21.2	100	100
SSD 100%	358	364	0.1	0.5	0	0
Tuned SSD	13	19	-0.0	0.5	0	0
H20 from SSV, SSD 100%	43	48	0.3	0.1	0	0
no power to open SSV	50	55	1.9	0.8	0	0
SSD 50%	57	60	2.7	1.2	0	0
SSD 100%	77	84	-0.0	-0.1	0	0
SSP	86	92	22.9	---	100	-
SSD 100%	93	100	0.3	-0.8	0	0
Final SSD	124	130	0.3	-0.1	0	0

[a]Abreviations used are: SS=subslab V=ventilation D=depresurization P=pressurization nn%=% power applied to SSV fan PerDr=perimeter drain BkrRod=backer rod Urethn=urethane.
[b]Frequency (in %) of 30-minute intervals during which radon levels are above 4 pCi/L.

Table 7.10. Cross Correlation Results for House #5 (12/86).

Dependent Variable	Independent Variable[a]	Peak Correlation[b]
Radon (upstairs)	Radon (basement)	None
Radon (basement)	DP (basement-upstairs)	++
	DP (basement-subslab)	++
	DP (basement-outdoors)	None
	DT (basement-upstairs)	++
	DT (basement-outdoors)	None

Table 7.11. Cross Correlation Results[c] for Radon-upstairs versus Radon-basement for 11/86 and 12/86.

House	November, 1986	December, 1986
1	None	None
2	+	None
3	++	No fit[d]
4	+	None
5	++	None
6	+	No fit
7	None	None

[a] DP means pressure difference; DT means temperature difference.
[b] None means $0<\rho_{max}<0.1$; + means $0.1<\rho_{max}<0.2$; ++ means $0.2<\rho_{max}<0.4$.
[c] Peak results are shown as in Table 7.2.
[d] A convergent solution to the algorithms was not found.

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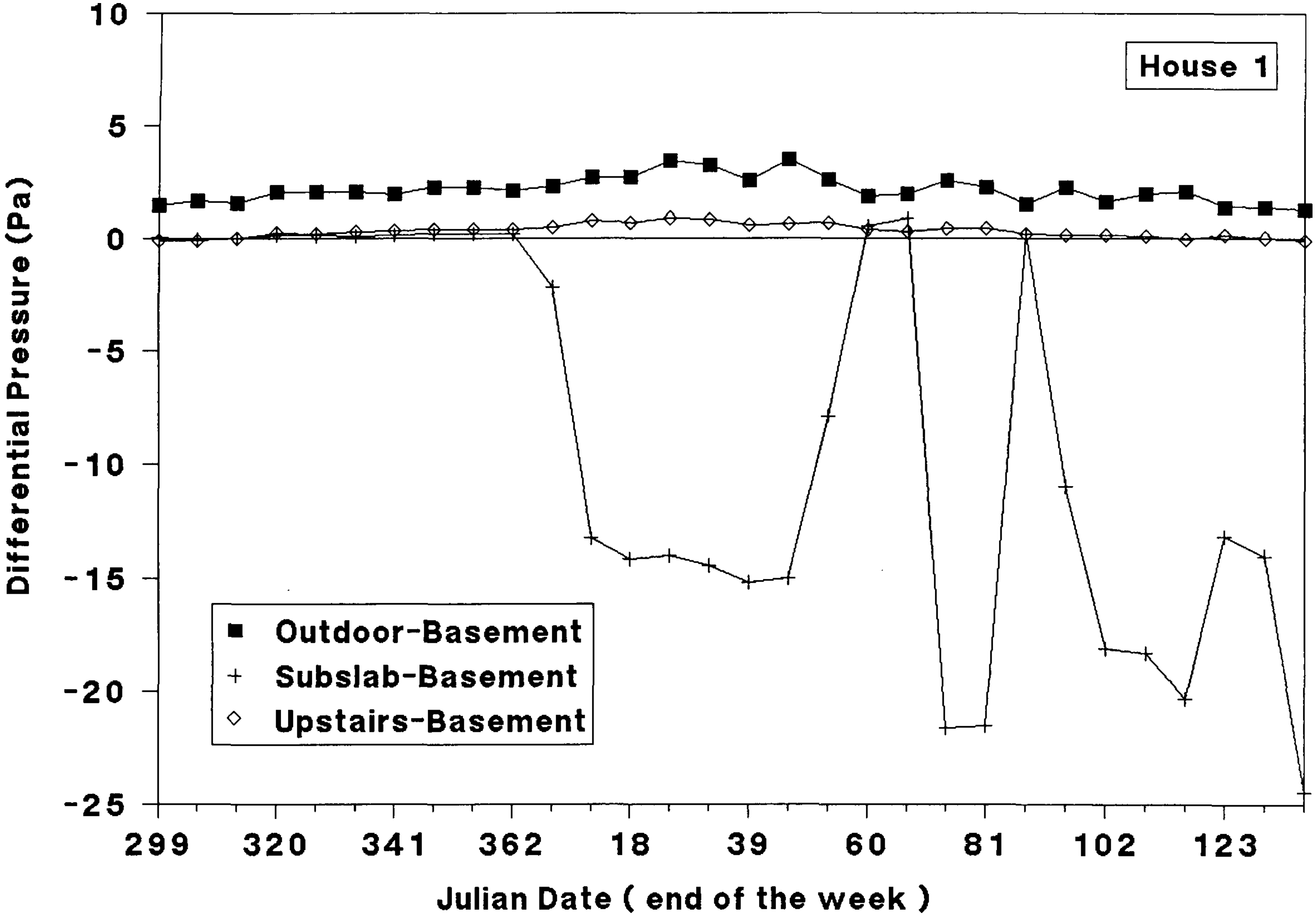


Fig. 7.1. House #1: Weekly averaged differential pressure data.

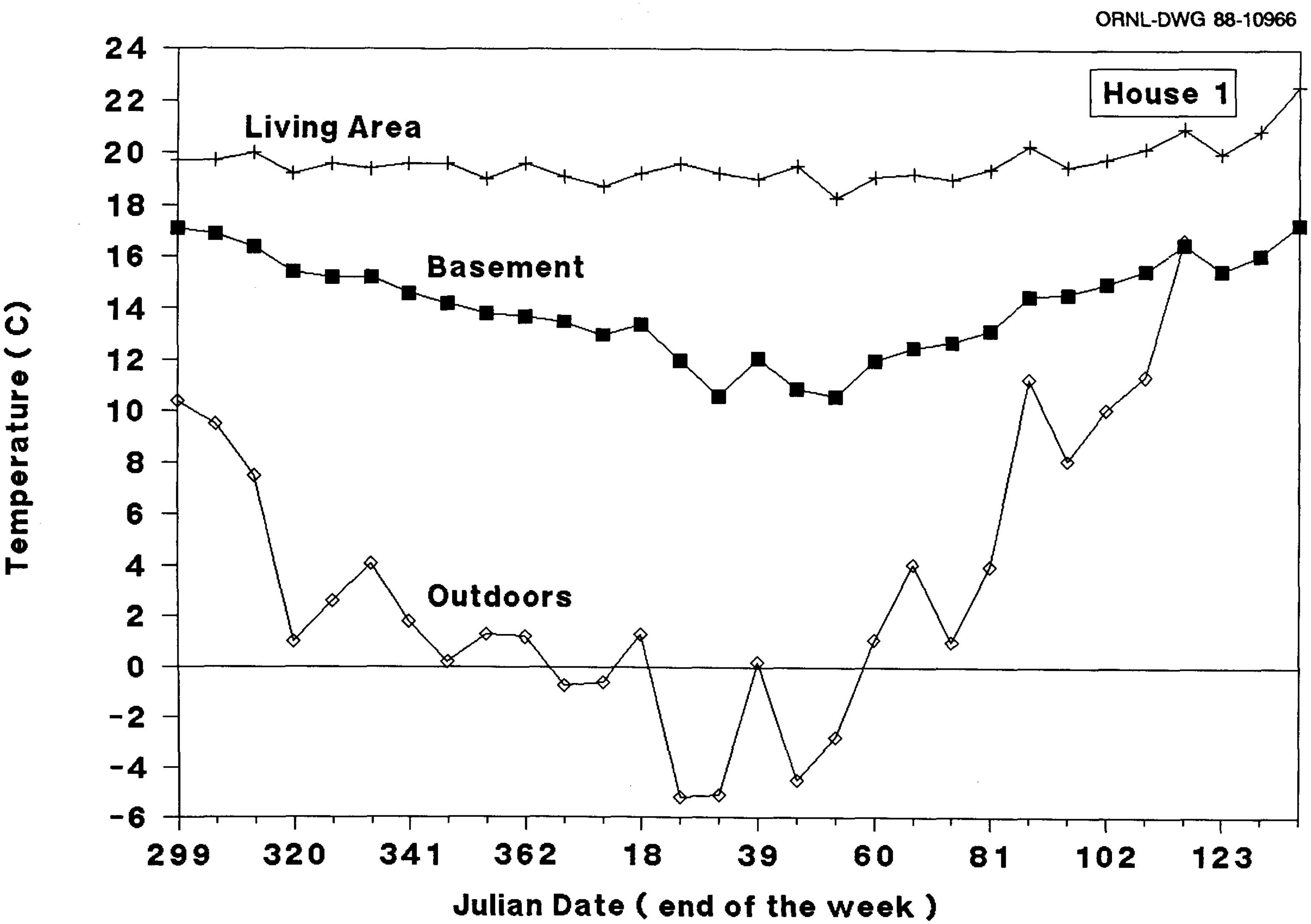


Fig. 7.2. House #1: Weekly averaged temperature data.

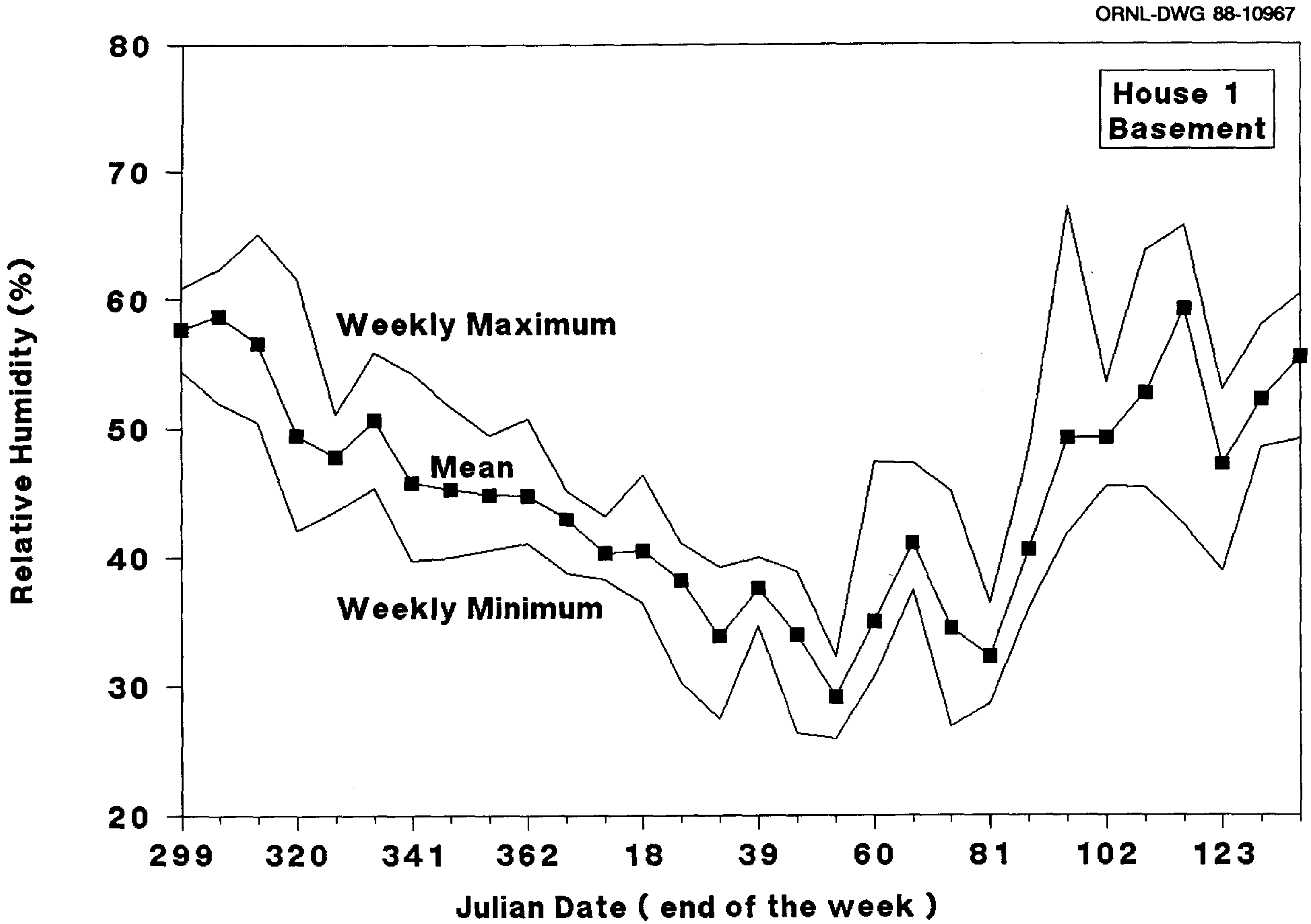


Fig. 7.3. House #1: Weekly means, minima, and maxima of relative humidity data.

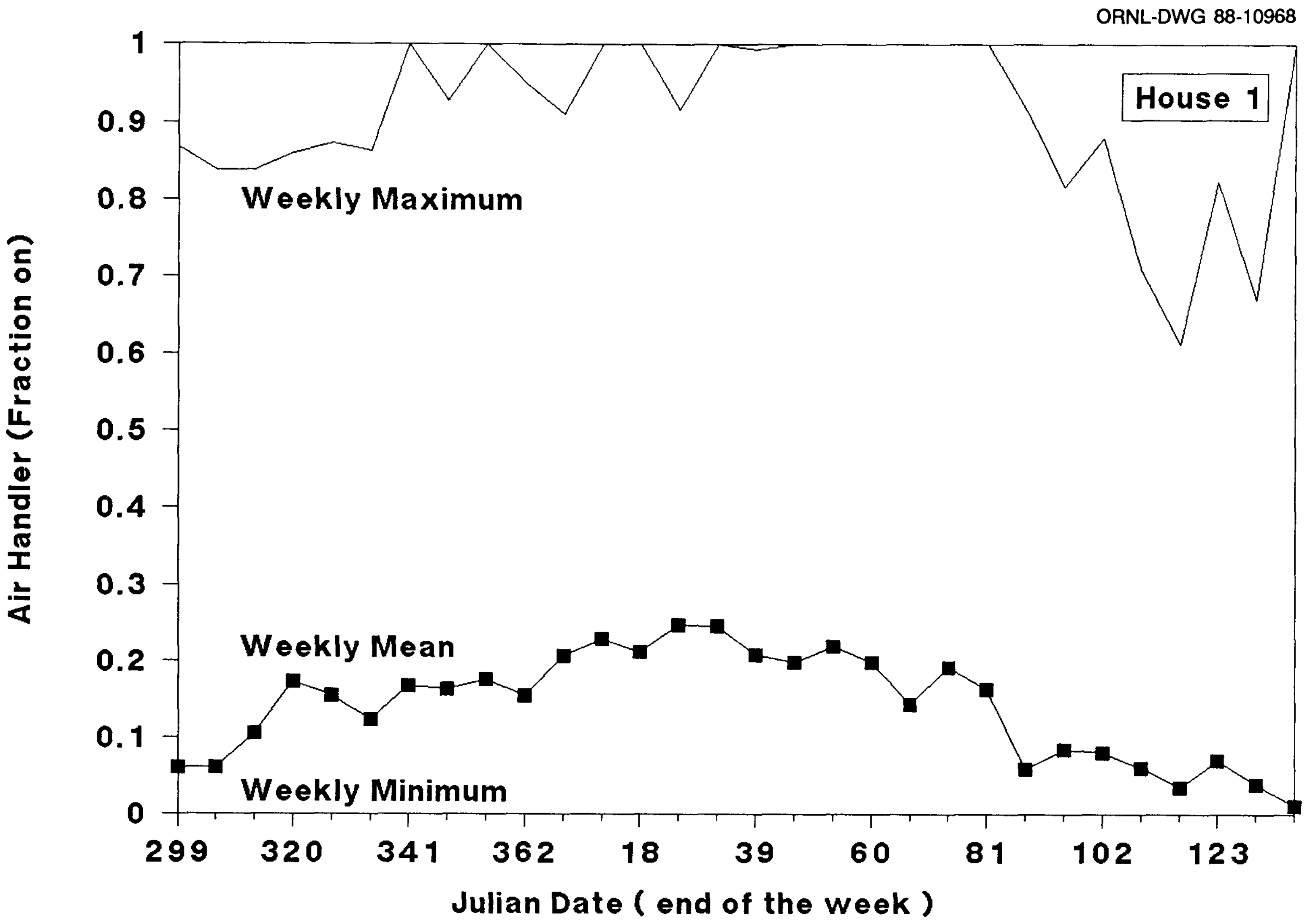


Fig. 7.4. House #1: Weekly means, minima, and maxima of fan usage data.

ORNL-DWG 88-10969

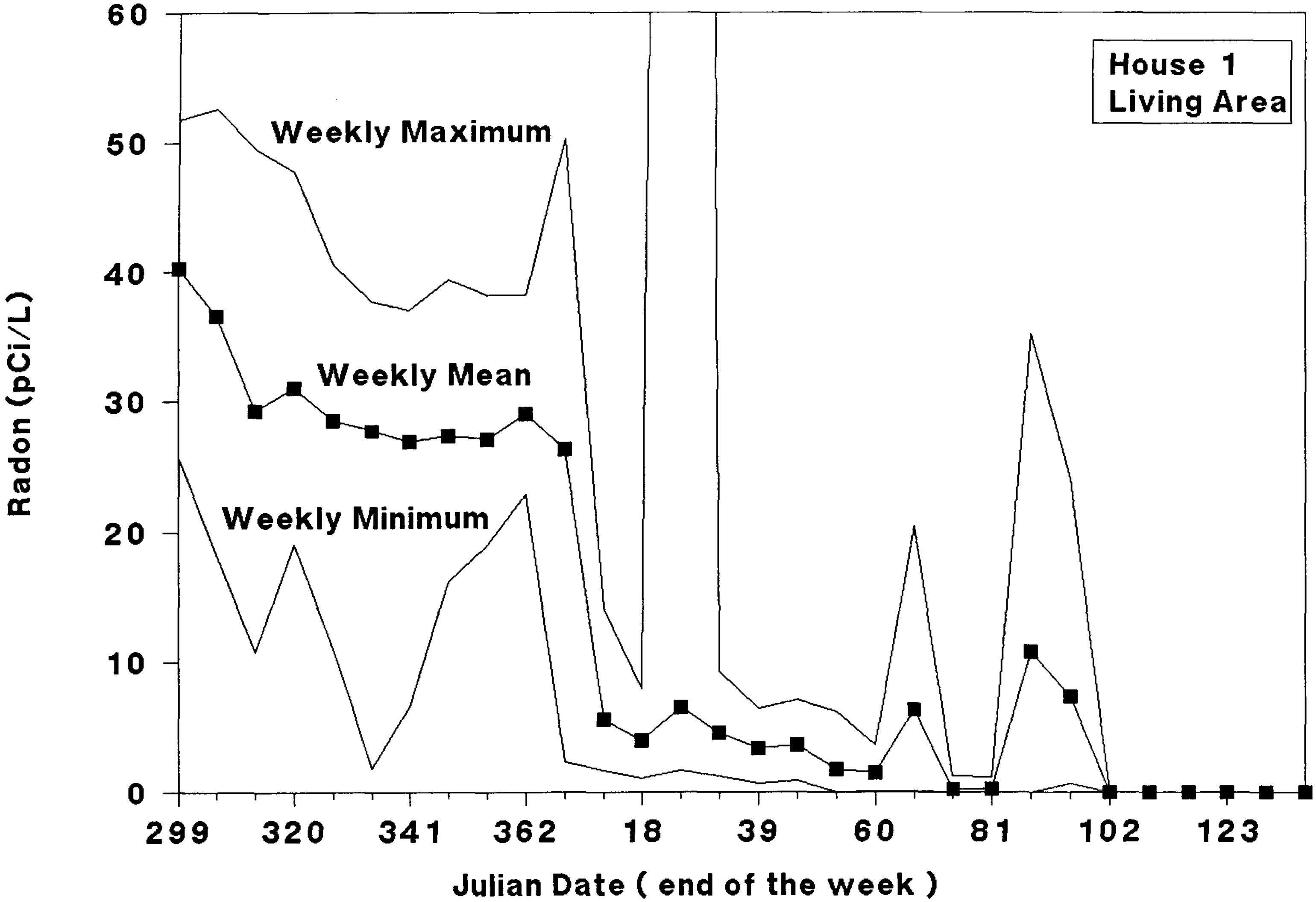


Fig. 7.5. House #1: Weekly means, minima, and maxima of living-area radon data.

ORNL-DWG 88-10970

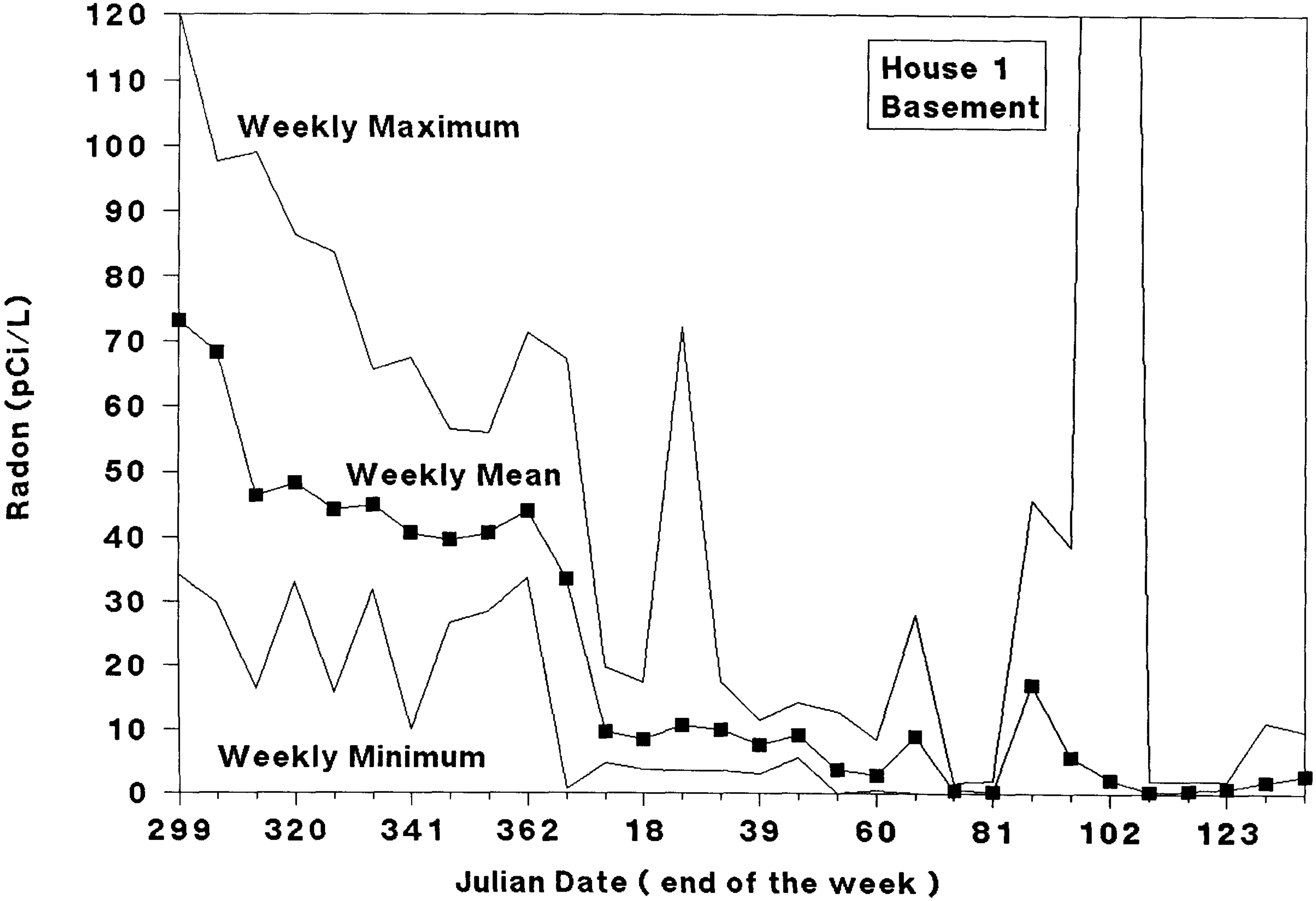


Fig. 7.6. House #1: Weekly means, minima, and maxima of basement radon data.

ORNL-DWG 88-10971

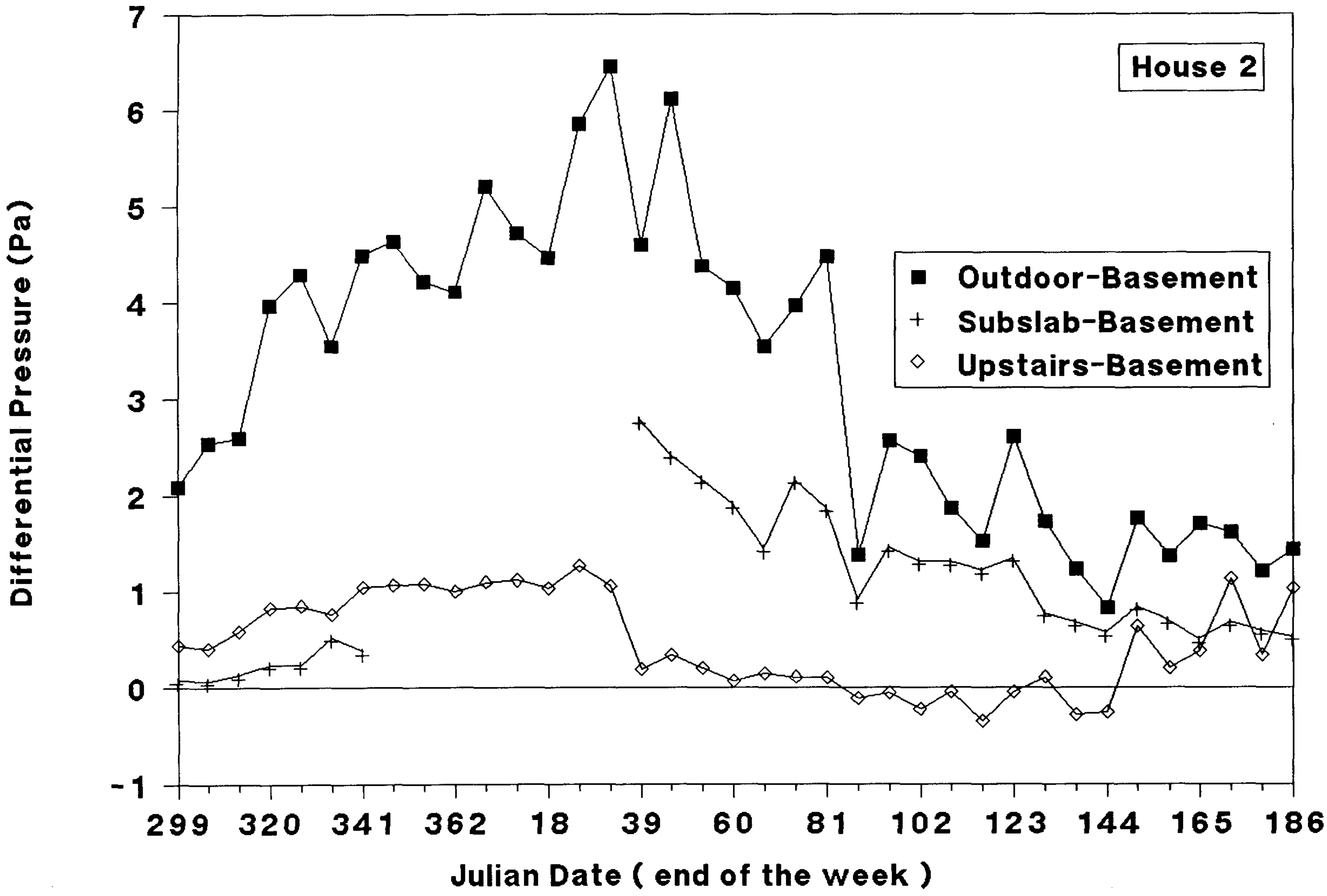


Fig. 7.7. House #2: Weekly averaged differential pressure data.

ORNL-DWG 88-10972

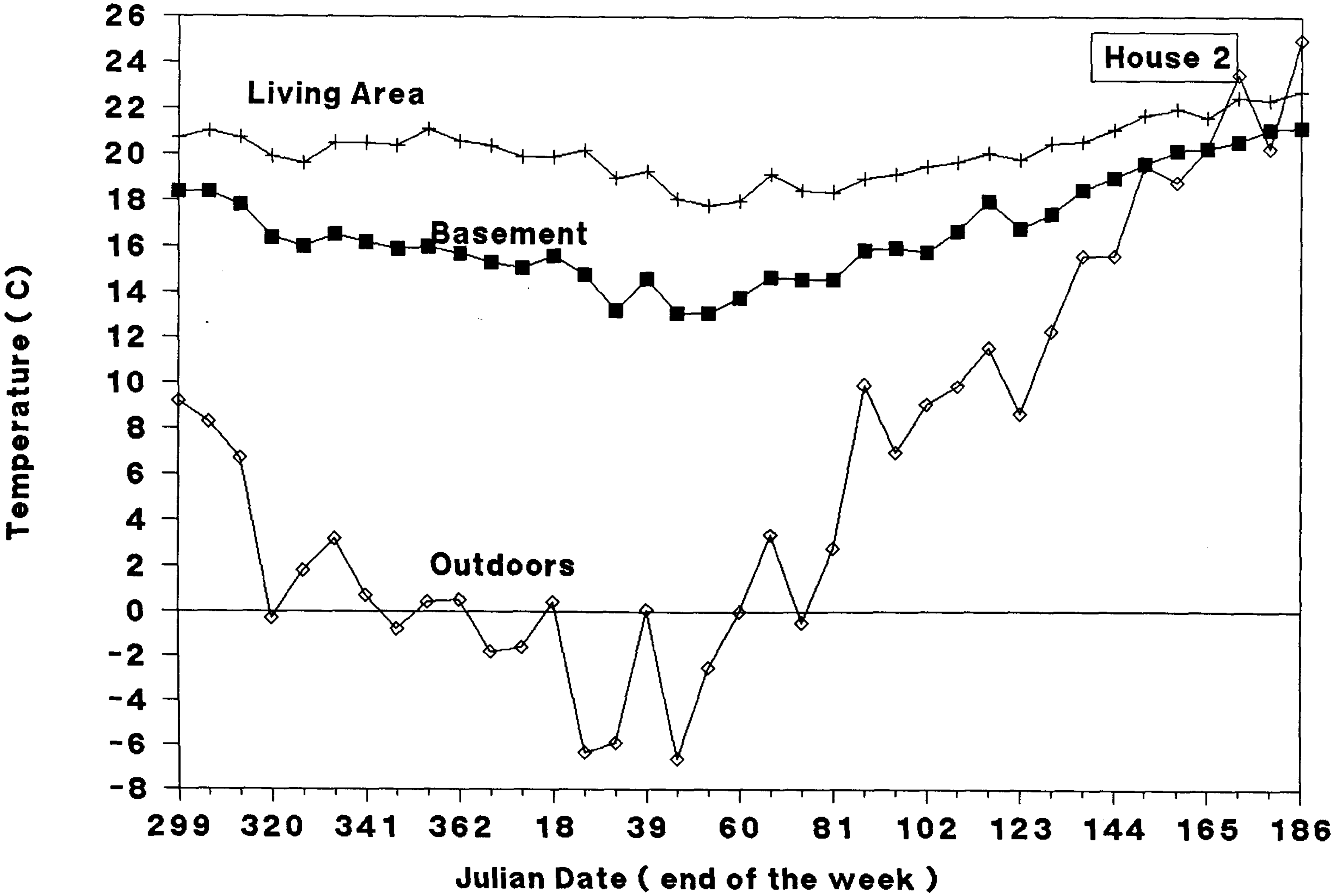


Fig. 7.8. House #2: Weekly averaged temperature data.

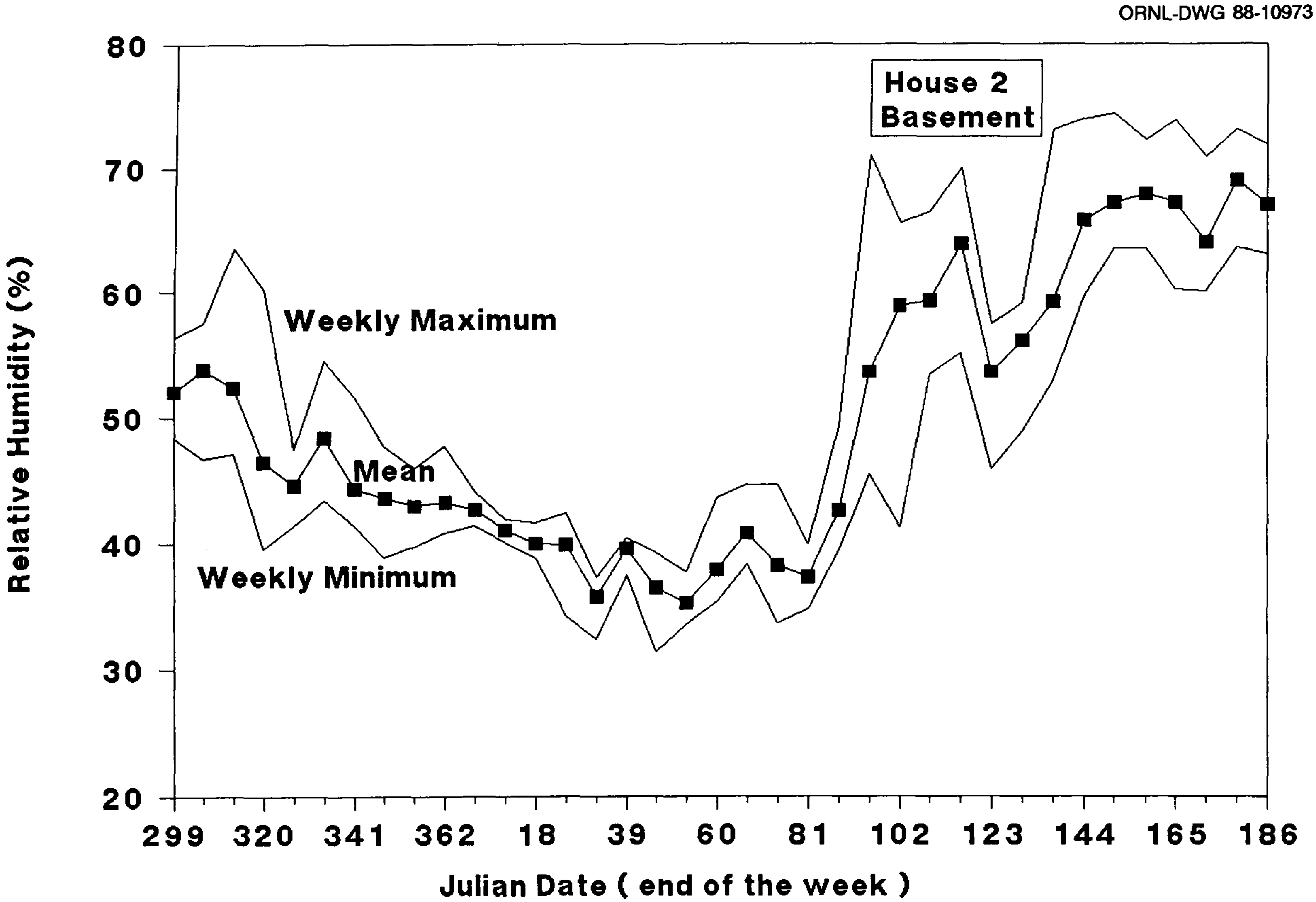


Fig. 7.9. House #2: Weekly means, minima, and maxima of relative humidity data.

ORNL-DWG 88-10974

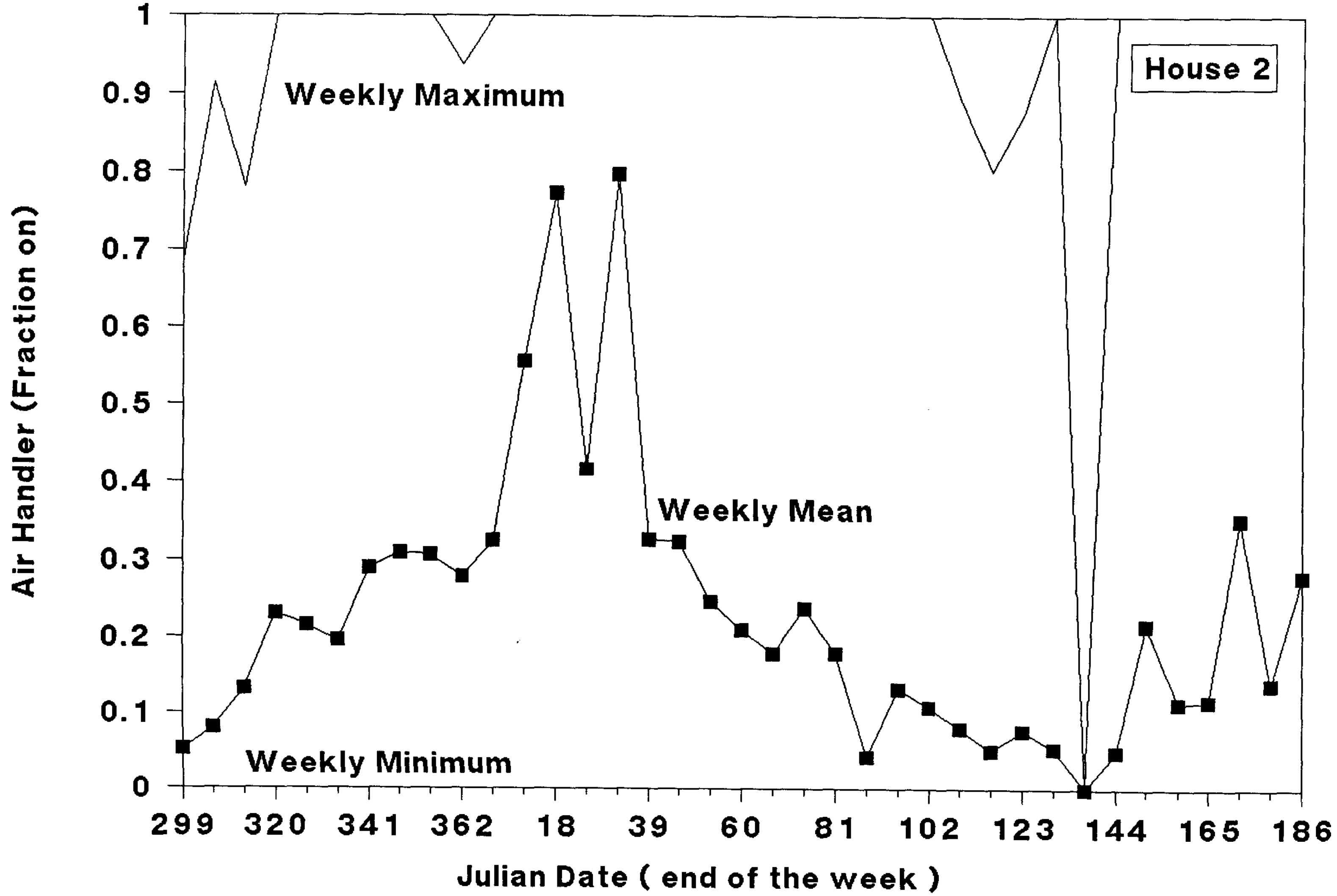


Fig. 7.10. House #2: Weekly means, minima, and maxima of fan usage data.

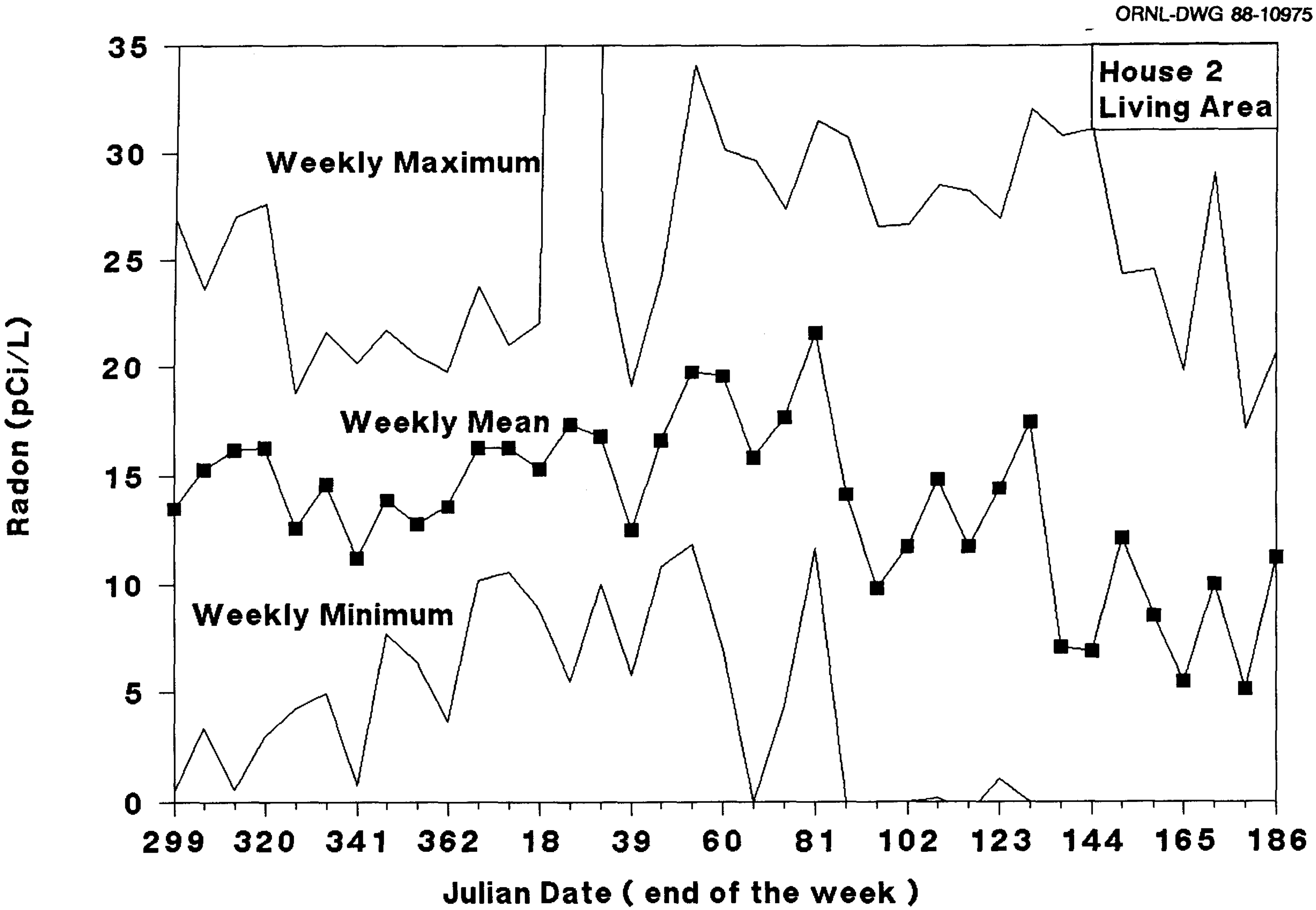


Fig. 7.11. House #2: Weekly means, minima, and maxima of living-area radon data.

ORNL-DWG 88-10976

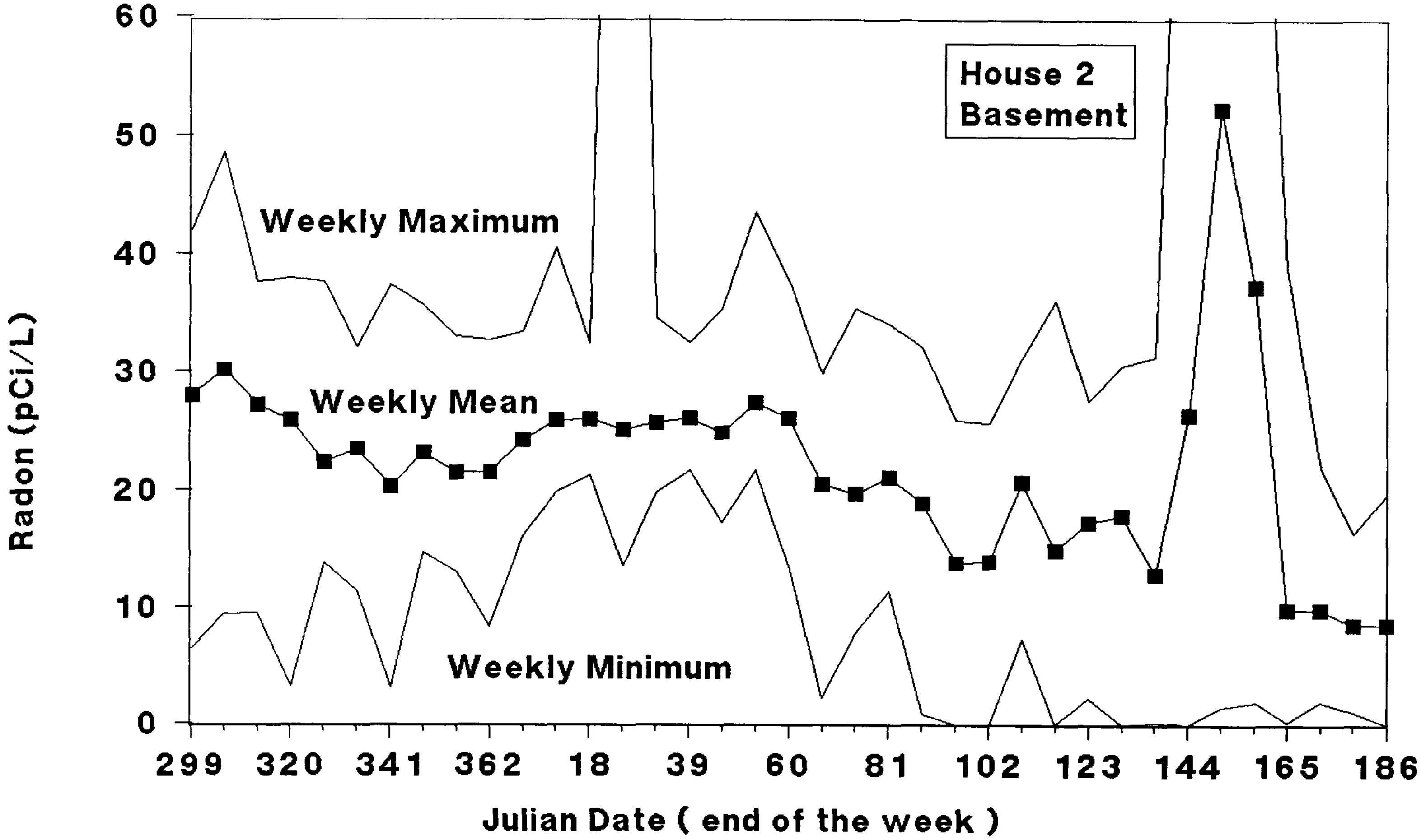


Fig. 7.12. House #2: Weekly means, minima, and maxima of basement radon data.

ORNL-DWG 88-10977

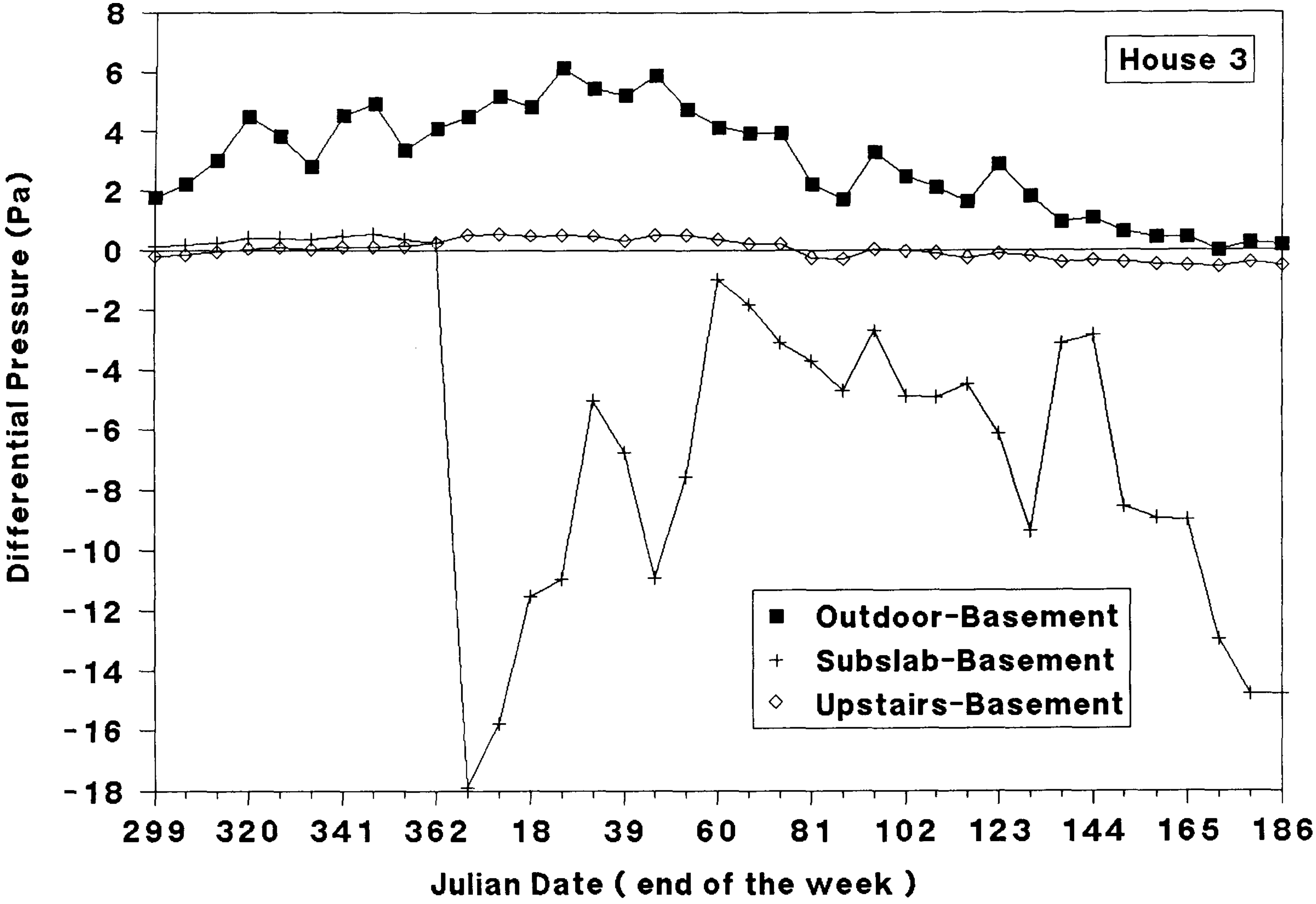


Fig. 7.13. House #3: Weekly averaged differential pressure data.

