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CASE STUDIES OF
RADON REDUCTION RESEARCH
IN 13 SCHOOL BUILDINGS

Prepared for

Office of Radiation and Indoor Air

Prepared by

Air and Energy Engineering Research
Laboratory
Research Triangle Park NC 27711

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FINAL REPORT

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ABSTRACT

This report details 13 case studies covering radon mitigation research in school buildings. The research was conducted by EPA's Air and Energy Engineering Research Laboratory's (AEERL's) Radon Mitigation Branch from 1990 to 1992. The 13 schools are located in Colorado, Maine, Minnesota, Ohio, South Dakota, Tennessee, and Washington state. Diagnostics were carried out in all of these schools and suggested mitigation plans were developed for each based on the diagnostic measurements. Mitigation systems were installed in five of the 13 schools as part of the research project.

The major objective of these research projects was to better understand the conditions under which heating, ventilating, and air-conditioning (HVAC) systems in existing school buildings could be used for effective radon reduction. Criteria used to evaluate the system effectiveness included: radon reduction; long-term reliability of operation; installation, maintenance, and operating costs; and impact on the indoor air quality in the school. An additional objective, studied in three of the schools, was to compare the effectiveness of HVAC system control of radon with active subslab depressurization (ASD) control in the same building.

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METRIC CONVERSION FACTORS

Although it is EPA policy to use metric units in its documents, non-metric units have been used in this report to be consistent with common practice in the radon mitigation field. Readers may refer to the following factors to convert to that system.

Non-Metric	Times	Yields Metric
cubic foot (ft^3)	28.3	liters (L)
cubic foot per minute (cfm)	0.47	liter per second (L/s)
degrees Fahrenheit (°F)	5/9 (°F-32)	degrees centigrade (°C)
foot (ft)	0.30	meter (m)
inch (in.)	2.54	centimeters (cm)
inch of water column (in.WC)	248	pascals (Pa)
mile per hour (mph)	1.6	kilometers (km)
picocurie per liter (pCi/L)	37	becquerels per cubic meter (Bq/m^3)
square foot (ft^2)	0.093	square meter (m^2)
square inch ($in.^2$)	6.452	square centimeters (cm^2)

SECTION 1

INTRODUCTION

The purpose of Environmental Protection Agency's (EPA's) Air and Energy Engineering Research Laboratory's (AEERL's) school radon research program is to develop and demonstrate low-cost radon mitigation options for existing and new schools and other large buildings. These mitigation options must address the unique features of these structures (i.e., large size, different types of HVAC systems, and varying occupancy patterns).

This report details case studies of the radon mitigation research conducted by AEERL in 13 school buildings during 1990-92. The first three sections of this report cover background information and objectives of this research project, overall conclusions from the research, and the radon diagnostic and mitigation techniques used in these 13 school buildings. The next seven sections detail the research conducted in each of the schools. The sections are organized alphabetically by state (Colorado, Maine, Minnesota, Ohio, South Dakota, Tennessee, and Washington). A discussion of the quality control and quality assurance follows. QA/QC requirements apply to this project. The data are supported by QA/QC documentation as required by U.S. Environmental Protection Agency policy. References are listed in the final section. All of the figures and tables for the report can be found in appendices A and B, respectively.

1.1 BACKGROUND

Since 1988 AEERL's Radon Mitigation Branch has conducted radon mitigation research in 50 schools buildings located in 13 states (1). Initially, AEERL's radon mitigation research in schools focused on active soil depressurization (ASD), the most successful radon control technique in residential houses. To provide an adequate background for the research efforts covered in this report, it is important to summarize the major conclusions from earlier research (2):

1) School buildings have a number of physical characteristics that make their mitigation different, and typically more complex, than houses.

2) Radon measurements in schools can vary dramatically over time (seasonally and diurnally), and this variation must be considered when conducting diagnostics and designing the mitigation system.

3) The following diagnostic procedures are important: review of all relevant building plans, investigation of the building, analysis of the HVAC system, and measurement of subslab pressure field extension (PFE).

4) ASD can be applied successfully in schools where the slab is underlain with a clean, coarse layer of aggregate of narrow particle size range as long as subslab barriers to communication are limited.

5) ASD in schools typically requires greater fan air flow capacity and suction pipe diameters than ASD in houses.

6) PFE measurements provide essential data on the extent and the nature of subslab barriers. If all the subslab walls surrounding the classrooms extend to footings, it is necessary to have one ASD point for every two rooms and, in many cases, one point for each room. If the walls between rooms are set on thickened-slab footings and the aggregate is continuous under the footings, then the subslab pressure field will extend under the footings.

7) In general, the correlation between classroom radon concentrations and subslab radon "sniffs" was not particularly good.

8) A majority of AEERL research schools have slab-on-grade substructures, although some of the schools had portions with basements and/or crawl space substructures.

9) HVAC systems in the AEERL research schools included unit ventilators (UVs), fan coil units, radiant heat, and central air handling systems. Many of the schools did not have HVAC systems that were designed to deliver conditioned outdoor air.

10) Many of the slab-on-grade schools run their utility lines in subslab utility tunnels. Although tunnel depressurization may be a mitigation option, many of the tunnels contain asbestos.

Because of complicated subslab structures and subslab fill material that sometimes make ASD systems expensive to install, and because of indoor air quality concerns (such as carbon dioxide), AEERL has concentrated part of its recent research efforts in schools on the use of HVAC systems for radon reduction.

Using the HVAC system to control radon can be beneficial in schools where ASD is not applicable, and can also be used as a supplemental radon reduction technique in schools where ASD systems are installed in order to further reduce radon levels (to reach the long-term national goal of ambient radon levels established in the 1988 Indoor Radon Abatement Act). The HVAC system can also provide improved indoor air quality in addition to radon reduction through the introduction of additional outdoor air.

Use of the HVAC system as a radon control technique depends on the specific building, but in general, it may be considered in any school that has a HVAC system that supplies outdoor air. Specifically, use of the existing HVAC system to control radon levels is not reasonably applicable in schools where the existing HVAC system is not designed to supply conditioned outdoor air (e.g., exhaust-only system, radiant heat, or fan coil units). Also, restrictions to the use of the existing HVAC system may apply where the HVAC system does not consistently supply outdoor air during all seasons, and radon control/indoor air quality concerns in the school system are overridden by energy cost concerns.

1.2 OBJECTIVES

In 1990 AEERL expanded research of HVAC systems for radon control. Continuous dataloggers were installed in a number of research schools to monitor several parameters simultaneously. The primary objective of these research projects was to better understand the conditions under which HVAC systems in existing buildings can be used for effective radon reduction. Criteria used to evaluate the mitigation system effectiveness included:

- degree of radon reduction,
- long-term reliability as related to mechanical durability and resistance to intervention,
- installation, maintenance, and operating costs, and
- impact on the indoor air quality in the school.

Since school facility managers may sometimes be faced with a decision to use either ASD, HVAC control, or a combination of the two techniques for radon reduction, an additional objective of this research was to compare the effectiveness of HVAC system control and ASD in the same building.

1.3 APPROACH

This report details case studies from the research conducted from 1990 through 1992 to address the two objectives discussed above. The research was conducted in 13 school buildings located throughout the U.S.: two in Colorado, two in Maine, one in Minnesota, four in Ohio, one in South Dakota, one in Tennessee, and two in Washington state. The schools were selected based on a number of parameters including radon levels, type of HVAC system, building substructure type, and location. Radon diagnostics were conducted in all 13 schools and mitigation plans were developed for each.

In addition to providing the details of the diagnostic measurements and mitigation system performance, this report also presents results from the first wide scale use of continuous dataloggers to study the interactions of various radon mitigation systems with school operation and use. Dataloggers were installed in seven of these research schools to continuously monitor relevant parameters including: radon concentration, differential pressure, differential temperature, percent open of outdoor air damper, operation of exhaust fans, opening and closing of doors in the building, and carbon dioxide (CO_2) levels. AEERL's datalogging systems are described in Section 3 and elsewhere (3).

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

This report acknowledges the fact that QA/QC requirements apply to this project. The data described in these conclusions are supported by QA/QC documentation as required by U.S. Environmental Protection Agency policy. The following conclusions can be drawn from the radon mitigation research conducted by AEERL in the 13 school building case studies discussed in this report:

- If PFE measurements indicate that an ASD system will be effective, this would be the preferred system for consistent, trouble-free, and economical radon control.

- If in addition, improvement in indoor air quality or further radon reduction is desired, the amount of outdoor air supplied through the HVAC system should be increased.Increasing the amount of outdoor air will help to approach the long-term national goal of ambient radon levels in buildings established in the 1988 Indoor Radon Abatement Act.

- Some existing central HVAC systems are not designed to supply conditioned outdoor air and hence are not suitable for use as year-round radon mitigation systems because of energy cost and/or comfort concerns.

- Since it appears that unit ventilators (UVs) reduce radon levels more by dilution rather than by preventing radon entry, their successful use as mitigation systems are probably restricted to buildings with initial levels in the 4 to 10 picocuries per liter of air (pCi/L) range.

- For school constructed over crawl spaces with exposed soil, the most successful and mitigation system is a variation of ASD -- submembrane depressurization (SMD) -- which depressurizes the area under a plastic membrane covering the soil.

- Where central HVAC or UV systems are used for radon mitigation, careful attention must be given to the operation of these units in setback mode at night and over the weekend. They must be turned on early enough to lower the radon levels before the building is occupied. In some of the research schools, HVAC system start-up at 7 am did not reduce the radon levels to below 4 pCi/L limits until after 12 noon.

- Carbon dioxide levels (an indicator of indoor air quality) were well above ASHRAE guidelines (4) of 1000 parts per million (ppm) at least part of the school day in most of the schools where levels were measured. Typical levels during school occupancy averaged from 1000 ppm to 1700 ppm. The CO_2 levels typically peaked around 10:00 am and again around 3:00 pm with a decrease during lunch (noon). The levels were also higher in the winter than other times of the year. In one kindergarten classroom in South Dakota the levels over a two-week period during January 1992 were above 1000 ppm about 7-8 % of the occupied time and in a classroom of 5th graders in the same school about 25 % of the time.

SECTION 3

COMMON DIAGNOSTIC MEASUREMENT AND MITIGATION TECHNIQUES

School buildings have a number of physical characteristics that make them different, and typically more complex, than residential houses. These characteristics include: building size, substructure, subslab barriers, HVAC system design and operation, and locations of utility lines. These physical characteristics can influence radon levels in the building since they affect radon entry routes, building pressure differentials, and radon mitigation approach.

The radon diagnostic procedures used in the schools discussed in this report include: a review of all radon screening and confirmatory measurements; a review of all available building plans and specifications including structural, mechanical, and electrical; a thorough building investigation to assess potential radon entry routes and to confirm and to supplement information cited in the building plans; an analysis of the HVAC system design and operation and its influence on pressure differentials and radon levels; and measurements of PFE to assess the potential for an ASD system.

Depending on the specific objectives of each project, varying levels of diagnostics were performed in the 13 schools discussed in this report. The discussion below is not intended to be all-inclusive. Other diagnostic tests that were site specific will be described in the section in which discusses the school where the measurements were made. The subsections below provide details on the common radon diagnostic procedures used for this research. The datalogging system, the development of the test matrices, and "good" techniques for ASD system design are also discussed.

3.1 REVIEW OF RADON SCREENING AND CONFIRMATORY MEASUREMENTS

Initial radon screening, confirmatory measurements, and any additional measurements followed EPA's interim radon measurement protocol (5) as closely as possible unless modified to determine the effects of specific variables. The measurement results were written on a copy of the school floor plan, along with a description of measurement conditions. Potentially important measurement conditions include: operational status of HVAC system(s), weather (outdoor temperature, precipitation, wind, barometric pressure, etc.), and occupied or unoccupied status of the building during the measurement period.

3.2 REVIEW OF BUILDING PLANS

Building plans and specification documents were obtained for review when available. Pertinent drawings include architectural, structural, mechanical, and electrical. The following information relevant to radon diagnostic and mitigation is typically provided by these plans.

The architectural drawings will give general information on building design and also provide details on typical wall sections.

The structural drawings will contain information on the foundation, footing and thickened slab footing locations, and subslab fill. These will be helpful to assess the potential effectiveness of an ASD system by indicating the presence, size, and thickness of subslab aggregate and any barriers to subslab communication such as below-grade walls. The structural drawings may also provide clues to possible radon entry routes such as expansion joints and pipe chases.

The mechanical drawings and specifications will provide information on the HVAC system design (such as duct system design, location, duct run length, supply/return air flow design capacity, outdoor air intake locations and flow capacities, and exhaust system locations and flow capacities). The mechanical specifications should summarize the HVAC system and identify equipment. For schools with intra-slab radiant heat systems, the plans are particularly important in locating subslab piping prior to measuring subslab communication. Where applicable, the balancing report should also be consulted. Note that 15 cfm of outdoor air per person is suggested for classrooms in the most recent ASHRAE indoor air quality standard (4).

The plumbing and electrical drawings should initially be reviewed for potential radon entry routes. If subslab PFE is to be measured to determine the potential for an ASD system, these plans must be studied to determine the locations of subslab utility lines prior to drilling test holes through the slab. Even if plumbing and/or electrical lines are run under the slab, review of the plans will usually reveal suitable locations for test holes. These plans will also indicate potential trouble spots for the ASD system. These could be subslab vents, water drains (that go to daylight) or other penetrations that could short-circuit the pressure field of the ASD system.

3.3 BUILDING INVESTIGATION

A thorough building investigation was conducted to assess potential radon entry routes and confirm information cited in the building plans and specifications. Entry routes include floor/wall cracks, unsealed (or deteriorated) expansion joints, utility penetrations, and open pores of block walls or unsealed tops of block walls that penetrate the slab.

A chemical smoke stick was used to determine the direction of air movement through potential entry routes, and a micromanometer was used to determine the magnitudes of pressure differentials under various HVAC system operational modes. A continuous radon monitor was used to sample potential radon entry routes and subslab radon levels. For schools discussed in this report, a Pylon AB-5 unit with a Lucas cell operated in a sniffer mode was typically used to assess the relative significance of suspected radon entry routes and sample subslab radon levels. Observations made during the building investigation were compared with the radon measurements and correlations noted.

3.4 HVAC SYSTEM AND PRESSURE DIFFERENTIALS

The HVAC system can have significant influences on pressure differentials in a school building. Where possible, the school engineer or other knowledgeable person(s) responsible for operation and maintenance of the HVAC system were present during the analysis.

The first step was to confirm information found in the mechanical plans and specifications. Is the HVAC system actually installed and operated as designed or, for example, have outdoor air intakes been restricted thus reducing the ventilation capability controlled?

A chemical smoke stick was used to determine whether the building envelope was pressurized or depressurized relative to the outdoors, hallway, or subslab, and a micromanometer was used to quantify the pressure differentials. When analyzing the pressure differentials induced by the HVAC system, measurements were attempted under "typical" operating conditions. Depending on the type of HVAC system and the testing constraints of a given school district, these may or may not be the same conditions under which screening and confirmatory measurements were made. Attention was also paid to include all exhaust fans that are not included as part of a central HVAC system.

If the HVAC system was a major contributor to the negative pressures in the building, it was determined if this was because of the HVAC system design or because of operation and maintenance practices. If the system has the design capacity to maintain all building zones under positive pressure, it may be possible to control radon levels by adjustment of the HVAC system by a qualified person and if the levels are not too high (< 20 pCi/L). Equipment and/or procedures to identify inadequate HVAC operation were also important.

If it was suspected that radon was being distributed in the school by the air-handling system (with a central HVAC system or unit ventilators), radon "sniffs" in the supply air were compared with radon levels in the room(s). Elevated levels of indoor radon caused by radon entry into the return-air system and distribution to classrooms with recirculated room air can result from, for example: leaky subslab return air ductwork, unducted return-air plenums in the drop ceiling that are open to the subslab via open tops of block walls extending through the slab, and air intakes for unit ventilators that are open to the soil or floor-wall joint.

Many schools have not been designed to supply conditioned outdoor air to occupied spaces and, as a result, do not have the option for HVAC pressurization with current system design. Typically, with such schools, the fresh air was intended to be provided through above-grade shell leakage and openings such as windows. However, many of these schools have been retrofitted for energy conservation, decreasing the amount of outdoor air infiltration from above grade. The lack of fresh outdoor air as a result of these tightening measures can reduce dilution of the indoor air and increase the driving forces which cause radon entry.

If schools operate an exhaust fan for ventilation purposes or to remove odors or chemicals and sufficient makeup air is not supplied, significant negative pressures can result. This will exacerbate radon entry into the building through below-grade cracks and openings.

In order to quantitate the HVAC system (or systems in the case of UV systems), several measurements were carried out using a micromanometer and a flow hood. The total air flow out of the unit and the outdoor air (OA) supplied into the unit are typically measured at various openings of the OA damper and at various fan speeds (if applicable). From these measurements the ventilation rates and the cfm of OA per person can be calculated. While measuring the flow rates under the various operating conditions, the pressure differentials between inside and outside are monitored with a micromanometer to determine the pressure effects produced by the HVAC system. These pressurization (or depressurization) effects become very important if the HVAC system is to be used as part of the mitigation system.

In addition to measuring air flow rates of the HVAC and UV systems, the flow capacities of exhaust fans are quite important. Use of these fans can increase or in some cases reduce the radon levels (6).

3.5 SUBSLAB PRESSURE FIELD EXTENSION (PFE) MEASUREMENTS

As discussed above, the first step in determining the potential effectiveness of a school ASD system was analysis of the building plans to determine the locations and types of subslab walls and footings and thickened slab footings that may serve as barriers to subslab communication. The plans typically indicated whether subslab aggregate was specified. It should be noted, however, that grading of aggregate is highly variable and the indication of subslab aggregate on the plans did not necessarily ensure good PFE. If the plans were unavailable, some of the necessary information was obtained during the building inspection. One excellent potential source of information about the subslab conditions may be the maintenance personnel who may have first hand information due to repairs or maintenance that required cutting through the slab. It was also crucial that the locations of all plumbing and electrical lines were identified from the plans and/or inspection before drilling into the slab for PFE measurements.

The most important parameter in assessing the applicability of ASD is subslab communication or PFE. Subslab PFE measurements were made following AEERL protocols. Clean, coarse aggregate, approximately 1/2 to 1 in. in diameter (ASTM #5), is preferable for good PFE. PFE was typically evaluated by using a shop-type vacuum cleaner for suction at one larger hole (normally located at the potential ASD point) and a micromanometer at other smaller holes. The suction hole was at least 1 in. in diameter, and the test holes were approximately 3/8 in. in diameter and located at various distances and in various directions from the suction hole, depending on building size and configuration. This approach helped to indicate the feasibility of developing a pressure field under various parts of the slab and also helped to identify the influence of subslab barriers such as thickened slab footings or below grade foundation walls. It is also helpful in indicating competing pressures or excessive leakage from subslab ductwork which would inhibit pressure field development in an ASD system.

Pressures at the primary suction point were typically measured at suctions of about 8, 6, 4, 2 and 0 in. WC. If communication testing indicated a pressure of - 0.001 in. WC or lower at a given test hole, it was likely that an ASD system would be able to depressurize the area.

Final ASD system design depended on the results of the PFE measurements and on other important factors including building codes (with regards to penetrating firewalls, etc.), convenience, and aesthetics.

3.6 MEASUREMENT OF SUBSLAB RADON LEVELS

The radon concentrations under the slab were measured with a Pylon AB-5 monitor operating in a "sniff" mode. In this mode, subslab gas samples are extracted through the 3/8 in. diameter test holes drilled in the slab (these holes were then used in the PFE tests discussed in Section 3.5).

The Pylon was operated in a continuous mode with the internal pump pulling approximately 2.5 L/min through a 300 ml scintillator cell. The counting time for the Pylon was 30 seconds. After obtaining several background counts, the sampling hose with an in-line membrane (1 µm) or glass fiber filter was inserted into the subslab hole. The number of counts obtained in each counting interval was observed and the tube was removed from the hole after two or three successive counts were obtained that were within about 10-20 percent of each other. The length of time that the sampling hose was in the hole was typically around 5 minutes. The radon concentration was then calculated by subtracting the average background from the in-hole count, converting the counts to counts per minute, and then dividing by the cell efficiency (which was usually 1.2 - 1.5 counts/min per pCi/L). When the background count of the cell increased to about 200 counts/min or more, the cell was replaced with a fresh cell and the "hot" cell was flushed with outdoor air and allowed to recover before it was used.

3.7 CONTINUOUS MONITORING AND DATALOGGING SYSTEM

A commercial datalogging device (Campbell Scientific, Inc.{CSI} 21X, Micrologger) was used in all the schools investigated in detail. This device was equipped with: pressure differential transmitters (Modus Instruments, Inc.), thermistor temperature sensors (CSI model 107), outdoor temperature and relative humidity probe (CSI model 207), wind direction and speed monitor (CSI model 05103), tipping bucket rain gage (CSI model TE525), and continuous radon monitors (femto-TECH model R210F). These sensors were arrayed in a configuration specific for each of the schools investigated. Data from each of the sensors was sampled once each 6 seconds (or 15 seconds) and 30-minute averaged results (or totalized counts for the radon monitors) were stored internally. Once per day the stored values were downloaded via telephone modem to a computer located in Birmingham, Alabama. The data were then analyzed using commercial software (Lotus 1-2-3, Quatro Pro, etc).

3.8 DEVELOPMENT OF TEST MATRICES

For each of the schools researched, a test matrix was developed to determine the operational parameters of the building and their effects upon the radon levels in the respective building. In some buildings the test matrix was fairly simple (i.e., measure radon and pressure differentials at 0, 50, 100 % OA damper openings) whereas in other schools the matrix was quite complicated. The degree of complexity of the matrix depended in some part upon the amount of cooperation obtained from the school personnel. The individual test matrices are provided in the respective sections below.

3.9 GOOD TECHNIQUES IN ASD MITIGATION SYSTEMS

In order to address the secondary objective for this research -- comparison of HVAC and ASD systems for radon reduction in schools -- ASD systems were installed in some of the schools. Some general details to consider when installing the ASD systems included the following (7,8).

- After coring the appropriate size hole through the slab (i.e., a 7 inch hole for an 6 inch diameter pipe), suction pits should be excavated under the slab (with a minimum diameter of 36 inches and a minimum depth of 12 inches). The pits will improve the PFE of the mitigation systems.

- A coupling joint should be used at the floor when inserting the vertical suction pipe into the suction pit. This allows the pipe to rest on the floor and reduces stress on the sealing caulk. A short piece of pipe should be glued to the bottom of the coupling to extend just past the bottom of the slab. This will ensure that the suction pipe does not fall down into the pit where it could cut off the suction.

- The horizontal overhead pipe runs should be sloped so that any condensation will drain back into the suction pit.

- The fans should be located outside of the building at or near roof level. They should be mounted vertically to prevent moisture collection in the fan housing. The fan exhaust should be located at least 30 feet from any air intakes, although, other than the unit ventilators, none were observed in the vicinity of these location during the building investigations. However some heat pumps are mounted on flat roofs.

- Care should be taken to seal all joints in the ASD piping system. In addition, sealing of the larger and more accessible cracks between the building interior and substructure will improve the effectiveness of the ASD systems.

- A pressure activated alarm system should be installed in a visible location for each of the ASD systems.

- Penetration of any fire walls should be accomplished using approved fire stop material.

SECTION 4

COLORADO SCHOOLS

4.1 BARTON ELEMENTARY SCHOOL

Initial radon screening measurements were made in December 1989 and January 1990. The measurements and other features of the school building are discussed in detail below (9). Radon diagnostic measurements made on August 16, 1990 are also discussed.

4.1.1 Building Description

This school building is located in Ft. Collins (Larimer County), Colorado. The original building was constructed in 1956 and included 7 classrooms and various other support offices and storage rooms with a total area of approximately 15,750 ft^2. The original building included a boiler room of about 1,300 ft^2 located in a basement in the southwest corner. The boiler room contains the HVAC system and the slab is approximately 11 ft below grade. The remainder of the building is slab-on-grade construction.

In 1958, an additional six classrooms, a kitchen, and several toilets and support rooms totaling about 9,500 ft^2 were added to the original building. In 1976, a 2,100 ft^2 media center was added to the end of the northeast wing of the 1958 addition to the building. The last addition to the building was in 1982 when a 200 ft^2 storage area was added to the southwest end of the multipurpose (gym) room. The total floor space in the building is now approximately 29,000 ft^2 with a soil footprint of approximately 27,700 ft^2 (this includes portions of the building located over the boiler room). The floorplan of both the original portion and the various additions of the building are shown in Figure 4.1.1. The layout of the boiler room is shown in Figure 4.1.2.

4.1.2 Pre-mitigation Radon Measurements

Radon screening measurements made from January 15 to 17, 1990 are tabulated in Table 4.1.1 and shown on the floorplan in Figure 4.1.3. The average radon level was 6.6 pCi/L with a minimum of 4.8 pCi/L measured in the kitchen and a maximum of 12.3 pCi/L measured in the main office of the school.

Most of the rooms were remeasured during follow-up tests carried out from February 14 to 16, 1990. The results of these tests are shown in Table 4.1.1 and in Figure 4.1.4. In these later measurements the average radon level was 7.6 pCi/L with a minimum value of 5.9 pCi/L in the coach's office and a maximum value of 10.2 pCi/L in the nurse's room. The January and February results are compared in Figure 4.1.5.

For both the screening and the follow-up tests made during the winter all rooms were above the 4 pCi/L guideline. An additional test using a continuous radon monitor was carried out in one room of the school over the period August 6 to 14, 1990. The levels over this period ranged from

0.25 pCi/L to 6.5 pCi/L with an average of about 4 pCi/L or less. The daily diurnal variation in the levels was quite large (in some cases varying by a factor of 4 to 6 times).

4.1.3 Building Investigation

On August 16, 1990 diagnostic tests were carried out at the school. The architectural drawings called for 4 in. of crushed stone under the slabs in most locations. The presence of subslab grade beams was indicated under all of the classroom walls including the walls separating the classrooms. These grade beams ranged in depth from 2 ft 8 in. to 3 ft and rested upon deep piers at each of the junctions. The presence of thickened slabs was also indicated in a few locations. The locations of the grade beams and thickened slabs are shown in Figure 4.1.6 The presence of crushed stone under the slab thickening could not be confirmed. If absent, this may reduce the intra-room subslab communication. The presence of the grade beams surrounding each of the classrooms will definitely limit the subslab communication between rooms.

The building plans also indicated that there were utility lines in the return-air tunnel with multiple penetrations in the walls of the tunnel. Visual inspection indicated that there were numerous openings to subslab soil in the return-air tunnel walls. Because of the negative pressures in the return-air tunnel during HVAC operation, these openings are likely radon entry routes. The presence of asbestos in the tunnel was suspected but not confirmed.

4.1.4 HVAC System And Pressure Differentials

The HVAC system for the building includes a central air handler with a single fan and individual controls in each of the rooms. The HVAC system operates by time control with the system operating approximately 9 hours during the daytime and off for approximately 15 hours at night. This schedule is supposedly maintained even during the weekend when the school is not occupied. The furnace and air handler are located in the boiler room in the basement at the southwest end of the building. The boiler room is located about 11 ft below the rooms on the west side of the Gym as shown in Figures 4.1.1 and 4.1.2.

The HVAC supply ducts are located below the slabs and are composed of cylindrical cardboard ducts surrounded by poured concrete. In those areas where these ducts were visible, large gaps were found between the cardboard tubing and the surrounding concrete. It is highly likely that in most locations the cardboard tubing has deteriorated to the point that the supply air is in direct contact with the concrete. Since the ducts are under positive pressure when the HVAC system is operating, this probably does not represent a major radon source when the system is on.

The return air from each of the classrooms exits through grill vents into the hallway, with the hallway of the building serving as a return air plenum. From the hallway, the return air is ducted into a central tunnel that leads back to the air handler in the basement. The air in the gym is returned through floor grilles in the northeast and northwest corners of the room directly into the return air tunnel as shown in Figure 4.1.1. The tunnel runs under the north edge of the gym as shown in Figure 4.1.1 and varies in size from about 3 ft by 3 ft up to 4 ft by 4 ft in cross section. The tunnel can be accessed in the boiler room.

The tunnel has numerous penetrations by utility lines that lead to direct soil contact and probably represent a major radon source. The fresh-air intake for the HVAC system is located at roof level, and the air is ducted directly into the HVAC fan chamber through a controlled louver. Visual observation of the fresh-air intake louver from inside the fan chamber with the fan operating indicated that the louver did not open during fan operation. Subsequent investigation by the school maintenance staff confirmed that the control rod for the fresh-air intake louver was disconnected. The rod was then reconnected so that the louver would open properly. It is not clear what control system determines when and how much the louver opens. During the cold winter days the louver may be only partially opened. This may be dependent upon the outdoor temperature.

Investigation of the room pressure differentials (Δp's) was carried out primarily in the kindergarten room using an electronic micromanometer. These measurements were made before the fresh-air louver was repaired. The Δp between the kindergarten room and the subslab was measured to be -0.005 in.W.C. with the HVAC on and the door to the hall open. When the door was closed the Δp dropped to -0.003 in.W.C. The Δp between the kindergarten room and the hallway was -0.005 in.W.C with the HVAC on and the door closed. The pressure of the room relative to outdoors was -0.005 in.W.C. No Δp measurements were made with the HVAC system off. However, it appears that the HVAC system is depressurizing the classroom relative to both the subslab region and outdoors. This indicates that even in the warm summer months when the HVAC system is used for ventilation purposes only, it causes room depressurization which could result in soil gas flow from the subslab into the room. However, measurements of the radon levels in the building during the period August 6-14, 1990 did not show any elevated levels.

Measurements made with a flow hood from one of the supply vents and into one of the return vents showed the air flow into the gym is about 235 cfm and about 650 cfm into the return. This unbalanced operation is a major contributor to room depressurization.

4.1.5 Diagnostic Measurements

Radon concentrations under the slab and at several possible entry points were measured using a Pylon AB5 in a "sniff" configuration. The subslab radon levels measured in 0.5 in. diameter holes drilled through the slab in the Kindergarten room and the office in Room #6 are shown in Figure 4.1.7. These levels were about 700 pCi/L. Levels of about 300 pCi/L were measured in a crack in the slab adjacent to one of the air supply registers in the kindergarten room. Sniffing in one of the supply registers in the gym showed levels of about 15 pCi/L with the air handler off and about 25 pCi/L with the fan on. Measurements in the wall cracks of the air return tunnel showed levels of between 50 and 100 pCi/L with the fan off. These levels increased to about 350 pCi/L when the fan was turned on and the tunnel depressurized. This indicates that the depressurization of the return duct can mine radon from the soil through the cracks and penetrations in the duct wall.

Examination of the air handler fan chamber revealed a large crack (about 0.1 in. wide) in the slab on which the chamber was sitting. The investigators sealed the crack with duct tape for a length of roughly 4 feet and sealed the hose of the Pylon under the tape. The levels were measured to be about 700 pCi/L with the fan off and about 800 pCi/L with the fan on. The AB5 was placed in the fan chamber sniffing the air in the chamber. The radon levels were about 70 pCi/L with the fan off and increased to 350 pCi/L to 700 pCi/L with the fan on, indicating that the slab crack in the fan chamber is a major radon entry route. It was also observed that the crack was very clean with little or no dust in the crack. Apparently there is sufficient air flow out of the crack (or turbulence in the air above) to keep the crack clean. The pressure in the fan chamber relative to the boiler room was measured to be approximately -2 in. W.C.

Subslab communication tests were conducted in the kindergarten room using the suction (Fa) and test holes (Fb, Fc, and Fd) shown in Figure 4.1.7. The results are shown in Table 4.1.2.

The measured Δp's are plotted as a function of the distance from the suction point in Figure 4.1.8. The values measured at test point Fd may not have been entirely due to the vacuum cleaner suction. These values may have been partly (or even entirely) due to wind effects on the building.

Based upon the limited tests carried out on August 16, 1990 it would appear that the subslab communications are fair to poor. Consequently, the pressure field extension that can be expected with an ASD system would be limited to one or perhaps two classrooms at most.

4.1.6 Mitigation Strategy

Before attempting to install or even design an ASD system for this school other approaches were attempted.

4.1.6.1 Measure Effects of Outdoor Air (OA) Intake

One obvious approach was to correct the inoperative fresh-air intake damper. Correction of this problem was necessary for reasons other than the radon problems. Also, a brief inspection visit to another school -- Moore Elementary School also in Ft. Collins -- revealed striking similarities and contrasts. The two schools have almost identical floor plans and HVAC systems. However, the radon levels measured in Moore during January 1990 averaged 0.5 pCi/L with one room measuring 5.6 pCi/L and the remainder at levels less than 2.1 pCi/L. During the short walk through examination of Moore it was found that the slab under the air handler fan was cracked similarly to that in Barton. However the crack in Moore was not clean and appeared to be filled with cement dust. The return air tunnel at Moore also had similar penetrations as seen at Barton. At the time no power was available in the school (the power boxes were being replaced) so that inspection of the operation of the fresh air inlet damper was not possible. Later investigations by the school maintenance personnel found that the damper was indeed opening as it should. Consequently, the first step in mitigating Barton started with correcting the fresh air inlet louver.

4.1.6.2 Determine Optimum HVAC Operation

The effectiveness of the HVAC system with OA dilution was evaluated to determine the advantages and disadvantages of this mitigation method. Even if correcting the OA damper did lower the radon levels to acceptable limits, it was not known what limits are placed on the damper operation during temperature extremes and how it would affect energy costs.

A continuous data logger was installed at the school from 1/12/91 until 6/13/91 to monitor building parameters such as: indoor/outdoor temperatures, indoor/outdoor pressure differences, ambient weather conditions (wind speed, direction, etc), half-hourly radon levels at key locations, and the operation of the fresh air supply vent to the heating system. These measurements were taken with the HVAC system operating in a variety of configurations. The data were analyzed and a series of adjustments were made to the HVAC system.

The most effective controlling factor for radon throughout the entire school was found to be the OA supply. When the OA vents remained closed, as they were when the original screening test were made, the radon concentrations remained high. This was because the blower was creating a large negative pressure along the underground return duct which extracted radon through cracks from the soil beneath the building. Since no OA was entering, ventilation was at a minimum and the radon was recirculated throughout the building. This is illustrated in Figure 4.1.9 where the continuous radon levels for the kindergarten room, room 1, and the levels in the return air tunnel are plotted as functions of time. Included in this figure are the positions of the OA damper. It is clear that opening the damper lowers the radon levels, apparently by dilution of the indoor air in the building.

Studies indicated that radon levels were reduced even when the OA supply was only partially opened, but that the concentration increased rapidly when the supply vents were closed. These results are shown in Figures 4.1.10 through 4.1.13. It is seen that by opening the OA damper by about 25-30% reduces the radon levels to approximately 2 pCi/L in the rooms and in the return air tunnel and to about 25 pCi/L under the slabs.

A test matrix was set up to operate the HVAC system so that the dampers would remain open about 18% during the night and 100% during the day. The radon concentration remained below 3 pCi/l at all times. In order to minimize radon exposures, without a large energy penalty, the system was adjusted to remain closed during the night, and then open to 10% at about 4:00 am and 100% from 10:00 am to 4:30 pm.

4.1.7 Results of Initial Mitigation System

Integrated post-mitigation radon levels were measured in December 1991 using E-Perms. The results are shown in Table 4.1.1 in the last three columns. The school average radon levels was found to be 2.9 pCi/L with a maximum reading of 3.4 pCi/L in the music room and a minimum of 2.6 pCi/L measured in the principal's office. These values are compared to the screening and follow-up readings made the previous winter in Figure 4.1.14.

4.1.8 Additional Phases of Diagnostics, Mitigation, Future Plans

No additional diagnostics are anticipated other than to have the custodian regularly monitor the operation of the OA damper openings. A simple device has been designed and installed to monitor the position of the OA supply vents. This was installed in the office of the custodian. This person was instructed to read and record the position of the dampers each day. If the dampers are not opening, maintenance should be informed immediately. The entire system should be checked routinely by the maintenance section at least three times per year.

4.1.9 Estimated Costs

It must be recognized that while using the OA damper to lower the radon levels is an acceptable solution, no estimate is available regarding the increased energy consumption. This must be carried out by the school board personal in order to calculate the annual costs of increased OA. It would be possible to install an ASD mitigation system that would reduce radon beneath the slab and foundation and thus eliminate it before it can enter the school. This would involve an initial cost in excess of $10,000, although the annual operating cost to operate the system would be relatively low.

4.1.10 Summary

The research effort at this school building has demonstrated that an improperly operated central HVAC system was the cause of the radon problem. This was qualitatively established by comparing the initial radon screening results and HVAC system operation to the sister building (Moore) which does not appear to have a radon problem. By using continuous monitors it was determined that the elevated radon levels were exacerbated by the inoperative OA damper. Through a series of tests, an optimum set of operating conditions were developed for the OA damper that reduced the radon levels to acceptable limits. Another benefit from the introduction of OA into the school should be an improvement in the health and well-being of all occupants in the building, although this was not documented in this study.

4.2 PLATTEVILLE ELEMENTARY SCHOOL

4.2.1 Building Description

This school was originally constructed in 1952 and included approximately 17,000 ft^2 of floor space including 10 classrooms, a gym, a kitchen, and several offices and storage rooms. In 1983 approximately 20,000 ft^2 of additional floor space was added at both the north and south ends of the original building. Both of the additions are separate from the original building and connected by outside walkways. The layout of the original building and the additions are shown in Figure 4.2.1. This figure also shows the location of the subslab footers that greatly influenced the degree of subslab communication found during the diagnostic tests described below. The school as it now exists includes a total area of 37,762 ft^2. The area has 24 classrooms or instructional support rooms, and several offices and conference rooms.

4.2.2 Pre-Mitigation Radon Measurements

Radon screening measurements were carried out over the period March 9-11, 1990 using 3 in. diameter charcoal canisters (CCs). During this measurement period, the HVAC systems were operational with less than 5% OA. Also during the measurement period the boiler was operated with outdoor make-up air for combustion (which is the usual operating procedure). The locations of the CC's are shown in Figure 4.2.2. The results of the screening test are shown in Table 4.2.1 and in Figure 4.2.3. The school average radon level at this time was 6.3 pCi/L with a maximum value of 11.1 pCi/L measured in one of the rooms in the original building and a minimum reading of 0.5 pCi/L measured in the North addition.

Follow-up measurements were carried out over the period August 8-10, 1990 using charcoal canisters. During this period the HVAC systems were off and the windows and doors were closed. The results are shown in Table 4.2.1 and in Figure 4.2.4. The levels measured during these warm summer days were much less than the March levels. The school average was only 1.8 pCi/L with a high of 3.8 pCi/L measured in CC 19 located in the northeast end of the original building, and a low of 0.9 pCi/L measured in CC 22 located in the North addition. The ambient temperature during the August tests was estimated to be about 70-80 °F.

The March and August data are shown in Figure 4.2.5 where the measured values are plotted as functions of the test locations in the building. It appears then, that the school radon problem can either be due to the wintertime stack effect, to the depressurization caused by the HVAC systems, or to a combination of the two. More diagnostic tests during the colder months were needed to determine the exact cause.

4.2.3 Building Investigation

On August 15, 1990 a team of scientists visited the school. During the walk-through, the design drawings were obtained. The entire building is slab-on-grade construction with footers surrounding each longitudinal group of rooms as shown in Figure 4.2.1. The building plans called for crushed stone under all slabs. This stone is most likely smooth river run and was not washed before it was used. Thus the subslab material likely has a large percentage of silt or fines mixed in so that subslab communication is likely to be poor. Also, the footers located under the classroom-to-hallway walls were expected to restrict the communication across the hallway. The walls of the building (both load bearing and non-load bearing) are constructed of concrete block. The walls along either side of the halls extend through the slab to footers in the soil and may be a significant source of radon entry. However, the walls between the classrooms do no penetrate the slab and consequently were not expected to be a major radon contributor.

The utility lines for the buildings are located under the slab and openings where they emerge from the slab are likely to be good entry routes for radon into the buildings. One rather large opening in the slab was found in the gym area underneath the front edge of the stage. The expansion joint at this location was cracked open with a hole of about 0.5 to 1.0 in. diameter that appeared to go down to soil level.

4.2.4 HVAC System And Pressure Differentials

There is no central air handler for the buildings. The heating for the building is provided by UVs located on the outside wall of each of the rooms. The UVs are controlled by individual room thermostats. They have provisions for OA ranging from 5% to over 25%. These OA intakes are thermostatically controlled. OA is also provided passively for boiler combustion. Cooling during the summer months is provided by opening the windows in the various rooms. There are no window mounted air conditioning units in the buildings.

The original building has fan powered exhausts located in the kitchen, the cafeteria, and in the restrooms. The 1983 additions also have fan powered exhausts in the rooms, the corridors and in the restrooms. These powered exhausts could also contribute to the elevated radon levels in the winter by increasing the room depressurizations. No room depressurization measurements were attempted due both to the temperature at the time of the diagnostic visits and to time limitations during the visit.

4.2.5 Diagnostic Measurements

During the August 15th visit to the school, subslab radon levels were measured at a limited number of locations. The subslab area was accessed through 0.5 in. diameter holes drilled through the slab. The locations of the slab penetrations are shown in Figure 4.2.6. Also shown in this figure are the approximate subslab radon levels (in pCi/L) measured with a Pylon AB5 radon detector operating in the sniffer mode. The levels under the slab of the original building were in the range of 1,500 - 1,600 pCi/L and in the south addition in the range of 1,800 - 4,800 pCi/L. These values are also shown in Figure 4.2.6. Sniffer measurements at other locations such as wall openings and in opening around the utility penetrations did not indicate any significant radon levels during the testing period.

Subslab PFE tests were carried out using the slab penetrations shown in Figure 4.2.6. The suction point, Fa, was located in room 16 (CC #) and the test hole Fb was located a distance of 12 in. from Fa. The test hole Fc was located in room 15 and Fd was in room 2. The suction point Fa in the south addition was located in resource area room 13 (CC #) with Fb 12 in. away. The test point Fc was in room 12 and Fd in room 10 as shown in Figure 4.2.6. The results of the subslab communication tests are summarized in Table 4.2.2 and are shown graphically in Figures 4.2.7 and 4.2.8. In order to plot the pressure differences on a log-scale, the suction point pressure is assumed to be at a distance of one-half the diameter of the suction hole (1.5 in. diameter) or 0.06 ft from the center of the suction point. In both tests no measurable depressurization could be measured at test points Fd located about 60 ft from Fa in room 15 and at Fd in the south addition located about 30 ft from Fa in room 13. The approximate PFEs that could be expected from a fan are shown in Figure 4.2.9. This maximum extension is about 30 ft in the original building and about 20 ft in the south addition.

4.2.6 Mitigation Strategy

Based upon the poor PFE and the presence of the subslab footers indicated by the design drawings, four separate ASD systems were designed for this school. These systems are shown in Figure 4.2.10. Specific design details, should the school system decide to install an ASD system, are provided in the following section.

4.2.7 Mitigation System Details

System 1 is located along the north-south corridor of the original building. In this system a 6 in. diameter PVC (SS-40) pipe would run along the corridor (above the ceiling tiles) and serve as the suction supply main. From this main pipe 4 in. diameter, schedule 40, PVC drops would connect to the suction points. The 4 in. suction pipes should enter the classrooms above the ceiling tiles if possible, and drop down to the slab penetrations. The suction pits under the slab at each penetration should be excavated to a minimum size of 36 in. diameter and 12 in. deep. When the 4 in. suction pipes are installed through the 4.5 in. cored holes in the slab, a coupling joint should be used as shown in Figure 4.2.11. The fan used should be capable of moving approximately 230 cfm at a static pressure of about 1 in.W.C. and be constructed for all weather conditions. The fan should be mounted at roof level with the exhaust directed back over the roof and away from any existing air intakes. In locating the 6 in. line, care should be exercised to insure that the water that condenses in the pipe will drain back down to soil level through the 4 in. suction pipes.

System 2 is located in the south addition of the school. The fan can be of the same type as in System 1 and could be located in the boiler room since there is adequate ventilation there, however it would be best located at roof level. In either location the exhaust should be directed back over the roof and away from any air intakes. From the fan a 6 in diameter PVC pipe would extend into the hallway and connect to a 6x4 in. tee. From the tee sections of 4 in. diameter PVC pipe would run east and west down the hallway. The individual pipe drops to the suction points in the various rooms could be constructed using 2 in. diameter PVC piping since the air flow will be fairly low (based on the communication tests). At the slab penetrations, the diameter of the holes need to be at least 4 in. diameter to facilitate excavation of the suction pits. The 2 in. suction pipes could be connected to the 4 in. slab penetrations using 4x2 in. reducers as illustrated in Figure 4.2.12.

System 3 would be located outside on the north side of the building adjacent to the main offices as shown in Figure 4.2.10. Two suction points should be sufficient to cover the rooms in this area. Because of the anticipated low air flows and the small area of coverage the system can be constructed of 4 in diameter PVC pipe with drops to the subslab of the same size. The fan for this system can be smaller that those in Systems 1 and 2, but should have at least a capacity of 135 cfm at 1 in.W.C. As mentioned in Section 3.9, care should be exercised during installation to insure that the water that condenses in the lines can drain back to the soil through the drops.

System 4, as shown in Figure 4.2.10, would be located in the gym area. The 4 in. diameter PVC suction pipe could enter the building on the north side of the gym at a height sufficient to discourage children from climbing the pipe outside the building. After entering the building at the rear of the stage the pipe could immediately drop down through the stage floor and run along under the stage to a point just behind the storage doors under the stage. Here the 4 in. pipe should turn down and go through the slab penetration as shown in Figure 4.2.11. The existing cracks and openings in the slab should also be sealed with cement and/or caulking. The fan for this system should be located at roof level with the exhaust directed back over the roof and well away from any air intakes.

Care should be exercised in installing the systems to ensure optimum performance. The suction pits under the slab at each penetration should be excavated to a minimum size of 36 in. diameter and 12 in. deep if possible. The fans should be mounted at on near roof level in a vertical or near vertical orientation (no more than 45° off the vertical). The fan exhaust should be directed back over the roof and at least 30 to 50 ft away from any roof mounted air intakes.

All local and state building codes should be followed. These may include: electrical wiring specifications for the fans such as using a separate circuit breaker and weather proof conduits outside the building, and the use of fire stop materials around the pipes where they penetrate the wall between the rooms and the hallway.

4.2.8 Additional Diagnostics and Mitigation

To determine the nature of the radon entry additional CC measurements were carried out over the period December 24-31, 1990. During this time two sets of measurements were taken. Over the period December 24-26 the measurements were made with the UVs on, and over the period December 28-31 the measurements were made with the UVs turned off. The results are tabulated in Table 4.2.1 and compared in Figure 4.2.13. The school radon average with the UVs on was 6.3 pCi/L and with the UVs off was 3.8 pCi/L. Based upon these results, it would seem that the UVs are depressurizing the rooms and thus increasing the radon levels. The room-by-room increase (or decrease) in radon level when the UVs were on as compared to when they were off is shown in Figure 4.2.14. The school average increase in radon was 64.3 %. One might conclude that the UVs are the major source of radon entry into the building. However, as discussed below, the ambient weather conditions must be considered in the evaluation.

The outdoor weather conditions were highly variable throughout the entire sampling periods. Over the first measurement period (12/24-26/90, UVs on) the average outdoor temperature was about 5°F with a high of 19°F and a low of -10°F, the wind speed ranged from calm to around 8 mph with an average speed of 4.6 mph. A low pressure winter storm front pushed through the area during the period 12/26-27/90. During the second testing period (12/28-21/90, UVs off) the average outdoor temperature was approximately 17°F with a high of 40°F and a low of -6°F, the wind speed ranged from calm to about 10 mph with an average speed of 4.4 mph. Also during this second period, the winter storm dropped about 11 feet of snow by 12/31/90. Thus, while it may appear that the UVs were responsible for the increased radon levels, it may be that the extreme weather conditions were affecting radon entry more than the UVs themselves.

An additional set of CC measurements was carried out over the period March 15-18, 1991 before any mitigation was applied to the school. During this testing period, the average outdoor temperature was 36°F with a high of 65°F and a low of 16°F. The average wind speed was approximately

2.5 mph with a high of 10 mph and a low of 0 mph, and the ambient atmospheric pressure ranged from 625.8 mmHg to 634.9 mmHg with an average of 630.8 mmHg. These data were taken to determine if the mitigation systems described above were really necessary. The results are shown in the last 3 columns of Table 4.2.1 and are compared to the March 1990 measurements in Figure 4.2.15. During this test, the school average radon level was 4.6 pCi/L. The highest reading was 7.5 pCi/L measured in one of the offices and the lowest reading of 1.4 pCi/L was measured in 4 office spaces. The school also conducted a set of long-term (9 month) alpha track detector (ATD) measurements from 9/12/90 through 12/13/90. These long-term tests showed an average radon level of 3.7 pCi/L and, as a result, an ASD system has not been installed in the building.

4.2.9 Estimated Costs

It is difficult to estimate the cost of the mitigation systems described above. However, the installed systems will probably cost more than $15,000.

4.2.10 Summary

This school demonstrates that radon levels can vary quite a lot during different measurement periods. Because of the seasonal differences, the first two sets of radon measurements (March 90 and August 90) gave widely different results. The 9 month ATD results taken over the period 9/12/90 through 12/13/90 fell somewhere between the first two test results. The CC measurements carried out to determine the effects of the HVAC units upon the radon levels (12/24-31/91) were done during a period of extremely unstable weather conditions and the results are suspect. And finally, followup CC measurements carried out in March 1991 indicate that the school average radon level (4.6 pCi/L) is border line.

Under the assumption that the school does have a radon problem severe enough to warrant mitigation of the entire building, the construction details of the building provide many obstacles that will have to be overcome in installing an effective mitigation system(s). The mitigation system needed to control a radon problem in these cases with poor subslab communication is quite complex as illustrated in Figure 4.2.10 above. It also demonstrates that there is no substitute for good diagnostic measurements before designing a mitigation system. Also, the variability of the CC and ATD results along with the low school average radon level obtained from all the tests (6.3, 1.8, 3.7, 6.3, 3.8, and 4.6 pCi/L in Table 4.2.1) would seem to indicate that mitigation need be applied only to those rooms that consistently measured above 4 pCi/L unless the intent is to bring all the indoor radon levels down to ambient levels.

SECTION 5

MAINE SCHOOLS

Two schools in Maine were investigated in September 1990. One of these schools was located in the town of Sanford about 50 miles southeast of Portland, Maine (10) and the other was located in the town of Gray about 20 miles north of Portland. The diagnostic measurements made and the mitigation systems installed in each school are discussed separately for each school.

5.1 SANFORD MIDDLE SCHOOL

5.1.1 Building Description

This school is located about 30 miles south of Portland in the southern tip of Maine. The original building was constructed prior to 1940. In 1940, the building was partially destroyed by fire. The existing building was constructed over the remains of the original building in about 1940-41. In some locations there exists portions of the old building slab under the slab of the new building. The portion of the school discussed in this report is a three-storied wing on the northwest end of the main school building. This wing has three floors each about 3,000 ft^2 in area. The lower floor or basement is approximately 4 ft below grade on all sides. The basement is shown in Figure 5.1.1 and has a concrete slab floor with footers located between rooms A13/A14 and room A15. The two floors above the basement are of wood construction. The roof of the building is flat and constructed of wooden joists and covered with 2 in. planking and a rubber membrane. The walls of the structure are brick.

5.1.2 Pre-Mitigation Radon Measurements

Screening measurements of the radon levels in the school were made by EPA's Office of Radiation Programs (ORP) as part of their School Evaluation Program (SEP). These measurements indicated that the lower levels of the school had radon levels consistently above 4 pCi/L with the highest levels in rooms A12, A13/14, and A15.

5.1.3 Building Investigation

September 11-14, 1990 diagnostic tests were carried out in the basement rooms shown in Figure 5.1.1. No design drawings for the building were available so the locations of subslab footers were estimated based upon previous PFE tests. It was concluded that there was some type of subslab barrier between rooms A13/14 and A15, consequently communication under the slab would be limited based upon the location or locations of possible suction points.

5.1.4 HVAC System and Pressure Differentials

The basement rooms shown in Figure 5.1.1 are not served by any central HVAC system. There is a ceiling mounted UV located in the A13/14 area, and there is a ventilation shaft that runs from the basement to the roof of the building. It was thought that this ventilation shaft could produce depressurization in the basement during winter conditions. Inspection of the vent hood on the roof revealed a damper, however the operation had been defeated so that the damper was always in the fully open condition. The UV in the basement did not appear to supply OA.

5.1.5 Diagnostic Measurements

Continuous radon monitors (Honeywell Model A9000A) have been located in the basement rooms over various time periods. During the time of the diagnostic visit, outdoor temperatures were in the range of 60° to 70° F, and the windows of the rooms were open. Consequently, no detailed measurement of radon levels or entry routes was carried out.

5.1.6 Mitigation Strategy

Due to the lack of other options, it was concluded that an ASD system was the logical choice. Because of the possibility of subslab flow obstruction caused by the footer between rooms A13/14 and A15, a suction point was installed in each room. The suction points were connected to a common suction pipe that ran up through the two floors above and out the roof of the building. On the roof, a single fan was used to provide suction to both points in the basement. The ASD system was constructed using schedule 40 PVC pipe as shown in Figure 5.1.2. The suction pits under the slab were excavated to a depth of about 12 in. and a diameter of about 36 in. The fan installed on the roof of the building had a flow capacity of 230 cfm at a static pressure of 1 in.W.C. The location of the fan on the roof of the building is shown in Figure 5.1.3.

5.1.7 Results of Initial Mitigation System

After the ASD system was installed, subslab PFE was measured using the fan and two suction points of the ASD system as the suction source. The results are shown in Figure 5.1.2, where the values on the left of the "/" were measured with the ASD system installed but with the fan turned off and the values to the right were made with the ASD fan running. From the values measured at the two suction points, it appears that a significant stack depressurization effect was produced by the PVC piping. This passive soil depressurization (PSD) may lower the subslab radon levels in the immediate vicinity of the suction points but as the data show, no depressurization could be measured at any of the other, more distant, test points drilled through the slab. In fact, the static pressures under the slab at most of the test points were positive as shown in Figure 5.1.2. This may have resulted from depressurization of the basement rooms by the open vent stack running from the basement to the roof.

When the fan was turned on the pressures measured at all of the test points were negative, indicating excellent subslab PFE. Negative pressure was also measured in room A12. This was somewhat surprising since this room is located in the original building rather than in the addition where the ASD system was installed. It would appear that the subslab regions can communicate most likely through the connecting hallway since the wall of room A12 appears to have been an exterior wall at one time. The flow out of each of the suction points was measured using a hot film anemometer. The flow from suction point #1 located in A15 was estimated to be 6 cfm and from suction point #2 in A13/14 was 15 cfm. These values are consistent with the operation curves for the fan used.

Post-mitigation radon measurements were taken using Honeywell continuous radon monitors. The results are shown in Figure 5.1.4. For these data, the monitors were started at 1015 hours on September 10, 1990 and recorded the radon level at 4 hour intervals through 1000 hrs on September 14, 1990. The monitors were located in rooms A14 and A15. Installation of the ASD systems began on Monday 10 September at around 1200 hrs and continued through 2000 hrs on the same day. Installation continued on Tuesday morning 11 September and the ASD fan was turned on at approximately 1300 hrs. The communication measurements were made at approximately 1600 hrs on Tuesday 11 September 1990. From the radon levels shown in Figure 5.1.4 it would appear that the ASD mitigation system will keep the levels in the basement below 2 pCi/L.

5.1.8 Summary

Although the initial subslab communications test results did not appear very promising at this school, the communication using two suction points with pits under the slab did provide excellent PFE. One other interesting observation was the existence of -0.01 in.W.C. pressure at the suction points produced by the stack effect. This is a fairly large depressurization in view of the time of the year (September 11, 1990) and minimal indoor/outdoor temperature differential. (The outdoor temperature was in the 65-75°F range.)

5.2 RUSSELL ELEMENTARY SCHOOL

5.2.1 Building Description

This school is located about 20 miles north of Portland in the small town of Gray. The building is "T" shaped with three wings connected to a central area as shown in Figure 5.2.1.

5.2.2 Pre-Mitigation Radon Measurements

Screening measurement indicated radon concentrations greater than 20 pCi/L in several schools in Gray. It was decided to include one of these schools in the research program an to assist in radon diagnostic testing and mitigation planning.

5.2.3 Building Investigation

During the summer of 1990, a diagnostic investigation of these schools was carried out. This investigation focused on the ventilation system configuration and operating condition and on the subslab and the radon source strengths and PFE. Russell Elementary presented a promising research opportunity as each of its three wings used different ventilation systems with the hot water heating offering an excellent setting to compare different mitigation approaches.

5.2.4 HVAC System

The West wing is the oldest wing and has no ventilation. This wing in the past has relied upon window and door leaks for ventilation but these sources have since been sealed for energy reasons. The North wing has powered exhaust systems to remove air from the rooms. UVs with OA vents provided the East wing ventilation. Thus, radon mitigation systems and indoor ventilation effectiveness could be investigated under three different conditions within one structure with a relatively consistent radon source strength.

5.2.5 Diagnostic Measurements

PFE tests were conducted in the North wing with the powered exhaust system to determine the subslab flow conditions. Limited PFE was measured, but at least one room could probably be mitigated with each suction point.