ORNL-DWG 88-10978

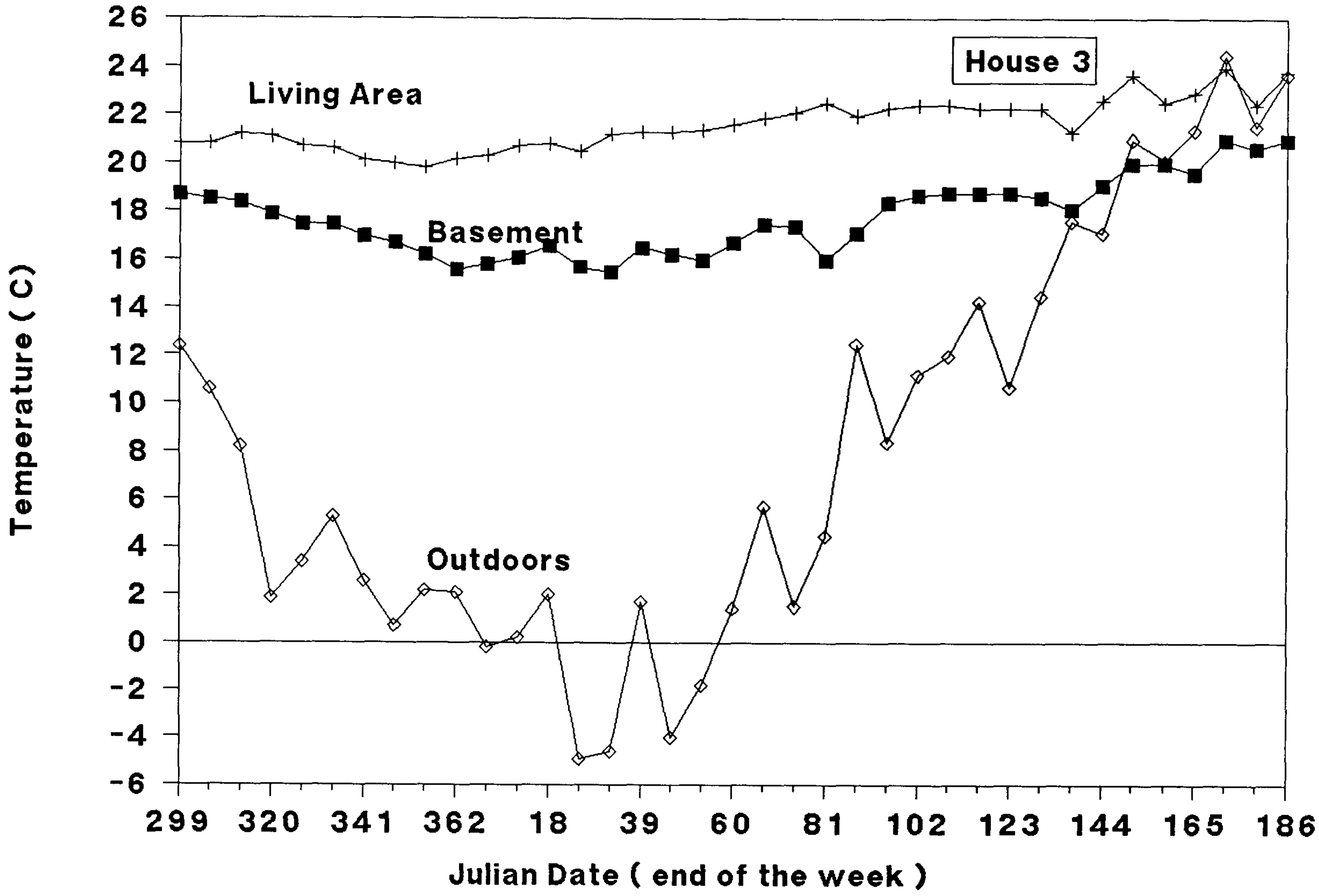


Fig. 7.14. House #3: Weekly averaged temperature data.

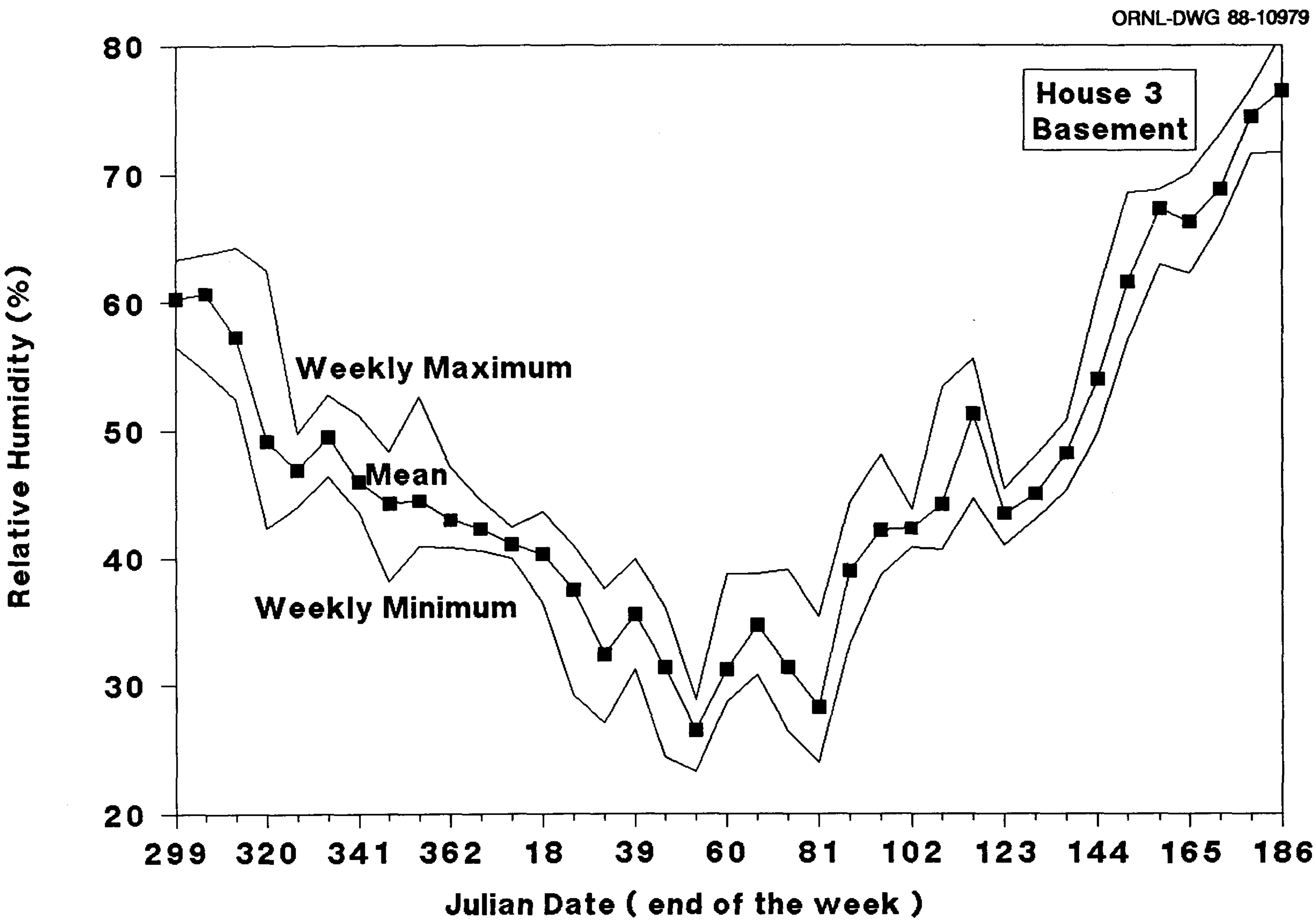


Fig. 7.15. House #3: Weekly means, minima, and maxima of relative humidity data.

ORNL-DWG 88-10980

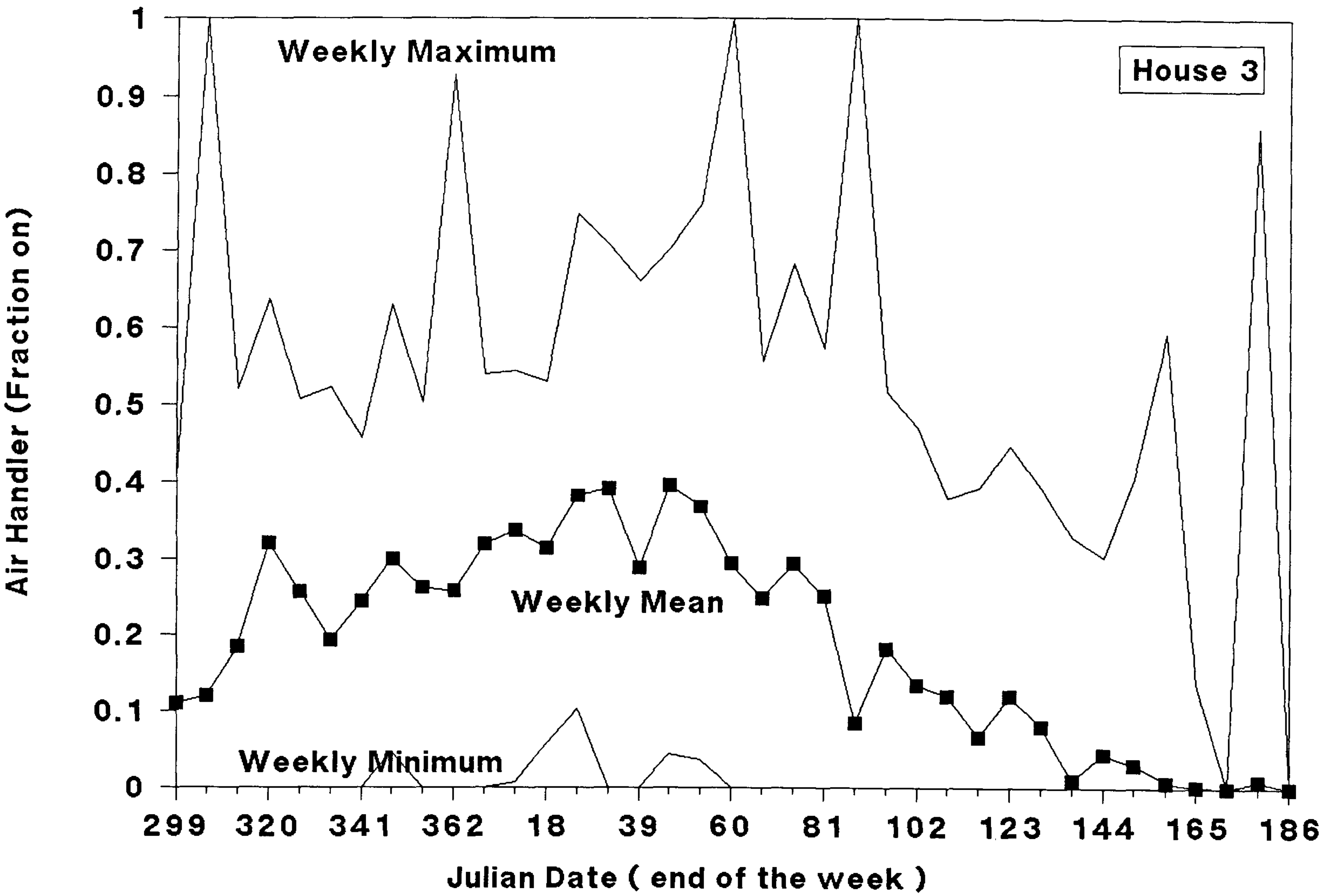


Fig. 7.16. House #3: Weekly means, minima, and maxima of fan usage data.

ORNL-DWG 88-10981

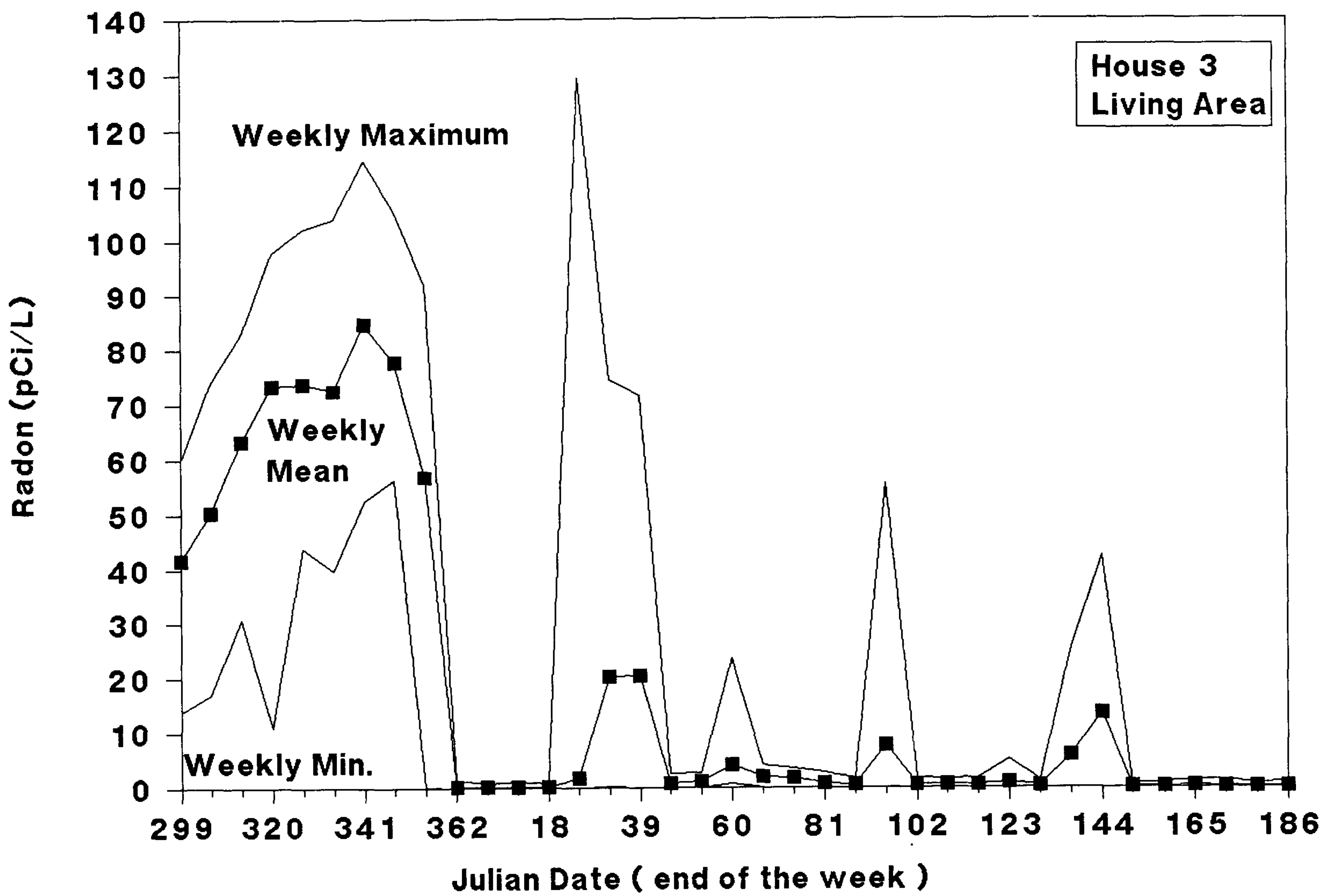


Fig. 7.17. House #3: Weekly means, minima, and maxima of living-area radon data.

ORNL-DWG 88-10982

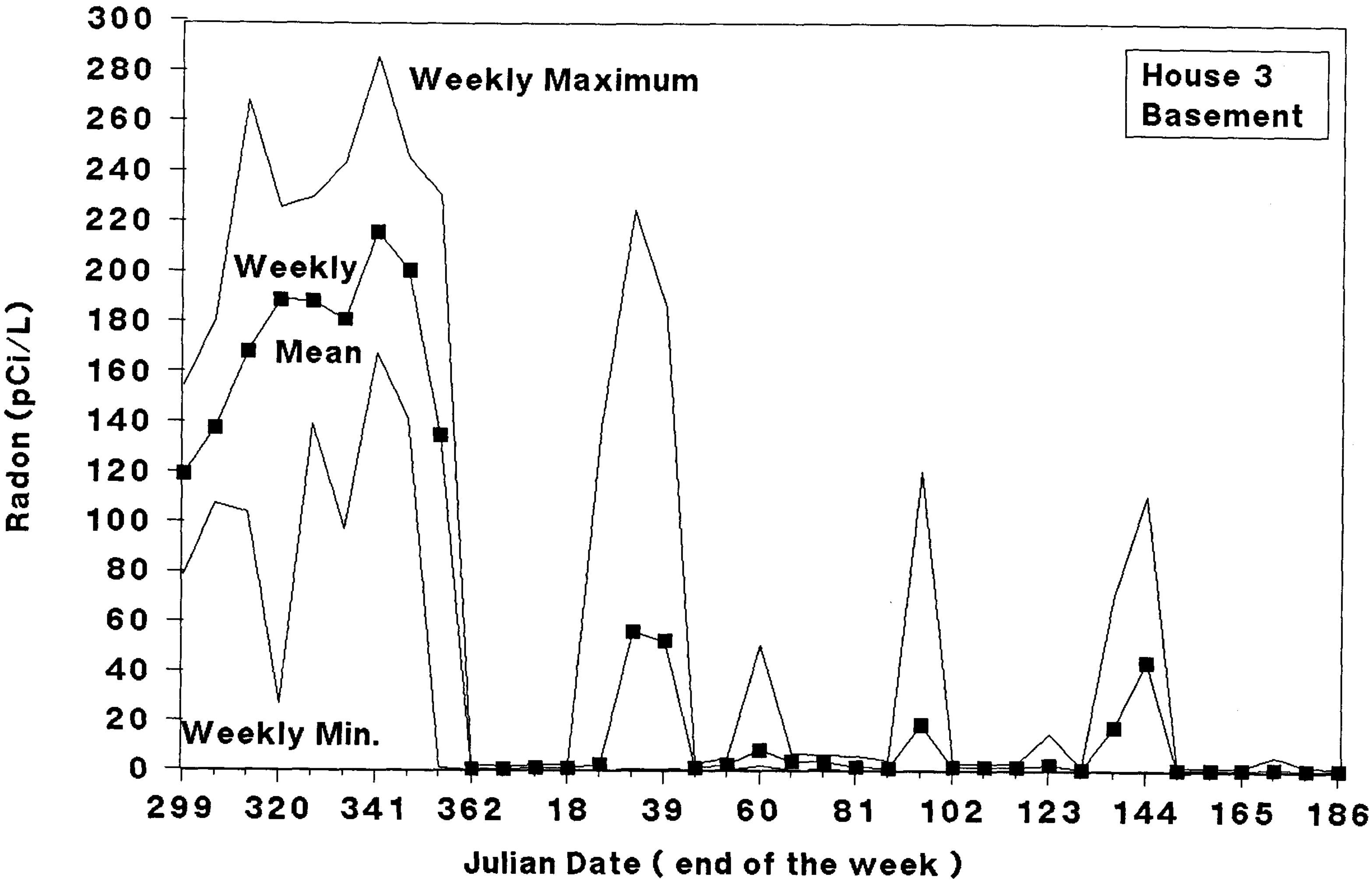


Fig. 7.18. House #3: Weekly means, minima, and maxima of basement radon data.

ORNL-DWG 88-10983

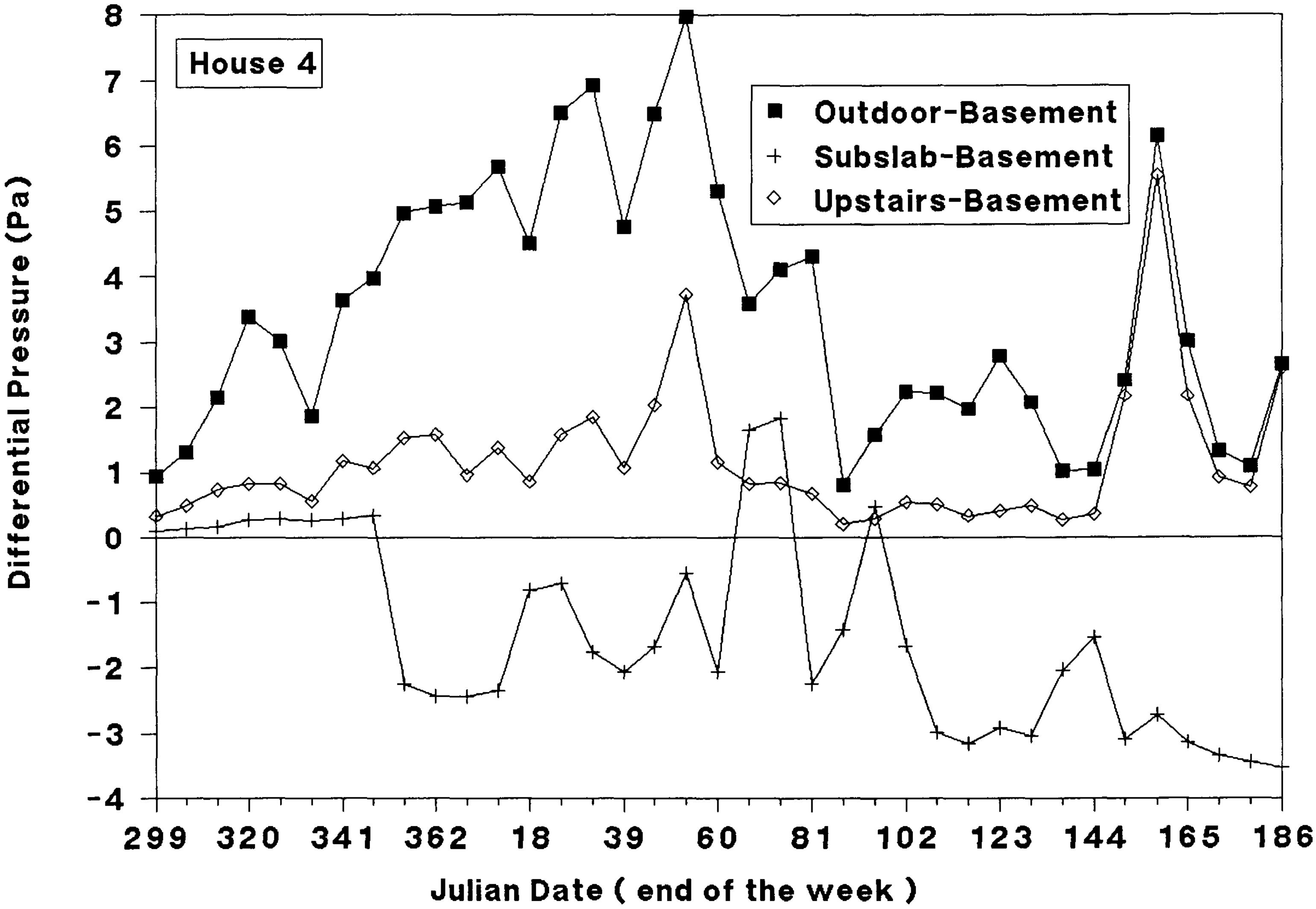


Fig. 7.19. House #4: Weekly averaged differential pressure data.

ORNL-DWG 88-10984

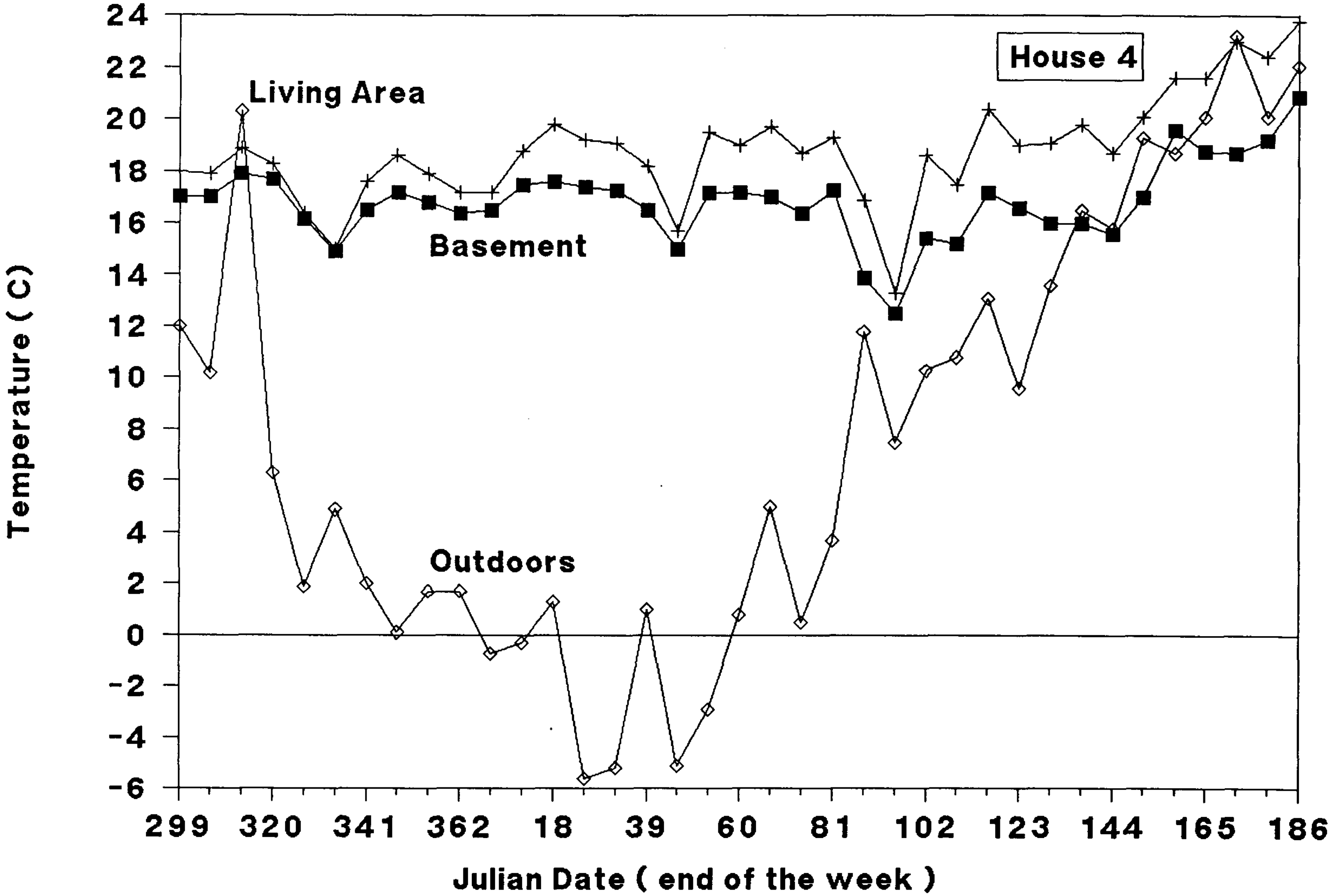


Fig. 7.20. House #4: Weekly averaged temperature data.

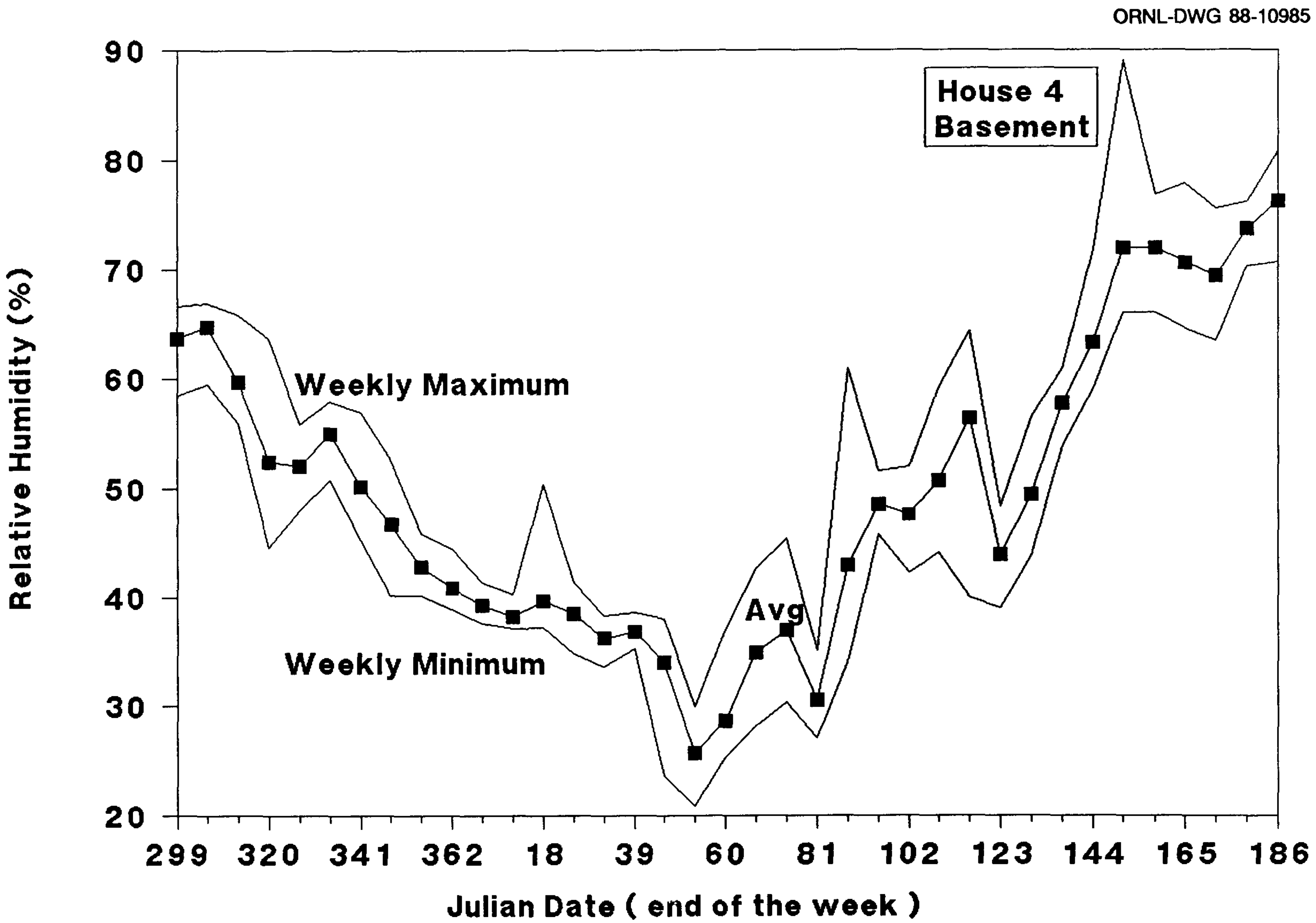


Fig. 7.21. House #4: Weekly means, minima, and maxima of relative humidity data.

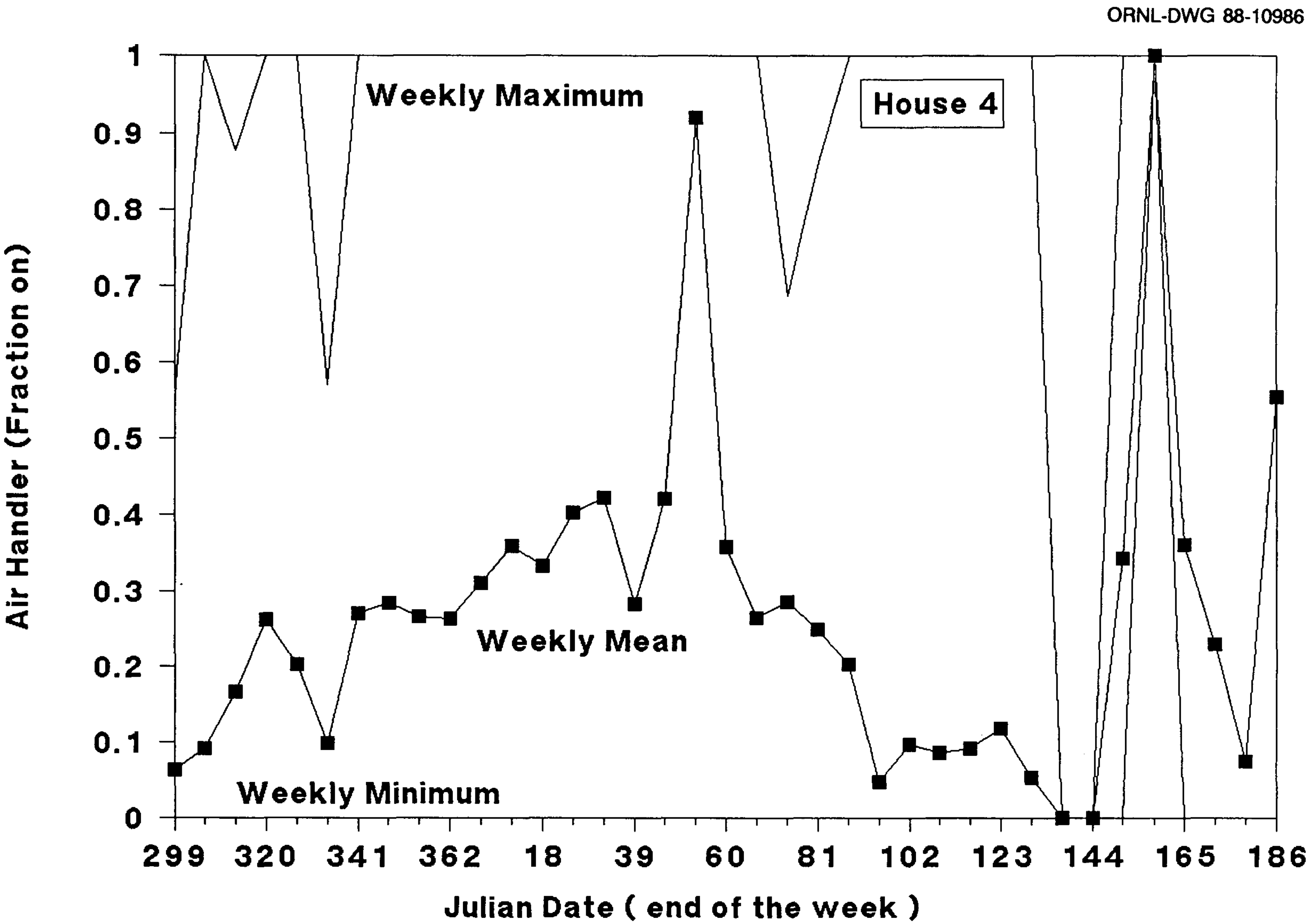


Fig. 7.22. House #4: Weekly means, minima, and maxima of fan usage data.

ORNL-DWG 88-10987

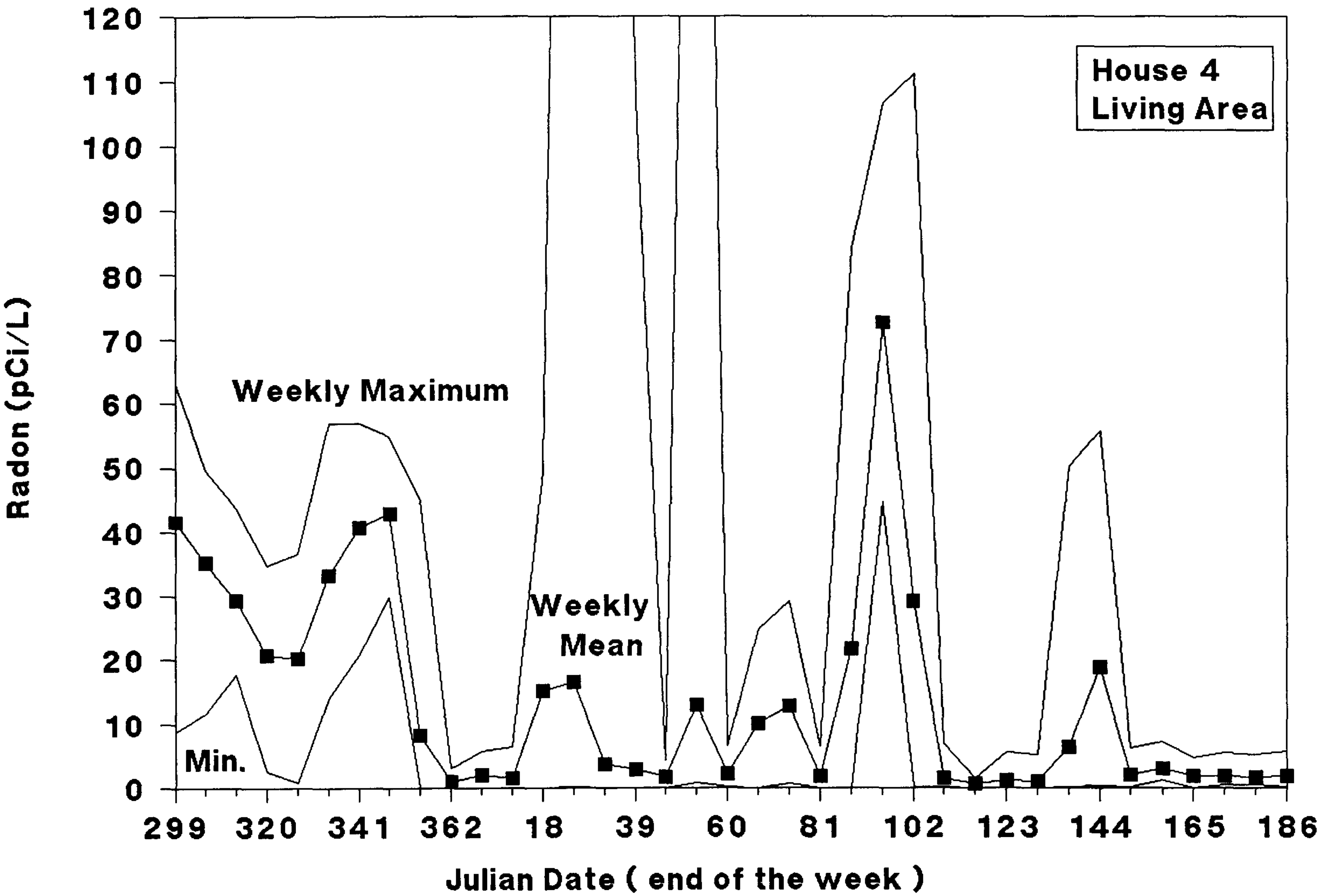


Fig. 7.23. House #4: Weekly means, minima, and maxima of living-area radon data.

ORNL-DWG 88-10988

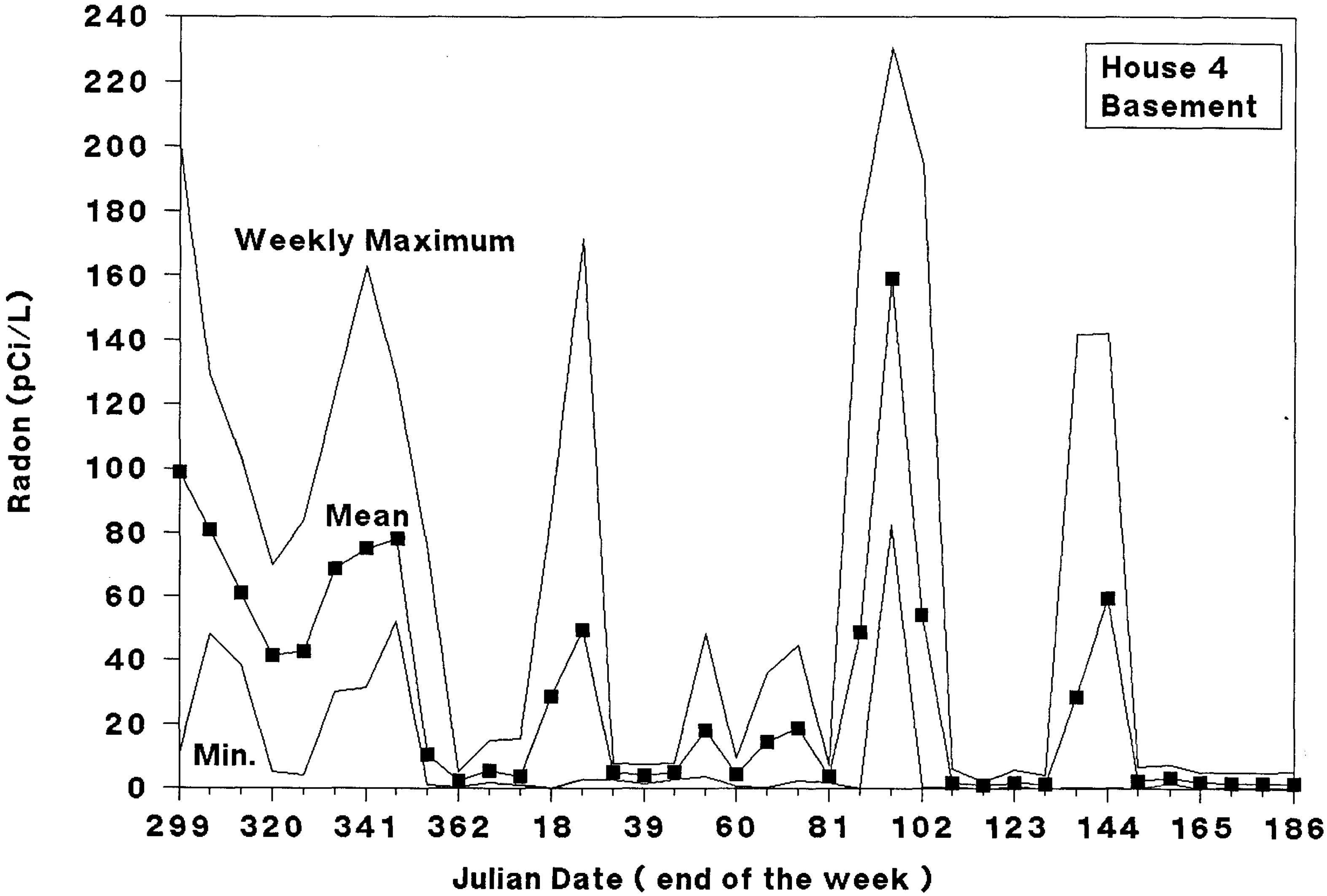


Fig. 7.24. House #4: Weekly means, minima, and maxima of basement radon data.

ORNL-DWG 88-10989

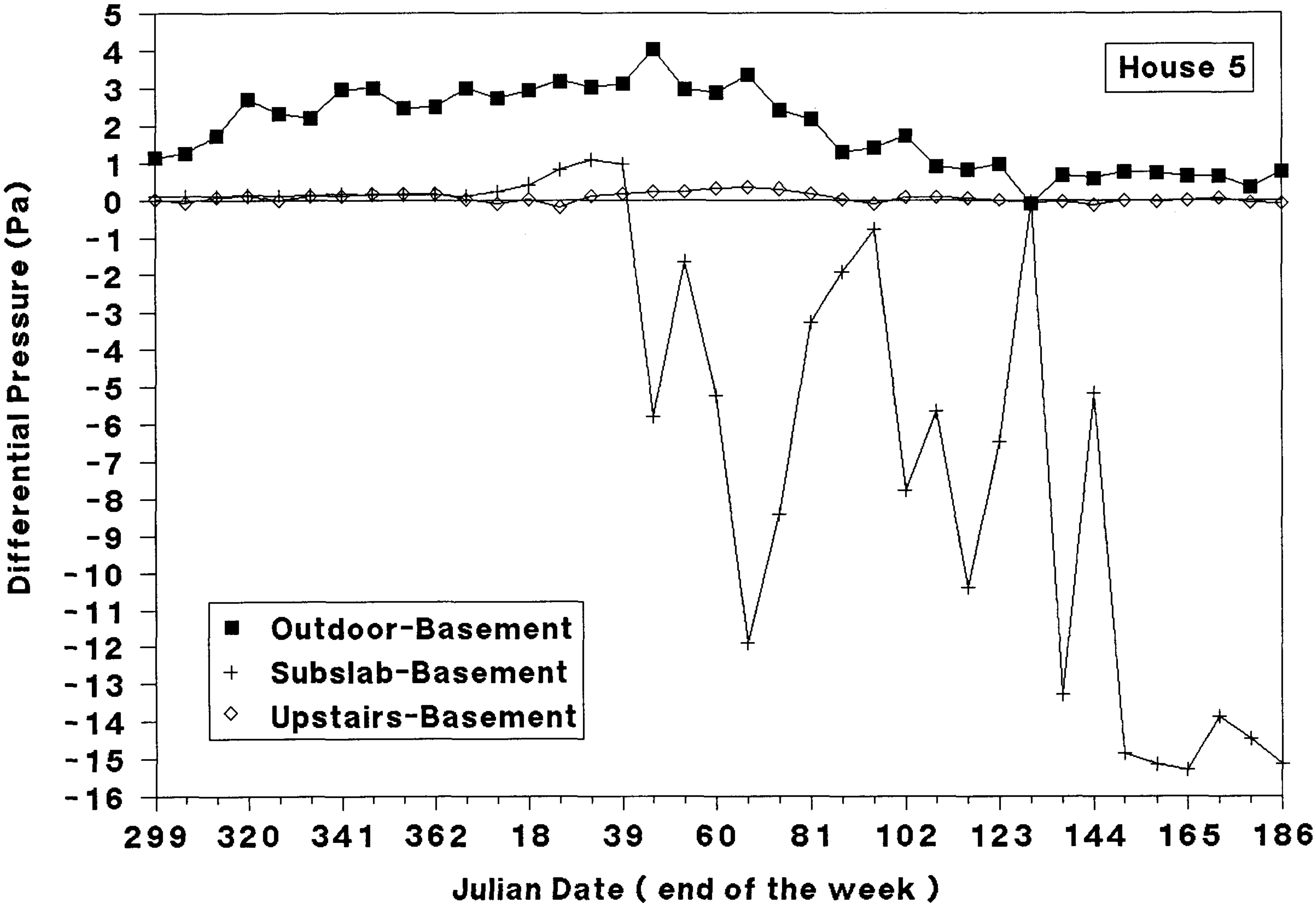


Fig. 7.25. House #5: Weekly averaged differential pressure data.

ORNL-DWG 88-10990

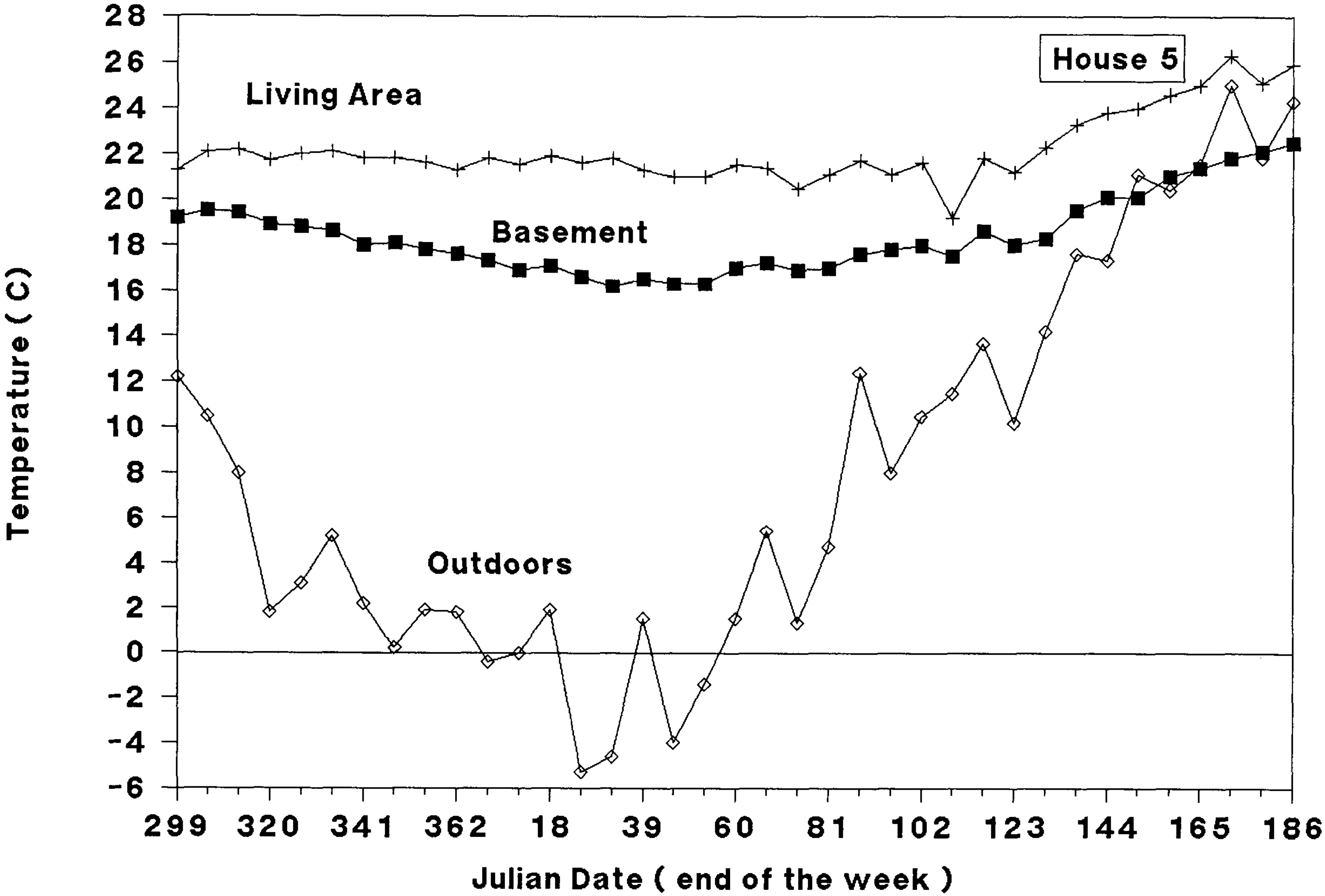


Fig. 7.26. House #5: Weekly averaged temperature data.