5.2.6 Initial Mitigation Systems

The West wing was an obvious choice to test the effectiveness of increased ventilation on total indoor air quality through the use of a heat recovery ventilator (HRV). A local ventilation contractor was hired by the SEP group (6) to install an HRV in one (room 1 of Figure 5.2.1) of five rooms in that wing. The unit was installed near the middle of the outside wall of that room. No electric reheat was included to limit energy usage. The discharge was ducted to four 8 in. circle diffusers in the ceiling. Return air was taken in at the bottom of the unit. Total design air delivery was 450 cfm on low speed and close to 600 cfm on high speed.

The ground surface outside the North wing was paved for playground activities and, thus, a unique situation presented itself to try to control the subslab radon levels by applying a suction beneath this outside area near the building. A two point system was installed on one side of this wing to test this concept.

The East wing was used to test the effectiveness of UVs as indoor air mitigation systems. These old systems were brought back to design condition by the controls manufacturer. The UV systems were repaired and adjusted and all filters were replaced at the same time.

5.2.7 Results of Initial Mitigation

Testing of these systems was performed during September, 1991 with CCs and At-Ease continuous radon monitors. The HRV in the West wing and UVs in the East wing showed pronounced control of the radon while the "playground ASD" did not solve the problem in the North wing

The lack of control in the North wing was traced to incomplete PFE across the rooms. Some pressure field was detectable along one interior wall, but none along the opposite wall. Further investigation revealed a break in the outside wall near one of the suction points. This break was for the sanitary drain line and was allowing the pressure field to develop across the wall, but the tight soil was not allowing it to extend across the room.

Monitoring of the other sections of the building showed the HRV was maintaining fairly good control of the radon while the UVs were ineffective when the cold outdoor temperatures caused the outdoor air vents for the UVs to close. The lack of reheat and high delivery meant the winter air supplied by the HRV was perceptibly colder. Dry bulb temperatures were equal to the rest of the building, but walking into the room was cooler to the skin. Measurements of the air flow in November

1991 showed 285 cfm on low and 328 cfm on high speed, about half the design values.

A noticeable increase of radon levels for a period of approximately 12 hours was noted in a number of instances. These periods correlated with the start of a significant drop in the barometric pressure as shown in Figure 5.2.2. It has been hypothesized that a "barometric pump" is created when the atmospheric pressure is lowered by a frontal passage, but the soil is sufficiently tight to prevent quick propagation through the soil under the building. The delay means the pressure under the slab remains at the higher pressure and the soil gas is pumped into the reduced pressure in the building.

5.2.8 Additional Diagnostics and Mitigation

Additional testing with continuous radon monitors confirmed the failure to control the radon with the external ASD. It was decided to use the school for research for applying ASD systems to tight soils. Extensive PFE testing was conducted in the North wing in November, 1991. Low flows were found from the test suction points (8 cfm) with vacuums in excess of 1.5 in. W.C. providing PFE across one room. The building plans indicated the rooms on each side of the hall were built on a common foundation box so pressure fields could be developed under the dividing walls. A multi-point suction system was designed to put a suction point in every other room. The low flows from each suction point meant that 2 in. diameter PVC pipe could be used for the drops from the 4 in. overhead pipe. A dual fan systems was built into the exhaust to allow comparison of standard mitigation fans and the newer high vacuum units. A valving and power switching system was installed so only one fan would operate at a time. The low-pressure, high-flowrate fan operated at 2.5 in. W.C. for the six suction points, but could not maintain all of the rooms below 4 pCi/L as shown in Figure 5.2.3. When the high vacuum fan was operated, better PFE and radon reduction was obtained from the 5.5 in. W.C. suction. Long term monitoring of the system was provided by an industrial control based datalogging system (3) and eight continuous radon monitors.

The failure of the UV systems to control the radon levels in the East wing in the winter and the success achieved with the North wing led to diagnostic and design work in the East wing to install a high vacuum ASD system. The flows out of the test holes were slightly higher than the North wing resulting in a higher total air flow which reduced the suction available from the fan as indicated by the fan curve. The performance of the system could be improved by splitting the installed system which cut the air being moved by the fan in half. The reduced flow would move the operating point of the fan up the curve and result in a higher suction increasing PFE. At this time, a single fan was installed to establish the ability to duplicate the performance obtained on the North wing.

The HRV was modified by replacing the small circular diffusers with 2 ft by 2 ft diffusers with four directionally adjustable grills. It was hoped that the reduction in delivery velocity by a factor of 4 would provide less of a wind chill effect. Also, it was suspected that the original small diffusers were responsible for the actual air flows being lower than the design values. After replacing the diffusers the flows in the HRV were remeasured. The low flow rate was 450 cfm, and the high rate was 600 cfm. These values represent the design values and should improve the efficiency of the unit. A design for a hot water reheat coil was also provided to the school.

The high vacuum fans for the ASD system were initially installed outside to prevent any radon leaks within the building. This was not recommended by the manufacturer and the researchers soon found out why. A power outage during an extended cold period stopped the fans for a significant length of time. The fan on the East wing failed to start when the power came back on. Examination of the fan by the manufacturer showed condensation had shorted the unprotected electric circuits in the box which are normally protected by the warm ambient temperatures when mounted inside the building. The fan was replaced and the radon levels were lowered almost as well as in the North wing.

The new diffusers greatly improved the perceived comfort in the HRV room well into the fall. The arrival of cold winter temperatures brought the return of the discomfort experienced the previous winter prior to the installation of the reheat coil. The radon levels were still under control except for some periods when the "barometric pump" was operating.

The data stations were modified for the second year by adding a commercial data logger which included a modem for direct data transfer to remote computers. In conjunction with the indoor air studies conducted at the school, continuous CO_2 monitors were added in a few rooms. The HRV data shown in Figure 5.2.4 shows levels less than 1000 ppm except Wednesdays when the readings doubled. This is probably due to increased activities of the children which increased their respiration rate.

5.2.9 Summary

The research conducted at Russell has shown that schools with tight soils can be mitigated using ASD systems if sufficient suction is applied. Occasional radon peaks have been noticed when low pressure fronts move through the area. The system recovers to levels near or below 2 pCi/L after about 12 hours.

The HRV does provide radon and CO_2 control, but at an unacceptable comfort penalty. Reheat is needed in the cold climates for the unit to be acceptable by the occupants.

Cold climates similarly limit the successful application of UVs for indoor air control. The freeze protection circuits of some state mandated energy requirements shuts off the outdoor air supply whenever temperatures fall below freezing. When the outdoor air is closed, radon control is limited.

SECTION 6

MINNESOTA SCHOOL

6.1 NOKOMIS ELEMENTARY SCHOOL

This school (11) is a single story concrete masonry building with a brick veneer and slab on grade foundation located in eastern St.Paul.

6.1.1 Building Description

The floor plan of Nokomis is shown in Figure 6.1.1. The total floor area is around 15,000 ft^2. The nature of the subslab footings is not available at the time of this report. The subslab material is packed sand.

6.1.2 Pre-Mitigation Radon Measurements

The average radon level in the school was 4.2 pCi/L as measured by CCs in October, 1990. The highest and lowest concentrations were 6.4 pCi/L and 2.8 pCi/L, respectively.

6.1.3 Building Investigation/HVAC System

The HVAC systems in the school are a combination of systems. Hot water for these systems is provided by a gas/oil fired boiler located in the northwest corner of the building. Each of the nine classrooms (rooms 101, 102, 103, 104, 105, 106, 107, 108, and 109) are heated with finned-tubes along the outside walls. In addition, the two classrooms on the south end of the building (rooms 107 and 108) have hydronic slab heating (these classrooms are used as kindergarten rooms). Heating and cooling in all of the classrooms is provided by UVs located along the exterior walls with outside air capability. The gym/lunchroom, kitchen, and the office complex are serviced by a central air handling unit (AHU) with ducted returns. The unit has provisions for OA intake at roof level. There are fan powered exhaust fans in the restrooms and in the kitchen. Previous investigations of the building indicated that the OA intake capabilities of the UVs and AHU unit exceed the exhaust fan capacities so that building pressurization appeared to be a viable option for radon control. A fan door test conducted on the building revealed an effective leakage area of around 500 $in.^2$ This indicates that about 3000 cfm of outdoor air is needed to pressurize the building adequately to prevent radon entry when the exhaust fans are on. PFE measurements indicated that a pressure field could be extended about 15 ft from the suction point.

6.1.4 Mitigation Strategy

In May 1991 a private contractor mitigated the school using three mitigation systems. One system used the UVs in rooms 101 to 106 to bring in the minimum amount of OA necessary to pressurize the rooms to reduce the radon entry. During normal operation the OA dampers modulate above this minimum setting as determined by indoor and outdoor temperatures. This was also attempted in rooms 107 and 108; however, the radon levels were not reduced below 4 pCi/L during the initial evaluation. An ASD system was then installed in these two rooms with a single suction pit installed in each of the two closets. The pipes from each point were connected and run to a single, roof-mounted, exhaust fan capable of moving 420 cfm at 0 in. W.C. and about 180 cfm at 1.6 in. W.C. The locations of the ASD points are shown in Figure 6.1.1.

The Gym/Office area in the north end of the building was mitigated using a combination of HVAC control and another single-point ASD system. The suction point was located in the boiler room very close to the utility tunnel. This location resulted in bypassing the subslab area by pulling air through the tunnel block walls instead of from the subslab. Post-mitigation radon levels with all systems operating averaged below 0.5 pCi/L.

6.1.5 Diagnostic Measurements

In January 1992 a datalogger was installed in the school in order to determine how the various mitigation systems performed relative to each other and the interactions between each pair of systems. Parameters monitored were: radon levels in rooms 106, 107, 108, and the principal's office; subslab differential pressure measurements in rooms 106, 107, and the principal's office; OA damper positions on the UVs in rooms 106 and 107 and on the office AHU; temperatures in rooms 106, 107, the principal's office, and outdoors; and wind speed and direction.

The test matrix shown in Table 6.1.1 was developed to evaluate each of the mitigation systems. School Officials were unwilling to turn the ASD systems off while the building was occupied (to test the HVAC systems alone). As a result, testing with the ASD systems off was done over the spring break, April 10 to 20, 1992. These tests should be representative of winter conditions as the outdoor temperatures during this testing period ranged from 18 to 43°F, with an average of 30°F. The testing schedule for this school was as follows:

Test 1, UVs and AHU at normal damper operation; ASD on: This test was used to measure the radon levels in the post-mitigation configuration with the ASD and HVAC systems all operating. Under normal conditions the OA damper modulated based on OA temperature. This is typically 20 to 25% damper opening.

Test 2, UVs, AHU, ASD off: To collect baseline (no mitigation) radon data, all UVs and the AHU were turned off. The ASD fan was turned off, and outlets on the roof were covered with plastic and sealed with duct tape on Friday afternoon, April 10, 1992. The ASD systems remained off through Test 6.

Test 3, UV's and AHU on, damper closed: On Monday morning, April 13, 1992, the UVs in rooms 101 to 108 and the AHU were turned on but the OA dampers were kept closed (UVs and AHU running 24 hours). The school was operated in this configuration until Wednesday morning, April 15, 1992.

Test 3A, UVs and AHU on, dampers closed, filters out: On Tuesday afternoon, April 14, 1992, it was found that the return air filters in the UVs and the AHU were extremely dirty. The filters were pulled out of the units and the systems continued to operate as described in Test 3, above.

Test 4, UVs and AHU at 10% damper open: On Wednesday morning, April 15, 1992, the OA vents were opened to 10% OA on both the UVs and the AHU (running 24 hours). The ASD systems remained off. The school was operated in this configuration until Friday morning, April 17, 1992.

Test 5, UVs and AHU at 50% damper open: On Friday morning, April 17, 1992, the OA vents were opened to approximately 50% OA on both the UVs and the office HVAC system (UVs and HVAC running 24 hrs). The school was operated in this configuration until Saturday afternoon, April 18, 1992.

Test 6, UVs and AHU at normal damper open: On Saturday afternoon, April 18, 1992, the UVs the office HVAC system were changed to normal day/night operation (night setback at 68°F). The ASD systems remained off with exhaust pipes covered.

Test 7, UVs and AHU at normal damper operation; ASD on: On Monday afternoon, April 20, 1992, the ASD system pipes were uncovered and fans turned on. The UVs and AHUs returned to the post-mitigation configuration.

Test 8, same as Test 7 (2 weeks later).

Test 9, UVs, AHU, ASD off: These additional tests were carried out in July 1992 to test the ASD systems. In this test all systems were shut down at 8:00 am on Friday, July 10, 1992 to let radon levels go to background (pre-mitigation) levels.

Test 10, UVs, AHU Off, ASD on: At noon on Wednesday, July 17, 1992 the ASD systems were turned on while the UVs and AHU remained off.

Test 11, UVs and AHU at normal damper operation; ASD on: At 1:00 pm on Wednesday, July 22, 1992 the UVs and AHU were turned on and operated as in the post-mitigation mode.

The amount of OA introduced into each of the UVs and the AHU as a function of damper position is shown in Table 6.1.2. Note that in this Table, the percent damper opening corresponds to different percentages of OA for each of the four locations monitored. For example, a 10% damper opening corresponds to 27, 38, 34, and 19% OA for rooms 106, 107, 108, and the office, respectively. For simplicity, the remainder of this discussion will refer to the percent damper opening rather than the percent OA. Refer to Table 6.1.2 for the specific quantity of OA for a given location and damper position.

6.1.6 Results of Diagnostic Measurements

The results of the nine initial tests are shown in Figure 6.1.2 and the three additional tests in Figure 6.1.3. The average radon levels for the principal's office, room 106, and room 107 are plotted for each of the test conditions (except for the three additional tests shown in Figure 6.1.3 where the radon monitor in room 106 lost power). Radon levels increase from Test 1 to 2 because of stack effect induced radon entry. With the ASD systems operating (Test 1), the stack effect is reversed. The operation of the UVs with OA also helps to reduce the stack effect.

The results shown under Test 3 and 3A are conditions in which the UVs and AHU are depressurizing the building because the OA dampers are completely closed. In addition to building depressurization, it is also possible that the radon levels increased from Test 2 to Tests 3 and 3A because background radon levels continued to build up in the building after turning off the ASD systems (Test 2).

With minimum OA (approximately 10%, damper opening in Table 6.1.2) the radon levels were reduced below 4 pCi/L during Test 4. With about 50% damper opening (Test 5), the radon levels are reduced to background levels. In fact, the levels during Test 5 were lower than normal UV and AHU operation together with the ASD system operation. In Test 6 the UVs and the AHU OA dampers were returned to the post-mitigation setting of approximately 20 to 25% OA. Turning on the ASD systems in Test 7 reduced the levels in the Office and in Room 107 but had little effect in Room 106 since there is no ASD system in Room 106.

Test 8 presents continuous data collected about 14 days after Test 7. Radon levels in the two areas with ASD systems are relatively consistent with those observed during Tests 1 and 7. The radon levels in room 106 (without the ASD system) are slightly lower than in Tests 1 and 7.

Test 9 results were obtained by turning off the UVs and AHU and turning off the ASD fans and covering the exhausts with plastic. These values represent the un-mitigated levels and are somewhat higher than those obtained in Test 2 above. This may be due to the fact that prior to construction of an addition to the building, a 4 ft square hole was cut through the slab in room 107 with the soil exposed to the room.

The results of Test 10 illustrate, at least in the office and in room 107 that the ASD systems operating alone are capable of effectively lowering the radon levels. The levels are further reduced when the UVs and the AHU are turned on in Test 11.

The lowest radon levels in these three rooms were observed during Test 5 when the UVs and AHU were operated at 50% damper position (refer to Table 6.1.2 for actual percent OA) and the ASD systems were off. However, it is often difficult to consistently depend on 50% damper position when outdoor temperatures drop below freezing. In this series of tests, the UVs do maintain radon levels below 4 pCi/L in all three rooms as long as the damper position is set to 10% OA (Test 4).

Results show that radon levels are consistently reduced below 1 pCi/L in rooms 107 and the office when the ASD systems for these areas are operating. During these tests, the radon levels in the rooms with the ASD systems were always lower than in the room with only the UV control (Room 106).

6.1.7 Summary

The UVs were effective in reducing the radon levels to below 4 pCi/L in Nokomis if a minimum amount of OA was supplied. If the damper position was set at 50%, then average radon levels were reduced below 1 pCi/L. Radon levels were consistently reduced below 1 pCi/L in rooms 107 and the office with the ASD systems operating and the HVAC system set to normal OA. During these tests, the radon levels in the rooms with the ASD systems were always lower than in the room with only the UV control. The effectiveness of the ASD system alone was evaluated in Test 10. From the results of this test it would appear that the ASD is quite successful in consistently lowering the radon levels to acceptable levels in room 107 and the office without the UV and AHU systems.

SECTION 7

OHIO SCHOOLS

Initial radon measurements (12) in the Columbus Public Schools (CPS) system were made during December 1990. These tests were carried out on approximately 152 of the 168 buildings in the school system. Of those tested, 80% were found to have at least one room above 4 pCi/L. A priority list was developed based upon these measurements to identify the buildings with the highest radon threat. The buildings that were located highest on the list were Fifth Avenue Alternative School, Oakmont Elementary School, Hubbard Elementary School, Clarfield Elementary School, Southwood Elementary School, and Sullivant Elementary School. These schools were visited on December 18, 1990. During this initial visit the architectural plans were examined and a brief walk-through was conducted at each school. Following this initial contact with the CPS, five buildings were identified for possible inclusion in EPA's school mitigation program: Oakmont Elementary, Fifth Avenue Elementary, Hubbard Elementary, Clarfield Elementary, and Southwood Elementary.

A second visit to the CPS was carried out March 4-8, 1991. During this diagnostic visit it was discovered that Fifth Avenue was not an appropriate choice for intensive evaluation and was replaced with Sullivant Elementary. Also, it was concluded that Hubbard Elementary might be susceptible to mitigation through changes in the building shell. Consequently, only two building were selected for long-term diagnostics and evaluation, these were Oakmont Elementary and Sullivant Elementary. Diagnostics were carried out on other schools but the body of this report will concentrate on these two schools.

7.1 OAKMONT ELEMENTARY SCHOOL

This building is located at the eastern edge of the CPS district near the community of Reynoldsburg. The original school building was constructed in 1966 and includes 13 classrooms, offices, and a multipurpose room. The area of this slab-on-grade building is 24,000 ft^2. A slab-on-grade addition was constructed in 1973, bringing the total area to 31,000 ft^2. The floor plan of the school is shown in Figure 7.1.1. The 1973 addition has a central HVAC system for heating and cooling. All of the ducting for this system is located overhead. Since pre-mitigation radon measurements indicated that the radon problem was more urgent in the original building than in the addition, the addition was not part of this research project.

7.1.1 Building Description

A subslab utility tunnel runs under the three corridors in the school. The tunnel walls are constructed of unpainted concrete blocks (both sides of the blocks were untreated), facilitating airflow from the soil to the tunnel. These utility tunnels run the length of the building both east and west and southward (as seen in Figure 7.1.1). Examination of the design drawings revealed subslab footings in addition to the tunnels. These footing locations are shown in Figure 7.1.2. The hall walls are continuations of the tunnel walls up through the slab; the walls between the classrooms sit on the slab rather than extend through it.

7.1.2 Pre-Mitigation Radon Measurements

Initial radon measurements in the school were made in December 1990 by the Columbus Department of Health using E-Perms. These values are shown in Table 7.1.1 and shown by location in Figure 7.1.3. During this period the school average radon level was 11.1 pCi/L with a high reading of 20.5 pCi/L in room 10. Follow-up charcoal canister measurements were made the weekend of March 22-25, 1991, when the HVAC system was off. The average radon level was 4.5 pCi/L with a high of 8.4 pCi/L measured in the east tunnel. The results of the follow-up measurements are tabulated in Table 7.1.1. The measurement numbers shown in this table refer to the location of the CCs as shown in Figure 7.1.4. The measured values are shown by location in Figure 7.1.5. The school average radon level for those rooms tested was 4.5 pCi/L with a high reading of 8.4 pCi/L measured in the East tunnel.

The weather was relatively mild during this measurement period, with a high of 72°F and an average of 56°F. One would expect these mild weather conditions to reduce the stack effect in the building. A reduced stack effect would result in reduced radon entry compared to colder weather.

7.1.3 Building Investigation

During the diagnostic visit March 4-8, 1991 it was concluded that the major source of radon entry was via the supply air tunnel below the hallways.

7.1.4 HVAC System and Pressure Differentials

The original building has 23 fan-coil units (FCUs) located in the subslab utility tunnel. The utility tunnel runs under the corridors to the east, west, and south, as shown in Figure 7.1.1. Supply air for the FCUs is distributed to the tunnel by a central fan located in a fan room adjacent to the tunnel. The OA supplied from the central fan ranges from 0 to 100%. Air in the tunnel (supplied by the central fan) is then supplied to each classroom by the FCUs. The air either passes through hot water coils for heating or bypasses the coils. The air from each FCU is then supplied to the classroom via a subslab duct which then distributes the air through registers located along the outside walls of the classroom. Return air from the classrooms passes through openings in the classroom-to-corridor wall and into the corridor. The return air is then pulled into a centrally located return air grille in the corridor near the central fan (Figure 7.1.6). During normal building operation (7 am to 6 pm) the central fan and the FCUs run continuously.

This type of HVAC system is sometimes referred to as a "face and bypass" system. Although a number of schools in the Columbus area have this type of system, it has not been observed by EPA in schools in other parts of the country. Central HVAC systems with subslab supply and/or return air ductwork have, however, been observed in many of EPA's research schools (1).

7.1.5 Diagnostic Measurements

Initial diagnostic measurements conducted in March 1991 indicated that the utility tunnel and associated air distribution system were the major contributing factors to elevated radon levels in the school. As a result, the focus of this research project was on the effect of HVAC system operational parameters on radon levels. PFE measurements were also conducted as part of the diagnostics. These tests indicated fairly good subslab communication except across foundation walls and across the corridor (or across the tunnel).

Inspection of the building HVAC system indicated that the system might not be operating per design. Reduced system maintenance due to budget limitations probably contributed to this situation. To obtain information on the current operation of the system, a local testing and balancing company was hired to measure system airflows in May 1991. A 60 point traverse on the suction side of the central fan was made with the fan set at its design of 550 revolutions per minute. Results showed that the fan was running at 27,264 cfm: 264 cfm above the design specification of 27,000 cfm. The results of the airflow measurements (actual measurements) for all 23 FCUs, together with the design airflow, are shown in Table 7.1.2. These measurements show that, although the overall airflow for the 23 FCUs is only 233 cfm above design, there is wide variation from design for most of the individual units.

During the following winter (1991-92), CPS maintenance personnel adjusted the FCUs to their original design airflow (third column of Table 7.1.2). The central air handling fan was set to maximum opening position with no change in operating speed and locked in place. Total air flow under 100% return air was later measured to be approximately 29,400 cfm. These adjustments of the HVAC fans helped to reduce the depressurization in the tunnel. School maintenance personnel also applied two coats of paint to the tunnel walls and caulked all floor and walls cracks in the tunnel. The authors were not informed of these changes (adjustments to the HVAC system and sealing of the tunnel) beforehand and, as a result, were not able to quantify the effect of the individual changes on radon levels.

During the spring of 1991, the school was instrumented with a continuous datalogger to record:

- radon concentrations (eight locations)
- differential pressure (seven locations)
- temperature (seven locations)
- percent open of return and outdoor air dampers (central fan)
- weather (humidity, wind speed and direction, rainfall)

The exact locations of the parameters measured are shown in Table 7.1.3.

Initial plans were to collect data during the spring of 1991 with the central HVAC fan supplying specified quantities of OA. The test matrix for these measurements is shown in Table 7.1.4. Unfortunately, school officials were unable to adjust the OA damper as required for the testing, so testing was delayed until the winter of 1991-92.

Note that the percent open of the return air and outdoor air dampers in this report refers to the actual damper position. Actual airflow would be expected to be a non-linear function of the damper position. However, to a first approximation this can be treated as a linear function. Another method of estimating the percentage of outdoor air in a mixed air stream is through measurements of the stream temperatures. Figure 7.1.6 shows the correlation of the OA damper position indicator with the percent OA calculated using the following formula:

$$OA(\%) = \frac{(T_{mix} - T_{RA})}{(T_{out} - T_{Ra})} \times 100.$$

Where T_{mix} is the temperature of the air in the mixing chamber immediately upstream of the return air fan, T_{RA} is the temperature of the air in the return duct, and T_{OUT} is the outdoor air temperature. The correlation equation shown in Figure 7.1.6 indicates that even with the OA Damper closed there is approximately 5% OA leakage, and at 50% damper opening there is only about 43% OA entering the system. Attempts to directly measure the RA and OA flows at 50% damper opening were unsuccessful.

7.1.6 Mitigation Strategy

The intent of the investigations at this school was to determine if the HVAC system could be used as a radon control technique by increasing the OA intake into the building.

7.1.7 Effect of OA Damper Position on Radon -- Before Adjustments

Data were collected for the test matrix both before and after school personnel adjusted the HVAC system and sealed the tunnel. Figures 7.1.7 and 7.1.8 show the effect of the OA damper position on radon levels in the school. These data were collected prior to adjustments to the HVAC system and sealing of the tunnel; however, it is possible that some of the work was initiated during the final test (with 100% OA). Since school officials did not inform the researchers of the work until it was underway, the exact timing is not known.

Figure 7.1.7 shows radon levels in five classrooms and the teacher's lounge; Figure 7.7.8 shows radon levels in the west and east tunnels. The average radon levels during each of the three test conditions in Table 7.1.4 (100% return air, 50% return air/50% OA, and 100% OA) were calculated from the continuous data collected during the test condition and are displayed in Figure 7.1.9. Three conclusions are apparent from these data:

(1) With 100% return air, average radon levels are much higher than the previous pre-mitigation E-Perm and charcoal canister measurements, averaging over 20 pCi/L.

(2) Average radon levels in the six rooms (Figure 7.1.7) closely track radon levels in the tunnels (Figure 7.1.8). The levels in the rooms tend to be slightly lower than in the tunnels, supporting the

assertion that the tunnels are the primary source of radon in the school.

(3) Radon levels are reduced by about 75% when the OA damper position is increased from 0 to 50%. No additional reduction is observed when the OA damper position is increased from 50 to 100%. However, the data collected during the 50% return air/50% OA damper conditions are limited to a 24 hour test and, thus, should be interpreted cautiously.

(4) Although radon levels are reduced by about 75% when the OA is increased to 50 or 100%, average radon levels in the classrooms still exceed 5 pCi/L.

7.1.8 Effects of OA Damper Position on Radon -- After Adjustments

The test matrix was then repeated after school maintenance personnel adjusted the HVAC system to design specifications and painted the tunnel walls. The results from these tests are shown in Figure 7.1.10. These data show similar trends in radon levels as Figures 7.1.7, 7.1.8, and 7.1.9 (before adjustments). However, average radon levels are about 6 pCi/L lower in the west tunnel and 1 pCi/L lower in the east tunnel after sealing. These reductions in tunnel radon levels are also reflected in the room radon levels. During the test run with 50% return air/50% OA, radon levels in the rooms average about 4 pCi/L. When the OA is increased to 100%, average radon levels in the classrooms are about 2.5 pCi/L.

Figure 7.1.11 summarizes the average radon levels in the two tunnels and six rooms after adjustment of the HVAC system and sealing of the tunnel. The percent reduction attributed to these changes is shown above each bar. All reductions exceeded 10%, with a high of 57% reduction when 100% outdoor air was supplied.

Prior to these adjustments, the differential pressure between the tunnel and the outdoors was negative to neutral (depending on the percent OA). After the HVAC system was adjusted and the tunnel sealed, the differential pressures under all three OA conditions were relatively neutral. This reduction of negative pressure reduced radon entry into the tunnels and, consequently, radon levels in the school.

7.1.9 Estimated Costs

It is obvious that operation of the HVAC unit in this school at an increased OA intake will result in increased energy costs. Also, since the HVAC system does not include a pre-heat unit, the comfort of the occupants is likely to decrease during weather extremes unless more energy is consumed to overcome the cold OA intake. The exact increase in energy costs were not estimated in this study.

7.1.10 Summary

Data from this school showed that radon levels could only be reduced from above 20 pCi/L to below 4 pCi/L when the HVAC system was adjusted to its design specifications, 100% OA was supplied to the central fan, and tunnel walls were sealed. Although radon reductions were about 75% prior to adjustment of the HVAC system and sealing of the tunnel, levels were not reduced to below 4 pCi/L even with 100% OA. Data from other schools discussed in this report support the conclusion that it is difficult to reduce radon levels from above 20 pCi/L to below 4 pCi/L using only the HVAC system.

The research project in this school indicated that, when 100% OA is introduced and major radon entry routes are sealed, radon reduction with the HVAC system is consistent. However, school personnel indicated that this condition is difficult to achieve during extremely cold weather due to concern with energy costs. Similar observations have been made in other research schools, particularly in schools with UVs.

Other building components were not monitored in this study. However, research in other schools has shown that (a) opening the classroom-to-corridor door affects classroom radon levels (may increase or decrease depending on the school), and (b) operation of exhaust fans may increase or decrease classroom radon levels depending on the building.

7.2 SULLIVANT ELEMENTARY SCHOOL

This school was selected to replace Fifth Avenue as a school in which to install the data logging system in order to study the manipulation of the HVAC system for radon control. This building is located at the southern edge of the city in an older and industrial area.

7.2.1 Building Description

The original part of this building has a two fan (supply and return) air handling system and adequate provision for the addition of OA to the delivery fan. Conditioned air is supplied to the classrooms through a ducted system above the ceiling in the hall. The return air is carried back to the return air fan through a subslab tunnel the width of the hall and about four feet high. Sidewalls of the tunnel are concrete block and are not coated on either side. The concrete tunnel floor has an occasional crack and obvious floor to wall cracks. Because the tunnel operates under negative pressure it was thought to be the primary radon source. Radon levels under the room slabs and the slab of the tunnel were moderately high and could readily explain the relatively high radon levels found in the building.

In addition to the return air tunnels, the building has subslab utility tunnels along the outside walls to carry hot water to fin heaters located under the windows in the classrooms. These tunnels are open to the boiler room and in some places were connected to the return air tunnels. They could also be a source of radon entry although radon levels under the slab of the utility tunnels were not as high as under the return air tunnel slab.

A four room addition to the building has the same type of HVAC system (but on separate fans) and was included in the study. The other additions to the building have different HVAC systems and were not part of the study.

Examination of the architectural drawings for this building showed subslab barriers on all sides of all rooms and the use of "pit-run" gravel as the fill under the slab. According to the drawings, the gravel was more than a foot thick under some of the building. Measurements of the PFE found moderately good communication under the slabs and it was possible to pull negative pressures through at least one of the subslab barriers.

7.2.2 Building Investigations

Continuous data logging equipment was installed in this school in March 1991 and remained until January 1992. During this eleven month period numerous attempts were made to obtain meaningful data on the radon levels and operation of the HVAC system. In every case the results were questionable due to uncertain operation conditions. The staff at the school refused to cooperate in the research study and in fact restricted the entry and operation of the building. It was finally decided to drop this school from the study as the equipment was needed in other locations.

7.3 FIFTH AVENUE ELEMENTARY SCHOOL

This school is located in the central part of Columbus adjacent to the Ohio State University campus. The building was originally visited on December 13, 1990 and again during a diagnostic visit March 4-8, 1991.

7.3.1 Building Description

This school was built in 1975 and is air-conditioned and heated with heat pumps located on the roof of the building. It was originally thought that this school would be good candidate for either ASD or mitigation through use of the HVAC systems. The building has a minimum of subslab barriers and indications of good aggregate under the slab.

7.3.2 Pre-Mitigation Radon Measurements

The initial radon screening measurements were carried out at a total of 29 locations in the school. All of these values were above 4 pCi/L with an average level of 8.7 pCi/L and a high reading of 13.9 pCi/L.

7.3.3 Building Investigations

The building plans call for aggregate underneath the slab and indicate that subslab barriers are located in the restroom and storage area near the library. The only other subslab barriers separate the classroom area from the multi-purpose room, utility room, and the front office area. PFE measurements were conducted in the classroom area and in the multi-purpose room and are discussed separately below.

7.3.4 HVAC System and Pressure Differentials

The HVAC system for this building consisted of a forced air system using water-source heat pumps, one AHU for each occupiable room in the building. Return air was ducted above the ceiling. OA was provided though duct penetrations in the roof, each penetration was manifolded to serve 4 to 6 AHUs. The OA supply was not fan powered, relying on near-equal pressure drops in the return and outdoor duct work to draw in OA.

7.3.5 Diagnostic Measurements

Air volume measurements made in one OA supply (serving two classrooms and half the library) indicated only 70 cfm of OA. Assuming 25 students per classroom, and no students in the library, each student is receiving about 1.2 cfm of OA, which is 8% of the ASHRAE recommended standard of 15 cfm per student for occupied classrooms (4).

Pressure measurements in the building indicated the interior to be at a negative pressure with respect to the outdoors, when the exhaust systems were turned off and when they were on. With exhaust systems on (three sets of boys and girls toilets, and an art room), the hallways were -0.015 to 0.030 in. W.C. with respect to outdoors. With these exhaust systems off, interior pressures were -0.010 with respect to outdoors.

The evidence suggests that the HVAC system is not pressurizing the building, and measurements indicate that the existing system cannot be operated so that pressurization occurs. Pressurization might be accomplished with the addition of fans in the OA supplies.

A 1.5 in. suction point for the PFE measurements was located in the office area next to the library, and six 0.5 in. test holes were drilled at distances from 1 to 71 ft from the suction hole. The results of these PFE measurements are summarized in Table 7.3.1. Although negative pressures were only observed at two of the test holes (b and g), measurements at three of the other test holes indicated that the subslab area became less positive relative to the building interior when a vacuum was applied to the suction hole, an indication of communication. Additionally, points c and d were located near the outside wall, and it is likely that leakage was occurring due to the large floor/wall crack along most of the building perimeter. Subslab sniffs in these two test holes near the outside wall were much lower than the interior test holes, indicating that some dilution was occurring.

The measurement at test point g was repeated using a fan for suction rather than the vacuum and the same results were observed. It is expected that the PFE in the classroom area will be greatly increased by excavating a large suction pit and using an appropriate fan since communication was observed at five of the six test points (all but test point f).

The suction point in the multi-purpose room area was located in the storage area with one test hole located at the far end of the multi-purpose room and the other test hole located in an adjacent closet that is surrounded on three sides by footings. As seen in Table 7.3.2, a slight depressurization was observed at both test points.

7.3.6 Mitigation Strategy

During the visit in March it was discovered that the amount of OA to the HVAC could not be increased hence it was decided that only minimal information could be obtained by installation of a datalogging system in this school. Further examination of the design drawings indicated that with the existence of aggregate under the slabs and only a minimal number of subslab barriers an ASD system was the preferred mitigation system.

PFE measurements made at this time indicated good communication under the slabs. It was anticipated that the 20,000+ ft^2 classroom wing could be mitigated with a minimum number of suction points.

7.3.7 Mitigation System Details

A suggested mitigation system was developed and forwarded to CPS as follows. It was recommended that two ASD points be installed, one at each suction point location used in the PFE measurements discussed above. It is possible that two additional points may be needed, one in the classroom area (in the vicinity of test point f) and one in the front office area. However, initially it is recommended that only two points be installed since it is possible that they will provide adequate ASD (particularly in the classroom area).

A separate fan should be used for each of the two ASD points. The fan in the classroom area should be an in-line fan capable of moving 410 cfm at 1 in. W.C., and the fan in the multi-purpose room should be capable of moving 230 cfm at 1 in. W.C. For the system in the classroom area, the drops to the suction points and the overhead piping should be 6 in. diameter PVC piping. There is adequate space in the classroom area dropped ceiling to run the overhead piping. For the system in the multi-purpose room area, 4 in. diameter PVC piping should be used for the suction point and 6 in. diameter PVC piping should be used overhead. A tee should be installed in the overhead piping for each of the ASD systems to facilitate addition of suction points if needed.

The suction pits under each ASD point should be excavated to a minimum diameter of 36 in. and a minimum depth of 12 in. to enhance PFE. A coupling joint should be used when inserting the suction pipes into the cored holes in the slab. Care should be taken to ensure that the suction pipe does not drop into the soil at the bottom of the excavated pit. The coupling assures this if the proper size core is drilled (4.5 or 5 in. for 4 in. pipe, and 6.5 or 7 in. for 6 in. pipe). An easily checked pressure activated alarm should be installed on the piping for each system to monitor system operation over time.

The fans should be located exterior to the school building and the exhaust should be located at least 30 to 50 ft (check local codes for exact distance) away from any outdoor air intakes, windows, or doors. The roof contains several outdoor air intakes, thus caution should be used in selecting the ASD system's exhausts. It is recommended that the fan be placed on the side of the building away from the playground. All local and state building codes should be carefully followed. These include: electrical wiring specifications for the fans (such as using a separate circuit breaker and weatherproof conduits outside the building), and the use of materials that cut off fire if the PVC pipes penetrate a designated fire wall. (This does not appear to be the case when exiting the piping from this school.)

7.3.8 Additional Diagnostics and Mitigation

Once the mitigation systems are installed, two sets of short-term radon measurements should be carried out, one with the ASD systems off and one with the systems operating. Since radon levels can vary substantially over seasons, these should provide an accurate assessment of system performance. The measurements should be made in all normally occupied rooms.

If radon levels are still elevated, an effort should be made to seal the large (at least 1/8 in. in some places) floor/wall crack located around much of the building perimeter. Radon sniffs below the slab at the floor/wall crack ranged from about 60 to 500 pCi/L. This indicates that the crack is probably a major radon entry route since the perimeter is approximately 580 lineal ft. Polyurethane caulking should be used, and manufacturer's instructions should be followed for proper surface preparation. Since the crack appears to be rather deep in some areas, it may be necessary to use backerod beneath the caulking. Because of the effort involved in sealing this crack, it is first recommended that the ASD system be evaluated without sealing. The system may perform adequately without sealing and, if it does, the leakage will increase OA entry into the classrooms which would improve ventilation.

7.3.9 Estimated Costs

If the ASD systems are installed by CPS personnel experienced in radon diagnostics, estimated person hours would be approximately 40 hours (not including the sealing). It is estimated that materials -- fans, piping, fittings, etc. -- will cost about $2000.

7.4 HUBBARD ELEMENTARY SCHOOL

This school is located in the central part of Columbus near Fifth Avenue Elementary described above. The building was originally visited on December 13, 1990 and again during a diagnostic visit March 4-8, 1991.

7.4.1 Building Description

This three story building was constructed in 1892. The ground floor is about 3 ft. below grade level and contains classrooms as well as storage areas, a boiler room, and fan room. The fan room has a very large air handling fan which, when operating, causes the room to be under extremely negative pressures relative to the ambient pressures outdoors. There is a slab-on-grade multi-purpose room which was added to the original building in recent years. No design drawings are available for the original building except for remodeling plans which describe the HVAC system.

7.4.2 Pre-Mitigation Radon Measurements

The initial radon screening measurements were carried out at 19 locations on the ground floor. Of these, 17 values were above 4 pCi/L. The average of these measurements was 14.7 pCi/L with a high reading of 42.7 pCi/L.

7.4.3 Building Investigation

Hubbard is representative of many schools built around the turn of the century in Columbus and elsewhere. The CPS has approximately 12 of these still in use and it was anticipated that Hubbard would be an excellent choice to research. Because of design, these old school buildings are expected to be difficult to mitigate.

7.4.4 HVAC System and Pressure Differentials

During the March visit it was found that the building has a central air handling system that was installed in 1950 with provisions for OA.

7.4.5 Diagnostic Measurements

Although no plans were available for the original building, it was assumed that no aggregate was placed under the slabs during construction (a common practice according to experts). However, a moderate amount of PFE was found and it is believed that ASD will work with one suction point in each ground floor room. While making the PFE measurements it was found that the lower floor was under about 0.03 in. W.C. negative pressure for no apparent reason.

Further examination of the building disclosed that it had a very high pitched roof with an attic which was about thirty ft tall with a dome on top of it. Stairs led to the dome which was found to have large openings on all four sides. The dome was floored, had a door over the steps, and had a large set of power louvers in the dome floor which were wide open (and looked like they had not been closed in a very long time). A stack effect (60 to 75 ft of height) was causing the severe depressurization of the ground floor.

7.4.6 Mitigation Strategy

An attempt was to have been made to interrupt the stack effect before any mitigation is attempted on the building. It is believed that the floor of the dome can be sealed in such a way that the stack effect can be minimized. However, due to unforeseen circumstances, no attempt was made by CPS to decrease the stack effect in the building.

7.4.7 Summary

This building is typical of several buildings in the Columbus (and probably other) School District(s). These older buildings are characterized by lack of (or incomplete) design drawings and inoperative HVAC equipment. The pre-mitigation diagnostic visit is crucial to developing an effective mitigation system that takes into account the various idiosyncrasies of the building and its operation.

SECTION 8

SOUTH DAKOTA SCHOOL

Initial radon measurements (11) in the Rapid City Area School District (RCASD) were made from November 1990 to February 1991 using ATDs. Based on these results, eight schools were identified by AEERL as potential research schools. The results from the ATD measurements at these schools are summarized in Table 8.1.1. The overall average radon level in all of these school buildings was 8.2 pCi/L. Abraham Lincoln Elementary school had the highest average level of 18.8 pCi/L and Grandview Elementary had the lowest average level of 4.9 pCi/L. Based upon these results, Lincoln Elementary was selected as having the highest priority for research. The other schools listed in Table 8.1.1 will not be discussed further in this report.

8.1 ABRAHAM LINCOLN ELEMENTARY

This school is located in western Rapid City on a hill side of exposed and crumbling shale.

8.1.1 Building Description

The original building was constructed in 1951 with 10 classrooms, a cafeteria/gym, and several offices and special purpose rooms. The original building had approximately 14,280 ft^2. Three classrooms and a library were added to the west side of the original building in 1957, increasing the total area to 22,132 ft^2. The plan of the building is shown in Figure 8.1.1. The circled numbers are the measurement locations described below.

8.1.2 Pre-Mitigation Radon Measurements

The initial radon screening measurements were carried out over the period from November 7, 1990 to February 5, 1991 as shown in Table 8.1.2. The results of these measurements by location is shown pictorially in Figure 8.1.2 The highest level measured was in room 16 (36.7 pCi/L) and the lowest value (7.9 pCi/L) was in room 4. The average radon level in all rooms tested during this time was 18.8 pCi/L.

A second set of screening measurements were made May 3-17, 1991 using CCs. The CCs were placed and retrieved by RCASD personnel. The results are tabulated in Table 8.1.2 and shown by location in Figure 8.1.2. The values circled are the Winter 1990-91 ATD results; those in parentheses were made with the building closed and all UVs off over the weekend of May 3-5, 1991; the final set of measurements in Figure 8.1.2 were made with the building closed and the UVs operating over the weekend of May 17-19, 1991. The school average with the UVs off was 10.9 pCi/L with the highest value of 35.6 pCi/L measured in room 16 and the lowest value of 1.3 pCi/L in room 9. With the UVs turned on the school average dropped to 5.7 pCi/L with the highest value of 14.1 pCi/L measured in room 16 and the lowest value of 0.6 pCi/L in room 12.

These measurements are compared in Figures 8.1.3 and 8.1.4 where the three sets of values are plotted for each room or location (note that not all the rooms were tested during the Winter 1990-91 ATD measurements).

The radon levels when the UVs are on compared to when they are off is shown in Figures 8.1.5 and 8.1.6. In half of the rooms (Rooms 1, 3, 11, 13, 16, and in the office, gym, principal's office, teacher's lounge, and the health room) the radon levels dropped with the UVs on compared to the levels measured with the UVs off. This would be expected because of the OA provided by the UVs. In the other rooms the levels increased with the UVs operating (rooms 9, 18, 20 and the boiler room showing the largest increases). The increases in these classroom radon levels are thought to be due to closed or inoperable OA intake dampers in those rooms. As mentioned previously, the UVs were repaired prior to the continuous datalogging. The higher radon level in the boiler room might be due to increased depressurization with the UVs operating.

The OA temperatures were significantly different for the two measurement periods so these data should be interpreted cautiously. Over the period May 3-5, 1991 (UVs off) the average high and low temperatures were 46.7 and 31.7°F, respectively. Over the period May 17-19, 1991 (UVs on) these average temperatures were 67.3 and 47.3°F. These large temperature differentials during the two charcoal canister measurements make comparison of the relative influence of the UVs difficult.

8.1.3 Building Investigation

The design drawings indicate that the original building has below-grade, poured concrete, foundation walls around the perimeter of the building and under the corridor walls but not between the classrooms as shown in Figure 8.1.7. The foundation walls penetrate the slabs along the exterior walls and the corridor walls. The slabs are poured on compressed soil covered with a minimum of 6 in. of gravel. The addition, rooms 17-20, has a subslab utility tunnel along the outside walls as shown in Figure 8.1.7. However, because of the lower radon levels in the addition, it was not included in this research project.

Floor/wall cracks were observed in many of the classrooms and are thought to be a major contributor to radon entry. Unfortunately cabinets and closets typically surround three of the four walls in each classroom (the fourth wall is the chalkboard) making access to and sealing of the floor/wall cracks difficult. One crack observed in room 16 -- a corner room with both the highest ATD (36.7 pCi/L) and followup measurements (35.9 and 14.1 pCi/L) -- was about 0.5 inch wide.

Each classroom has a UV for heating and ventilating. The units are located along the outside wall. Most of the classrooms also have a fan-powered exhaust located in the closet along the wall parallel to the corridor.

8.1.4 Diagnostic Measurements

On May 1, 1991, CO_2 measurements were made in most of the rooms. The measurements, in most cases, were made while the rooms were occupied and the hall doors were open. The CO_2 concentrations shown in Table 8.1.3 ranged from 700 to 4000 ppm with an average value of 1687 ppm. Because ASHRAE (4) recommends CO_2 levels below 1000 ppm the researchers recommended that school personnel make the necessary repairs to bring the UVs up to design specifications. This was before continuous datalogging began.

During the week of 30 July 1991 an intensive diagnostic evaluation was carried out at this school building (in addition to the other seven schools in Rapid City). During this evaluation, measurements of the subslab radon levels, the PFE under the slab, UV operation, and other items of interest were carried out.

8.1.5 HVAC Systems and Pressure Differentials

Measurements of UV airflows and differential pressures across the building shell were made in July 1991. The measurements were taken under various building operating conditions in all classrooms in the original building:

- UV speed (high, medium, and low)
- UV outdoor air damper (completely open and completely closed)
- closet exhaust systems (on and off, each room)
- room-to-corridor door position (open and closed)

For these spot measurements the greatest negative pressure differentials across the building shell occurred when the hallway door was closed and the exhaust fan on. With the UV outdoor air damper open and the exhaust fan operating, the differential pressure for the classrooms averaged -0.022 in. W.C. The differential pressure averaged -0.032 in. W.C. with the UV OA damper closed.

Operation of the exhaust fans (one for each room) had a dramatic effect on the pressures in the room and tended to override any pressurizing abilities of the UVs. The total exhaust measured for the 10 classroom fans was 5,554 cfm while the maximum OA capability of the UVs totaled 1,590 cfm -- 3.5 times more exhaust than supply. The exhaust fans are new and draw 630 to 1,021 cfm per room, compared to the old fans that exhausted about 100 cfm per room.

Opening the hallway doors tended to have a neutralizing effect on the classroom differential pressures. The negative pressures caused by exhaust fan operation were near zero when the hallway doors were open.

The UVs were able to pressurize the rooms on average, 0.003 in. W.C. with the exhaust fan was off and the hallway door closed. A positive pressure was also observed when the UVs were on, the exhaust fan was off, and the hallway door was open.

The subslab radon levels obtained are shown in Table 8.1.2 and shown by location in Figure 8.1.8. In this figure the point labeled Fa is the point suction was applied during the subslab PFE tests. As shown in Table 8.1.2, the subslab radon levels averaged approximately 4260 pCi/L with the highest level of 6600 pCi/L measured under room 14. In general, the source strengths were lower under the slabs in the East wing than those under the North wing of the building. These levels correlate somewhat with the winter ATD and the May CC measurements shown in Table 8.1.2.

Subslab PFE measurements were carried out using a 1.5 in. diameter hole drilled through the slab in the closet of room 14 (in the north wing) and also through a hole located in the closet of room 4 (in the east wing). The pressure difference between the subslab and the classroom was then measured (as a minimum) at the center of each room. The subslab PFE was found to be much better in the north wing than in the east wing.

A computer based datalogger monitoring system was installed in the school in July 1991. Remote monitoring of the school was carried out via a telephone modem. Data were downloaded to a personal computer in Birmingham, Alabama for data analysis and storage. This system monitored the following parameters every 15 seconds and stored averaged (or in the case of the radon monitors totalized) values every 30 minutes:

- Ten continuous radon monitors measured the radon levels in rooms 1, 2, 3, 4, 9, 11, 12, 13, 14, and 16.
- Nine pressure transducers monitored differential pressures between both the rooms and the subslab areas in rooms 1, 4, 13, and 16. These pressure differentials were referenced to the pressure in the hallway which in turn was monitored relative to outdoor pressure.
- The temperatures in rooms 1, 4, 13, 16, the hallway, and outdoors were monitored.
- The operation of the UVs in rooms 1, 4, 13, and 16 was monitored. This included the on/off times and the positions of the outdoor air dampers.
- The on/off times of the closet exhaust fans and the position of the doors (open or closed) for rooms 1, 4, 13, and 16 were also monitored.
- A weather station was used to continuously monitor wind speed and direction and precipitation.

8.1.6 Mitigation Strategy

Because of the existence of the exhaust fans in the rooms and due to uncertainty with regards to using UVs to control the radon levels it was believed that ASD systems should be used in this school. The ASD systems installed in this school are shown in Figure 8.1.9. As indicated in this figure, suction points were placed in rooms 1 through 4 and in rooms 13 and 16. Because of the different PFEs in the two wings of the building, the systems for the two wings are discussed separately.

8.1.6.1 Mitigation System Details - North Wing

The PFE in the north wing was better than that in the east wing. As indicated in Figure 8.1.9 one suction point was placed on each side of the corridor, because subslab footings separate the two areas. One point was placed in room 14 (to treat rooms 12, 16, the teacher's lounge, and the health clinic) and one point was placed in room 11 (to treat rooms 9, 13, and the office areas). At each suction point a 8 in. diameter hole was cored through the slab and a pit was excavated in the soil about 36 in. in diameter and approximately 12 in. deep. Both systems use 8 in. diameter, Schedule 40 PVC piping for both vertical and horizontal runs. Each suction point uses a fan rated at approximately 300 cfm at 1 in.

W.C. The fans are located on the roof, with the exhaust directed vertically upward.

8.1.6.2 Mitigation System Details - East Wing

Because of the poorer PFE measured during the diagnostic testing in the east wing, one suction point was installed in each of the four rooms. The overhead piping for rooms 1 and 2 and for rooms 3 and 4 were manifolded together so that only two fans were needed. In rooms 1 and 3, the piping was run from the rooms and manifolded above the hall ceiling tile. A single pipe then ran across the hall and up through the chase above the closets in room 4. The piping from room 2 was run across the bathrooms and joined to the piping from the suction point in room 4. A single pipe was then run around the room to exit through the chase above the closet. In the top of the chase the pipes exited the building through an old window opening (now closed with plywood).

Because of the lower PFE, the fan flow rate is expected to be much lower than that in the north wing. Also, a fan capable of a higher pressure head was anticipated. Due to the low flowrate and high pressure expected in these east wing systems, the piping used was much smaller in diameter than the systems in the north wing. All piping in this wing was 2 in. diameter, Schedule 40 PVC. At each of the four suction points, a 5 in. diameter hole was cored through the slab to enable the installers to hand excavate a pit in the soil under the slab. The suction pits were about 36 in. diameter by about 12 in. deep. The fans used in this wing were capable of moving roughly 25 cfm at a static pressure of around 30-35 in. W.C.

8.1.7 Results Of Initial Mitigation System

The test matrix used to evaluate both the UVs and the ASD system's effects on radon is shown in Table 8.1.4. Testing occurred November 18, 1991, through January 31, 1992. The results of this series of tests are summarized in Figures 8.1.10, 8.1.11, 8.1.12, and 8.1.13 for rooms 1, 4, 13, and 16, respectively. In each of these figures the results are shown first (left) with the ASD off to evaluate the UV alone and second (right) with the ASD operating to evaluate both ASD alone and ASD in conjunction with the UVs. The results with the ASD system off are discussed first, followed by a discussion of the results with the ASD system on.

Room 1 was the only classroom with a door directly to the outdoors. In Figure 8.1.10 it is quite evident that opening the outside door was very effective in lowering room radon levels. However, this approach is not recommended as a practical year-round approach to radon control. It is interesting to note that opening the hall door also lowered the radon levels for all modes of operation of the UV and the exhaust fan. In fact, the radon levels in all four rooms decreased when the hall door was open. This was most likely the result of increased ventilation and consequent dilution of the radon concentrations. There may also have been some pressure neutralization thereby reducing the driving force for radon entry.

With the ASD systems off (left-hand graphs in Figures 8.1.10, 8.1.11, 8.1.12, and 8.1.13) operation of the closet exhaust fans without the UVs resulted generally in either lowering the radon levels or having little effect. One exception is seen in the left side of Figure 8.1.11 where operation of the exhaust fan in room 4 with the hall door open actually increased the radon levels. Other research has shown that operation of exhaust fans can either decrease or increase radon levels, depending on the relative leakage between above grade (decreases radon levels through infiltration of outdoor air) or below grade (increases radon levels through infiltration of radon-containing soil gas).

Operation of the UVs (with ASD and exhaust fan off) reduced the radon levels in rooms 1, 4, and 16 by about 10%. However, UV operation increased the levels in room 13 by approximately 25%. These results are not consistent with the CC results obtained in May 1991 (shown in Figure 8.1.6). However, during the period that these continuous radon measurements were taken (November 1991 to January 1992) the average outdoor high and low temperatures were 44.2 and 19.9°F, considerably lower than in May, 1991 resulting in less OA supplied through the UV dampers. It is possible that the UV in room 13 pulled radon from the floor/wall crack, distributing it to the room and increasing the radon levels.

With the ASD systems operating (the right-hand graphs in Figures 8.1.10, 8.1.11, 8.1.12, and 8.1.13), the average radon levels in all classrooms dropped to less than 3 pCi/L and in some cases to less than 1 pCi/L. The percent reductions ranged from about 80 to 99% with an average reduction of about 90%. These reductions appear to be fairly independent of the mode of operation of the UVs and exhaust fans, indicating that ASD and HVAC together did not outperform ASD alone. Thus, while the UV and exhaust fan operation may lower the radon levels in many of the classrooms, the levels were not consistently reduced to below 4 pCi/L. Only the ASD systems effectively and reliably maintained radon levels below 4 pCi/L.

8.1.8 Additional Phases of Diagnostics and/or Mitigation

The suction pressures at the suction points in rooms 1, 2, 3, and 4 were measured to be -0.24, -0.14, -0.27, and -0.10 in. W.C. and at the high pressure fan inlets the suction pressure was measured to be approximately -0.03 in. W.C. for both fans. These results indicated that the fans were running at maximum air flow (about 50 cfm for each fan). This indicated that the subslab communication was much better using the installed ASD systems than was indicated during the diagnostic tests using the vacuum cleaner technique. The two high pressure fans were replaced in June 1992 with a single fan capable of moving 95 cfm at 1 in. W.C. The radon levels in rooms 1, 2, 3, and 4 with the new fan operating were essentially the same as with the two high pressure fans. The new fan not only uses less energy (70-150 watts as compared to 180-320 watts each for the other fans) but also is not as susceptible to failure during down times as the high pressure fans.

8.1.9 Final Radon Levels

Upon the completion of this research (summer 1992), the radon levels were averaging about 1 pCi/L as measured with the datalogger. However, ATD measurements the following winter exceeded 4 pCi/L in the wing where the high suction fans had been replaced (east wing). This led researchers to the conclusion that subslab PFE had deteriorated due to increased rainfall during this time period. As a result, the two high suction fans were reinstalled in this wing. School officials plan to remeasure radon levels in this wing during the winter of 1993-94.

8.1.10 Estimated Cost

Costs for the Schedule 40 PVC piping, PVC elbows and fittings, sealants, and miscellaneous parts were on the order of $1,200. The costs for the four fans were $390 for each of the two low pressure fans and $1,425 for the two high pressure fans. Other supplies (e.g. electrical wire and fittings) had a total cost of approximately $3,500. Installation of the ASD systems used on the order of 10 person days total (2 people x 5 days).

8.1.11 Summary

In this school, Lincoln, the UVs alone were not able to consistently maintain radon levels below 4 pCi/L. The exhaust fans and the opening of the classroom-to-hallway doors had varying effects on radon levels. The ASD systems, however, provided excellent radon control, even better than that predicted during the diagnostic tests. Operation of the UVs together with the ASD system did not provide much additional radon reduction over the ASD system alone.

SECTION 9

TENNESSEE SCHOOL

9.1 GLENVIEW ELEMENTARY SCHOOL

School buildings that are constructed over crawl spaces can present unique challenges to radon mitigation since they are often quite large (at least 4,000 ft^2 in area) and may contain support walls with footings that extend below the soil surface. The perimeter walls in the crawl space can also be extensive (on the order of 500 to 1,000 lineal ft). In this research project, natural ventilation using the existing vents in the foundation walls, depressurization and pressurization of the crawl space, and ASD under a polyethylene liner covering the soil were compared in a wing of a school building in Nashville, Tennessee. The wing has four classrooms constructed over a crawl space area of 4,640 ft^2. The building and crawl space were monitored throughout each mitigation phase with continuous sampling devices that recorded radon levels both in the crawl space and in the rooms above, in addition to environmental conditions such as temperatures and pressure differences in the building.

9.1.1 Building Description

This 29,266 ft^2, Nashville school building (13) was originally constructed in 1954, with subsequent additions in 1957 and 1964. The original building and the first addition are slab-on-grade construction, and the 1964 four-classroom addition is constructed over a crawl space connected to the slab-on-grade section by a walkway.

9.1.2 Pre-mitigation Radon Measurements

Initial charcoal canister measurements in this school in 1989 indicated that the 18 slab-on-grade rooms measured presented the most severe radon problems, averaging 34.1 pCi/L with a standard deviation of 7.5 pCi/L. In fact, levels over 100 pCi/L were subsequently measured in some of the slab-on-grade rooms. Radon levels in the four classrooms constructed over the crawl space were relatively much lower, averaging 9.7 pCi/L with a standard deviation of 0.7 pCi/L. As a result, initial remediation efforts during the summer of 1989 focussed on reducing levels in the slab-on-grade wings with ASD (2, 8). Post-mitigation measurements during February 1990 indicated that levels in the slab-on-grade rooms averaged below 2 pCi/L, and at this time plans were initiated to research the effectiveness of various mitigation techniques in the crawl space wing.

9.1.3 Building Investigation

The crawl space is approximately 4,640 ft^2 in area, and the height ranges from 46 to 80 in. with a total air volume of approximately 25,500 ft^3. The plan view of the crawl space is shown in Figure 9.1.1. Access to the crawl space is excellent and the surface of the soil is not complex (i.e., no inaccessible areas, rock outcroppings, or large piles of soil). The floor of the classrooms over the crawl space is a suspended concrete slab poured over corrugated steel sheets supported by a network of steel trusses. There are two internal concrete block support walls in the crawl space that extend below the soil. These walls do not penetrate the slab overhead; however, the walls effectively subdivide the crawl space into three sections, as shown in Figure 9.1.1. This type of construction is quite different from that found in residential houses. In many existing houses, the floor is composed of wood decking (either 1 by 6 in. boards or plywood sheathing) supported by wooden floor joists. This type of house construction has been shown to be quite leaky and nearly impossible to seal all the openings between the crawl space and the rooms overhead (14, 15). Construction of this wing over a crawl space with a suspended concrete slab appears to be typical for crawl space schools as more of these have been seen than any other type. Wood floor construction is rare.

9.1.4 HVAC System and Pressure Differentials

Since the crawl space does not contain any ductwork or any asbestos, it was of interest to determine if the crawl space in this school building could be sealed well enough to permit pressurization or depressurization of the crawl space volume as a mitigation option.

9.1.5 Diagnostic Measurements

The crawl space is ventilated naturally with eight block vents (four each on the east and west sides of the building). Each of these foundation wall vents has a screened opening with the same gross area as a concrete block (8 by 16 in.) or approximately 128 $in.^2$ The results of fan door leakage tests (shown in Table 9.1.1) carried out on the crawl space resulted in an effective leakage area (ELA) at 0.016 in. W.C. of pressure difference of 251 $in.^2$ with the vents open and 83 $in.^2$ with the vents sealed (using closed-cell foam board and caulking). Thus, the vents were providing approximately 168 $in.^2$ of total open area, or about 21 $in.^2$ per vent. This value is consistent with that measured in houses using similar techniques (16). The important point is that the leakage area (independent of the block vents) is very low (83 $in.^2$) compared to that measured in 15 houses in the same geographic area which ranged from 198 to 424 $in.^2$ with a mean of 262 $in.^2$ (16). Thus, this building was thought to be an ideal candidate to test a variety of possible mitigation techniques.

9.1.6 Mitigation Strategy

Mitigation systems typically installed in crawl space houses include: isolation of the crawl space from the rooms above, isolation and depressurization or pressurization of the crawl space, isolation and ventilation of the crawl space (either natural or forced), and ASD under a plastic membrane -- submembrane depressurization (SMD) covering the exposed soil (10). Each of these mitigation techniques (with the exception of the forced ventilation) was tested in this school crawl space in an effort to compare their effectiveness when applied to a building having a larger size and a different construction type (concrete slab over the crawl space).

9.1.7 Results of Initial Mitigation (Spring/Summer)

Initial baseline testing was carried out before any modifications were made to the building. Following the baseline measurements, the accessible openings (e.g., utility penetrations) from the crawl space to the upstairs rooms were sealed with a combination of closed-cell foam and urethane caulking. The block vents were also sealed with rigid closed-cell foam board and caulking. Following testing with the vents closed, a network of 4 in. PVC ducting was installed as shown in Figure 9.1.1. The fan installed is rated at 200 cfm at 1.5 in. W.C. The fan and the air distribution network were used to test the effectiveness of crawl space pressurization and depressurization as mitigation options for the building.

After the evaluation of crawl space depressurization and pressurization tests were complete, two suction pits approximately 24 in. in diameter and 12 to 18 in. in depth were excavated in each of the three sections of the crawl space for a total of six suction pits as shown in Figure 9.1.1. Each suction pit was covered with a piece of 36 in. square by 1 in. thick marine grade plywood. The plywood covers were supported at the corners by four common bricks. Both the suction pits and the exposed soil were covered with two-ply high-density polyethylene sheeting. The plastic film was installed in three pieces, one in each section of the crawl space. No attempt was made to seal the plastic to the outer or inner foundation walls. The edges of the plastic were cut approximately 12 in. wider than necessary in the event that sealing to the walls was necessary. The excess material was then simply folded up the walls or allowed to fold back upon itself. The network of PVC ducting was connected to the suction pits to complete the active soil depressurization systems, as in previous house research (9). A side view of the SMD installation is illustrated in Figure 9.1.2.

Throughout the entire testing period, several parameters were monitored continuously using a datalogger. The parameters monitored include: pressure differentials between room 116 and outside the building on the east and west sides; pressure differentials between room 116 and the crawl space interior; pressure differentials between room 116 and the sub-poly region during the SMD testing; temperatures outdoors, in room 116, in the crawl space, and in the soil; wind speed and direction; the outdoor relative humidity and rainfall; and the radon levels in both Room 116 and the crawl space. Each of these parameters was sampled every 6 seconds and averaged or totaled at the end of every 30 minute interval. These measurements and their locations are summarized in Table 9.1.2.

The data were accumulated in the datalogging device and periodically downloaded to a personal computer and stored on magnetic disks for later analysis. A sample of this continuous data is shown in Figure 9.1.3 where the radon levels in both the classroom and the crawl space are plotted for various conditions. Initial testing of the building began on March 1, 1990, and continued through July 20, 1990, for a total of 152 days (3648 hours). The datalogger was reinstalled from December 18, 1990, to January 17, 1991, in order to evaluate the mitigation systems during winter conditions. The most significant results are described in the following sections for both the spring/summer and winter measurements.

9.1.7.1 Baseline Measurements

The baseline radon measurements made with the block vents open averaged 5.1 pCi/L in room 116 and 10.8 pCi/L in the crawl space, as shown in Figure 9.1.4. Figure 9.1.5 shows the averaged pressure differences between the crawl space and outdoors and between room 116 and outdoors during each phase of the mitigation. Also plotted in Figure 9.1.5 are the average testing period temperatures outdoors, in the crawl space, and in room 116. Following closing and sealing of the block vents and sealing the major openings between the crawl space and the classrooms above, the average radon levels in the classroom increased by about a factor of three to 17.1 pCi/L and the crawl space levels by a factor of eight to 87.2 pCi/L. During this time the average pressure difference in the classroom increased by a factor of about one and a half to - 0.019 in. W.C., and the crawl space pressure increased by a factor of almost four to - 0.016. It is obvious that closing up the crawl space greatly enhanced the depressurization produced mainly by the stack effect. Also, the temperature differences between the interior of the building and the outdoors were much larger than during the other testing periods, thus increasing the stack effect. These results clearly indicate the effect on radon when the crawl spaces vents are closed.

9.1.7.2 Crawl Space Pressurization

The next mitigation technique tested was crawl space pressurization using the fan installed near the roof level of the building and the network of PVC ducting to distribute the flow with the crawl space vents closed. During pressurization, the average fan flowrate was 234 cfm which was equivalent to about 0.6 air changes per hour (ACH). During this time the average crawl space pressure difference was reduced to - 0.006 in. W.C. and the average classroom pressure difference was reduced to - 0.01 in. W.C. as seen in Figure 9.1.5. The average radon levels in the classroom and crawl space were 10.6 and 29.1 pCi/L, respectively, as shown in Figure 9.1.4. It is apparent that the flowrate of OA into the crawl space is not sufficient to raise the pressure in the crawl space above the outdoor pressure and could only negate about 60% of that produced by the stack effect in the crawl space and about 50% of that produced in the classroom. It is possible that by doubling the flowrate (to around 500 cfm) the crawl space and the classroom could have been pressurized above the outdoor conditions and the radon levels further reduced. However, this option did not appear as a desirable year-round solution because unconditioned air was being used for pressurization.

9.1.7.3 Crawl Space Depressurization

Following the crawl space pressurization testing, the fan was reversed so that air was withdrawn from the crawl space and exhausted above the roof of the building. In this configuration, the fan flowrate increased slightly to 279 cfm or about 0.7 ACH. The negative pressures in the classroom were similar. However, the pressure differential in the crawl space increased by approximately 73% (from - 0.006 to - 0.01 in. W.C.). The radon levels in the classroom were reduced by about 94% (from 10.6 to 0.6 pCi/L) even though the levels in the crawl space increased by a factor 1.8 (from 29.1 to 53.6 pCi/L). Therefore, while depressurizing the crawl space lowered the levels in the classroom, it nearly doubled the levels in the crawl space. This was not unexpected since a similar technique applied to a residential house increased the levels in the crawl space by about a factor of 3 (14,15).

9.1.7.4 Submembrane Depressurization

The third type of mitigation system implemented was SMD -- a type of ASD applied under a plastic membrane covering the exposed soil. The total flowrate exhausted from under the plastic liners was 260 cfm when using all six suction points shown in Figure 9.1.1. As seen in Figure 9.1.3, the radon levels in the classroom were reduced within a matter of hours to around background (0.5 pCi/L), and in the crawl space the levels decreased to 3.5 pCi/L. In an attempt to determine if fewer suction points could be used, the two suction points in the central sector of the crawl space were disconnected and the suction pipes to both the fan and the suction pits were capped. The results are shown in Figure 9.1.4. The decrease in the crawl space levels is probably not significant, and the levels in the classroom are the same within the level of uncertainty of the measurement.

The results from the SMD mitigation technique are consistent with those found when the same method is applied to residential houses (10, 11, 12), where the area of the exposed soil is typically in the range of 1,000 to 2,000 ft^2. In this building the area is much larger (4,640 ft^2); however, the resulting reduction in the radon levels using SMD is as good as that achieved in smaller crawl spaces. The next important research step is to apply the SMD technique to crawl space areas on the order 10,000 ft^2 or larger.

9.1.8 Results of Initial Mitigation (Winter)

The above measurements were repeated during the winter (December 18, 1990, to January 17, 1991) in order to determine if the results were consistent with the spring and summer measurements. Analysis of the winter data (also shown in Figure 9.1.4) supports the results of previous measurements and the integrity of the SMD system during cold weather. Detailed analysis of the winter data is described below.

9.1.8.1 Baseline Measurements

No attempt was made to reproduce the open vent (natural ventilation) condition as this was felt to be an inappropriate operating mode for wintertime conditions due to freezing pipes. The results for the closed vent mode in winter were much the same as those obtained in the spring/summer, with the possible exception that the winter radon levels in the crawl space were slightly lower than the previous values (63.4 pCi/L compared to 87.2 pCi/L). The lower readings could be due in part to the fact that the winter measurements were carried out after the soil was covered with the polyethylene liners. The presence of the plastic liners covering the soil could act as a partial barrier to soil gas exhalation. The lower readings could also be due to the fact that the winter measurement period was much shorter than the spring/summer measurement period.

9.1.8.2 Crawl Space Pressurization

The wintertime crawl space pressurization levels were much the same as obtained previously. These results indicate that, with the amount of unconditioned air used, the radon reductions achieved with this mitigation technique are still less than desirable.

9.1.8.3 Crawl Space Depressurization

Using this technique during cold weather conditions gave very similar results to those obtained in the spring/summer tests. The wintertime levels in both the classroom and the crawl space were somewhat higher and could be due to an increased stack effect normally expected during cold weather. In order for this technique to be successfully applied year-round, it is obvious that the installation and testing must be done during extreme temperature conditions in order to ensure that an adequate amount of air is exhausted from the crawl space.

9.1.8.4 Submembrane Depressurization

The wintertime radon levels measured with the SMD system operative were almost identical to the levels measured previously. The average level in the classroom was within the uncertainty of the measurement techniques, and the levels in the crawl space were slightly lower than before. These results clearly indicate that the SMD technique is not only effective but stable in its ability to lower the radon levels in both the classroom and the crawl space under varying weather conditions.

9.1.9 Final Radon Levels

As shown in Figure 9.1.4 and discussed above, radon levels for the rooms located above the crawlspace are well below 4 pCi/L in the wintertime with the SMD system operating.

9.1.10 Estimated Costs

Cost for the polyethylene liner was $430 and the PVC piping supplies were approximately $500. The single fan was $170. Total material costs for the SMD
system was roughly $1,100. No estimate is available for the person hour costs, however installation and testing required about 80 person hours (2 men X 5 days).

9.1.11 Summary

The results of this project indicate that the SMD technique is the most effective in reducing elevated levels in both the crawl space and the classrooms. In this application, the crawl space was large but fairly simple in geometry. Access to the exposed soil areas was excellent and, with the exception of the two internal support walls, did not contain a large number of obstructions such as support piers or utility pipes lying on the soil. The topology of the soil surface in this crawl space was relatively smooth. Other crawl spaces may have some or all of the complications that were absent in this application (17,18). Application of the SMD technique in these more difficult crawl spaces needs further investigation.

Depressurization of the crawl space is effective in reducing levels in the classrooms; however, the levels in the crawl space will be increased. This could pose a problem in buildings that have openings from the crawl space into the occupied rooms above (e.g., HVAC ducts in the crawl space, wooden floors over the crawl space, or doors or other entry openings from the crawl space into the rooms above) or if the crawl space is occupied on a regular basis. In this building the overhead floor was a poured concrete slab with very few openings to the classrooms above. This fact helped to contribute to the effectiveness of crawl space depressurization.

Pressurization of the crawl space was found to be less effective in reducing the radon levels than natural ventilation. This method may be more effective if larger quantities of air are supplied to the crawl space; however, this may result in increased energy losses and perhaps could increase the risk of damage to utility lines in cold weather.

Natural ventilation of the crawl space also appears to be ineffective in reducing the radon levels to acceptable levels. Increasing the ventilation through larger or more numerous vents may increase radon reduction; however, the effectiveness of this method depends to a large extent on the wind patterns outdoors. Also, this method can easily be defeated by closing vent openings during the colder periods.

The number of school buildings constructed over crawl spaces is not quantified at the present, although EPA research in over 40 schools has shown that only 7 of the buildings contain crawl spaces (in combination with slab-on-grade substructures). There is little information available regarding crawl space characteristics, such as floor construction, number of vents, number of piers and support walls, and the presence of HVAC ductwork or asbestos in the crawl space. While the SMD technique appears to be the method of choice for reducing levels in both the crawl space and the rooms above, further investigations need to be carried out in crawl spaces that are not as simple as the one used in this study to determine if it can indeed be applied successfully in non-ideal conditions.

SECTION 10

WASHINGTON STATE SCHOOLS

Initial radon screening measurements were made in the Spokane Schools during 1989, and four of the schools were selected as possible candidates for additional study. Two Spokane schools identified as having the highest radon levels investigated in August 1990. The diagnostic measurements and the recommended mitigation approaches for these two schools, Lidgerwood and Sheridan, are discussed separately below.

10.1 LIDGERWOOD ELEMENTARY SCHOOL

10.1.1 Building Description

This school is located in the northern part of Spokane. The school has 16 classrooms, a multipurpose room (gym/cafeteria), and several special purpose rooms and offices. Eight of the classrooms are built over a crawl space, and the remaining eight are slab-on-grade. A partial floor plan of the school is shown in Figure 10.1.1.

10.1.2 Pre-Mitigation Radon Measurements

Several radon measurements were made over all four seasons (spring, summer, fall, and winter) under a number of ventilation conditions using two-day CCs, short and long term E-perms, and ATDs as part of an EPA/ORP study.

These measurements indicate that the eight rooms built over the crawl space do not have elevated radon levels. As a result, the diagnostic measurements discussed in this report include only the eight slab-on-grade classrooms that have consistently measured above 4 pCi/L.

10.1.3 Building Investigation

During August 21-23, 1990 various radon diagnostic tests were conducted, focussing on the eight slab-on-grade classrooms shown in Figure 10.1.1. These classrooms are located in the northwest wing of the school and occupy approximately 8,400 ft^2. The design drawings indicated the presence of aggregate under the slab. Since Lidgerwood contains several classrooms additions, the foundation drawings available were not particularly clear on specific subslab foundation locations. The subslab foundations include both poured concrete footings and thickened slab footings. Their exact locations can only be inferred from the PFE measurements discussed in Section 10.1.5.

There is a utility tunnel in each wing located as shown in Figure 10.1.1 under the slabs along the perimeters of the classrooms. This tunnel is approximately 4 ft wide by 4 ft high with a dirt floor. The walls of the tunnel are poured concrete and have numerous penetrations leading to open soil. Access to the tunnels are in rooms 140 and 141 in the west section and in rooms 127 and 128 in the eastern section. The tunnel contains the steam pipes that connect the boiler with the UVs in each of the rooms. Room 130, located just south of room 128 was also inspected for radon entry routes since it also had consistently elevated radon levels. There were numerous utility penetrations in the slab that probably constitute the major radon entry routes in this room.

10.1.4 HVAC System and Pressure Differentials

10.1.4.1 HVAC System Design and Operation

The HVAC system for this facility consists of heating-only, three-speed UVs located in each room, as shown in Figure 10.1.1. Each room has an electronic thermostat that controls the OA damper and the hot water valve in the UV. Each unit has a low-limit stat that modulates a hot water valve to maintain a minimum supply air temperature (typically 60° F). The units appeared to be in excellent working order in the subject rooms (139-142), however from the measurements of OA it would appear that the damper on the UV in room 142 is not opening fully. Rooms 141 and 142 each have a wind-turbine exhaust ducted into their storage/coat closets. The turbine for room 142 was inoperable (not turning) during the investigation. A passive exhaust is located in room 140 and there is no exhaust in room 139 (library).

One section of the school (room 124 specifically) has older UVs that have been retrofitted with replacement actuators that lack the proper stroke to open the outdoor air damper. However, this area was not of concern in the investigation since room radon levels in this section of the building were relatively low, regardless of the unit ventilator operation, during all seasonal measurements performed by ORP.

There is no automatic shutoff of the UVs, nor is there an automatic temperature setback control. It appears that each unit fan runs continuously, and the unit cabinets and thermostats are inaccessible without a hex key, thus the fan speeds and temperature settings cannot be adjusted by the teachers. The unit fans can be shut off at the electrical panelboard.

10.1.4.2 Potential Radon Impact

The hot water piping is routed to each UV through tunnels under the perimeter of the slab, as seen in Figure 10.1.1. The return air plenum for the UV is not isolated from the slab over the tunnel; thus any opening in the slab (e.g., a pipe sleeve, crack) would allow air from the tunnel to enter the UV and mix with the room return and OA. The tunnel could be a contributor to elevated radon levels in the room. Some openings were found around pipe penetrations but radon sniffs in the tunnel in room 141 did not exceed 100 pCi/l.

10.1.4.3 Measurements

Air flow quantities were measured for each UV and static pressure readings were taken in each of the four rooms (139-142). The readings were taken for the various operating modes of the UVs: 1) UV off; 2) UV on low, medium, high fan speed; 3) UV with OA damper open and closed. In addition to these UV modes of operation, the measurements of room static pressure (relative to outdoors) were taken with the door to the hallway opened and closed. The results of the pressure measurements are shown in Table 10.1.1 through Table 10.1.4 and in Figures 10.1.2 through 10.1.5. From past research it has been shown that pressurization of a space can reduce radon entry. It can be determined from these measurements that the optimal operating mode for the reduction of soil gas infiltration would require the UV to be on (any speed) with the OA damper in the open position, and the door to the hallway closed. No other operating mode, or door position would allow for pressurization of the room. Only the library (room 139 shown in Figure 10.1.2) could be pressurized with the hallway door closed and the OA damper in the closed (roughly 10% open) position, likely due the lack of any exhaust system in the room.

With the UV on, the OA damper open, and the hallway door closed, relative pressures (room vs. outdoors) in those rooms with wind turbine and passive exhaust (rooms 140-142) ranged from 0.020 in.W.C. to 0.036 in. W.C. These pressures should be adequate to prevent soil gas infiltration into the rooms, but require each door to the hallway to be closed. It should be noted that the differential pressure measurements made with the classroom doors open could be different (perhaps positive) if measurements were repeated with all UVs in the school turned on. Due to teacher and staff activity, these conditions were not possible during the building investigation.

10.1.4.4 HVAC Influence on Mitigation

From the results of this investigation, the unit ventilators could be used as a mitigation technique and would help to insure ASHRAE guideline (4) adherence for fresh air delivery to the classrooms (15 cfm minimum). The initial cost for this technique is relatively low (only requiring calibration of the UV control systems), however school operations officials should consider the overall cost which would include electrical and fuel costs for 24 hour operation and possibly increased maintenance costs. Officials should also consider the practicability of requiring all classroom doors to remain closed at all times. Should an ASD approach be chosen, the system should be sized large enough to overcome the negative pressures that could occur in the rooms (-0.008 in.).

10.1.5 Diagnostic Measurements

In addition to the HVAC systems measurements above, the subslab radon levels were measured using a Pylon AB5 in the sniffer mode. Radon measurements were also made in cracks and in openings around utility penetrations and in the utility tunnels. The locations of the test holes drilled in the slabs are shown in Figure 10.1.6 along with the subslab radon levels measured at these points. Also shown in Figure 10.1.6 are the radon levels measured in the utility tunnels. The first values (ones with a single asterisk) were measured on 8/22/90 with the results indicating that the west tunnel (under rooms 139-142) had lower levels than the east tunnel (under rooms 126-129), 25 pCi/L compared to 180 pCi/L respectively. Each tunnel has four vents (approximately 4 in. by 6 in.) that open to the outdoors. However, the vents for the east tunnel had been cemented closed probably because of a water problem since the vents for the east tunnel were at or below grade level. The vents for the west tunnel were open and fairly clear of debris so that air could move in and out of this tunnel. The vents to the west tunnel were closed off using duct tape and left overnight. On 8/23/90 the radon levels in both tunnels were again measured. The east tunnel (where the vents were permanently closed) increased slightly from 180 pCi/L the day before to 200 pCi/L. However, the levels in the west tunnel had increased from 25 pCi/L the day before (with the vents open) to 80 pCi/L (with the vents closed) as seen in Figure 10.1.6. It would appear that ventilation helps to dilute the radon levels in the west utility tunnel.

Other radon sniffer measurements were made at several locations. Measurements in a slab hole under the unit ventilator in Room 139 measured only about 10 pCi/L; however, a hole around a utility pipe entrance in Room 141 measured about 100 pCi/L. Thus there are probably ample radon entry routes into the classrooms. Some of these could possibly be easily sealed, while others may be difficult to locate.

Subslab PFE measurements were conducted in rooms 139, 140, and 141 using the test holes shown in Figure 10.1.6. The suction point was located in room 141 and suction was provided by an industrial shop vacuum cleaner. The results of these differential pressure and flow measurements are summarized in Table 10.1.5.

In the data shown in Table 10.1.5 note that Fa is the suction point located in the southwest corner of room 141, Fb is a test hole located 12 in. from the suction point, Fc is a test hole in the center of room 141 and approximately 20 ft. from Fa, Fd is a test hole in the center of room 140 approximately 32 ft from Fa, and Fe is a test point in the library office (room 139), approximately 35 ft from Fa. These points are shown in Figure 10.1.6. Also notice that with no suction at Fa, the subslab pressure relative to the room was: -0.003 in. W.C. at Fc and +0.005 in. W.C. at both Fd and Fe. The values measured at the test points with vacuum cleaner suction have been corrected for these baseline values before arriving at the net pressure differences presented in Table 10.1.5.

The subslab PFEs are summarized in Figure 10.1.7 where the net pressure differences have been plotted as a function of the distance from the center of the suction hole. The pressure at the suction point has been assumed to be at a distance of 0.06 ft from the center of the suction point (i.e. at the edge of the 1.5 in. diameter suction hole in the slab) so that the pressure values could be plotted on a log-log basis. As shown in Figure 10.1.7 the PFE is excellent out to a distance of 20 ft from Fa but drops off sharply at the test points in the other rooms. This is probably due to subslab footings that likely surround each of the classrooms. The footings are poured concrete and serve as barriers to subslab communication.

10.1.6 Mitigation Strategy

Reducing radon levels by using the UVs to pressurize the classrooms was discussed in Section 10.1.4 above. An alternate mitigation scheme for this school would be to use an ASD system. Based upon the subslab PFE, the pressure field produced under the slab could possibly be extended up to 40 ft or more if the field was not blocked by the subslab footings.

One ASD approach is shown in Figures 10.1.8 and 10.1.9. Two subslab suction points should be installed in each of the two classroom wings, one each in rooms 139 and 140 and one each in rooms 128 and 129. The holes through the slab should be at least 4.5 in. in diameter and located close to the wall. After the holes are cored in the slabs and the suction pits are excavated under the slabs (at least 1 ft deep and 2 ft in diameter), a hole of about 4 in. diameter should be broken through the foundation walls to the subslab regions under the adjacent rooms, as illustrated in Figure 10.1.9. This should allow the pressure field to extend to the subslab regions of the adjacent classroom. These suction points could be moved slightly from the locations shown in Figure 10.1.8 as long as the points are located along the internal wall to facilitate breaking through the foundation wall.

For both systems, the slab penetrations from rooms 139 and 140 and rooms 128 and 129 should be manifolded together overhead and connected with fans mounted on the roof with 4 in. diameter schedule 40 PVC piping . Each fan should have a flow capacity of 230 cfm at 1 in. W.C. The exhaust from the fans should be directed vertically to achieve maximum mixing with ambient air. A rain shield should be attached at the top of the exhaust to minimize water collection in the fan. The fans should be wired to separate circuit breakers and operated continuously. A low pressure indicator alarm should also be installed on each mitigation system to give a visual and/or audio alarm if the breaker is opened or the fan suction decreases below a given level.

10.1.6.1 Additional Phases of Diagnostics

As discussed above, the two mitigation options for the school are ASD and pressurization using the UVs. Based on the measurements made during the diagnostic visit, it is anticipated that installation of ASD systems in those areas with elevated radon levels will be the most effective approach for long-term radon control.

However, to determine the ability of the UVs to reduce radon levels during normal occupancy conditions, a datalogger was installed in this school from November 29, 1990 to January 8, 1991. Continuous radon levels were measured in rooms 139, 140, 141, and in the tunnel (a continuous radon monitor was also located in room 142, however the data were inadvertently lost when someone unplugged the battery charger). Differential pressures, temperatures, wind speeds, and directions, and classroom door openings and closings were also monitored.

The results of these measurements are shown in Figures 10.1.10 through 10.1.39 where the various measured parameters are plotted for each week (or portion of a week) from November 30, 1990 through January 7, 1991. Each of the 6 groups of figures contain 5 plots each; data for room 139, data for Room 140, data for room 141, average temperatures in each room along with the outdoor temperature, and the mean and maximum wind speeds measured outside the building.

A key factor in the ability of the UVs to lower the radon levels in the classrooms is the amount of time that the classroom door is open or closed. The averaged values of: Percent Time Door Open, Percent Time UV On, and the room Radon Level, are shown in Table 10.1.6 for rooms 139, 140, and 141 where the averaging periods are daytime (8 hours) when class is (or should be) in session, and the 24 hour period from mid-night to midnight.

The data for the period 11/30/90 to 12/3/90 (shown in Figures 10.1.10 through 10.1.14) illustrate typical weekend conditions (data for Friday, Saturday, and Sunday) when the UVs are turned off at about 4:00 pm in the evening and the doors to the classrooms are closed (the UVs are generally turned on at about 8:00 am and off at 4:00 pm on school days and off over the weekend, however there is no time clock controlling their operation, the exact on and off times are controlled by the janitors). With the UVs off and the doors closed (over the weekend), the air pressures in the classrooms averaged about - 0.02 in. W.C. relative to the utility tunnel thus providing a good driving force for radon entry from the tunnel into the classrooms. During this same period, the pressure differences between that inside the classrooms and outdoors were rather small and influenced more by wind effects than any other building parameter.

During this time the outdoor temperatures averaged approximately 30°F and the room temperatures were about 70°F. The mean wind speeds were on the order of 5 mph with wind gusts of around 15 mph as shown in Figure 10.1.14. As might be expected, when the UVs are turned off and the rooms closed, the radon levels begin to increase reaching a maximum on 12/1/90 and then appear to follow a typical diurnal variation with time. The averaged values for these three days are shown in Table 10.1.6 where the daytime (8 hour) values increase from less than 1 pCi/L on Friday to a maximum of just under 20 pCi/L on Saturday and then back to around 5 pCi/L on Sunday.

Data for the week 12/3/90 through 12/9/90 are shown in Figures 10.1.15 through 10.1.19. Operation of the school classrooms during this period reflect a typical school week and the measured parameters constitute baseline conditions. During this "normal operation" period the UVs are on for a period of approximately 8 hours during the daytime and off at night and over the weekend. The classroom door positions are controlled by teacher preference with the exception of room 139. This room houses the library, and it is closed for a slightly larger percentage of the day than the regular classrooms. The percent of time that the doors remained open during the daytime was 64.6% for the library (room 139), 59.7% for room 140, and 52.4% for room 141 as shown in Table 10.1.6. Unfortunately, the radon level data for room 140 during this period were lost. The average radon levels in the other two rooms were 2.6 pCi/L in room 139, and 1.7 pCi/L in room 141. The large increase in radon levels seen in both rooms 139 and 141 beginning approximately at midnight on 12/4/90 is likely the result of wind induced building depressurization. As seen in Figure 10.1.19 the wind speeds averaged 5 to 10 mph with gusts from 15 to 30 mph. These higher wind conditions began at a time when the UVs were off and resulted in increased radon entry from the tunnel and subslab areas. Once the UVs were turned on, the increased air flow into the classrooms reduced the radon entry and began to lower the room levels as seen in Figures 10.1.15 and 10.1.17.

For the week of 12/10/90 through 12/14/90 (shown in Figures 10.1.20 through 10.1.24) the teachers in this wing of the school were asked to keep the classroom doors closed as much as possible. In Table 10.1.6 it is seen that this request was carried out quite well. The percent of time that the doors remained open during the daytime was reduced to 7.5 %, 21.9%, and 32% for rooms 139, 140, and 141 respectively. Also, the unit ventilators were operated near continuously during this week as opposed to the normal schedule of turning them off at night. The radon levels remained quite low throughout the week (with the exception of the levels measured in the early hours of monday morning 12/10/90 in rooms 139 and 141 before the UVs were turned on). The average radon levels for this week were less than 0.8 pCi/L during the daytime and less than 2.2 pCi/L for the complete set of 24 hours of measurement. On Saturday and

Sunday (12/15-16/90) after the UVs were turned off, the radon levels in rooms 140 and 141 increased in a manner similar to the previous weekend. The 8 hour and 24 hour averages are shown in Table 10.1.6. During this same period (Saturday and Sunday), the radon levels in the library (room 139) remained low, averaging less than 1 pCi/L for either the 8 hour or the 24 hour periods. The reason for this is likely due to the lack of an exhaust vent in this room and perhaps also due to the higher in-leakage through the closed OA damper. Data for the remaining weeks of the test period (12/24/90 through 1/6/91) are shown in the remaining Figures 10.1.25 through 10.1.39.

Rather than carry out a day-by-day or even a week-by-week analysis of the data, we chose to look at weekly averages of the 8 hour (daytime) and 24 hour data. We excluded the weekend data since typically the UVs were turned off over the weekend. These averages are tabulated in Table 10.1.7. From this table all weekly averaged data for which values were available for radon, percent time the classroom doors were open, and the percent time the UVs were on were sorted by increasing radon levels for both the 8 hour and 24 hour periods. These results are shown in Figures 10.1.40 and 10.1.41. Here it can be seen the overall trends or effects of door openings and UV operation upon the room radon levels. In particular, in Figure 10.1.40 it is clear that as the amount of time the doors were open increases so also does the radon levels. In like manner but less clearly, as the percent of time that the UVs were running decreases the radon levels increases. The correlation between the UV on time and the radon levels is less clear in Figure 10.1.41 because over the 24 hour period, the UVs are turned off for a much larger percentage of the time (overnight) than that during normal occupation.

These data indicate that if the classroom to hall doors are kept closed and the UVs left running, radon levels in the classrooms can be reduced. The slightly lower levels in room 139 (the library) are probably due to a combination of factors including: a lower source strength, no exhaust vent (passive or turbine), and the library door is probably closed more frequently than the classroom doors.

10.1.7 Estimated Cost

The costs of the materials for each of the two ASD system would be about $2,000 for piping, fittings, fans, and caulking. The labor costs could be quite low if the work is performed in-house by the school maintenance staff, otherwise labor costs from a private firm could run in the neighborhood of $4,000 for 5 days of work for two persons. The total maximum cost should be around $6,000 or less for each of the two systems.

10.1.8 Summary and Recommendations

This school building has both slab-on-grade and utility tunnel construction details. It also has UVs that, with some effort could possibly be made to pressurize the rooms for radon control. However, because the UVs are not controlled by any type of energy management system or even by a time clock, radon control could be a hit-or-miss situation. There are too many operational uncertainties to recommend using the unit ventilators as a reliable mitigation option.

Another interesting aspect of the school was the absence of elevated radon levels in those classrooms located over the crawl space areas. With the amount of exposed soil under the rooms and the fact that the floors were of wood construction would lead one to expect just the inverse of what the measurements indicate. No answer is immediately obvious.

10.2 SHERIDAN ELEMENTARY SCHOOL

10.2.1 Building Description

This school is located in the southeastern corner of Spokane. The building has two floors with some of the rooms on the first floor located below grade by about 5 ft. The total number of classrooms in the school is approximately 35 with additional space for a gymnasium, cafeteria, kitchen, counseling and general offices, and storage rooms. The building has a central HVAC system with the air handling equipment located on the second floor. The Spokane School district has several schools that have the same floor plan as Sheridan.

10.2.2 Pre-Mitigation Radon Measurements

Several radon measurements were made over all four seasons (spring, summer, fall, and winter) under a number of ventilation conditions using two-day CCs, short and long term E-perms, and ATDs. The results of these measurements indicate that several rooms on the first floor of the school do indeed have elevated radon levels when the HVAC System is not operating. However, during the HVAC system operation, the radon levels are well below 4 pCi/L. This suggests that the HVAC system is pressurizing the building and thereby preventing radon entry. More detailed information is discussed below in Section 10.2.4.

10.2.3 Building Investigation

On August 22, 1990 the school was visited for a short diagnostic examination. Investigations centered around the HVAC system and its ability to pressurize the building. Tests of the HVAC operation were carried out primarily on the first floor in rooms 129 and 133. The results of these tests are described below in Section 10.2.4. The building is of modern construction (less than 10 years) and the design drawings indicate the presence of aggregate under the slabs. The floors of most rooms in the school are carpeted.

10.2.4 HVAC System and Pressure Differentials

10.2.4.1 HVAC System Design and Operation

The HVAC system for this facility consisted of a central forced-air system with variable air volume (VAV)/hot water reheat temperature control. There are three AHUs located in a mechanical room on the second floor, one unit serves the gym/multi-purpose room, one serves other interior rooms, and one large unit serves all exterior rooms (classrooms and administrative offices). Since all classrooms and administrative areas are served by the large unit, only the large AHU will be discussed.

The AHU contains a cooling coil and OA return/relief damper system (capable of 100% outdoor air). The unit supplies conditioned air to all external rooms on two floors of the building. The return air system is not ducted from each room, rather grilles in the dropped ceiling of each room transfer the return air to the ceiling plenum. A return/exhaust fan in the mechanical room draws air through another grille located above the second floor ceiling, drawing the return air through the plenum space above the dropped ceiling and through a few open chases to the first floor plenum ceiling.

Each room has a pneumatic thermostat that controls a VAV box by modulating the control damper, and by modulating a hot water control valve in the box. On a call for cooling, the hot water valve modulates to a closed position and the control damper modulates to maintain the desired conditions. On a call for heating, the VAV boxes modulate to a minimum supply air position and the hot water valve modulates to maintain desired room conditions. According to building construction documents, the VAV boxes have a minimum supply air position that is 50% of the maximum supply.

The AHU operates from 7:00 a.m. until 4:30 p.m., and is shut off completely during summer vacation. The controls system was in the process of being changed over to the central plant's energy management system during the investigation, but there was no plan for a change in the operating hours.

10.2.4.2 Potential Radon Impact

This HVAC system operates in such a manner so as to pressurize the building, this pressurization should prevent soil gas infiltration as the ORP radon test data shows, (the lowest levels tend to occur when the AHU is running). As long as the HVAC system is operating, the radon levels in the school should be low.

Caution should be exercised with this radon control approach since the return air system has no means for balancing (no dampers). The lack of a ducted return system contributes to less-than-ideal air distribution in this building and could result in varied relative static pressures throughout the building. Those areas nearest the return fan louver may experience negative static pressures (relative to outdoors) due to excess return air and could experience increased soil gas entry. Other areas of the building farther from the return air louver could experience slightly higher static pressures relative to outdoors due to lack of sufficient return air.

10.2.4.3 Measurements

Air flow quantities were measured in room 133 and were found to be in the range of air flow called for on the prints (523 - 1045 cfm). Smoke pencil tests near the windows and floor/wall cracks indicated the room to be at a positive pressure.

10.2.4.4 HVAC Influence on Mitigation

Pressurization via the HVAC system is the most likely mitigation choice for this facility since the system is designed to pressurize the facility continuously and has demonstrated the ability to reduce radon levels below 2 pCi/l. Further data acquisition is recommended, however, to determine the effect of night and weekend shut-off of the AHU. Continuous data of radon levels in room 133 should be taken with various operating schedules of the HVAC system. From this, the radon build-up rate and the radon mitigation rate can be determined so that the optimal HVAC system start-stop time may be determined.

10.2.5 Diagnostic Measurements

No other diagnostic measurements other than those described above in Section 10.2.4 were carried out at this school.

10.2.6 Mitigation Strategy

The recommended mitigation strategy for this school is to use the HVAC system to maintain building pressures above ambient levels. The determination of optimum set-back time for the system can best be determined through the use of continuous radon monitors and perhaps by continuous measurements of the pressure differences between the building interior and outdoors in several of the classrooms, each located a different distance from the central air-handler.

10.2.7 Summary and Recommendations

It is recommended that continuous radon and possibly pressure transmitters be installed at various locations in the building during the winter to monitor the building for at least one week. This could be done using the school districts monitoring equipment during the winter months.

SECTION 11

QUALITY CONTROL AND QUALITY ASSURANCE

11.1 INTRODUCTION

This section covers quality control (QC) and quality assurance (QA) for the research conducted in the 13 schools discussed in this report. QA/QC requirements apply to this project. The data are supported by QA/QC documentation as required by U.S. Environmental Protection Agency policy. The schools are located in Colorado (2 schools), Maine (2 school), Minnesota (1 school), Ohio (4 schools), South Dakota (1 school), Tennessee (1 school), and Washington (2 schools). Investigations in these schools centered on the use of ASD (4 schools), SMD (1 school), central HVAC systems (3 schools), and UV (4 schools) systems as used for radon mitigation.

11.2 QUALITY ASSURANCE PROJECT PLAN

A Quality Assurance Project Plan (QAPP) was submitted April 30, 1991 and revised and approved June 24, 1992 for the work performed by SRI. The Data Quality Objectives as described in that QAPP were met during the course of this research project.

11.3 CHARCOAL CANISTER MEASUREMENTS

In the course of these school investigations, radon screening measurements were carried out by local officials of the school board or their representatives using charcoal canisters provided by EPA. The CCs were provided by and analyzed by EPA's National Air Radiation Laboratory (NAREL) in Montgomery, Alabama.

11.3.1 Assessment of Precision

Ten percent of the CCs provided by NAREL were deployed as duplicate measurements. The collocated detector results are listed in Table 11.3.1 along with: the average value of each collocated pair, the standard deviation expressed in pCi/L, and the coefficient of variation (CV) expressed as a percentage for each set of measurements. The average of the standard deviations for all of the measurements was 0.2 pCi/L with the highest and lowest values of 2.3 and 0.0 pCi/L respectively. The average of the CV values for all of the measurements was 3.9 % with a maximum and minimum of 23.1 % and 0.0 % respectively. The average value of 3.9 % for the overall CV was well within the data quality objective of 10 %.

11.3.2 Assessment of Accuracy

No spiked measurements were carried out to assess the accuracy of the CC measurements. The CC measurements in these projects relied instead upon the QA/QC checks carried out by NAREL itself.

11.3.3 Assessment of Completeness

With the exception of less than 10 CCs deployed, valid results were obtained. This is well within a completeness criteria of 90 %.

11.4 CONTINUOUS RADON MONITORS

11.4.2 Assessment of Accuracy

The continuous radon monitors (CRMs) used in this study were calibrated by the manufacturer as shown in Table 11.4.1. Background checks of the instruments were carried out both before and after each field use. The average background counts were subtracted from the gross field counts before the actual radon levels were calculated.

11.5 DIFFERENTIAL PRESSURE MEASUREMENTS

Before deploying the cells in the field and once upon their return to the laboratory, the calibration span was checked using a Dwyer No. 1420 Hook Gage. This instrument is capable of calibration over a range of 0 to 2 in.W.C. to an accuracy of 0.001 in.W.C. The Dwyer No. 1420 complies with Federal specifications GGG-C-105A and is traceable to a master at the National Institute of Science and Technology (formerly the National Bureau of Standards).

11.6 CONTINUOUS MONITORING PROCEDURES

Continuous monitoring of parameters other than radon were used where it was determined to be helpful. The primary mechanism for continuous data acquisition of time-dependent parameters was a programmable electronic datalogger incorporated in the monitoring instrumentation package for each study school building. Analog signals, such as from temperature and relative humidity probes, were sampled once every 0.1 min. Thirty minute averages of 300 one-tenth-minute readings were stored in datalogger memory as a single record. Pulsed outputs from the Continuous Radon Monitors was integrated for the entire 30 minute interval. Logic signals, such as from sail switches for HVAC operation or classroom door opening switches, were interrogated every 0.1 min. The duty cycle for switch-on operation was recorded as a fraction (i.e., 0.5 for 50%) for every 30-minute interval.

Indoor and outdoor temperatures were monitored on a near-continuous basis using either/or Type K thermocouples and calibrated thermistors. Differential pressure transducers (Modus, Inc., Model T20) were used to monitor differential pressures from an indoor reference point to locations outside, under the slab, and possibly at other points within the school building. Radon signals from the continuous radon monitors were counted using the datalogger as well as the Pylon AB-5 counting circuitry.

11.7 NON-CONTINUOUS MEASUREMENT PROCEDURES

Other measurements included air infiltration tests (blower door or tracer gas), sub-slab communication tests (pressure field extension), sub-slab radon profile mapping, CO_2 concentration measurements, HVAC flow rate measurements, and spot pressure differential measurements. These measurements were made following current AEERL protocol.

11.8 AUDITS

No EPA Field or Internal Audits were conducted during the period covered by this report.

SECTION 12

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APPENDIX A

FIGURES

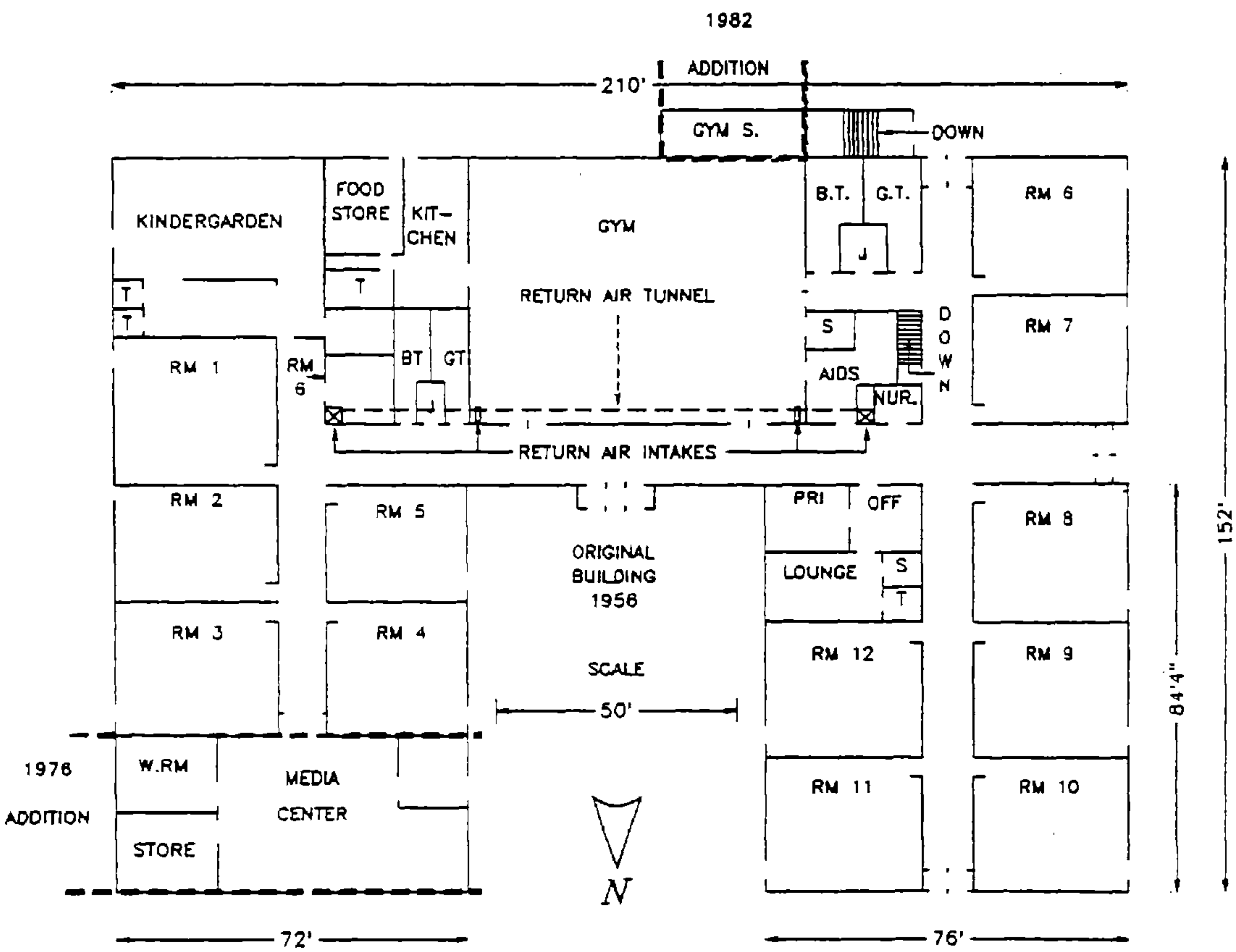


Figure 4.1.1. Floor plan showing additions, room numbers, return air tunnel, and dimensions at Barton Elementary School.

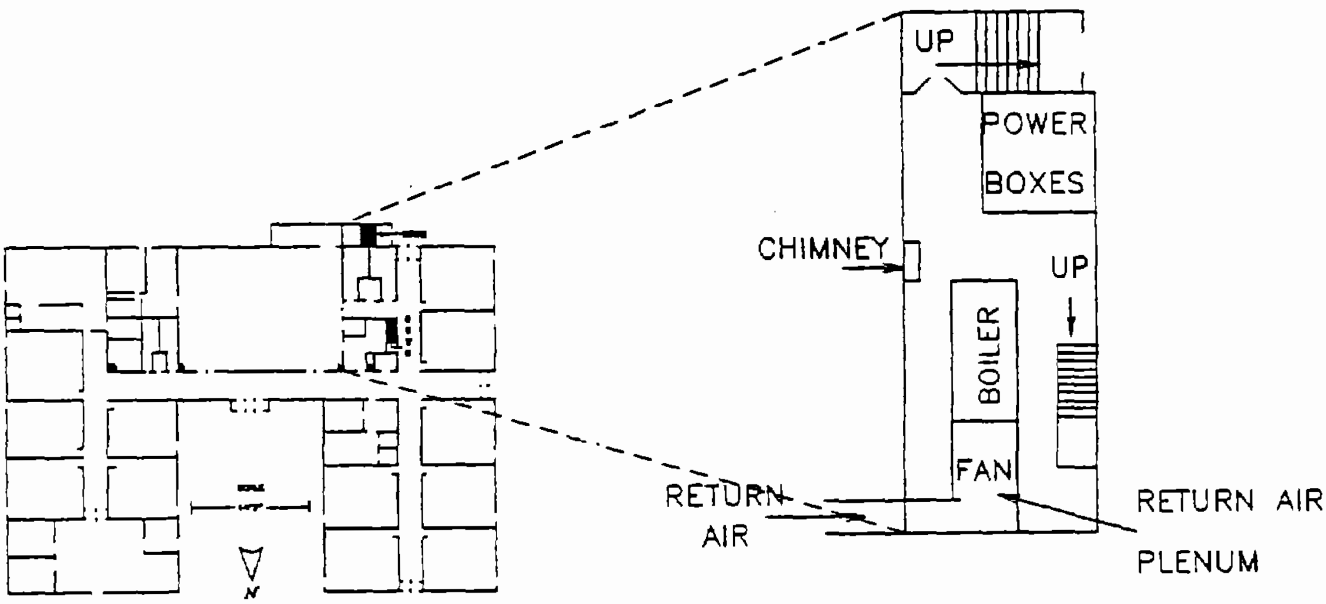


Figure 4.1.2. Floor plan and location of the boiler room at Barton Elementary School.

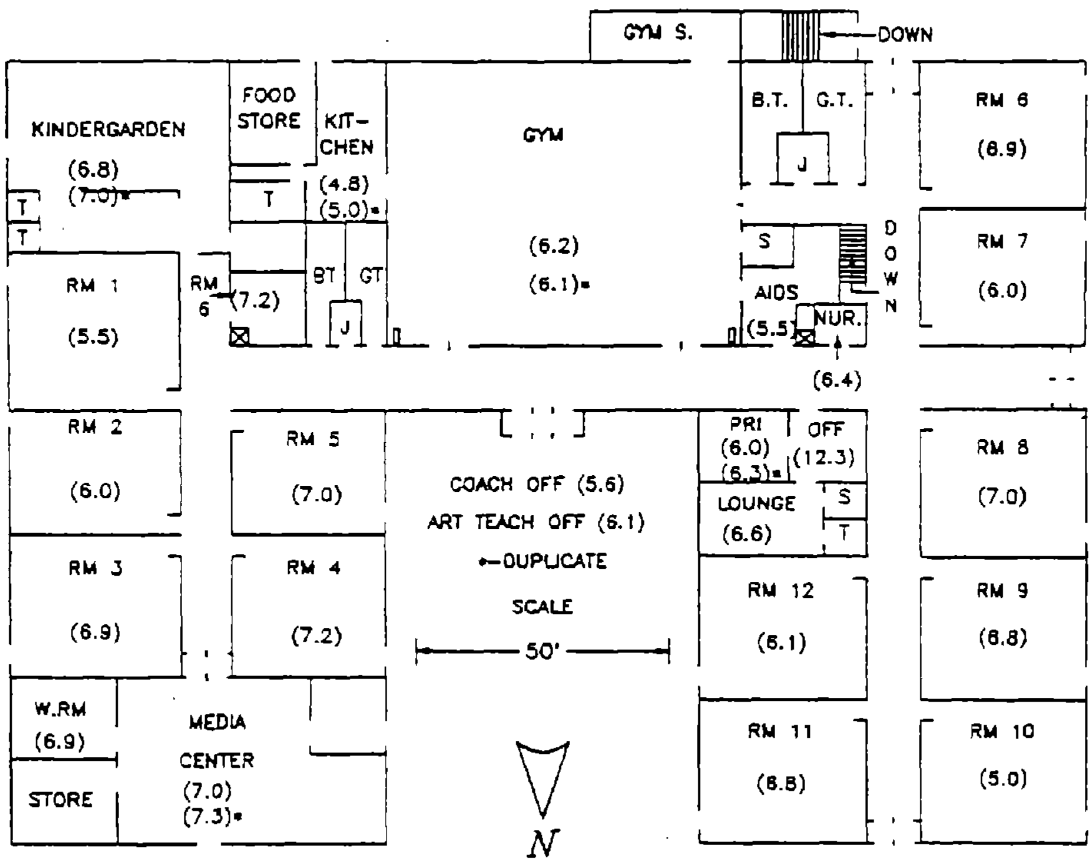


Figure 4.1.3. Results of January 1990 radon screening measurements at Barton Elementary School, in pCi/L.

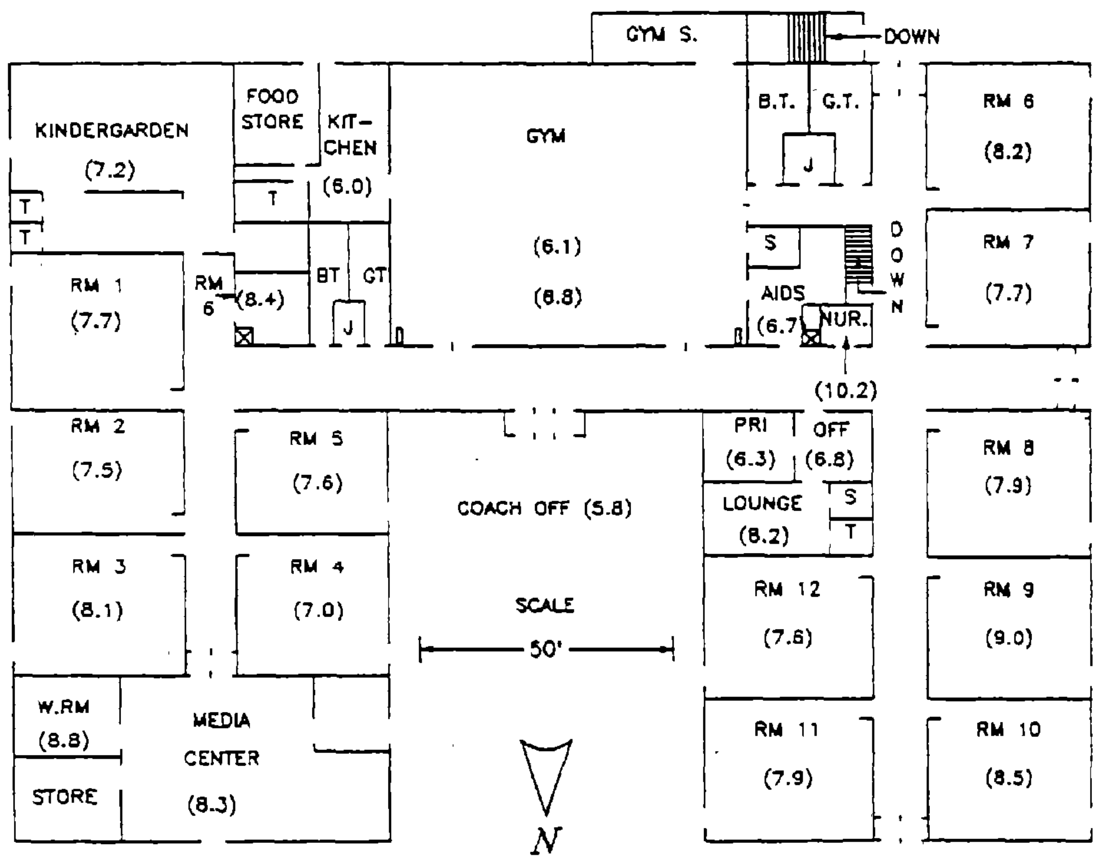


Figure 4.1.4. Results of February 1990 radon follow-up measurements at Barton Elementary School, in pCi/L.