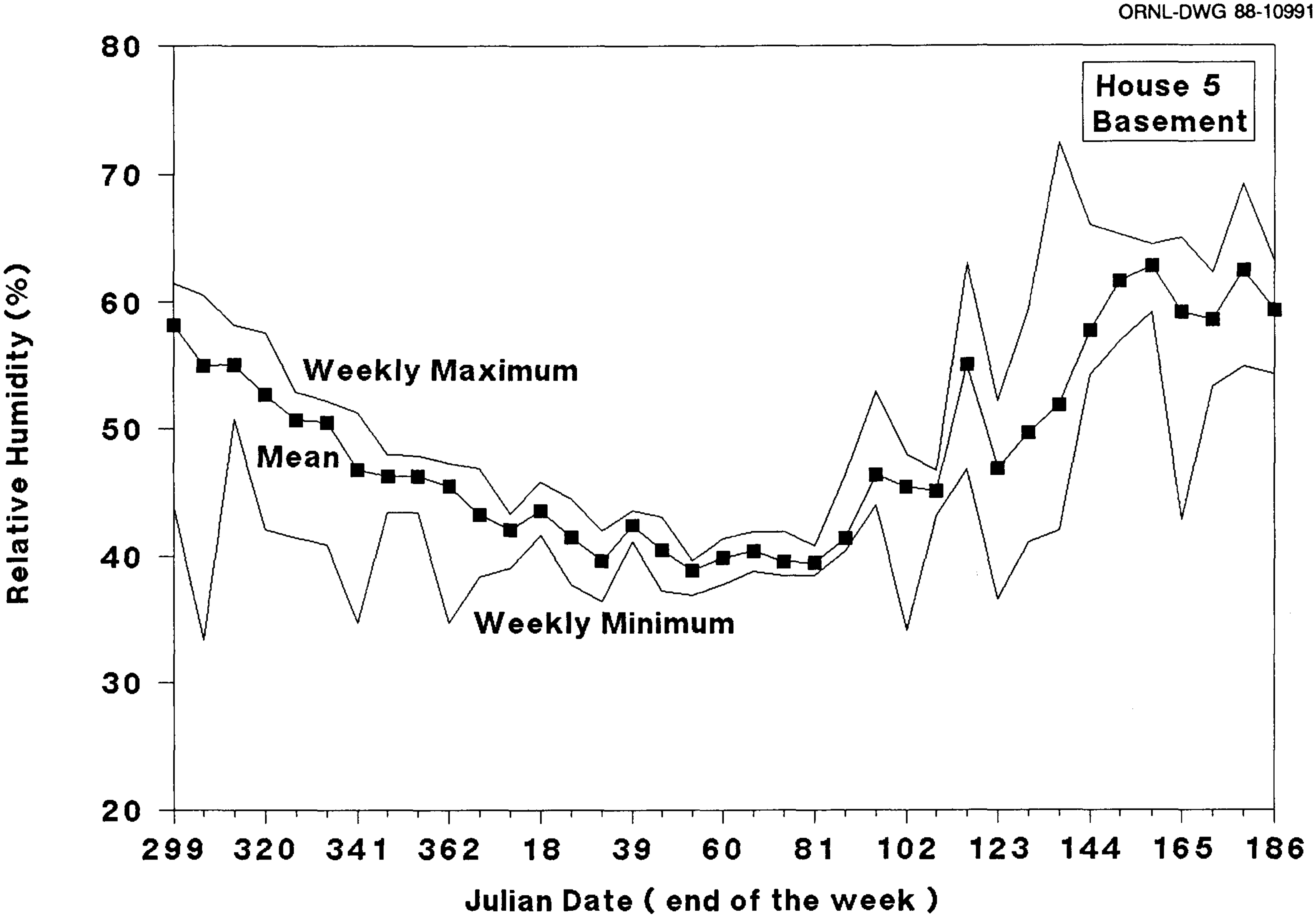


Fig. 7.27. House #5: Weekly means, minima, and maxima of relative humidity data.

ORNL-DWG 88-10992

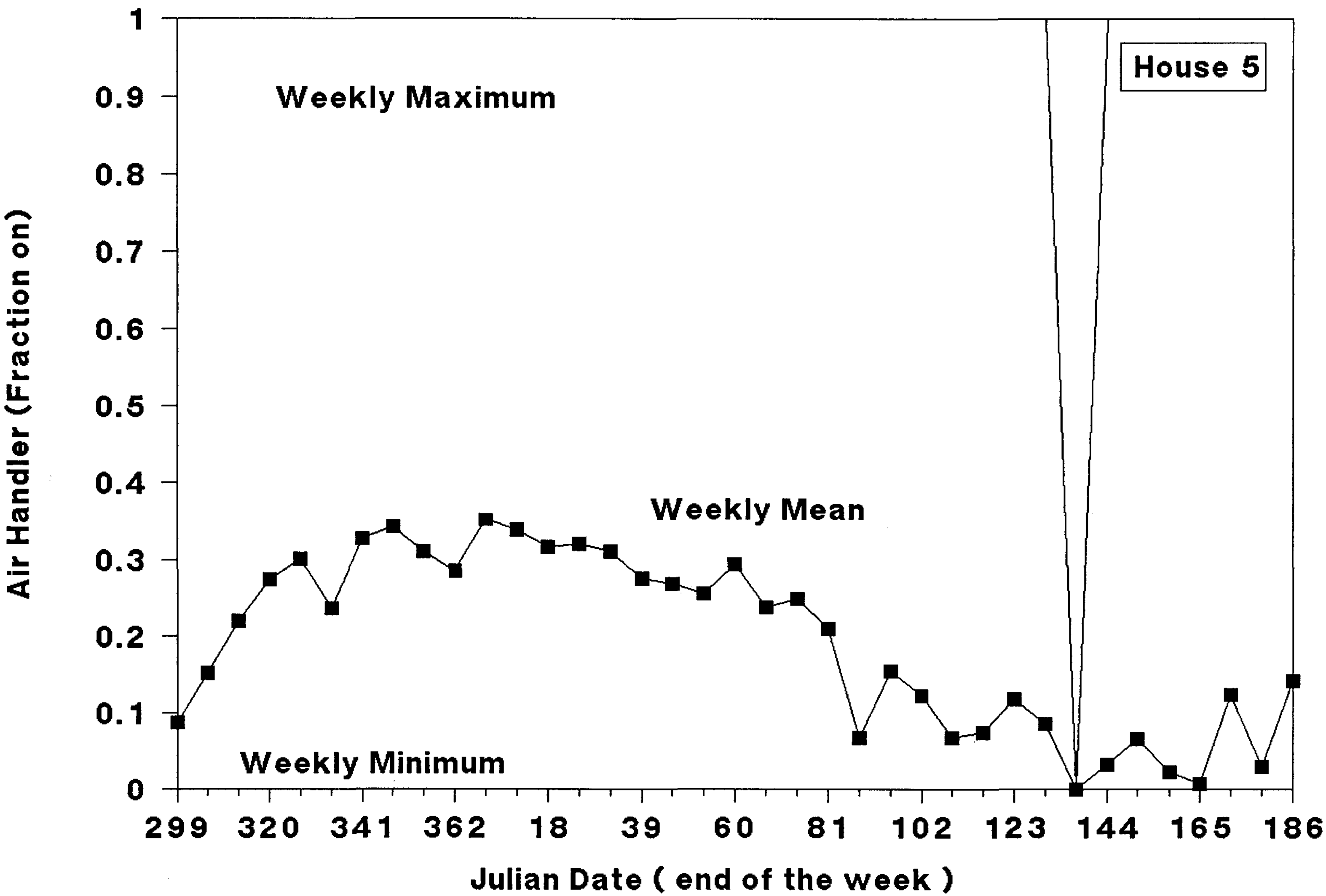


Fig. 7.28. House #5: Weekly means, minima, and maxima of fan usage data.

ORNL-DWG 88-10993

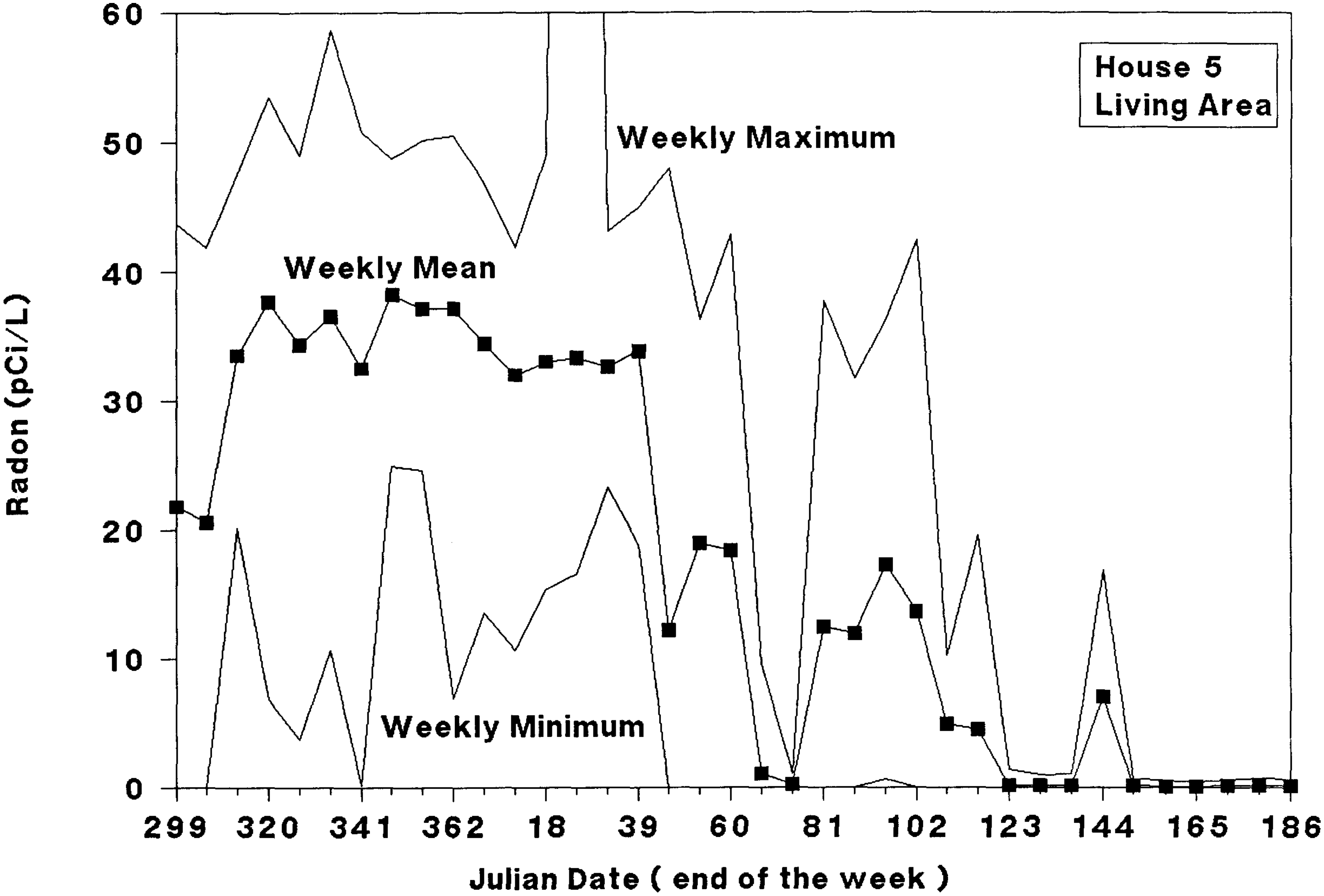


Fig. 7.29. House #5: Weekly means, minima, and maxima of living-area radon data.

ORNL-DWG 88-10994

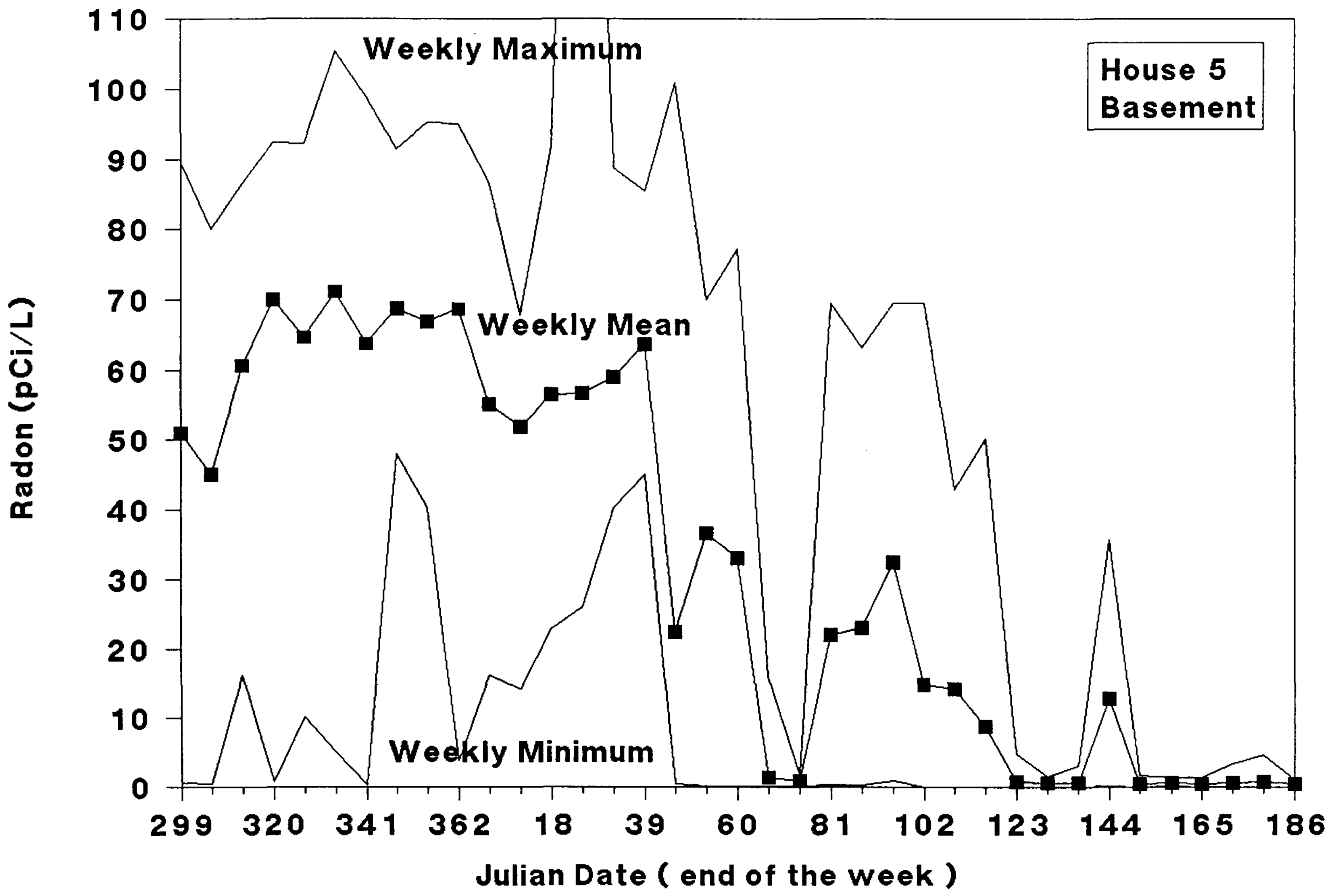


Fig. 7.30. House #5: Weekly means, minima, and maxima of basement radon data.

ORNL-DWG 88-10995

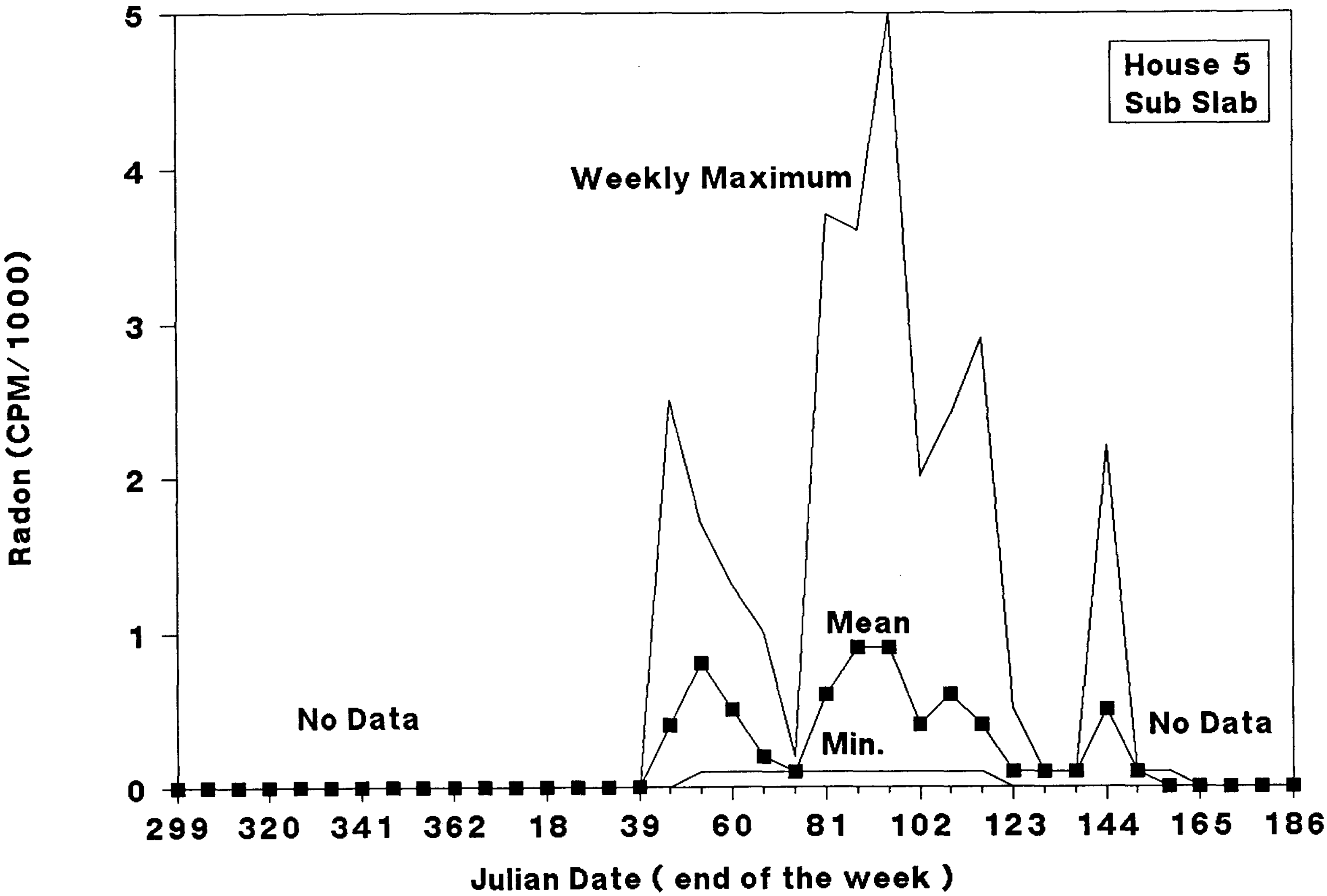


Fig. 7.31. House #5: Weekly means, minima, and maxima of subslab radon data.

ORNL-DWG 88-10996

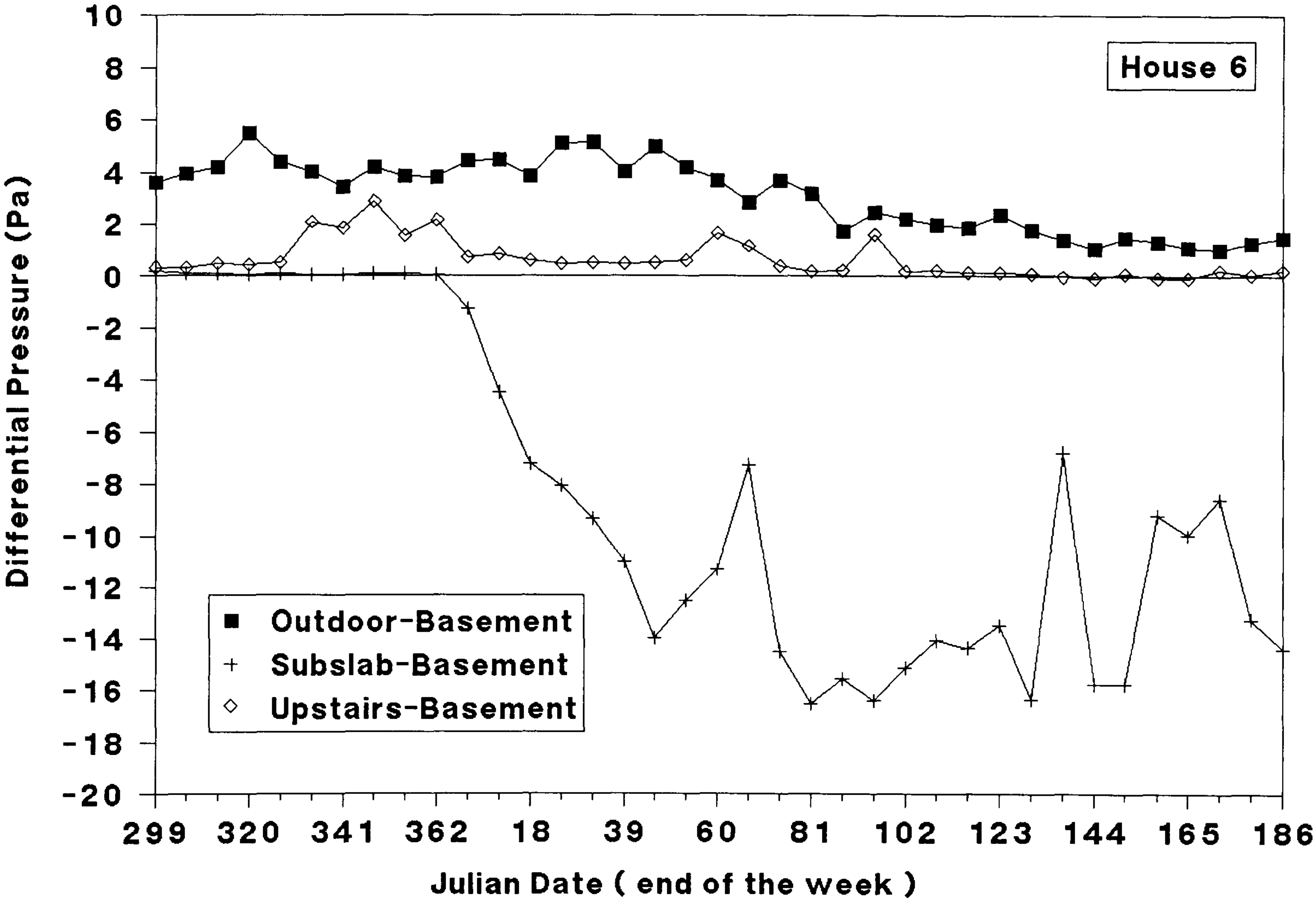


Fig. 7.32. House #6: Weekly averaged differential pressure data.

ORNL-DWG 88-10997

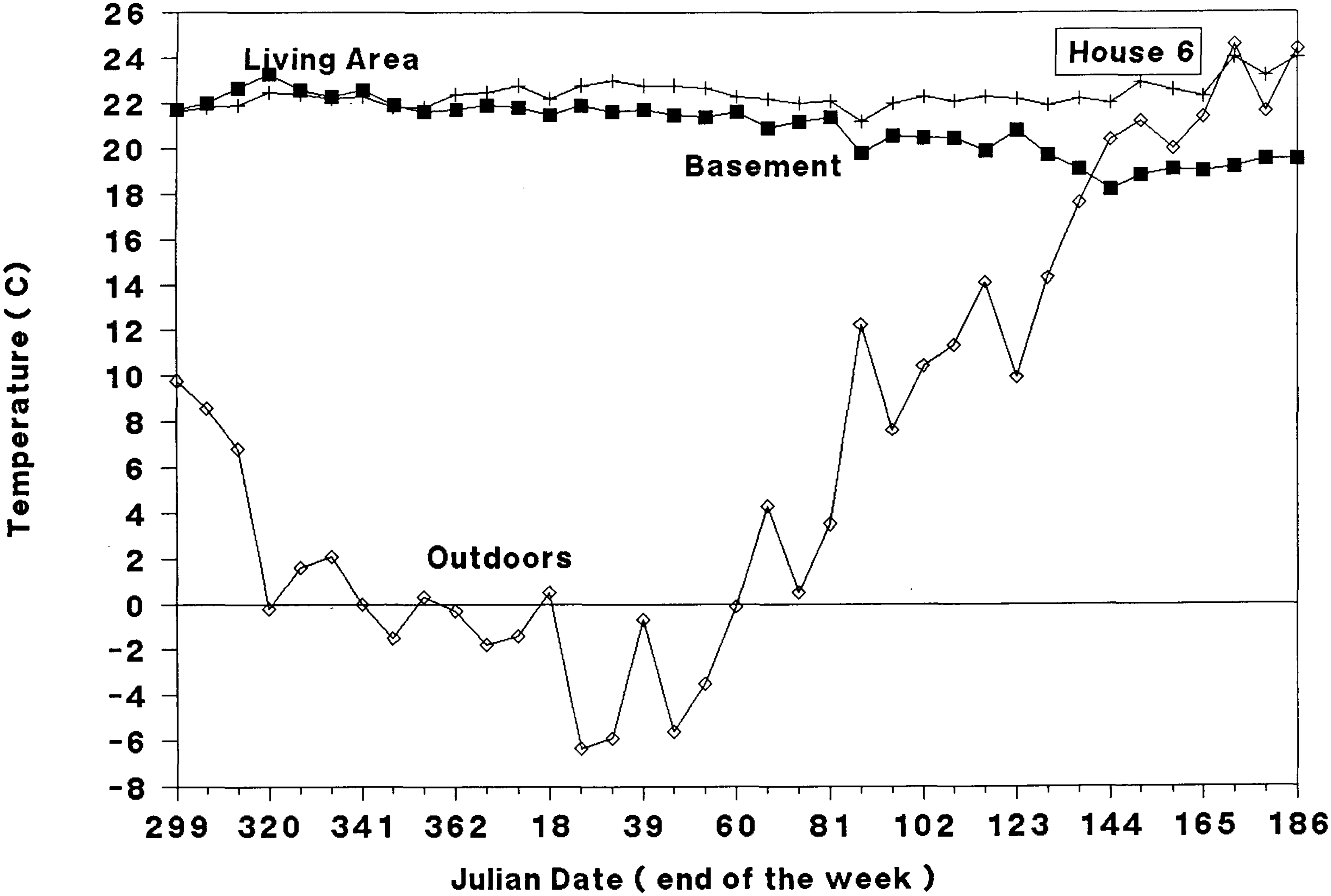


Fig. 7.33. House #6: Weekly averaged temperature data.

ORNL-DWG 88-10998

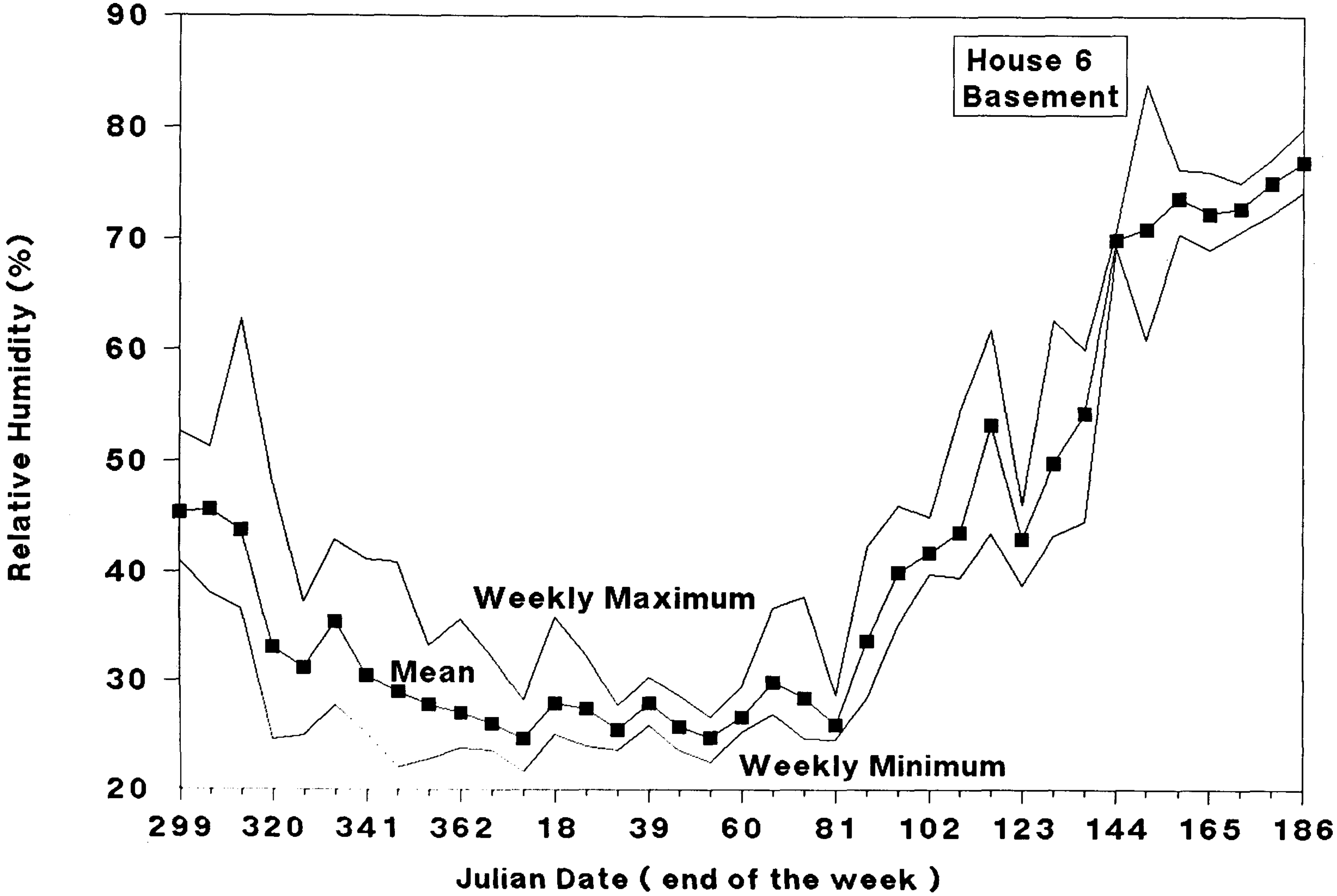


Fig. 7.34. House #6: Weekly means, minima, and maxima of relative humidity data.

ORNL-DWG 88-10999

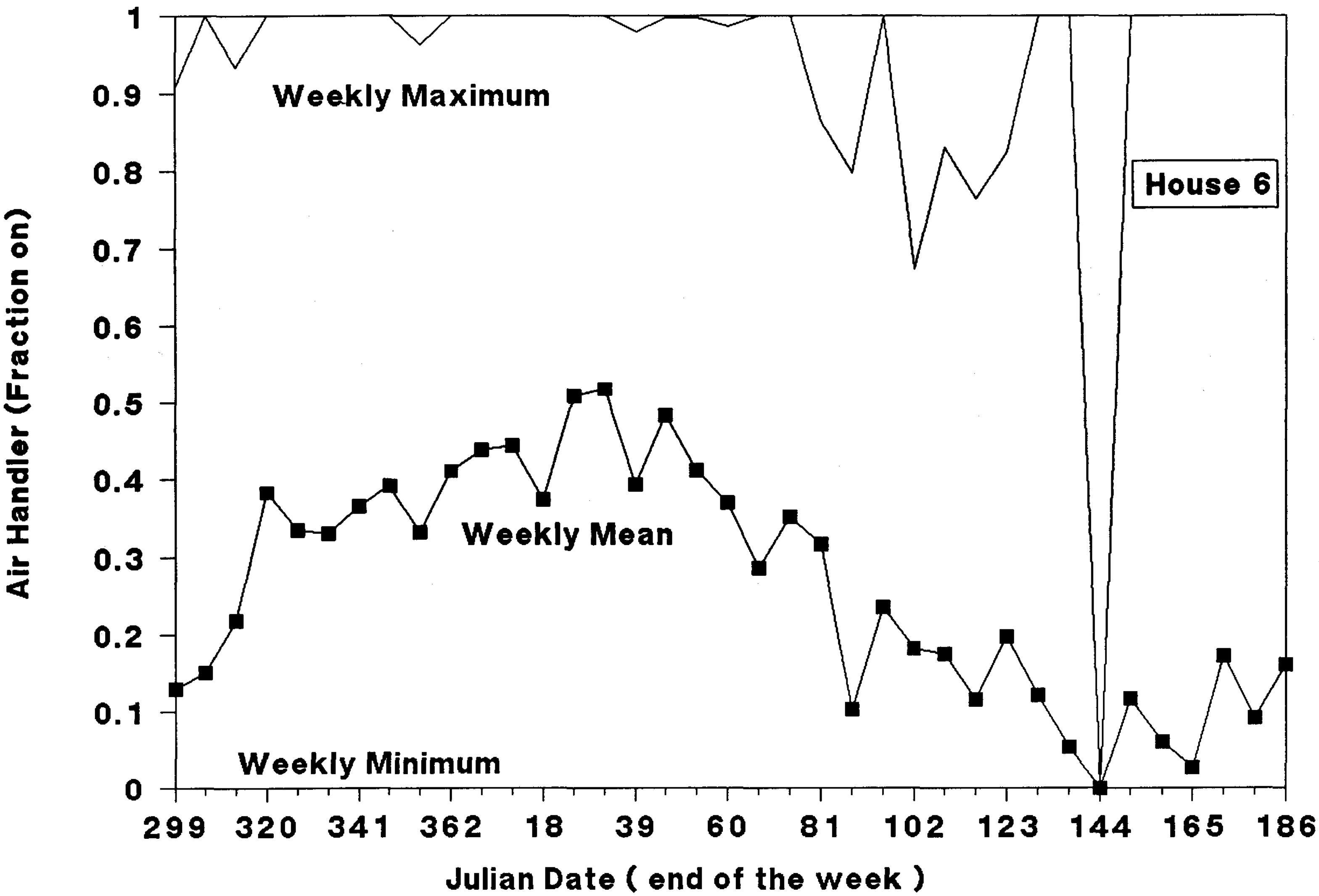


Fig. 7.35. House #6: Weekly means, minima, and maxima of fan usage data.

ORNL-DWG 88-11000

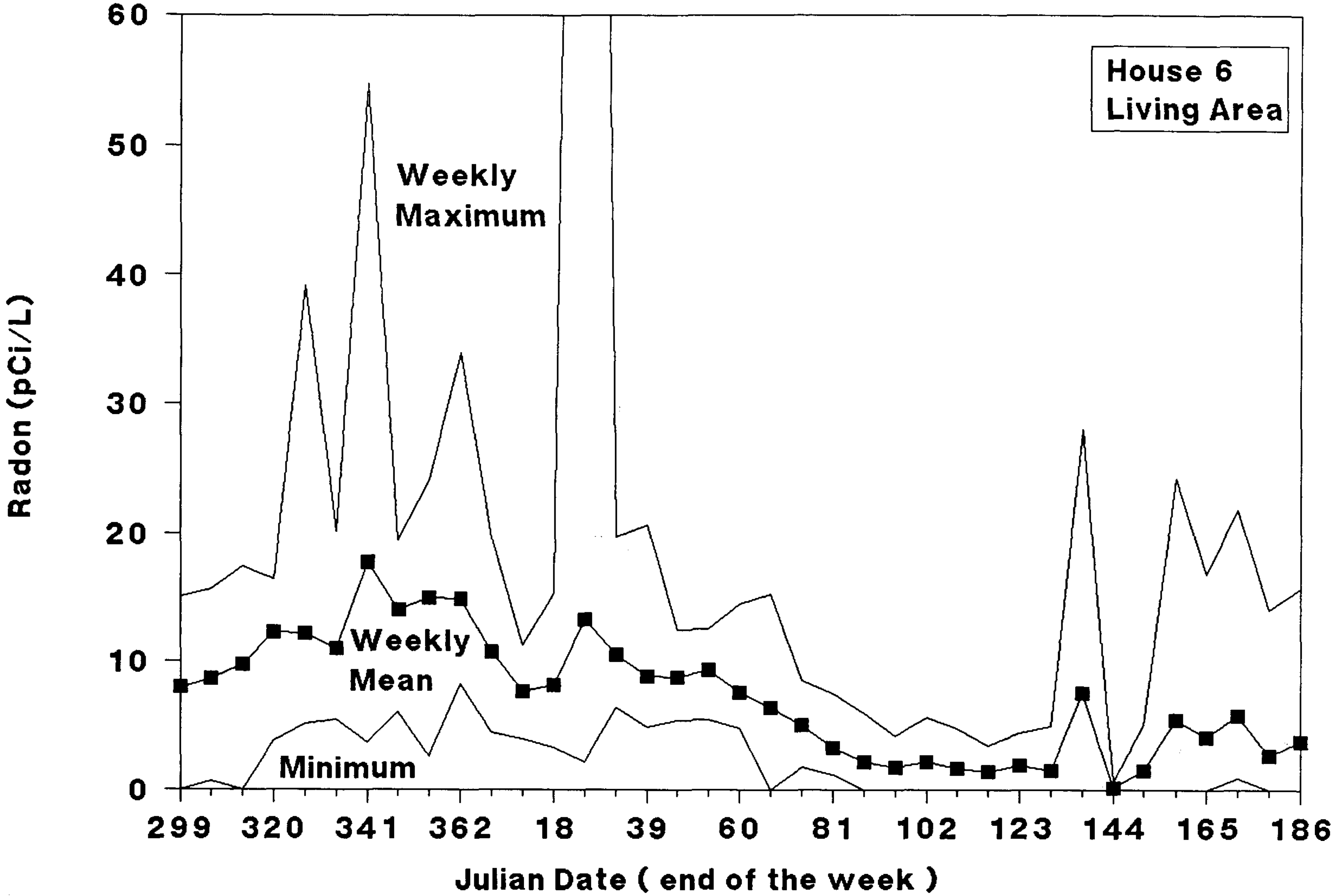


Fig. 7.36. House #6: Weekly means, minima, and maxima of living-area radon data.

ORNL-DWG 88-11001

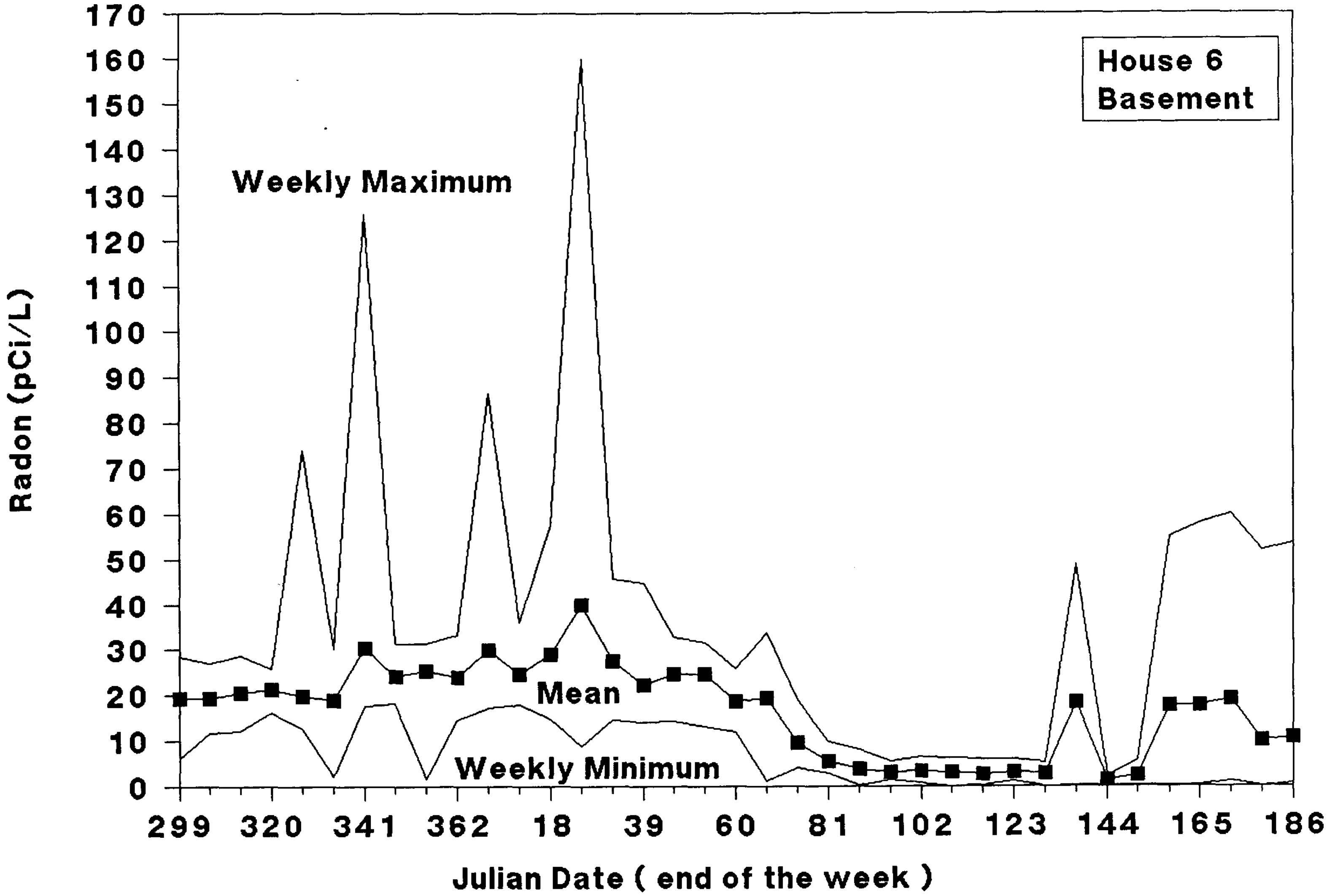


Fig. 7.37. House #6: Weekly means, minima, and maxima of basement radon data.

ORNL-DWG 88-11002

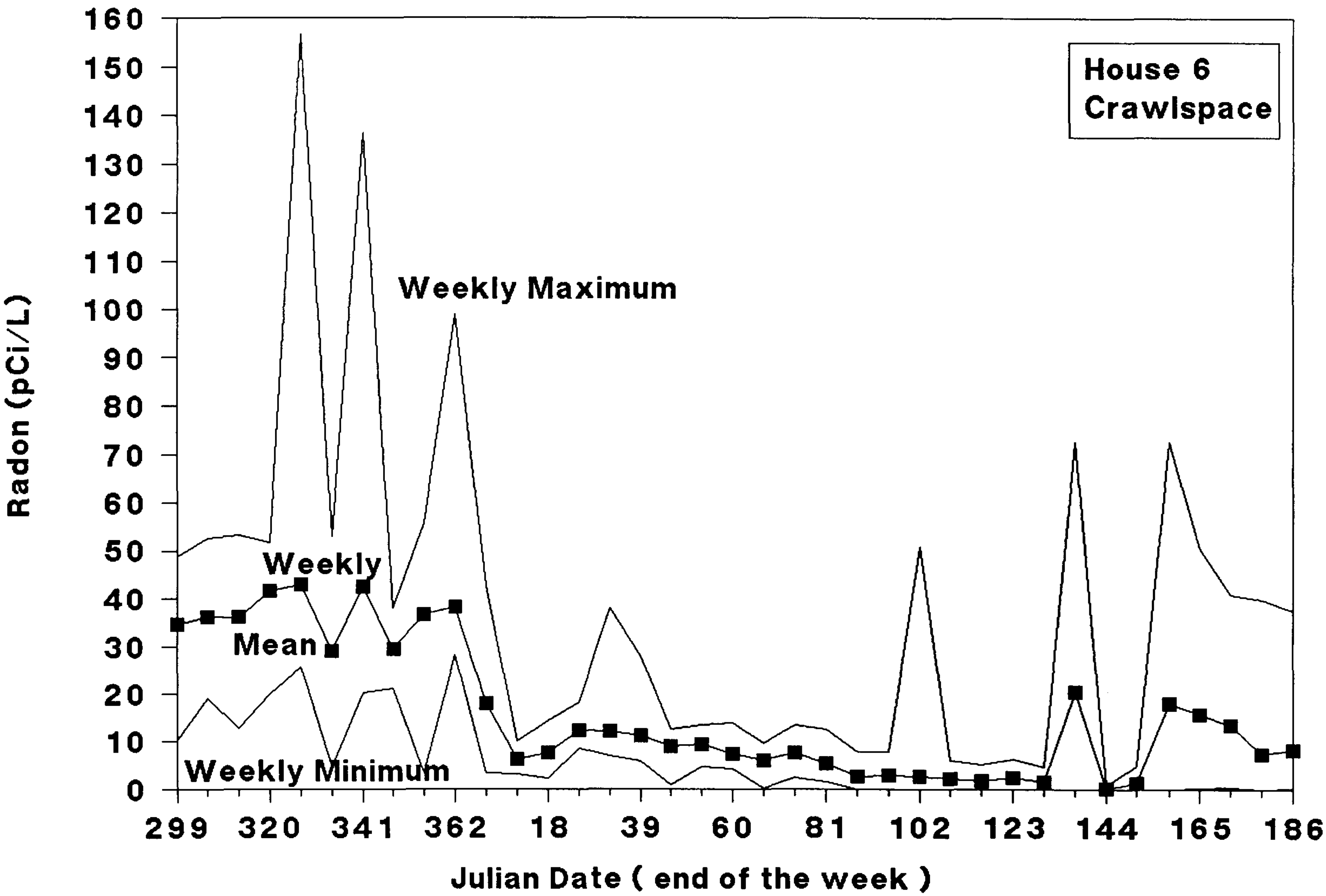


Fig. 7.38. House #6: Weekly means, minima, and maxima of crawlspace radon data.

ORNL-DWG 88-11003

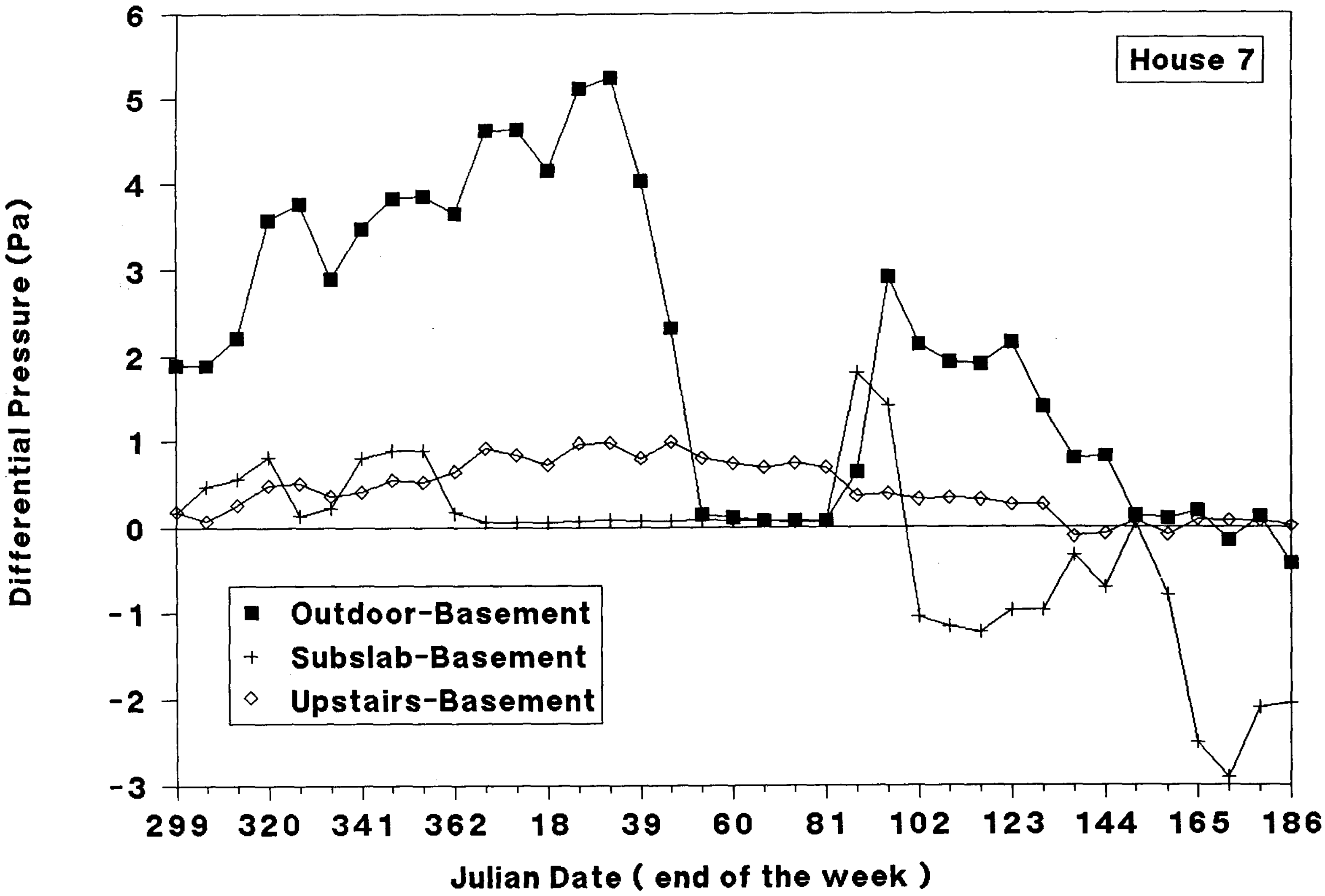


Fig. 7.39. House #7: Weekly averaged differential pressure data.