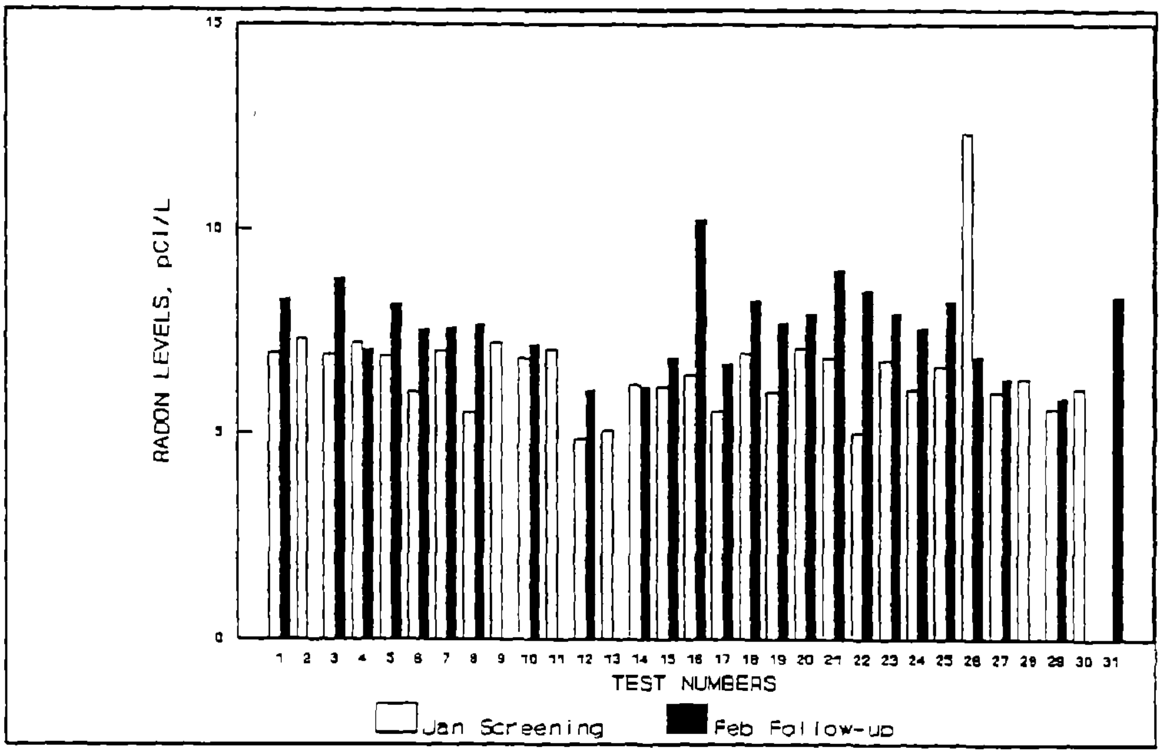


Figure 4.1.5. Comparison of the January 1990 and February 1990 radon measurements at Barton Elementary School (some of the January tests were not repeated in February).

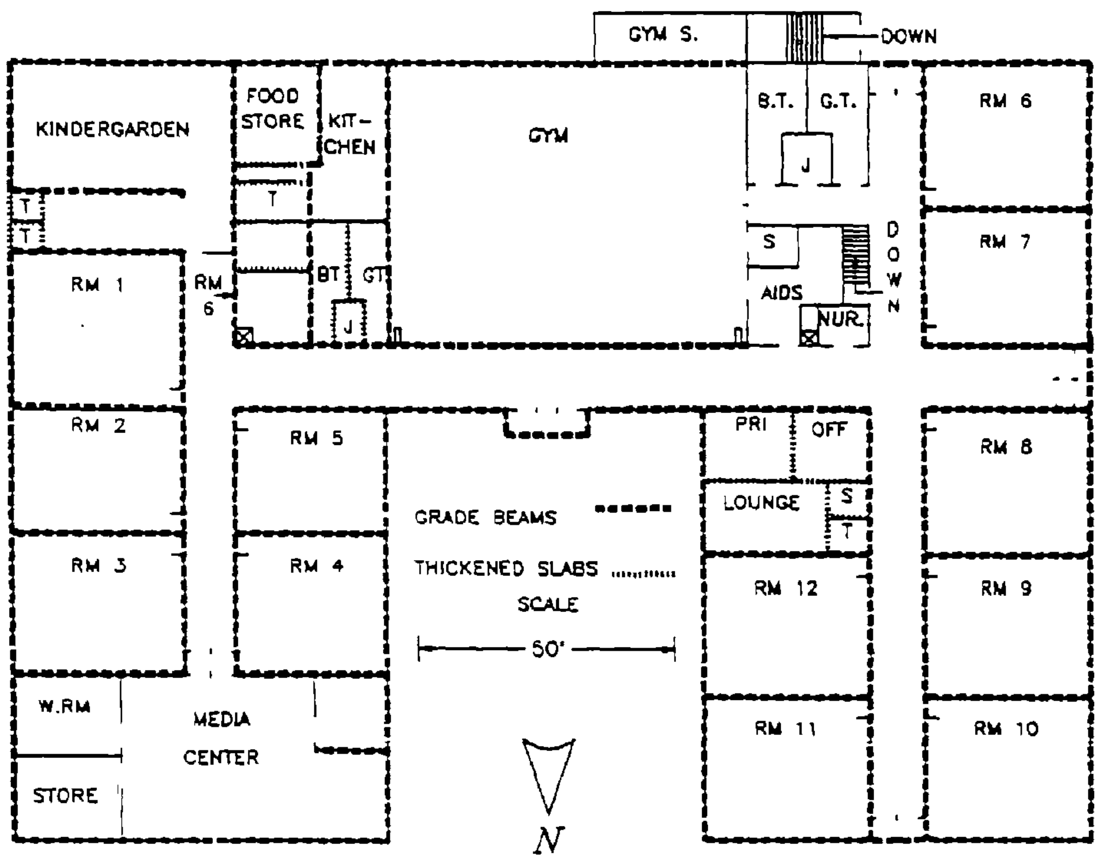


Figure 4.1.6. Floor plan showing the locations of subslab grade beams and thickened slabs at Barton Elementary School.

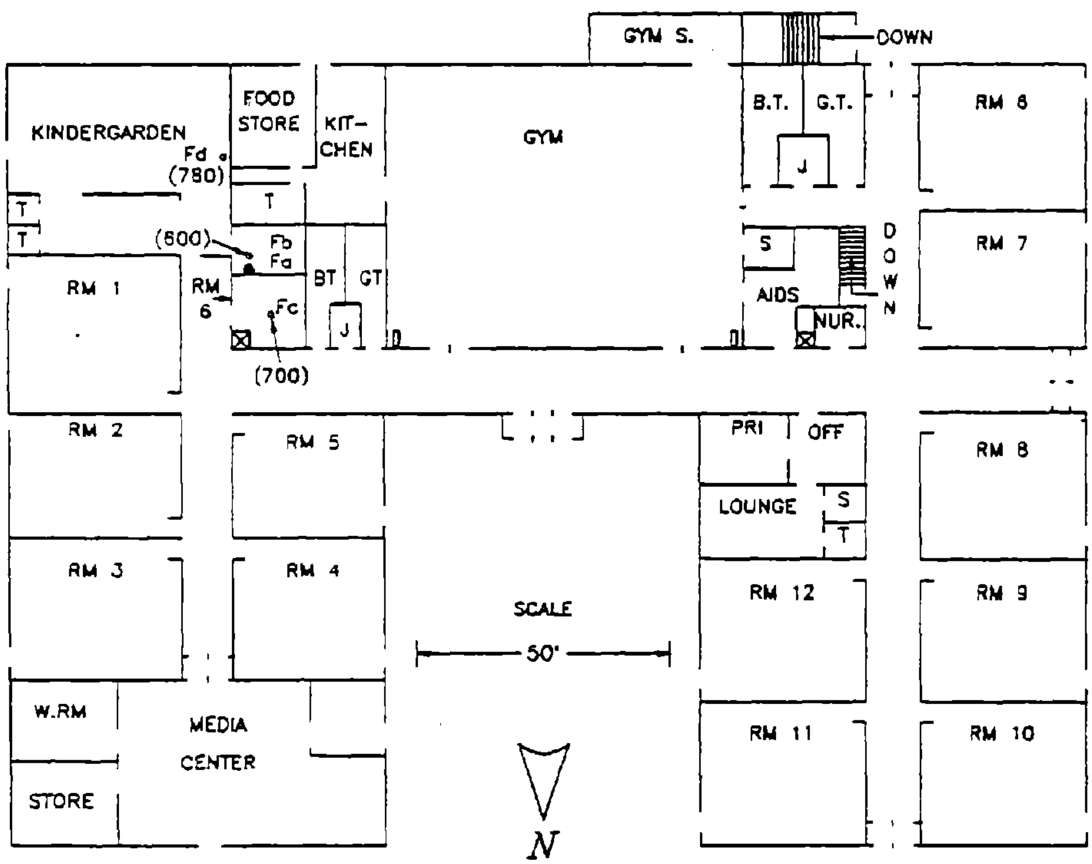


Figure 4.1.7. Location of subslab test points used during the communication and radon profile tests at Barton Elementary School, radon levels in pCi/L.

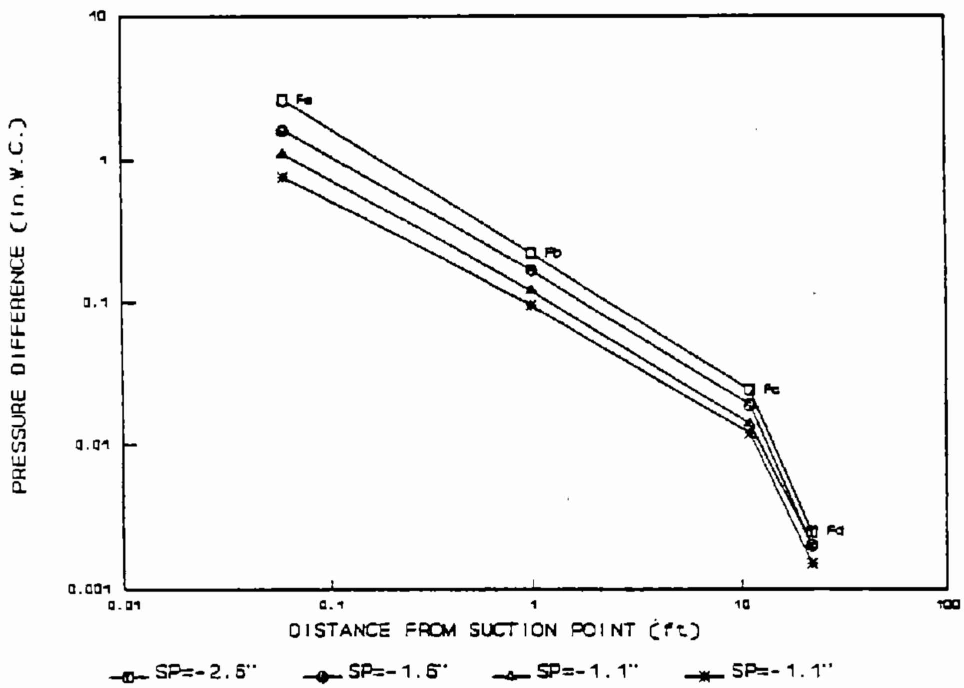


Figure 4.1.8. Subslab communication test results at Barton Elementary School (the SP values are the applied suction pressures).

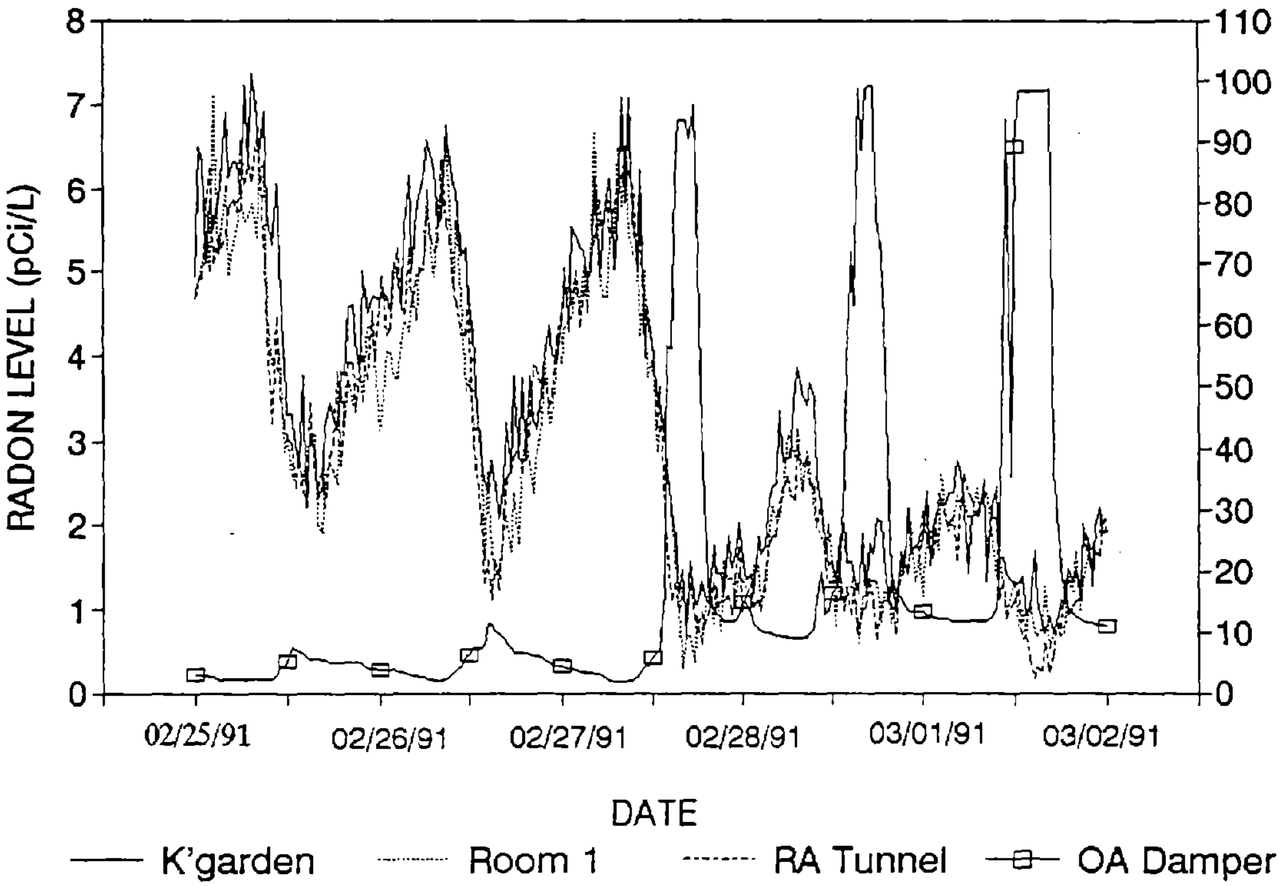


Figure 4.1.9. Effects of opening OA damper upon radon levels at Barton Elementary.

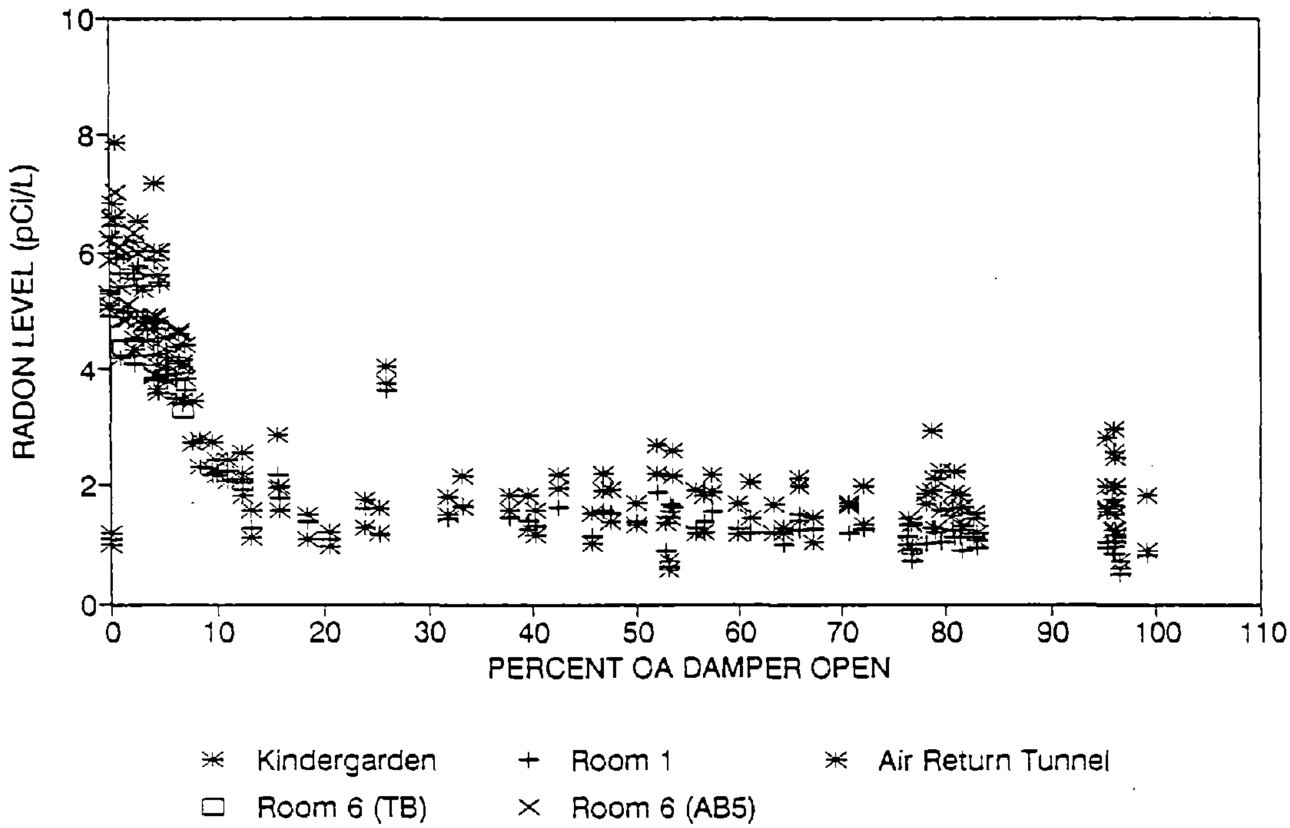


Figure 4.1.10. Correlation of the 8 hour average radon levels with the 8 hour average OA damper positions at Barton Elementary.

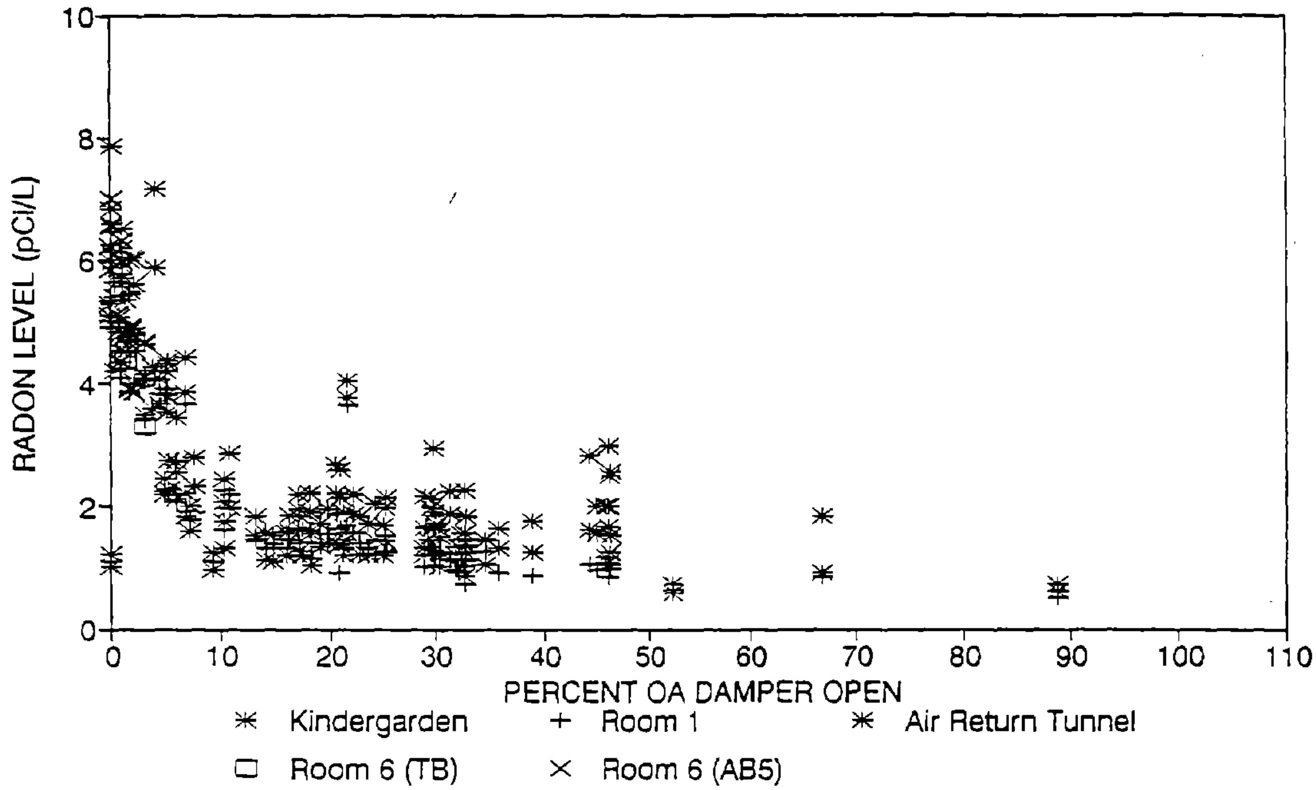


Figure 4.1.11. Correlation of the 24 hour average radon levels with the 24 hour average OA damper positions at Barton Elementary.

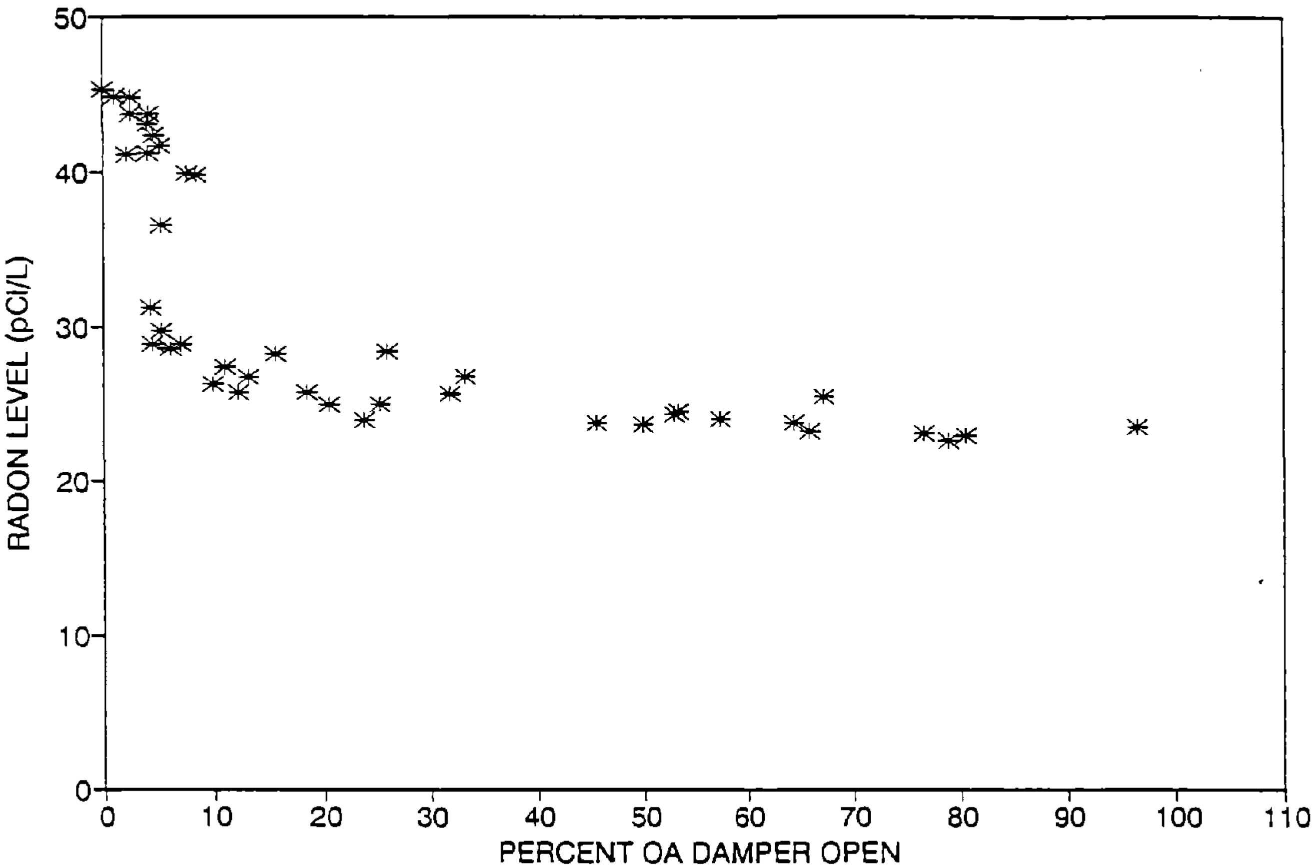


Figure 4.1.12. Correlation of the 8 hour average subslab radon levels with the average OA damper positions at Barton Elementary.

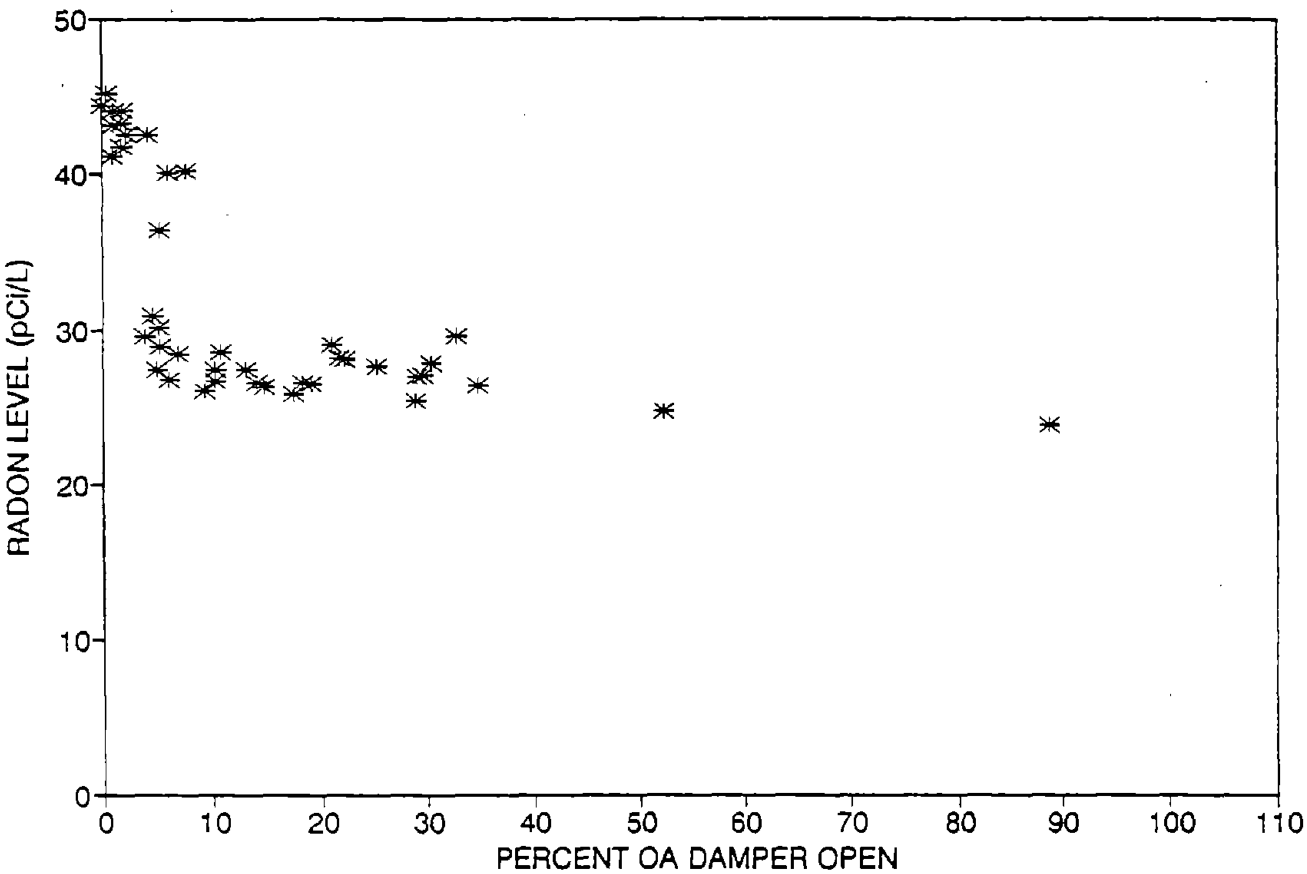


Figure 4.1.13. Correlation of the 24 hour average subslab radon levels with the average OA damper positions at Barton Elementary.

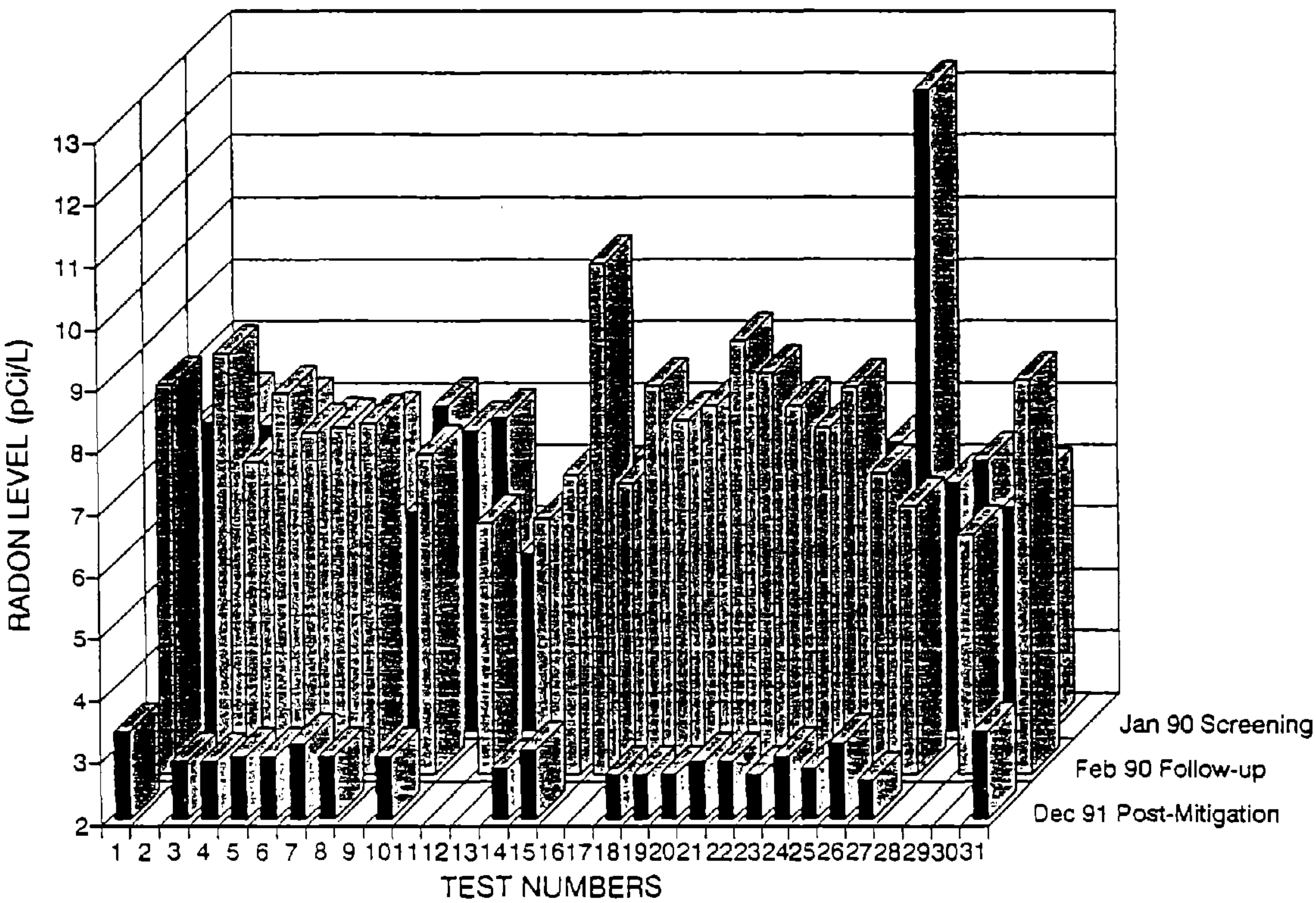


Figure 4.4.14 Comparison of all radon measurements made at Barton Elementary School (some tests were not repeated each time).

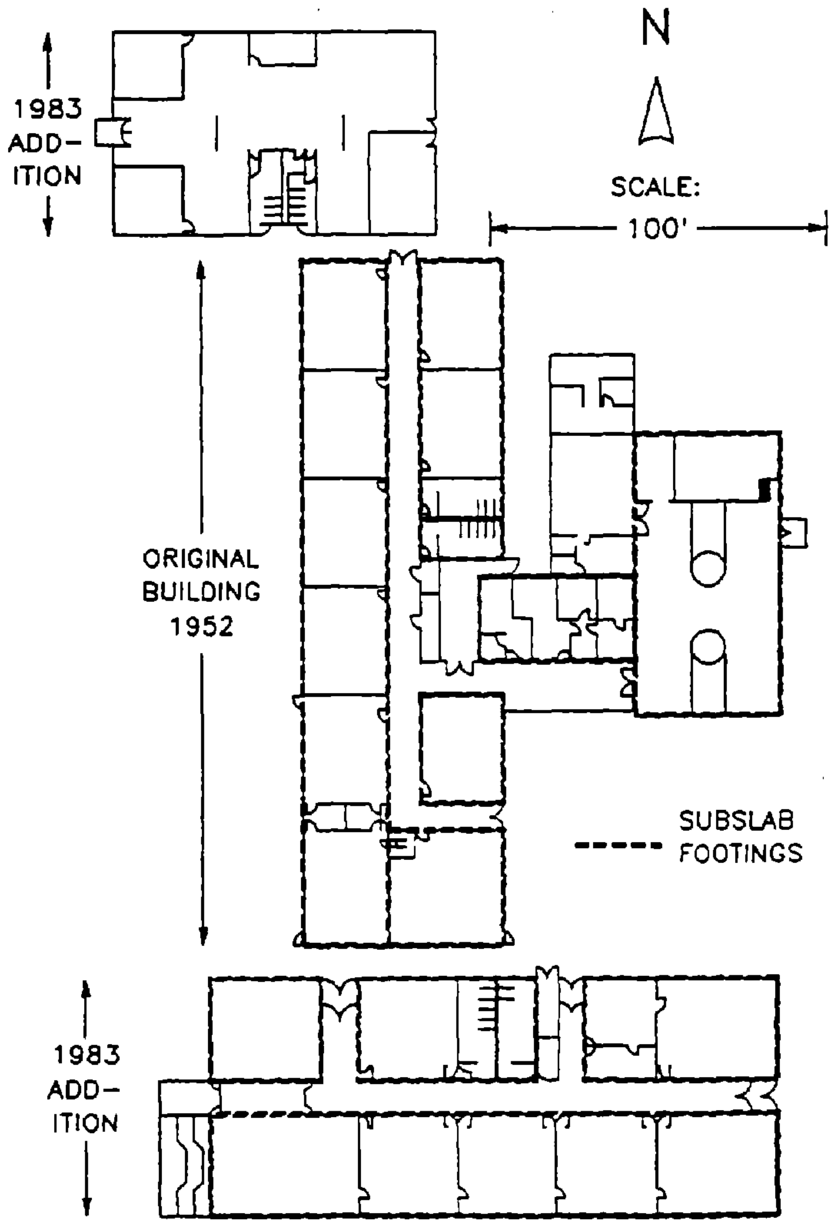


Figure 4.2.1. Floor plan showing building additions and subslab footer locations at Platteville Elementary School.

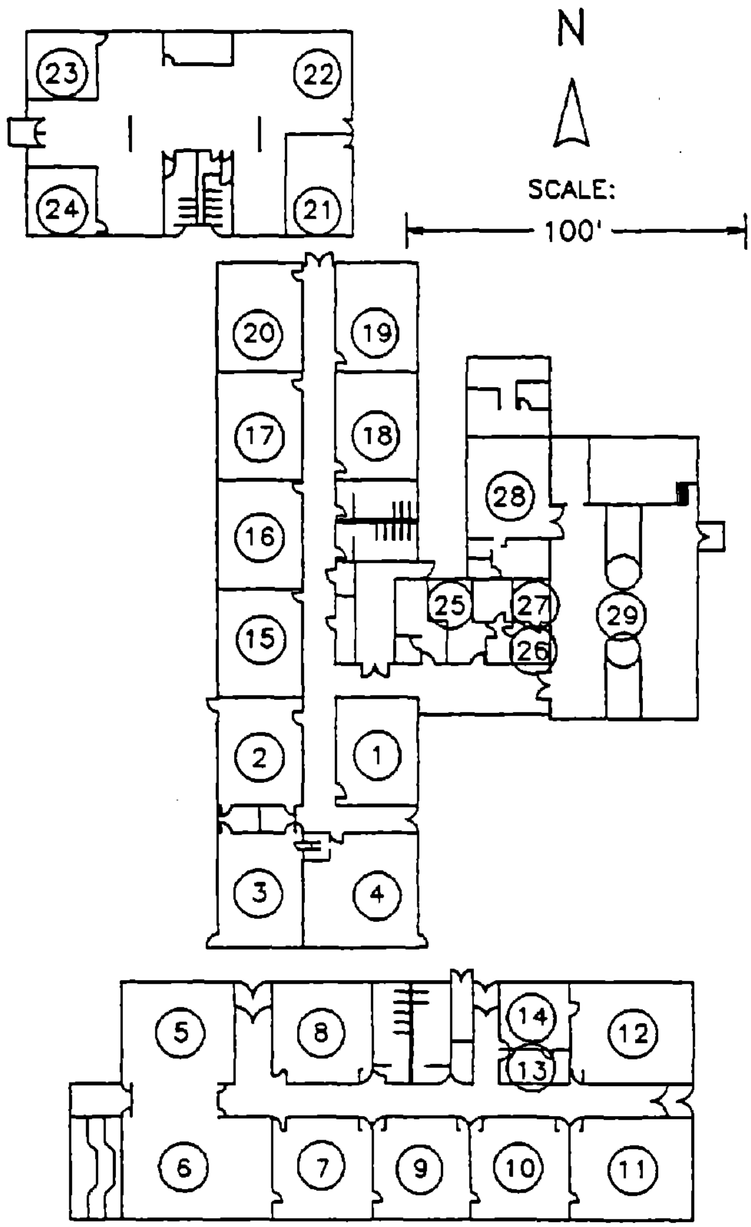


Figure 4.2.2. Location of canister numbers for CC measurements in Platteville Elementary School.

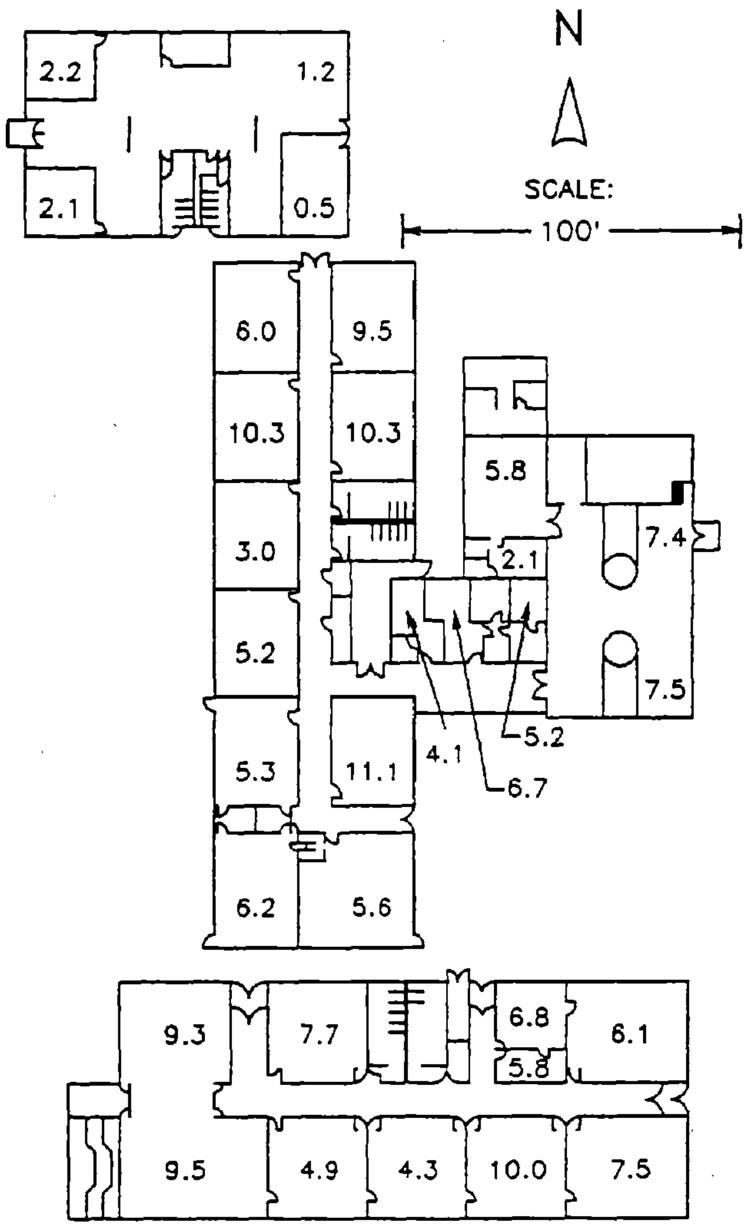


Figure 4.2.3. Results of March 1990 radon screening measurements in Platteville Elementary School, in pCi/L.

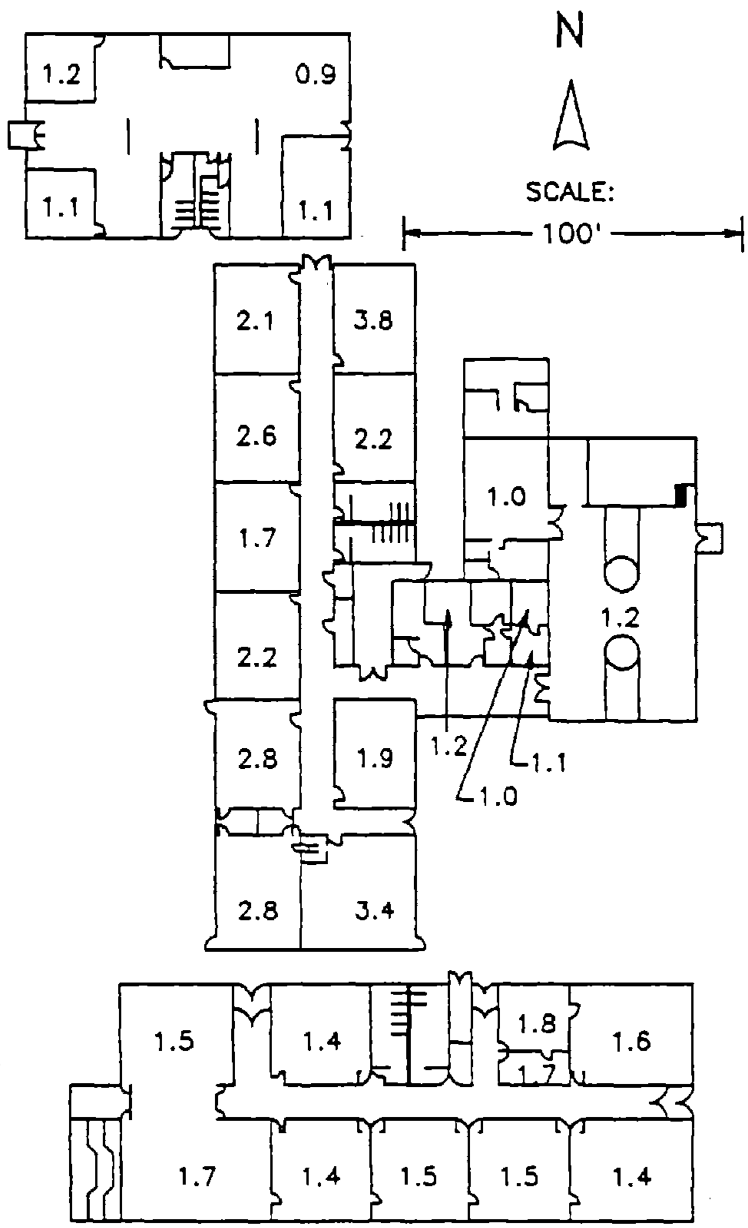


Figure 4.2.4. Results of August 1990 follow-up radon measurements in Platteville Elementary School, in pCi/L.

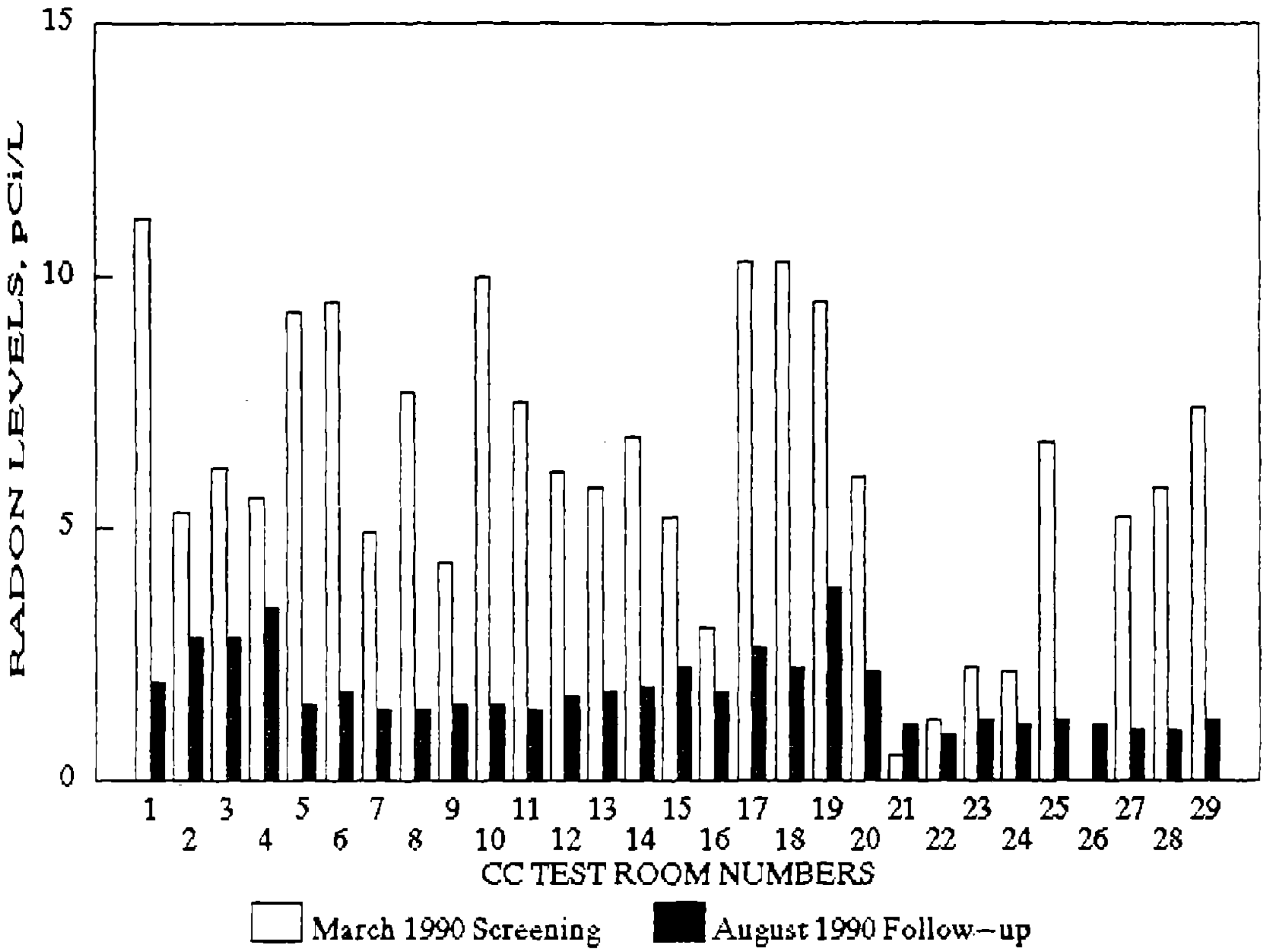


Figure 4.2.5. Comparison of the March 1990 and August 1990 measurements at Platteville Elementary School, in pCi/L.

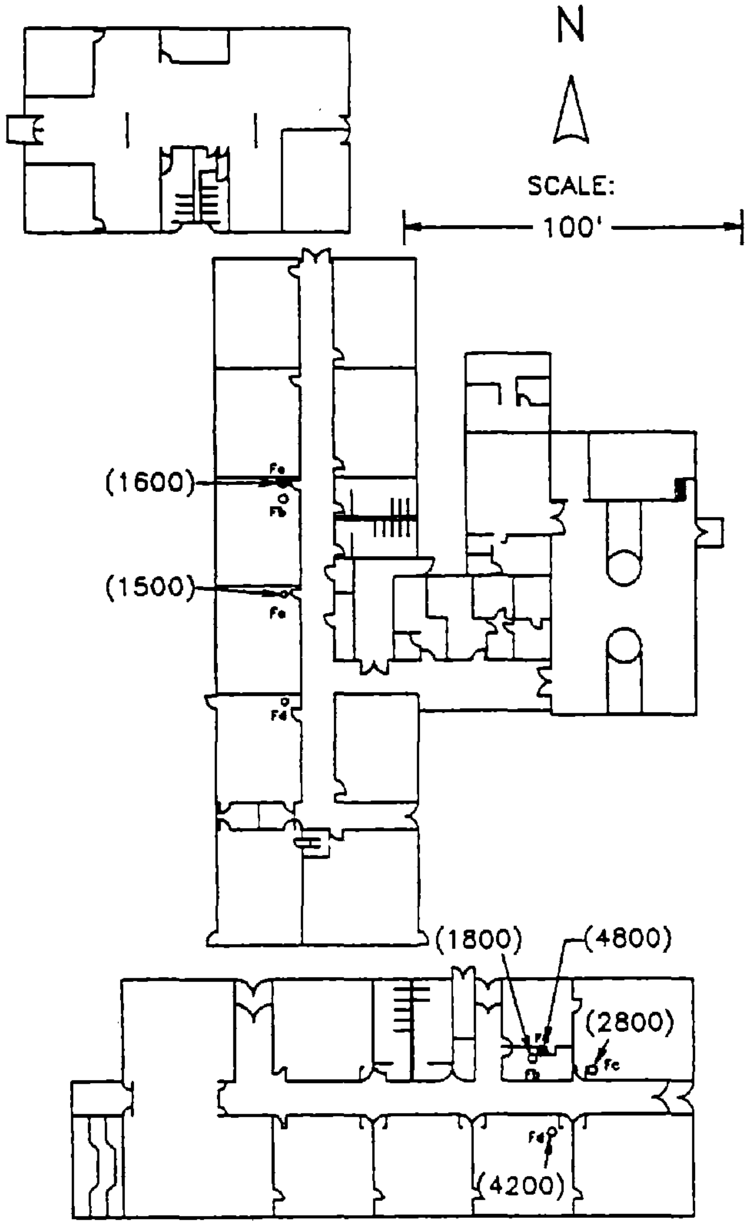


Figure 4.2.6. Locations of suction and test points used in subslab communication tests and the radon levels under the slab at Platteville Elementary School, in pCi/L.

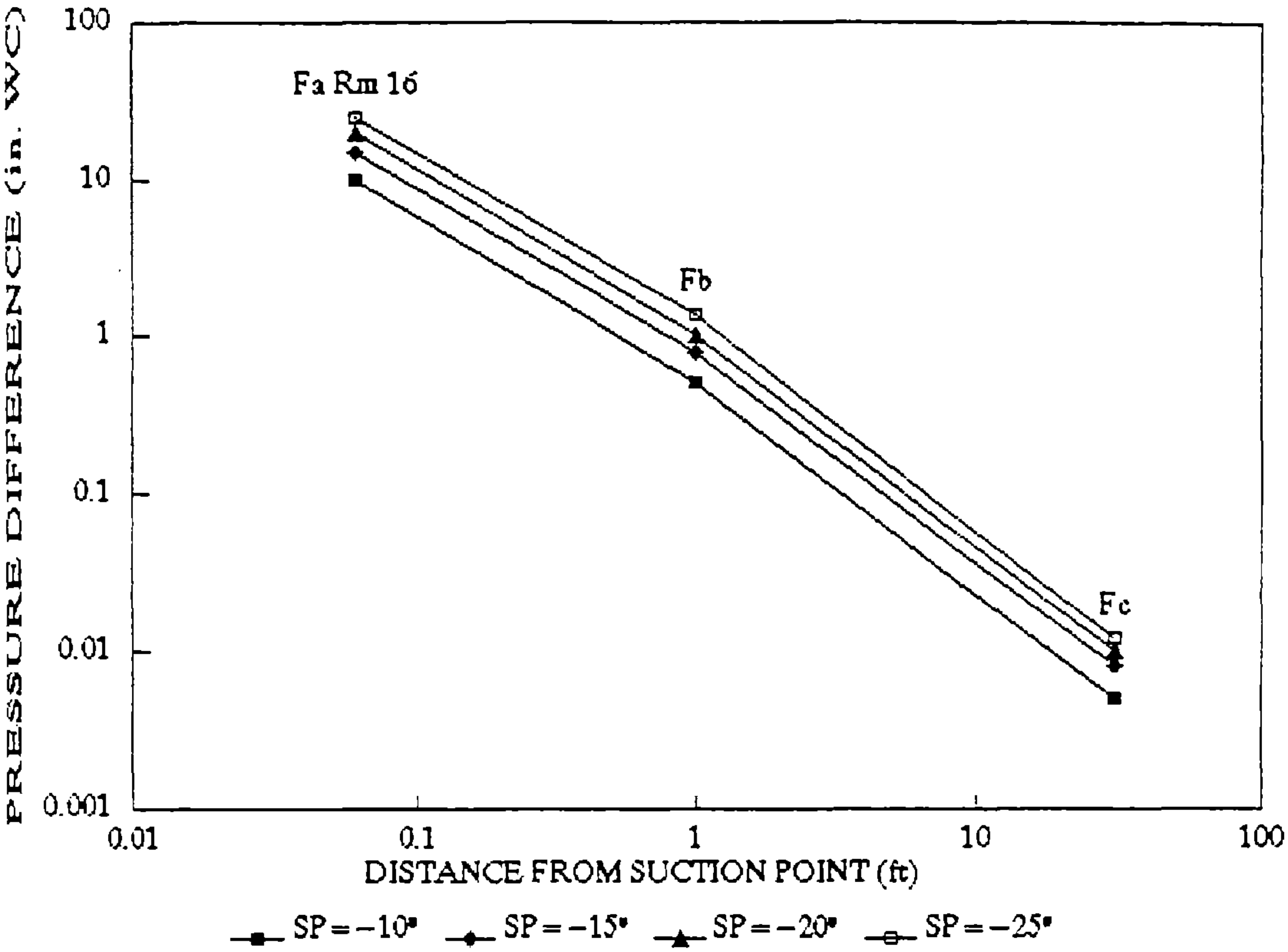


Figure 4.2.7. Pressure field extensions from suction point 1 located in Room 16 at Platteville Elementary School, the SP values are the applied suction pressure in inches of water column.