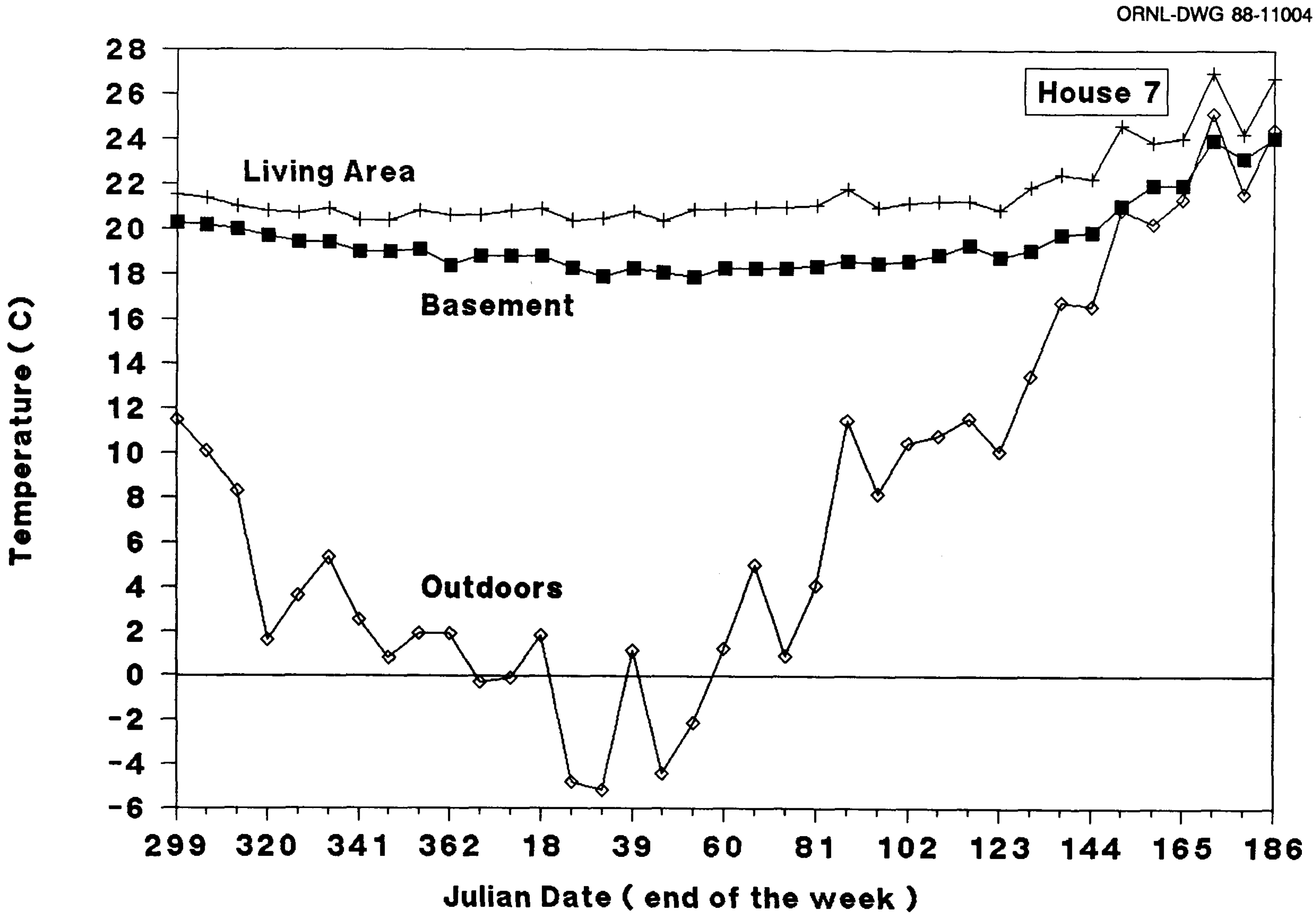


Fig. 7.40. House #7: Weekly averaged temperature data.

ORNL-DWG 88-11005

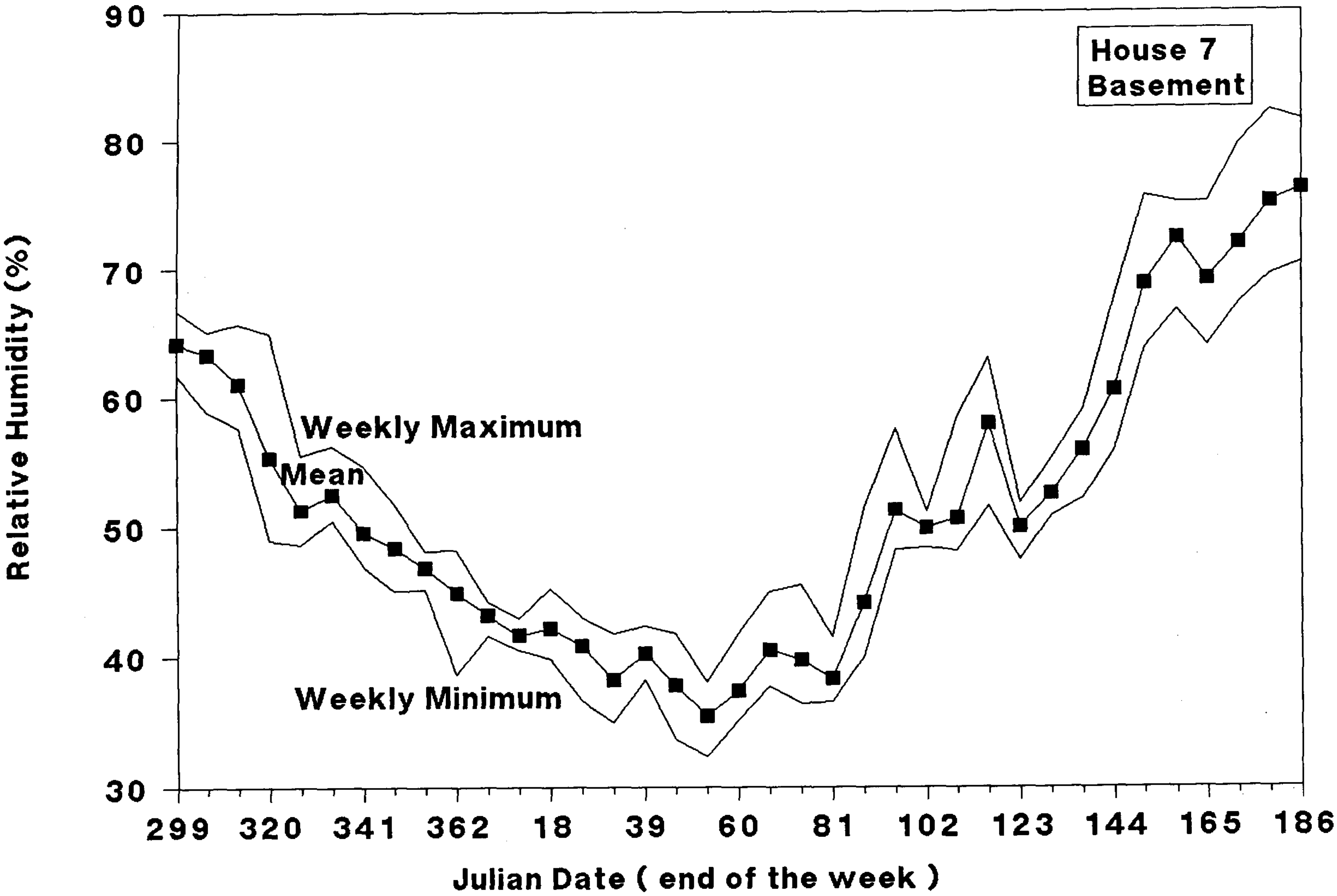


Fig. 7.41. House #7: Weekly means, minima, and maxima of relative humidity data.

ORNL-DWG 88-11006

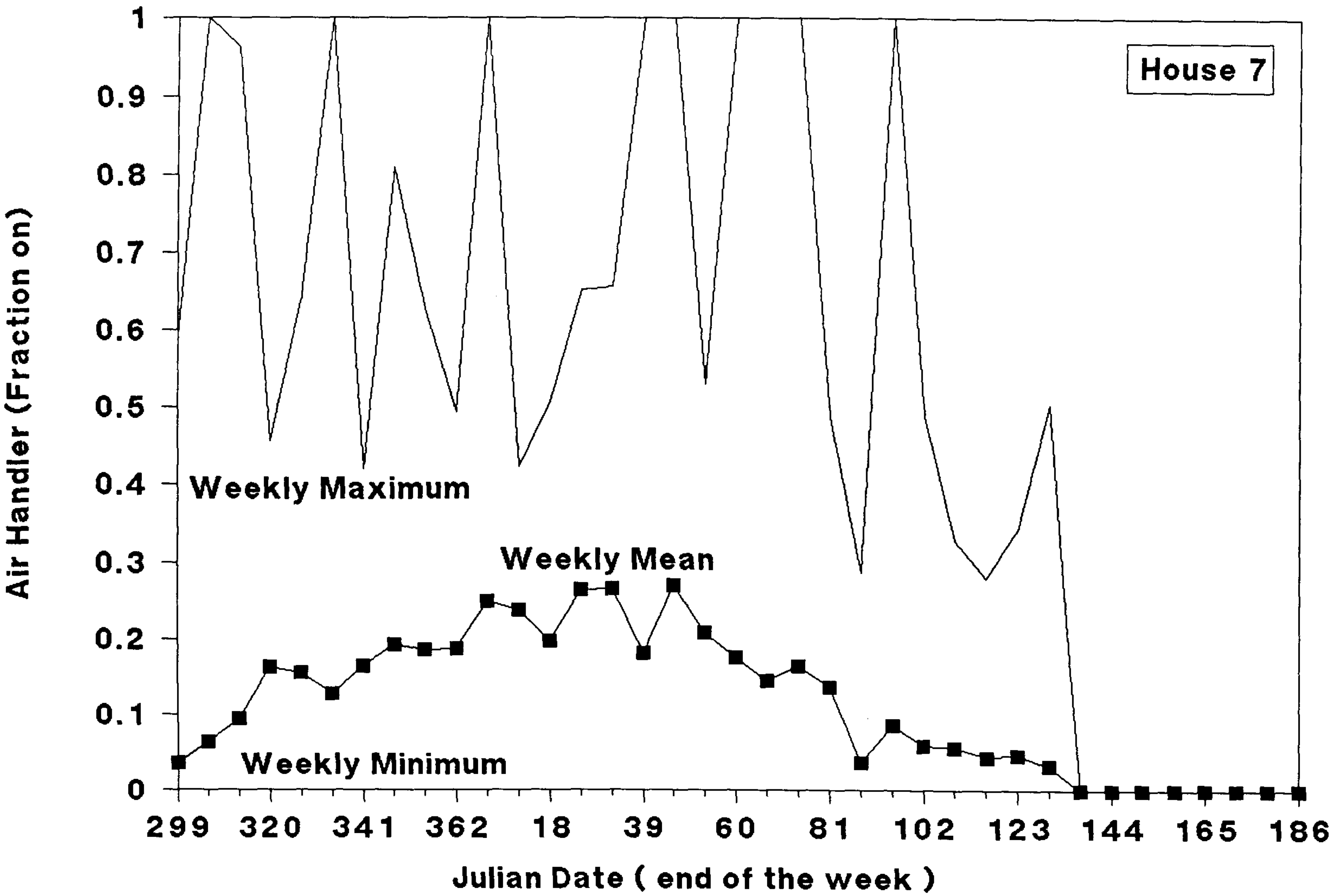


Fig. 7.42. House #7: Weekly means, minima, and maxima of fan usage data.

ORNL-DWG 88-11007

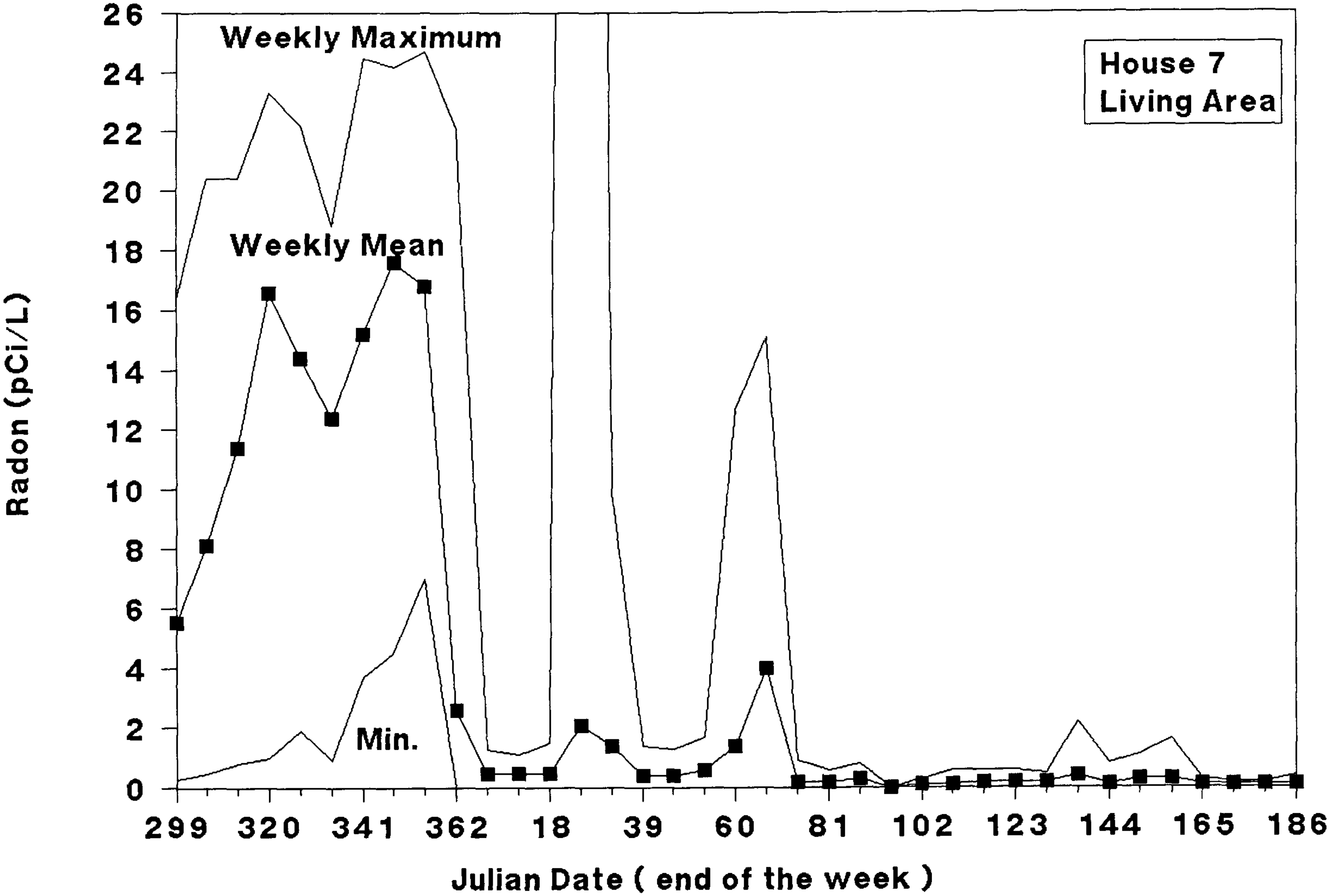


Fig. 7.43. House #7: Weekly means, minima, and maxima of living-area radon data.

ORNL-DWG 88-11008

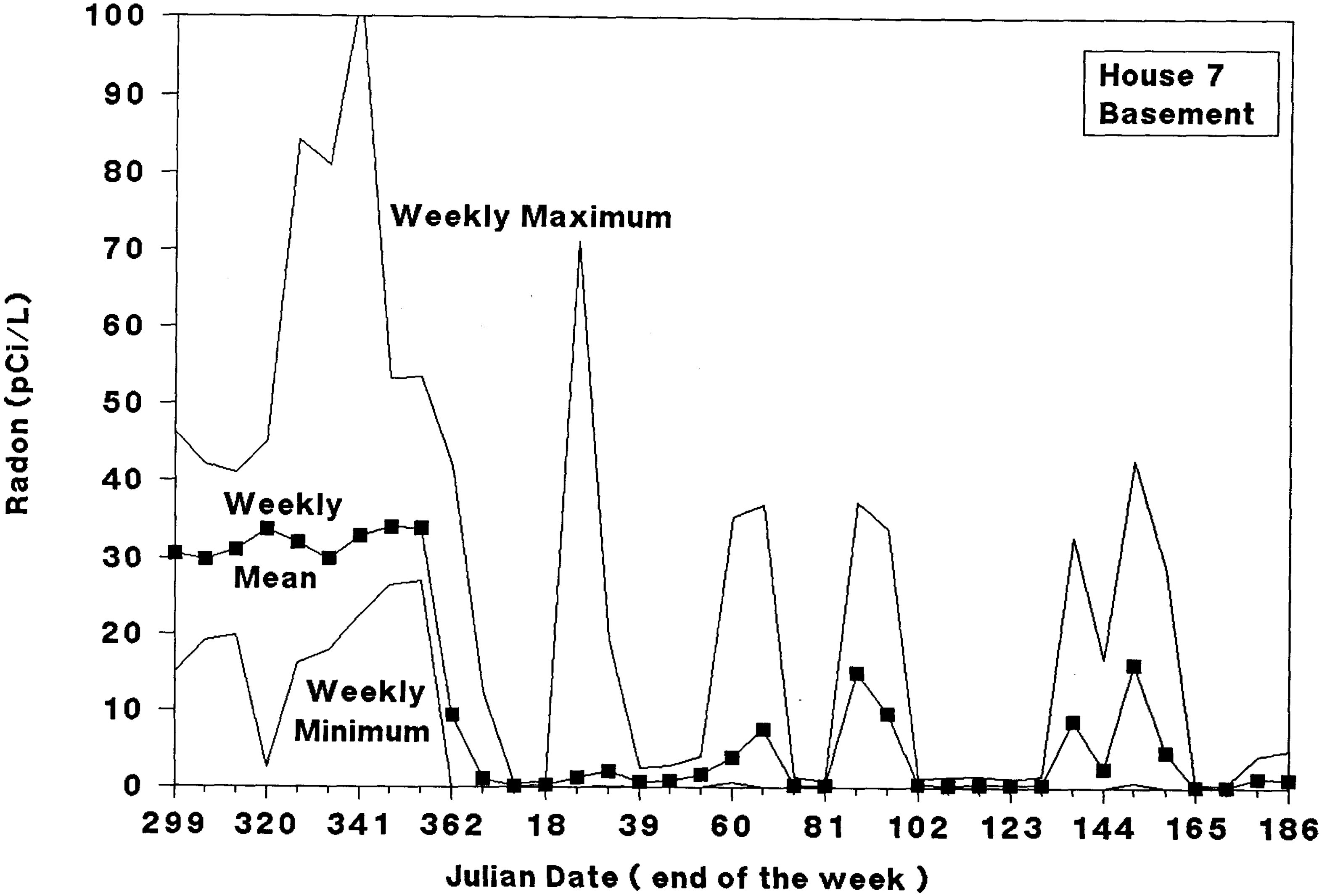


Fig. 7.44. House #7: Weekly means, minima, and maxima of basement radon data.

ORNL-DWG 88-11081

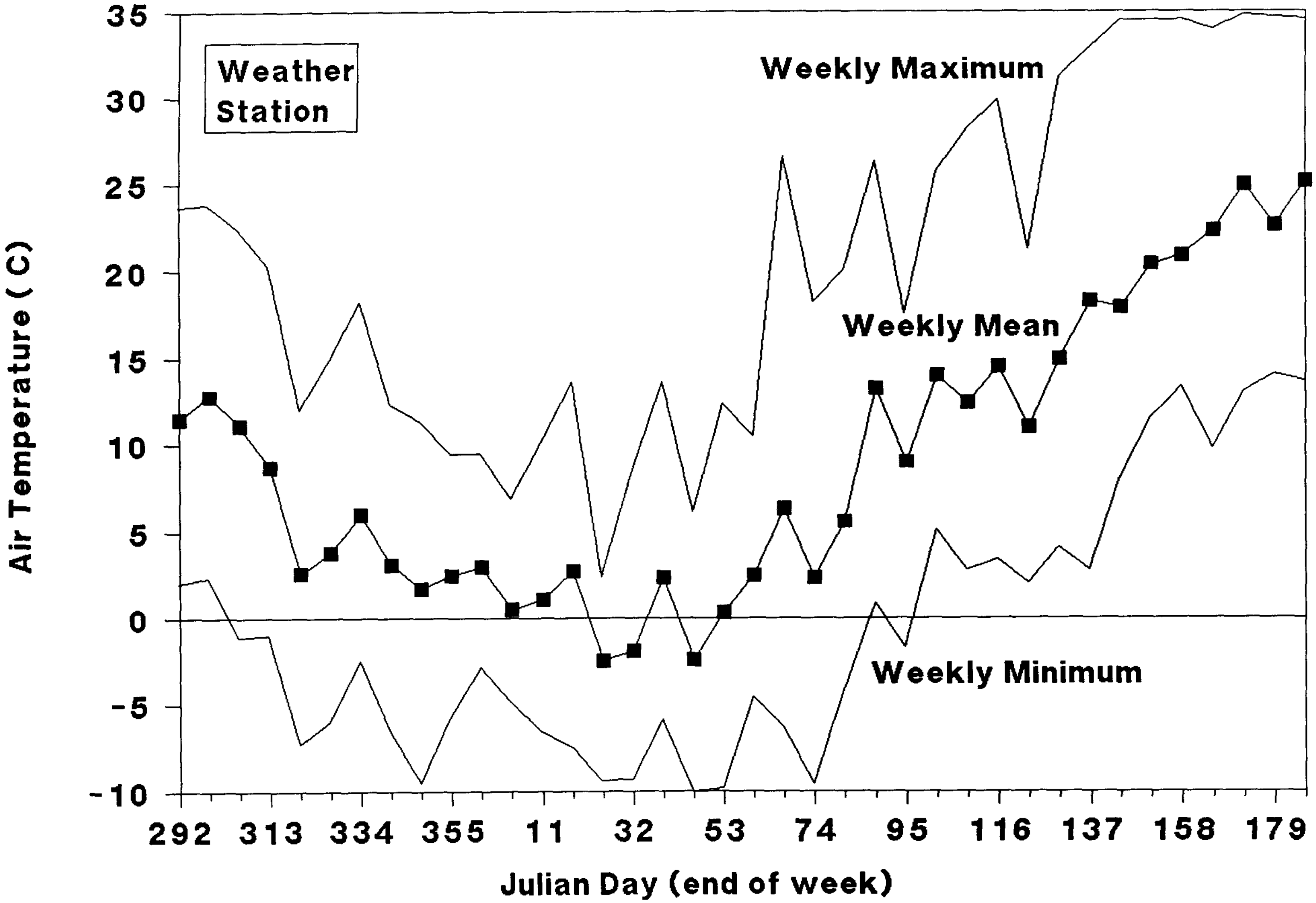


Fig. 7.45. Weather station: weekly means, minima, and maxima of outdoor air temperature data.

ORNL-DWG 88-11082

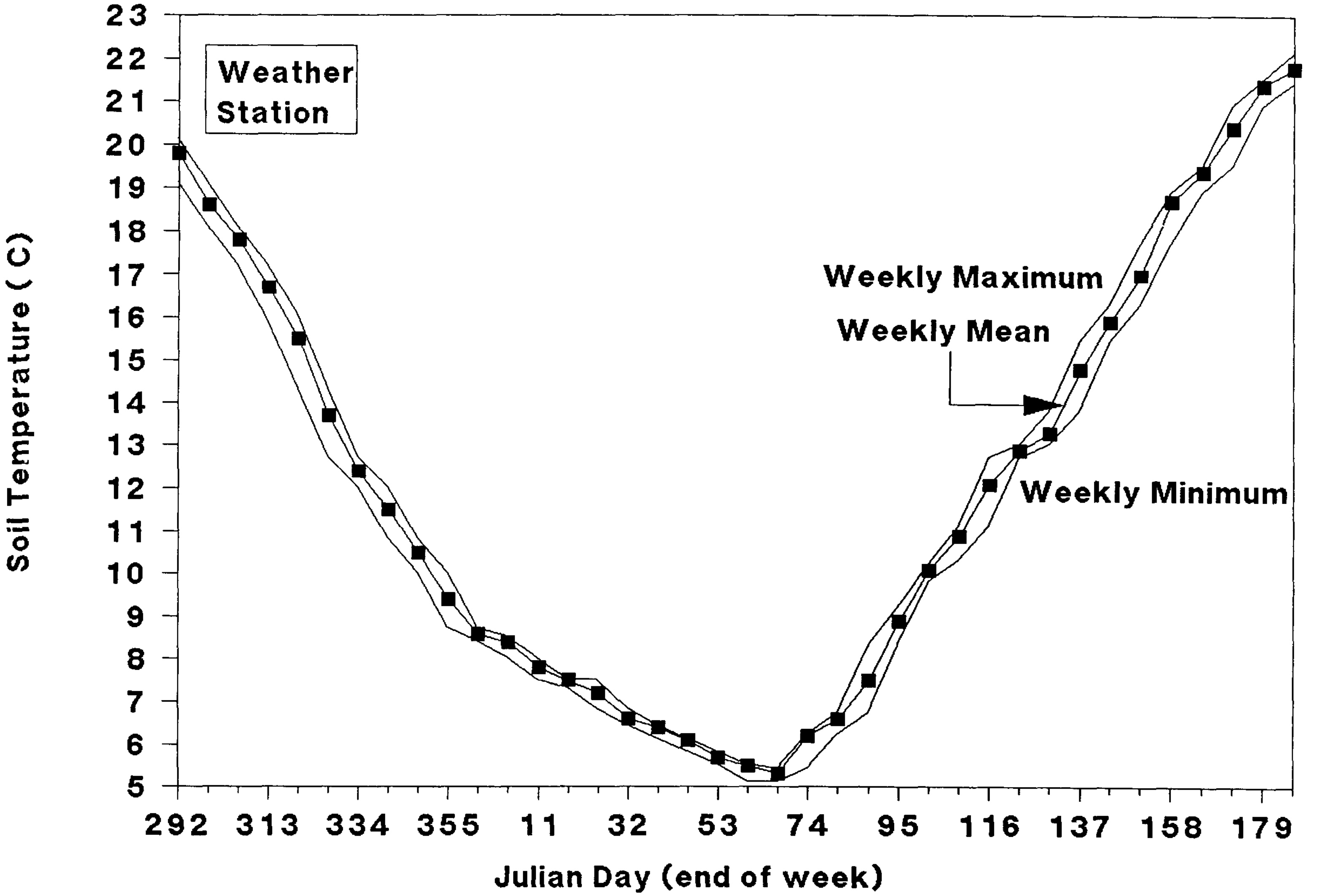


Fig. 7.46. Weather station: weekly means, minima, and maxima of soil temperature data.

ORNL-DWG 88-11083

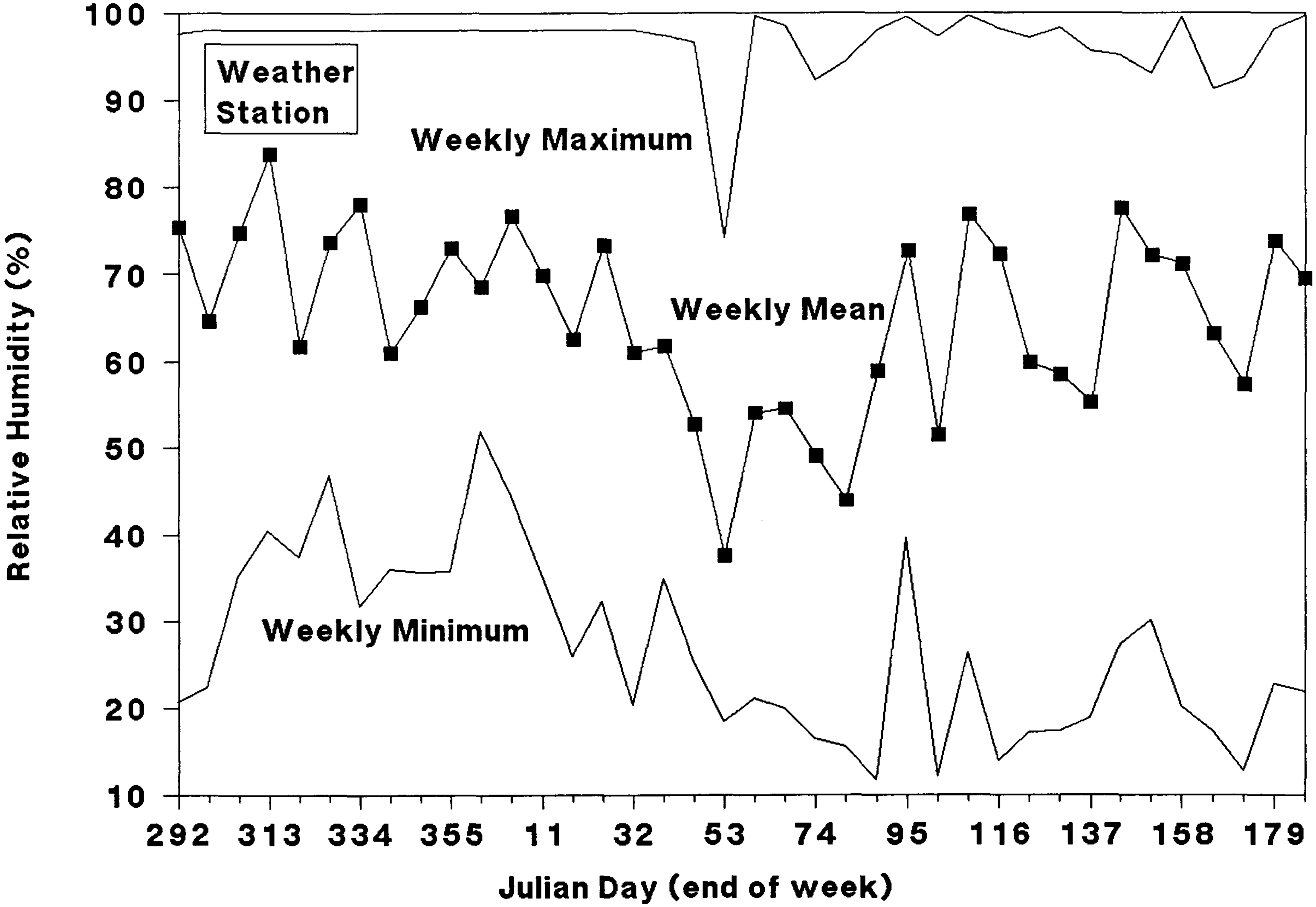


Fig. 7.47. Weather station: weekly means, minima, and maxima of outdoor relative humidity data.

ORNL-DWG 88-11084

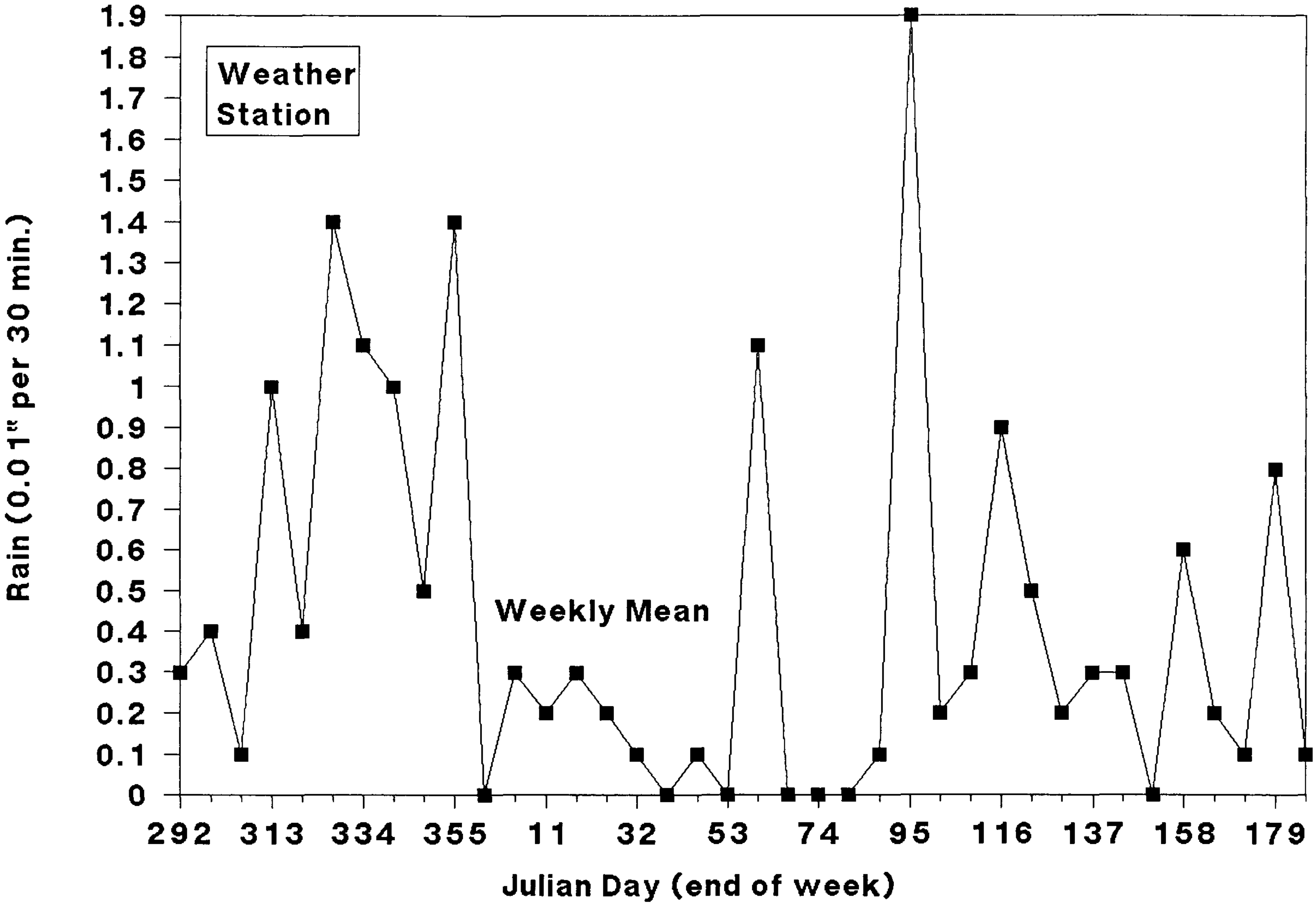


Fig. 7.48. Weather station: weekly means of rainfall data.

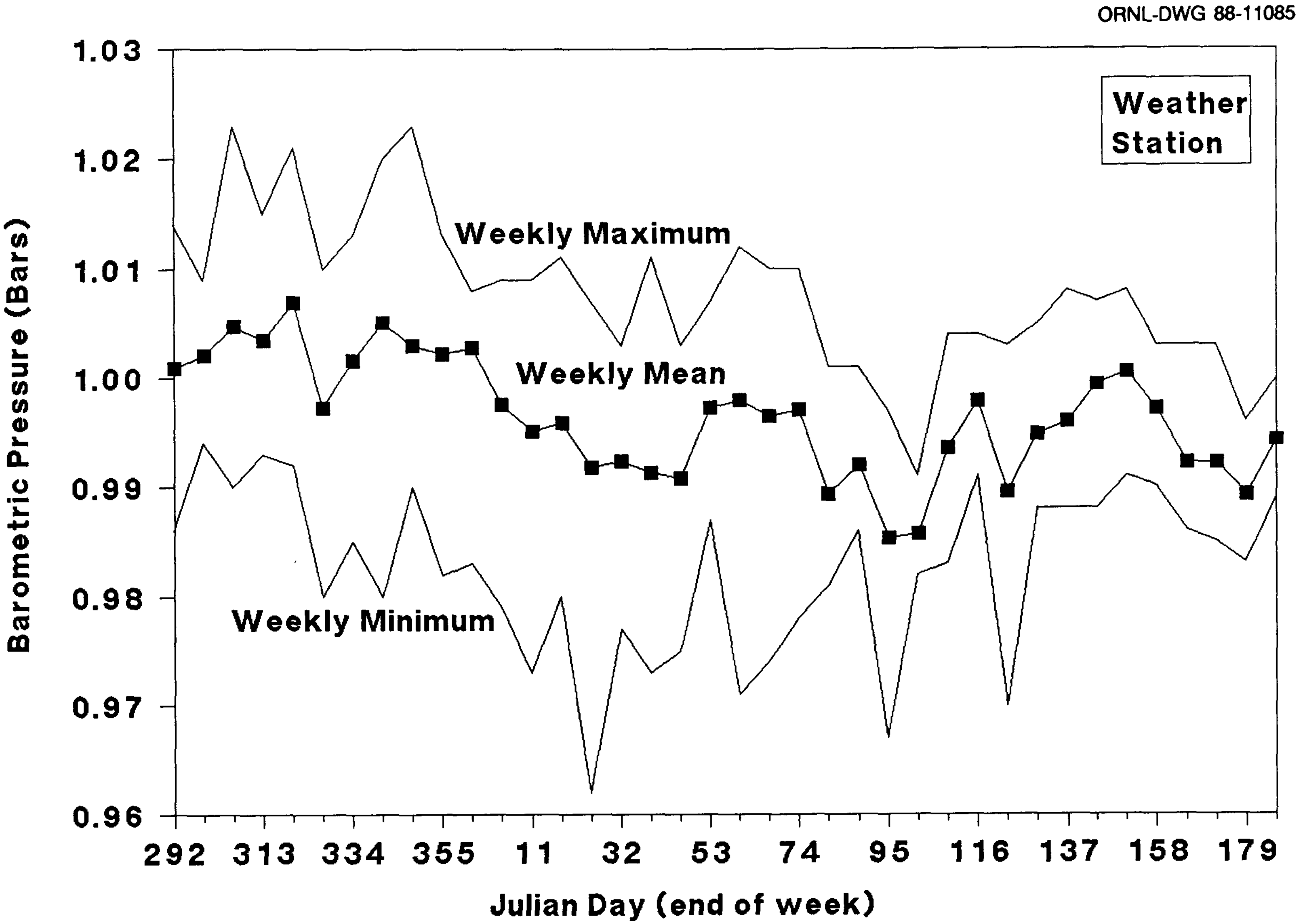


Fig. 7.49. Weather station: weekly means, minima, and maxima of barometric pressure data.

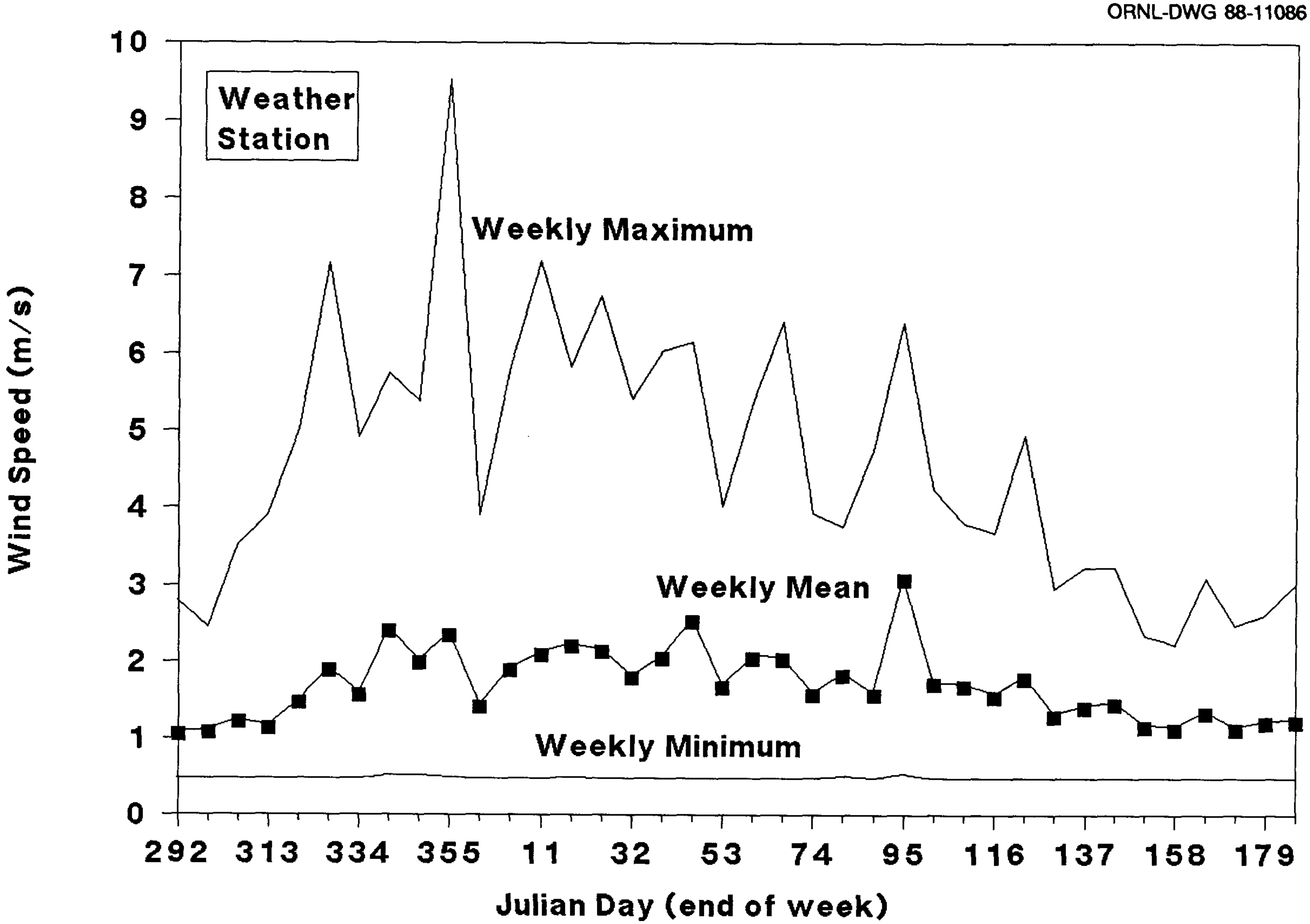


Fig. 7.50. Weather station: weekly means, minima, and maxima of wind speed data.

ORNL-DWG 88-11087

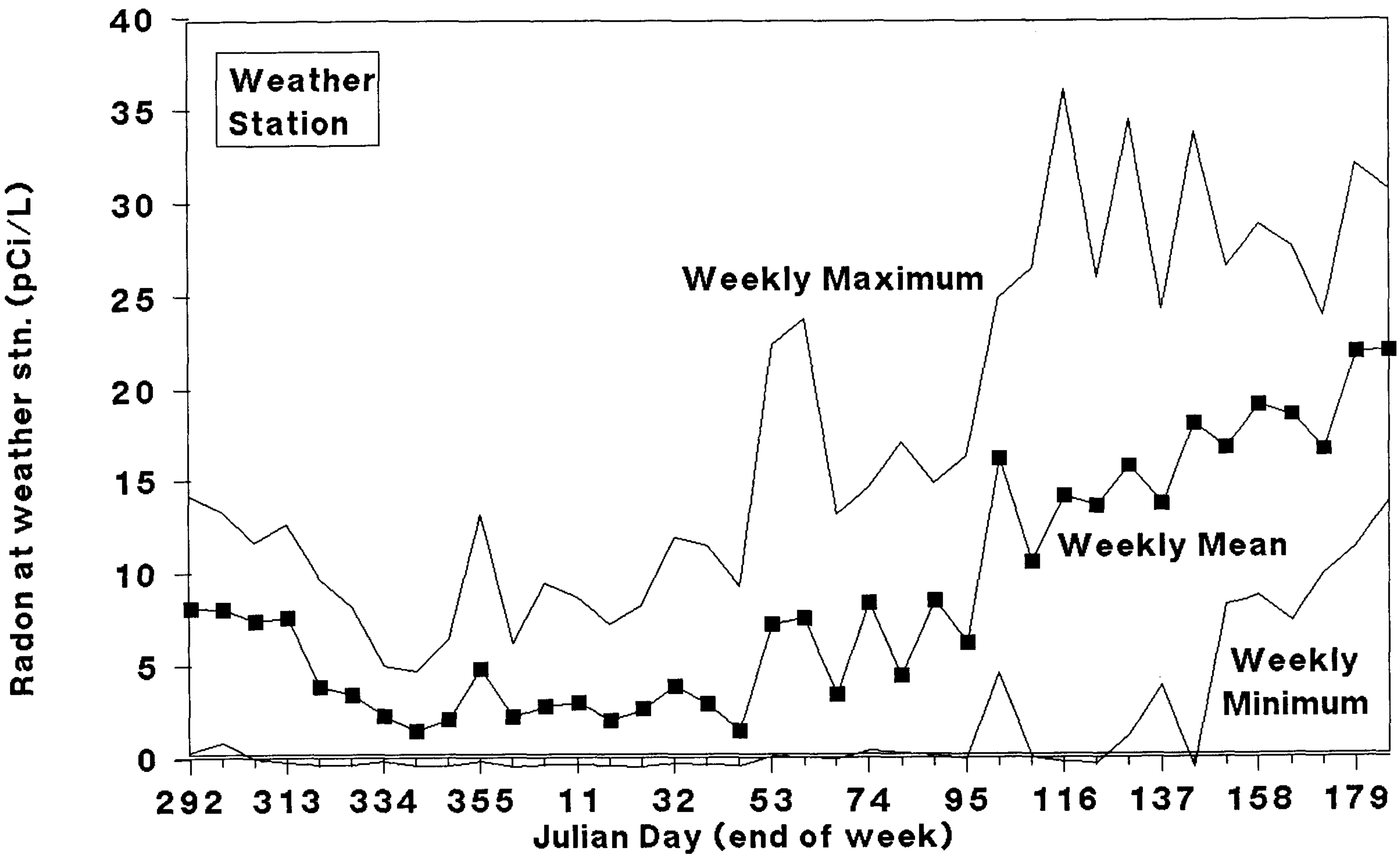


Fig. 7.51. Weather station: weekly means, minima, and maxima of radon data at site near weather station.

ORNL-DWG 88-11088

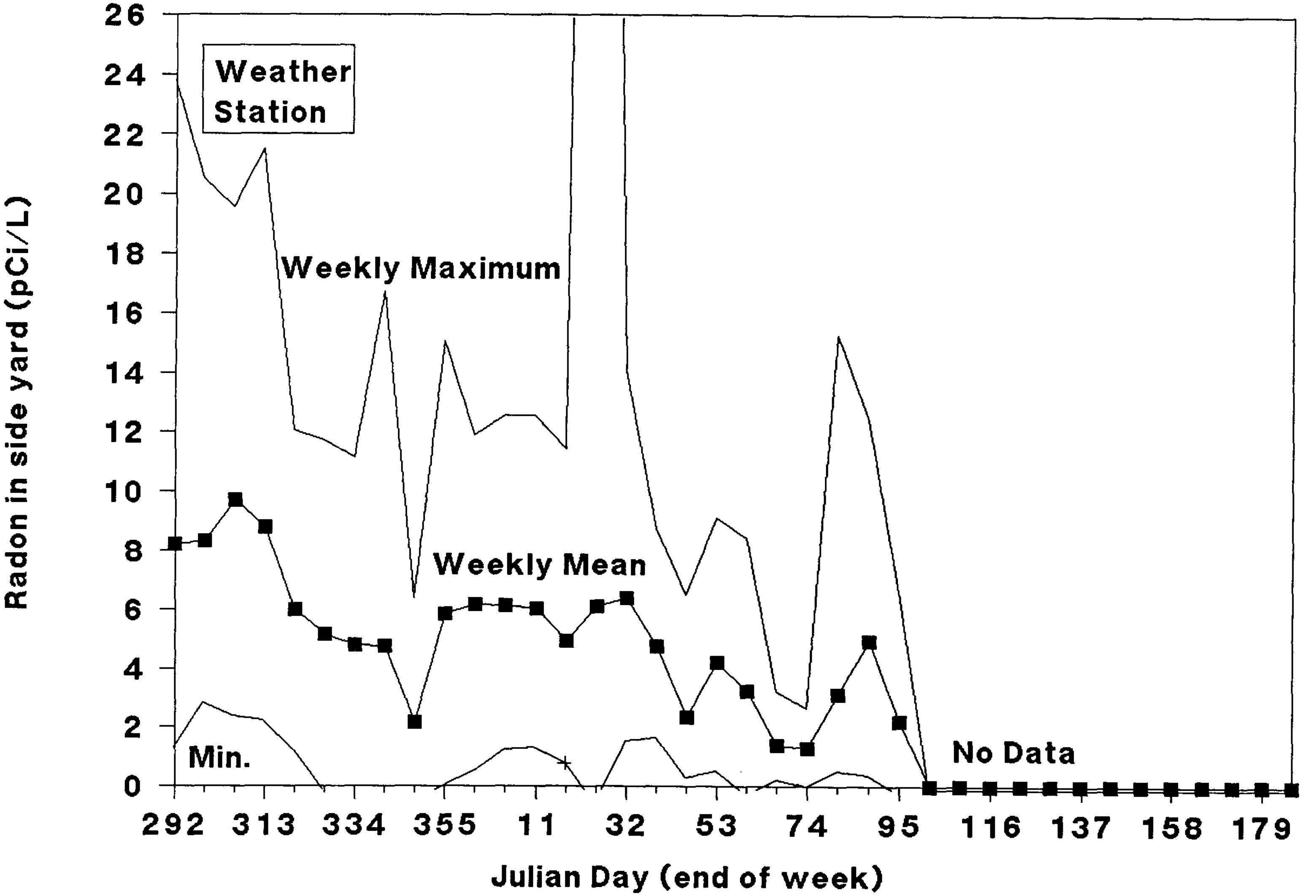


Fig. 7.52. Weather station: weekly means, minima, and maxima of radon data at site in side yard.

ORNL-DWG 88-11089

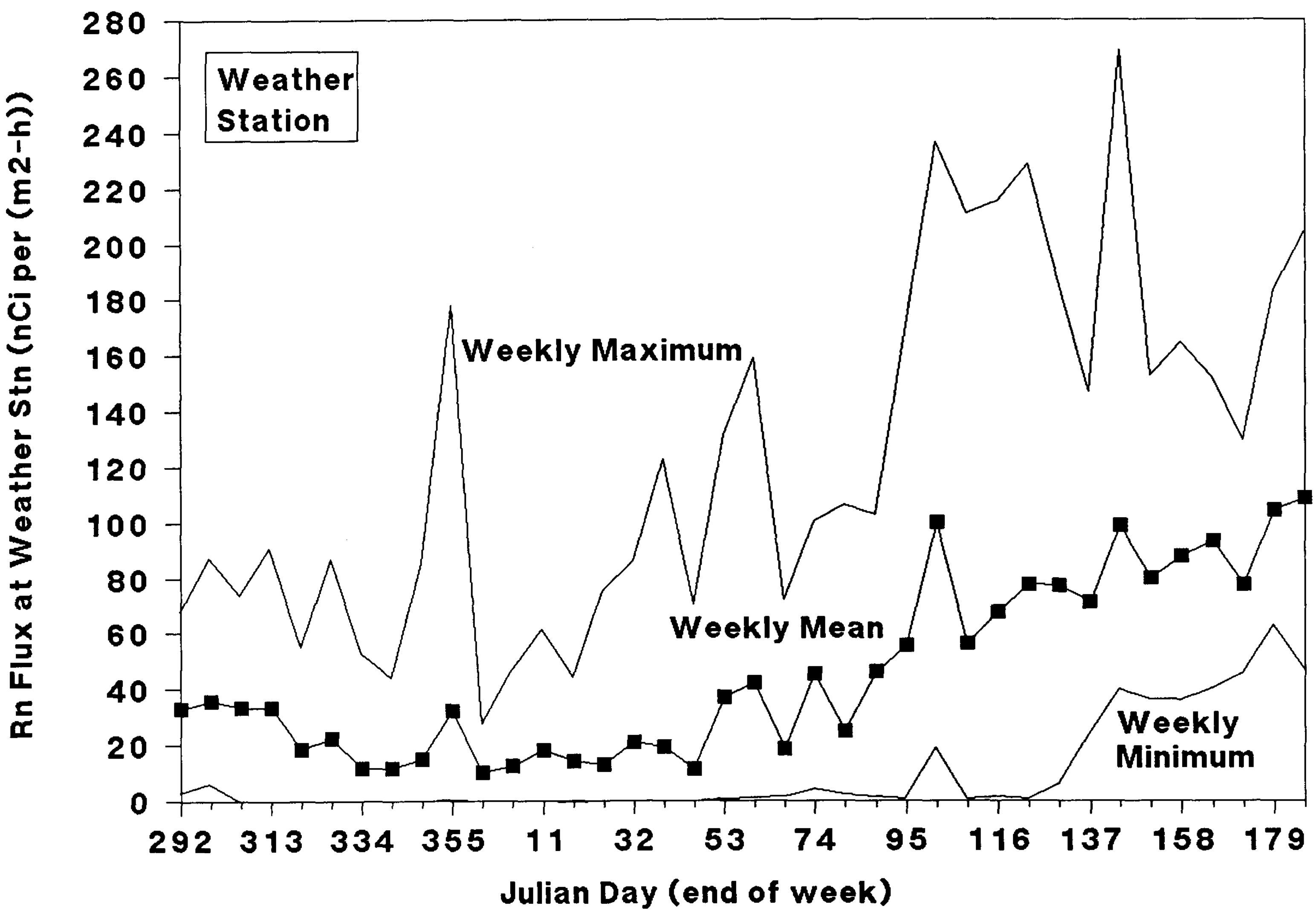


Fig. 7.53. Weather station: weekly means, minima, and maxima of radon flux data at site near weather station.

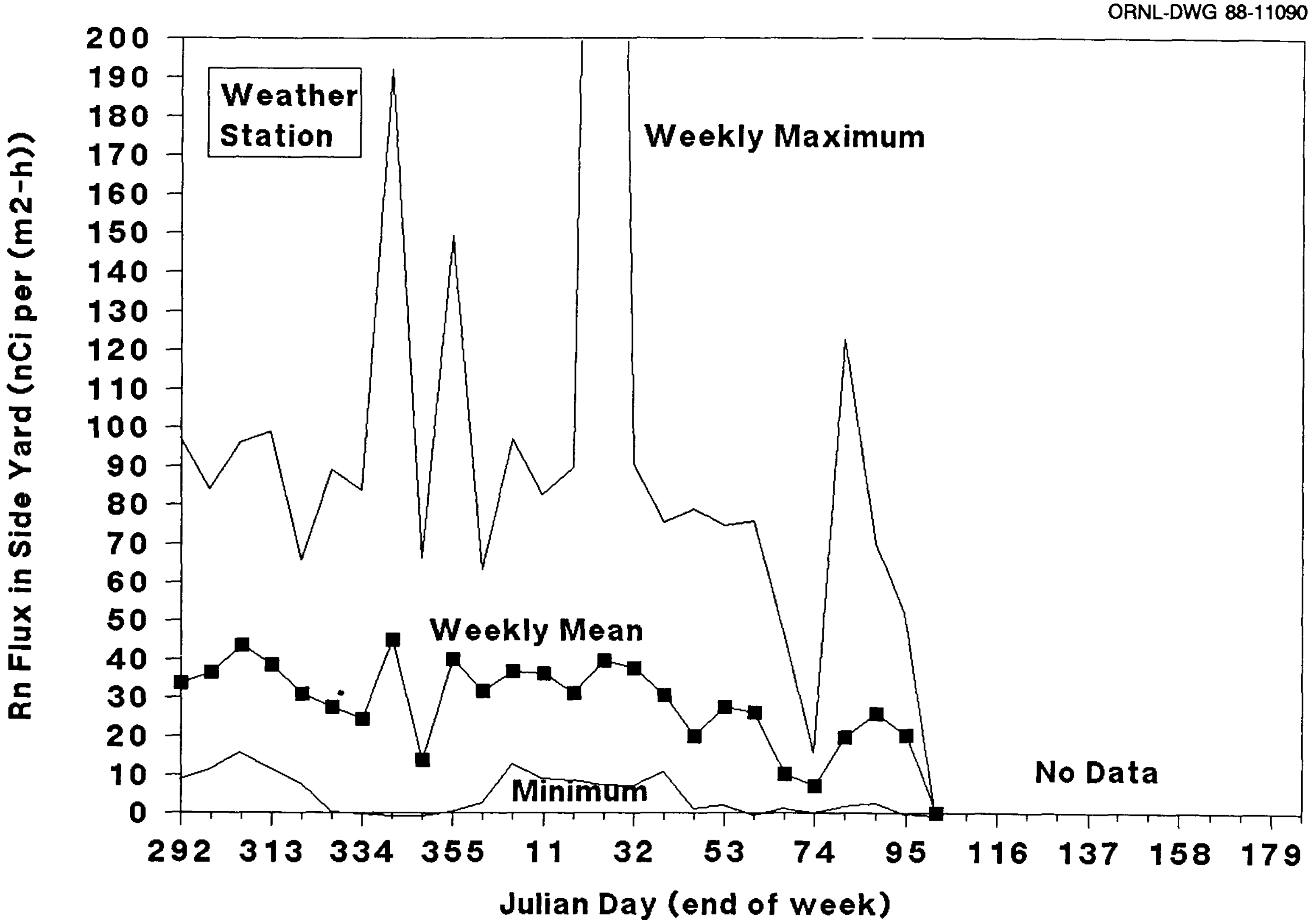


Fig. 7.54. Weather station: weekly means, minima, and maxima of radon flux data in side yard.

ORNL-DWG 89-13761

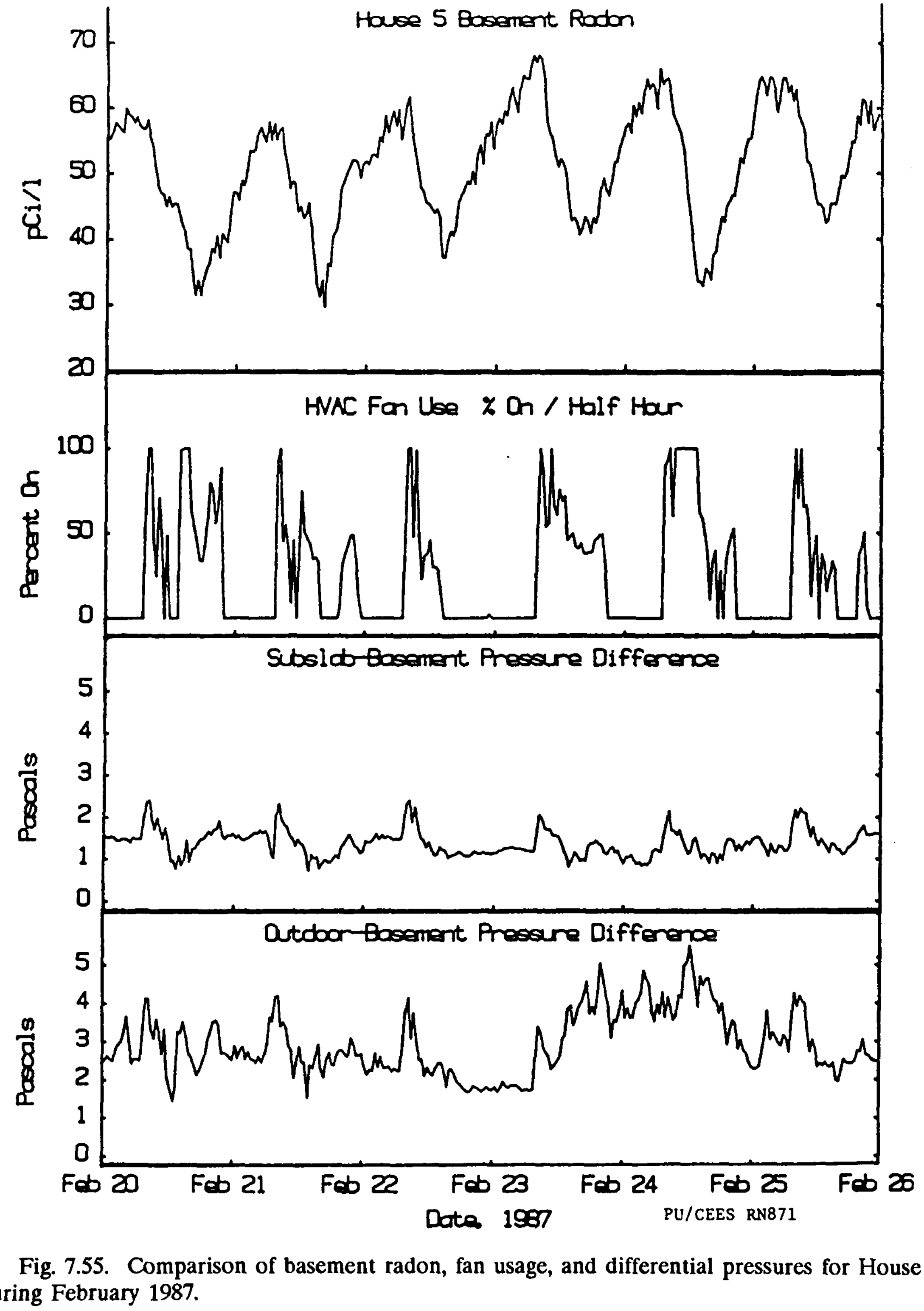


Fig. 7.55. Comparison of basement radon, fan usage, and differential pressures for House #5 during February 1987.

ORNL-DWG 89-13762

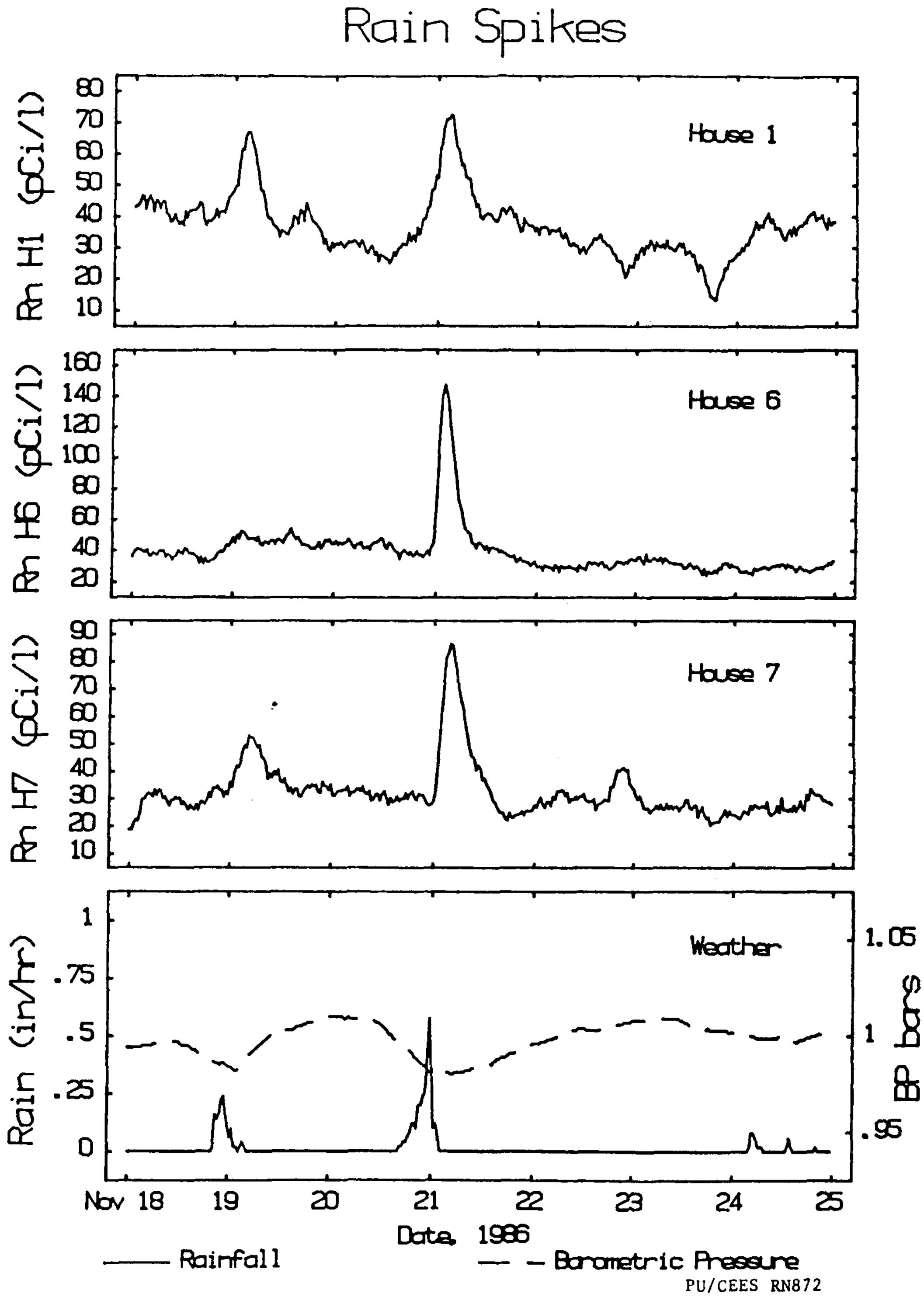


Fig. 7.56. Comparison of basement radon (Houses #1, #6, and #7), rainfall, and barometric pressure.

ORNL-DWG 88-11093

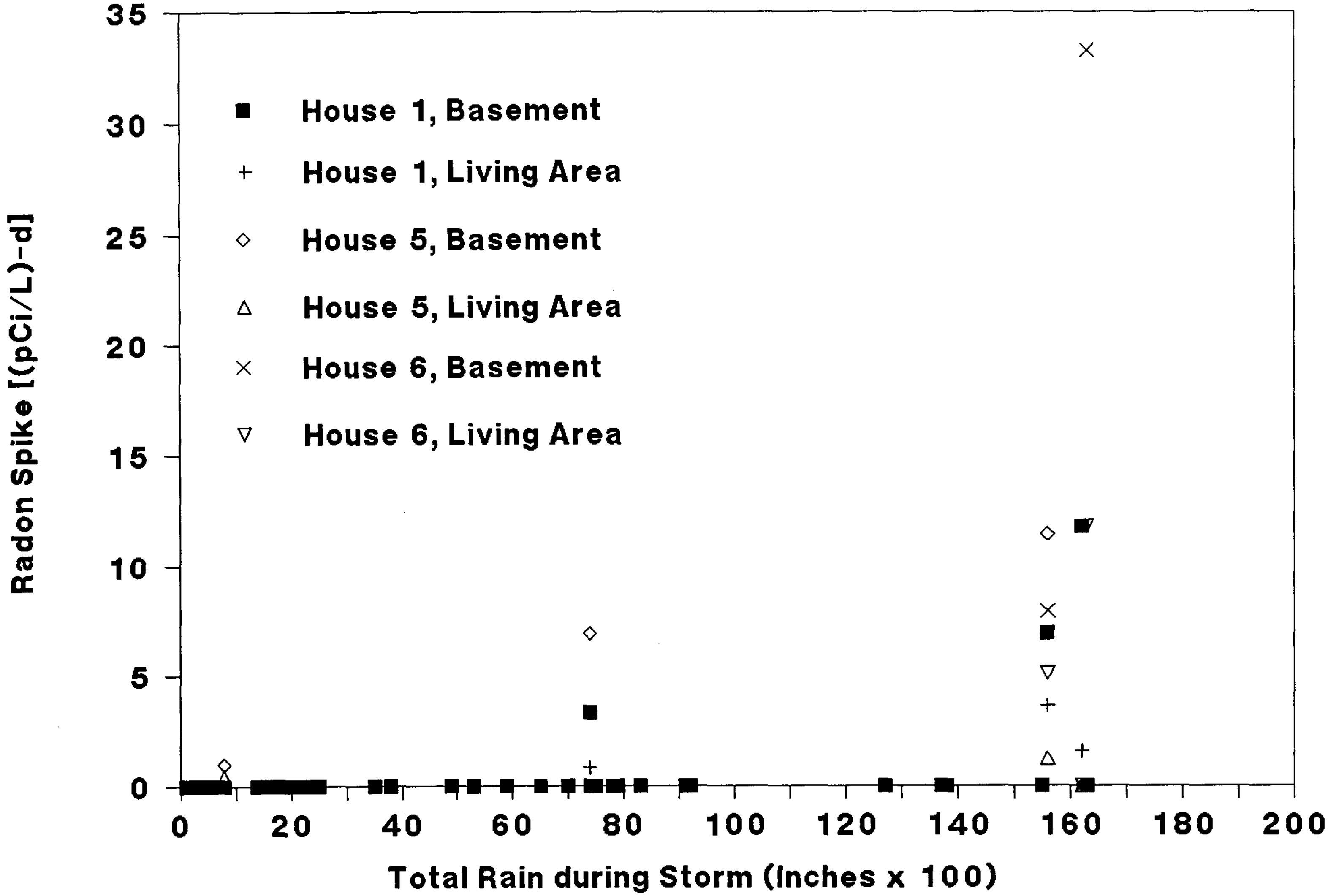


Fig. 7.57. Comparison of rain-induced radon increase and total rainfall.

ORNL-DWG 89-13763

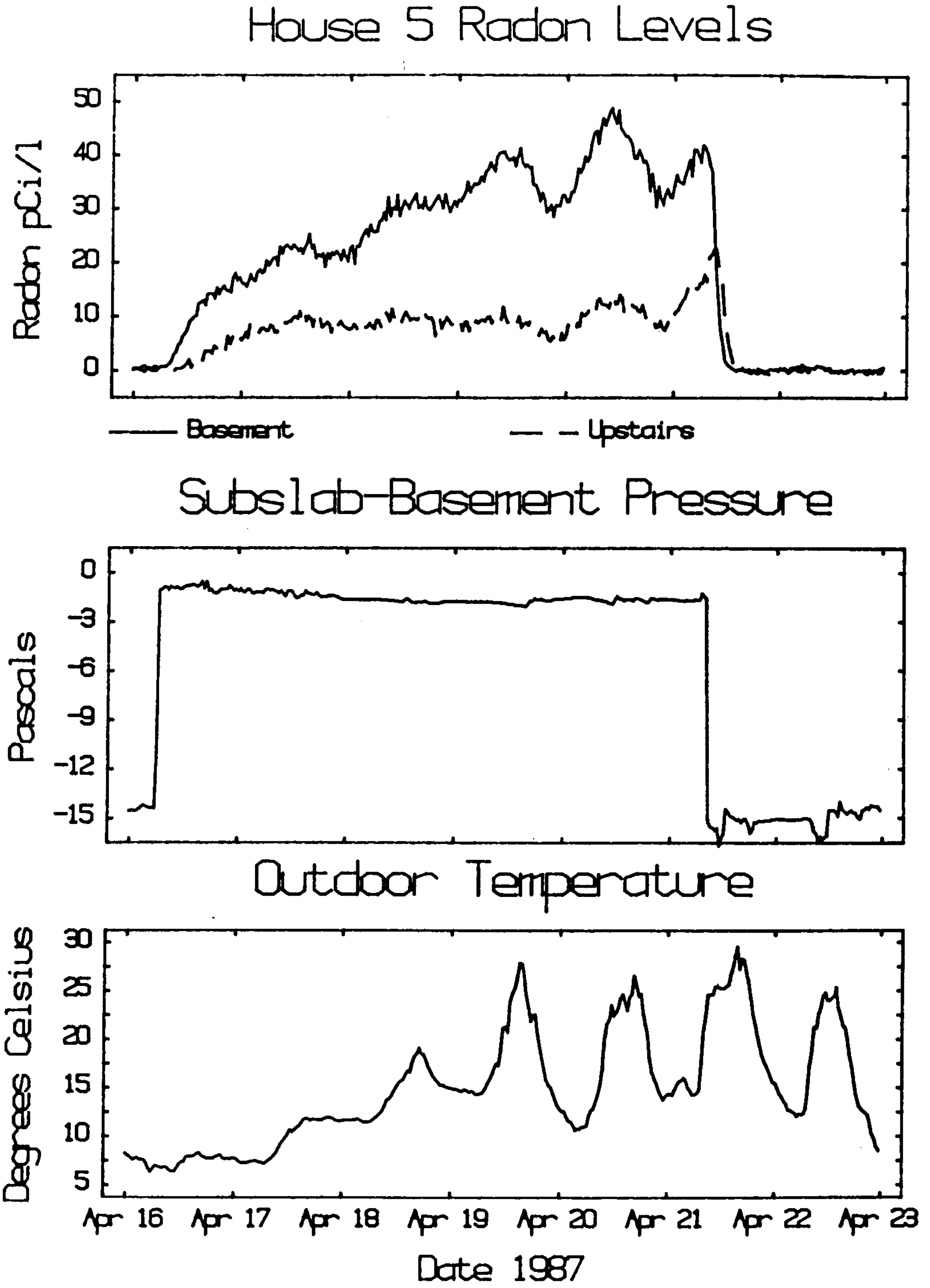
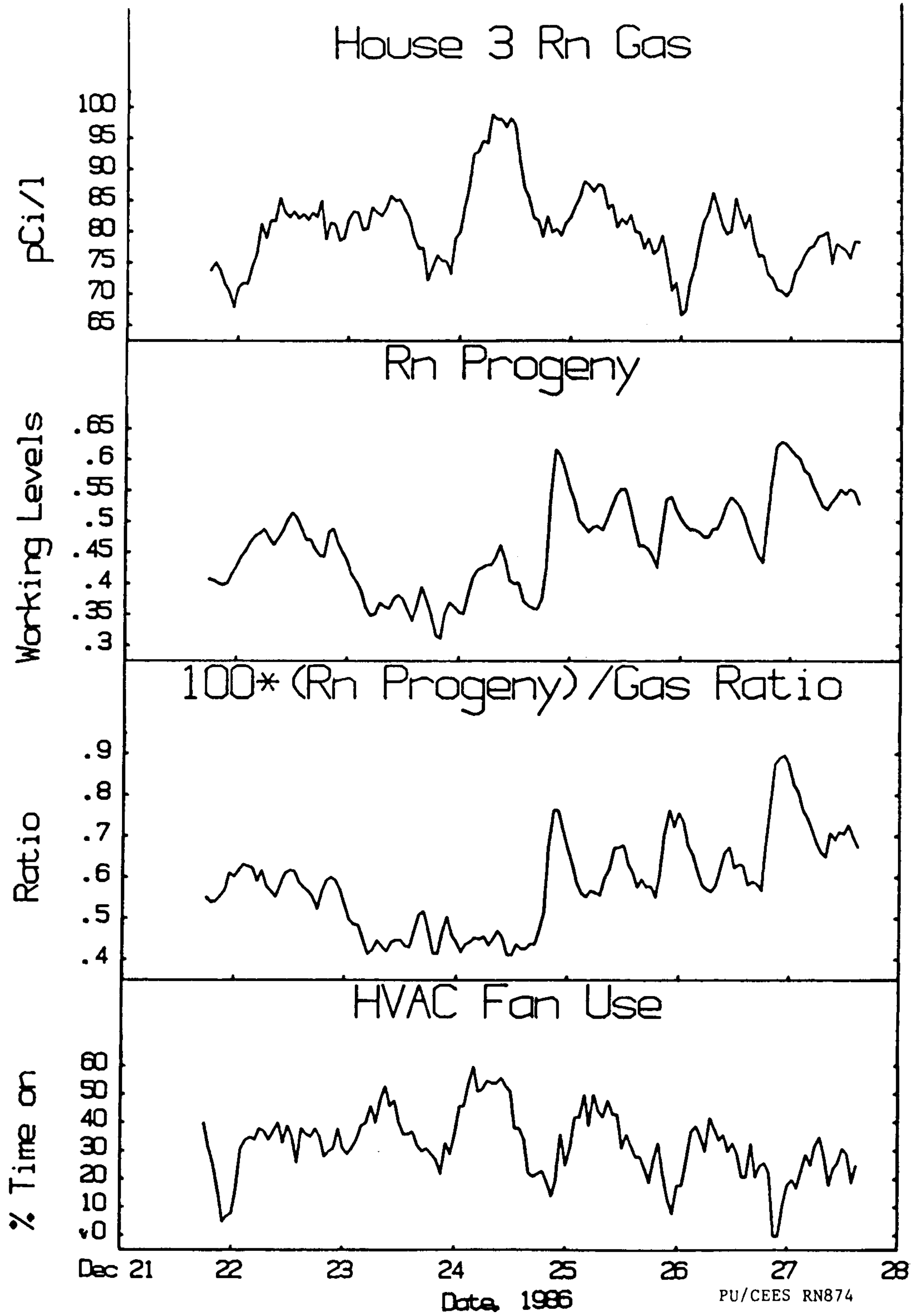


Fig. 7.58. Comparison of radon, subslab/basement pressure difference, and outdoor temperature for House #5 during April 1987.

ORNL-DWG 89-13764



PU/CEES RN874

Fig. 7.59. Comparison of radon equilibrium and fan usage.

ORNL-DWG 88-11091

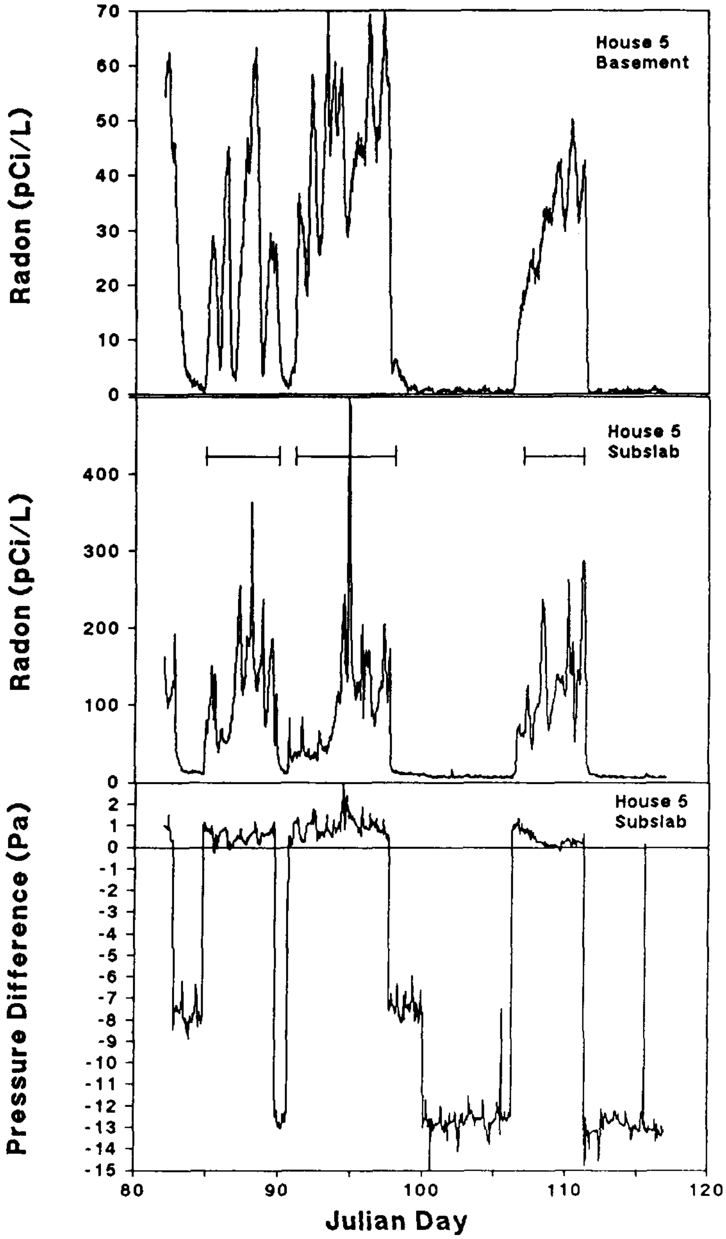


Fig. 7.60. Comparison of radon and subslab/basement pressure difference in House #5 during March/April 1987.

ORNL-DWG 88-11076

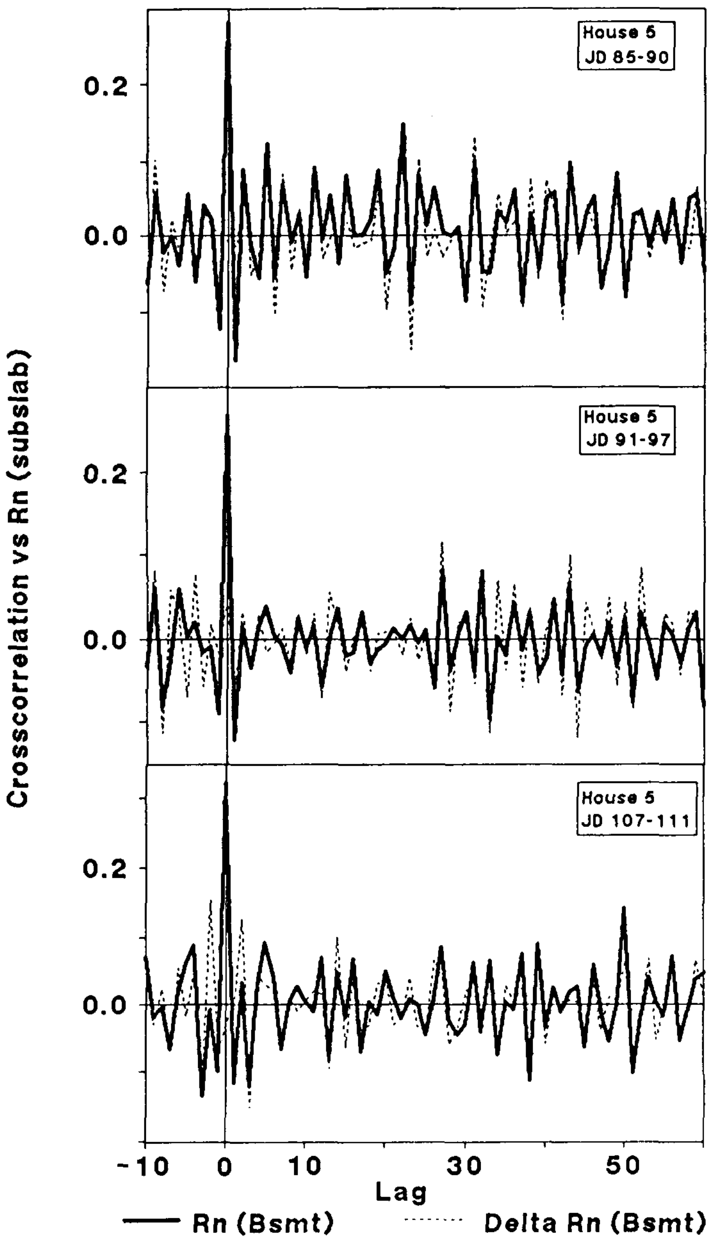


Fig. 7.61. Cross-correlation of radon (and change in radon) with subslab radon concentration.

ORNL-DWG 88-11077

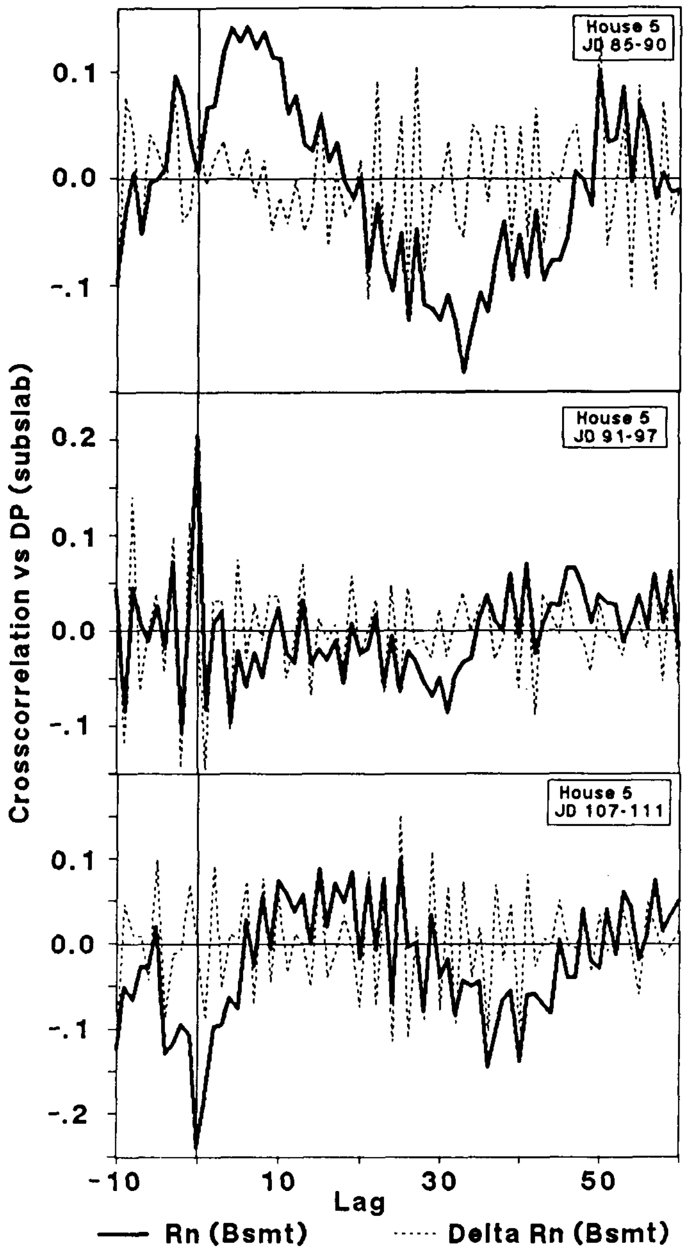


Fig. 7.62. Cross-correlation of radon (and change in radon) with subslab/basement pressure difference.

ORNL-DWG 88-11078

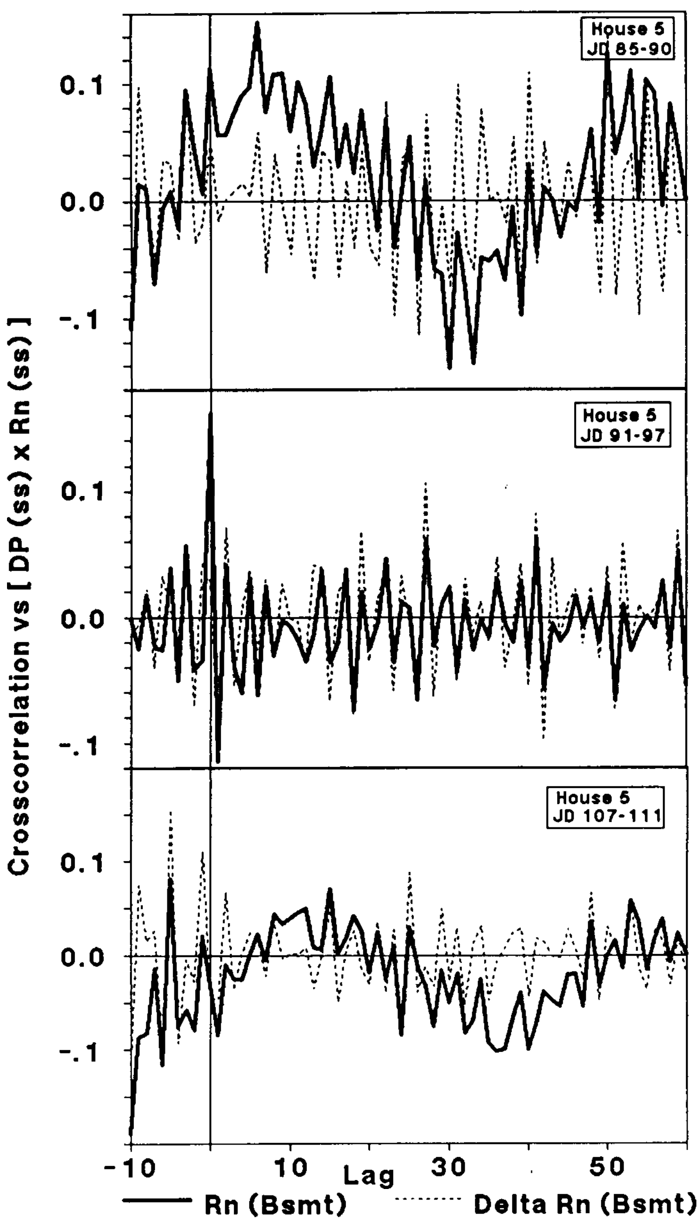


Fig. 7.63. Cross-correlation of radon (and change in radon) with product of pressure difference across the slab and the radon concentration beneath the slab.

ORNL-DWG 88-11079

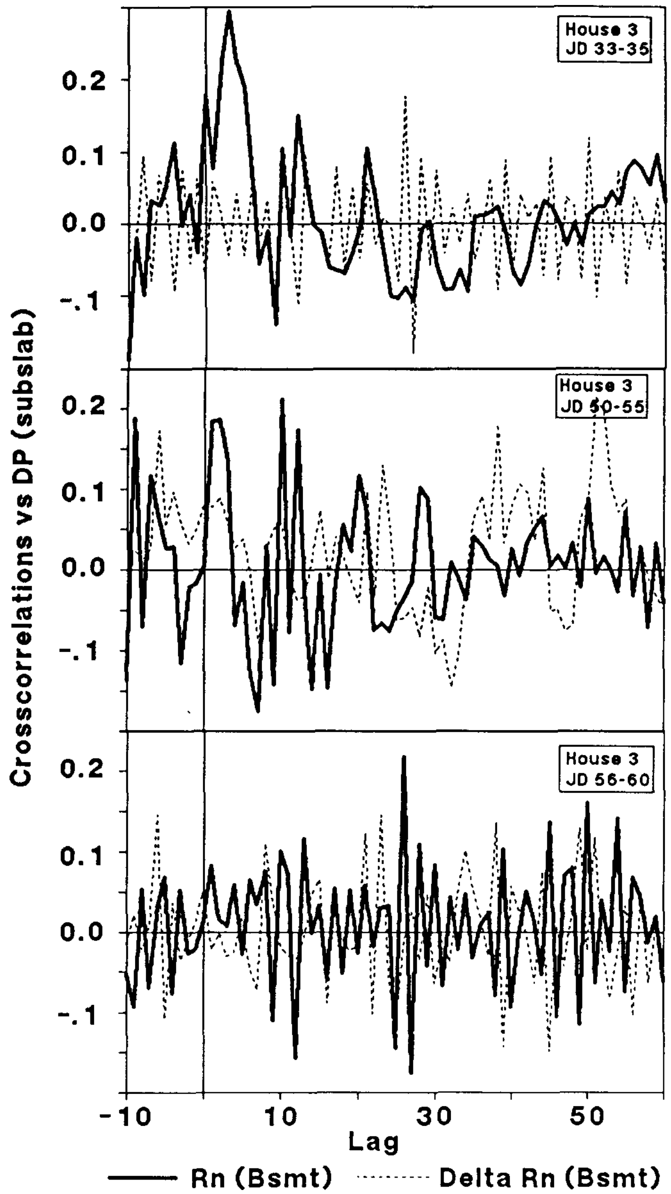


Fig. 7.64. House #3 (November 1986): Cross-correlation of radon (and change in radon) with subslab/basement pressure difference.

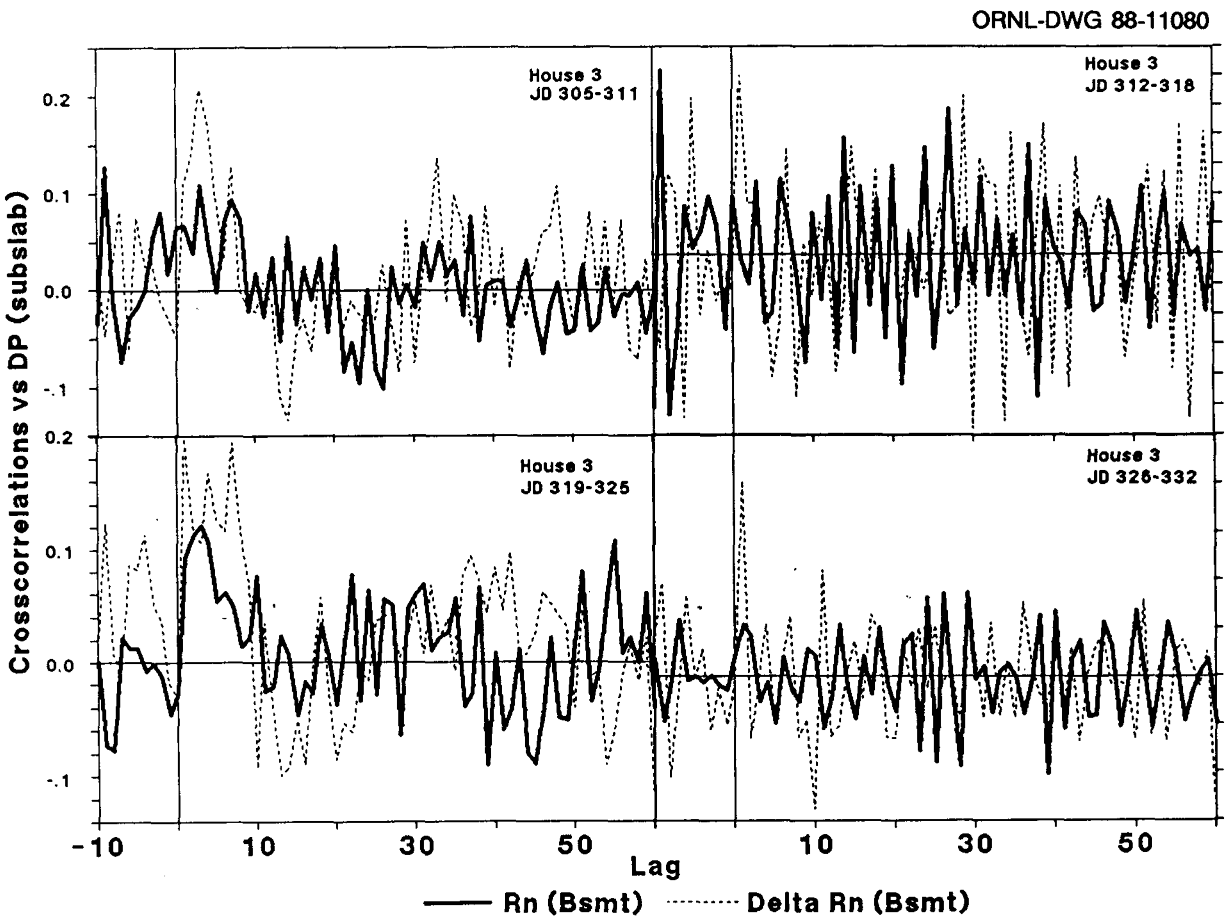


Fig. 7.65. House #3 (February 1987): Cross-correlation of radon (and change in radon) with subslab/basement pressure difference.

APPENDICES

A. Data Management

B. Weekly Data Summaries

APPENDIX A

- Program for Transmission Error Trapping and Formatting of Data Files
- Data Base Structures Used for Data Storage
- Program for Checking Completeness of Data Files
- Subroutines to Excur.Prg.
- Programs for Summary Statistics

PROGRAM FOR TRANSMISSION ERROR TRAPPING AND FORMATTING OF DATA FILES

This program was used in the initial processing of data files. It is written in BASIC and runs on an IBM personal computer. The data as originally captured by PC-TALK included extraneous characters that the data logger generated. There were also nonsense characters generated in transmission. This program calculates a checksum from the data and compares the result with the checksum computed by the data logger. If the sums did not match, the data were retransmitted from the data logger to the computer. The program also strips out the extraneous characters to create a file that can be imported into the data bases.

```
100 REM Program to perform checksum test and format data
150 REM Version 1.5    Alan Hawthorne & KPM 4/21/87
200 CLS: LOCATE 9,1: PRINT"CSI 21x checksum testing and formatting
program"
250 LOCATE 10,12: PRINT "Version 1.5   4/21/87
300 LOCATE 12,12: PRINT "1. List *.21x files"
400 LOCATE 14,12: PRINT "2. Checksum test"
500 LOCATE 16,12: PRINT "3. Format data to ???.dat file"
520 LOCATE 18,12: PRINT "4. Checksum test - Read filenames from CK21X.LST"

540 LOCATE 20,12: PRINT "5. Format data to ???.dat file - Input file as
#4"
550 LOCATE 22,12: PRINT "6. Exit to DOS"
600 A$=INKEY$: IF A$="" THEN 600
610 IF A$="1" THEN PRINT: FILES "*.21X": GOSUB 9000
620 IF A$="2" THEN GOSUB 1000: GOSUB 9000
630 IF A$="3" THEN GOSUB 5000: GOSUB 9000
640 IF A$="4" THEN GOSUB 800: GOSUB 9000
650 IF A$="5" THEN GOSUB 900: GOSUB 9000
660 IF A$<>"6" THEN 200
680 CLS: END
800 REM Do series of checksum tests reading filenames from CK21X.LST
820 OPEN "ck21x.lst" FOR INPUT AS #3
830 CLS: PRINT "Working on a series of files.......": PRINT
840 WHILE NOT EOF(3)
850 INPUT #3, F$
860 GOSUB 1020
870 WEND
875 CLOSE 3: RETURN
900 REM Do series of format conversions reading filenames from CK21X.LST
920 OPEN "ck21x.lst" FOR INPUT AS #3
930 CLS: PRINT "Working on a series of files.......": PRINT
940 WHILE NOT EOF(3)
950 INPUT #3, F$: G$ = F$: PRINT: PRINT "Filename:", F$
960 GOSUB 5060
970 WEND
975 CLOSE 3: RETURN
1000 PRINT: INPUT "Data File (assumes ???.21x extension)"; F$
1020 OPEN F$+".21x" FOR INPUT AS #1
1040 C=0
```

PROGRAM FOR TRANSMISSION ERROR TRAPPING AND FORMATTING OF DATA FILES (cont.)

```
1060 A=ASC(INPUT$(1,#1))
1070 Z$=INKEY$: IF Z$ <> "" THEN 1190
1080 C=C+A
1100 IF A <> ASC("C") THEN 1060
1120 INPUT #1, CKSUM
1140 K=INT(C/8192):C=C-K*8192
1150 PRINT F$,
1160 IF C = CKSUM THEN PRINT "Checksum OK" ELSE PRINT "Checksum Error:";
C;" not equal "; CKSUM
1190 CLOSE 1: RETURN
5000 REM Read *.21x file and produce *.dat file
5005 REM
5010 REM format: house #, Julian day, time, RH, T1, T2, T3, T4,
5015 REM         dp1, dp2, dp3, dp4, sw1, sw2, sw3, sm1, rn1, rn2, rn3
5020 REM
5040 PRINT: INPUT "Input File (assumes .21x extension)"; F$
5050 PRINT: INPUT "Output File (assumes .dat extension)"; G$
5060 OPEN F$+".21x" FOR INPUT AS #1: OPEN G$+".dat" FOR OUTPUT AS #2
5070 PRINT "HOUSE DAY  TIME   Radon (cpm)              Other"
5080 PRINT "----- ---  ----   --------------------    -----"
5090 LINE INPUT #1, Z$
5100 LINE INPUT #1, Z$: IF LEFT$(Z$,2)=" L" THEN 5990
5120 X1=VAL(MID$(Z$,14,5))
5140 X2=VAL(MID$(Z$,25,3))
5160 X3=VAL(MID$(Z$,33,6))
5180 X4=VAL(MID$(Z$,43,6))
5200 X5=VAL(MID$(Z$,53,6))
5220 X6=VAL(MID$(Z$,63,6))
5240 X7=VAL(MID$(Z$,73,6))
5260 LINE INPUT #1, Z$
5280 X8=VAL(MID$(Z$,3,6))
5300 X9=VAL(MID$(Z$,13,6))
5320 X10=VAL(MID$(Z$,23,6))
5340 X11=VAL(MID$(Z$,33,6))
5360 X12=VAL(MID$(Z$,43,6))
5380 X13=VAL(MID$(Z$,63,6))
5390 IF X1=0 THEN X20=VAL(MID$(Z$,53,6)): X21=VAL(MID$(Z$,73,6))
5400 LINE INPUT #1, Z$
5420 X14=VAL(MID$(Z$,3,6))
5440 X15=VAL(MID$(Z$,23,6))
5460 X16=VAL(MID$(Z$,33,6))
5480 X17=VAL(MID$(Z$,43,6))
5500 X18=VAL(MID$(Z$,53,6))
5550 X19=VAL(MID$(Z$,63,6))
5555 X22=VAL(MID$(Z$,73,6))
5570 IF X1 = 0 THEN 5620
5600 PRINT USING "#### ### ####    ###.## ###.## ###.## ###.##"; X1, X2,
X3, X17, X18, X19, X22
```

PROGRAM FOR TRANSMISSION ERROR TRAPPING AND FORMATTING OF DATA FILES (cont.)

```
5620 IF X1>0 THEN PRINT #2, X1; X2; X3; X4; X5; X6; X7; X8; X9; X10; X11;
X12; X13; X14; X15; X16; X17; X18; X19; X22 ELSE IF X1=0 THEN PRINT #2,
X1; X2; X3; X4; X5; X6; X7; X8; X9; X10; X11; X12; X20; X13; X21; X14
5700 GOTO 5100
5990 CLOSE 1: CLOSE 2: RETURN
9000 PRINT: PRINT "Press any key to continue...."
9100 B$=INKEY$: IF B$="" THEN 9100
9200 RETURN
^Z11; X12; X13; X14; X15; X16; X17; X18; X19; X22
5700 GOTO 5100
5990 CLOSE 1: CLOSE 2: RETURN
9000 PRINT: PRINT "Press any key to continue...."
9100 B$=INKEY$: IF B$="" THEN 9100
9200 RETURN
```

DATA BASE STRUCTURES USED FOR DATA STORAGE

The data were stored using the dBaseIII data management software. The structures of those files are given below.