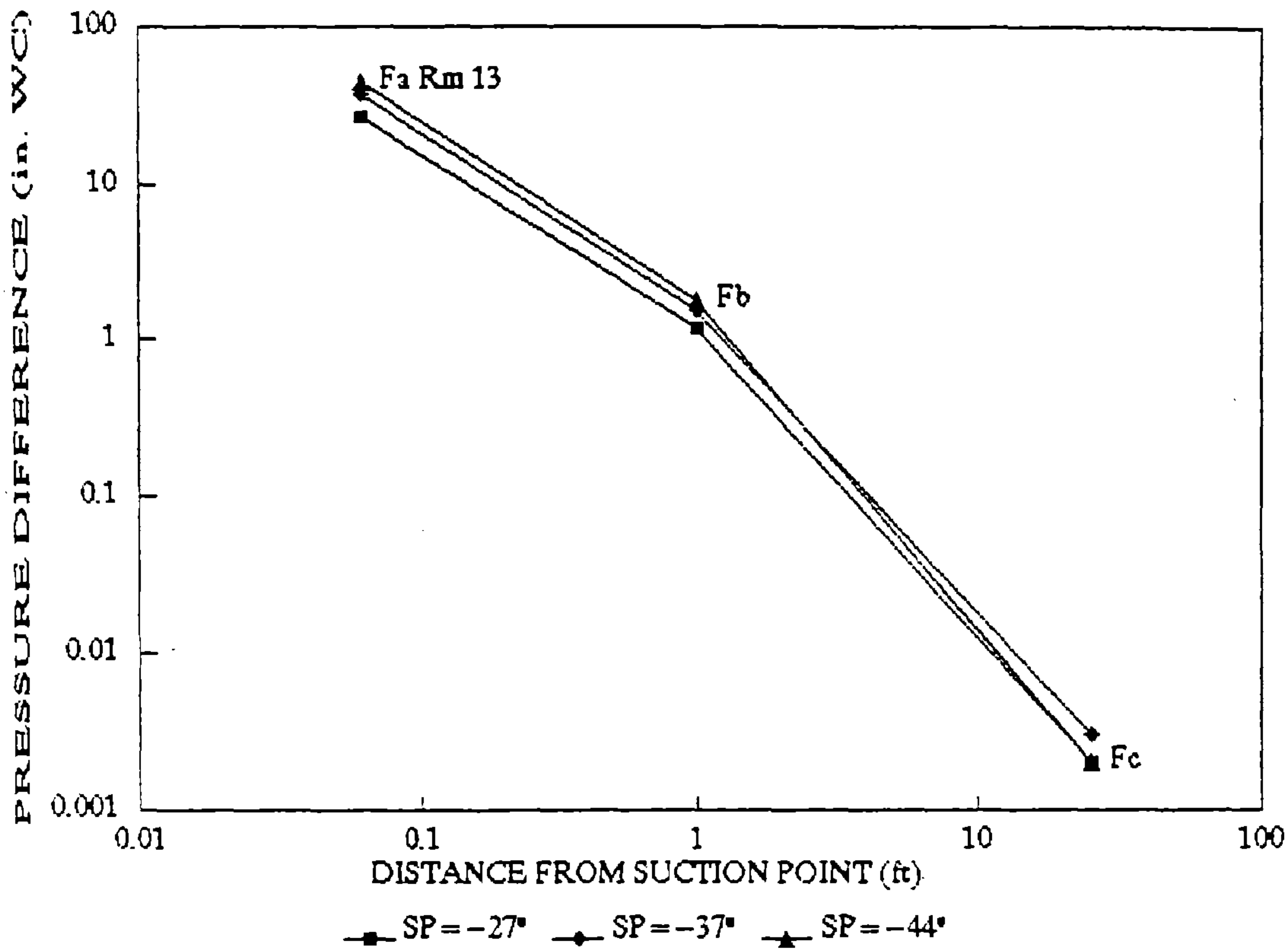


Figure 4.2.8. Pressure field extensions from suction point 2 located in Room 13 at Platteville Elementary School, the SP values are the applied suction pressure in inches of water column.

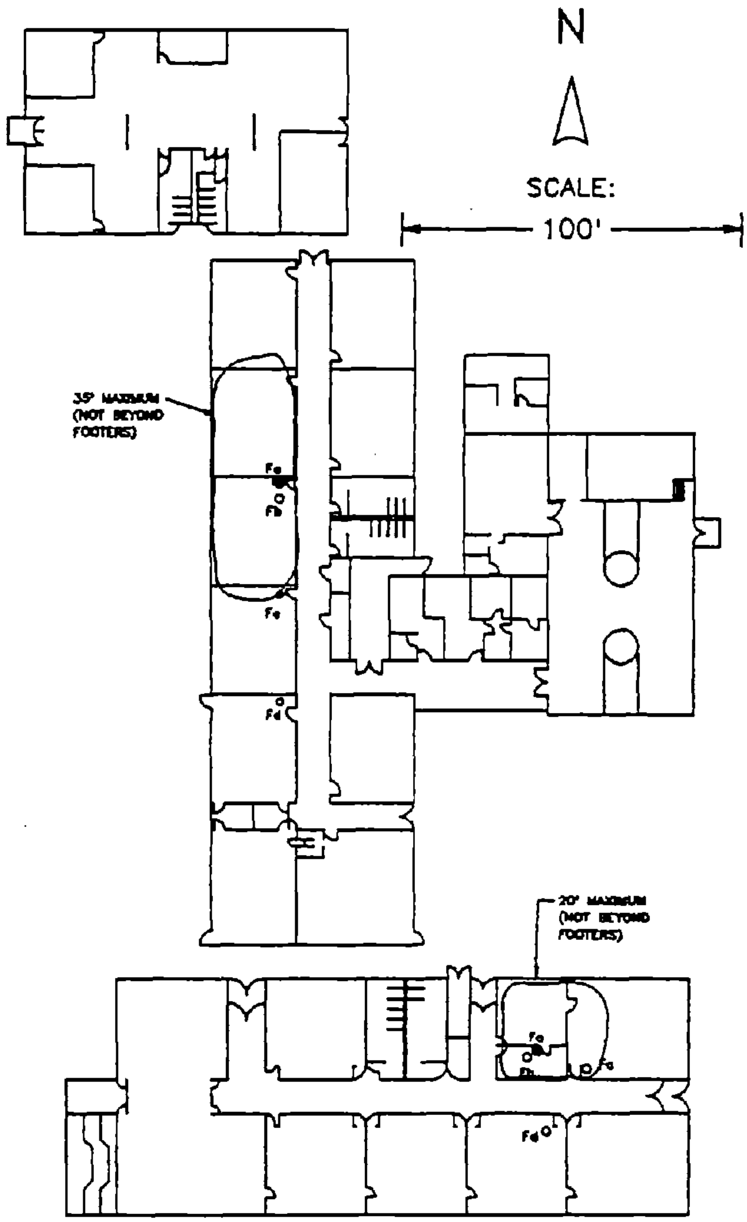


Figure 4.2.9. Approximate pressure field extensions measured at Platteville Elementary School.

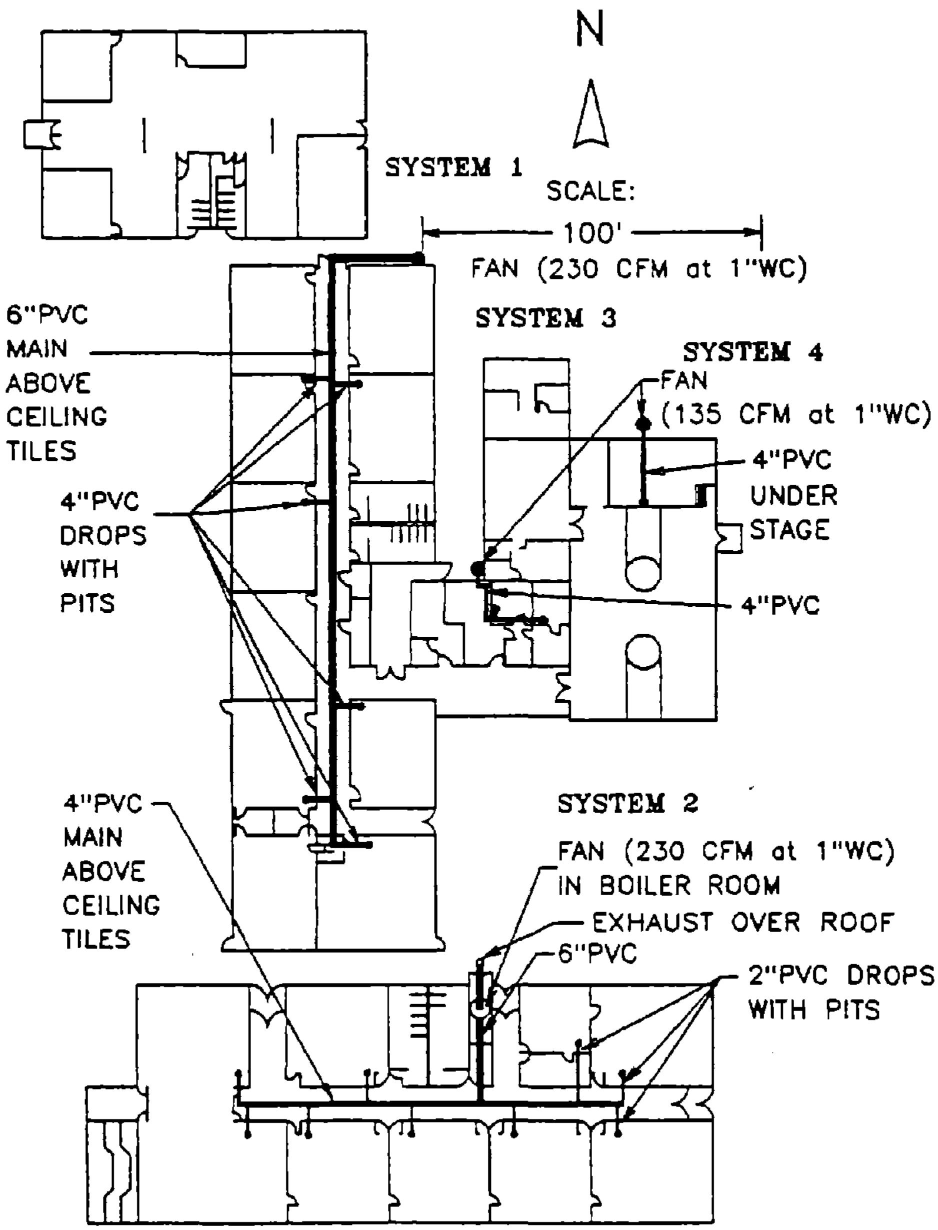


Figure 4.2.10. Proposed mitigation systems for Platteville Elementary School.

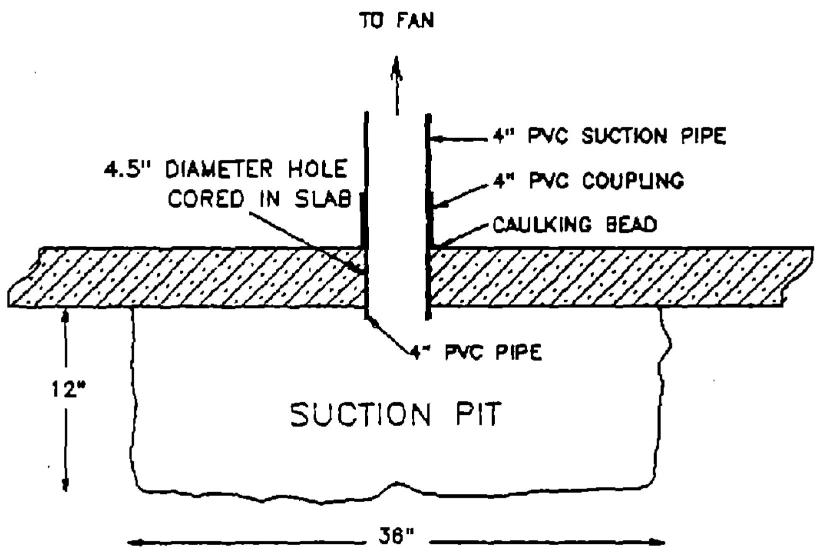


Figure 4.2.11. Subslab suction point details for 4 inch diameter suction pipe.

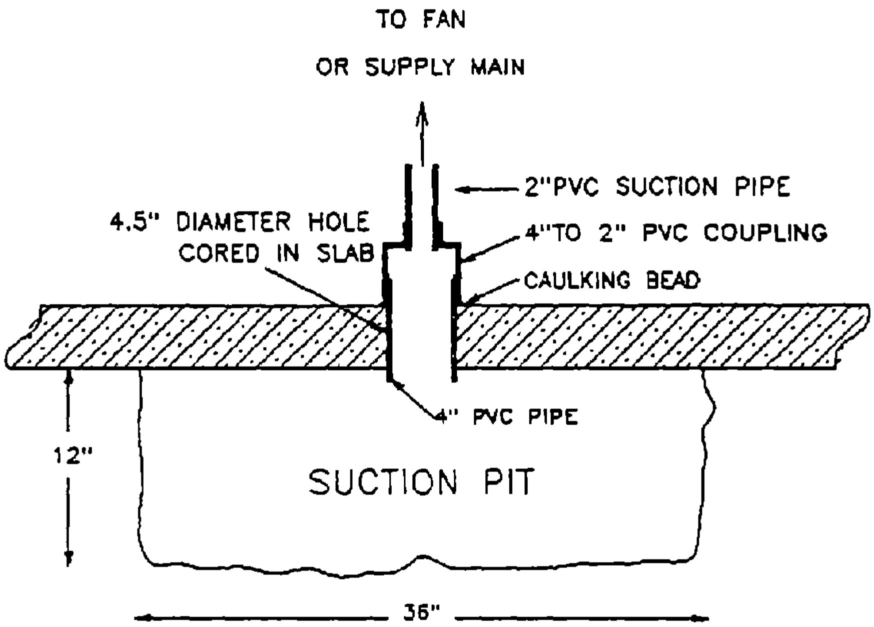


Figure 4.2.12. Subslab suction point details for 2 inch diameter suction pipe.

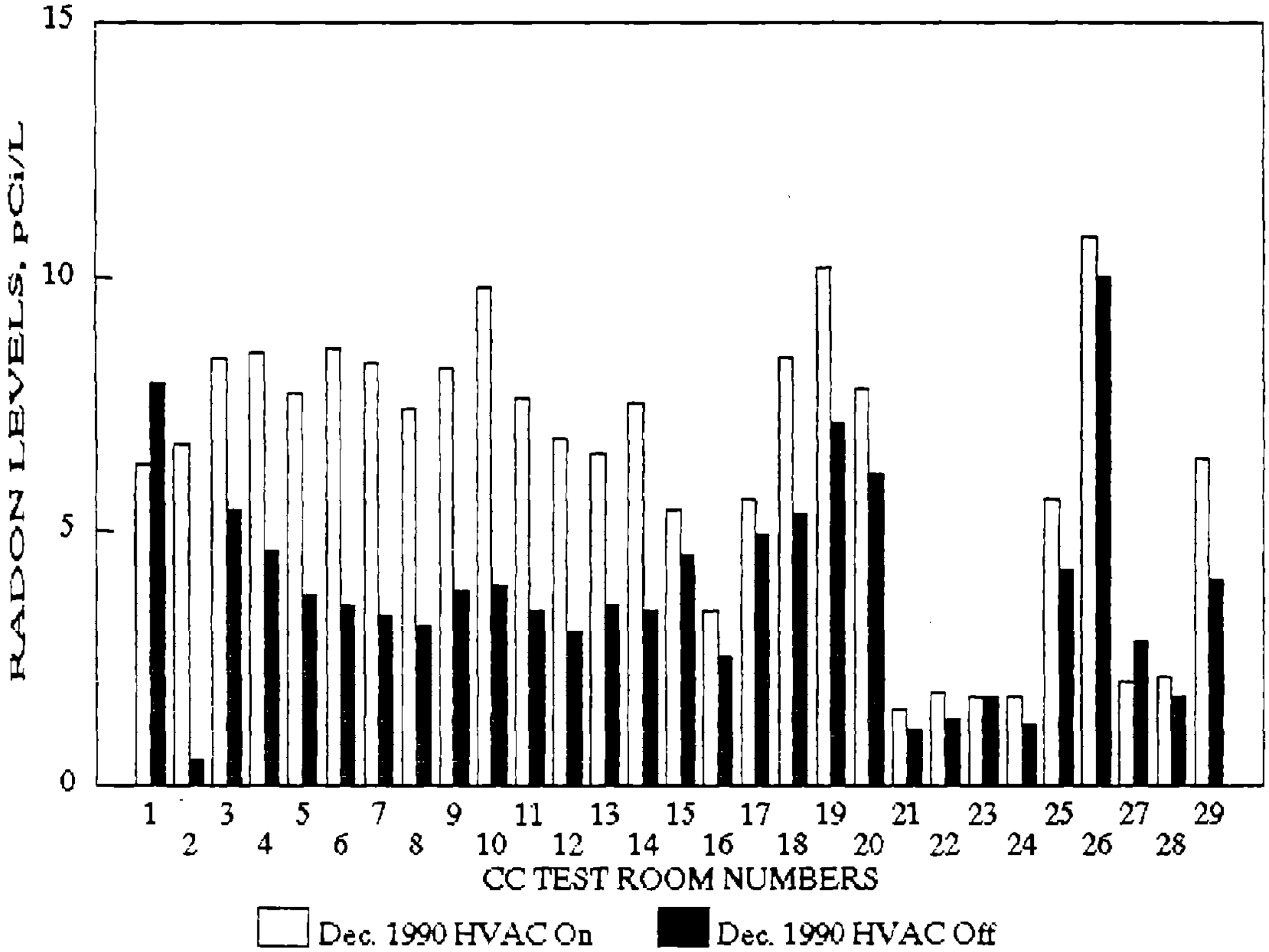


Figure 4.2.13. Comparison of the December 1990 cc measurements made with the HVAC units on and off at Platteville Elementary, Platteville, CO.

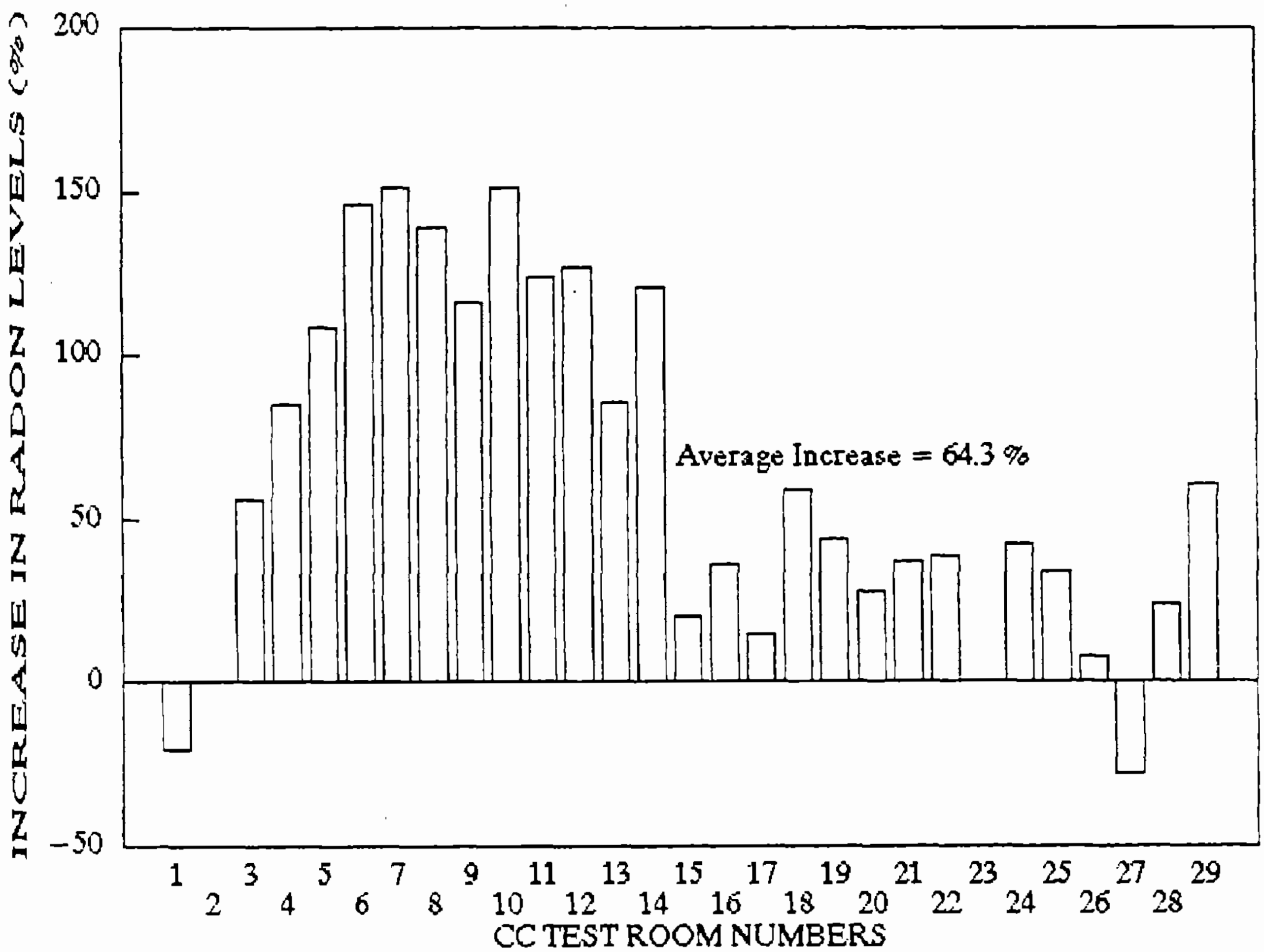


Figure 4.2.14. Changes in the radon levels when the HVACs on versus when off at Platteville Elementary, Platteville, CO.

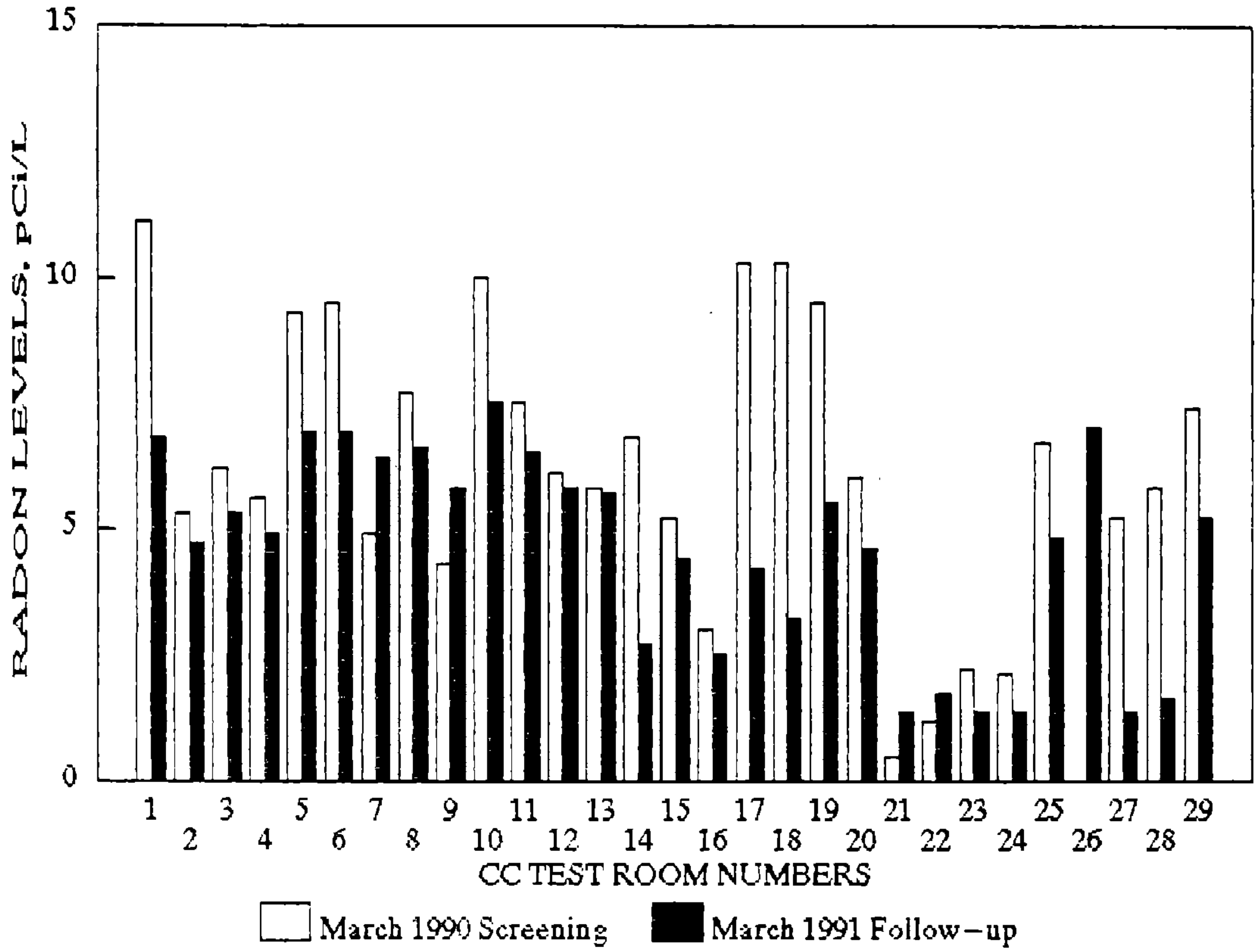


Figure 4.2.15. Comparison of the March 1990 and March 1991 measurements at Platteville Elementary, Platteville, CO.

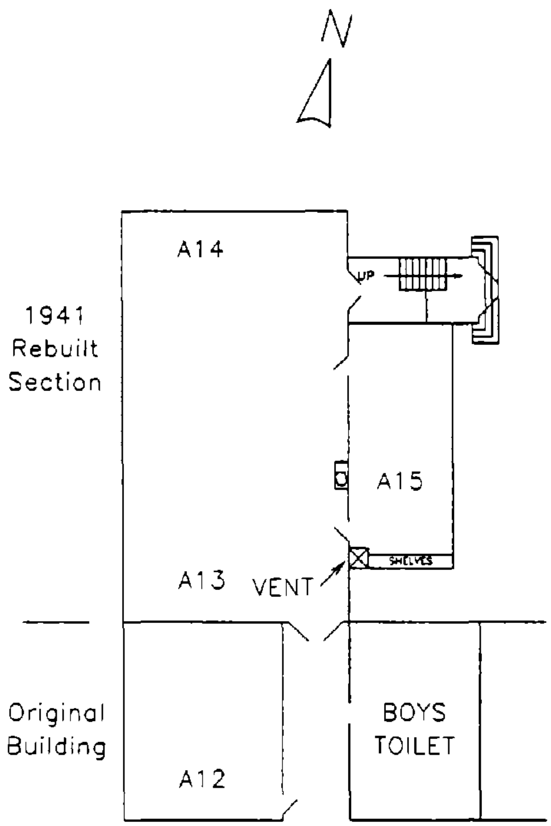


Figure 5.1.1 Floor plan of the basement rooms of the NW wing of Sanford Middle School, Sanford, ME.

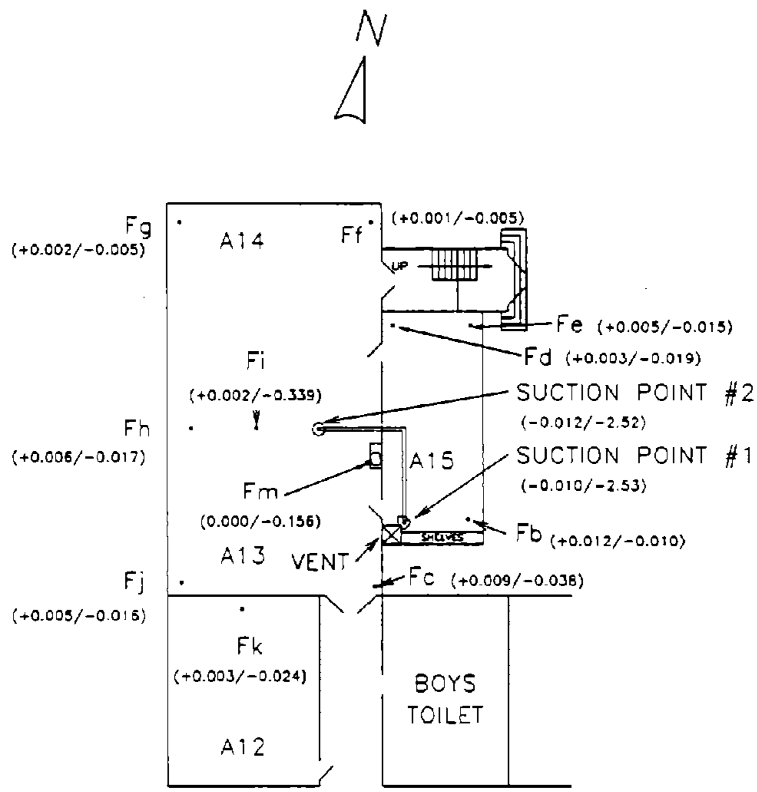


Figure 5.1.2 Location of mitigation system installed and subslab communication test results in the NW wing of Sanford Middle School, Sanford, ME (in.W.C.-fan off/in.W.C.-fan on).

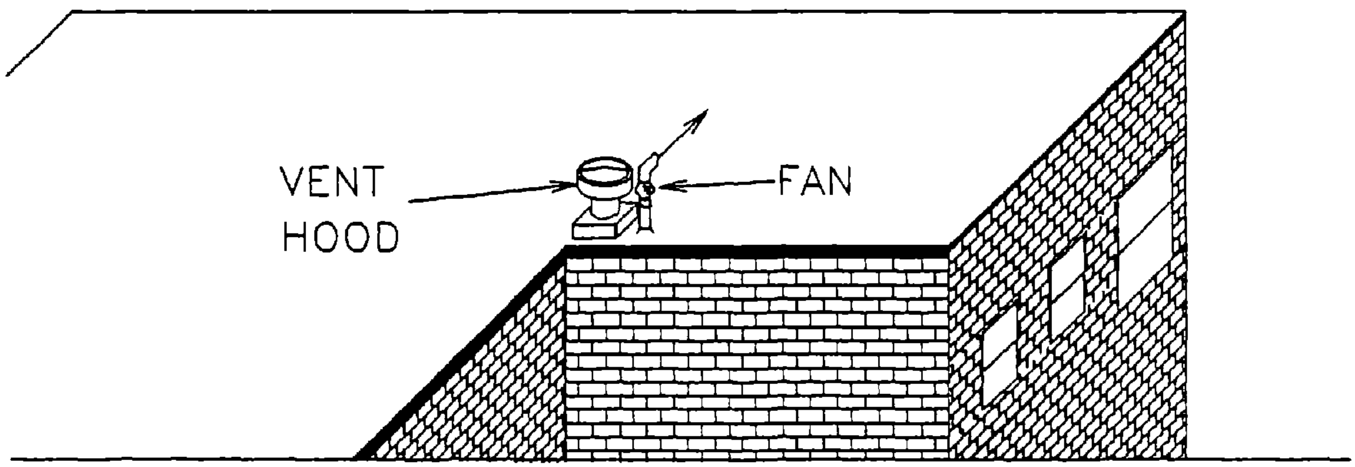


Figure 5.1.3. Location of fan mounted on the roof of Sanford Middle School, Sanford, ME.

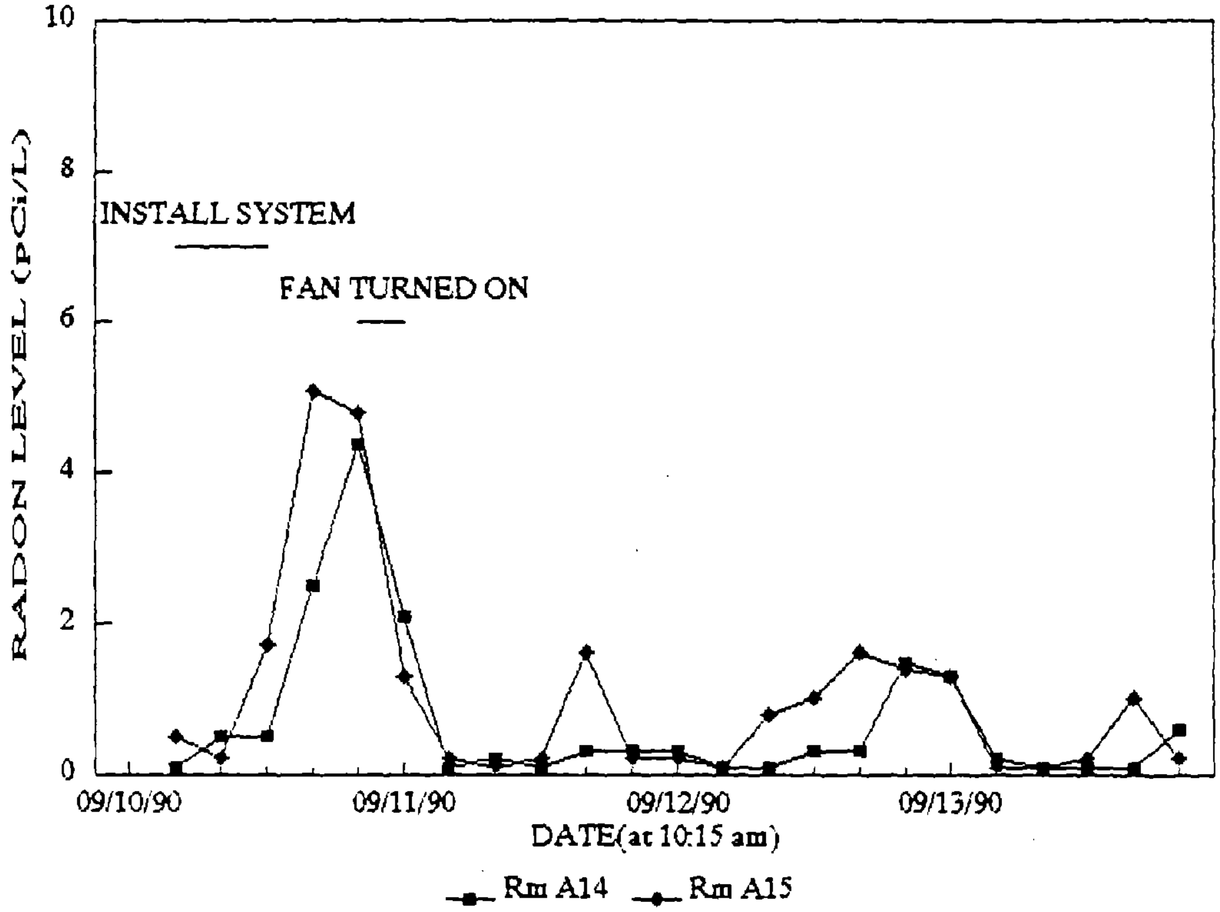


Figure 5.1.4. Tentative results of the mitigation system installed in Sanford Middle School, Sanford, ME.

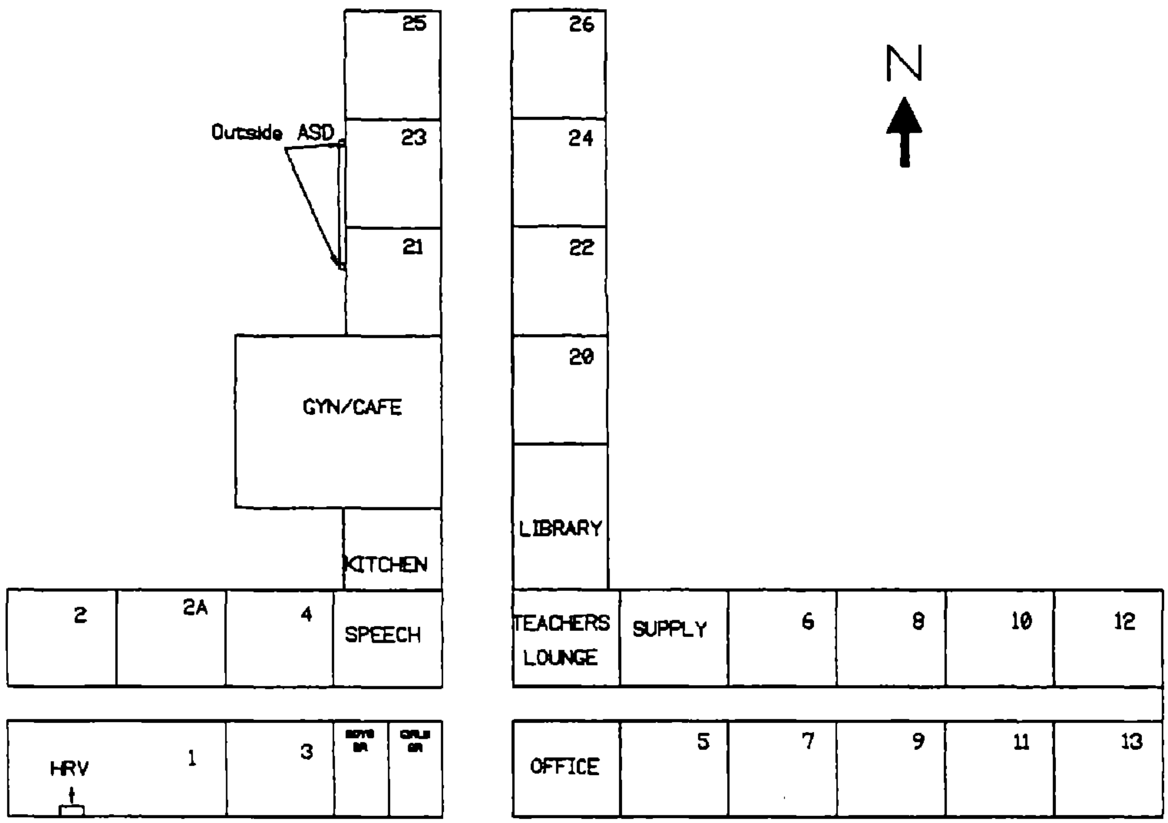


Figure 5.2.1 Plan view of Russell Elementary, Gray, ME.

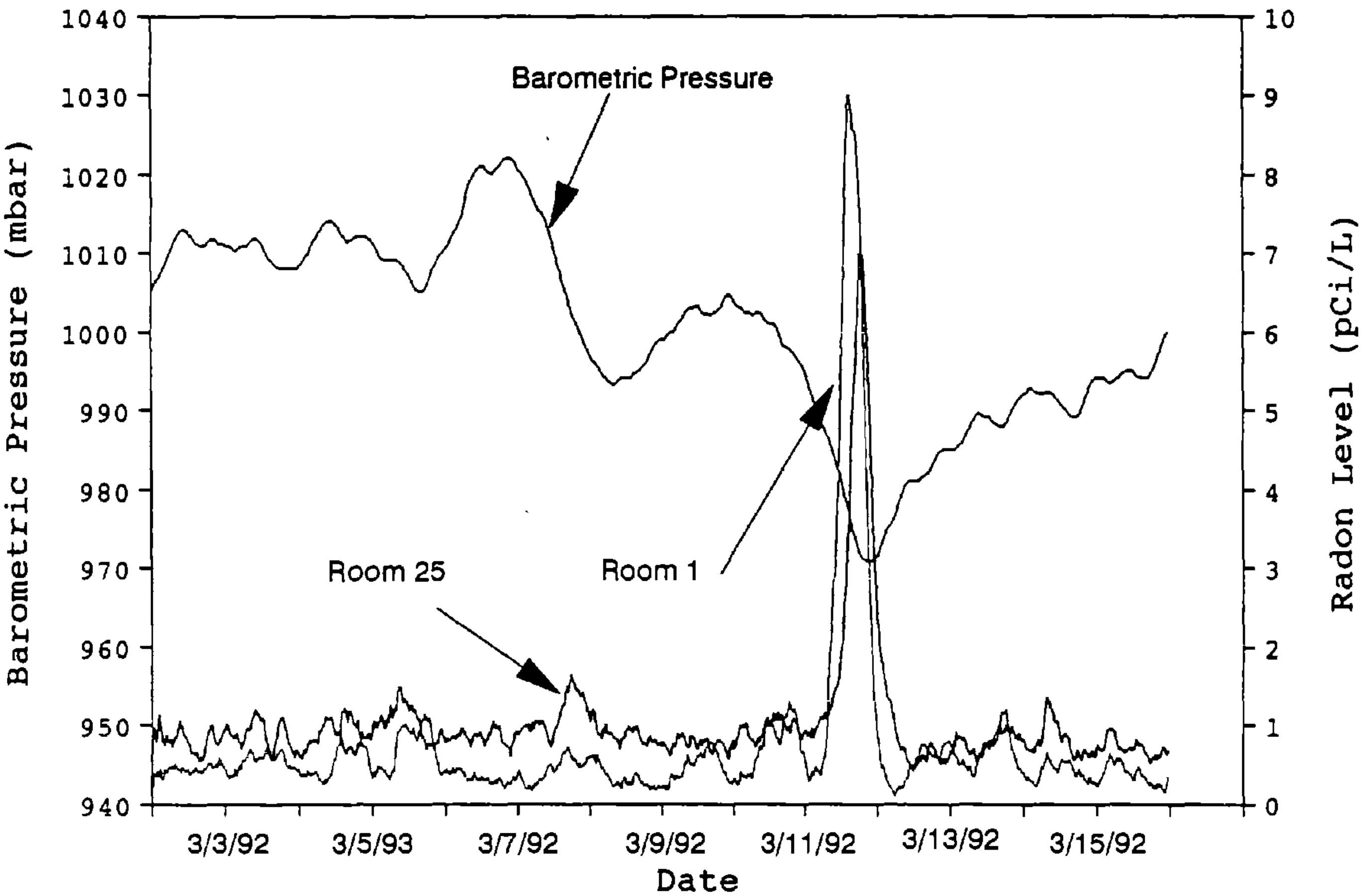


Figure 5.2.2. Correlation of radon level increases with changes in barometric pressure at Russell Elementary School, Gray, ME.

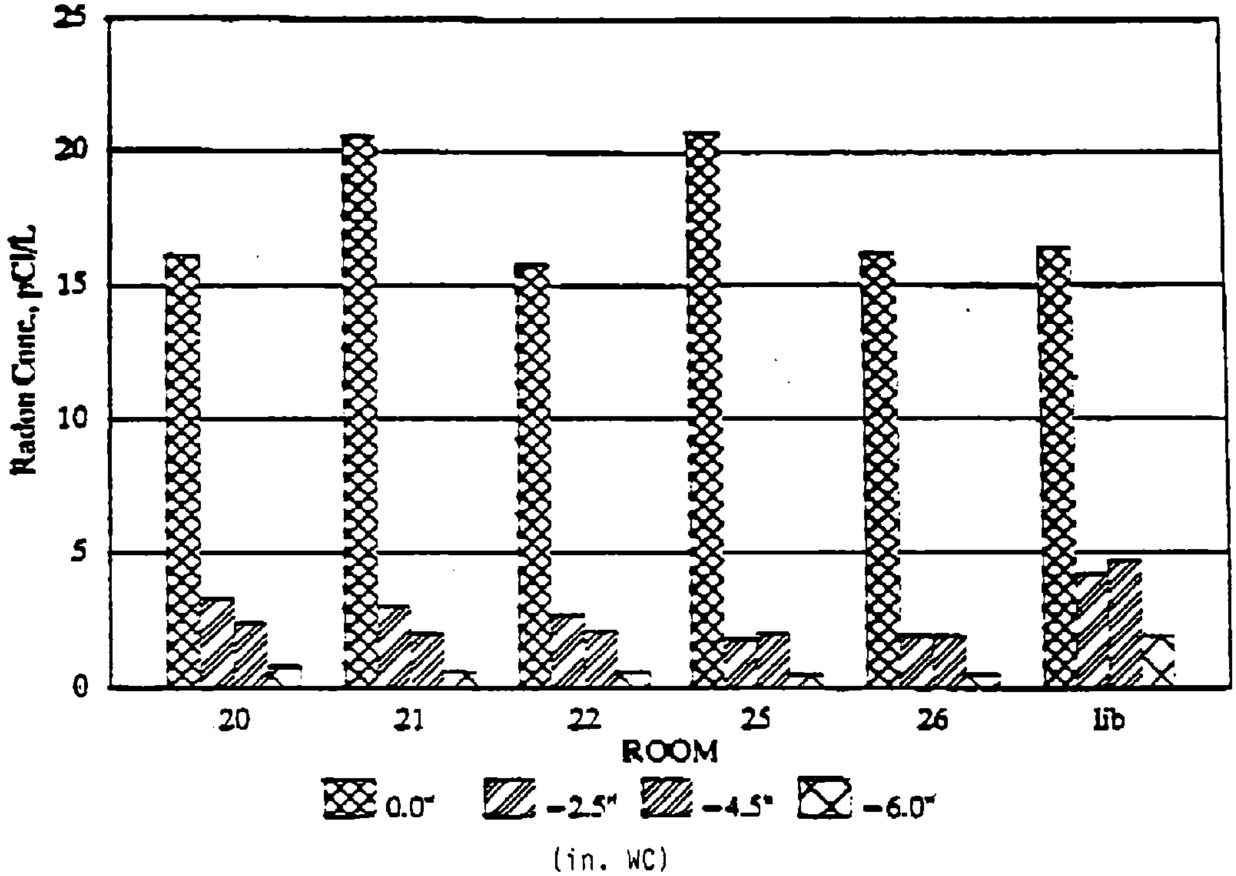


Figure 5.2.3. ASD performance, for center wing of Russell Elementary.

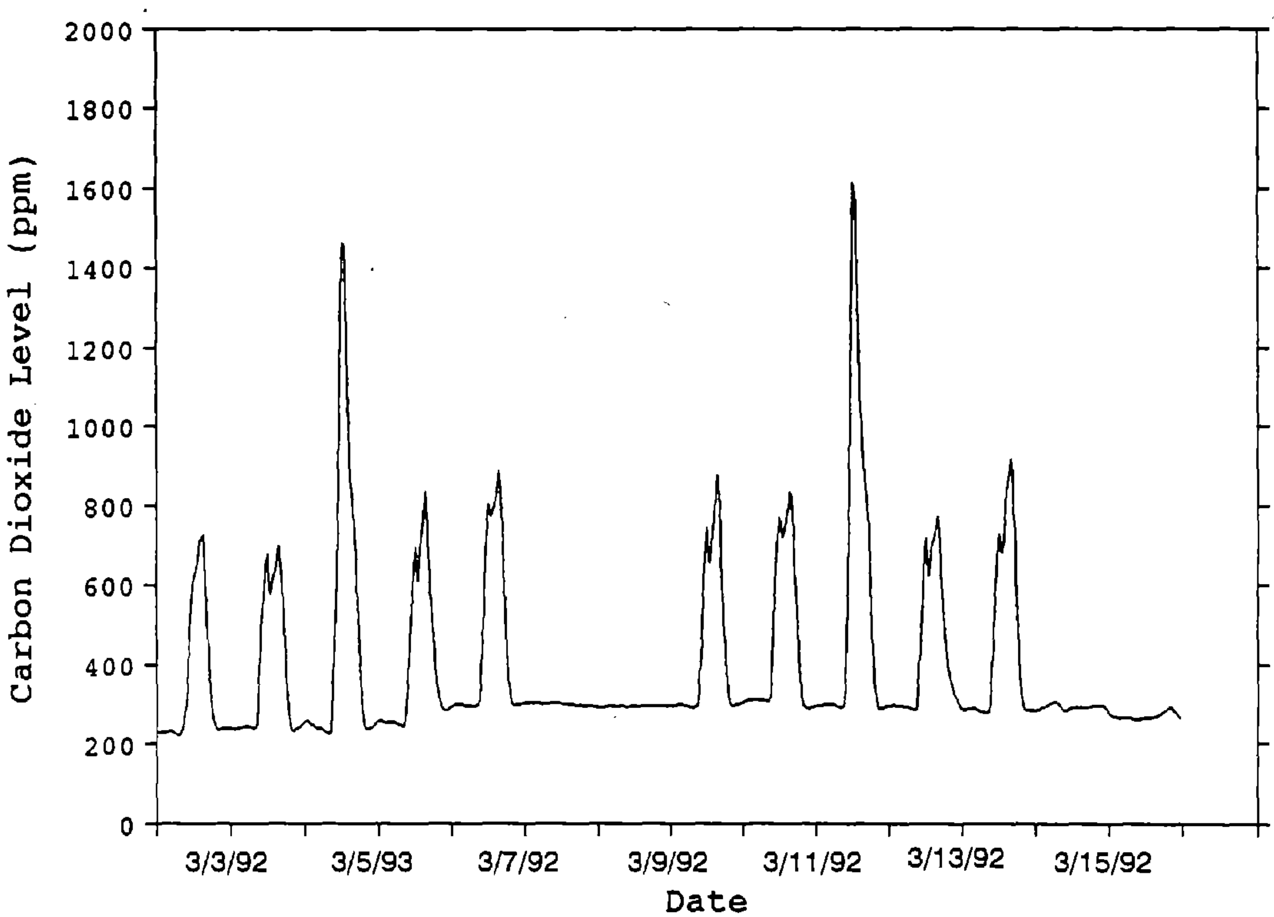


Figure 5.2.4. Continuous CO2 levels in HRV room at Russell Elementary, Gray, ME.

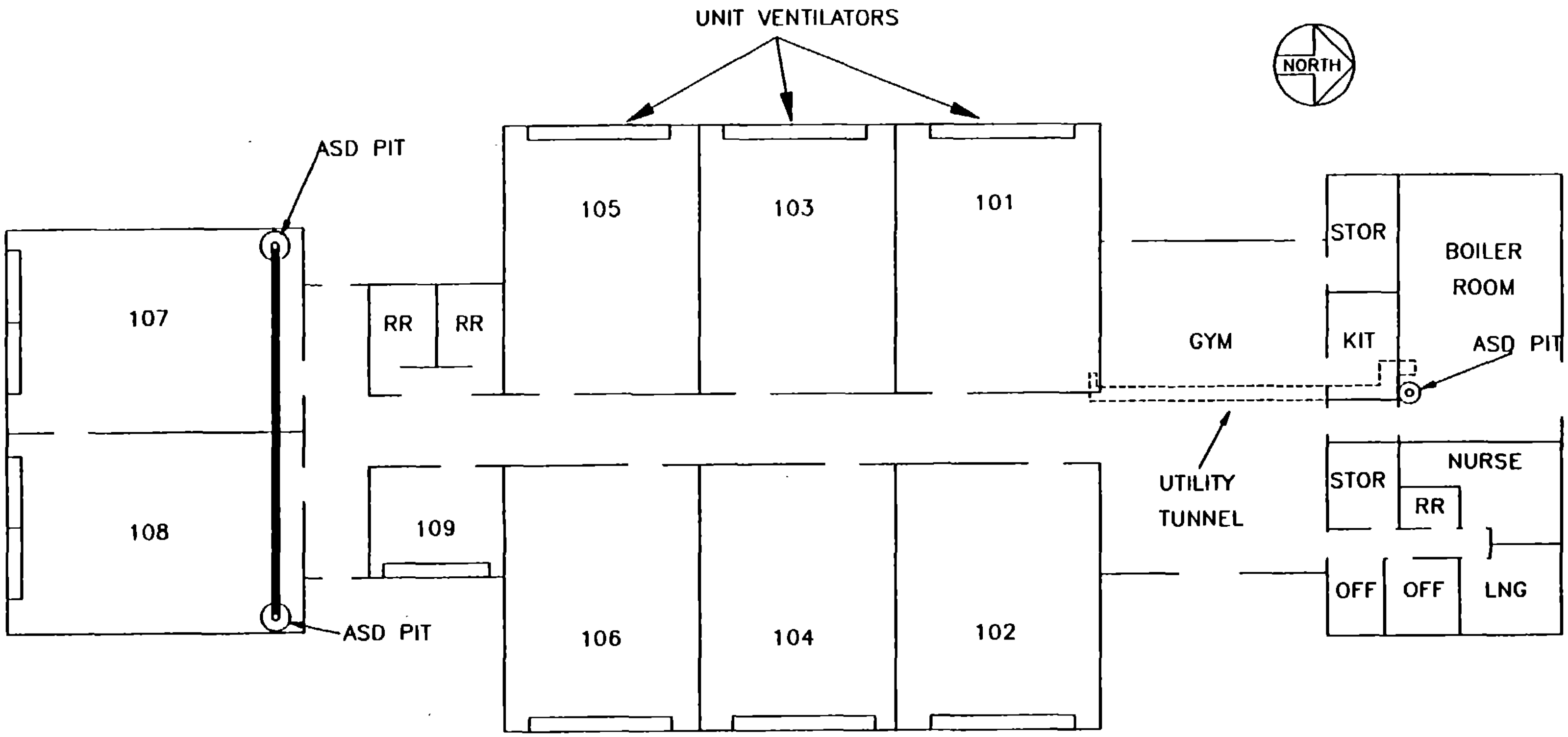


Figure 6.1.1. Floor plan of Nokomis Elementary School, St. Paul, MN, showing radon mitigation system locations.

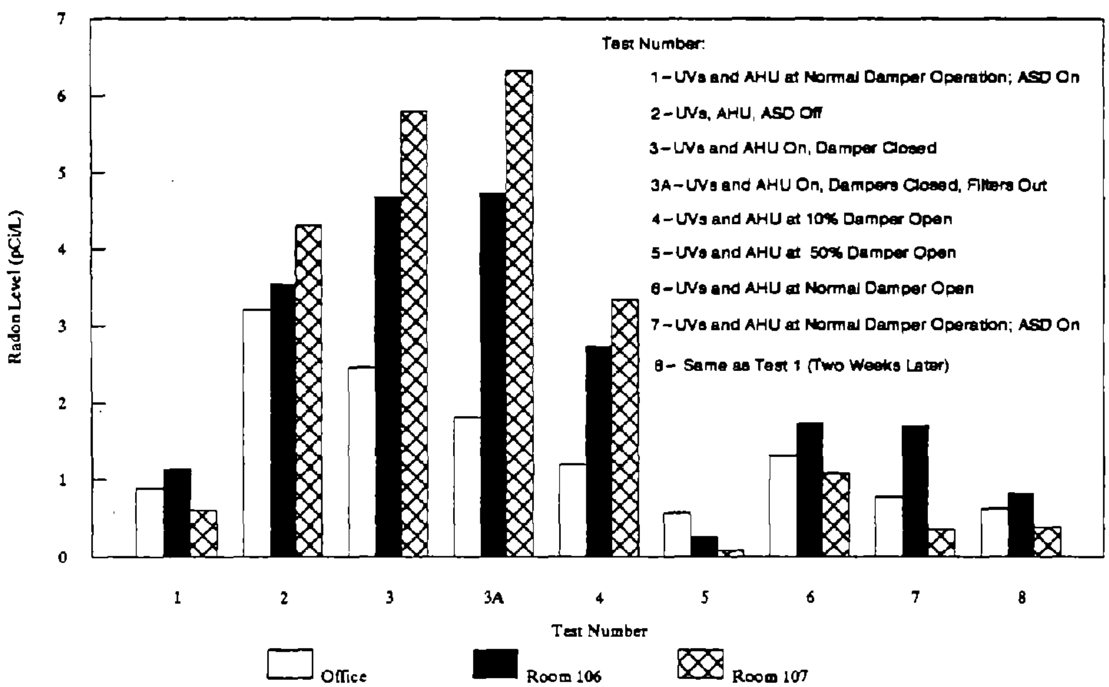


Figure 6.1.2. Radon levels during the testing period at Nokomis Elementary School.

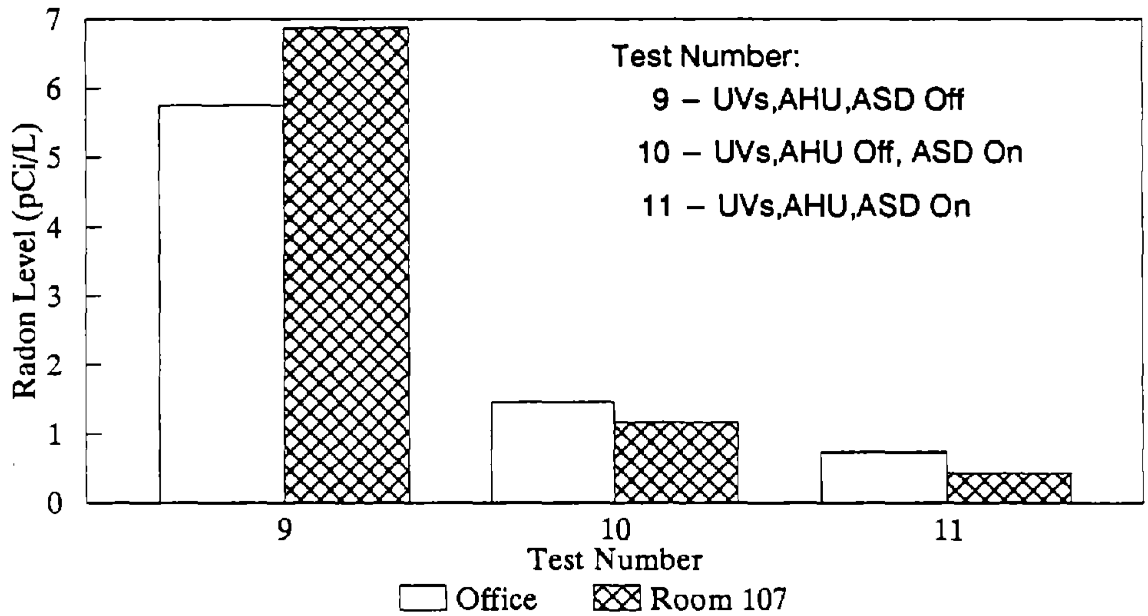


Figure 6.1.3. Radon levels during additional testing period at Nokomis Elementary School (no data for Room 106)

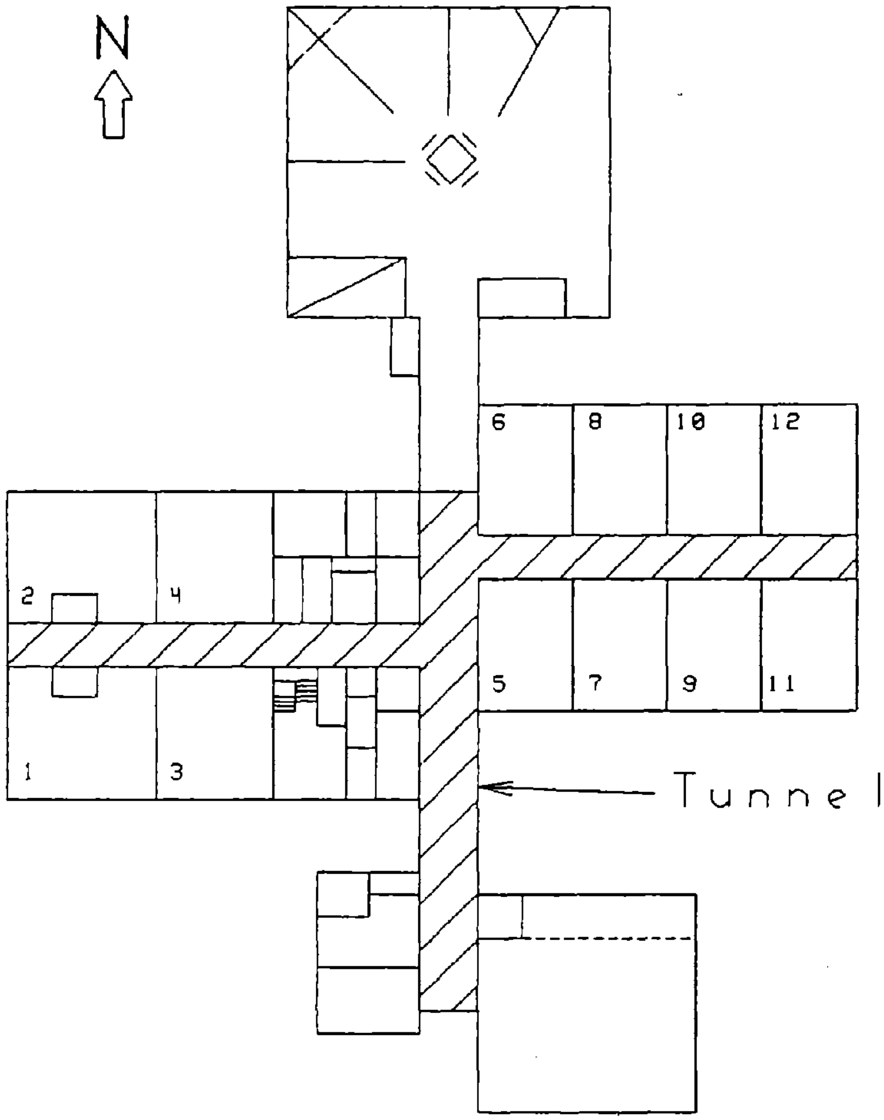


Figure 7.1.1 Plan view of Oakmont Elementary School, Columbus, OH.

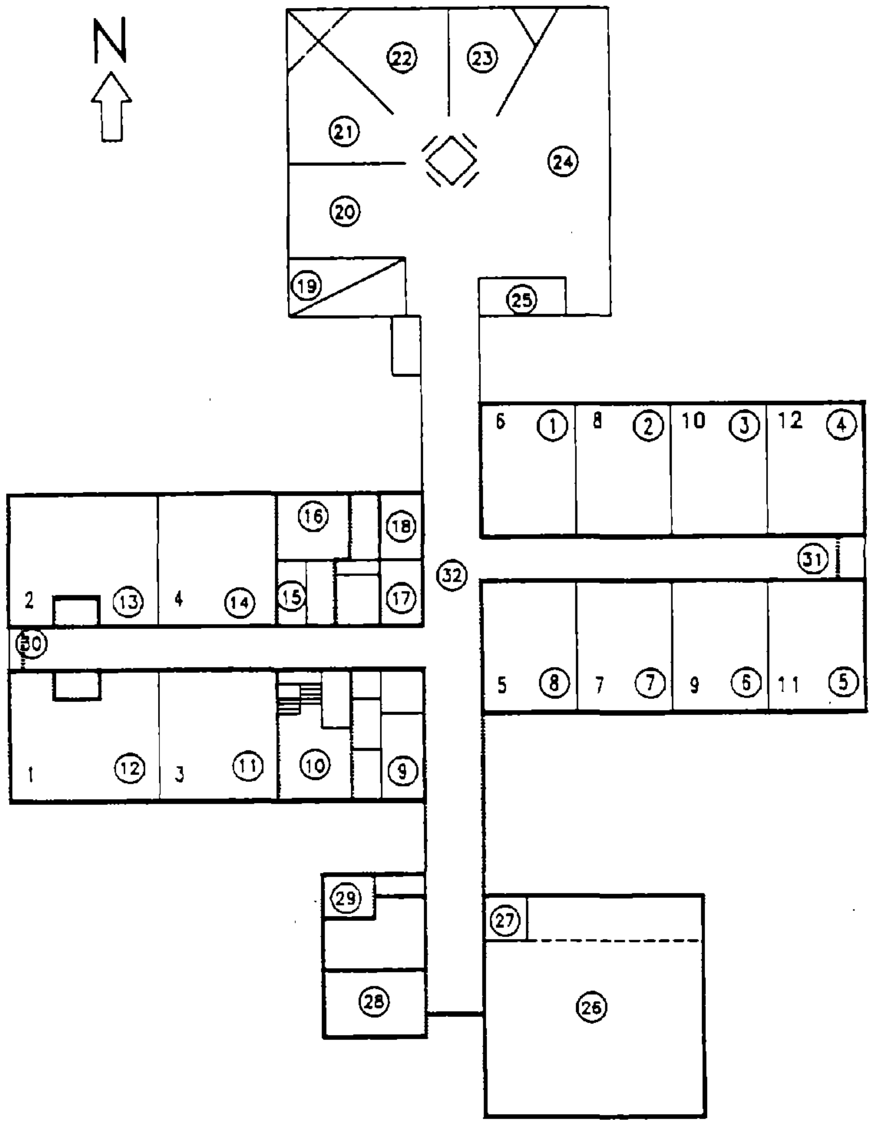


Figure 7.1.2. Location of canister numbers for CC measurements and foundation walls and footings in Oakmont Elementary School.

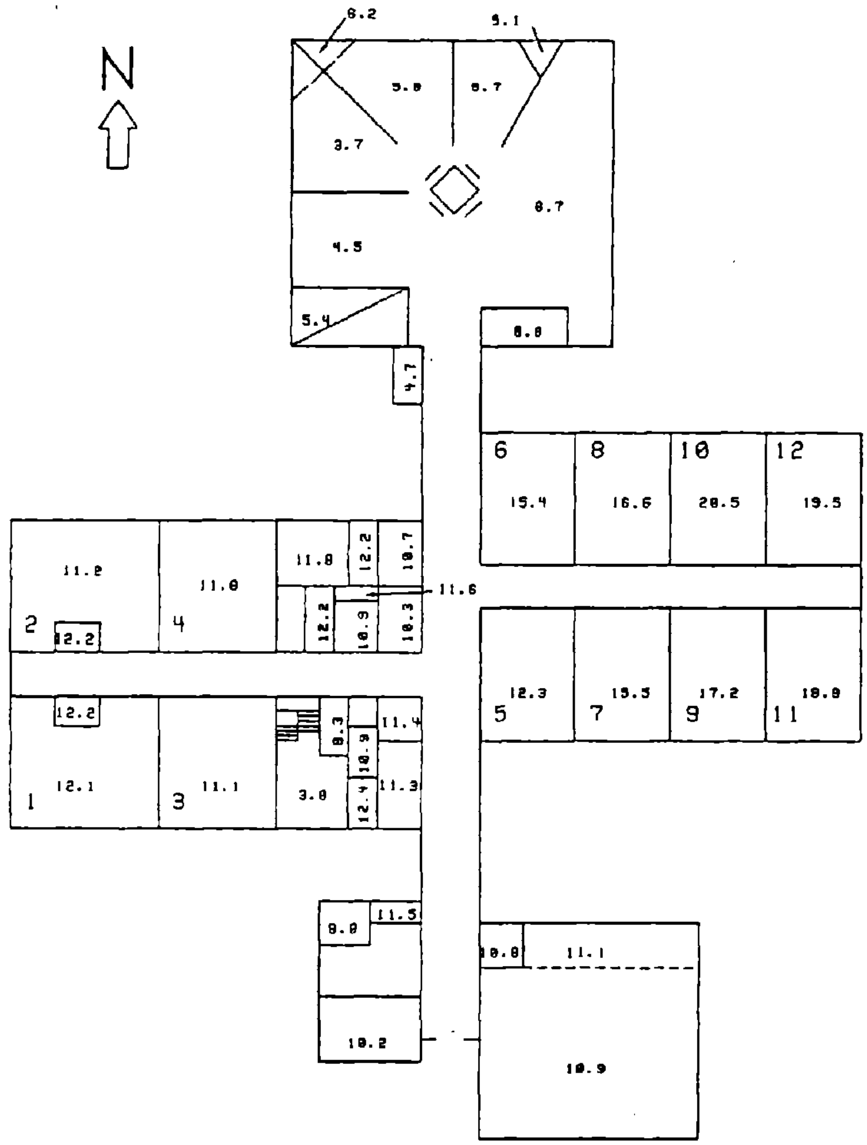


Figure 7.1.3 Results of E-Perm measurements, Oakmont Elementary School during the Winter of 1990-91, in pCi/L.

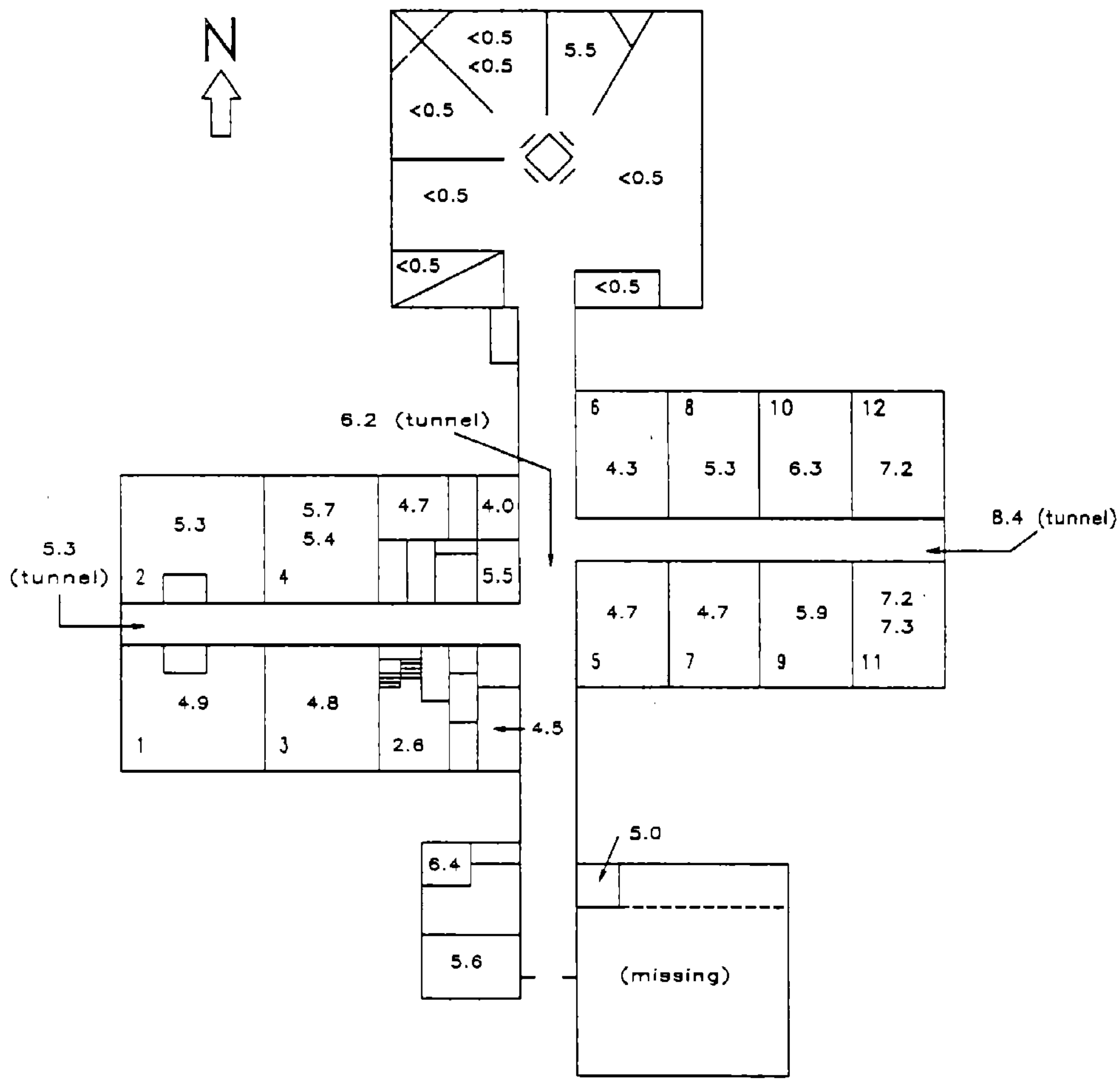


Figure 7.1.4. Results of the CC screening measurements carried out in Oakmont Elementary School during March 1991, in pCi/L.

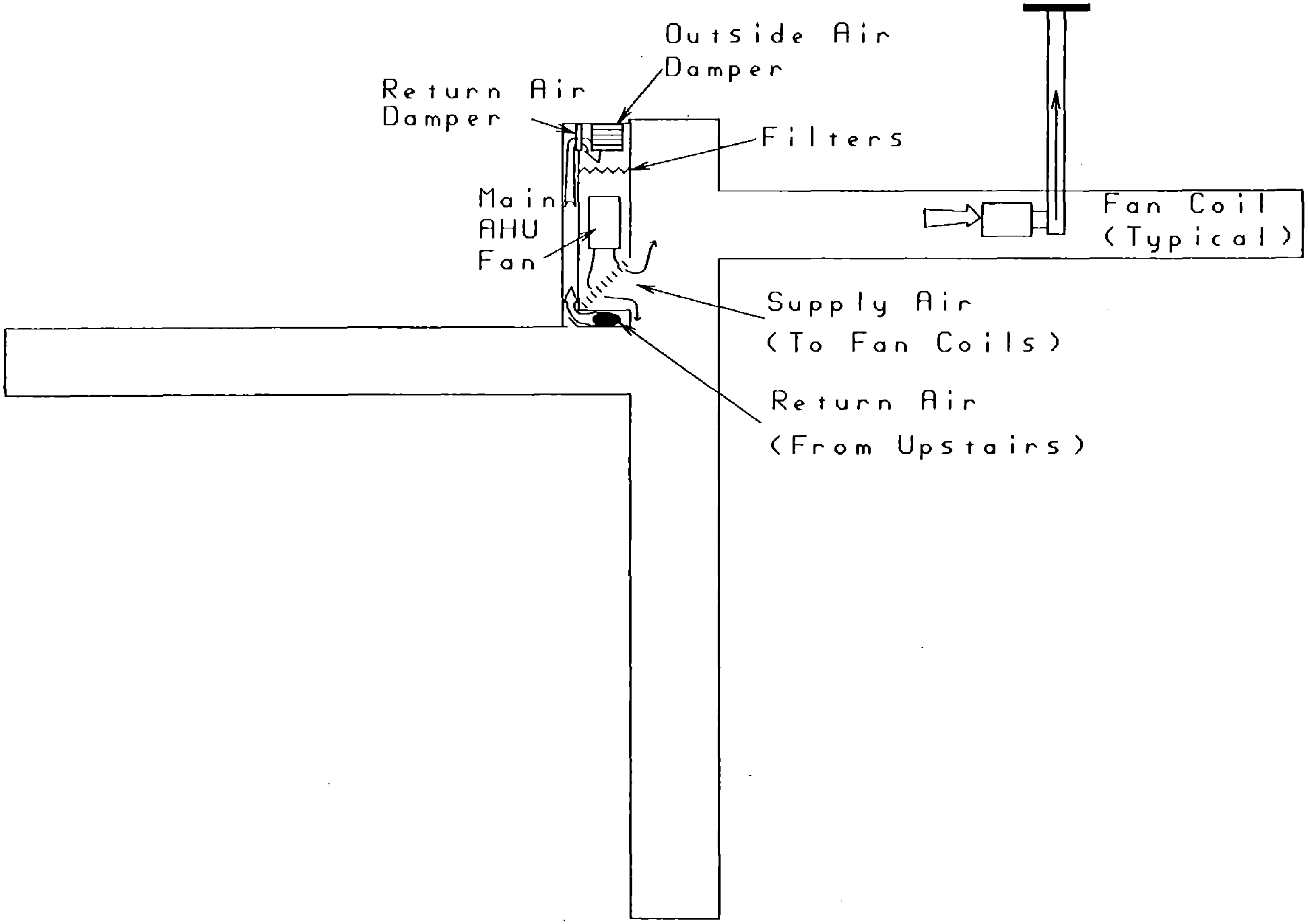


Figure 7.1.5. Plan view of the tunnel and arrangement of the HVAC system at Oakmont Elementary School.

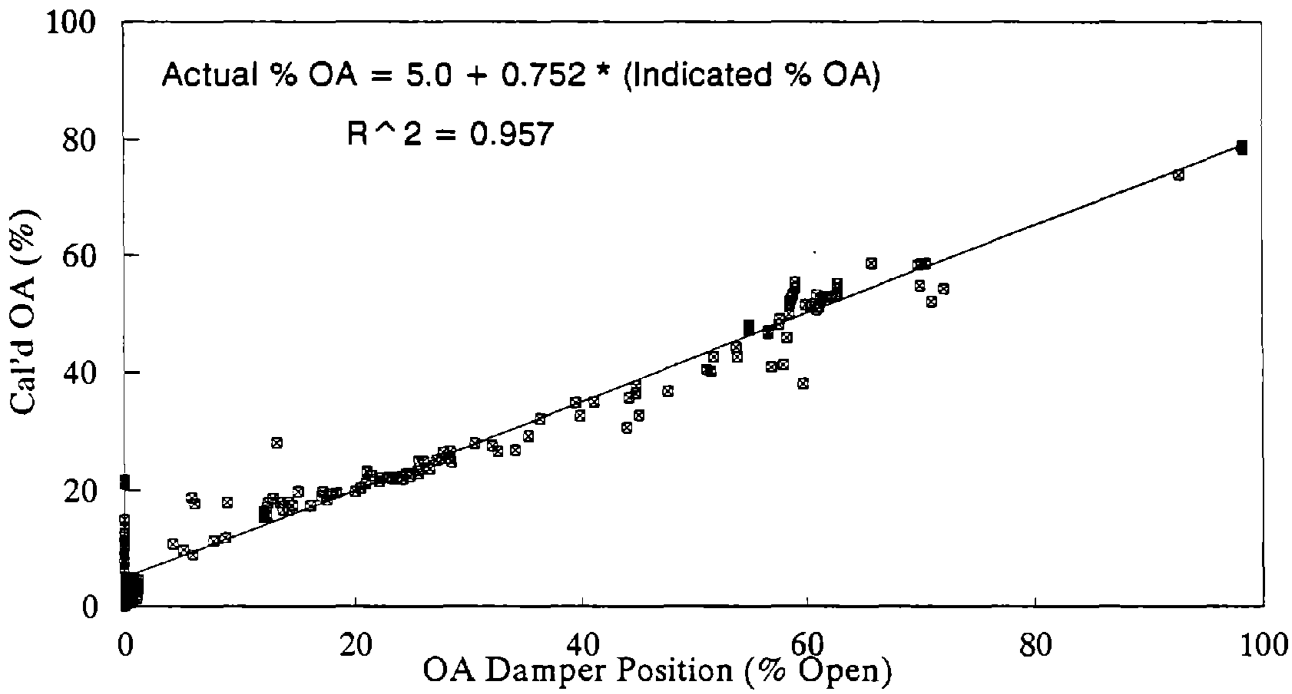


Figure 7.1.6. Correlation of OA damper indicator and calculated percent OA using temperatures at Oakmont Elementary School, Columbus, OH.

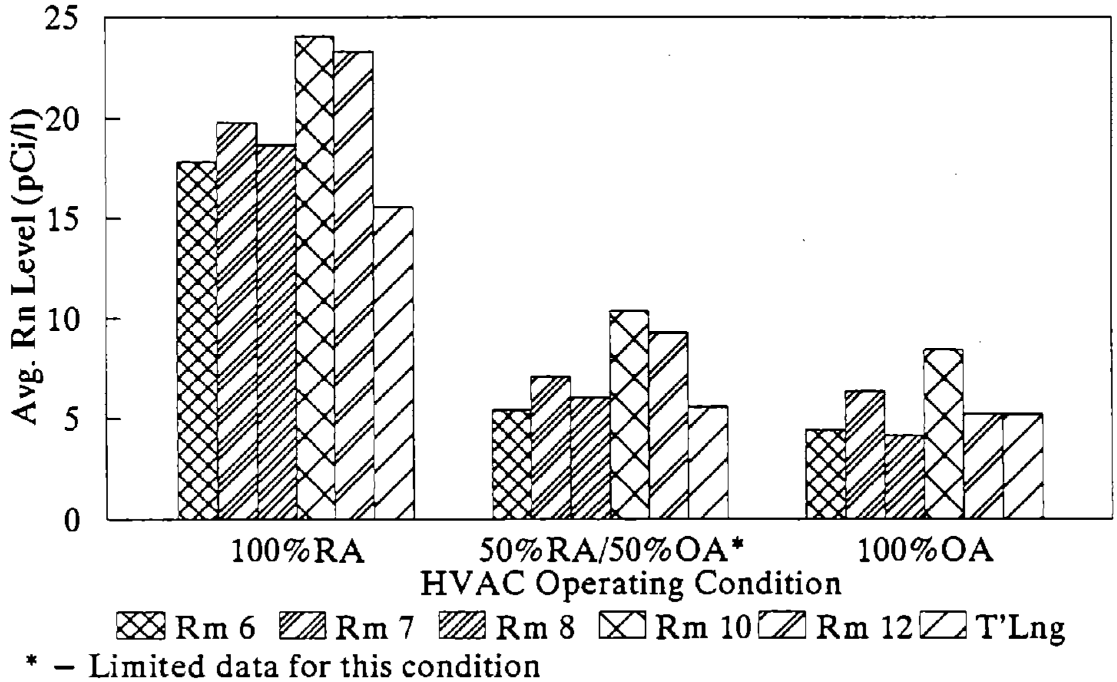


Figure 7.1.7. Effects of outdoor air in HVAC system on room radon levels at Oakmont Elementary (before tunnel sealing).

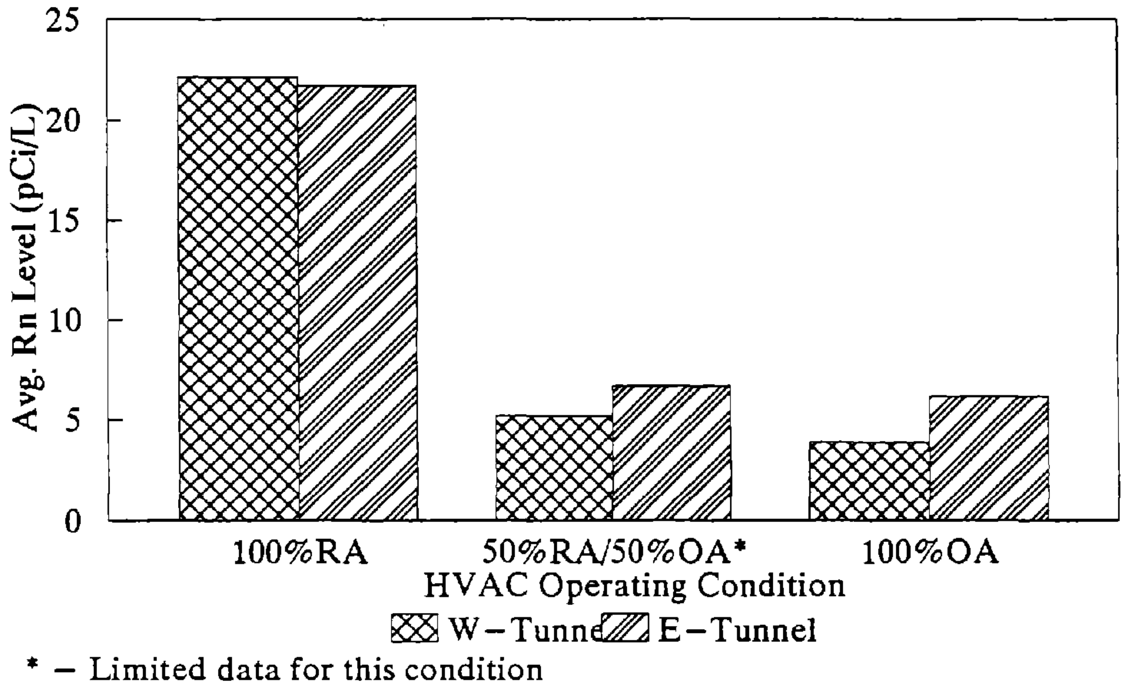


Figure 7.1.8. Effects of outdoor air in HVAC system on tunnel radon levels at Oakmont Elementary (before sealing tunnel).

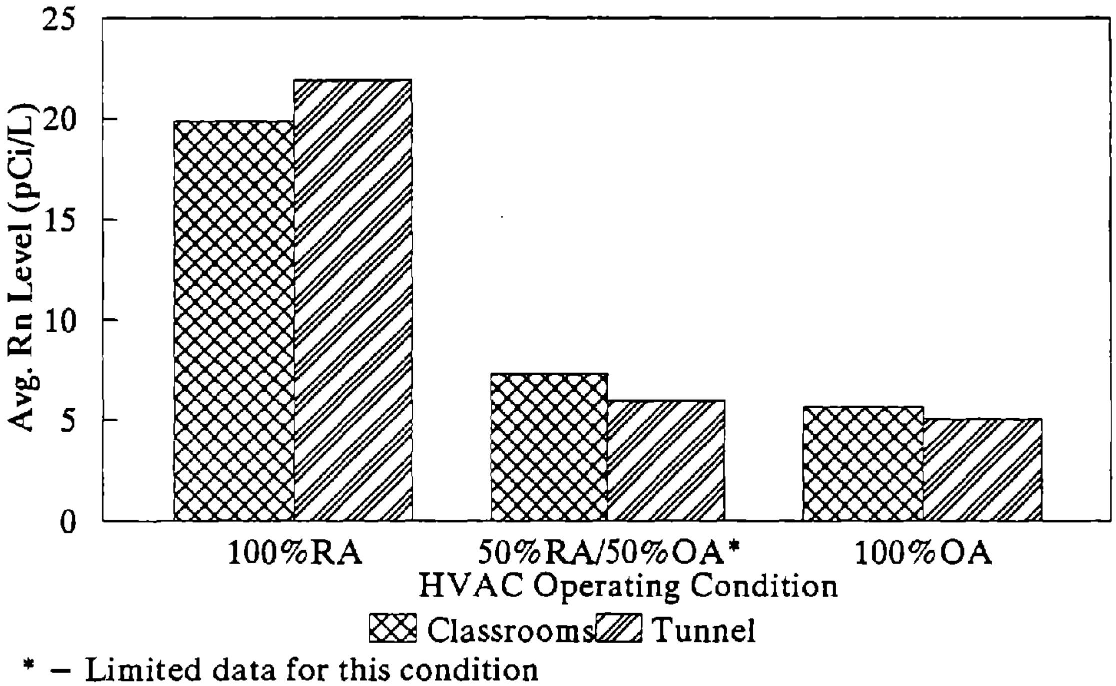


Figure 7.1.9. Effects of outdoor air in HVAC system on radon levels at Oakmont Elementary (before tunnel sealing).

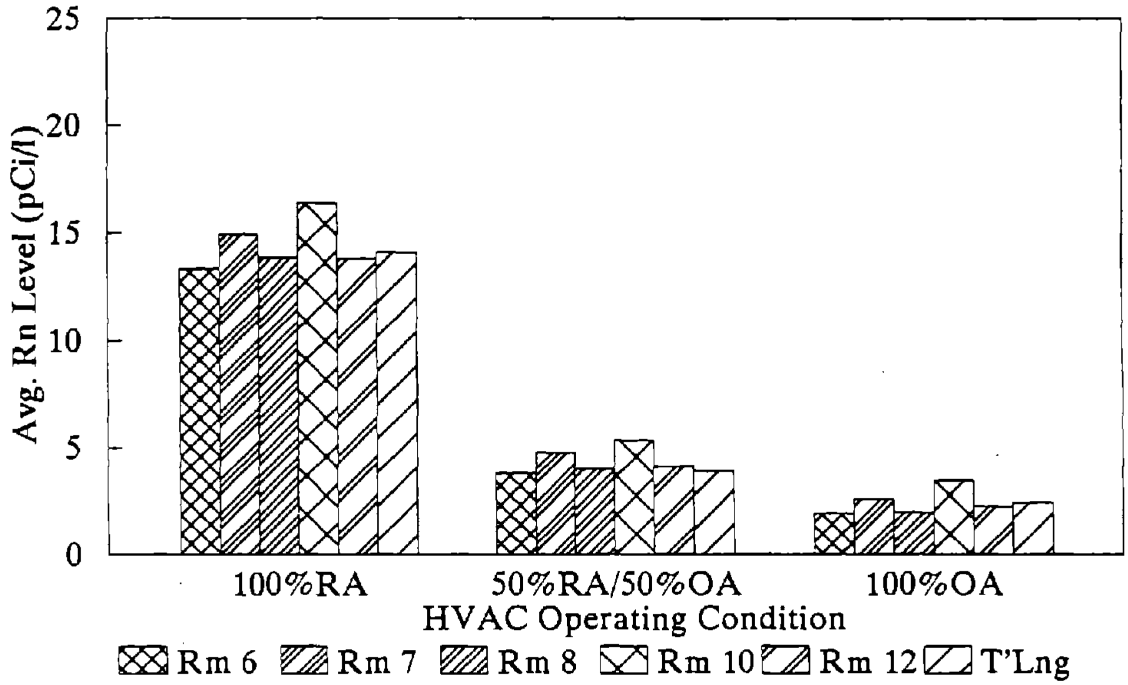
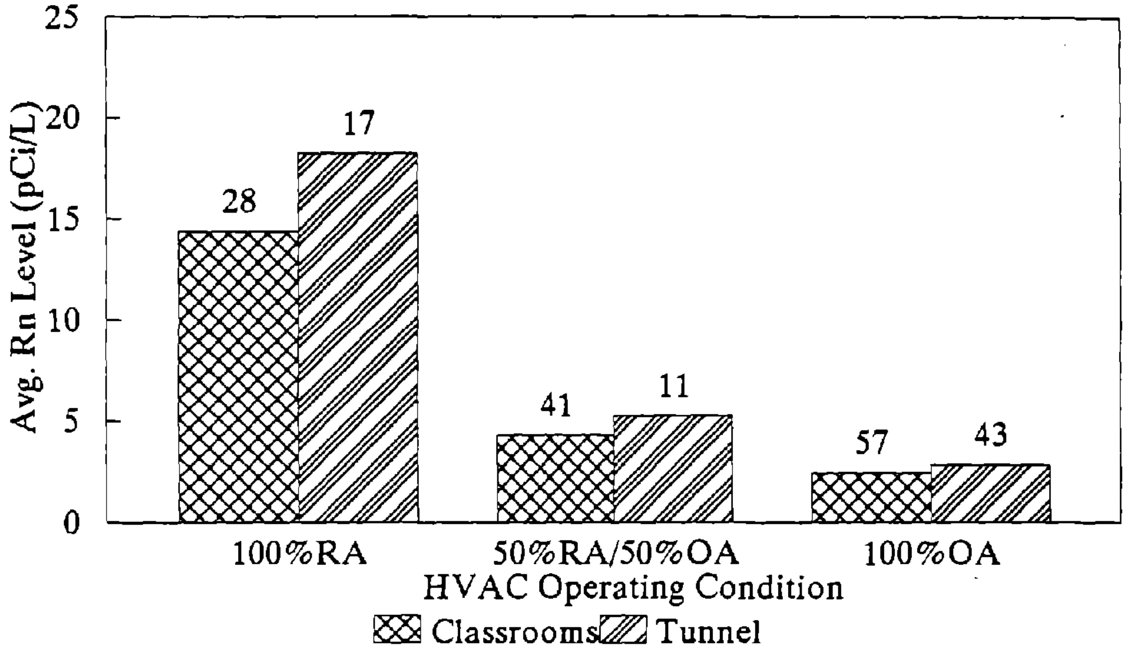


Figure 7.1.10. Effects of outdoor air in HVAC system on room radon levels at Oakmont Elementary (after tunnel sealing).



Note: Numbers above bars are percent reduction due to sealing tunnel.

Figure 7.1.11. Effects of outdoor air in HVAC systems on tunnel radon levels at Oakmont Elementary (after tunnel sealing).

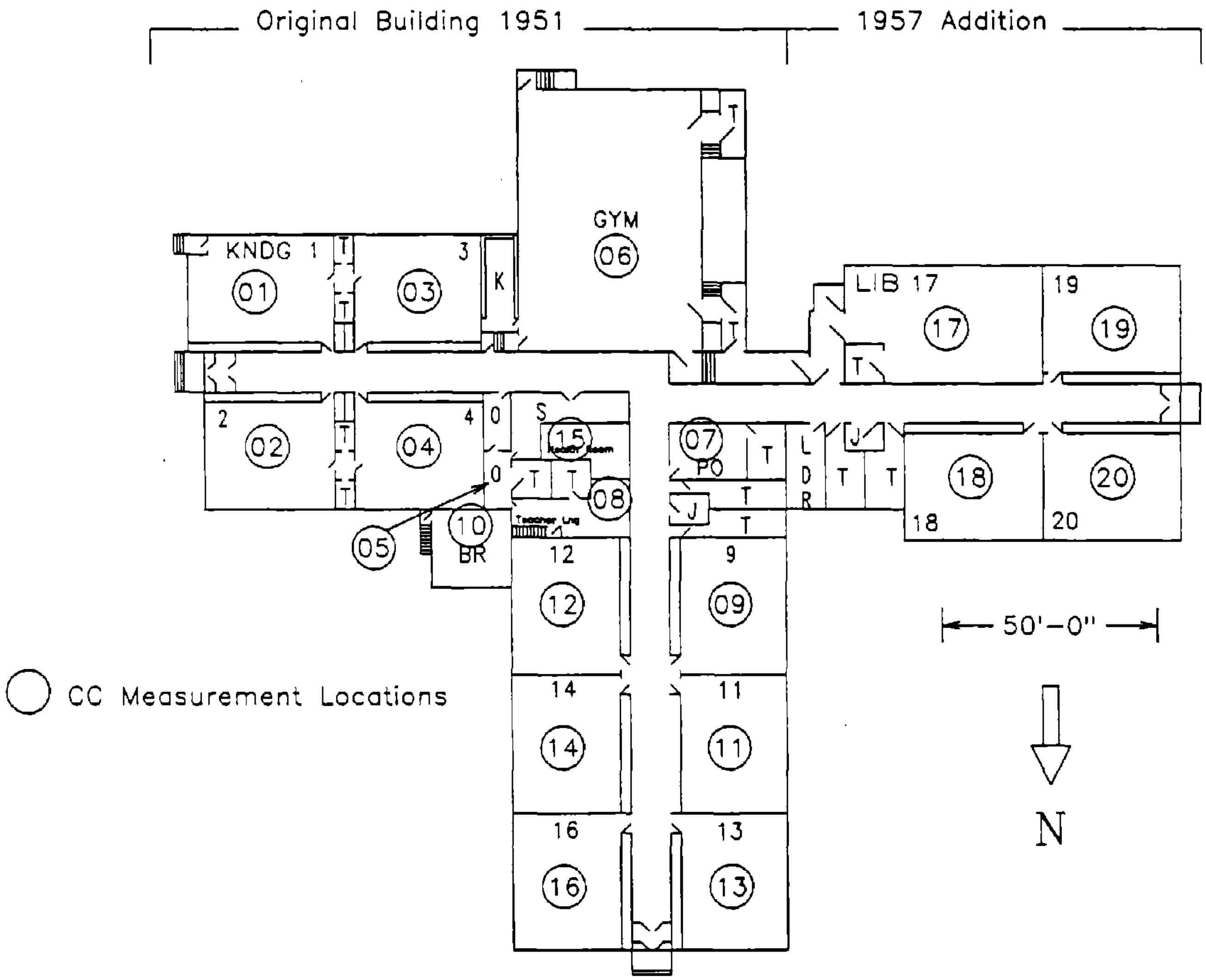


Figure 8.1.1. Floor plan of Lincoln Elementary School showing addition dates, room locations, and CC measurement location.

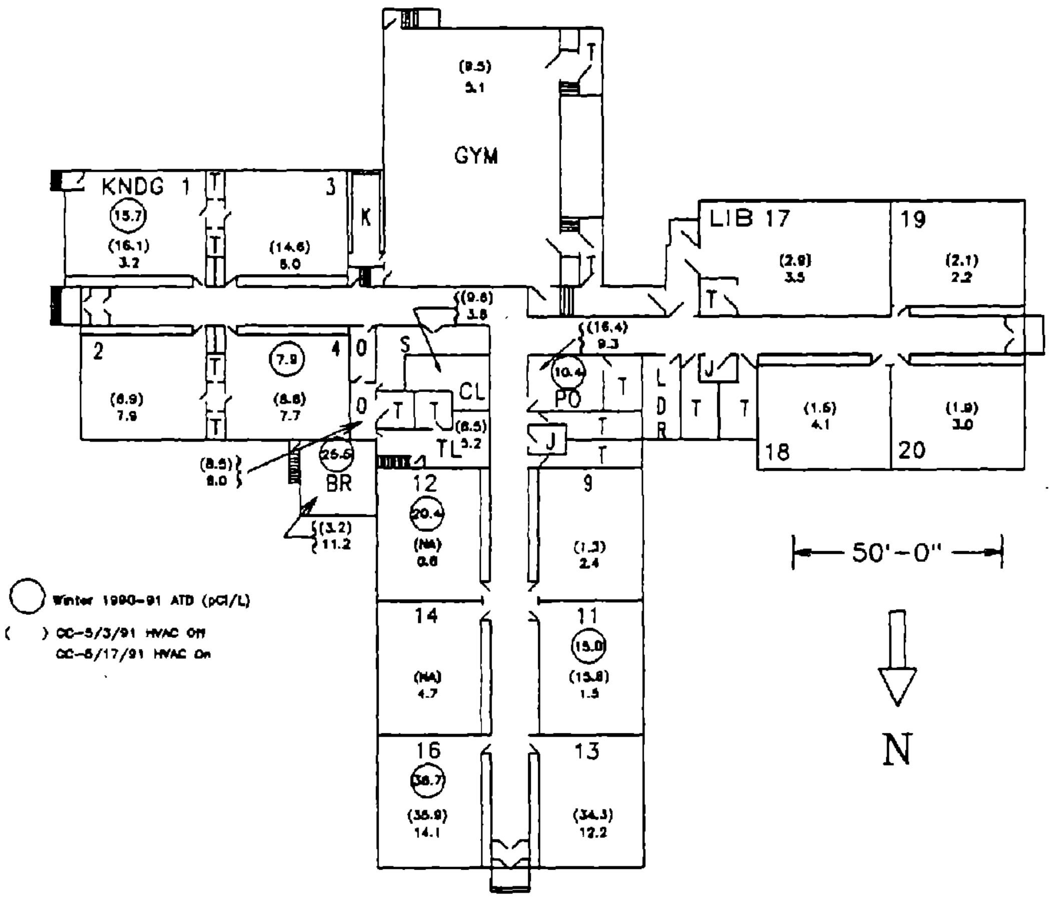


Figure 8.1.2. Winter 1990-91 ATD results and the May 1991 CC measurements made with UV's on/off at Lincoln Elementary, in pCi/L.

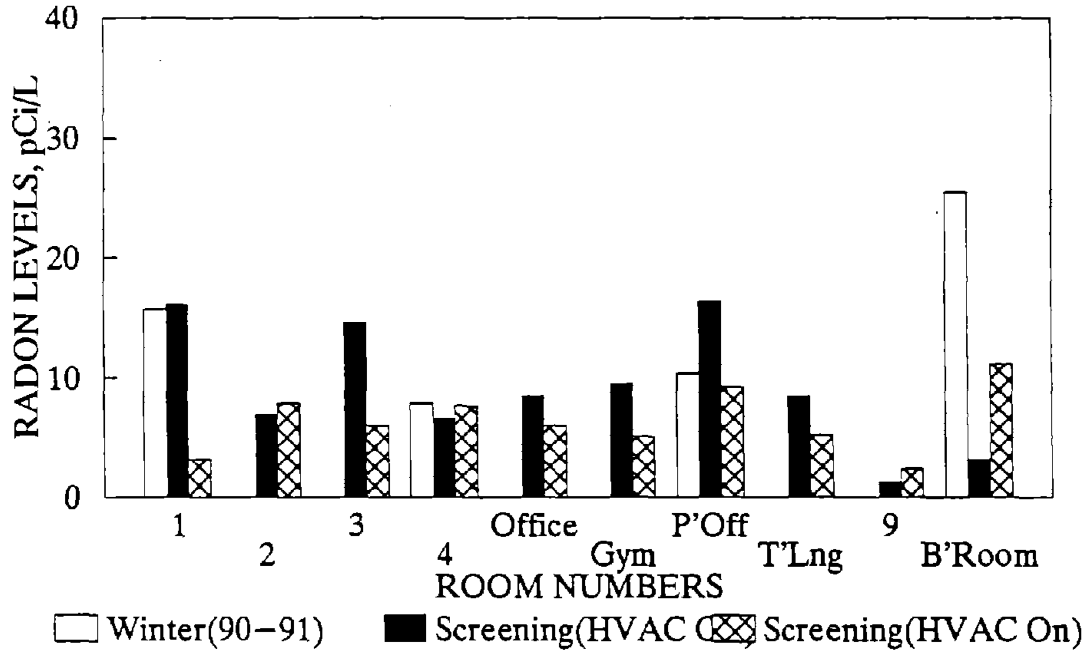


Figure 8.1.3. Comparison of radon levels in Abraham Lincoln Elementary School (part 1).

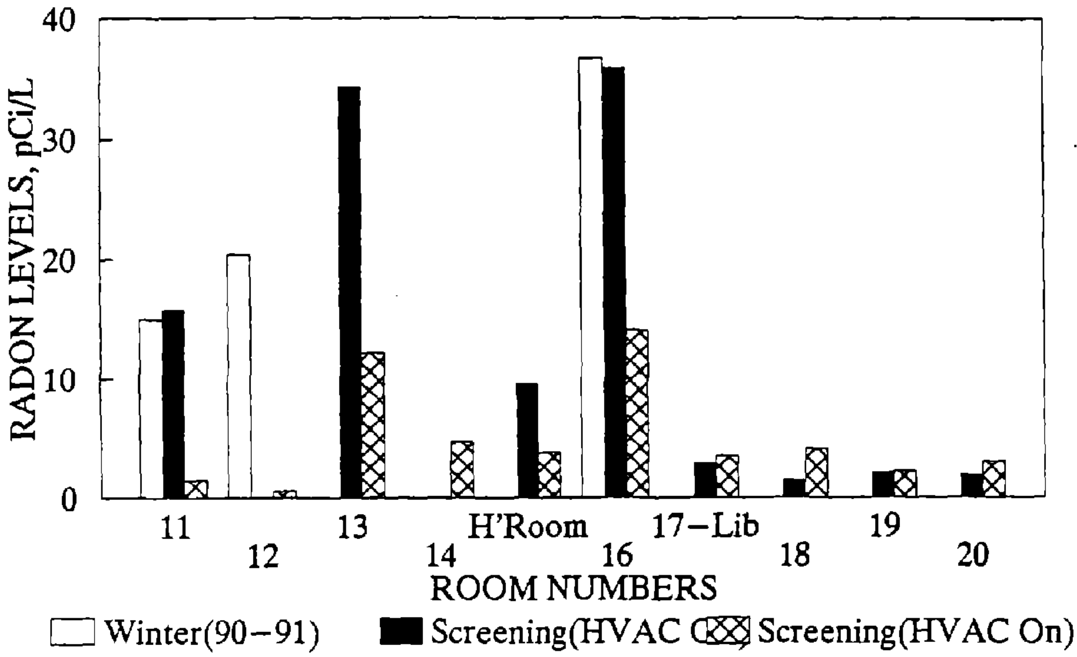


Figure 8.1.4. Comparison of radon levels in Abraham Lincoln Elementary School (part 2).

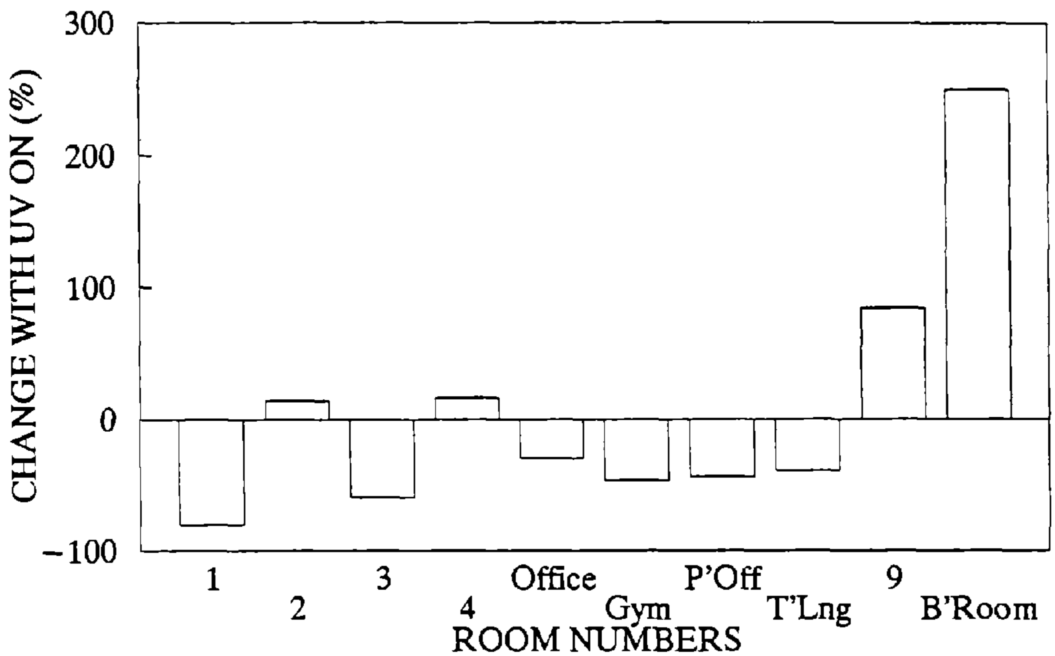


Figure 8.1.5. Changes in radon levels with unit ventilator on compared to levels when off at Lincoln Elementary, (part 1).

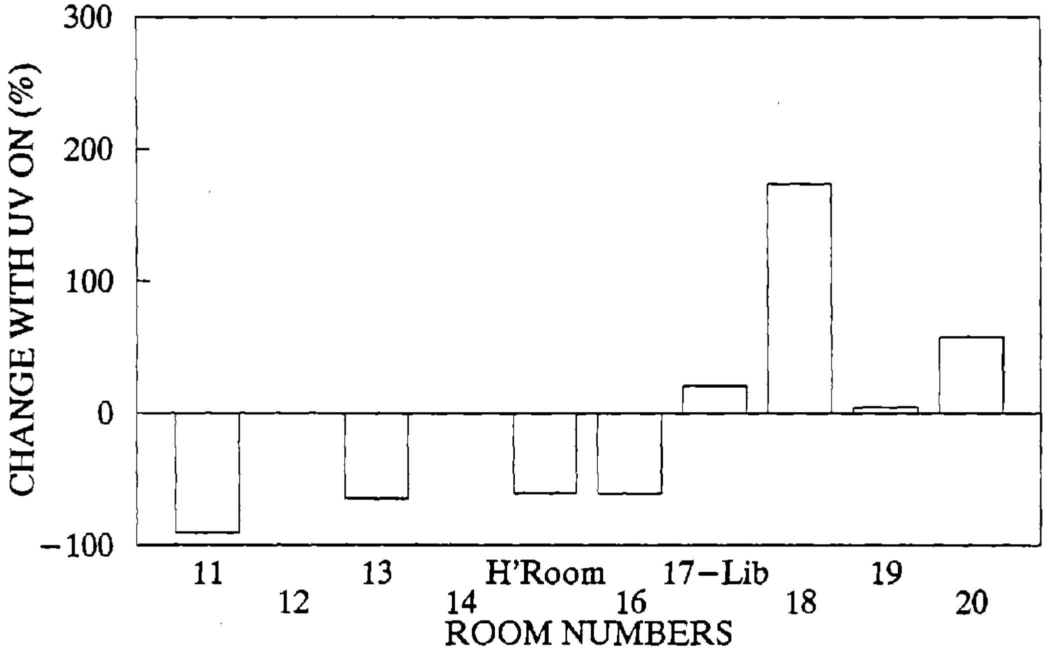


Figure 8.1.6. Changes in radon levels with unit ventilator on compared to levels when off at Lincoln Elementary, (part 2).

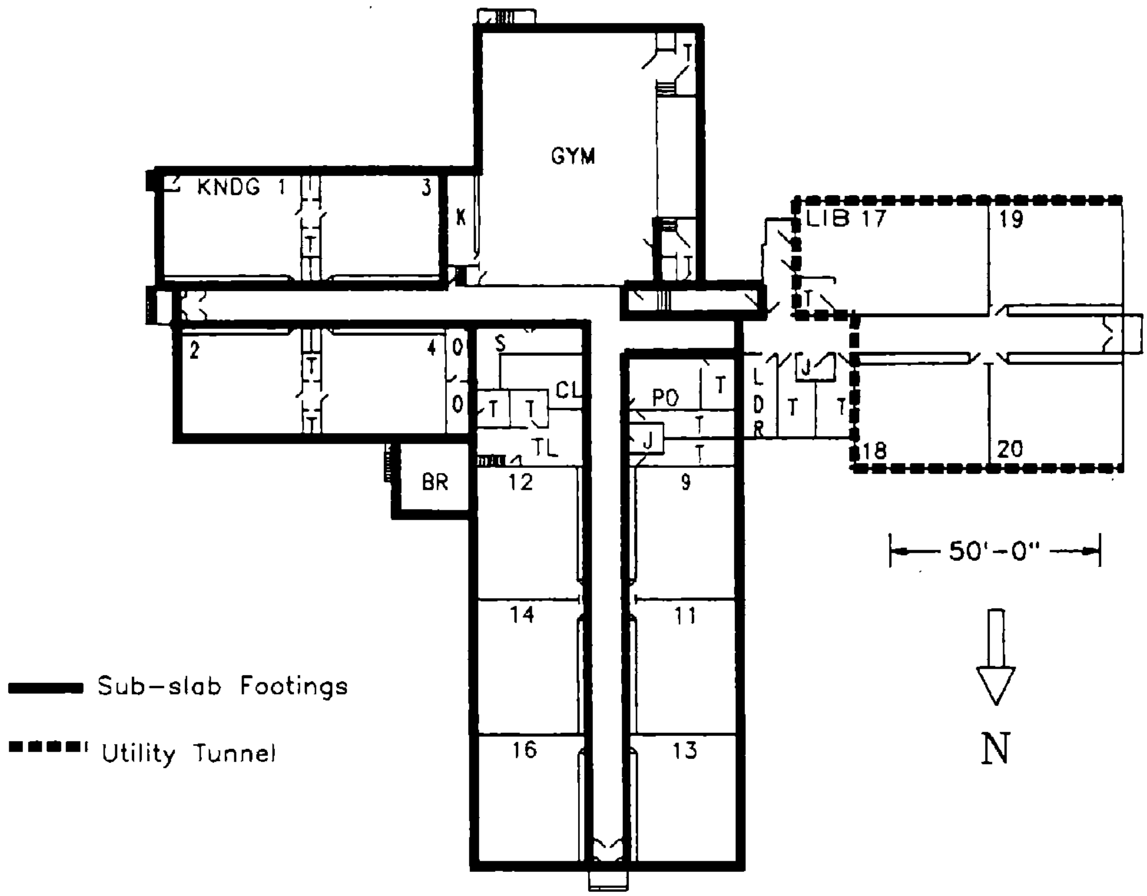


Figure 8.1.7. Floor plan of Lincoln Elementary showing locations of the subslab footings and utility tunnels.

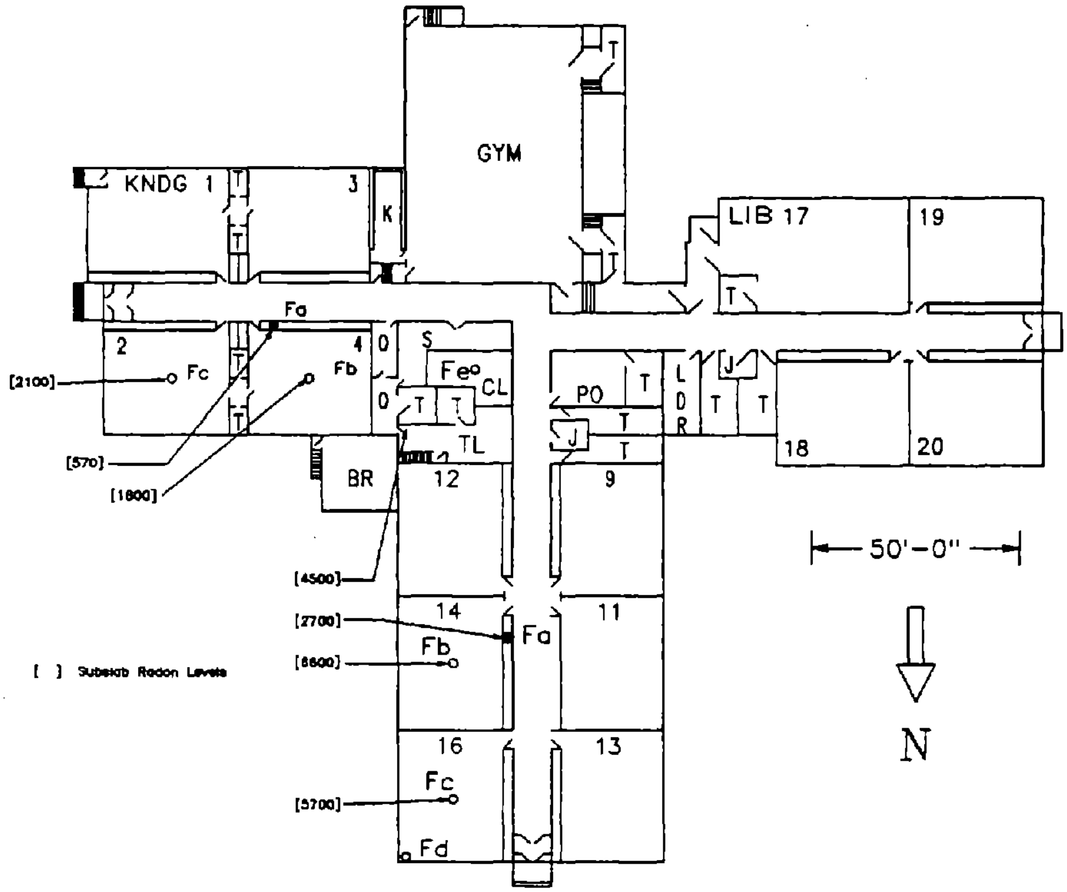


Figure 8.1.8. Locations of the subslab communication test points and the subslab radon levels measured at Lincoln Elementary, in pCi/L.

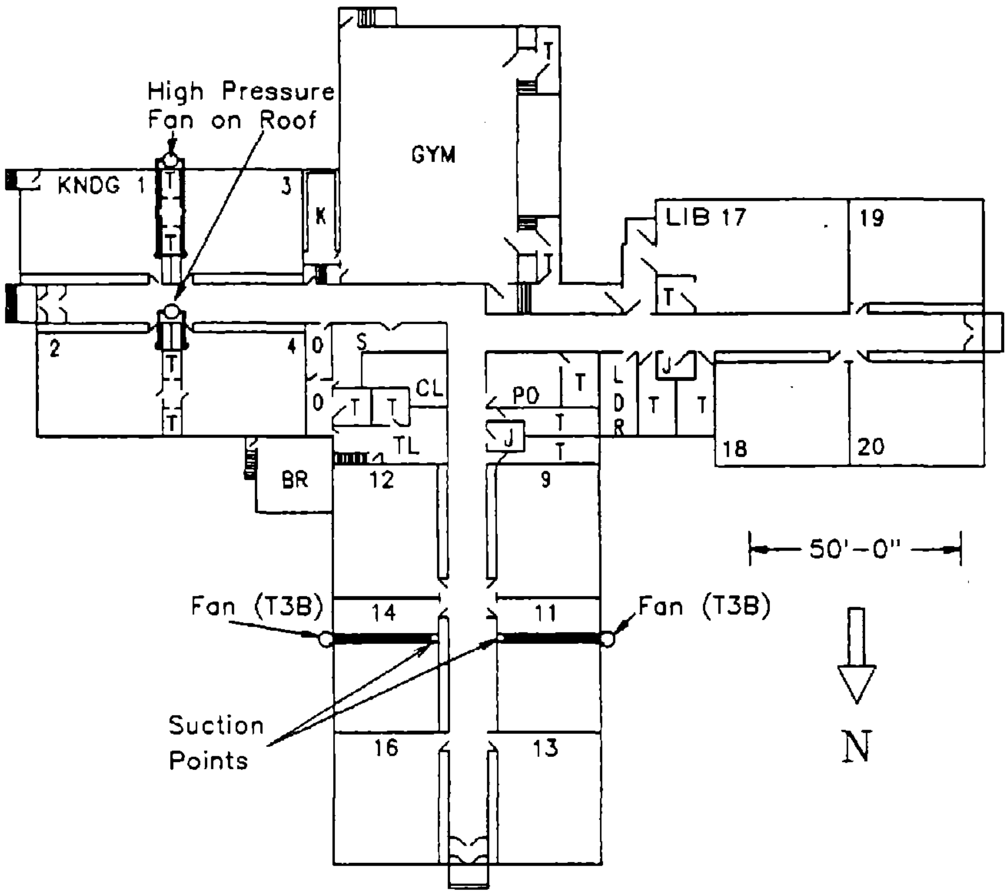
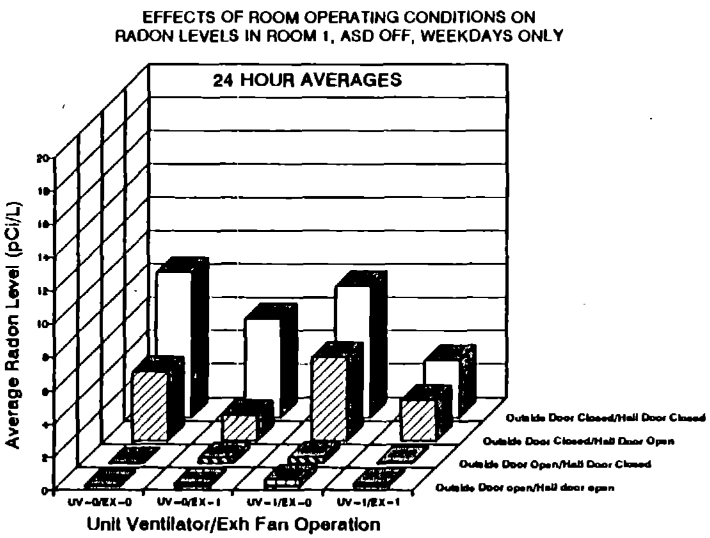


Figure 8.1.9. Proposed mitigation systems for Lincoln Elementary.