Structure for database: D:a_pre.dbf (House data)
Number of data records: 5376
Date of last update : 03/28/88

Field	Field Name	Type	Width	Dec	
1	HSENO	Character	1		House ID
2	DAY	Character	5		Day in 'MM/DD' format
3	JDAY	Numeric	3		Julian Date
4	TIME	Numeric	4		Time in military format
5	RH	Numeric	7	2	Relative humidity
6	T1	Numeric	7	2	Temperature in basement
7	T2	Numeric	7	2	Temperature in living area
8	T3	Numeric	7	2	Temperature outdoors
9	T4	Numeric	7	2	Spare temperature channel
10	DP1	Numeric	7	2	Bsmt/out pressure
11	DP2	Numeric	7	2	Bsmt/subslab pressure
12	DP3	Numeric	7	2	Bsmt/up pressure
13	DP4	Numeric	7	2	Spare pressure channel
14	SW1	Numeric	7	3	Air Handler usage
15	SW2	Numeric	7	3	Spare voltage channel
16	SW3	Numeric	7	3	Spare voltage channel
17	SM1	Numeric	7	2	Soil moisture
18	RN1	Numeric	7	2	Radon in basement
19	RN2	Numeric	7	2	Radon in living area
20	RN3	Numeric	7	2	Radon in crawlspace
21	OTHER	Numeric	7	3	Spare channel
** Total **			133		

DATA BASE STRUCTURES USED FOR DATA STORAGE (cont.)

Structure for database: D:\w_pre.dbf (Weather Station data)
Number of data records: 5328
Date of last update : 06/01/88

Field	Field Name	Type	Width	Dec	
1	HSENO	Character	4		House ID
2	DAY	Character	5		Day in 'MM/DD' format
3	JDAY	Numeric	3		Julian Date
4	TIME	Numeric	4		Time in military format
5	RH_OUT	Numeric	8	2	Relative humidity
6	T_OUT	Numeric	8	3	Air temperature
7	T_SOIL	Numeric	8	3	Soil Temperature
8	BP	Numeric	8	2	Barometric pressure
9	RN_WS	Numeric	8	2	Radon in WS chamber
10	RN_SIDE	Numeric	8	2	Radon in Side chamber
11	RAIN	Numeric	8	3	Rainfall
12	WIND_SPD	Numeric	8	3	Wind speed
13	WS_RMS	Numeric	8	3	Wind speed (root mean square)
14	WIND_DIR	Numeric	8	3	Avg wind direction
15	WD_STD	Numeric	8	3	Std Dev of wind direction
16	R_FLUX_S	Numeric	8	1	Rn flux in Side chamber
17	R_FLUX_W	Numeric	8	1	Rn flux in WS chamber
** Total **			121		

PROGRAM FOR CHECKING COMPLETENESS OF DATA FILES

This program was used to test data files for temporal continuity. The program compares each record with its predecessor and calculates the difference in time. If the temporal increment is not 30 minutes, then the record is flagged. The program is written in the language for the dBaseIII data management system.

```
SET TALK OFF
use d:\nj\dbf\we_0531
go top
h=hseno
d=jday+int(time/100)/24+(time-100*int(time/100))/(24*60)
skip
do while .not. eof()
if .not. h=hseno
   delete
   list next 1 hseno,jday,time to print
endif
if .not. d+(1/48)=jday+int(time/100)/24+(time-100*int(time/100))/(24*60)
   delete
   list next 1 hseno,jday,time to print
endif
h=hseno
d=jday+int(time/100)/24+(time-100*int(time/100))/(24*60)
skip
enddo
set talk on
```

excur.prg and subs

This program will take data from H_0131.dbf and H_0531.dbf files and produce output files named H_pre.dbf or H_post.dbf. The new files will contain information that is in engineering units with no more than 7 characters per field. Unused fields in a record will be set to 6999 and fields with obviously bad data (i.e., excursions beyond common sense bounds) will be set to 9999. Date information will be formatted as "MM/DD". The program is written in the language for the dBaseIII data management system.

```
set talk off &&  EXCUR.PRG
clear
?"This program is expecting data from House E."
?"The input data set is a:E_0131.dbf and output is c:\E_pre.dbf."
ACCEPT "Hit Return to begin." to mbegin
t1_off=0.33
t2_off=-0.58
t3_off=-1.46
rh_off=-4.35
rn1_off=0.68
rn2_off=0.59
rn3_off=0
rn1_slp=1/.87
rn2_slp=1/.64
rn3_slp=1
rn1_pre=1/0.87
rn2_pre=1/0.64
rn3_pre=1
m1=1/889
m2=1/941
m3=1
int1=0.848
int2=0.619
int3=0
dp1_off=2499
dp2_off=2476
dp3_off=2509
dp1_slp=0.00995
dp2_slp=0.00999
dp3_slp=0.00994
hse="E"
sele 1
use e_0131
mday=day
do day
sele 2
use e_pre
day_end=999
tim_end=0
do lbl
```

SUBROUTINES TO EXCUR.PRG

DAY.PRG

This program is a subroutine to LBL.PRG. It accepts 3-digit Julian dates and outputs dates formatted as a 5 character string, MM/DD. It also updates rn_slp values to reflect ramp from JD86020 to JD86180.

```
public xday
mm="XX"
s="/"
DD="DD"
m=-9999
do case
   case mday>273 .and. mday<305
        mm="10"
        m=273
   case mday>304 .and. mday<335
        mm="11"
        m=304
   case mday>334 .and. mday<366
        mm="12"
        m=334
   case mday>000 .AND. mDAY<032
        mm="01"
        m=0
     CASE mDAY>031 .AND. mDAY<060
        mm="02"
        m=031
     case mday>059 .and. mday<091
        mm="03"
        m=059
     case mday>090 .and. mday<121
        mm="04"
        m=090
     case mday>120 .and. mday<152
        mm="05"
        m=120
     case mday>151 .and. mday<182
        mm="06"
        m=151
     case mday>181 .and. mday<213
        mm="07"
        m=181
endcase
xday=mm+s+dd
if m<0
   return
endif
```

DAY.PRG (cont.)

```
d=mday-m
dd=str(d,2)
xday=mm+s+dd
do case
   case mday<20 .or. mday>270
        rn1_slp=rn1_pre
        rn2_slp=rn2_pre
        rn3_slp=rn3_pre
   otherwise
        rn1_slp=1/(int1+m1*mday)
        rn2_slp=1/(int2+m2*mday)
        rn3_slp=1/(int3+m3*mday)
endcase
? hse,xday,mday,rn1_slp,rn2_slp,rn3_slp
return
```

SUBROUTINES TO EXCUR.PRG (cont.)

LBL.PRG

This program is a subroutine to EXCUR.PRG. This program does the actual conversion of raw data to a dbf file that can be output using form LBL.FRM to produce ASCII files on HD floppies for transmittal to LBL.

```
sele 1
do while .not. (day=day_end .and. time=tim_end)
   if time=0
      mday=day
      do day
   endif
   xsw1=1-sw1
   xsw2=sw2
   xsw3=sw3
   xsm1=sm1
   xtime=time
   xrh=rh+rh_off  && Units are % relative humidity.
   do case
   case (xrh>0 .and. xrh<=100)
      xrh=xrh
   case rh=-6999 .or. rh=6999
      xrh=6999
   otherwise
      xrh=9999
   endcase
   xt1=t1+t1_off  && Units are degrees Celsius.
   do case
   case (xt1>=-10 .and. xt1<=35)
      xt1=xt1
   case t1=-6999 .or. t1=6999
      xt1=6999
   otherwise
      xt1=9999
   endcase
```

LBL.PRG (cont.)

```
xt2=t2+t2_off  && Units are degrees Celsius.
do case
case (xt2>=-10 .and. xt2<=35)
   xt2=xt2
case t2=-6999 .or. t2=6999
   xt2=6999
otherwise
   xt2=9999
endcase
xt3=t3+t3_off  && Units are degrees Celsius.
do case
case (xt3>=-25 .and. xt3<=50)
   xt3=xt3
case t3=-6999 .or. t3=6999
   xt3=6999
otherwise
   xt3=9999
endcase
xt4=t4  && Units are degrees Celsius.
do case
case (xt4>=-10 .and. xt4<=35)
   xt4=xt4
case t4=-6999 .or. t4=6999
   xt4=6999
otherwise
   xt4=9999
endcase
xdp1=(dp1-dp1_off)*dp1_slp && units are pascals
do case
case (xdp1>=-25 .and. xdp1<=25)
   xdp1=xdp1
case dp1=-6999 .or. dp1=6999
   xdp1=6999
otherwise
   xdp1=9999
endcase
```

LBL.PRG (cont.)

```
   xdp2=(dp2-dp2_off)*dp2_slp && units are pascals
   do case
   case (xdp2>=-25 .and. xdp2<=25)
      xdp2=xdp2
   case dp2=-6999 .or. dp2=6999
      xdp2=6999
   otherwise
      xdp2=9999
   endcase
   xdp3=(dp3-dp3_off)*dp3_slp && units are pascals
   do case
   case (xdp3>=-25 .and. xdp3<=25)
      xdp3=xdp3
   case dp3=-6999 .or. dp3=6999
      xdp3=6999
   otherwise
      xdp3=9999
   endcase
if hse<>"F"
   dp4_slp=1
   dp4_off=2500
endif
   xdp4=(dp4-dp4_off)*dp4_slp && units are pascals
   do case
   case (xdp4>=-25 .and. xdp4<=25)
      xdp4=xdp4
   case dp4=-6999 .or. dp4=6999
      xdp4=6999
   otherwise
      xdp4=9999
   endcase
xrnl=(rnl-rnl_off)*rnl_slp*
     (1.27-0.025*((xrh/100)*(-2.3676+10**(0.832519+0.023388*xtl))))
                        && units are pCi/L
   do case
   case (xrnl>=-2 .and. xrnl<=500)
      xrnl=xrnl
   case rnl=-6999 .or. rnl=6999
      xrnl=6999
   otherwise
      xrnl=9999
   endcase
```

LBL.PRG (cont.)

```
    xrn2=(rn2-rn2_off)*rn2_slp && units are pCi/L
    do case
    case (xrn2>=-2 .and. xrn2<=500)
       xrn2=xrn2
    case rn2=-6999 .or. rn2=6999
       xrn2=6999
    otherwise
       xrn2=9999
    endcase
    xrn3=(rn3-rn3_off)*rn3_slp && units are pCi/L
    do case
    case (xrn3>=-2 .and. xrn3<=500)
       xrn3=xrn3
    case rn3=-6999 .or. rn3=6999
       xrn3=6999
    otherwise
       xrn3=9999
    endcase
    xother=other
    sele 2
    go bottom
    append blank
    replace hseno with hse
    replace DAY with xday
    replace jday with mday
    replace TIME with xtime
    replace   RH with xrh
    replace   T1 with xt1
    replace   T2 with xt2
    replace   T3 with xt3
    replace   T4 with xt4
    replace   DP1 with xdp1
    replace   DP2 with xdp2
    replace   DP3 with xdp3
    replace   DP4 with xdp4
    replace   SW1 with xsw1
    replace   sw2 with xsw2
    replace   sw3 with xsw3
    replace   SM1 with xsm1
    replace   RN1 with xrn1
    replace   RN2 with xrn2
    replace   RN3 with xrn3
    replace   other with xother
    sele 1
    skip
enddo
return
```

PROGRAMS FOR SUMMARY STATISTICS

This program was used to compute the weekly summary statistics that are reported in this appendix and in Chapter 7.

```
set talk off && avg_main.prg
sele 2
use nj_avg
sele 1
h="E"
use E_pre
go top
ds=286
do while ds<=356
do avg
ds=ds+7
enddo
ds=-2
do avg
ds=5
do while ds<=19
do avg
ds=ds+7
enddo
sele 1
h="E"
use E_post
go top
locate for jday=33
ds=33
do while ds<=180
do avg
ds=ds+7
enddo
sele 1
h="F"
use F_pre
go top
locate for jday=293
ds=293
do while ds<=356
do avg
ds=ds+7
enddo
ds=-2
do avg
ds=5
do while ds<=19
do avg
ds=ds+7
enddo
```

AVG_MAIN.PRG (cont.)

```
sele 1
h="F"
use F_post
go top
locate for jday=33
ds=33
do while ds<=180
do avg
ds=ds+7
enddo
sele 1
h="G"
use \sandy\G_pre
go top
locate for jday=293
ds=293
do while ds<=356
do avg
ds=ds+7
enddo
ds=-2
do avg
ds=5
do while ds<=19
do avg
ds=ds+7
enddo
```

SUBROUTINE TO AVG_MAIN.PRG

AVG.PRG

```
df=ds+7 && avg.prg
if df>365
   df=df-365
endif
dy=jday
do zero
do while .not. ((jday=df .and. time=0) .or. eof())
do accum
enddo
do calc
return
```

SUBROUTINES TO AVG.PRG

ZERO.PRG

```
public fn_rh,fx_rh,fx2_rh,fmin_rh,fmax_rh && zero.prg
public fn_t1,fx_t1,fx2_t1,fmin_t1,fmax_t1
public fn_t2,fx_t2,fx2_t2,fmin_t2,fmax_t2
public fn_t3,fx_t3,fx2_t3,fmin_t3,fmax_t3
public fn_dp1,fx_dp1,fx2_dp1,fmin_dp1,fmax_dp1
public fn_dp2,fx_dp2,fx2_dp2,fmin_dp2,fmax_dp2
public fn_dp3,fx_dp3,fx2_dp3,fmin_dp3,fmax_dp3
public fn_rn1,fx_rn1,fx2_rn1,fmin_rn1,fmax_rn1
public fn_rn2,fx_rn2,fx2_rn2,fmin_rn2,fmax_rn2
public fn_rn3,fx_rn3,fx2_rn3,fmin_rn3,fmax_rn3
public fn_sw1,fx_sw1,fx2_sw1,fmin_sw1,fmax_sw1
fn_rh=0
fx_rh=0
fx2_rh=0
fmin_rh=rh
fmax_rh=rh
if abs(rh)>1000
   fmin_rh=abs(rh)
   fmax_rh=-abs(rh)
endif
fn_t1=0
fx_t1=0
fx2_t1=0
fmin_t1=t1
fmax_t1=t1
if abs(t1)>1000
   fmin_t1=abs(t1)
   fmax_t1=-abs(t1)
endif
fn_t2=0
fx_t2=0
fx2_t2=0
fmin_t2=t2
fmax_t2=t2
if abs(t2)>1000
   fmin_t2=abs(t2)
   fmax_t2=-abs(t2)
endif
fn_t3=0
fx_t3=0
fx2_t3=0
fmin_t3=t3
fmax_t3=t3
if abs(t3)>1000
   fmin_t3=abs(t3)
   fmax_t3=-abs(t3)
endif
fn_dp1=0
fx_dp1=0
```

ZERO.PRG (cont.)

```
fx2_dp1=0
fmin_dp1=dp1
fmax_dp1=dp1
if abs(dp1)>1000
   fmin_dp1=abs(dp1)
   fmax_dp1=-abs(dp1)
endif
fn_dp2=0
fx_dp2=0
fx2_dp2=0
fmin_dp2=dp2
fmax_dp2=dp2
if abs(dp2)>1000
   fmin_dp2=abs(dp2)
   fmax_dp2=-abs(dp2)
endif
fn_dp3=0
fx_dp3=0
fx2_dp3=0
fmin_dp3=dp3
fmax_dp3=dp3
if abs(dp3)>1000
   fmin_dp3=abs(dp3)
   fmax_dp3=-abs(dp3)
endif
fn_sw1=0
fx_sw1=0
fx2_sw1=0
fmin_sw1=sw1
fmax_sw1=sw1
fn_rn1=0
fx_rn1=0
fx2_rn1=0
fmin_rn1=rn1
fmax_rn1=rn1
if abs(rn1)>1000
   fmin_rn1=abs(rn1)
   fmax_rn1=-abs(rn1)
endif
fn_rn2=0
fx_rn2=0
fx2_rn2=0
fmin_rn2=rn2
fmax_rn2=rn2
if abs(rn2)>1000
   fmin_rn2=abs(rn2)
   fmax_rn2=-abs(rn2)
endif
fn_rn3=0
fx_rn3=0
```

ZERO.PRG (cont.)

```
fx2_rn3=0
fmin_rn3=rn3
fmax_rn3=rn3
if abs(rn3)>1000
   fmin_rn3=abs(rn3)
   fmax_rn3=-abs(rn3)
endif
return
```

SUBROUTINES TO AVG.PRG

ACCUM.PRG

```
&& accum.prg
if rh<100.1 .and. rh>-0.01
   fn_rh=fn_rh+1
   fx_rh=fx_rh+rh
   fx2_rh=fx2_rh+rh^2
   if rh<fmin_rh
      fmin_rh=rh
   endif
   if rh>fmax_rh
      fmax_rh=rh
   endif
endif
if t1<45 .and. t1>-20
   fn_t1=fn_t1+1
   fx_t1=fx_t1+t1
   fx2_t1=fx2_t1+t1^2
   if t1<fmin_t1
      fmin_t1=t1
   endif
   if t1>fmax_t1
      fmax_t1=t1
   endif
endif
if t2<45 .and. t2>-20
   fn_t2=fn_t2+1
   fx_t2=fx_t2+t2
   fx2_t2=fx2_t2+t2^2
   if t2<fmin_t2
      fmin_t2=t2
   endif
   if t2>fmax_t2
      fmax_t2=t2
   endif
endif
if t3<45 .and. t3>-20
   fn_t3=fn_t3+1
   fx_t3=fx_t3+t3
   fx2_t3=fx2_t3+t3^2
   if t3<fmin_t3
      fmin_t3=t3
   endif
   if t3>fmax_t3
      fmax_t3=t3
   endif
endif
```

ACCUM.PRG (cont.)

```
if abs(dp1)<60
   fn_dp1=fn_dp1+1
   fx_dp1=fx_dp1+dp1
   fx2_dp1=fx2_dp1+dp1^2
   if dp1<fmin_dp1
      fmin_dp1=dp1
   endif
   if dp1>fmax_dp1
      fmax_dp1=dp1
   endif
endif
if abs(dp2)<60
   fn_dp2=fn_dp2+1
   fx_dp2=fx_dp2+dp2
   fx2_dp2=fx2_dp2+dp2^2
   if dp2<fmin_dp2
      fmin_dp2=dp2
   endif
   if dp2>fmax_dp2
      fmax_dp2=dp2
   endif
endif
if abs(dp3)<60
   fn_dp3=fn_dp3+1
   fx_dp3=fx_dp3+dp3
   fx2_dp3=fx2_dp3+dp3^2
   if dp3<fmin_dp3
      fmin_dp3=dp3
   endif
   if dp3>fmax_dp3
      fmax_dp3=dp3
   endif
endif
   fn_sw1=fn_sw1+1
   fx_sw1=fx_sw1+sw1
   fx2_sw1=fx2_sw1+sw1^2
   if sw1<fmin_sw1
      fmin_sw1=sw1
   endif
   if sw1>fmax_sw1
      fmax_sw1=sw1
   endif
```

ACCUM.PRG (cont.)

```
if rn1<500 .and. rn1>-0.01
   fn_rn1=fn_rn1+1
   fx_rn1=fx_rn1+rn1
   fx2_rn1=fx2_rn1+rn1^2
   if rn1<fmin_rn1
      fmin_rn1=rn1
   endif
   if rn1>fmax_rn1
      fmax_rn1=rn1
   endif
endif
if rn2<500 .and. rn2>-0.01
   fn_rn2=fn_rn2+1
   fx_rn2=fx_rn2+rn2
   fx2_rn2=fx2_rn2+rn2^2
   if rn2<fmin_rn2
      fmin_rn2=rn2
   endif
   if rn2>fmax_rn2
      fmax_rn2=rn2
   endif
endif
if rn3<500 .and. rn3>-0.01
   fn_rn3=fn_rn3+1
   fx_rn3=fx_rn3+rn3
   fx2_rn3=fx2_rn3+rn3^2
   if rn3<fmin_rn3
      fmin_rn3=rn3
   endif
   if rn3>fmax_rn3
      fmax_rn3=rn3
   endif
endif
if .not. eof()
   skip
endif
return
```

SUBROUTINES TO AVG.PRG

CALC.PRG

```
sele 2 && calc.prg
go bottom
append blank
replace house with h
replace day_end with df-1
replace n_rh with fn_rh
if 0<fn_rh
replace avg_rh with fx_rh/fn_rh
replace std_rh with sqrt((fx2_rh-n_rh*(fx_rh/fn_rh)^2)/(fn_rh-1))
endif
replace min_rh with fmin_rh
replace max_rh with fmax_rh
replace n_t1 with fn_t1
if 0<fn_t1
replace avg_t1 with fx_t1/fn_t1
replace std_t1 with sqrt((fx2_t1-n_t1*(fx_t1/fn_t1)^2)/(fn_t1-1))
endif
replace min_t1 with fmin_t1
replace max_t1 with fmax_t1
replace n_t2 with fn_t2
if 0<fn_t2
replace avg_t2 with fx_t2/fn_t2
replace std_t2 with sqrt((fx2_t2-n_t2*(fx_t2/fn_t2)^2)/(fn_t2-1))
endif
replace min_t2 with fmin_t2
replace max_t2 with fmax_t2
replace n_t3 with fn_t3
if 0<fn_t3
replace avg_t3 with fx_t3/fn_t3
replace std_t3 with sqrt((fx2_t3-n_t3*(fx_t3/fn_t3)^2)/(fn_t3-1))
endif
replace min_t3 with fmin_t3
replace max_t3 with fmax_t3
replace n_dp1 with fn_dp1
if 0<fn_dp1
replace avg_dp1 with fx_dp1/fn_dp1
replace std_dp1 with sqrt((fx2_dp1-n_dp1*(fx_dp1/fn_dp1)^2)/(fn_dp1-1))
endif
replace min_dp1 with fmin_dp1
replace max_dp1 with fmax_dp1
replace n_dp2 with fn_dp2
if 0<fn_dp2
replace avg_dp2 with fx_dp2/fn_dp2
replace std_dp2 with sqrt((fx2_dp2-n_dp2*(fx_dp2/fn_dp2)^2)/(fn_dp2-1))
endif
replace min_dp2 with fmin_dp2
replace max_dp2 with fmax_dp2
replace n_dp3 with fn_dp3
```

CALC.PRG (cont.)

```
if 0<fn_dp3
replace avg_dp3 with fx_dp3/fn_dp3
replace std_dp3 with sqrt((fx2_dp3-n_dp3*(fx_dp3/fn_dp3)^2)/(fn_dp3-1))
endif
replace min_dp3 with fmin_dp3
replace max_dp3 with fmax_dp3
replace n_swl with fn_swl
if 0<fn_swl
replace avg_swl with fx_swl/fn_swl
replace std_swl with sqrt((fx2_swl-n_swl*(fx_swl/fn_swl)^2)/(fn_swl-1))
endif
replace min_swl with fmin_swl
replace max_swl with fmax_swl
replace n_rnl with fn_rnl
if 0<fn_rnl
replace avg_rnl with fx_rnl/fn_rnl
replace std_rnl with sqrt((fx2_rnl-n_rnl*(fx_rnl/fn_rnl)^2)/(fn_rnl-1))
endif
replace min_rnl with fmin_rnl
replace max_rnl with fmax_rnl
replace n_rn2 with fn_rn2
if 0<fn_rn2
replace avg_rn2 with fx_rn2/fn_rn2
replace std_rn2 with sqrt((fx2_rn2-n_rn2*(fx_rn2/fn_rn2)^2)/(fn_rn2-1))
endif
replace min_rn2 with fmin_rn2
replace max_rn2 with fmax_rn2
replace n_rn3 with fn_rn3
if 0<fn_rn3
replace avg_rn3 with fx_rn3/fn_rn3
replace std_rn3 with sqrt((fx2_rn3-n_rn3*(fx_rn3/fn_rn3)^2)/(fn_rn3-1))
endif
replace min_rn3 with fmin_rn3
replace max_rn3 with fmax_rn3
sele 1
return
```

APPENDIX B

- Weekly Summary Statistics for Seven Houses and One Weather Station

Table 9.1. Weekly summary of temperatures (°C) for house #1

End date	Basement				Upstairs				Outdoors			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	17.1	15.7	18.0	0.5	19.7	16.4	22.0	1.3	10.4	-0.9	22.8	5.8
306	16.9	15.1	17.7	0.6	19.7	17.3	21.2	0.9	9.5	-2.4	20.7	5.3
313	16.4	14.4	17.7	0.6	20.0	17.9	21.8	0.9	7.5	-3.1	20.1	5.4
320	15.4	13.5	16.9	0.8	19.2	16.2	20.7	0.9	1.0	-9.2	11.1	4.8
327	15.2	12.7	16.5	0.7	19.6	17.9	22.4	0.8	2.6	-7.1	12.6	4.6
334	15.2	14.1	16.3	0.5	19.4	17.1	21.3	1.0	4.1	-5.0	17.2	4.6
341	14.6	12.9	16.2	0.7	19.6	17.1	22.7	1.0	1.8	-8.3	11.7	5.0
348	14.2	10.1	15.7	1.2	19.6	17.1	22.1	0.9	0.2	-13.9	11.7	5.2
355	13.8	11.4	15.1	0.7	19.0	17.5	20.7	0.8	1.3	-8.8	6.5	3.7
362	13.7	11.4	15.3	0.8	19.6	17.2	23.4	1.2	1.2	-8.3	9.7	4.5
4	13.5	11.8	14.9	0.6	19.1	17.1	21.1	1.0	-0.7	-7.0	5.5	2.9
11	13.0	11.6	14.6	0.7	18.7	16.5	21.3	1.1	-0.6	-9.7	5.5	3.6
18	13.4	11.5	15.1	0.8	19.2	17.1	21.0	0.9	1.3	-7.7	12.0	4.5
25	12.0	9.0	14.0	1.2	19.6	17.3	23.4	1.4	-5.2	-17.6	2.0	5.1
32	10.6	7.1	12.7	1.3	19.2	15.8	23.1	1.4	-5.1	-19.8	3.7	5.2
39	12.1	10.2	13.6	0.7	19.0	17.4	23.6	1.1	0.2	-8.0	9.9	4.7
46	10.9	7.2	13.5	1.3	19.5	16.8	23.6	1.4	-4.5	-17.7	7.6	4.8
53	10.6	6.9	12.8	1.0	18.3	16.6	20.8	1.2	-2.8	-15.6	10.2	5.4
60	12.0	10.6	13.7	0.8	19.1	16.8	22.7	1.1	1.1	-6.1	9.4	4.0
67	12.5	11.0	14.7	0.9	19.2	16.2	22.6	1.2	4.1	-8.2	24.6	7.3
74	12.7	10.7	15.1	1.0	19.0	16.3	21.6	1.1	1.0	-11.3	16.1	5.9
81	13.2	11.7	14.7	0.7	19.4	16.8	21.1	1.0	4.0	-6.1	18.0	5.5
88	14.5	12.4	15.8	0.7	20.3	17.5	22.7	1.1	11.3	-2.2	25.6	6.9
95	14.6	13.5	16.4	0.6	19.5	17.4	22.4	0.9	8.1	-3.3	17.7	5.2
102	15.0	13.7	16.7	0.6	19.8	17.4	22.2	1.1	10.1	0.7	26.8	6.1
109	15.5	14.3	17.4	0.6	20.2	18.0	24.1	1.4	11.4	0.3	28.1	5.2
116	16.5	15.2	18.2	0.7	21.0	18.5	24.8	1.6	16.7	9.0	27.9	5.1
123	15.5	14.4	17.1	0.5	20.0	18.0	21.6	0.9				
130	16.1	14.6	18.3	0.7	20.9	17.9	26.9	1.9				
137	17.3	-0.4	18.7	1.5	22.6	-0.3	26.2	2.5				

Table 9.2. Weekly summary statistics of differential pressures (Pa) for house #1

End date	Basement-out				Basement-subslab				Basement-upstairs			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	1.48	0.39	2.79	0.48	0.03	-0.24	0.43	0.18	-0.12	-0.32	0.79	0.16
306	1.65	0.25	3.08	0.56	-0.07	-0.18	0.14	0.08	-0.10	-0.39	0.72	0.18
313	1.54	0.56	3.07	0.57	-0.03	-0.19	0.13	0.08	-0.01	-0.50	0.83	0.17
320	2.03	0.57	4.08	0.75	0.13	-0.05	0.35	0.09	0.23	-0.26	1.00	0.21
327	2.05	0.09	4.37	0.75	0.11	-0.03	0.30	0.08	0.19	-0.16	1.12	0.22
334	2.08	-0.29	3.19	0.53	0.09	-0.08	0.27	0.08	0.26	-0.19	1.55	0.26
341	1.96	0.46	12.38	0.78	0.12	-1.73	0.35	0.16	0.33	-1.70	1.49	0.32
348	2.26	0.91	4.72	0.63	0.17	-0.03	0.47	0.09	0.36	-0.05	1.61	0.26
355	2.23	0.63	5.55	0.83	0.17	0.07	0.33	0.06	0.40	-0.04	1.71	0.29
362	2.12	0.45	3.47	0.55	0.18	0.02	0.34	0.08	0.36	-0.15	1.64	0.30
4	2.30	-1.14	4.71	0.71	-2.18	-11.33	0.32	4.59	0.49	-0.95	1.95	0.34
11	2.68	0.49	4.76	0.68	-13.27	-22.58	0.03	3.74	0.75	0.11	2.39	0.39
18	2.68	0.65	5.13	0.80	-14.17	-14.52	-13.29	0.17	0.68	-0.26	2.22	0.41
25	3.43	1.57	5.17	0.72	-14.00	-14.26	-13.61	0.13	0.89	0.25	2.24	0.41
32	3.25	0.86	5.52	0.95	-14.48	-15.19	-7.76	0.74	0.82	0.14	2.30	0.47
39	2.57	0.78	5.31	0.74	-15.19	-15.46	-14.86	0.12	0.58	0.08	1.99	0.38
46	3.50	1.45	7.84	1.27	-15.03	-15.36	-12.54	0.26	0.65	0.16	2.25	0.41
53	2.60	0.65	5.33	0.83	-7.85	-23.80	0.20	7.59	0.68	-0.10	2.08	0.39
60	1.84	0.68	5.57	0.74	0.52	0.06	24.26	2.90	0.36	-0.41	1.81	0.33
67	1.96	-0.30	3.77	0.76	0.88	-4.71	1.54	0.53	0.29	-0.15	1.78	0.35
74	2.52	0.97	5.72	1.03	-21.60	-24.72	-18.49	4.41	0.45	-0.21	1.81	0.35
81	2.28	0.92	3.84	0.55	-21.50	-21.50	-21.50	****	0.43	0.00	1.61	0.30
88	1.51	0.09	3.37	0.58	0.17	-5.47	0.79	0.52	0.16	-0.76	1.70	0.28
95	2.24	-0.58	4.47	0.94	-10.97	-22.75	0.68	8.62	0.15	-0.16	1.36	0.25
102	1.60	-0.89	3.06	0.66	-18.11	-19.48	-16.70	0.55	0.14	-0.65	1.57	0.28
109	1.94	0.42	3.84	0.46	-18.30	-19.63	-16.85	0.59	0.08	-2.06	1.19	0.26
116	2.06	0.02	4.45	0.64	-20.31	-22.78	-17.07	1.33	-0.05	-0.30	1.24	0.20
123	1.39	0.26	3.13	0.51	-13.19	-23.04	-6.79	4.42	0.13	-0.17	1.31	0.23
130	1.37	0.03	2.82	0.69	-14.04	-24.99	-9.97	5.51	0.02	-0.24	1.20	0.24
137	1.26	0.19	2.21	0.48	-24.45	-24.98	-23.47	0.42	-0.13	-0.28	0.92	0.13

Table 9.3. Weekly summary statistics of radon concentrations (pCi/L) for house #1

End date	Basement				Upstairs			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	73.2	34.2	120.7	13.8	40.3	25.7	51.8	6.5
306	68.3	29.9	97.7	15.2	36.6	18.3	52.6	6.8
313	46.3	16.3	99.0	20.6	29.3	10.8	49.5	9.2
320	48.2	33.1	86.3	9.4	31.0	19.1	47.7	5.9
327	44.2	15.7	83.6	11.6	28.5	11.1	40.6	6.3
334	44.8	31.9	65.6	6.4	27.7	1.9	37.7	5.9
341	40.7	10.0	67.5	8.7	26.9	6.6	37.0	4.2
348	39.6	26.7	56.5	6.1	27.3	16.2	39.4	4.8
355	40.7	28.6	56.1	4.6	27.1	19.0	38.2	3.3
362	44.1	33.8	71.3	5.7	29.0	22.9	38.2	2.7
4	33.6	0.7	67.3	15.5	26.3	2.4	50.3	12.7
11	9.6	4.8	19.8	3.2	5.6	1.7	14.2	2.7
18	8.4	3.8	17.4	2.0	4.0	1.1	8.0	1.3
25	10.7	3.6	72.3	6.2	6.5	1.7	370.4	20.3
32	10.0	3.5	17.5	2.7	4.6	1.3	9.3	1.8
39	7.7	3.1	11.5	1.9	3.4	0.7	6.4	1.4
46	9.2	5.5	14.2	1.9	3.6	0.9	7.1	1.3
53	3.8	0.0	12.8	3.6	1.8	0.0	6.2	1.7
60	2.9	0.5	8.5	1.4	1.5	0.1	3.6	0.8
67	8.9	0.0	28.0	9.4	6.3	0.1	20.4	6.7
74	0.5	0.0	1.7	0.4	0.3	0.0	1.3	0.3
81	0.4	0.0	2.1	0.4	0.3	0.0	1.2	0.3
88	17.1	0.0	45.7	17.0	10.8	0.0	35.2	11.7
95	5.8	0.0	38.7	8.8	7.3	0.7	24.0	5.7
102	2.3	0.0	459.2	26.6				
109	0.4	0.0	2.0	0.4				
116	0.5	0.0	2.0	0.4				
123	0.9	0.0	2.1	0.5				
130	1.8	0.0	11.2	2.4				
137	2.9	0.0	9.8	2.7				

Table 9.4. Weekly summary statistics of relative humidity (%) and central air handler usage (%) for house #1

End date	Relative humidity				Air handler, fraction on			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	57.7	54.5	60.9	1.6	0.060	0.000	0.867	0.118
306	58.7	52.0	62.3	3.0	0.060	0.000	0.837	0.128
313	56.6	50.4	65.1	4.2	0.106	0.000	0.837	0.138
320	49.5	42.1	61.7	5.2	0.173	0.000	0.860	0.158
327	47.8	43.6	51.1	2.2	0.155	0.000	0.873	0.155
334	50.7	45.4	55.9	2.3	0.124	0.000	0.863	0.132
341	45.8	39.8	54.3	3.9	0.168	0.000	1.000	0.163
348	45.3	40.0	51.7	2.9	0.163	0.000	0.927	0.155
355	44.9	40.6	49.5	2.3	0.176	0.000	1.000	0.174
362	44.8	41.1	50.8	2.8	0.155	0.000	0.950	0.174
4	43.0	38.8	45.2	1.6	0.207	0.000	0.910	0.155
11	40.3	38.3	43.2	1.2	0.230	0.000	1.000	0.194
18	40.5	36.5	46.4	2.4	0.213	0.000	1.000	0.207
25	38.2	30.3	41.1	3.4	0.248	0.000	0.917	0.198
32	33.9	27.5	39.2	3.3	0.246	0.000	1.000	0.248
39	37.6	34.7	40.0	1.5	0.208	0.000	0.993	0.204
46	34.0	26.4	38.9	3.1	0.199	0.000	1.000	0.228
53	29.2	26.0	32.3	1.5	0.219	0.000	1.000	0.210
60	35.0	30.7	47.4	3.8	0.199	0.000	1.000	0.191
67	41.1	37.5	47.3	2.4	0.144	0.000	1.000	0.208
74	34.5	26.9	45.1	4.7	0.191	0.000	1.000	0.204
81	32.3	28.7	36.4	2.1	0.163	0.000	1.000	0.174
88	40.6	36.0	48.2	3.4	0.059	0.000	0.917	0.136
95	49.3	41.8	67.1	5.9	0.085	0.000	0.817	0.138
102	49.3	45.5	53.6	1.9	0.081	0.000	0.880	0.143
109	52.7	45.4	63.8	5.1	0.060	0.000	0.707	0.111
116	59.2	42.5	65.7	5.2	0.036	0.000	0.613	0.078
123	47.2	38.9	53.0	3.1	0.070	0.000	0.823	0.122
130	52.2	48.5	58.0	1.5	0.040	0.000	0.670	0.106
137	55.5	49.2	60.4	3.3	0.012	0.000	1.000	0.090

Table 9.5. Weekly summary statistics of temperature (°C) for house #2

End date	Basement				Upstairs				Outdoors			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	18.4	16.7	19.5	0.6	20.7	17.8	23.2	1.0	9.2	-2.5	21.5	5.8
306	18.4	16.0	19.7	0.7	21.0	18.1	23.4	1.0	8.3	-3.5	18.6	5.4
313	17.8	16.1	19.6	0.7	20.7	18.0	22.6	0.9	6.7	-4.2	20.1	5.5
320	16.4	13.5	18.4	1.0	19.9	15.7	23.9	1.5	-0.3	-11.1	9.4	4.8
327	16.0	13.7	18.6	1.0	19.6	16.1	23.4	1.6	1.8	-7.6	11.9	4.8
334	16.5	14.4	18.8	0.8	20.5	16.8	24.1	1.3	3.2	-6.6	16.4	4.8
341	16.2	13.3	17.9	1.0	20.5	16.0	23.1	1.4	0.7	-10.0	10.5	5.0
348	15.9	12.1	17.2	1.0	20.4	14.9	24.0	1.4	-0.8	-14.6	10.1	5.1
355	16.0	12.7	17.0	0.6	21.1	15.9	23.2	0.8	0.4	-8.2	5.8	3.4
362	15.7	13.5	16.9	0.6	20.6	17.0	23.2	1.0	0.5	-8.9	8.0	4.3
4	15.3	13.1	16.2	0.7	20.4	16.7	23.9	1.3	-1.8	-8.2	4.2	2.9
11	15.1	13.0	16.4	0.9	19.9	17.3	23.6	1.3	-1.6	-11.2	4.4	3.5
18	15.6	13.7	17.5	0.8	19.9	18.6	22.3	0.7	0.4	-9.2	10.8	4.8
25	14.8	11.3	16.7	1.2	20.2	15.3	23.5	1.7	-6.3	-16.2	-0.2	4.5
32	13.2	10.1	15.3	1.2	19.0	14.1	24.0	2.1	-5.9	-19.9	1.9	4.6
39	14.6	12.8	15.3	0.7	19.3	16.0	20.5	1.3	0.1	-4.5	5.9	3.3
46	13.1	9.7	15.5	1.3	18.1	14.4	23.1	1.6	-6.6	-18.0	3.1	4.9
53	13.1	10.6	14.7	0.9	17.8	14.9	19.8	1.3	-2.5	-12.5	7.1	3.9
60	13.8	3.3	15.8	1.1	18.0	8.2	19.9	1.3	0.0	-8.3	7.8	4.0
67	14.7	11.9	16.7	1.0	19.2	15.5	22.7	1.4	3.4	-9.6	21.4	7.4
74	14.6	12.0	16.8	1.1	18.5	15.5	20.2	1.2	-0.5	-11.9	17.8	5.9
81	14.6	12.4	16.2	0.8	18.4	15.7	20.0	1.1	2.8	-7.0	11.8	4.5
88	15.9	14.1	17.6	0.8	19.0	16.5	22.0	1.1	10.0	-3.8	19.8	6.3
95	16.0	13.4	18.2	1.0	19.2	16.2	21.1	0.9	7.0	-4.9	16.9	5.2
102	15.8	10.5	19.4	1.3	19.5	17.2	22.4	1.0	9.1	0.2	22.9	5.9
109	16.7	14.9	19.1	0.8	19.7	14.0	22.3	1.5	9.9	-1.9	22.8	4.7
116	18.0	15.2	20.9	1.0	20.1	17.3	23.4	1.2	11.6	-1.9	23.8	5.6
123	16.8	15.4	17.9	0.5	19.8	17.8	21.4	0.7	8.7	-2.2	18.0	4.6
130	17.4	15.8	21.8	1.0	20.5	17.9	27.2	1.6	12.3	0.5	29.1	7.3
137	18.5	15.8	22.5	1.3	20.6	16.9	26.4	1.8	15.6	-0.5	29.1	6.8
144	19.0	15.0	22.7	1.6	21.1	16.9	26.2	2.1	15.6	6.4	30.6	6.4
151	19.6	18.1	23.1	1.1	21.7	17.6	27.5	1.9	19.5	9.3	35.0	7.6
158	20.2	19.0	21.7	0.6	22.0	19.7	24.2	1.0	18.8	10.2	33.1	5.2
165	20.3	18.1	22.1	0.8	21.6	12.4	25.4	2.3	20.3	4.8	31.2	5.9
172	20.6	19.3	22.1	0.6	22.5	20.8	26.4	1.0	23.5	10.0	34.8	6.0
179	21.1	19.9	22.9	0.6	22.4	19.1	26.9	1.2	20.3	12.0	31.4	4.7
186	21.2	20.0	22.7	0.6	22.8	17.4	28.3	1.6	25.0	9.9	43.3	5.6

Table 9.6. Weekly summary statistics of differential pressures (Pa) for house #2

End date	Basement-out				Basemenmt-subslab				Basement-upstairs			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	2.09	0.42	5.35	0.87	0.03	-0.05	0.20	0.04	0.44	-0.04	2.30	0.35
306	2.54	0.61	8.00	1.41	0.02	-0.08	0.20	0.05	0.41	-0.53	2.76	0.50
313	2.60	0.00	6.03	1.16	0.08	-0.06	0.25	0.05	0.58	-0.06	2.49	0.51
320	3.97	1.77	13.01	1.71	0.19	0.01	0.43	0.09	0.84	-0.05	3.19	0.74
327	4.29	0.04	12.45	2.30	0.19	0.04	0.34	0.05	0.85	0.01	3.58	0.80
334	3.55	-1.25	10.43	1.45	0.47	0.09	0.82	0.24	0.76	-0.03	3.50	0.67
341	4.49	1.10	12.13	1.94	0.33	-0.10	0.87	0.36	1.05	-0.02	3.44	0.71
348	4.63	1.31	13.55	2.01	0.02	-0.09	0.23	0.06	1.07	-0.06	3.24	0.69
355	4.22	2.20	11.21	1.53	0.00	-0.13	0.18	0.05	1.08	0.04	3.07	0.41
362	4.11	1.62	9.39	1.15	-0.01	-0.16	0.17	0.05	1.00	0.04	3.21	0.61
4	5.21	2.48	10.77	1.87	0.03	-0.08	0.22	0.05	1.10	0.02	2.94	0.62
11	4.72	2.67	8.46	1.30	0.05	-0.04	0.23	0.06	1.12	0.00	3.06	0.65
18	4.46	2.70	7.62	0.85	0.01	-0.11	0.15	0.06	1.04	0.02	2.49	0.47
25	5.86	2.48	15.97	2.49	0.07	-0.13	0.37	0.11	1.27	-0.19	3.45	0.80
32	6.45	2.68	10.72	1.78	0.11	-0.05	0.33	0.09	1.06	-0.38	3.03	0.85
39	4.60	0.27	13.17	2.68	2.73	1.21	5.55	1.53	0.19	-0.57	1.78	0.61
46	6.12	2.41	12.82	2.36	2.37	1.25	4.40	0.75	0.34	-0.68	2.33	0.69
53	4.38	1.16	11.43	1.61	2.12	1.05	3.50	0.42	0.21	-0.57	2.30	0.67
60	4.15	0.46	10.50	1.93	1.86	0.51	3.05	0.48	0.07	-25.00	2.52	1.54
67	3.54	-1.12	10.38	1.86	1.40	-0.21	3.11	0.71	0.15	-0.49	2.49	0.62
74	3.97	0.57	11.41	2.19	2.11	0.60	4.91	0.78	0.11	-0.56	1.83	0.52
81	4.48	1.38	10.56	2.07	1.82	0.93	3.27	0.47	0.10	-0.51	2.28	0.58
88	1.38	-4.96	5.29	1.60	0.87	-0.79	2.60	0.55	-0.11	-0.63	2.16	0.40
95	2.57	-5.01	12.11	2.97	1.41	-24.39	3.47	2.41	-0.05	-1.12	2.07	0.57
102	2.41	-1.99	6.87	1.46	1.27	-3.35	2.71	0.82	-0.22	-8.16	4.06	1.42
109	1.87	-0.82	5.81	0.92	1.26	-0.20	2.66	0.49	-0.04	-0.68	2.11	0.40
116	1.53	-5.58	5.64	1.49	1.17	-2.48	2.98	0.65	-0.35	-4.49	2.13	0.86
123	2.61	-1.42	9.64	1.80	1.30	0.61	2.77	0.42	-0.04	-0.79	2.25	0.45
130	1.73	-4.08	4.95	1.52	0.73	-2.83	2.58	0.95	0.11	-0.33	2.64	0.55
137	1.24	-1.41	5.90	1.06	0.63	-5.39	2.29	0.84	-0.28	-8.55	7.60	1.19
144	0.83	-3.07	3.70	1.28	0.52	-2.96	2.54	0.80	-0.26	-4.33	3.73	1.00
151	1.77	-0.01	5.14	1.00	0.80	-0.41	2.04	0.50	0.64	-1.13	4.39	1.57
158	1.37	-1.73	5.84	0.93	0.65	-0.24	2.69	0.43	0.20	-1.39	4.01	1.05
165	1.71	-1.15	9.00	1.55	0.45	-0.72	1.60	0.39	0.39	-0.33	4.77	1.07
172	1.62	-0.47	6.08	1.18	0.63	-0.74	1.89	0.46	1.14	-0.35	5.44	1.58
179	1.21	-0.77	5.15	0.88	0.54	-0.41	2.16	0.42	0.34	-0.44	3.91	0.98
186	1.44	-2.91	6.31	1.65	0.48	-1.20	1.86	0.53	1.04	-0.32	4.93	1.53

Table 9.7. Weekly summary statistics of radon concentrations (pCi/L) for house #2