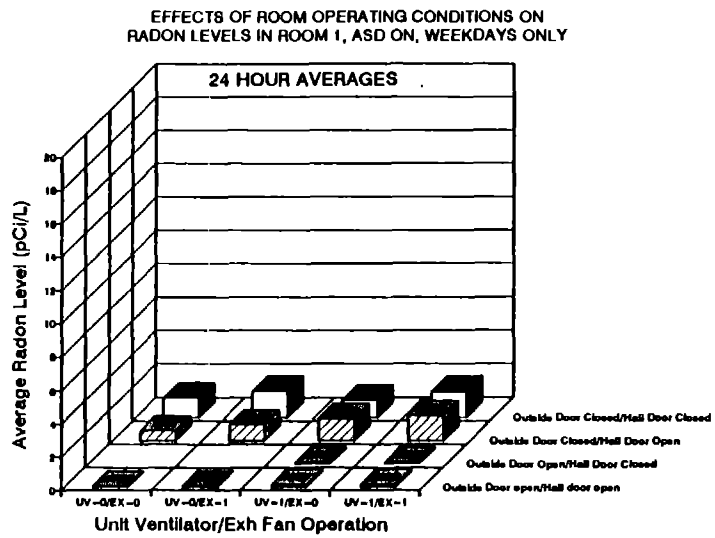
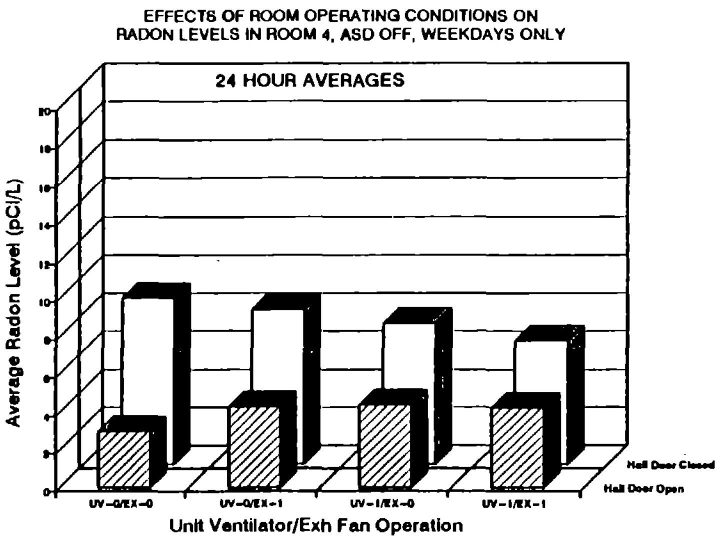


Figure 8.1.10. Comparison of HVAC and ASD in Room 1, Lincoln Elementary.



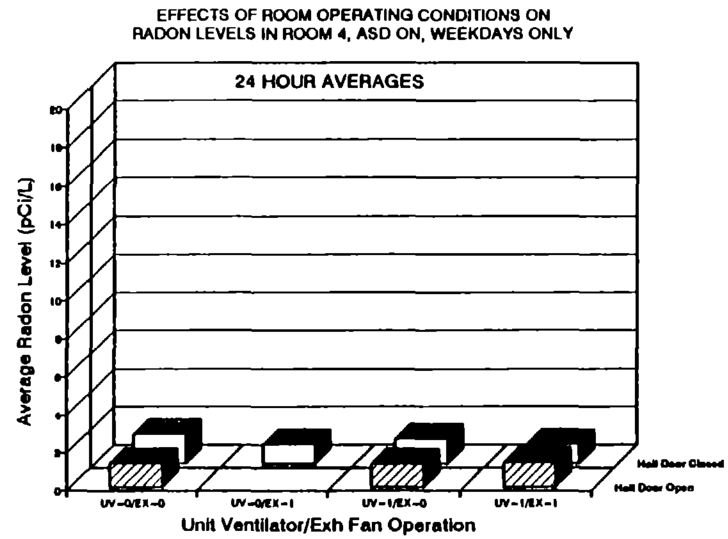
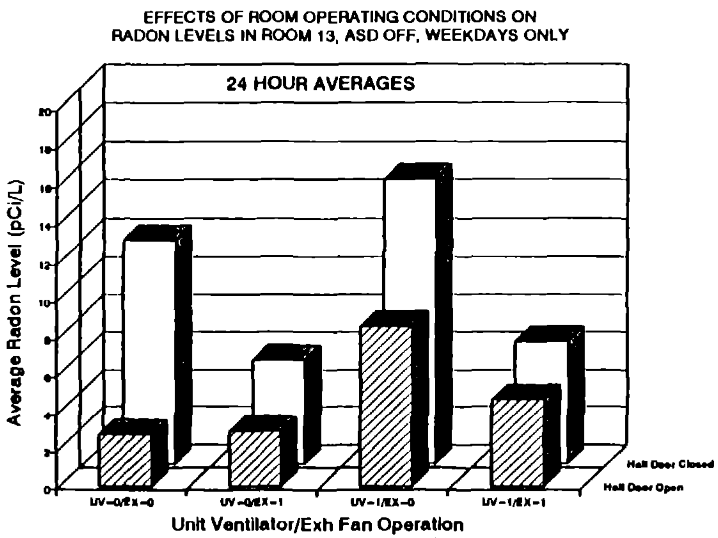


Figure 8.1.11. Comparison of HVAC and ASD in Room 4, Lincoln Elementary.



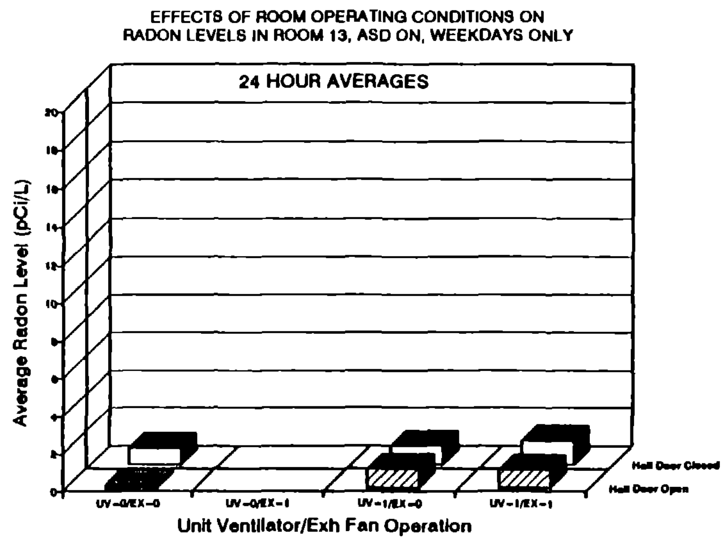


Figure 8.1.12. Comparison of HVAC and ASD in Room 13, Lincoln Elementary.

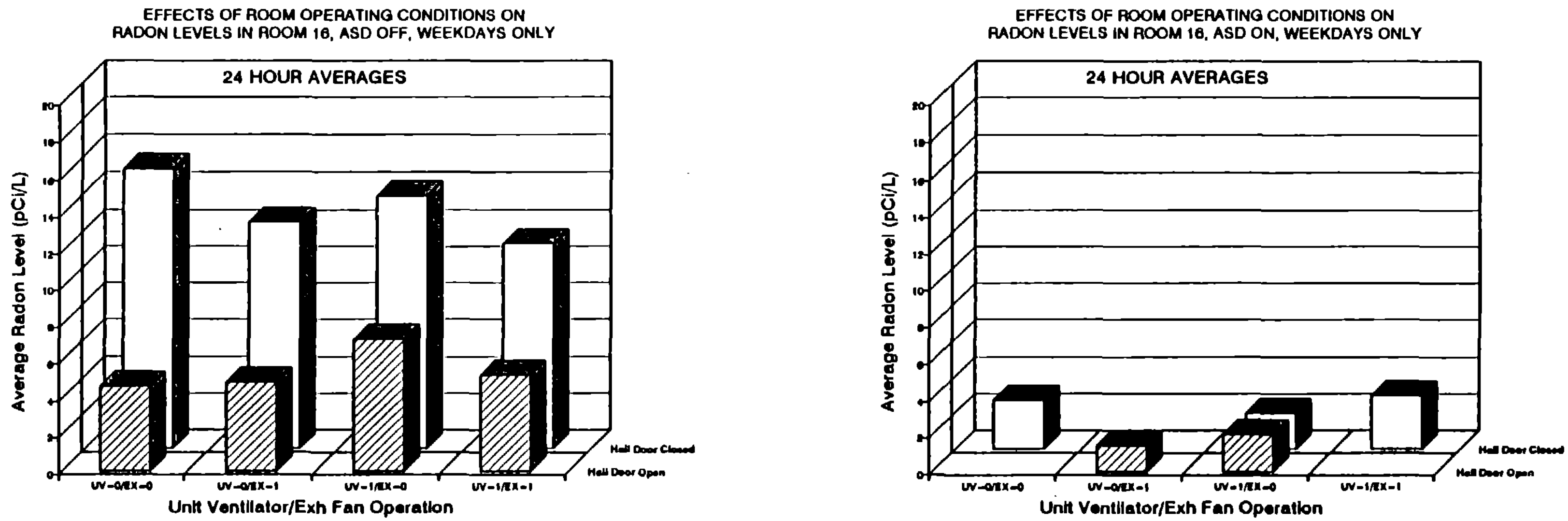


Figure 8.1.13. Comparison of HVAC and ASD in Room 16, Lincoln Elementary.

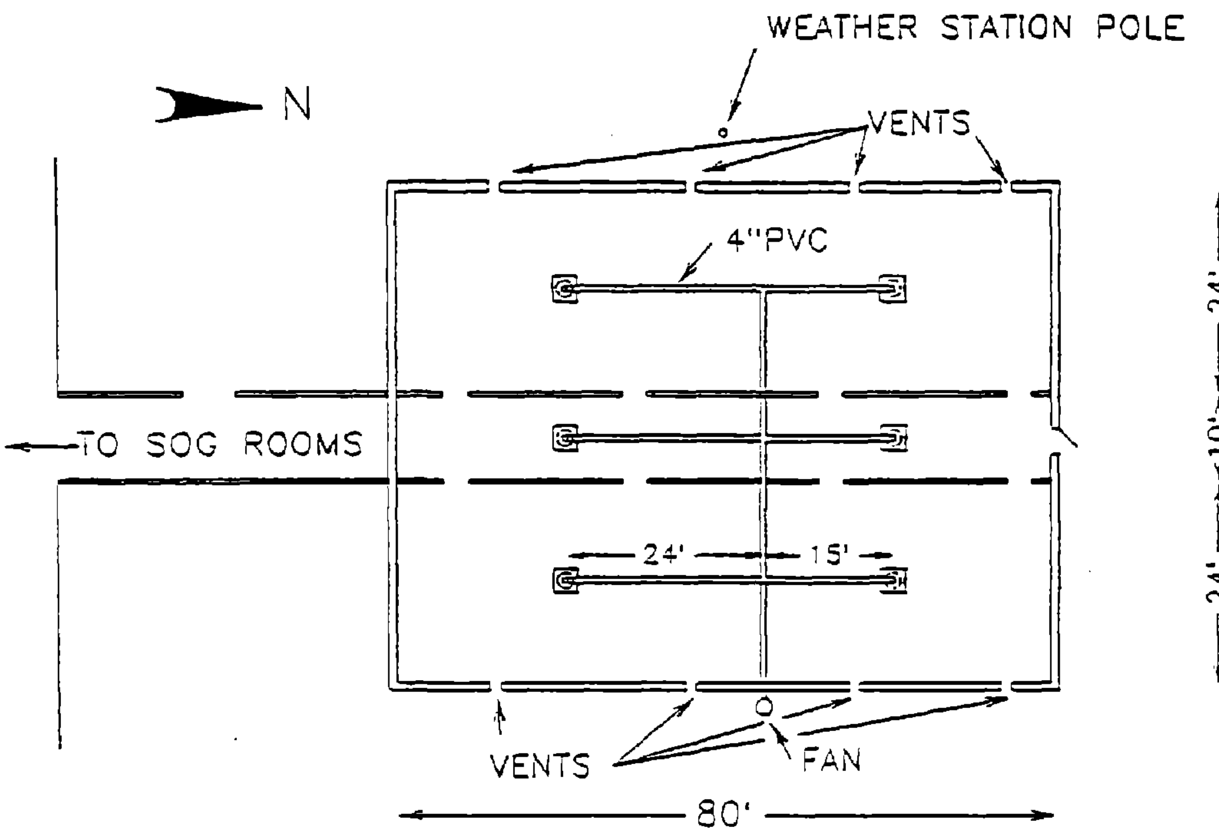


Figure 9.1.1. Plan view of the crawl space and installed ducting network at Glenview Elementary School, Nashville, TN.

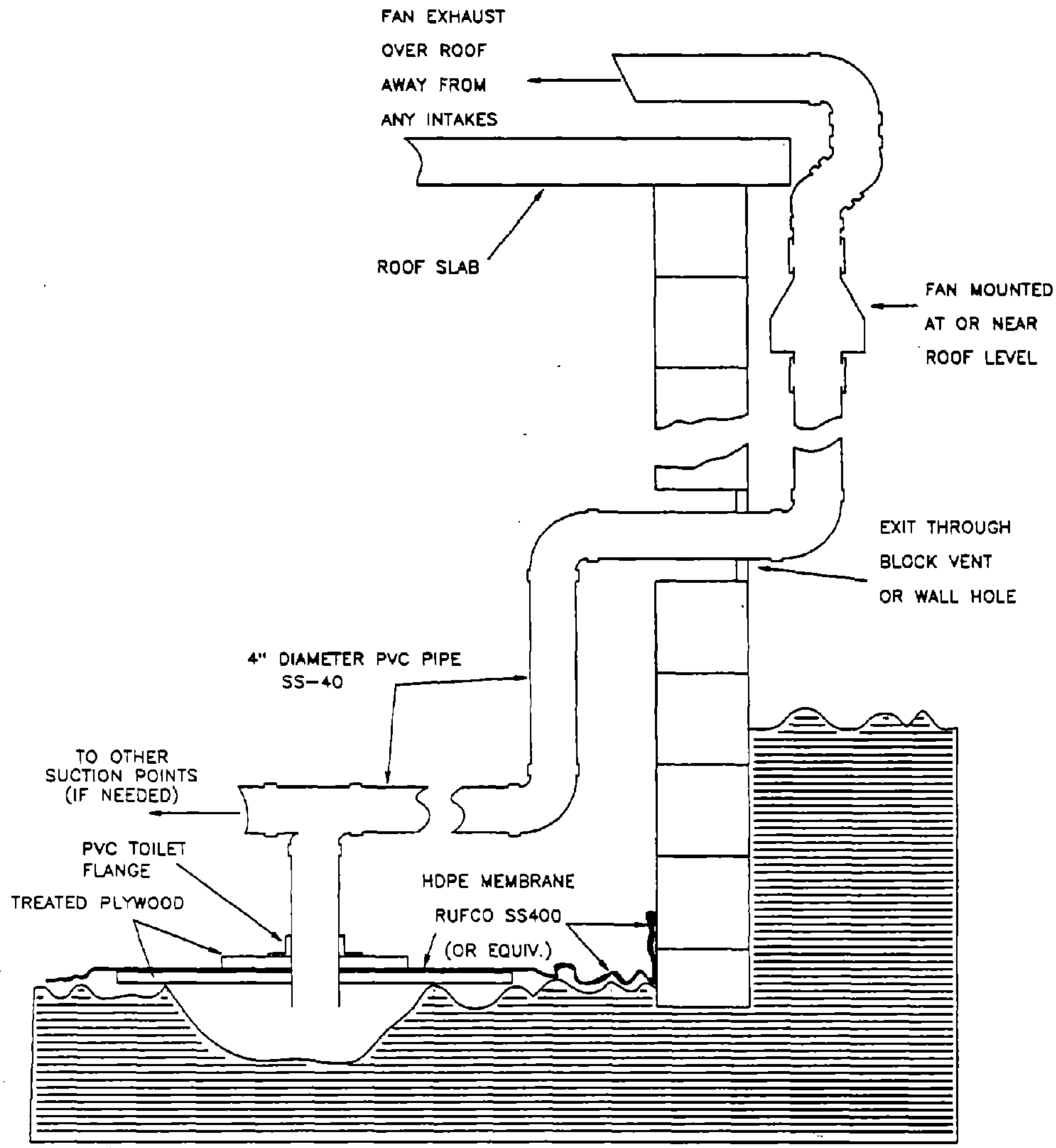


Figure 9.1.2. Typical sub-membrane depressurization system for crawl spaces.

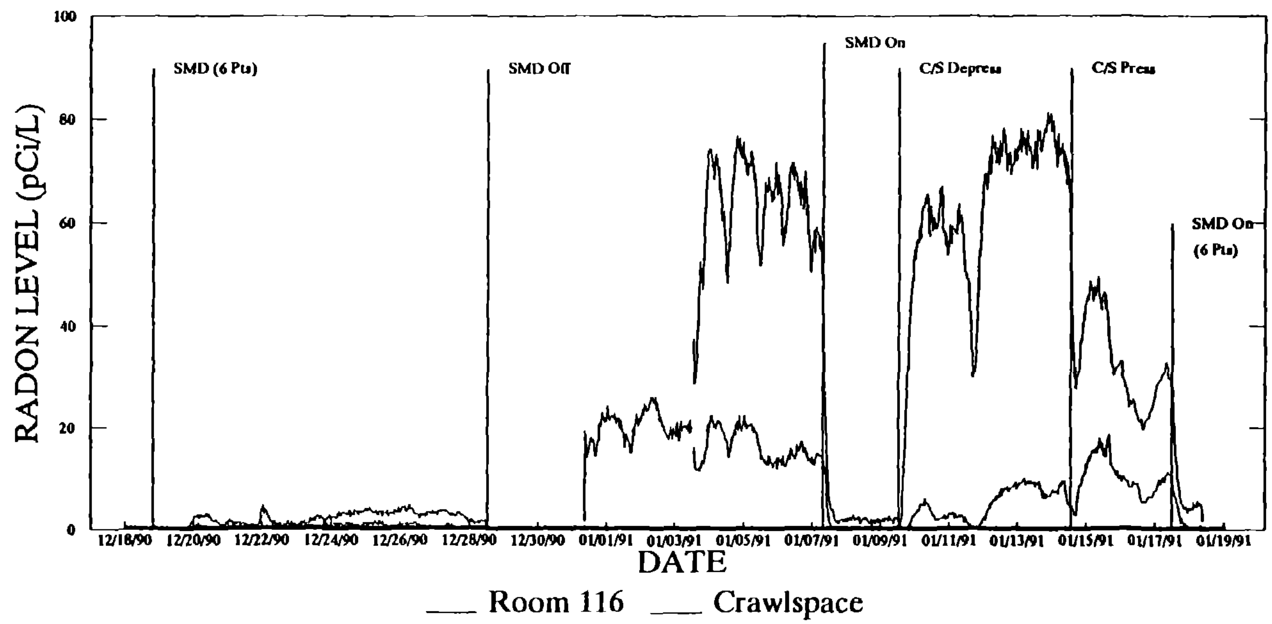


Figure 9.1.3. Continuous radon levels during the winter follow-up measurements during various mitigation options at Glenview Elementary, Nashville, TN.

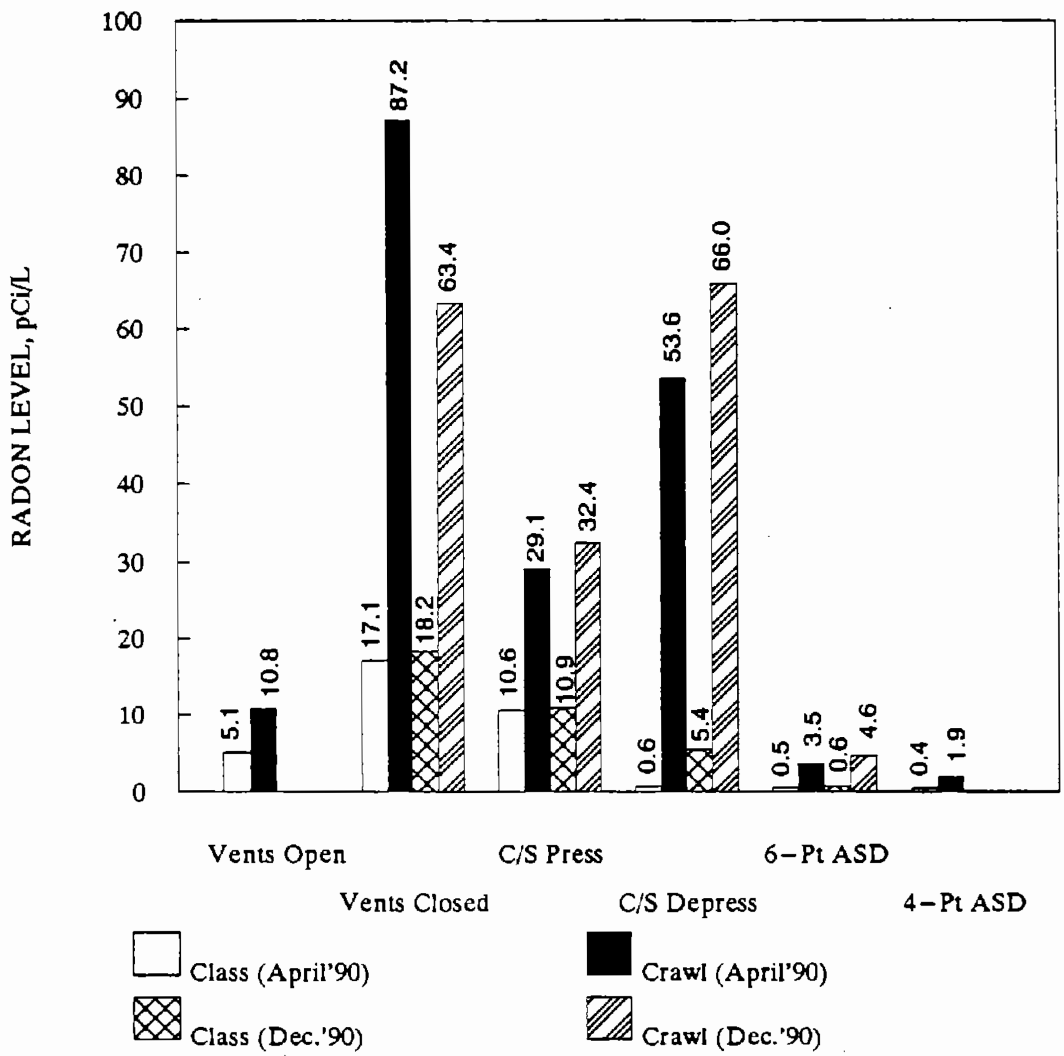


Figure 9.1.4. Summary of the radon levels in Glenview Elementary classroom and crawlspace during each of the testing periods, both Spring/Summer and Winter.

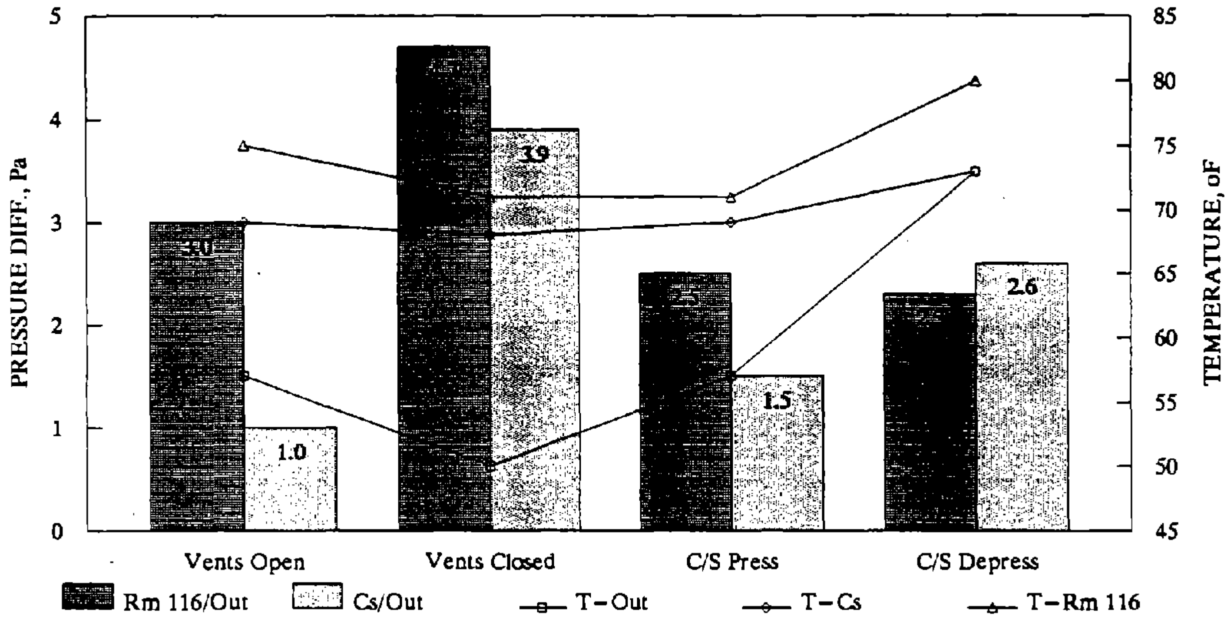


Figure 9.1.5. Differential pressures and temperatures in both the classroom and the crawlspace during the testing period at Glenview Elementary, Nashville, TN.

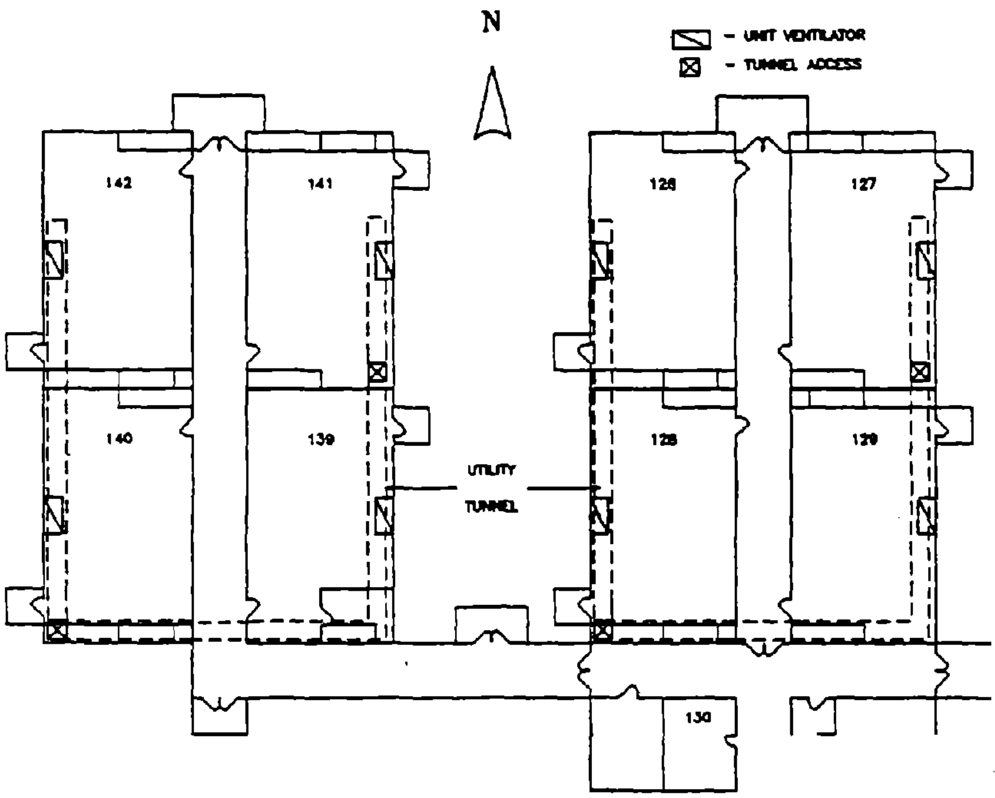


Figure 10.1.1. Partial floor plan showing utility tunnel and room locations at Lidgerwood Elementary School, Spokane, WA.

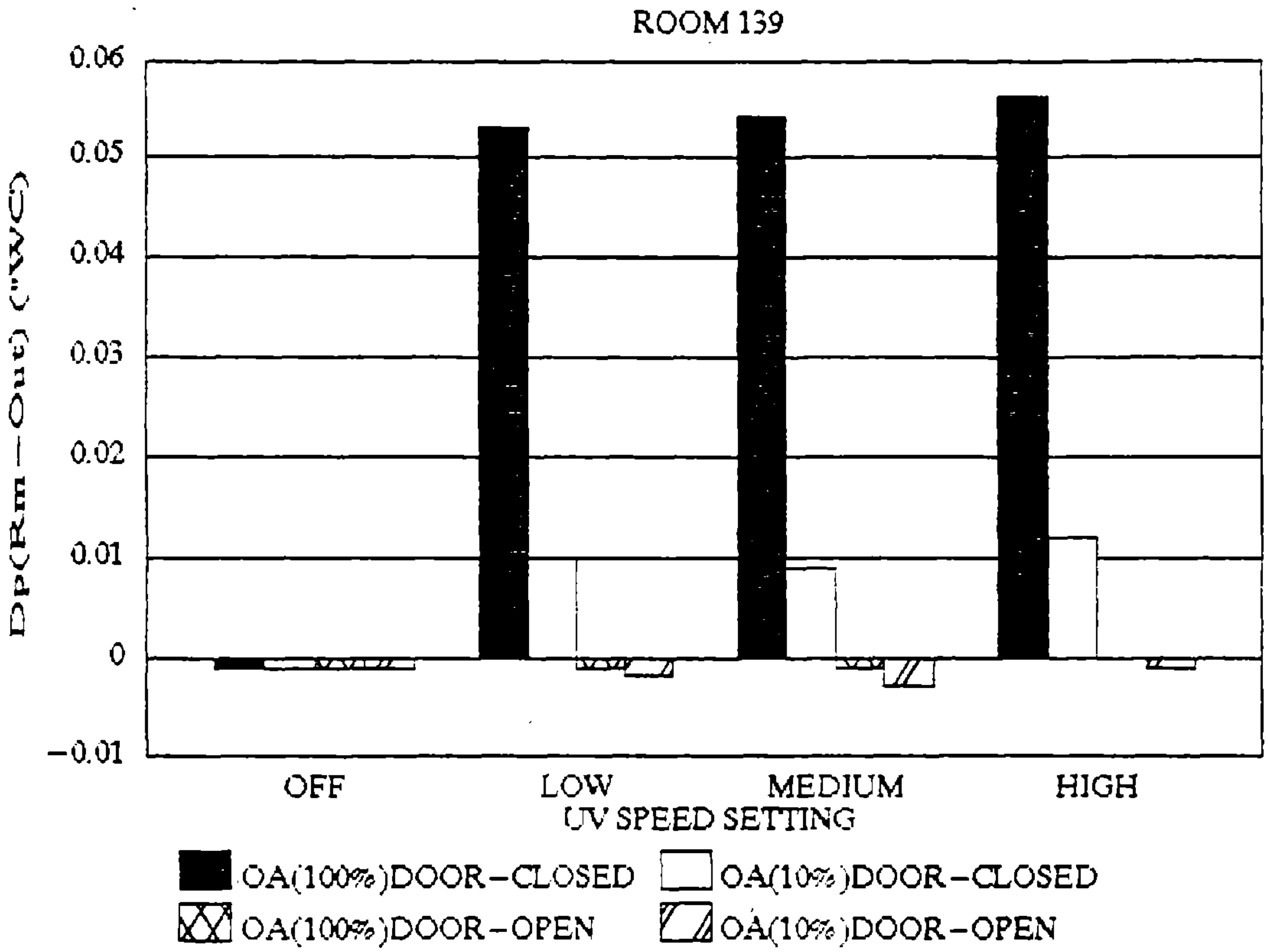


Figure 10.1.2. Room over-pressures achieved in Room 139 using the unit ventilator, Lidgerwood Elementary School.

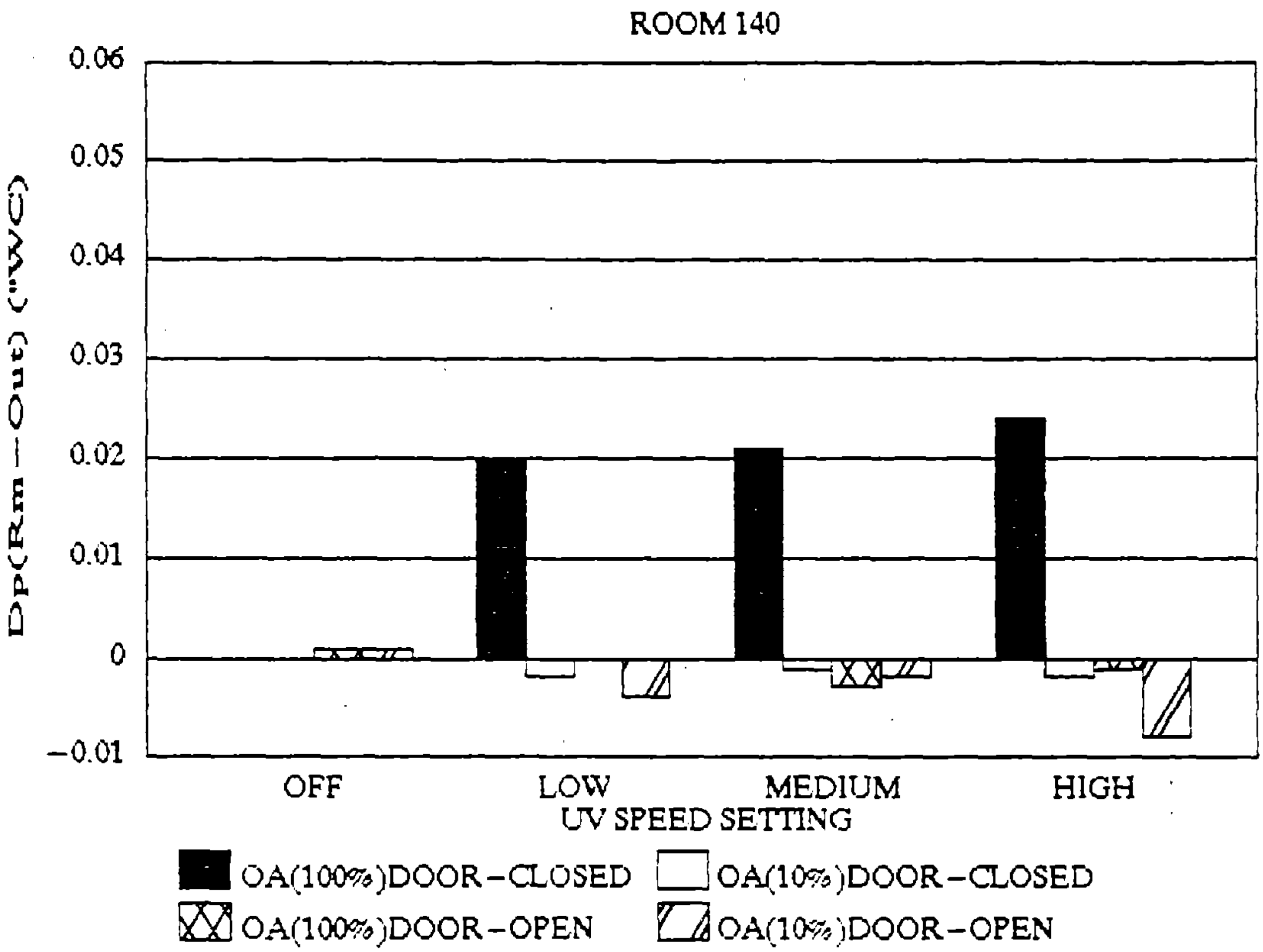


Figure 10.1.3. Room over-pressures achieved in Room 140 using the unit ventilator, Lidgerwood Elementary School.

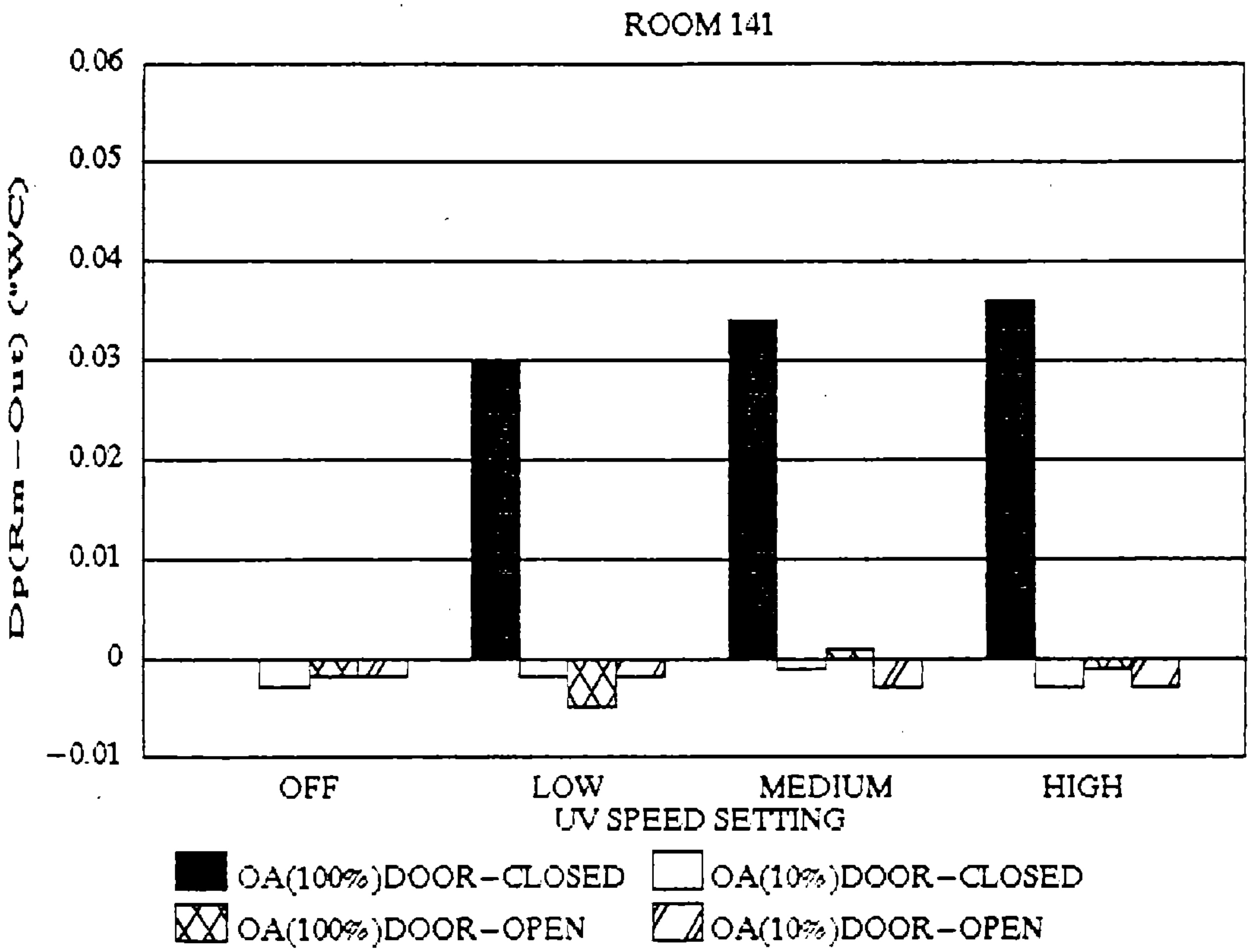


Figure 10.1.4. Room over-pressures achieved in Room 141 using the unit ventilator, Lidgerwood Elementary School.

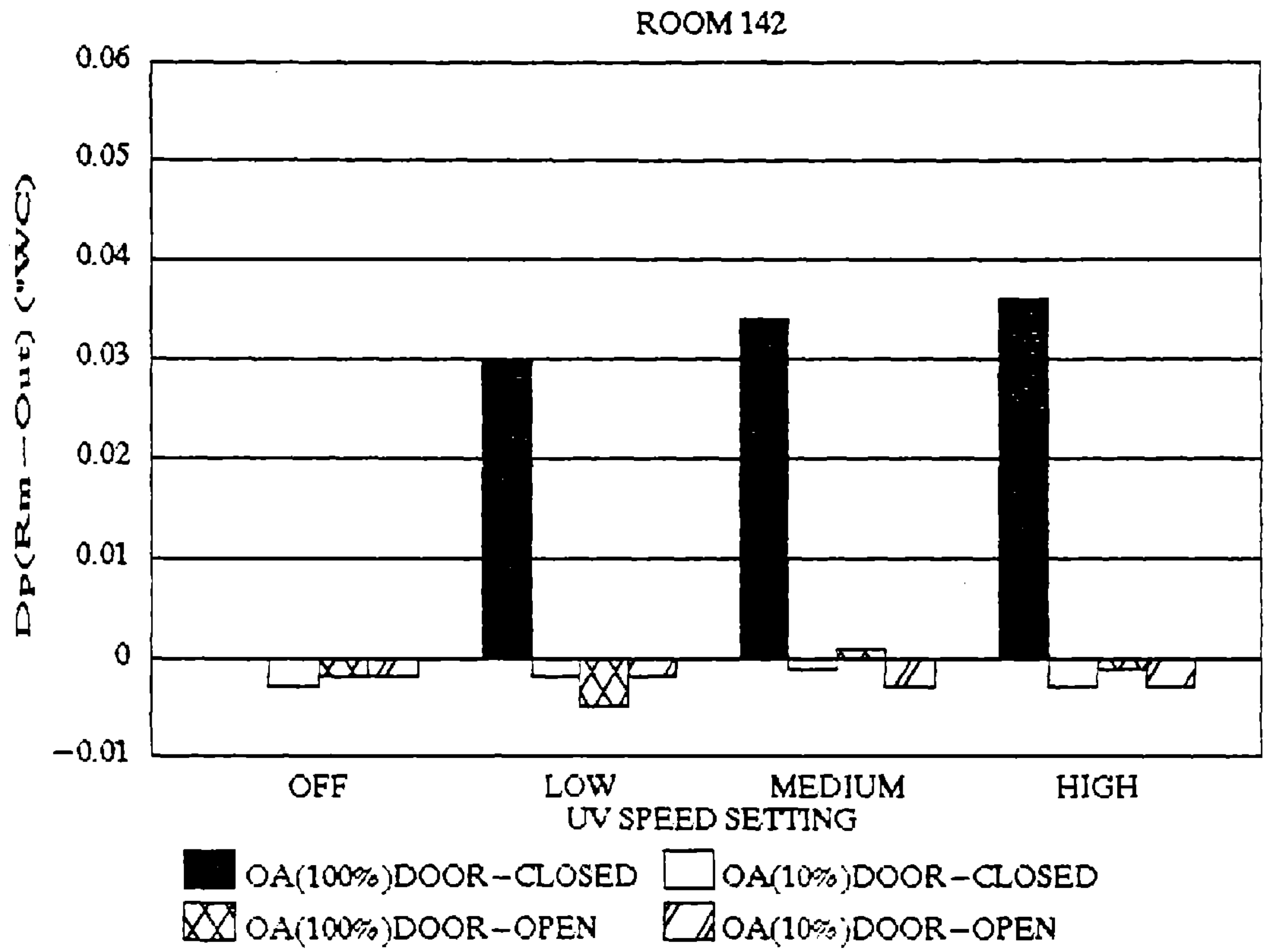


Figure 10.1.5. Room over-pressures achieved in Room 142 using the unit ventilator, Lidgerwood Elementary School.

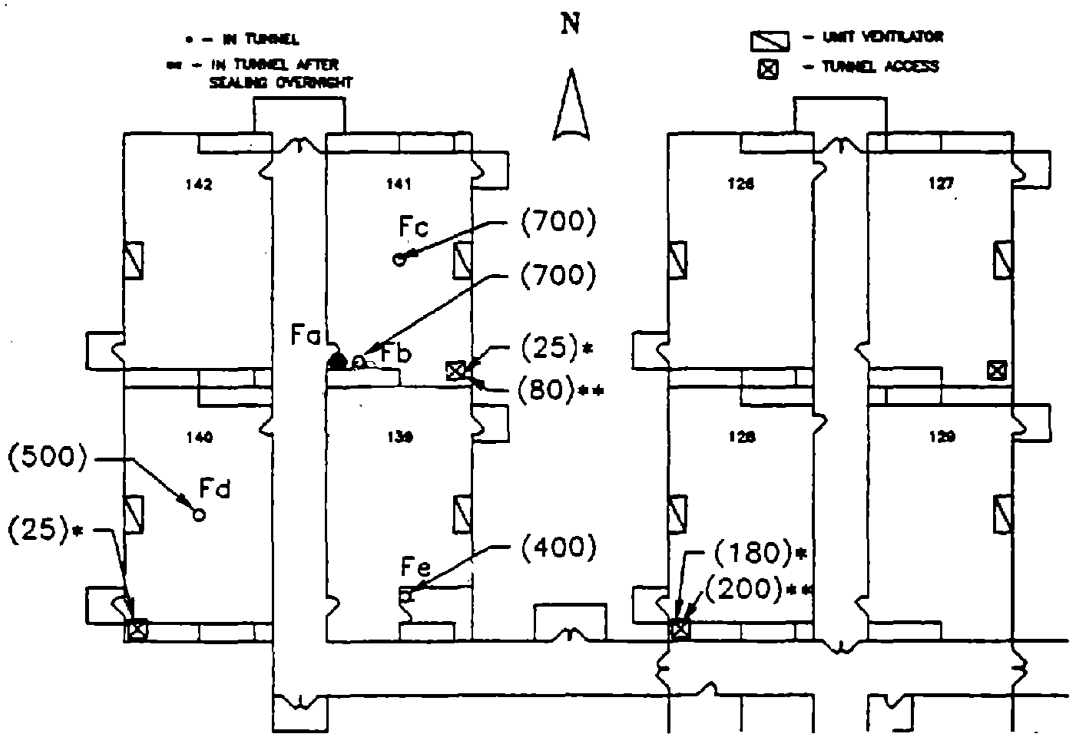


Figure 10.1.6. Location of the suction and test points used during the subslab communication tests and the radon levels measured at these points, Lidgerwood Elementary School, values in pCi/L.

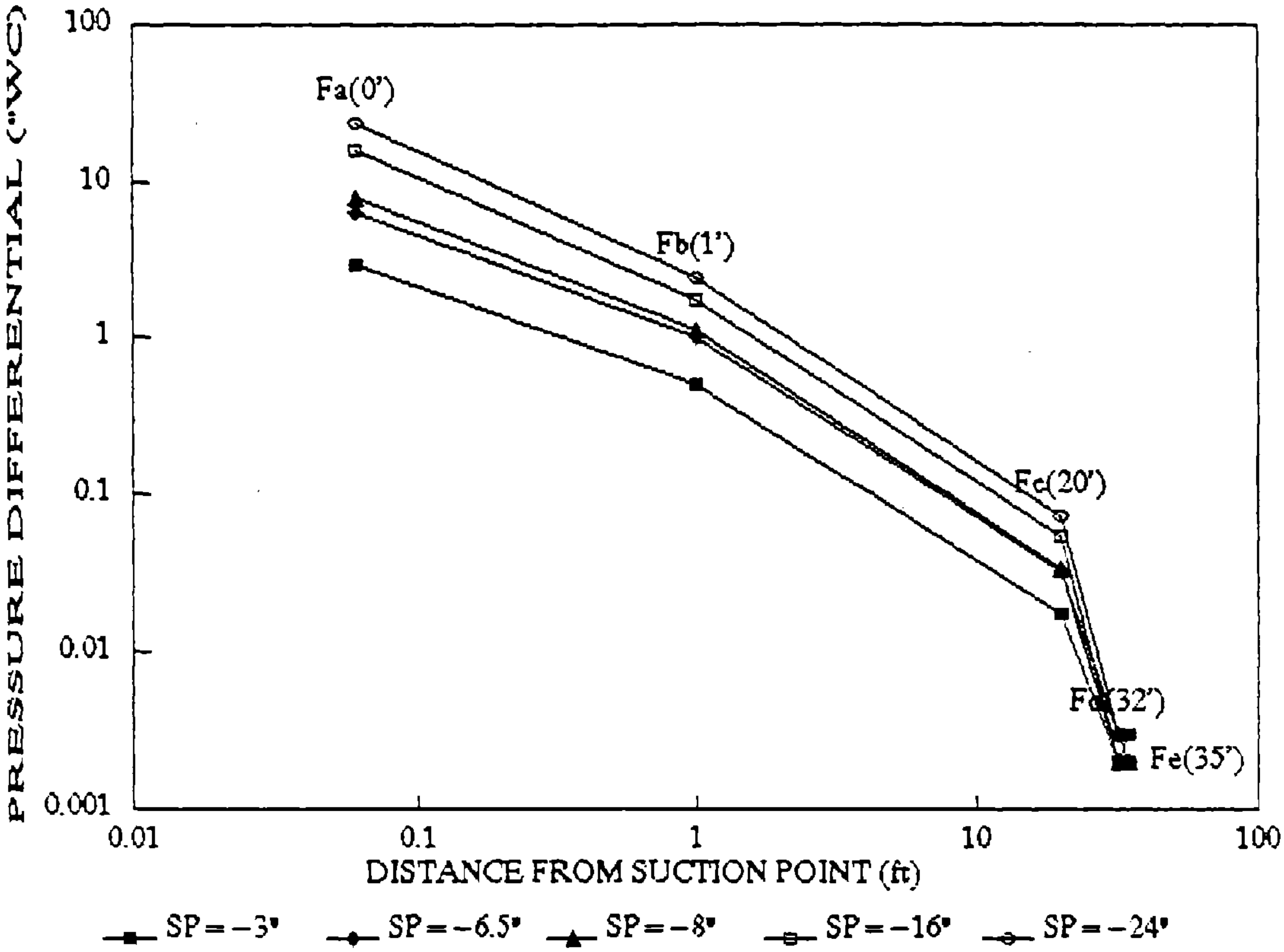


Figure 10.1.7. Results of the subslab communication tests, the values of SP are the vacuum cleaner suction applied to the suction point at Lidgerwood Elementary School.

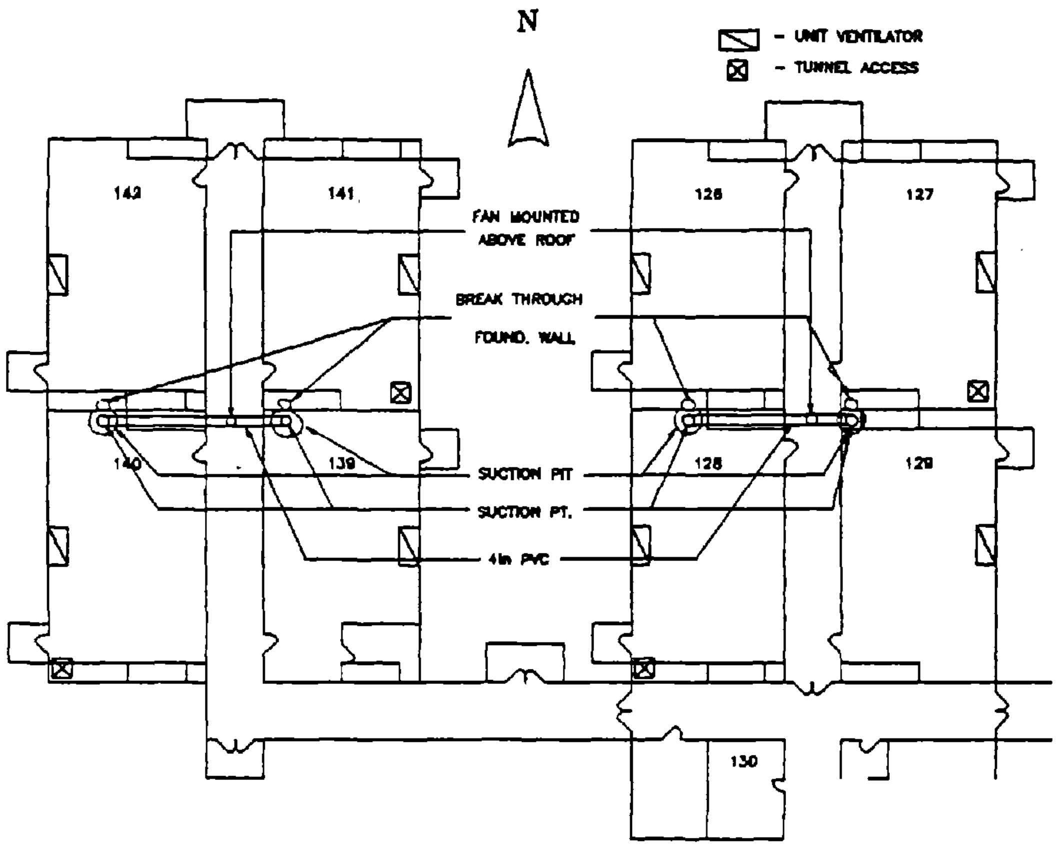


Figure 10.1.8. Proposed ASD systems at Lidgerwood Elementary School.

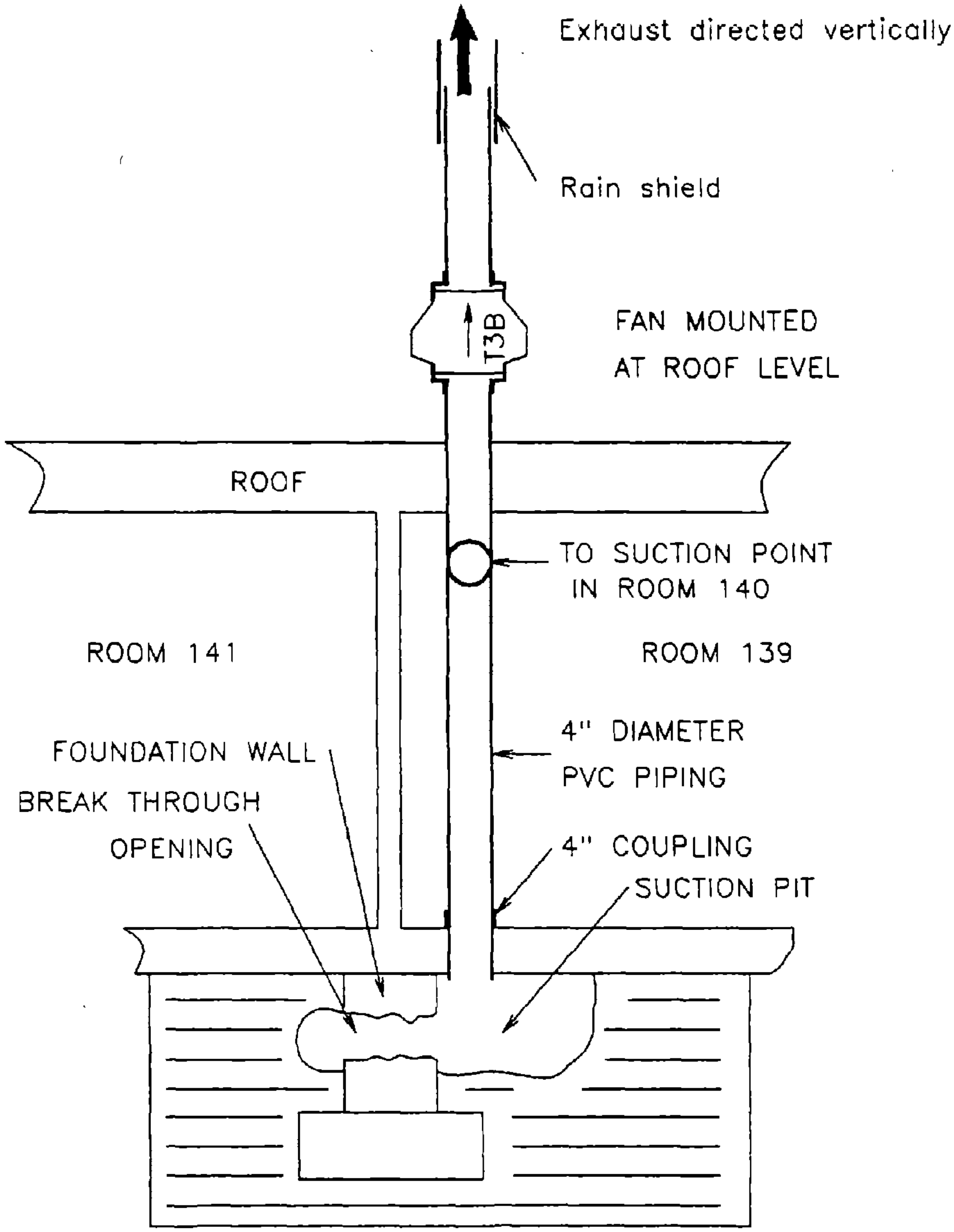


Figure 10.1.9. Cross-section view of the suction points proposed for Lidgerwood Elementary School (the same design should be used in Rooms 128 and 129).