End date	Basement				Upstairs			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	28.0	6.4	42.0	6.8	13.5	0.5	26.9	5.5
306	30.2	9.4	48.5	5.8	15.3	3.4	23.6	3.7
313	27.2	9.5	37.6	6.2	16.2	0.6	27.0	6.0
320	25.9	3.2	37.9	4.4	16.3	3.0	27.6	3.4
327	22.4	13.8	37.6	4.7	12.6	4.3	18.8	3.3
334	23.5	11.3	32.1	4.1	14.6	5.0	21.6	3.1
341	20.3	3.1	37.3	6.3	11.2	0.8	20.2	4.5
348	23.2	14.7	35.7	3.8	13.9	7.7	21.7	2.8
355	21.5	13.0	33.0	3.5	12.8	6.4	20.5	2.4
362	21.5	8.3	32.7	4.9	13.6	3.7	19.8	3.9
4	24.2	16.1	33.4	3.5	16.3	10.2	23.7	2.7
11	25.9	19.8	40.5	3.9	16.3	10.6	21.0	2.0
18	26.0	21.3	32.4	2.1	15.3	8.8	22.0	3.2
25	25.1	13.5	143.9	10.0	17.3	5.5	184.0	15.8
32	25.7	19.8	34.5	3.5	16.8	10.0	25.9	2.9
39	26.1	21.7	32.5	2.9	12.5	5.8	19.1	4.4
46	24.9	17.2	35.4	3.1	16.6	10.8	24.2	2.5
53	27.4	21.7	43.5	2.7	19.7	11.8	34.1	2.7
60	26.1	13.5	37.8	4.0	19.5	7.0	30.1	4.5
67	20.5	2.2	29.8	5.6	15.8	0.0	29.6	6.7
74	19.7	7.7	35.4	4.9	17.6	4.4	27.3	4.6
81	21.1	11.4	34.1	3.2	21.5	11.6	31.5	3.1
88	18.9	0.8	32.1	8.0	14.1	0.0	30.7	8.9
95	13.8	0.0	25.9	6.5	9.8	0.0	26.5	7.1
102	13.9	0.0	25.7	6.6	11.7	0.0	26.6	7.5
109	20.7	7.2	31.1	4.8	14.8	0.2	28.5	8.1
116	14.9	0.0	36.0	8.8	11.7	-0.6	28.2	6.7
123	17.3	2.2	27.6	5.2	14.4	1.1	26.9	5.9
130	17.9	0.0	30.5	9.0	17.4	0.0	32.0	10.7
137	12.8	0.1	31.3	9.0	7.1	0.0	30.8	7.2
144	26.4	0.0	107.6	28.6	6.9	-0.1	31.1	9.5
151	52.3	1.5	128.6	36.3	12.1	0.0	24.3	6.9
158	37.2	1.9	90.9	21.1	8.5	0.0	24.5	6.7
165	9.8	0.1	38.8	7.6	5.5	0.0	19.8	6.8
172	9.8	1.9	22.1	3.8	10.0	0.0	29.0	6.9
179	8.5	1.0	16.4	3.3	5.2	-0.2	17.1	4.9
186	8.5	0.0	19.7	4.3	11.2	0.0	20.6	5.8

Table 9.8. Weekly summary statistics of relative humidity (%) and central air handler usage (%) for house #2

End date	Relative humidity				Air handler, fraction on			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	52.1	48.4	56.4	2.1	0.053	0.000	0.687	0.112
306	53.8	46.7	57.5	2.9	0.081	0.000	0.913	0.157
313	52.4	47.2	63.5	4.0	0.132	0.000	0.780	0.164
320	46.5	39.6	60.2	5.6	0.231	0.000	1.000	0.239
327	44.6	41.4	47.5	1.5	0.215	0.000	1.000	0.246
334	48.4	43.5	54.5	2.6	0.195	0.000	1.000	0.219
341	44.4	41.4	51.6	3.0	0.290	0.000	1.000	0.225
348	43.6	38.9	47.7	2.0	0.309	0.000	1.000	0.233
355	43.0	39.8	46.0	1.4	0.307	0.000	1.000	0.140
362	43.3	40.8	47.7	2.1	0.278	0.000	0.937	0.201
4	42.7	41.4	44.1	0.6	0.324	0.000	1.000	0.216
11	41.1	40.1	41.9	0.5	0.556	0.000	1.000	0.366
18	40.0	38.8	41.7	0.8	0.773	0.000	1.000	0.332
25	39.9	34.3	42.4	2.4	0.417	0.000	1.000	0.278
32	35.8	32.4	37.3	1.3	0.797	0.000	1.000	0.326
39	39.6	37.5	40.4	0.7	0.326	0.000	1.000	0.273
46	36.4	31.4	39.2	1.9	0.323	0.000	1.000	0.278
53	35.3	33.6	37.7	0.9	0.245	0.000	1.000	0.260
60	37.9	35.4	43.6	1.8	0.210	0.000	1.000	0.263
67	40.8	38.3	44.6	1.6	0.179	0.000	1.000	0.253
74	38.2	33.7	44.6	2.8	0.237	0.000	1.000	0.264
81	37.3	34.8	39.9	1.3	0.179	0.000	1.000	0.246
88	42.6	39.4	49.3	2.6	0.042	0.000	1.000	0.146
95	53.6	45.5	71.0	7.2	0.132	0.000	1.000	0.217
102	58.9	41.3	65.5	5.9	0.108	0.000	1.000	0.209
109	59.3	53.4	66.5	3.0	0.081	0.000	0.893	0.144
116	63.9	55.1	70.0	3.4	0.051	0.000	0.803	0.121
123	53.6	45.9	57.4	2.3	0.078	0.000	0.877	0.159
130	56.1	48.9	59.1	1.7	0.054	0.000	1.000	0.148
137	59.2	52.9	73.1	3.5	0.000	0.000	0.000	0.000
144	65.8	59.6	74.0	3.9	0.049	0.000	1.000	0.167
151	67.2	63.5	74.4	2.3	0.217	0.000	1.000	0.373
158	67.9	63.5	72.3	2.3	0.114	0.000	1.000	0.265
165	67.2	60.2	73.9	3.6	0.117	0.000	1.000	0.263
172	64.0	60.0	70.9	2.1	0.353	0.000	1.000	0.405
179	69.0	63.6	73.1	1.8	0.139	0.000	1.000	0.263
186	67.1	63.1	71.9	1.9	0.279	0.000	1.000	0.359

Table 9.9. Weekly summary statistics of temperature (°C) for house #3

End date	Basement				Upstairs				Outdoors			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	18.7	17.8	19.2	0.3	20.8	19.9	21.8	0.3	12.4	1.9	22.7	4.9
306	18.5	17.3	19.1	0.4	20.8	20.0	21.9	0.3	10.6	-1.4	21.4	4.7
313	18.4	17.8	19.2	0.2	21.2	20.1	22.4	0.4	8.2	-1.4	19.8	5.1
320	17.9	16.8	18.9	0.6	21.1	19.9	22.0	0.4	1.9	-7.8	10.9	4.4
327	17.5	15.8	18.1	0.4	20.7	20.0	21.7	0.4	3.4	-6.5	12.1	4.5
334	17.5	15.9	18.9	0.5	20.6	18.8	22.2	0.6	5.3	-2.3	17.5	3.8
341	17.0	15.8	17.8	0.4	20.1	19.4	20.8	0.3	2.6	-6.1	11.8	4.4
348	16.7	15.5	17.7	0.6	20.0	18.9	20.7	0.4	0.7	-12.0	11.5	5.0
355	16.2	14.1	17.2	0.7	19.8	18.9	20.8	0.4	2.2	-6.1	7.0	2.8
362	15.6	12.2	16.9	1.1	20.2	17.3	21.5	0.7	2.1	-5.7	9.8	3.6
4	15.8	13.3	16.5	0.5	20.3	19.4	21.8	0.5	-0.2	-5.5	5.5	2.4
11	16.1	15.4	16.7	0.3	20.7	20.1	21.4	0.3	0.2	-6.8	4.6	2.7
18	16.6	15.9	18.0	0.4	20.8	20.1	21.6	0.4	2.0	-8.1	11.9	4.6
25	15.7	14.4	16.6	0.7	20.5	19.2	21.9	0.5	-4.9	-14.9	1.4	4.6
32	15.5	13.6	16.5	0.5	21.2	18.7	22.4	0.6	-4.6	-16.1	5.2	4.8
39	16.5	14.5	18.2	0.5	21.3	19.4	22.5	0.5	1.7	-6.4	12.3	4.1
46	16.2	14.3	17.3	0.7	21.3	20.5	22.3	0.4	-4.0	-17.4	5.3	4.7
53	16.0	14.3	16.9	0.5	21.4	20.4	22.3	0.5	-1.8	-15.2	11.7	5.4
60	16.7	15.6	17.6	0.5	21.6	21.0	22.6	0.3	1.4	-5.5	8.5	3.6
67	17.5	16.8	19.7	0.5	21.9	20.5	23.8	0.5	5.7	-5.7	25.7	7.6
74	17.4	16.4	18.2	0.4	22.1	20.7	23.3	0.5	1.5	-11.0	17.1	6.1
81	16.0	14.9	17.9	0.7	22.5	21.5	23.5	0.4	4.5	-3.8	14.9	4.7
88	17.1	14.9	18.5	0.9	22.0	20.5	24.1	0.6	12.5	1.4	23.6	5.9
95	18.4	16.8	19.4	0.5	22.3	20.9	23.9	0.7	8.4	-2.0	18.6	5.0
102	18.7	17.5	19.3	0.3	22.4	20.4	24.6	0.7	11.2	4.0	28.0	5.8
109	18.8	17.6	19.4	0.4	22.4	21.4	24.8	0.6	12.0	3.0	28.7	4.9
116	18.8	17.6	19.7	0.5	22.3	20.5	25.7	0.9	14.3	3.2	30.5	6.4
123	18.8	17.5	19.5	0.4	22.3	21.2	24.0	0.5	10.7	1.6	20.9	4.6
130	18.6	16.8	19.7	0.8	22.3	18.9	28.2	1.7	14.5	5.7	33.6	7.4
137	18.1	16.9	19.6	0.6	21.3	18.0	26.4	1.7	17.6	3.0	33.9	6.8
144	19.1	18.1	19.7	0.4	22.6	18.6	27.7	1.3	17.1	7.6	35.7	6.3
151	20.0	17.9	22.0	1.2	23.7	19.9	28.6	2.5	21.0	11.3	37.9	7.3
158	20.0	18.4	22.0	1.1	22.5	19.7	27.7	1.9	20.1	13.5	35.5	4.9
165	19.6	18.5	21.0	0.6	22.9	19.9	28.1	1.8	21.4	10.6	34.7	5.5
172	21.0	19.5	22.3	0.7	24.0	20.4	27.6	1.7	24.5	13.2	35.8	5.4
179	20.6	19.7	21.6	0.5	22.4	19.2	26.6	1.5	21.5	14.3	36.4	4.5
186	21.0	19.1	22.2	0.7	23.8	19.6	28.7	1.9	23.7	14.8	35.0	4.7

Table 9.10. Weekly summary statistics of differential pressures (Pa) for house #3

End date	Basement-out				Basement-subslab				Basement-upstairs			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	1.81	0.09	4.08	0.70	0.17	0.03	0.34	0.07	-0.18	-0.68	0.33	0.23
306	2.25	0.73	4.40	0.74	0.20	0.07	0.37	0.07	-0.14	-0.66	0.44	0.25
313	3.04	0.97	5.57	0.99	0.27	0.10	0.42	0.07	-0.03	-0.52	0.74	0.24
320	4.52	2.76	7.89	0.95	0.44	0.28	0.62	0.09	0.07	-0.72	0.48	0.24
327	3.84	1.74	7.94	1.31	0.44	0.27	0.63	0.09	0.12	-0.78	0.59	0.26
334	2.84	-1.91	4.77	0.61	0.39	0.28	0.56	0.05	0.05	-0.62	0.69	0.24
341	4.56	1.71	10.17	1.33	0.51	0.29	0.73	0.08	0.12	-0.55	0.49	0.22
348	4.95	2.43	8.93	1.36	0.56	0.37	0.80	0.10	0.11	-0.44	0.61	0.16
355	3.38	0.07	8.55	1.25	0.39	0.22	0.63	0.13	0.14	-0.77	0.76	0.32
362	4.12	0.37	7.57	1.52	0.26	0.22	0.33	0.02	0.26	-1.40	2.13	0.56
4	4.51	0.27	7.96	0.82	-17.89	-21.61	0.30	5.45	0.53	-0.93	1.05	0.31
11	5.19	3.36	12.51	1.40	-15.75	-20.67	-9.25	3.90	0.55	-0.27	0.93	0.20
18	4.85	2.57	10.73	1.56	-11.52	-13.58	-9.54	0.80	0.51	0.00	0.88	0.18
25	6.16	3.38	15.38	2.35	-10.94	-13.11	-8.64	0.90	0.54	0.05	1.19	0.22
32	5.46	3.34	7.91	0.95	-5.01	-12.05	1.62	5.64	0.50	-0.49	1.00	0.28
39	5.22	2.93	9.93	1.39	-6.75	-13.20	1.35	5.84	0.33	-0.54	0.73	0.25
46	5.90	3.45	10.39	1.41	-10.92	-13.07	-9.07	0.89	0.54	-0.36	1.00	0.20
53	4.77	3.07	7.91	0.94	-7.56	-12.47	-2.95	3.33	0.52	-0.08	0.97	0.22
60	4.16	2.24	8.74	0.96	-0.98	-5.27	0.06	1.83	0.37	-0.25	0.80	0.20
67	3.97	-3.03	11.34	1.86	-1.81	-6.33	-0.01	1.99	0.25	-0.48	0.89	0.27
74	3.97	1.15	5.94	1.07	-3.10	-5.51	-1.58	0.82	0.25	-0.44	0.67	0.24
81	2.24	0.81	5.11	0.83	-3.71	-5.42	-1.73	0.71	-0.23	-0.94	0.58	0.30
88	1.74	-0.15	5.50	0.81	-4.71	-5.92	-3.21	0.59	-0.27	-1.12	0.52	0.30
95	3.29	-0.04	8.79	1.48	-2.70	-14.10	1.03	2.57	0.05	-0.54	0.46	0.23
102	2.51	-0.04	5.27	0.85	-4.87	-6.55	-3.27	0.64	-0.01	-0.69	0.48	0.26
109	2.14	0.04	4.04	0.84	-4.92	-6.81	-3.45	0.68	-0.08	-0.60	0.35	0.23
116	1.66	-0.15	3.68	0.93	-4.48	-5.85	-3.22	0.56	-0.23	-0.71	0.44	0.25
123	2.89	0.88	6.70	1.05	-6.11	-10.45	0.37	3.41	-0.10	-0.75	0.42	0.25
130	1.85	-0.77	3.52	0.98	-9.36	-11.14	-7.25	0.86	-0.18	-0.64	0.38	0.29
137	0.97	-0.95	3.07	0.69	-3.12	-10.99	0.95	4.66	-0.40	-0.64	0.44	0.16
144	1.10	-0.35	2.69	0.85	-2.83	-9.94	0.79	4.34	-0.33	-0.70	0.12	0.19
151	0.63	-0.71	2.30	0.87	-8.53	-9.99	-7.05	0.75	-0.38	-0.73	0.64	0.21
158	0.46	-0.47	2.58	0.48	-8.91	-10.28	-7.06	0.78	-0.47	-0.74	0.94	0.14
165	0.46	-0.46	2.10	0.51	-8.98	-10.38	-7.60	0.70	-0.50	-0.69	-0.21	0.09
172	0.02	-0.59	0.93	0.31	-12.96	-15.86	-4.90	2.51	-0.53	-0.72	-0.34	0.08
179	0.27	-0.40	1.35	0.30	-14.79	-16.48	-12.80	0.89	-0.38	-0.70	12.24	0.85
186	0.18	-0.39	0.94	0.25	-14.78	-16.59	-12.53	0.89	-0.50	-0.70	-0.36	0.07

Table 9.11. Weekly summary statistics of radon concentrations (pCi/L) for house #3

End date	Basement				Upstairs			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	119.0	78.5	154.3	19.0	41.8	13.9	60.0	9.9
306	137.4	107.2	180.7	18.6	50.4	17.2	74.1	10.5
313	167.8	103.8	267.7	25.3	63.4	30.9	82.9	11.2
320	188.5	26.8	225.8	21.3	73.5	11.1	97.8	11.3
327	188.3	139.2	229.6	22.3	73.8	43.9	102.0	11.9
334	180.8	97.1	242.8	21.5	72.5	39.8	104.0	12.6
341	215.6	167.7	285.5	22.4	84.8	52.6	114.4	13.1
348	200.4	141.3	244.9	22.4	77.8	56.2	105.5	10.0
355	134.8	1.1	230.4	81.8	56.8	0.3	91.8	32.4
362	0.9	0.1	2.4	0.4	0.3	0.0	1.3	0.2
4	0.8	0.0	1.8	0.3	0.2	0.0	0.9	0.2
11	1.1	0.1	2.4	0.5	0.3	-0.3	1.2	0.2
18	1.2	0.3	2.5	0.5	0.3	0.0	0.8	0.2
25	2.6	0.2	138.4	10.9	1.7	0.0	129.5	9.7
32	56.2	0.9	224.5	69.2	20.4	0.3	74.4	24.5
39	52.2	0.6	186.1	67.3	20.5	0.1	71.6	25.8
46	1.4	0.1	2.8	0.5	0.8	0.1	2.7	0.4
53	2.4	0.4	5.3	1.2	1.2	0.0	2.8	0.6
60	8.2	2.1	50.9	9.4	4.1	0.8	23.6	4.3
67	3.9	0.4	7.1	1.6	2.0	0.0	4.1	0.9
74	3.8	0.6	6.6	1.2	1.9	0.1	3.6	0.7
81	1.6	0.1	6.1	1.2	0.9	0.1	2.8	0.6
88	1.2	0.0	4.5	0.9	0.6	0.0	1.9	0.4
95	18.8	0.4	120.3	30.1	7.8	0.1	55.5	12.6
102	1.5	0.3	2.9	0.5	0.7	0.0	1.8	0.4
109	1.5	0.1	3.1	0.6	0.6	0.0	1.6	0.4
116	1.5	0.2	3.2	0.6	0.6	0.0	1.8	0.4
123	2.7	0.2	15.0	3.0	1.1	0.0	5.2	1.2
130	0.7	0.1	1.6	0.3	0.4	0.0	1.4	0.3
137	17.8	0.2	71.3	19.2	5.9	0.0	25.6	6.3
144	43.9	0.3	110.9	38.6	13.7	0.0	42.2	14.7
151	0.9	-0.6	1.5	0.2	0.3	0.0	0.9	0.2
158	0.8	0.1	1.7	0.3	0.3	0.0	1.1	0.2
165	0.8	0.1	1.7	0.3	0.4	0.0	1.5	0.3
172	1.2	0.1	6.3	0.9	0.3	0.0	1.3	0.2
179	0.9	0.2	1.9	0.3	0.3	0.0	0.9	0.2
186	0.8	0.2	1.5	0.2	0.3	0.0	1.0	0.2

Table 9.12. Weekly summary statistics of relative humidity (%) and central air handler usage (%) for house #3

End date	Relative humidity				Air handler, fraction on			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	60.3	56.6	63.3	1.6	0.110	0.000	0.407	0.100
306	60.7	54.7	63.8	2.7	0.119	0.000	1.000	0.110
313	57.3	52.5	64.3	3.2	0.184	0.000	0.520	0.120
320	49.2	42.3	62.5	5.4	0.321	0.000	0.637	0.143
327	46.9	44.0	49.8	1.7	0.256	0.000	0.507	0.119
334	49.5	46.4	52.8	1.4	0.193	0.000	0.523	0.103
341	46.0	43.6	51.2	2.2	0.244	0.000	0.457	0.108
348	44.3	38.1	48.3	2.4	0.300	0.047	0.630	0.110
355	44.5	40.9	52.6	2.4	0.261	0.000	0.503	0.100
362	43.0	40.8	47.2	1.8	0.257	0.000	0.927	0.143
4	42.3	40.6	44.5	0.7	0.319	0.000	0.540	0.100
11	41.1	40.0	42.5	0.7	0.337	0.007	0.543	0.085
18	40.3	36.5	43.6	1.8	0.314	0.057	0.530	0.098
25	37.5	29.2	41.0	4.2	0.383	0.103	0.747	0.138
32	32.4	27.1	37.6	3.2	0.392	0.000	0.707	0.141
39	35.5	31.2	39.9	2.8	0.289	0.000	0.660	0.134
46	31.4	24.4	36.1	2.9	0.396	0.043	0.703	0.124
53	26.5	23.3	28.9	1.1	0.369	0.037	0.760	0.144
60	31.2	28.7	38.7	2.3	0.293	0.000	1.000	0.120
67	34.7	30.8	38.7	2.1	0.247	0.000	0.557	0.136
74	31.4	26.4	39.1	3.3	0.293	0.000	0.683	0.156
81	28.3	24.0	35.4	3.0	0.250	0.000	0.573	0.132
88	39.0	33.2	44.4	3.0	0.084	0.000	1.000	0.106
95	42.2	38.6	48.1	2.2	0.181	0.000	0.517	0.132
102	42.3	40.8	43.8	0.7	0.134	0.000	0.470	0.105
109	44.2	40.7	53.4	2.8	0.119	0.000	0.380	0.101
116	51.3	44.6	55.6	2.6	0.067	0.000	0.393	0.090
123	43.5	41.0	45.4	1.1	0.119	0.000	0.447	0.102
130	45.0	43.0	48.0	0.8	0.080	0.000	0.393	0.102
137	48.2	45.3	50.8	1.2	0.010	0.000	0.330	0.038
144	54.0	49.8	60.5	3.6	0.043	0.000	0.303	0.072
151	61.6	57.0	68.6	3.8	0.030	0.000	0.407	0.058
158	67.3	62.9	68.8	1.3	0.007	0.000	0.593	0.048
165	66.3	62.2	70.1	1.9	0.001	0.000	0.137	0.011
172	68.8	66.1	73.1	2.1	0.000	0.000	0.000	0.000
179	74.5	71.6	76.7	1.2	0.009	0.000	0.860	0.065
186	76.5	71.7	80.9	2.6	0.000	0.000	0.000	0.000

Table 9.13. Weekly summary statistics of temperature (°C) for house #4

End date	Basement				Upstairs				Outdoors			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	17.0	16.0	18.2	0.5	18.0	16.9	19.1	0.4	12.0	3.6	25.8	4.5
306	17.0	14.0	19.2	1.2	17.9	12.7	20.5	1.8	10.2	-0.1	21.6	4.3
313	17.9	16.4	19.3	0.7	18.9	17.5	19.9	0.6	20.3	-1.4	32.6	5.8
320	17.7	15.4	18.8	0.8	18.3	16.7	19.4	0.7	6.3	-8.8	22.0	7.1
327	16.2	11.3	19.9	2.2	16.4	7.9	20.3	3.6	1.9	-6.2	11.9	4.5
334	14.9	13.1	18.9	1.9	15.0	12.6	20.3	2.9	4.9	-2.0	16.7	3.6
341	16.5	12.9	20.6	2.0	17.6	12.6	21.8	2.9	2.0	-6.2	11.4	4.3
348	17.2	14.5	19.4	1.0	18.6	16.5	20.9	1.0	0.1	-11.8	9.9	4.9
355	16.8	12.7	19.2	1.5	17.9	13.0	20.5	1.8	1.7	-4.9	6.0	2.5
362	16.4	13.8	17.7	1.1	17.2	15.0	18.4	1.0	1.7	-6.0	8.4	3.2
4	16.5	13.4	18.1	1.2	17.2	13.8	18.8	1.6	-0.7	-6.5	4.5	2.2
11	17.5	13.2	20.8	1.8	18.8	14.2	21.2	1.8	-0.3	-6.5	4.4	2.6
18	17.6	13.3	19.6	1.7	19.8	14.8	21.3	1.5	1.3	-8.1	10.7	4.6
25	17.4	12.5	19.7	2.0	19.2	14.0	21.2	1.9	-5.6	-15.8	1.0	4.8
32	17.3	12.7	19.7	2.1	19.1	14.1	21.1	1.9	-5.2	-14.6	2.3	4.4
39	16.5	12.9	19.4	1.7	18.2	14.1	21.2	1.6	1.0	-7.3	8.3	3.6
46	15.0	7.2	21.1	4.1	15.7	3.5	23.1	5.7	-5.1	-18.4	3.8	4.8
53	17.2	11.0	20.2	1.8	19.5	11.2	22.4	2.0	-2.9	-16.3	10.1	5.2
60	17.2	13.2	19.1	1.0	19.0	14.3	20.8	0.9	0.8	-5.7	7.4	3.6
67	17.0	13.8	20.5	1.8	19.7	16.6	22.6	1.6	5.0	-5.0	24.6	7.2
74	16.4	13.8	18.3	1.2	18.7	17.8	20.9	0.8	0.5	-10.5	16.1	5.9
81	17.3	15.4	18.3	0.6	19.3	18.6	20.1	0.3	3.7	-3.4	14.5	4.5
88	13.9	12.4	18.0	1.3	16.9	14.2	20.6	1.8	11.8	2.5	23.6	5.1
95	12.5	10.3	19.2	2.0	13.3	9.4	22.1	3.1	7.5	-2.8	15.9	4.7
102	15.4	13.6	19.3	1.6	18.6	15.6	22.0	1.5	10.3	4.1	26.0	5.1
109	15.2	13.1	19.9	1.8	17.5	14.7	21.8	2.0	10.8	2.8	24.8	4.5
116	17.2	15.3	19.8	1.0	20.4	16.6	23.4	1.3	13.1	3.4	26.7	5.3
123	16.6	13.8	19.7	1.6	19.0	15.1	21.9	1.7	9.6	2.3	19.9	4.2
130	16.0	14.2	19.8	1.3	19.1	16.1	25.4	1.7	13.6	5.5	31.8	6.6
137	16.0	14.4	17.7	0.9	19.8	16.1	24.4	2.0	16.5	3.0	29.9	5.8
144	15.6	13.6	17.3	1.1	18.7	13.9	24.2	2.8	15.8	7.0	31.9	5.6
151	17.0	14.7	21.5	2.0	20.1	15.7	25.9	3.3	19.3	10.3	32.4	6.7
158	19.6	18.0	21.9	0.7	21.6	19.2	25.9	1.4	18.7	12.9	31.0	3.8
165	18.8	17.3	21.8	1.0	21.6	18.9	24.9	1.2	20.1	11.3	30.2	4.2
172	18.7	16.9	19.8	0.6	23.0	21.2	25.7	0.9	23.2	14.1	31.2	4.0
179	19.2	17.6	20.3	0.4	22.4	20.7	25.5	0.9	20.1	13.8	31.0	3.4
186	20.9	17.4	23.2	1.4	23.8	20.9	26.2	1.2	22.1	15.9	30.2	3.3

Table 9.14. Weekly summary statistics of differential pressures (Pa) for house #4

End date	Basement				Basement-subslab				Basement-upstairs			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	0.94	-0.90	3.72	0.97	0.09	0.01	0.18	0.03	0.33	0.03	3.07	0.61
306	1.31	-0.10	6.60	1.11	0.13	0.06	0.33	0.04	0.49	0.03	5.20	0.89
313	2.16	-0.18	6.48	1.45	0.17	0.06	0.29	0.05	0.73	-10.44	21.56	2.19
320	3.39	1.26	8.82	1.45	0.27	0.10	0.47	0.07	0.82	-0.22	4.50	1.04
327	3.02	0.69	12.25	1.70	0.29	-1.10	0.60	0.11	0.82	-0.69	5.37	1.24
334	1.87	-0.39	5.14	1.15	0.26	0.19	0.36	0.03	0.55	-0.14	2.65	0.81
341	3.64	0.28	7.71	1.42	0.29	-2.38	0.45	0.20	1.18	-0.28	4.96	1.15
348	3.98	1.19	8.94	1.50	0.34	0.19	0.57	0.07	1.07	-0.24	4.37	1.10
355	4.98	1.23	10.37	1.66	-2.25	-3.26	0.51	0.95	1.53	-0.38	6.25	1.50
362	5.08	2.60	10.16	1.59	-2.43	-3.11	-0.06	0.29	1.59	-0.03	6.11	1.42
4	5.15	1.00	9.45	1.33	-2.43	-2.79	-0.87	0.18	0.97	-0.13	5.87	1.30
11	5.68	3.13	10.58	1.77	-2.35	-2.83	1.02	0.43	1.38	-0.18	5.81	1.71
18	4.52	-1.35	9.63	1.82	-0.82	-2.96	1.75	1.78	0.86	-0.33	5.68	1.31
25	6.51	2.25	11.90	2.54	-0.72	-2.28	1.64	1.41	1.58	-0.35	5.55	1.79
32	6.92	3.44	11.60	2.07	-1.75	-2.32	-1.00	0.29	1.85	-0.21	5.35	1.83
39	4.78	2.51	10.29	1.66	-2.05	-2.47	-1.29	0.25	1.08	-0.17	5.61	1.56
46	6.49	1.56	13.37	3.29	-1.67	-2.29	-0.77	0.39	2.04	-0.15	5.95	2.28
53	7.98	3.51	12.43	2.00	-0.56	-2.25	1.82	1.51	3.72	-0.22	5.17	1.51
60	5.32	2.15	8.57	1.38	-2.05	-2.85	-1.55	0.26	1.16	-0.20	4.63	1.30
67	3.59	-0.70	9.61	2.79	1.65	-2.62	6.14	3.74	0.83	-0.42	5.18	1.35
74	4.11	-0.02	7.69	1.83	1.84	-2.49	6.54	3.94	0.84	-0.34	3.56	1.04
81	4.32	2.06	6.73	1.22	-2.24	-2.64	-1.88	0.19	0.67	-0.29	2.85	1.02
88	0.81	-0.85	5.69	1.00	-1.41	-3.26	0.49	1.58	0.21	-0.54	2.52	0.73
95	1.58	0.24	6.94	1.15	0.47	-1.72	1.24	0.21	0.29	-0.05	4.53	0.71
102	2.24	-0.39	8.64	1.55	-1.66	-3.43	1.22	1.78	0.54	-0.05	5.69	1.13
109	2.23	0.40	8.35	1.41	-2.98	-3.36	-2.16	0.21	0.51	0.01	6.41	1.15
116	1.98	0.58	7.25	0.87	-3.16	-3.49	-2.49	0.16	0.33	0.06	5.23	0.42
123	2.79	1.30	9.13	1.23	-2.92	-3.17	-2.19	0.17	0.40	-0.09	6.06	1.08
130	2.08	-0.15	9.25	1.68	-3.03	-3.45	-2.12	0.22	0.48	0.04	6.16	1.05
137	1.03	-0.49	3.10	0.86	-2.03	-3.49	0.40	1.60	0.27	0.13	0.43	0.07
144	1.04	-0.42	2.20	0.57	-1.53	-3.43	0.36	1.75	0.35	0.10	0.58	0.15
151	2.42	0.08	5.96	2.05	-3.09	-3.51	-2.62	0.25	2.18	0.48	6.23	2.40
158	6.16	1.19	7.29	1.42	-2.71	-3.25	-2.51	0.16	5.54	0.58	6.21	1.25
165	3.01	0.29	7.55	2.27	-3.14	-3.53	-0.94	0.34	2.18	0.33	8.06	2.46
172	1.33	0.12	6.15	1.29	-3.34	-3.57	-2.70	0.19	0.92	0.19	6.02	1.41
179	1.09	-0.11	5.76	1.05	-3.44	-3.78	-2.77	0.16	0.78	0.33	5.83	1.11
186	2.67	-0.11	6.79	2.44	-3.52	-4.27	-1.61	0.37	2.60	0.43	6.00	2.35

Table 9.15 Weekly summary statistics of radon concentrations (pCi/L) for house #4

End date	Basement				Upstairs			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	98.9	10.9	200.4	31.8	41.6	8.8	63.0	10.3
306	80.9	48.4	129.1	18.3	35.2	11.7	49.6	7.4
313	60.9	38.5	103.2	13.0	29.3	17.7	43.7	5.2
320	41.5	5.3	69.8	7.7	20.8	2.6	34.7	3.7
327	42.9	4.2	84.0	16.3	20.2	0.9	36.6	6.7
334	68.7	29.9	123.7	25.3	33.3	14.1	56.9	12.8
341	75.1	31.5	163.0	17.0	40.6	20.7	56.9	7.9
348	78.2	52.5	127.8	14.1	42.8	29.9	54.8	6.6
355	10.5	0.9	74.4	19.3	8.2	0.0	45.1	15.2
362	2.5	0.5	5.3	1.1	1.0	0.0	3.1	0.6
4	5.5	1.6	14.8	4.0	2.0	0.0	5.8	1.5
11	3.7	1.1	15.6	1.6	1.5	0.0	6.4	0.9
18	28.7	0.1	87.8	31.0	15.2	0.0	49.4	17.1
25	49.5	2.8	171.8	36.8	16.5	0.3	358.1	24.9
32	5.2	2.8	7.8	1.0	3.8	0.1	357.2	19.4
39	4.0	1.5	7.5	1.1	2.8	0.1	107.1	6.8
46	5.1	2.8	7.8	0.9	1.7	0.0	4.2	1.2
53	18.2	3.7	48.7	17.5	13.0	0.9	278.9	19.2
60	4.4	0.7	9.6	1.5	2.2	0.3	6.7	1.1
67	14.4	0.5	36.2	12.9	10.2	0.0	24.8	9.4
74	18.9	2.5	44.8	14.3	12.9	0.7	29.1	10.1
81	3.9	1.6	7.1	0.9	1.9	0.1	6.6	1.0
88	49.1	0.0	176.8	67.4	21.7	0.0	84.2	28.4
95	159.3	82.8	230.7	31.9	72.6	44.6	106.6	14.9
102	54.2	0.5	194.5	67.8	29.1	0.3	111.1	35.5
109	1.9	0.3	6.0	0.9	1.6	0.3	7.0	1.1
116	1.1	0.1	2.2	0.4	0.7	0.1	1.6	0.3
123	1.7	0.5	5.6	0.8	1.3	0.0	5.5	0.9
130	1.4	0.2	4.2	0.7	1.0	0.1	5.2	0.8
137	28.8	0.4	142.1	43.7	6.5	0.3	50.1	11.3
144	59.9	0.6	142.2	58.0	18.9	0.4	55.6	20.5
151	2.4	0.2	6.9	1.5	2.0	0.2	6.3	1.3
158	3.5	1.8	7.6	1.0	3.1	1.3	7.2	0.9
165	2.0	0.2	5.2	0.9	1.8	0.0	4.8	1.0
172	1.9	0.5	5.1	1.0	1.8	0.5	5.6	0.9
179	1.8	0.4	5.3	0.7	1.7	0.5	5.3	0.8
186	1.8	0.5	5.5	0.8	1.9	0.3	5.7	0.9

Table 9.16. Weekly summary statistics of relative humidity (%) and central air handler usage (%) for house #4

End date	Relative humidity				Air handler, fraction on			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	63.7	58.5	66.6	1.6	0.063	0.000	0.557	0.137
306	64.8	59.6	66.9	1.9	0.091	0.000	1.000	0.191
313	59.7	56.0	65.8	2.6	0.166	0.000	0.877	0.218
320	52.5	44.6	63.7	5.2	0.261	0.000	1.000	0.242
327	52.1	48.0	55.9	2.1	0.203	0.000	1.000	0.254
334	55.0	50.8	58.0	1.9	0.099	0.000	0.570	0.166
341	50.2	45.3	57.0	3.3	0.270	0.000	1.000	0.245
348	46.8	40.2	52.7	3.2	0.284	0.000	1.000	0.240
355	42.8	40.2	45.9	1.3	0.266	0.000	1.000	0.254
362	40.9	38.9	44.5	1.5	0.263	0.000	1.000	0.242
4	39.3	37.6	41.3	0.7	0.311	0.000	1.000	0.213
11	38.2	37.1	40.3	0.6	0.360	0.000	1.000	0.285
18	39.7	37.2	50.4	2.5	0.333	0.000	1.000	0.309
25	38.5	34.8	41.3	1.4	0.404	0.000	1.000	0.345
32	36.2	33.6	38.3	0.7	0.423	0.000	1.000	0.348
39	36.8	35.3	38.6	0.8	0.283	0.000	1.000	0.298
46	34.0	23.6	38.0	3.4	0.422	0.000	1.000	0.442
53	25.7	20.9	29.9	2.0	0.920	0.000	1.000	0.269
60	28.7	25.3	37.0	2.5	0.359	0.000	1.000	0.256
67	34.9	28.2	42.7	3.7	0.264	0.000	1.000	0.259
74	36.9	30.3	45.4	3.9	0.285	0.000	0.687	0.219
81	30.5	27.1	35.1	1.6	0.249	0.000	0.863	0.215
88	42.9	34.0	60.9	6.0	0.202	0.000	1.000	0.384
95	48.5	45.8	51.6	1.1	0.048	0.000	1.000	0.181
102	47.6	42.2	52.0	2.0	0.098	0.000	1.000	0.239
109	50.7	44.1	59.3	3.1	0.086	0.000	1.000	0.238
116	56.4	40.0	64.4	6.6	0.092	0.000	1.000	0.221
123	43.9	39.0	48.4	2.2	0.118	0.000	1.000	0.260
130	49.4	43.8	56.5	2.5	0.054	0.000	1.000	0.184
137	57.8	53.9	60.9	1.5	0.000	0.000	0.000	0.000
144	63.3	59.0	71.7	4.2	0.000	0.000	0.000	0.000
151	72.0	66.1	89.1	5.1	0.343	0.000	1.000	0.474
158	72.0	66.1	76.9	2.2	1.000	1.000	1.000	0.000
165	70.6	64.5	77.9	3.3	0.362	0.000	1.000	0.477
172	69.4	63.5	75.6	2.4	0.229	0.000	1.000	0.409
179	73.7	70.2	76.2	1.2	0.074	0.000	1.000	0.256
186	76.3	70.7	80.8	2.5	0.555	0.000	1.000	0.489

Table 9.17. Weekly summary statistics of temperatures (°C) for house #5

End date	Basement				Upstairs				Outdoors			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	19.2	18.5	20.0	0.4	21.3	18.3	24.4	1.4	12.2	1.2	25.8	6.2
306	19.5	16.1	20.6	0.7	22.1	18.9	24.2	1.2	10.5	-2.2	24.5	5.7
313	19.4	18.6	20.0	0.3	22.2	19.5	24.4	1.2	8.0	-2.1	19.8	5.5
320	18.9	17.3	19.7	0.5	21.7	16.3	25.9	1.9	1.8	-8.7	15.0	5.2
327	18.8	17.3	20.1	0.5	22.0	17.8	25.5	1.6	3.1	-7.0	15.4	4.8
334	18.6	16.4	19.6	0.5	22.1	18.4	26.3	1.5	5.2	-3.3	17.1	4.7
341	18.0	14.3	19.3	0.9	21.8	17.5	24.9	1.7	2.2	-7.3	11.7	4.7
348	18.1	16.4	19.1	0.5	21.8	16.4	25.3	1.8	0.2	-13.3	12.4	5.1
355	17.8	16.6	19.5	0.6	21.6	17.6	26.2	1.9	1.9	-6.8	10.1	3.4
362	17.6	15.9	18.5	0.5	21.3	17.2	25.6	2.0	1.8	-6.5	12.7	4.2
4	17.3	15.7	18.9	0.6	21.8	17.0	25.5	2.1	-0.4	-6.2	9.4	3.1
11	16.9	15.6	18.3	0.6	21.5	16.7	25.2	2.1	0.0	-7.5	10.3	3.3
18	17.1	15.8	18.0	0.6	21.9	16.8	25.5	2.1	1.9	-7.8	13.7	4.9
25	16.6	14.3	18.4	0.8	21.6	14.8	25.5	2.4	-5.3	-16.9	2.5	4.9
32	16.2	14.5	17.3	0.7	21.8	15.2	25.8	2.4	-4.6	-17.3	8.7	5.4
39	16.5	15.2	17.3	0.6	21.3	16.9	25.0	2.0	1.5	-6.8	13.0	4.9
46	16.3	13.6	18.2	0.9	21.0	16.0	24.9	2.1	-4.0	-18.1	9.6	5.2
53	16.3	14.2	17.5	0.7	21.0	14.9	25.2	2.1	-1.4	-16.1	12.9	6.7
60	17.0	15.8	18.0	0.6	21.5	16.8	24.9	2.0	1.5	-6.0	12.9	4.4
67	17.2	15.9	18.3	0.5	21.4	16.9	25.1	1.7	5.4	-7.2	30.5	8.3
74	16.9	15.6	17.9	0.6	20.5	15.6	24.1	2.0	1.3	-11.7	16.4	6.3
81	17.0	15.8	17.9	0.5	21.1	16.6	25.0	2.0	4.7	-3.9	20.3	5.7
88	17.6	16.7	18.5	0.4	21.7	18.9	25.1	1.3	12.4	-0.2	28.1	6.7
95	17.8	16.6	18.9	0.5	21.1	16.9	24.1	1.6	8.0	-2.8	17.7	5.2
102	18.0	17.2	19.9	0.4	21.6	18.4	24.9	1.3	10.5	3.4	25.9	5.8
109	17.5	16.2	19.5	1.0	19.2	15.1	25.5	3.1	11.5	1.5	28.8	5.1
116	18.6	16.8	20.9	0.9	21.8	17.8	25.7	1.7	13.7	2.3	30.3	6.3
123	18.0	17.2	19.1	0.4	21.2	17.6	24.2	1.3	10.2	1.1	21.0	4.7
130	18.3	16.4	21.4	0.7	22.3	19.1	28.7	1.7	14.2	3.7	31.9	7.6
137	19.5	18.2	21.6	0.6	23.3	19.7	29.0	1.9	17.6	2.3	31.9	7.1
144	20.1	19.1	21.0	0.5	23.8	20.1	27.8	1.9	17.3	7.3	35.0	6.7
151	20.1	18.9	21.8	0.8	24.0	20.3	29.6	2.8	21.1	11.0	38.1	7.8
158	21.0	20.3	22.0	0.4	24.6	21.8	29.7	1.8	20.4	12.5	36.0	5.6
165	21.4	19.8	25.3	0.7	25.0	21.8	30.8	1.7	21.5	9.2	33.8	6.0
172	21.8	20.9	23.7	0.5	26.3	23.7	30.4	1.4	25.0	12.1	38.5	6.3
179	22.1	20.9	23.8	0.5	25.1	22.9	29.1	1.3	21.8	12.9	36.7	5.2
186	22.5	21.3	24.4	0.7	25.9	23.5	29.5	1.2	24.3	12.7	34.5	6.1

Table 9.18. Weekly summary statistics of differential pressures (Pa) for house #5

End date	Basement-out				Basement-subslab				Basement-upstairs			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	1.15	-0.93	2.13	0.42	0.12	0.07	0.16	0.01	0.02	-1.97	0.64	0.19
306	1.27	-1.83	2.99	0.68	0.11	0.07	0.19	0.02	-0.07	-3.13	0.76	0.41
313	1.73	0.12	6.67	0.80	0.12	0.08	0.17	0.02	0.09	-0.48	0.79	0.22
320	2.70	0.04	6.92	1.03	0.14	0.10	0.22	0.02	0.12	-0.71	0.90	0.26
327	2.33	-5.72	9.95	1.27	0.13	0.08	0.32	0.03	0.00	-15.56	3.68	1.38
334	2.20	0.20	7.14	0.78	0.14	0.08	0.20	0.02	0.11	-0.54	0.91	0.23
341	2.97	-3.02	11.02	1.96	0.16	0.10	0.25	0.03	0.12	-2.13	0.92	0.42
348	3.02	0.50	10.21	1.21	0.14	0.05	0.23	0.02	0.18	-0.20	0.91	0.23
355	2.49	0.14	5.58	0.83	0.14	0.09	0.21	0.02	0.19	-0.28	0.88	0.25
362	2.51	-0.34	7.41	0.90	0.14	0.10	0.22	0.02	0.16	-1.15	0.89	0.27
4	3.02	0.00	8.75	1.63	0.11	0.06	0.21	0.03	0.03	-0.65	0.82	0.20
11	2.73	0.00	8.37	1.44	0.25	0.07	0.55	0.13	-0.09	-0.86	0.79	0.26
18	2.96	0.67	8.46	1.45	0.42	0.14	0.88	0.16	0.03	-0.52	1.32	0.35
25	3.19	0.44	11.41	1.69	0.84	0.43	1.70	0.26	-0.19	-0.90	1.31	0.38
32	3.03	1.39	5.00	0.73	1.08	-1.19	1.82	0.27	0.11	-0.65	1.29	0.41
39	3.12	1.51	11.69	1.38	0.96	0.68	1.54	0.18	0.18	-0.27	1.45	0.35
46	4.04	2.02	9.08	1.20	-5.79	-12.80	1.67	6.38	0.24	-0.79	1.88	0.43
53	2.97	1.50	5.80	0.77	-1.64	-12.76	2.44	5.70	0.22	-0.27	1.82	0.42
60	2.90	-0.56	5.53	0.89	-5.22	-13.85	2.40	6.87	0.32	-1.11	1.99	0.44
67	3.35	-0.28	13.31	1.81	-11.88	-13.83	1.49	2.85	0.34	-0.56	1.86	0.38
74	2.42	0.33	4.96	0.72	-8.41	-13.52	-5.73	2.36	0.30	-0.21	1.72	0.38
81	2.17	0.46	4.12	0.71	-3.27	-8.26	1.74	4.20	0.17	-0.20	1.48	0.33
88	1.28	-0.74	7.06	1.05	-1.93	-8.88	1.49	3.82	0.03	-0.76	1.32	0.27
95	1.43	-5.38	10.93	2.19	-0.78	-13.07	2.95	4.52	-0.08	-0.65	1.00	0.21
102	1.74	-3.07	5.72	0.88	-7.76	-15.00	1.61	5.36	0.09	-2.23	1.28	0.33
109	0.92	-0.78	5.12	0.98	-5.65	-13.81	1.35	6.52	0.09	-0.83	1.55	0.25
116	0.84	-5.59	2.64	1.02	-10.39	-14.80	0.60	5.29	0.07	-1.48	2.48	0.39
123	0.98	-1.17	4.92	1.31	-6.46	-13.67	0.00	6.46	0.01	-2.13	0.89	0.21
130	-0.09	-0.21	-0.01	0.03	-0.04	-0.13	0.00	0.02	-0.06	-0.22	0.01	0.04
137	0.67	-2.91	2.27	0.84	-13.28	-15.70	-0.08	3.51	-0.02	-1.65	2.79	0.40
144	0.60	-0.43	2.35	0.46	-5.16	-15.28	1.29	7.39	-0.12	-1.36	0.83	0.21
151	0.76	-1.49	3.29	0.76	-14.86	-15.89	-13.71	0.49	-0.01	-0.97	1.22	0.37
58	0.73	-0.51	2.95	0.57	-15.15	-15.90	-14.19	0.28	-0.03	-0.61	0.68	0.13
165	0.66	-0.80	2.04	0.45	-15.28	-17.17	-13.86	0.33	0.00	-0.88	1.37	0.26
172	0.65	-1.13	3.61	0.79	-13.86	-15.94	0.53	4.27	0.06	-0.59	0.94	0.23
179	0.34	-2.49	7.09	0.71	-14.47	-16.57	0.75	3.30	-0.06	-2.79	7.05	0.64
186	0.78	-0.99	3.45	0.90	-15.13	-16.21	-14.19	0.41	-0.08	-1.59	0.71	0.43

Table 9.19. Weekly summary statistics of radon concentrations (pCi/L) for house #5

End date	Basement				Upstairs				Subslab[a]			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	51.0	0.7	89.5	23.0	21.8	0.0	43.8	11.5	0.0	0.0	0.0	0.0
306	45.2	0.5	80.0	22.1	20.6	0.0	41.9	11.3	0.0	0.0	0.0	0.0
313	60.7	16.2	86.6	12.0	33.6	20.2	47.6	6.1	0.0	0.0	0.0	0.0
320	70.0	0.8	92.5	15.8	37.7	6.9	53.5	9.5	0.0	0.0	0.0	0.0
327	64.7	10.2	92.3	15.4	34.4	3.8	49.0	8.1	0.0	0.0	0.0	0.0
334	71.2	5.2	105.5	19.1	36.6	10.7	58.7	9.1	0.0	0.0	0.0	0.0
341	63.8	0.4	99.0	20.3	32.6	0.2	50.8	11.3	0.0	0.0	0.0	0.0
348	68.8	48.1	91.5	10.1	38.3	25.0	48.7	5.4	0.0	0.0	0.0	0.0
355	67.0	40.3	95.3	13.3	37.2	24.6	50.2	5.6	0.0	0.0	0.0	0.0
362	68.7	3.9	95.1	15.9	37.2	7.0	50.5	8.0	0.0	0.0	0.0	0.0
4	55.2	16.3	86.5	10.1	34.5	13.6	46.9	4.7	0.0	0.0	0.0	0.0
11	52.0	14.2	67.9	8.9	32.1	10.7	41.9	5.1	0.0	0.0	0.0	0.0
18	56.6	22.9	92.0	13.3	33.1	15.4	49.0	7.2	0.0	0.0	0.0	0.0
25	56.7	26.0	216.7	19.3	33.4	16.6	187.6	12.8	0.0	0.0	0.0	0.0
32	59.1	40.4	88.8	9.4	32.7	23.3	43.2	3.9	0.0	0.0	0.0	0.0
39	63.7	45.2	85.5	7.4	33.9	18.8	45.0	5.1	0.0	0.0	0.0	0.0
46	22.4	0.5	100.9	31.3	12.2	0.0	48.0	16.0	0.4	0.0	2.5	0.4
53	36.7	0.1	70.1	23.6	19.0	0.0	36.3	12.5	0.8	0.1	1.7	0.4
60	33.1	0.1	77.3	30.0	18.4	0.0	42.9	14.8	0.5	0.1	1.3	0.4
67	1.5	0.1	16.0	2.5	1.1	0.0	9.6	1.9	0.2	0.1	1.0	0.2
74	1.0	0.1	1.9	0.4	0.3	-0.3	1.1	0.2	0.1	0.1	0.2	0.0
81	22.0	0.4	69.6	23.8	12.5	0.0	37.8	13.6	0.6	0.1	3.7	0.8
88	23.1	0.3	63.3	19.6	12.0	0.0	31.8	8.8	0.9	0.1	3.6	0.7
95	32.5	0.9	69.6	17.5	17.3	0.7	36.3	9.5	0.9	0.1	5.0	0.8
102	14.9	0.0	69.5	23.7	13.7	0.0	42.5	15.8	0.4	0.1	2.0	0.5
109	14.2	0.0	43.0	14.6	5.0	-0.4	10.3	3.4	0.6	0.1	2.4	0.6
116	8.8	0.0	50.2	16.1	4.6	0.0	19.6	5.6	0.4	0.1	2.9	0.7
123	0.8	0.0	4.9	0.6	0.2	-0.3	1.4	0.3	0.1	0.0	0.5	0.1
130	0.6	0.0	1.6	0.3	0.2	0.0	1.0	0.2	0.1	0.0	0.1	0.0
137	0.6	0.0	3.1	0.5	0.2	-0.3	1.1	0.2	0.1	0.0	0.1	0.0
144	12.9	0.1	35.8	11.6	7.1	-0.1	16.9	4.9	0.5	0.0	2.2	0.4
151	0.5	0.0	1.8	0.3	0.2	-0.4	0.7	0.2	0.1	0.0	0.1	0.0
158	0.6	0.1	1.4	0.3	0.1	-0.1	0.6	0.1	0.0	0.0	0.1	0.0
165	0.5	0.0	1.4	0.3	0.1	0.0	0.4	0.1	0.0	0.0	0.0	0.0
172	0.7	0.0	3.4	0.6	0.2	0.0	0.6	0.1	0.0	0.0	0.0	0.0
179	0.8	0.0	4.7	1.0	0.2	0.0	0.8	0.2	0.0	0.0	0.0	0.0
186	0.5	0.0	1.1	0.3	0.2	-0.3	0.7	0.1	0.0	0.0	0.0	0.0

[a]Units are counts per minute. Conversion factor and background count rate can be obtained from Dr. L. M. Hubbard, H201 Engineering Quad, CEES, Princeton University, Princeton, NJ.

Table 9.20. Weekly summary statistics of relative humidity (%) and central air handler usage (%) for house #5

End date	Relative humidity				Air handler, fraction on			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	58.2	43.9	61.5	2.5	0.087	0.000	1.000	0.214
306	55.0	33.4	60.6	5.6	0.152	0.000	1.000	0.271
313	55.1	50.8	58.2	1.3	0.219	0.000	1.000	0.299
320	52.7	42.1	57.6	2.8	0.274	0.000	1.000	0.313
327	50.7	41.4	52.9	1.7	0.301	0.000	1.000	0.340
334	50.5	40.9	52.2	1.7	0.236	0.000	1.000	0.287
341	46.8	34.8	51.3	3.6	0.327	0.000	1.000	0.347
348	46.3	43.5	48.0	0.9	0.343	0.000	1.000	0.327
355	46.3	43.5	47.9	1.0	0.310	0.000	1.000	0.345
362	45.6	34.8	47.3	1.9	0.285	0.000	1.000	0.342
4	43.3	38.4	46.9	1.1	0.352	0.000	1.000	0.344
11	42.1	39.1	43.4	0.7	0.339	0.000	1.000	0.344
18	43.6	41.7	45.9	1.1	0.317	0.000	1.000	0.335
25	41.5	37.8	44.5	1.9	0.320	0.000	1.000	0.324
32	39.7	36.5	42.0	1.3	0.310	0.000	1.000	0.319
39	42.5	41.2	43.6	0.6	0.276	0.000	1.000	0.326
46	40.5	37.3	43.1	1.4	0.269	0.000	1.000	0.305
53	38.9	37.0	39.7	0.6	0.256	0.000	1.000	0.317
60	39.9	37.8	41.4	0.5	0.294	0.000	1.000	0.325
67	40.4	38.8	41.9	0.6	0.237	0.000	1.000	0.311
74	39.6	38.5	41.9	1.0	0.249	0.000	1.000	0.348
81	39.5	38.5	40.8	0.6	0.209	0.000	1.000	0.336
88	41.4	40.4	46.4	1.2	0.068	0.000	1.000	0.197
95	46.4	44.0	53.0	1.8	0.155	0.000	1.000	0.260
102	45.5	34.2	48.0	2.4	0.122	0.000	1.000	0.232
109	45.1	43.2	46.7	0.7	0.068	0.000	1.000	0.179
116	55.1	46.8	63.1	4.7	0.075	0.000	1.000	0.192
123	46.9	36.6	52.2	3.4	0.118	0.000	1.000	0.259
130	49.7	41.1	59.5	3.8	0.086	0.000	1.000	0.210
137	51.9	42.0	72.5	4.3	0.000	0.000	0.000	0.000
144	57.8	54.2	66.0	3.4	0.033	0.000	1.000	0.116
151	61.7	56.9	65.3	2.5	0.067	0.000	1.000	0.199
158	62.8	59.2	64.5	1.1	0.023	0.000	1.000	0.122
165	59.2	42.9	65.0	5.1	0.008	0.000	1.000	0.083
172	58.6	53.3	62.3	2.1	0.124	0.000	1.000	0.235
179	62.5	54.9	69.2	2.2	0.029	0.000	1.000	0.137
186	59.4	54.3	63.2	1.9	0.142	0.000	1.000	0.266

Table 9.21. Weekly summary statistics of temperatures (°C) for house #6

End date	Basement				Upstairs				Outdoors			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	21.7	20.1	23.9	0.9	21.6	20.1	22.9	0.6	9.8	-2.5	26.3	6.3
306	22.0	20.3	24.2	0.8	21.8	20.3	23.7	0.6	8.6	-4.8	22.6	5.7
313	22.7	20.8	24.6	0.8	21.9	21.0	23.3	0.5	6.8	-5.8	19.0	5.8
320	23.3	21.2	24.8	0.7	22.5	20.9	24.0	0.6	-0.2	-12.1	10.8	5.0
327	22.6	20.5	24.0	0.6	22.4	21.4	23.6	0.6	1.6	-9.5	13.3	5.4
334	22.3	20.2	24.6	0.7	22.2	19.4	24.7	0.7	2.1	-6.9	11.0	4.7
341	22.6	20.8	25.3	0.7	22.3	20.8	23.7	0.6	0.0	-10.4	11.8	4.8
348	21.9	20.4	23.5	0.6	21.8	20.6	23.4	0.6	-1.5	-15.2	11.1	5.3
355	21.6	20.1	23.3	0.5	21.8	20.6	23.1	0.6	0.3	-8.2	8.4	3.9
362	21.7	19.7	23.1	0.7	22.4	20.6	24.4	0.7	-0.3	-10.6	7.5	4.3
4	21.9	17.8	24.1	1.0	22.5	17.0	25.3	1.3	-1.8	-8.6	5.2	3.3
11	21.8	20.4	23.1	0.5	22.8	21.7	24.1	0.6	-1.4	-9.9	5.1	3.3
18	21.5	18.9	25.3	1.5	22.2	19.9	26.5	1.9	0.5	-11.0	12.8	5.2
25	21.9	20.4	23.0	0.5	22.8	21.6	24.3	0.5	-6.3	-19.8	0.6	5.2
32	21.6	18.7	22.9	0.7	23.0	21.8	24.4	0.6	-5.9	-20.0	1.9	5.2
39	21.7	20.0	23.0	0.6	22.8	21.5	24.2	0.6	-0.7	-9.7	10.4	4.9
46	21.5	20.0	23.0	0.6	22.8	21.4	24.1	0.6	-5.6	-19.2	7.9	5.2
53	21.4	16.9	23.2	1.0	22.7	19.5	24.7	0.7	-3.5	-17.1	19.2	6.6
60	21.6	20.0	22.9	0.5	22.3	21.1	23.9	0.6	-0.1	-8.4	15.6	5.3
67	20.9	18.1	22.4	0.9	22.2	21.1	23.4	0.5	4.3	-9.9	34.2	9.0
74	21.2	17.9	23.6	1.1	22.0	18.9	24.8	0.8	0.5	-13.2	20.7	7.2
81	21.4	19.4	22.9	0.6	22.1	21.1	23.5	0.5	3.5	-7.1	22.5	7.2
88	19.8	17.6	22.4	1.1	21.2	19.0	23.1	0.9	12.2	-3.4	33.4	9.8
95	20.6	18.0	22.8	0.8	22.0	20.6	23.4	0.5	7.6	-5.1	22.0	6.6
102	20.5	17.8	22.8	1.1	22.3	21.4	23.4	0.4	10.4	-0.3	34.3	8.6
109	20.5	18.0	22.9	1.0	22.1	21.0	23.8	0.5	11.3	-2.6	36.6	7.1
116	19.9	17.7	22.5	1.2	22.3	20.9	24.2	0.7	14.1	-2.5	37.5	8.8
123	20.8	18.5	23.0	0.9	22.2	20.8	23.5	0.5	9.9	-2.9	28.9	7.3
130	19.7	16.8	22.9	1.9	21.9	18.4	25.8	1.5	14.3	0.2	41.2	10.4
137	19.1	17.0	23.2	1.3	22.2	18.1	26.2	1.8	17.6	-1.9	40.9	10.5
144	18.2	17.7	18.8	0.3	22.0	20.5	23.8	0.9	20.4	13.2	33.3	6.7
151	18.8	16.9	23.4	1.3	22.9	18.0	28.9	2.9	21.2	9.4	44.8	9.5
158	19.1	17.1	20.9	0.6	22.6	20.3	25.4	1.3	20.0	8.2	44.5	7.8
165	19.0	17.3	19.9	0.4	22.3	18.9	26.0	1.5	21.4	5.7	42.5	8.7
172	19.2	17.3	20.4	0.7	24.0	21.2	25.6	0.9	24.6	8.4	44.6	9.5
179	19.5	17.3	20.4	0.5	23.2	20.2	25.1	1.1	21.6	10.9	44.8	7.4
186	19.5	17.9	20.9	0.6	24.0	20.2	26.1	1.3	24.4	9.3	41.3	8.2

Table 9.22. Weekly summary statistics of differential pressures (Pa) for house #6

End date	Basement-out				Basement-subslab				Basement-upstairs			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	3.59	1.34	7.18	1.17	0.21	-0.10	0.68	0.25	0.34	-0.19	2.39	0.50
306	3.94	1.83	7.58	1.15	0.11	-0.08	0.32	0.09	0.33	-0.23	2.13	0.52
313	4.19	1.17	7.40	1.31	0.11	-0.05	0.32	0.08	0.47	-0.20	2.05	0.54
320	5.50	2.93	7.65	1.01	0.08	-0.07	0.23	0.06	0.46	-0.29	1.83	0.50
327	4.41	-20.69	7.76	3.68	0.11	-0.04	0.36	0.06	0.53	-0.33	5.02	0.65
334	4.01	-12.09	10.95	1.48	0.06	-0.28	0.30	0.07	2.11	-1.43	23.34	5.39
341	3.46	-18.02	6.36	2.31	0.05	-0.15	0.19	0.06	1.87	-0.50	22.99	4.47
348	4.19	1.01	7.35	1.21	0.11	0.00	0.24	0.05	2.91	-0.09	23.33	5.98
355	3.89	1.54	6.35	0.89	0.11	-0.01	0.21	0.05	1.58	-0.07	22.15	3.59
362	3.83	-0.87	6.01	0.92	0.07	-0.11	0.21	0.06	2.16	-0.25	23.28	5.00
4	4.44	2.07	6.52	0.98	-1.24	-2.15	0.38	0.99	0.74	-0.70	2.15	0.60
11	4.51	2.18	7.00	0.91	-4.42	-7.69	-1.84	2.59	0.89	-0.14	1.93	0.52
18	3.87	1.22	6.89	1.40	-7.18	-7.64	-3.08	0.33	0.63	-0.49	2.03	0.52
25	5.15	3.10	8.01	1.08	-8.01	-9.75	-6.80	0.81	0.50	-0.38	1.42	0.42
32	5.18	3.04	8.43	1.20	-9.28	-10.02	0.66	1.37	0.52	-0.80	1.36	0.44
39	4.03	1.65	6.16	0.97	-10.96	-21.14	15.18	9.94	0.50	-0.28	1.57	0.45
46	5.01	2.41	8.29	1.26	-13.96	-19.24	-10.36	2.56	0.52	-0.31	1.38	0.42
53	4.20	1.33	8.51	1.27	-12.48	-13.76	-5.79	0.97	0.63	-1.00	1.92	0.49
60	3.71	1.97	5.68	0.73	-11.28	-12.48	-7.67	0.58	1.66	-0.18	23.13	3.98
67	2.86	-0.38	5.48	1.38	-7.20	-11.05	-2.03	1.74	1.19	-0.19	23.28	3.40
74	3.71	1.19	6.10	1.01	-14.45	-20.06	-3.45	4.55	0.41	-0.32	1.61	0.39
81	3.21	1.48	4.77	0.72	-16.48	-24.61	-8.53	3.21	0.21	-21.01	1.25	1.67
88	1.76	-0.60	4.26	1.00	-15.51	-20.66	-4.30	2.33	0.25	-0.12	1.27	0.29
95	2.47	-23.47	10.48	3.34	-16.38	-19.82	-14.75	0.72	1.64	-0.33	23.08	4.52
102	2.23	-1.30	3.86	0.92	-15.11	-17.41	-13.68	0.64	0.20	-0.31	1.14	0.33
109	2.02	-0.99	4.63	1.00	-14.07	-15.61	-12.41	0.55	0.23	-0.25	1.23	0.36
116	1.88	-1.06	4.35	0.99	-14.36	-15.72	-11.92	0.45	0.14	-0.37	1.12	0.33
123	2.40	0.31	4.78	0.77	-13.44	-15.64	-9.77	1.30	0.16	-0.38	3.70	0.49
130	1.79	-0.46	4.95	1.17	-16.31	-20.18	0.03	2.70	0.11	-0.81	1.86	0.32
137	1.42	-0.93	5.25	1.03	-6.74	-20.93	1.91	9.24	0.00	-0.48	1.80	0.27
144	1.09	0.35	1.69	0.44	-15.74	-16.38	-15.37	0.26	-0.04	-0.11	0.14	0.06
151	1.51	-0.13	4.63	0.77	-15.73	-17.02	-13.99	0.61	0.11	-0.34	2.30	0.63
158	1.35	0.40	6.75	0.57	-9.16	-24.43	0.60	9.22	-0.04	-1.98	2.51	0.53
165	1.12	0.28	2.89	0.49	-9.94	-22.36	0.88	10.05	-0.04	-0.26	2.02	0.31
172	1.03	-19.16	5.72	1.82	-8.52	-23.33	0.76	9.93	0.25	-0.22	2.34	0.70
179	1.30	-10.29	19.87	1.70	-13.23	-23.42	0.46	10.01	0.07	-0.28	2.27	0.60
186	1.51	0.27	3.45	0.75	-14.38	-23.63	0.71	9.82	0.23	-0.26	2.44	0.78

Table 9.23. Weekly summary statistics of radon concentrations (pCi/L) for house #6

End date	Basement				Upstairs				Crawlspace			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	19.5	6.2	28.6	4.4	8.0	0.0	5.1	3.7	34.6	10.3	48.9	8.4
306	19.3	11.7	27.1	3.3	8.7	0.7	15.7	3.2	36.2	19.1	52.8	7.3
313	20.5	12.2	28.7	3.0	9.8	0.0	17.5	3.8	36.1	12.9	53.4	8.7
320	21.2	16.3	25.8	2.0	12.3	3.8	16.4	2.1	41.7	20.1	51.9	4.9
327	19.9	12.7	74.0	6.2	12.2	5.2	39.2	4.5	42.9	25.7	156.8	17.0
334	18.9	2.3	30.2	3.5	11.1	5.5	20.2	2.5	29.0	4.8	53.0	6.7
341	30.3	17.8	125.9	13.2	17.8	3.7	54.8	8.8	42.4	20.2	136.5	21.4
348	24.1	18.2	31.2	2.8	14.1	6.1	19.5	2.3	29.6	21.1	38.1	3.7
355	25.3	1.6	31.2	3.6	15.0	2.6	24.1	2.7	36.8	3.3	55.7	7.1
362	24.0	14.7	33.2	4.0	14.9	8.3	34.0	4.1	38.3	28.2	98.9	9.6
4	29.8	17.2	86.5	11.1	10.8	4.5	19.7	3.9	18.1	3.5	42.8	14.2
11	24.7	17.9	36.1	3.3	7.7	4.0	11.3	1.4	6.4	3.2	10.1	1.3
18	29.0	14.8	57.5	9.8	8.2	3.3	15.4	2.4	7.6	2.3	14.4	3.4
25	39.9	8.8	160.2	10.5	13.3	2.2	214.9	20.3	12.3	8.5	18.2	1.7
32	27.6	14.6	45.7	8.5	10.6	6.4	19.8	3.2	12.1	7.1	37.9	4.0
39	22.3	14.1	44.8	7.3	8.9	4.9	20.7	3.5	11.2	5.9	28.0	5.5
46	24.5	14.4	32.9	4.8	8.8	5.4	12.5	1.4	9.1	1.0	12.6	1.5
53	24.6	13.2	31.6	3.6	9.4	5.5	12.6	1.4	9.4	4.8	13.5	1.5
60	18.6	12.0	25.8	2.8	7.6	4.8	14.5	1.5	7.4	4.3	13.9	1.5
67	19.3	1.2	33.6	9.6	6.4	0.0	15.3	2.2	6.2	0.3	9.8	2.4
74	9.6	4.1	18.9	2.4	5.1	1.8	8.5	1.3	7.7	2.5	13.5	2.3
81	5.5	3.0	9.7	1.3	3.3	1.2	7.5	1.3	5.5	1.6	12.7	2.5
88	3.9	0.3	8.1	1.5	2.2	0.0	6.0	1.5	2.7	0.0	7.8	2.0
95	3.2	1.5	5.5	1.0	1.8	0.0	4.2	0.9	2.9	0.0	7.8	1.6
102	3.4	0.9	6.5	0.9	2.2	0.0	5.7	1.1	2.8	0.1	50.8	3.0
109	3.2	0.1	6.2	1.2	1.7	0.0	4.8	1.0	2.3	0.0	6.1	1.5
116	2.7	0.3	6.0	1.1	1.4	0.0	3.5	0.7	1.8	0.0	5.3	1.2
123	3.1	1.2	6.0	0.9	2.0	0.0	4.5	0.9	2.6	0.1	6.4	1.2
130	3.0	0.1	5.3	0.9	1.5	0.0	5.0	1.0	1.6	0.0	4.8	1.0
137	18.3	0.3	48.8	14.1	7.6	0.0	28.1	8.3	20.5	0.0	72.7	20.4
144	1.4	0.2	2.5	0.6	0.2	0.0	0.7	0.2	0.4	0.0	1.0	0.2
151	2.5	0.4	5.7	1.0	1.5	0.0	5.1	1.3	1.4	0.0	4.9	1.0
158	17.7	0.3	54.9	18.9	5.5	0.0	24.3	6.0	18.1	0.1	72.6	22.5
165	17.8	0.3	57.9	17.5	4.1	0.0	16.9	4.3	15.8	0.2	50.5	15.4
172	19.2	1.1	60.0	16.9	5.8	0.9	21.9	4.4	13.5	0.5	41.1	12.1
179	10.0	0.1	51.8	13.1	2.7	0.0	14.1	2.9	7.4	0.0	39.7	10.2
186	10.9	0.7	53.5	13.3	3.8	0.0	15.8	3.0	8.3	0.4	37.6	9.9

Table 9.24. Weekly summary statistics of relative humidity (%) and central air handler usage (%) for house #6

End date	Relative humidity				Air handler, fraction on			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	45.4	41.0	52.7	2.8	0.129	0.000	0.907	0.221
306	45.7	38.1	51.3	3.6	0.150	0.000	1.000	0.234
313	43.8	36.6	62.8	6.3	0.218	0.000	0.933	0.249
320	33.1	24.6	48.0	5.5	0.383	0.000	1.000	0.282
327	31.2	25.0	37.3	2.9	0.335	0.000	1.000	0.272
334	35.4	27.8	42.9	2.8	0.331	0.000	1.000	0.308
341	30.5	25.2	41.1	4.3	0.366	0.000	1.000	0.281
348	29.1	22.1	40.9	3.9	0.392	0.000	1.000	0.289
355	27.9	22.9	33.3	2.4	0.332	0.000	0.963	0.250
362	27.1	23.9	35.6	2.7	0.411	0.000	1.000	0.270
4	26.1	23.6	32.2	1.7	0.439	0.000	1.000	0.273
11	24.7	21.7	28.3	1.7	0.444	0.000	1.000	0.246
18	28.0	25.1	35.9	3.1	0.374	0.000	1.000	0.304
25	27.5	24.0	32.3	1.5	0.509	0.000	1.000	0.231
32	25.5	23.6	27.8	1.2	0.518	0.000	1.000	0.235
39	28.0	25.9	30.3	1.1	0.394	0.000	0.980	0.251
46	25.8	23.6	28.7	1.2	0.483	0.000	0.997	0.245
53	24.8	22.6	26.7	0.7	0.412	0.000	0.997	0.275
60	26.7	25.3	29.6	0.9	0.370	0.000	0.987	0.239
67	29.9	27.0	36.7	2.0	0.285	0.000	1.000	0.266
74	28.5	24.7	37.7	3.5	0.351	0.000	1.000	0.268
81	26.0	24.6	28.8	1.1	0.316	0.000	0.863	0.240
88	33.7	28.5	42.2	3.7	0.102	0.000	0.797	0.185
95	40.0	35.2	46.1	2.4	0.235	0.000	1.000	0.245
102	41.7	39.8	45.0	1.0	0.181	0.000	0.673	0.206
109	43.6	39.5	54.6	3.4	0.174	0.000	0.830	0.203
116	53.4	43.5	61.9	4.8	0.115	0.000	0.763	0.185
123	43.0	38.8	46.2	1.3	0.197	0.000	0.823	0.224
130	49.9	43.3	62.8	5.4	0.121	0.000	1.000	0.200
137	54.4	44.6	60.1	3.7	0.054	0.000	1.000	0.165
144	70.0	69.3	70.9	0.5	0.000	0.000	0.000	0.000
151	71.0	61.0	83.9	5.3	0.117	0.000	1.000	0.303
158	73.7	70.5	76.3	1.4	0.060	0.000	1.000	0.225
165	72.4	69.1	76.1	1.8	0.027	0.000	1.000	0.152
172	72.8	70.8	75.1	0.9	0.172	0.000	1.000	0.361
179	75.1	72.3	77.3	1.1	0.092	0.000	1.000	0.274
186	77.0	74.3	80.0	1.5	0.160	0.000	1.000	0.354

Table 9.25. Weekly summary statistics of temperature (°C) for house #7

End date	Basement				Upstairs				Outdoor			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	20.3	19.7	21.2	0.3	21.5	19.8	24.2	0.9	11.5	0.5	22.9	5.2
306	20.2	19.5	21.0	0.2	21.4	19.5	23.9	0.8	10.1	-1.6	19.9	5.0
313	20.0	19.5	20.5	0.2	21.0	19.7	22.1	0.5	8.3	-1.2	21.7	5.2
320	19.7	18.9	20.7	0.4	20.8	19.4	22.6	0.5	1.6	-9.1	10.8	4.6
327	19.4	18.4	20.0	0.3	20.7	18.5	21.6	0.6	3.6	-6.3	13.4	4.9
334	19.4	18.4	20.3	0.3	20.9	18.7	22.2	0.5	5.3	-3.5	17.6	4.6
341	19.0	17.8	20.1	0.4	20.4	18.6	21.2	0.5	2.5	-7.3	12.0	4.9
348	19.0	18.3	19.4	0.2	20.4	19.2	21.8	0.4	0.8	-12.4	11.7	4.9
355	19.1	18.5	19.5	0.2	20.8	19.4	21.7	0.4	1.9	-5.8	7.1	3.3
362	18.4	16.3	19.0	0.6	20.6	18.9	21.8	0.5	1.9	-7.3	10.3	4.1
4	18.8	18.2	19.4	0.2	20.6	19.5	21.6	0.5	0.3	-6.3	6.0	2.8
11	18.8	18.1	19.2	0.2	20.8	19.5	21.7	0.4	-0.1	-8.2	6.1	3.3
18	18.8	18.3	19.5	0.2	20.9	18.0	22.5	0.6	1.8	-8.5	12.0	4.8
25	18.3	17.2	19.4	0.5	20.4	19.0	22.5	0.7	-4.8	-16.9	1.6	4.8
32	17.9	17.0	18.7	0.4	20.5	19.5	22.0	0.5	-5.2	-19.9	2.7	5.4
39	18.3	17.7	19.4	0.2	20.8	11.7	21.8	0.7	1.1	-6.3	9.6	4.0
46	18.1	17.2	18.8	0.3	20.4	18.8	21.8	0.5	-4.4	-16.6	5.0	4.4
53	17.9	17.2	18.7	0.3	20.9	19.4	22.4	0.6	-2.1	-15.6	8.7	5.2
60	18.3	17.7	18.9	0.2	20.9	19.7	22.2	0.5	1.2	-7.2	12.6	4.3
67	18.3	17.6	19.0	0.3	21.0	19.4	23.8	0.8	5.0	-6.3	23.1	7.3
74	18.3	17.7	18.9	0.2	21.0	19.6	23.6	0.7	0.9	-10.2	19.0	6.1
81	18.4	17.7	19.0	0.2	21.1	19.6	23.6	0.8	4.1	-3.8	13.3	4.6
88	18.6	18.0	19.4	0.3	21.8	18.7	23.9	0.9	11.5	-1.5	21.4	5.8
95	18.5	17.8	19.1	0.3	21.0	19.4	23.9	0.7	8.2	-2.4	17.5	5.2
102	18.6	17.9	19.7	0.3	21.2	19.3	24.8	1.0	10.5	2.1	24.1	5.8
109	18.9	18.2	19.9	0.3	21.3	20.0	24.2	0.8	10.8	0.0	24.1	4.7
116	19.3	18.7	20.2	0.3	21.3	19.9	23.6	0.8	11.6	-0.1	23.4	5.0
123	18.8	17.9	19.5	0.4	20.9	18.8	23.0	0.9	10.1	0.4	18.4	4.4
130	19.1	18.2	21.2	0.5	21.9	19.1	29.7	2.0	13.5	3.7	29.9	7.3
137	19.8	18.5	21.2	0.7	22.5	16.8	29.7	2.3	16.8	1.1	30.6	6.7
144	19.9	18.0	21.5	1.0	22.3	17.7	27.9	2.6	16.6	8.0	32.8	6.3
151	21.1	19.1	24.5	1.8	24.7	20.1	34.1	3.9	20.9	9.1	36.8	8.0
158	22.0	20.3	24.2	1.1	23.9	19.2	32.5	2.7	20.3	12.1	33.3	5.3
165	22.0	20.2	23.8	0.9	24.1	18.1	30.2	2.2	21.4	8.2	34.1	5.6
172	24.0	22.4	25.5	0.7	27.0	21.5	33.0	2.4	25.2	13.9	37.2	5.8
179	23.2	22.1	24.9	0.6	24.3	20.6	30.1	2.0	21.6	13.6	34.5	4.8
186	24.1	22.1	25.8	0.7	26.8	20.9	32.5	2.0	24.5	14.0	34.0	5.1

Table 9.26. Weekly summary statistics of differential pressures (Pa) for house #7

End date	Basement-out				Basement-subslab				Basement-upstairs			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	1.90	-0.68	7.26	0.99	0.18	-0.18	0.92	0.29	0.19	-0.33	1.54	0.36
306	1.89	-0.04	4.28	0.81	0.48	0.18	1.02	0.17	0.08	-0.23	2.96	0.42
313	2.21	-0.11	5.70	0.94	0.57	0.17	1.27	0.20	0.26	-0.70	2.42	0.41
320	3.58	2.05	7.64	1.11	0.82	-1.01	1.74	0.32	0.49	-0.16	1.36	0.34
327	3.77	1.25	11.35	1.69	0.14	-2.48	2.77	0.88	0.52	-2.23	2.06	0.39
334	2.89	0.35	5.57	0.79	0.23	-2.30	3.14	0.84	0.36	-0.48	1.98	0.31
341	3.48	1.22	7.63	1.11	0.81	0.36	2.02	0.25	0.42	-0.69	1.19	0.22
348	3.83	1.87	9.81	1.26	0.90	0.48	2.16	0.28	0.56	0.07	1.41	0.21
355	3.86	2.17	10.63	1.35	0.90	0.55	2.34	0.30	0.53	0.09	1.14	0.17
362	3.65	0.04	10.07	1.53	0.17	0.08	0.99	0.22	0.65	-1.37	1.93	0.69
4	4.63	3.24	7.05	0.63	0.06	-0.51	0.10	0.04	0.92	0.12	1.77	0.21
11	4.64	3.17	8.96	1.15	0.06	0.04	0.08	0.01	0.85	0.34	1.46	0.17
18	4.16	1.55	8.87	1.39	0.06	0.04	0.09	0.01	0.73	0.17	1.47	0.26
25	5.12	2.89	11.63	1.51	0.07	0.03	0.10	0.01	0.98	0.19	2.03	0.31
32	5.25	3.21	8.80	1.21	0.09	0.06	0.11	0.01	0.99	0.27	1.79	0.26
39	4.04	2.11	8.99	1.14	0.08	0.05	0.10	0.01	0.80	0.26	4.07	0.33
46	2.32	0.07	10.74	3.14	0.08	0.05	0.10	0.01	1.00	0.19	1.99	0.29
53	0.15	0.11	0.20	0.02	0.09	0.07	0.12	0.01	0.81	0.24	1.47	0.26
60	0.11	0.07	0.15	0.02	0.08	0.06	0.10	0.01	0.74	0.20	1.27	0.23
67	0.08	0.04	0.14	0.02	0.07	0.04	0.09	0.01	0.69	0.09	2.55	0.33
74	0.07	0.02	0.11	0.02	0.06	0.04	0.08	0.01	0.74	0.15	2.56	0.33
81	0.08	0.03	0.12	0.02	0.06	0.04	0.09	0.01	0.69	0.21	1.61	0.28
88	0.64	-4.13	2.52	0.89	1.80	0.04	4.55	1.85	0.36	-0.54	5.26	0.52
95	2.91	-0.48	6.89	1.20	1.42	-7.53	5.51	2.92	0.39	-0.01	3.05	0.39
102	2.12	-1.53	5.02	0.95	-1.05	-1.98	-0.09	0.28	0.32	-0.84	2.26	0.41
109	1.92	-1.71	4.78	0.83	-1.16	-2.28	-0.48	0.24	0.34	-0.14	3.52	0.36
116	1.90	-0.38	3.72	0.82	-1.23	-2.30	-0.65	0.25	0.32	-0.05	2.79	0.38
123	2.15	-1.07	5.23	0.97	-0.98	-1.65	0.04	0.35	0.26	-1.23	4.74	0.42
130	1.40	-4.06	3.40	1.05	-0.97	-1.94	-0.31	0.29	0.26	-0.57	4.04	0.58
137	0.80	-1.94	2.69	0.77	-0.33	-1.74	0.57	0.71	-0.11	-0.24	0.43	0.09
144	0.83	-0.97	3.16	0.77	-0.71	-1.64	0.22	0.57	-0.08	-0.28	0.79	0.14
151	0.14	-3.21	2.00	0.99	0.05	-0.49	0.47	0.19	0.07	-0.39	1.80	0.42
158	0.10	-1.87	2.10	0.60	-0.80	-2.68	0.41	1.06	-0.09	-0.80	4.16	0.59
165	0.19	-2.46	2.04	0.63	-2.51	-3.32	-1.13	0.35	0.09	-0.61	2.97	0.42
172	-0.16	-2.85	0.89	0.71	-2.91	-3.45	-0.53	0.32	0.08	-0.43	3.24	0.45
179	0.13	-9.54	6.76	0.86	-2.10	-5.97	1.89	1.46	0.08	-0.78	3.91	0.45
186	-0.42	-4.15	0.84	0.92	-2.05	-4.36	-0.08	1.41	0.02	-1.01	3.59	0.75

Table 9.27. Weekly summary statistics of radon concentrations (pCi/L) for house #7

End date	Basement				Upstairs			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	30.5	14.9	46.2	5.6	5.5	0.3	16.4	4.0
306	29.8	19.1	42.2	4.3	8.1	0.5	20.4	4.5
313	31.0	19.8	41.0	3.6	11.4	0.8	20.4	5.0
320	33.7	2.6	45.1	3.1	16.6	1.0	23.3	3.2
327	32.1	16.1	84.2	9.8	14.4	1.9	22.2	4.2
334	29.9	17.9	80.9	9.7	12.4	0.9	18.8	3.4
341	32.9	22.6	103.5	13.4	15.2	3.7	24.5	3.8
348	34.0	26.4	53.2	4.4	17.6	4.5	24.2	3.4
355	33.9	27.0	53.5	4.9	16.8	7.0	24.7	3.4
362	9.4	0.0	41.9	13.7	2.6	0.0	22.1	4.8
4	1.2	-0.3	12.6	3.1	0.5	0.0	1.3	0.2
11	0.1	-0.2	0.5	0.1	0.5	0.0	1.1	0.2
18	0.3	-0.3	0.9	0.2	0.5	0.0	1.5	0.2
25	1.3	0.0	71.1	6.2	2.1	0.0	153.2	13.6
32	2.2	0.1	19.4	3.9	1.4	0.0	9.9	2.2
39	0.8	0.0	2.5	0.5	0.4	0.0	1.4	0.3
46	0.9	0.0	2.8	0.6	0.4	0.0	1.3	0.3
53	1.7	0.0	4.1	1.0	0.6	0.0	1.7	0.4
60	4.0	0.8	35.4	5.3	1.4	0.0	12.7	1.7
67	7.6	0.0	37.0	10.4	4.0	0.0	15.1	5.0
74	0.3	-0.4	1.4	0.2	0.2	0.0	0.9	0.1
81	0.3	0.0	0.9	0.2	0.2	0.0	0.6	0.1
88	15.0	-0.2	37.4	14.4	0.3	0.0	0.8	0.2
95	9.8	0.0	33.8	9.5				
102	0.4	0.0	1.3	0.3	0.1	0.0	0.3	0.1
109	0.3	0.0	1.4	0.2	0.1	-0.1	0.6	0.1
116	0.4	0.0	1.5	0.3	0.2	-0.1	0.6	0.1
123	0.4	0.0	1.2	0.3	0.2	0.0	0.6	0.1
130	0.5	0.0	1.5	0.3	0.2	0.0	0.5	0.1
137	8.7	0.0	33.0	8.7	0.4	0.0	2.2	0.5
144	2.5	0.0	16.9	4.0	0.1	0.0	0.8	0.1
151	16.1	0.7	42.8	13.8	0.3	-0.3	1.1	0.3
158	4.6	0.0	28.7	5.1	0.3	0.0	1.6	0.4
165	0.1	0.0	0.4	0.1	0.1	0.0	0.3	0.1
172	0.1	-0.1	0.5	0.1	0.1	-0.1	0.2	0.1
179	1.3	-0.1	4.2	1.5	0.1	-0.3	0.2	0.1
186	1.1	0.0	5.0	1.2	0.1	-0.1	0.4	0.1

Table 9.28. Weekly summary statistics of relative humidity (%) and central air handler usage (%) for house #7

End date	Relative humidity				Air handler, fraction on			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
299	64.2	61.8	66.8	1.1	0.036	0.000	0.590	0.085
306	63.4	58.9	65.2	1.5	0.063	0.000	1.000	0.137
313	61.1	57.7	65.8	1.9	0.094	0.000	0.963	0.126
320	55.4	49.0	65.0	4.4	0.163	0.000	0.457	0.115
327	51.3	48.6	55.6	1.6	0.156	0.000	0.643	0.116
334	52.5	50.5	56.3	1.3	0.128	0.000	1.000	0.138
341	49.6	47.0	54.7	2.1	0.165	0.000	0.420	0.090
348	48.4	45.1	51.8	1.5	0.192	0,000	0.810	0.103
355	46.9	45.2	48.1	0.7	0.186	0.000	0.627	0.084
362	44.9	38.7	48.2	2.3	0.187	0.000	0.493	0.095
4	43.2	41.7	44.3	0.6	0.249	0.000	1.000	0.127
11	41.7	40.5	43.0	0.7	0.238	0.000	0.423	0.089
18	42.2	39.9	45.3	1.3	0.197	0.000	0.507	0.110
25	40.9	36.7	43.1	2.0	0.264	0.000	0.653	0.110
32	38.3	35.0	41.8	1.7	0.265	0.000	0.657	0.103
39	40.3	38.3	42.4	1.0	0.182	0.000	1.000	0.112
46	37.9	33.7	41.8	1.8	0.270	0.000	1.000	0.113
53	35.5	32.4	38.1	1.2	0.208	0.000	0.530	0.118
60	37.4	35.2	41.8	1.3	0.176	0.000	1.000	0.103
67	40.5	37.8	45.0	1.5	0.145	0.000	1.000	0.136
74	39.8	36.4	45.5	2.4	0.165	0.000	1.000	0.135
81	38.4	36.6	41.6	1.0	0.137	0.000	0.487	0.108
88	44.2	40.0	51.4	2.9	0.037	0.000	0.287	0.072
95	51.3	48.2	57.6	2.0	0.086	0.000	1.000	0.123
102	49.9	48.4	51.2	0.6	0.059	0.000	0.490	0.086
109	50.7	48.1	58.5	2.4	0.057	0.000	0.330	0.078
116	58.0	51.6	63.1	2.8	0.046	0.000	0.280	0.071
123	50.0	47.5	51.8	1.0	0.047	0.000	0.343	0.077
130	52.6	50.8	55.3	1.0	0.032	0.000	0.503	0.068
137	56.0	52.2	59.0	1.4	0.000	0.000	0.000	0.000
144	60.6	55.9	67.7	3.9	0.000	0.000	0.000	0.000
151	68.8	63.8	75.6	4.1	0.000	0.000	0.000	0.000
158	72.3	66.8	75.1	2.5	0.000	0.000	0.000	0.000
165	69.1	64.0	75.1	3.5	0.000	0.000	0.000	0.000
172	71.9	67.3	79.7	3.1	0.000	0.000	0.000	0.000
179	75.1	69.5	82.3	2.3	0.000	0.000	0.000	0.000
186	76.1	70.4	81.5	2.9	0.000	0.000	0.000	0.000

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

End date	Outdoor temp (°C)				Soil temp. (°C)			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
292	11.5	2.0	23.9	5.0	19.8	19.2	20.2	0.3
299	12.8	2.3	24.0	5.4	18.6	18.2	19.2	0.3
306	11.1	-1.1	22.6	5.0	17.8	17.3	18.2	0.2
313	8.7	-1.0	20.5	5.2	16.7	16.0	17.3	0.4
320	2.6	-7.3	12.2	4.7	15.5	14.4	16.1	0.5
327	3.8	-6.0	15.1	4.6	13.7	12.8	14.4	0.5
334	6.0	-2.5	18.4	4.1	12.4	12.1	12.8	0.2
341	3.1	-6.6	12.5	4.5	11.5	10.9	12.1	0.3
348	1.7	-9.5	11.5	4.4	10.5	10.1	10.9	0.2
355	2.5	-5.7	9.7	3.5	9.4	8.8	10.1	0.3
362	3.0	-2.9	9.7	2.8	8.6	8.5	8.8	0.0
4	0.5	-4.9	7.1	2.8	8.4	8.1	8.6	0.2
11	1.1	-6.6	10.3	3.3	7.8	7.6	8.1	0.1
18	2.7	-7.5	13.8	4.7	7.5	7.4	7.6	0.1
25	-2.5	-9.4	2.6	2.9	7.2	6.9	7.6	0.2
32	-1.9	-9.3	8.7	3.6	6.6	6.5	6.9	0.1
39	2.3	-5.9	13.8	4.4	6.4	6.2	6.5	0.1
46	-2.4	-10.0	6.3	3.7	6.1	5.9	6.2	0.1
53	0.3	-9.8	12.5	5.3	5.7	5.6	5.9	0.1
60	2.5	-4.6	10.7	4.1	5.5	5.2	5.6	0.1
67	6.3	-6.3	26.8	7.6	5.3	5.2	5.5	0.1
74	2.3	-9.6	18.4	6.0	6.2	5.5	6.3	0.2
81	5.6	-4.2	20.2	5.2	6.6	6.3	6.8	0.2
88	13.2	0.9	26.5	6.3	7.5	6.8	8.4	0.5
95	9.0	-1.7	17.7	5.8	8.9	8.4	9.3	0.3
102	14.0	5.1	25.9	6.0	10.1	9.9	10.3	0.1
109	12.4	2.8	28.4	5.0	10.9	10.4	11.2	0.2
116	14.5	3.4	30.1	6.1	12.1	11.2	12.8	0.5
123	11.0	2.0	21.4	4.4	12.9	12.8	13.1	0.1
130	14.9	4.1	31.4	7.1	13.3	13.1	13.9	0.2
137	18.3	2.8	33.1	6.8	14.8	13.9	15.5	0.5
144	17.9	8.1	34.7	6.6	15.9	15.5	16.4	0.2
151	20.4	11.5	34.7	6.7	17.0	16.4	17.8	0.3
158	20.9	13.3	34.8	4.8	18.7	17.8	19.0	0.4
165	22.3	9.8	34.2	5.8	19.4	19.0	19.6	0.2
172	25.0	13.0	35.0	5.5	20.4	19.6	21.0	0.4
179	22.6	14.0	34.9	4.6	21.4	21.0	21.6	0.2
186	25.2	13.6	34.8	5.1	21.8	21.5	22.2	0.2

Table 9.30. **Weekly summary statistics of wind speed, barometric pressure, and rainfall for the weather station**

End date	Wind speed (m/s)				Barometric pressure (millibars)				Rainfall (0.01"/30 min.)			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
292	1.04	0.45	2.76	0.54	1000.9	986.0	1014.0	7.2	0.3	0.0	18.0	1.6
299	1.07	0.45	2.40	0.50	1002.1	994.0	1009.0	3.3	0.4	0.0	16.0	1.7
306	1.21	0.45	3.49	0.69	1004.8	990.0	1023.0	9.7	0.1	0.0	4.0	0.5
313	1.13	0.45	3.87	0.79	1003.5	993.0	1015.0	5.7	1.0	0.0	18.0	2.5
320	1.46	0.45	4.97	0.89	1006.9	992.0	1021.0	7.0	0.4	0.0	14.0	2.0
327	1.88	0.45	7.12	1.26	997.3	980.0	1010.0	8.5	1.4	0.0	58.0	5.6
334	1.56	0.45	4.88	0.82	1001.6	985.0	1013.0	5.4	1.1	0.0	42.0	4.9
341	2.39	0.49	5.71	1.31	1005.1	980.0	1020.0	11.0	1.0	0.0	44.0	3.9
348	1.99	0.49	5.34	1.15	1003.0	990.0	1023.0	8.7	0.5	0.0	14.0	2.1
355	2.33	0.47	9.48	1.65	1002.2	982.0	1013.0	7.5	1.4	0.0	36.0	4.7
362	1.41	0.45	3.87	0.72	1002.8	983.0	1008.0	5.7	0.0	0.0	2.0	0.2
4	1.89	0.45	5.79	1.17	997.6	979.0	1009.0	8.8	0.3	0.0	8.0	1.1
11	2.08	0.45	7.16	1.48	995.1	973.0	1009.0	10.4	0.2	0.0	14.0	1.3
18	2.19	0.47	5.79	1.38	995.9	980.0	1011.0	9.0	0.3	0.0	18.0	1.7
25	2.12	0.45	6.70	1.51	991.8	962.0	1007.0	11.1	0.2	0.0	14.0	1.3
32	1.78	0.45	5.37	1.07	992.4	977.0	1003.0	6.9	0.1	0.0	8.0	0.8
39	2.04	0.45	6.00	1.22	991.3	973.0	1011.0	10.5	0.0	0.0	0.0	0.0
46	2.52	0.45	6.12	1.16	990.8	975.0	1003.0	6.0	0.1	0.0	6.0	0.5
53	1.66	0.45	3.98	0.72	997.3	987.0	1007.0	4.7	0.0	0.0	6.0	0.3
60	2.04	0.45	5.32	1.25	998.0	971.0	1012.0	11.0	1.1	0.0	26.0	3.8
67	2.02	0.45	6.38	1.28	996.5	974.0	1010.0	9.6	0.0	0.0	2.0	0.2
74	1.56	0.45	3.89	0.67	997.1	978.0	1010.0	8.1	0.0	0.0	0.0	0.0
81	1.82	0.48	3.72	0.70	989.3	981.0	1001.0	5.2	0.0	0.0	0.0	0.0
88	1.56	0.45	4.70	1.01	992.0	986.0	1001.0	3.4	0.1	0.0	8.0	0.8
95	3.06	0.51	6.37	1.15	985.3	967.0	997.0	7.9	1.9	0.0	50.0	5.2
102	1.70	0.45	4.20	0.86	985.7	982.0	991.0	2.0	0.2	0.0	12.0	1.1
109	1.68	0.45	3.77	0.78	993.6	983.0	1004.0	5.2	0.3	0.0	12.0	1.3
116	1.54	0.45	3.64	0.85	997.9	991.0	1004.0	3.4	0.9	0.0	24.0	3.6
123	1.77	0.45	4.91	1.00	989.5	970.0	1003.0	7.2	0.5	0.0	38.0	2.7
130	1.28	0.45	2.91	0.63	994.8	988.0	1005.0	4.8	0.2	0.0	6.0	0.8
137	1.40	0.45	3.19	0.66	996.0	988.0	1008.0	5.5	0.3	0.0	48.0	3.2
144	1.44	0.45	3.19	0.59	999.4	988.0	1007.0	4.5	0.3	0.0	10.0	1.1
151	1.14	0.45	2.29	0.40	1000.5	991.0	1008.0	5.1	0.0	0.0	4.0	0.3
158	1.11	0.45	2.18	0.44	997.2	990.0	1003.0	3.0	0.6	0.0	26.0	2.4
165	1.32	0.45	3.05	0.61	992.2	986.0	1003.0	4.3	0.2	0.0	10.0	1.2
172	1.11	0.45	2.43	0.47	992.2	985.0	1003.0	4.6	0.1	0.0	8.0	0.8
179	1.19	0.45	2.58	0.49	989.2	983.0	996.0	3.3	0.8	0.0	28.0	2.3
186	1.21	0.45	2.98	0.55	994.3	989.0	1000.0	2.6	0.1	0.0	10.0	0.7

Table 9.31. Weekly summary statistics of radon concentrations (pCi/L) in outdoor radon flux monitors and relative humidity (%) logged at the weather station

End date	Monitor in side yard (pCi/L)				Monitor at weather station (pCi/L)				Relative humidity (%)			
	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	S.D.
292	8.21	1.41	23.91	4.57	8.07	0.43	14.29	3.12	75.4	21.0	97.9	20.1
299	8.33	2.93	20.66	2.89	8.02	0.93	13.51	2.62	64.6	22.7	98.3	19.3
306	9.72	2.50	19.70	3.81	7.40	0.07	11.79	2.88	74.8	35.5	98.3	19.3
313	8.79	2.33	21.62	3.73	7.58	-0.10	12.76	2.80	83.8	40.8	98.3	15.7
320	6.01	1.33	12.18	2.37	3.88	-0.24	9.84	2.69	61.7	37.7	98.3	15.8
327	5.15	-0.03	11.84	3.26	3.43	-0.23	8.27	2.39	73.6	47.2	98.3	13.3
334	4.79	0.09	11.24	3.11	2.30	-0.05	5.14	1.55	78.0	32.0	98.3	17.7
341	4.74	-0.40	16.82	3.90	1.48	-0.27	4.84	1.40	61.0	36.4	98.3	15.1
348	2.16	-0.35	6.51	1.59	2.07	-0.26	6.57	1.76	66.3	36.0	98.3	17.0
355	5.85	0.14	15.16	3.71	4.78	-0.05	13.34	3.43	73.0	36.1	98.3	15.3
362	6.18	0.64	12.01	2.39	2.24	-0.34	6.32	1.95	68.6	52.3	98.3	8.7
4	6.13	1.36	12.70	2.55	2.78	-0.22	9.56	2.96	76.7	44.9	98.3	16.3
11	6.04	1.42	12.67	3.05	2.99	-0.22	8.84	2.94	69.8	35.8	98.3	16.4
18	4.94	0.88	11.54	2.66	2.05	-0.27	7.37	2.25	62.5	26.2	98.3	14.8
25	6.11	-0.51	88.56	5.44	2.64	-0.34	8.35	2.59	73.3	32.6	98.3	20.1
32	6.41	1.64	14.18	2.91	3.84	-0.15	12.03	3.46	61.0	20.6	98.3	19.4
39	4.74	1.75	8.88	1.76	2.89	-0.25	11.55	3.42	61.8	35.2	97.6	16.9
46	2.33	0.40	6.62	1.26	1.45	-0.26	9.40	2.32	52.8	25.6	96.9	18.9
53	4.21	0.65	9.24	1.93	7.20	0.18	22.54	6.24	37.6	18.8	74.4	12.1
60	3.23	-0.19	8.56	2.29	7.55	0.13	23.92	6.40	54.1	21.5	99.9	22.0
67	1.39	0.35	3.32	0.56	3.39	0.10	13.32	3.17	54.6	20.3	98.8	17.2
74	1.29	0.12	2.75	0.58	8.38	0.52	14.83	4.00	49.1	16.7	92.6	20.8
81	3.11	0.62	15.40	2.64	4.45	0.39	17.24	4.05	44.0	15.9	94.8	20.6
88	4.93	0.48	12.55	2.86	8.50	0.25	15.01	3.38	58.8	12.0	98.3	26.5
95	2.21	-0.12	6.95	1.80	6.17	0.08	16.45	5.69	72.6	39.9	99.8	20.3
102	0.00	0.00	0.00	0.00	16.22	4.72	25.09	4.11	51.5	12.5	97.5	24.5
109	0.00	0.00	0.00	0.00	10.56	0.13	26.66	7.95	76.8	26.6	99.9	21.9
116	0.00	0.00	0.00	0.00	14.17	-0.12	36.27	9.31	72.3	14.2	98.5	25.5
123	0.00	0.00	0.00	0.00	13.58	-0.19	26.11	6.91	59.8	17.5	97.4	26.3
130	0.00	0.00	0.00	0.00	15.77	1.32	34.58	7.05	58.5	17.7	98.6	28.8
137	0.00	0.00	0.00	0.00	13.70	4.01	24.45	4.56	55.3	19.1	95.9	22.4
144	0.00	0.00	0.00	0.00	18.09	-0.46	33.93	7.26	77.5	27.6	95.4	18.4
151	0.00	0.00	0.00	0.00	16.74	8.35	26.67	3.96	72.1	30.5	93.4	17.6
158	0.00	0.00	0.00	0.00	19.13	8.85	29.01	4.91	71.1	20.5	99.8	22.4
165	0.00	0.00	0.00	0.00	18.55	7.46	27.76	5.05	63.1	17.6	91.6	22.7
172	0.00	0.00	0.00	0.00	16.67	10.04	24.05	2.60	57.3	13.1	92.9	24.9
179	0.00	0.00	0.00	0.00	21.93	11.46	32.19	4.53	73.8	23.1	98.5	21.0
186	0.00	0.00	0.00	0.00	22.00	14.02	30.79	3.19	69.4	22.2	99.9	22.7

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