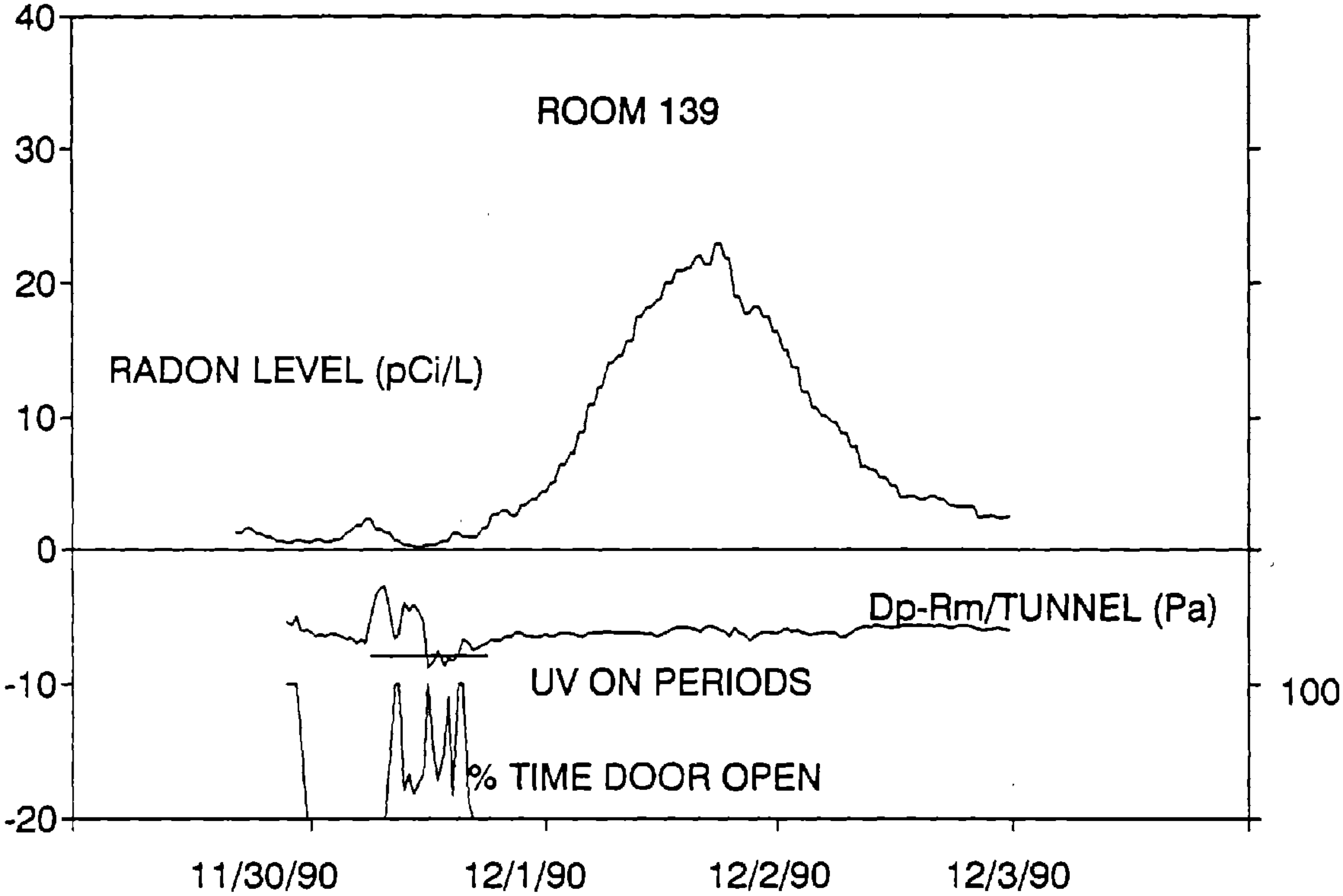


Figure 10.1.10. Summary of the data measured in Room 139 over the period November 29, 1990 through December 3, 1990.

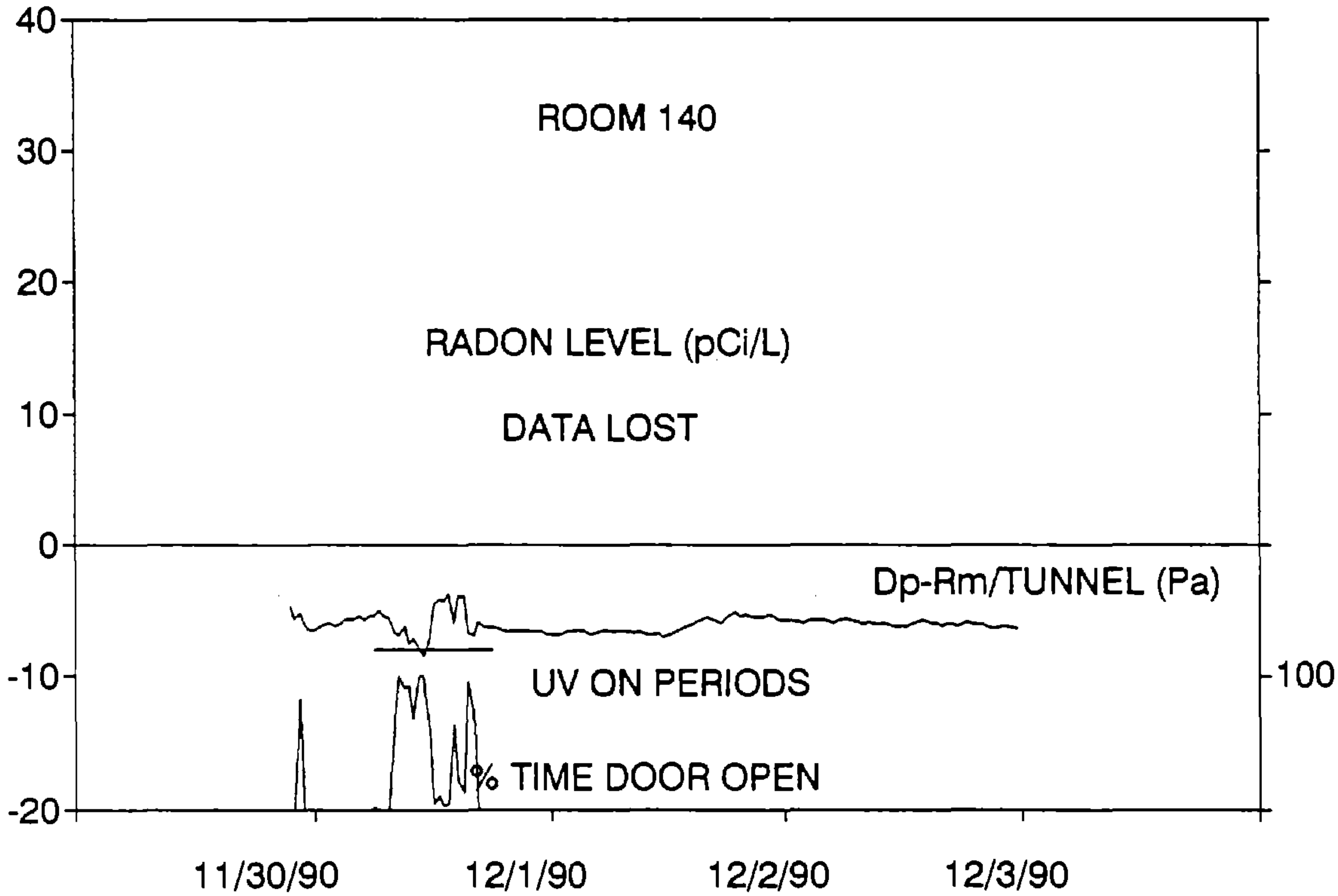


Figure 10.1.11. Summary of the data measured in Room 140 over the period November 29, 1990 through December 3, 1990.

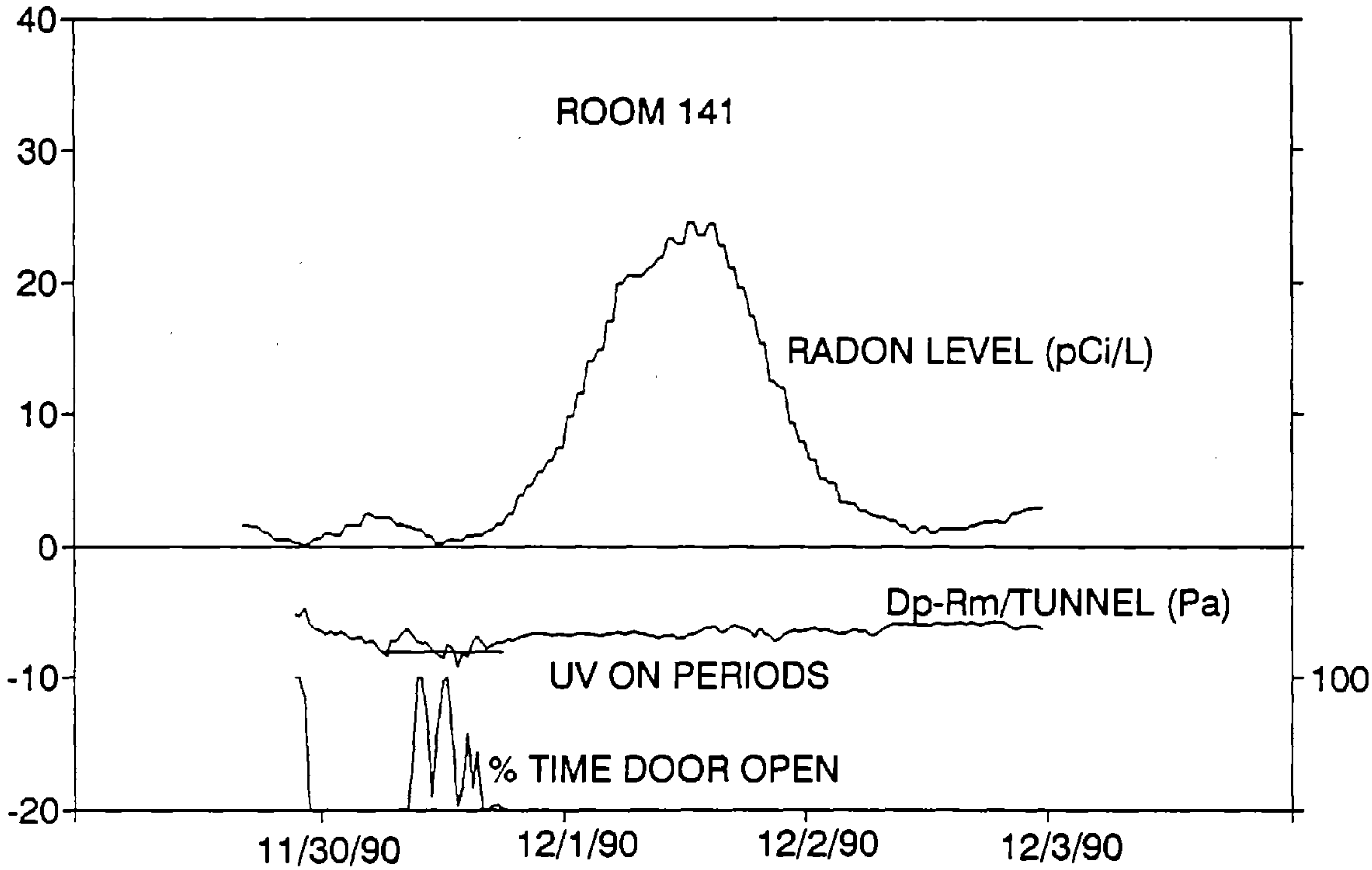


Figure 10.1.12. Summary of the data measured in Room 141 over the period November 29, 1990 through December 3, 1990.

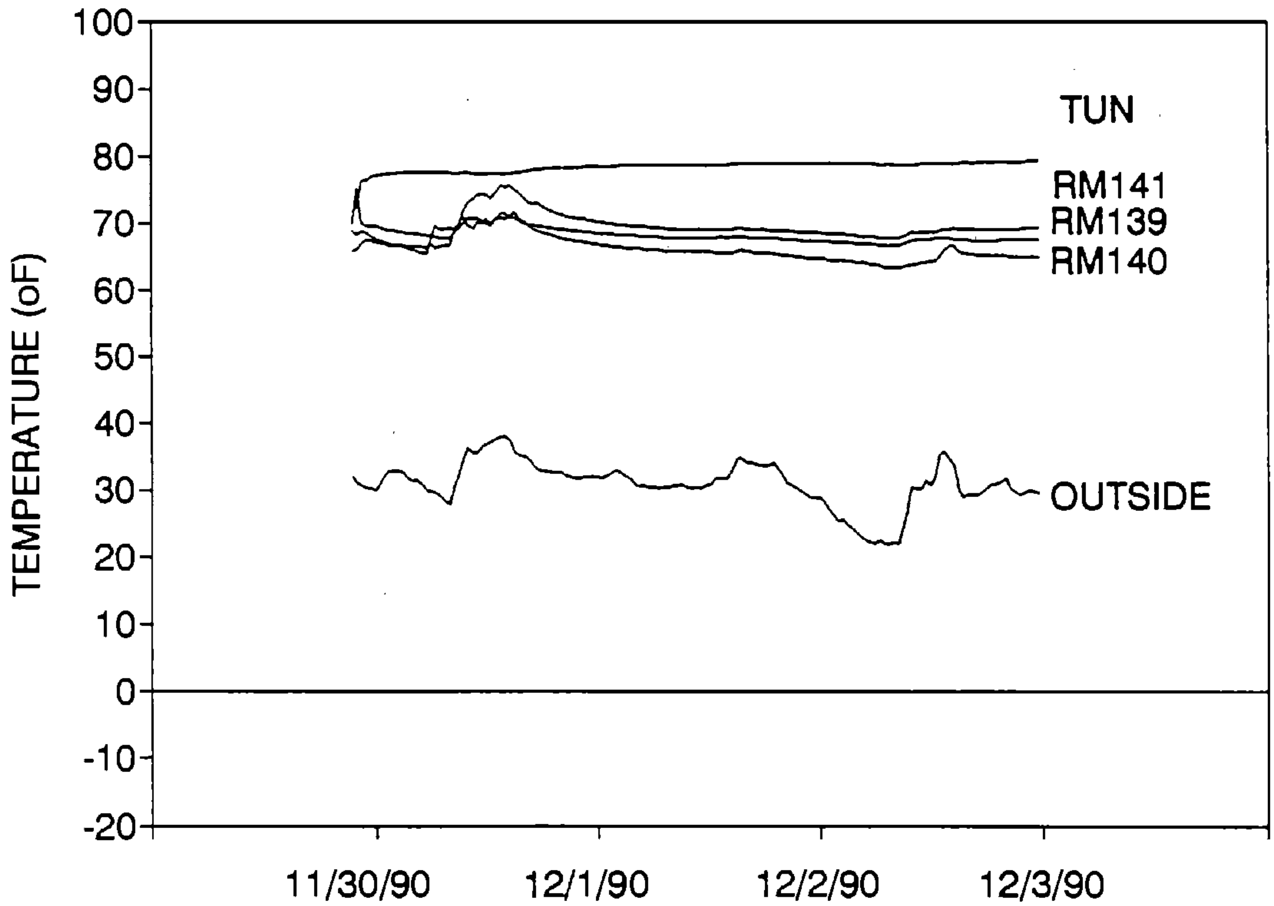


Figure 10.1.13. Summary of the temperature data measured in the classrooms and outside over the period November 29, 1990 through December 3, 1990.

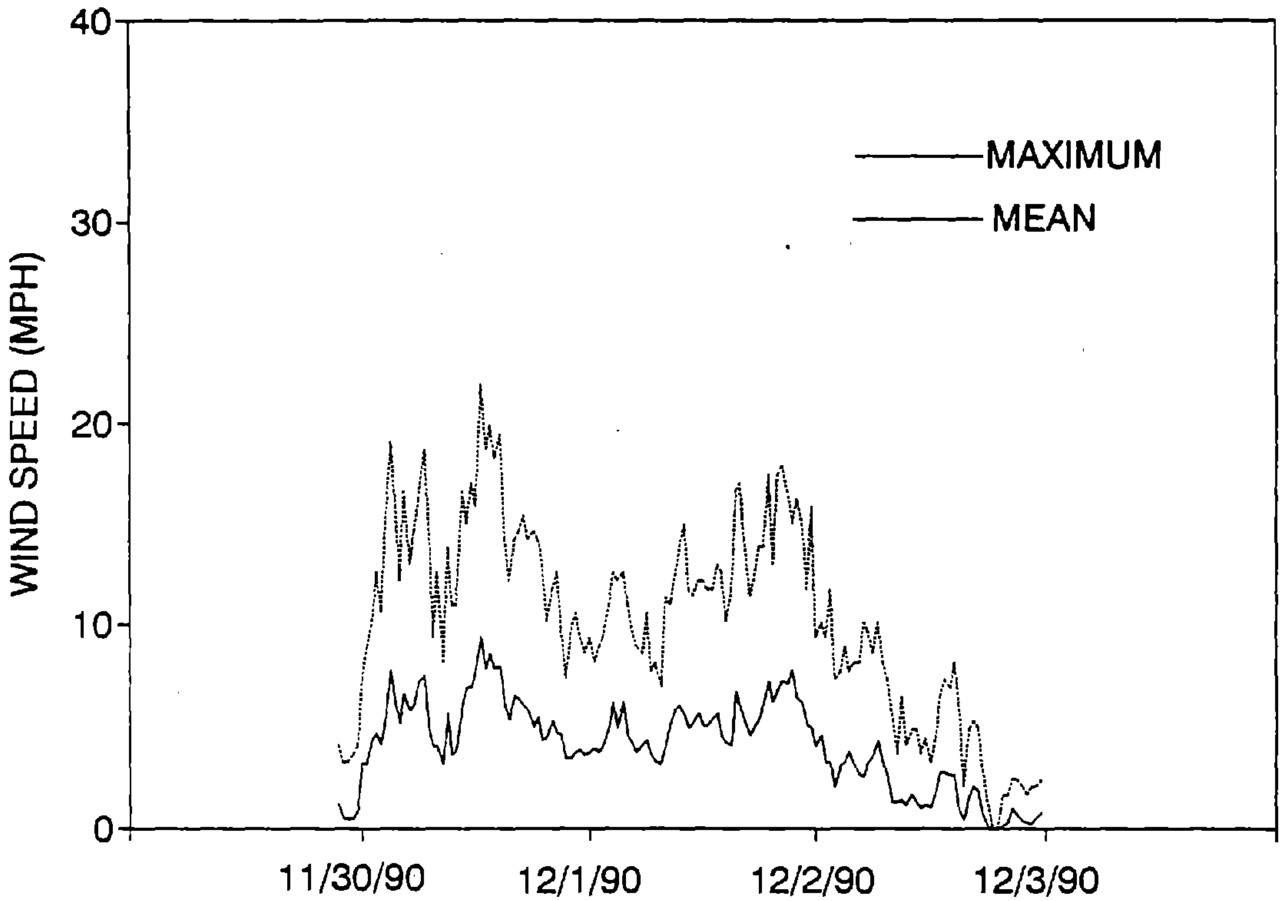


Figure 10.1.14. Summary of the wind data measured over the period November 29, 1990 through December 3, 1990.

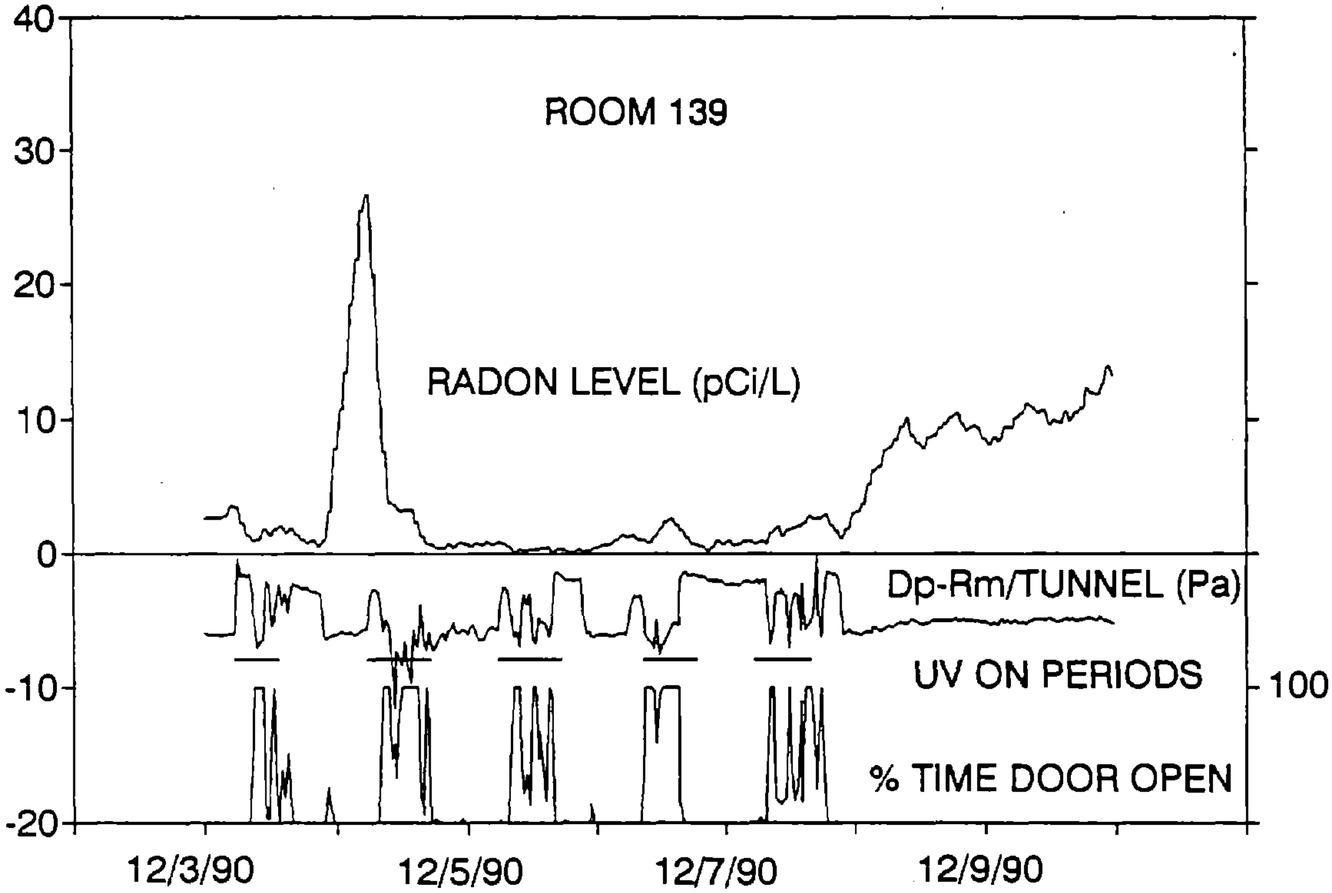


Figure 10.1.15. Summary of the data measured in Room 139 over the period December 3, 1990 through December 9, 1990.

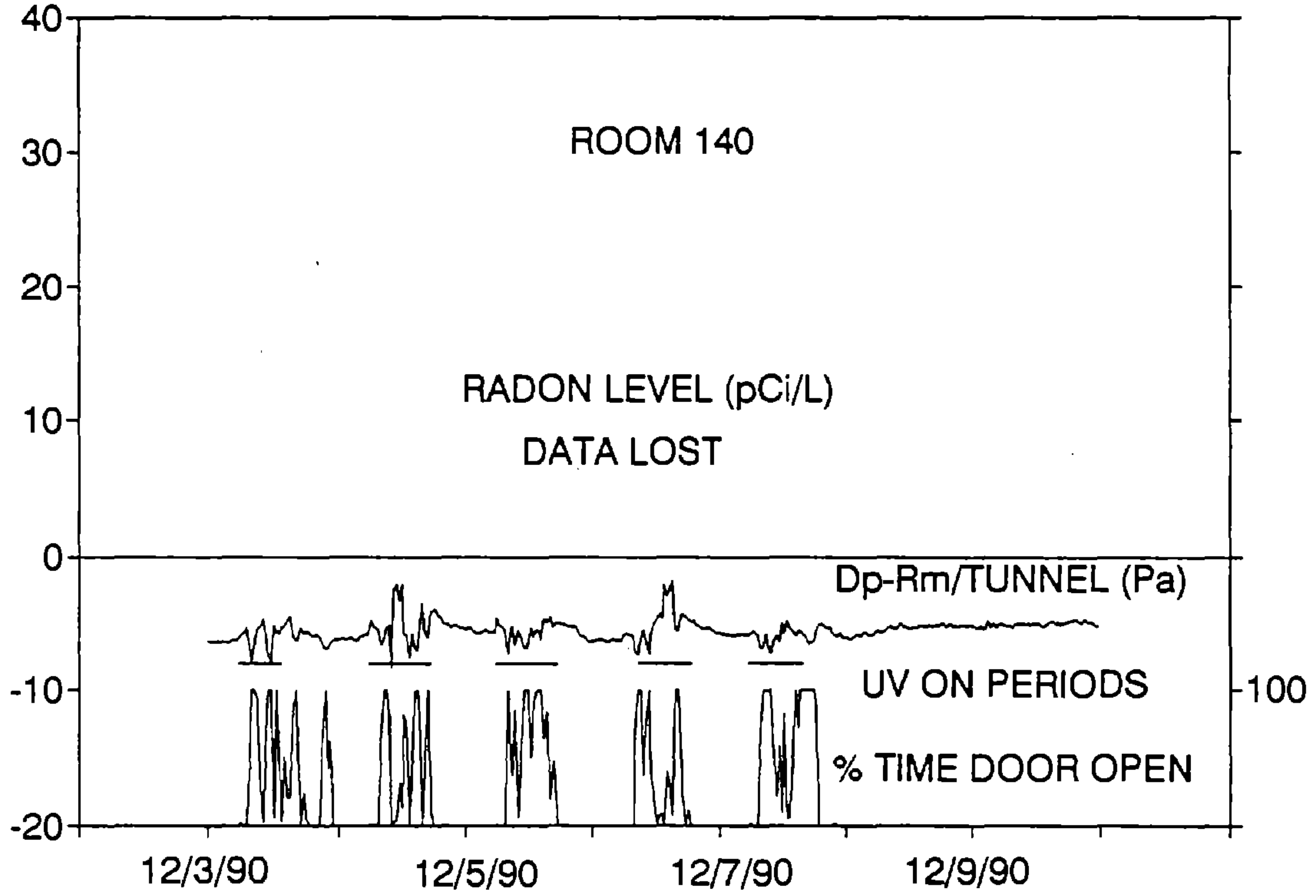


Figure 10.1.16. Summary of the data measured in Room 140 over the period December 3, 1990 through December 9, 1990.

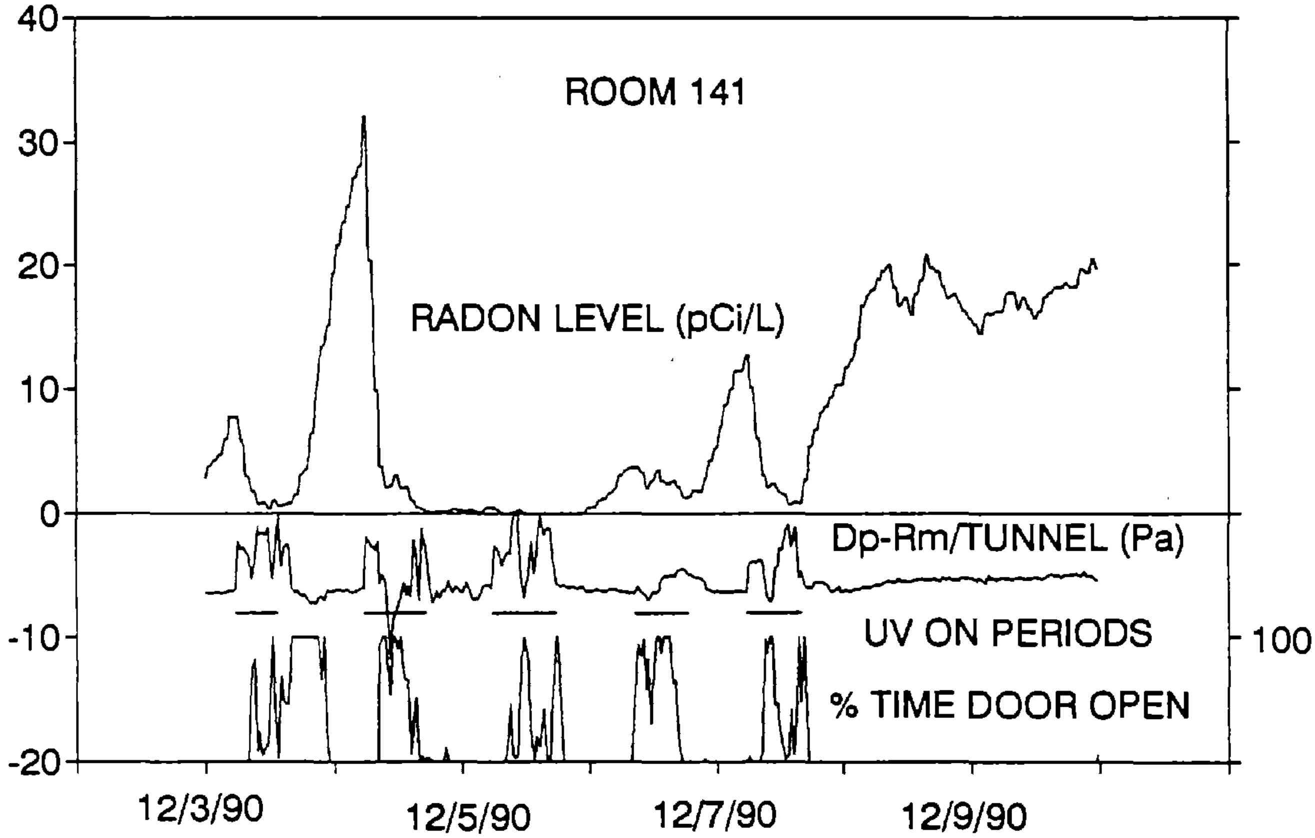


Figure 10.1.17. Summary of the data measured in Room 141 over the period December 3, 1990 through December 9, 1990.

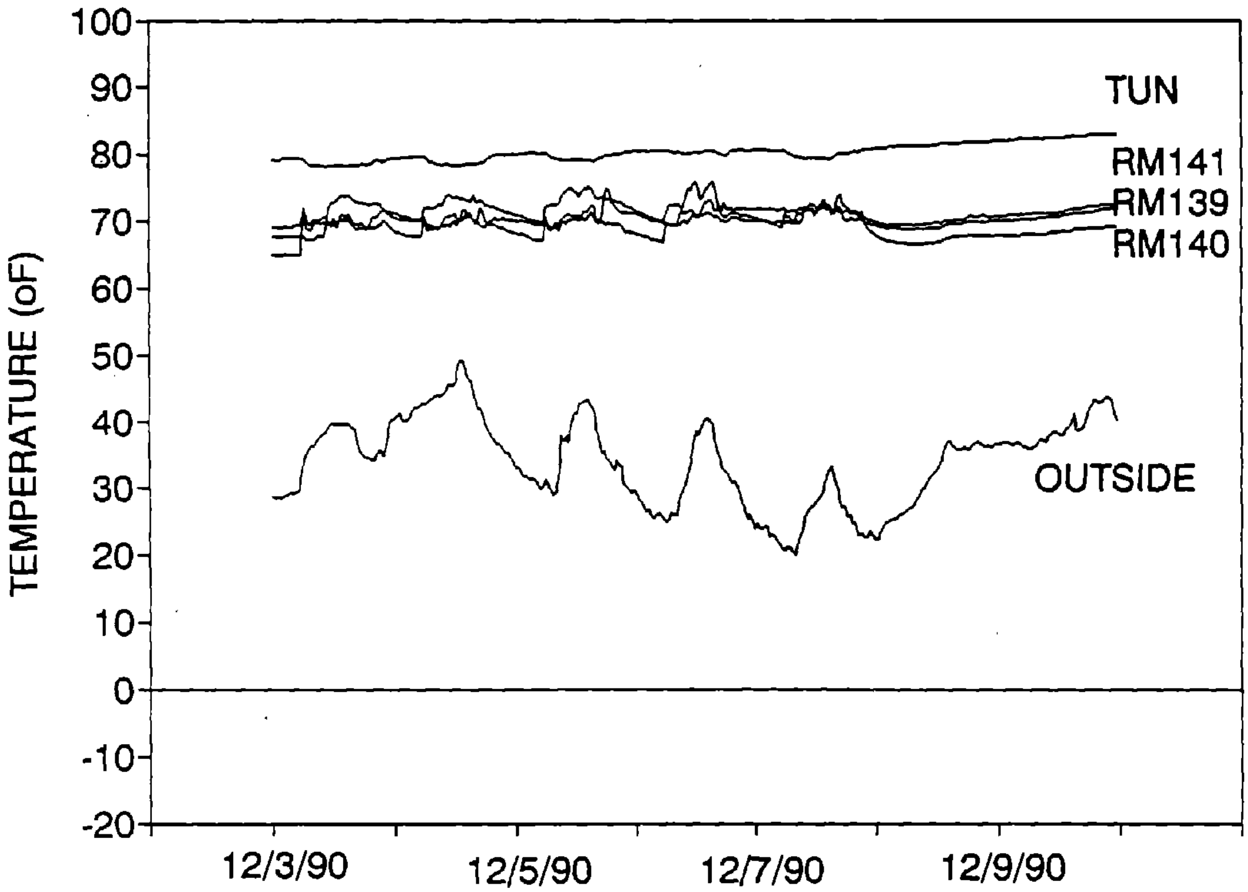


Figure 10.1.18. Summary of the temperature data measured in the classrooms and outside over the period December 3, 1990 through December 9, 1990.

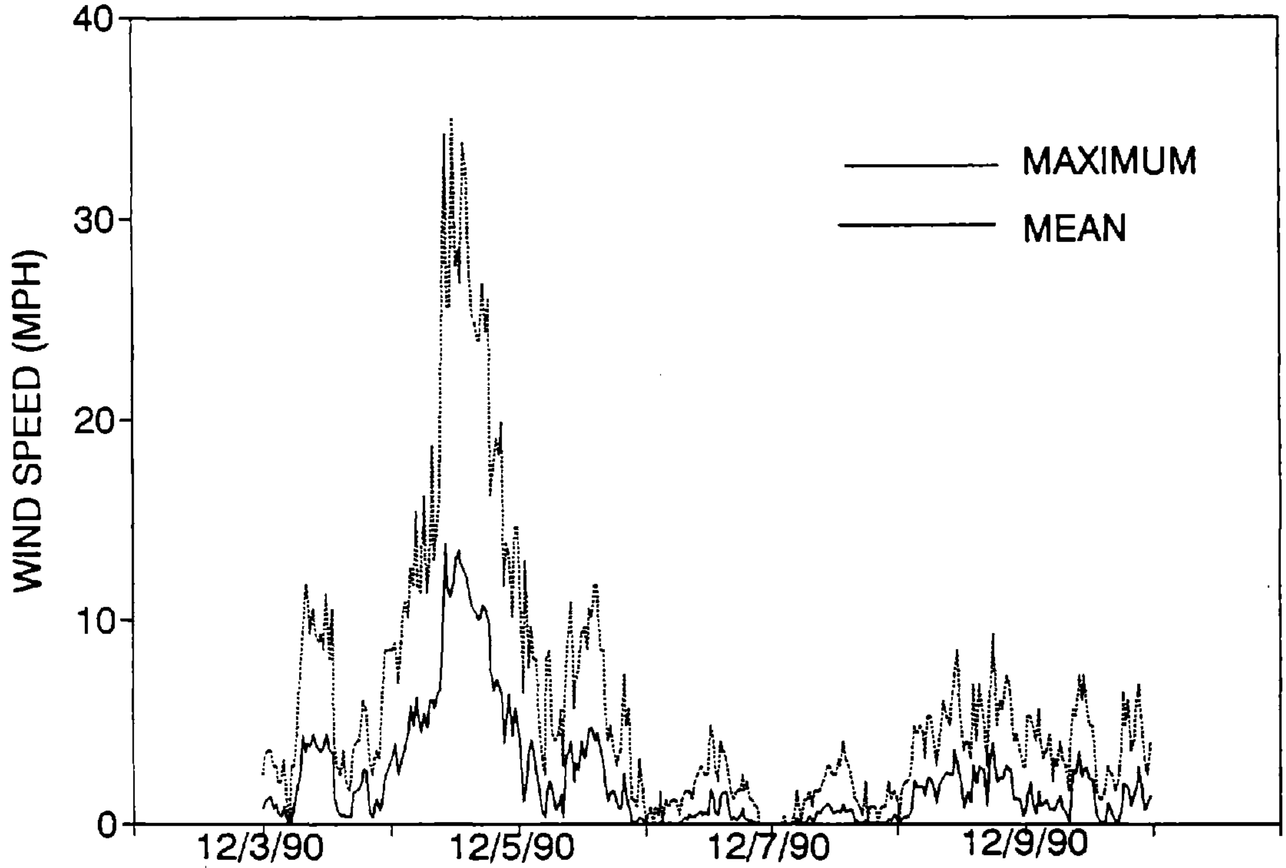


Figure 10.1.19. Summary of the wind data measured over the period December 3, 1990 through December 9, 1990.

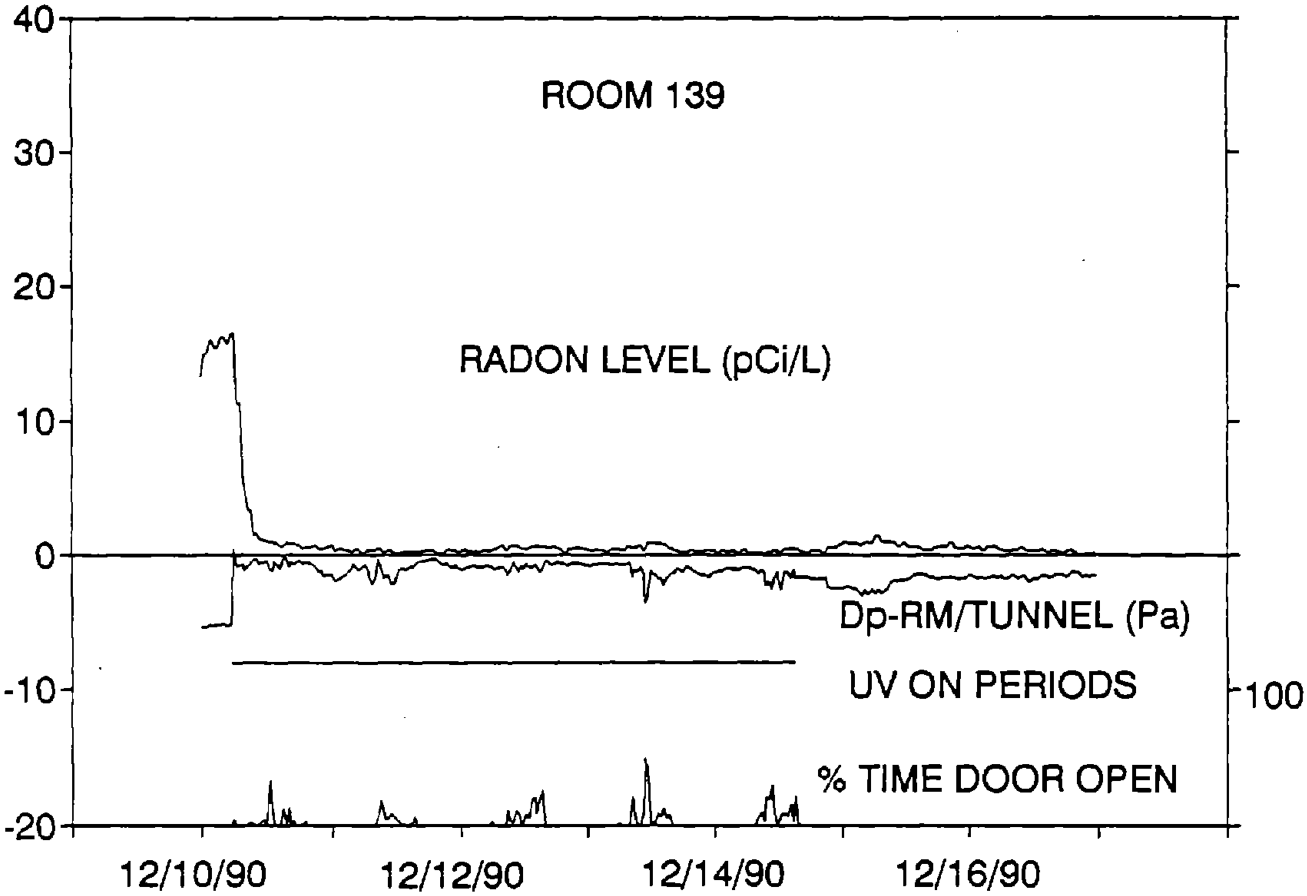


Figure 10.1.20. Summary of the data measured in room 139 over the period December 10, 1990 through December 16, 1990.

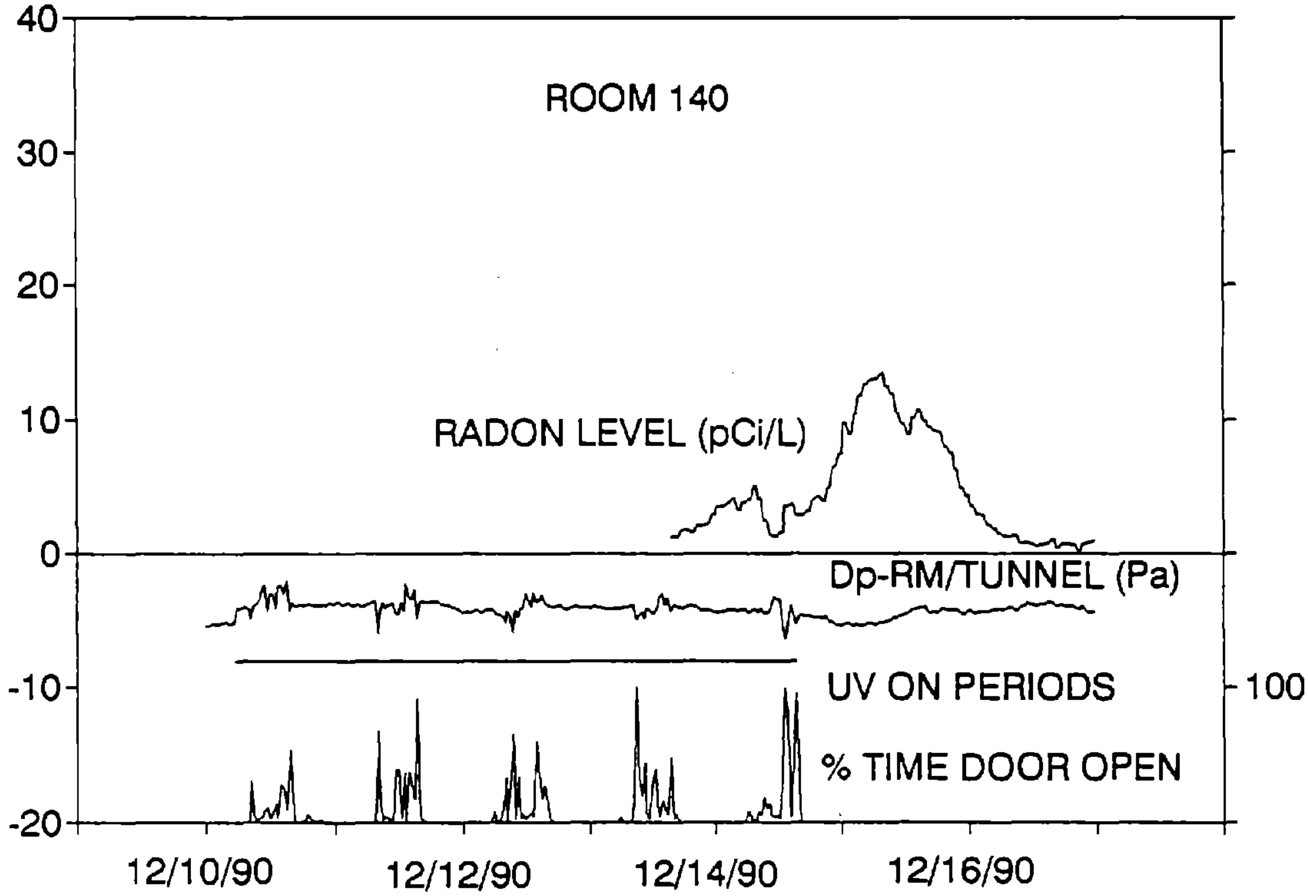


Figure 10.1.21. Summary of the data measured in Room 140 over the period December 10, 1990 through December 16, 1990.

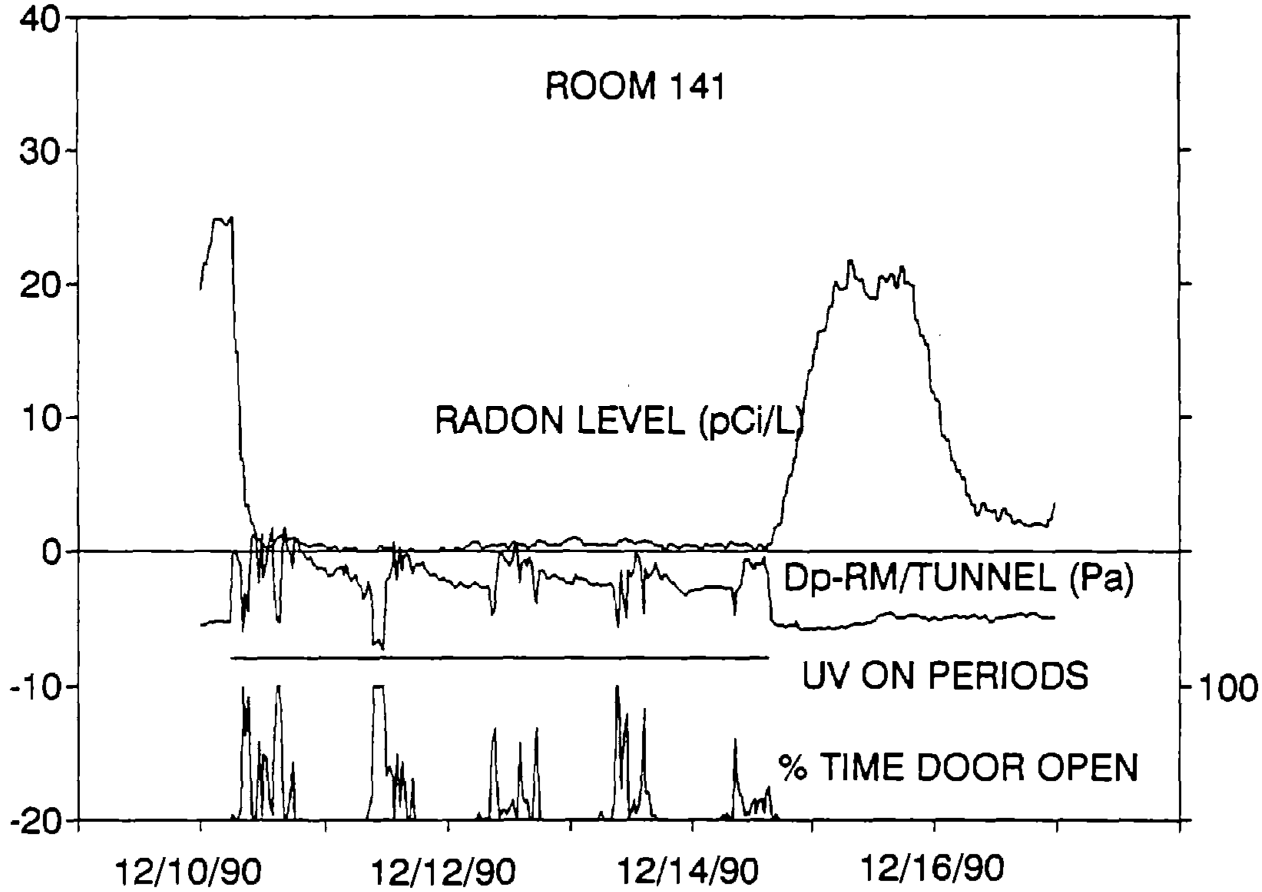


Figure 10.1.22. Summary of the data measured in Room 141 over the period December 10, 1990 through December 16, 1990.

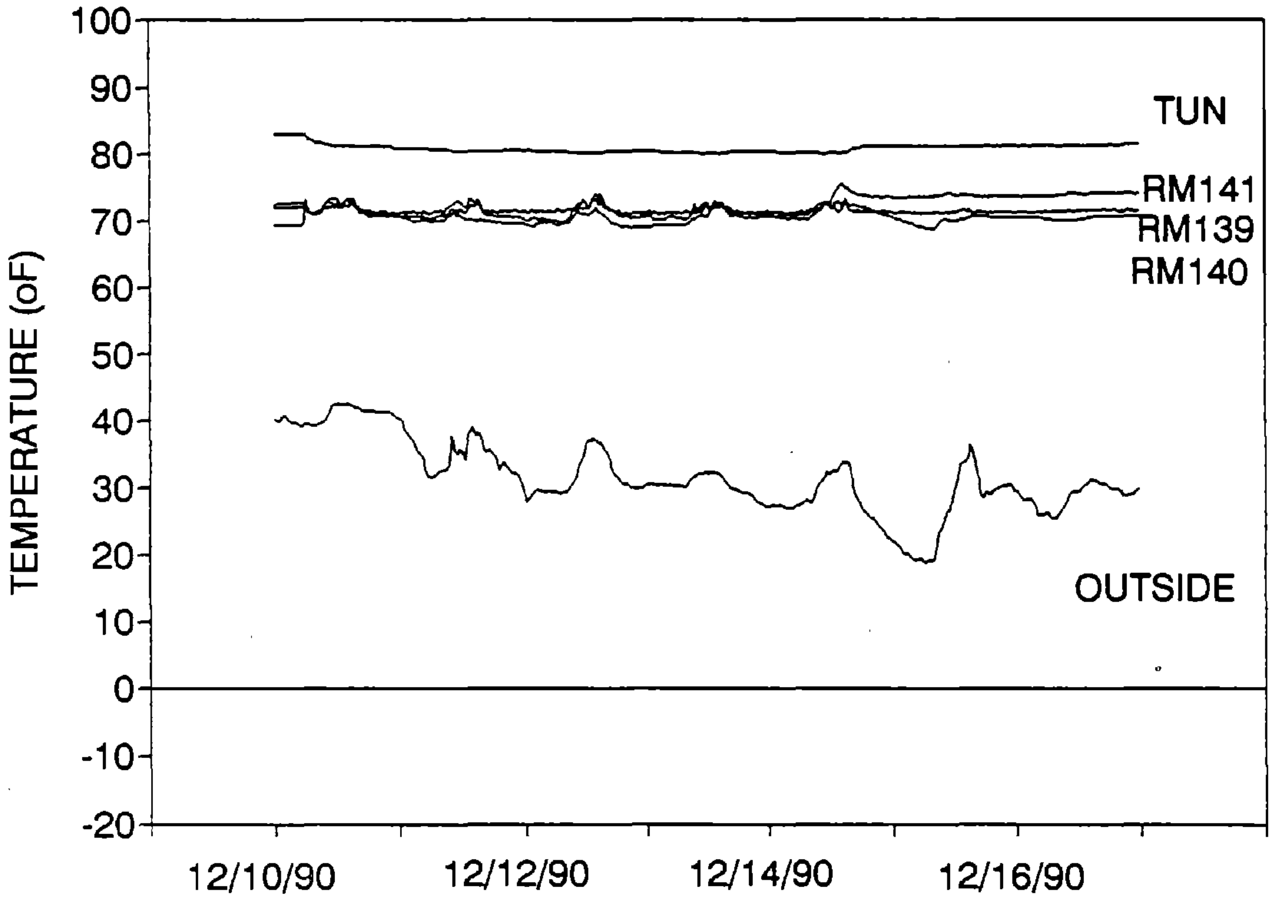


Figure 10.1.23. Summary of the temperature data measured in the classrooms and outside over the period December 10, 1990 through December 16, 1990.

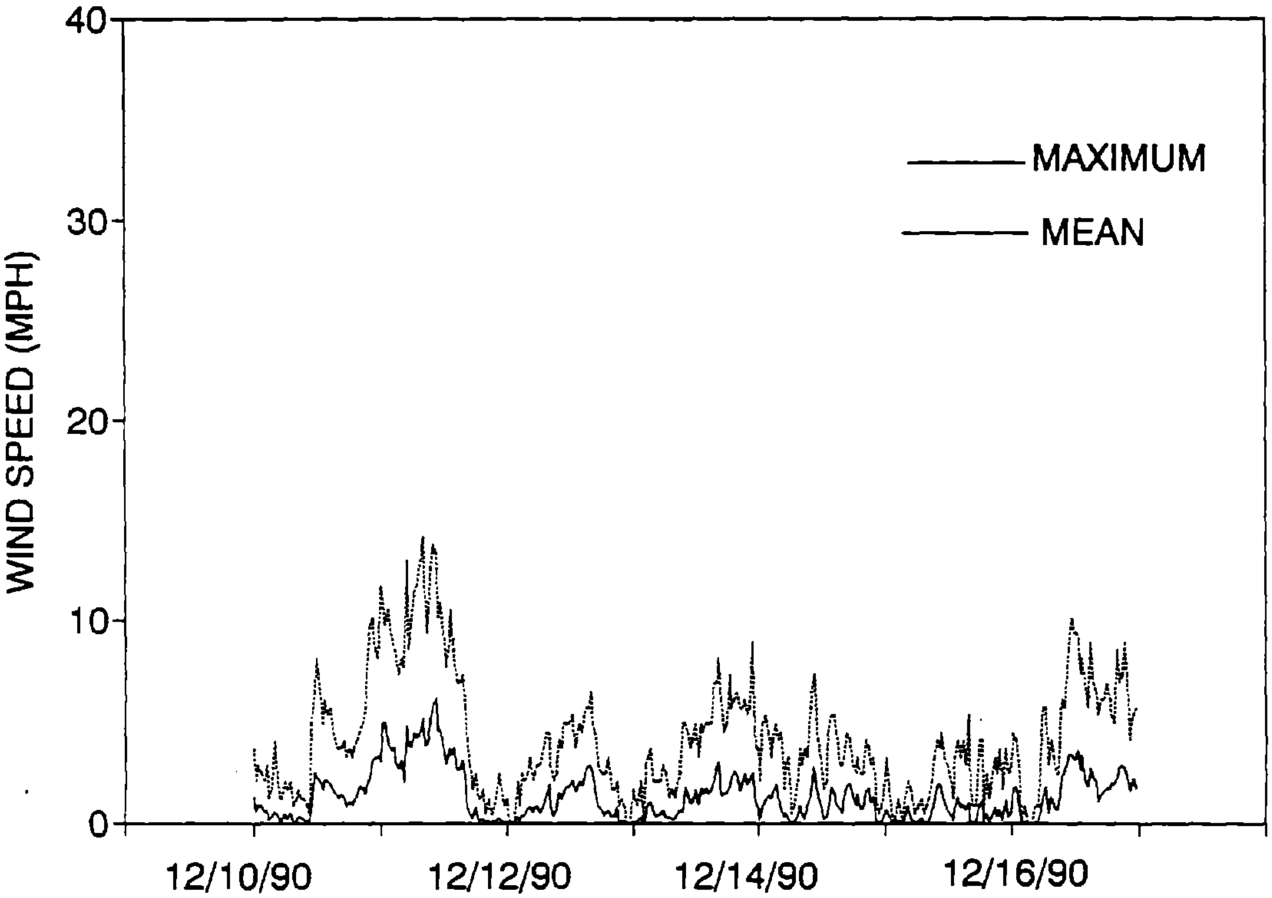


Figure 10.1.24. Summary of the wind data measured over the period December 10, 1990 through December 16, 1990.

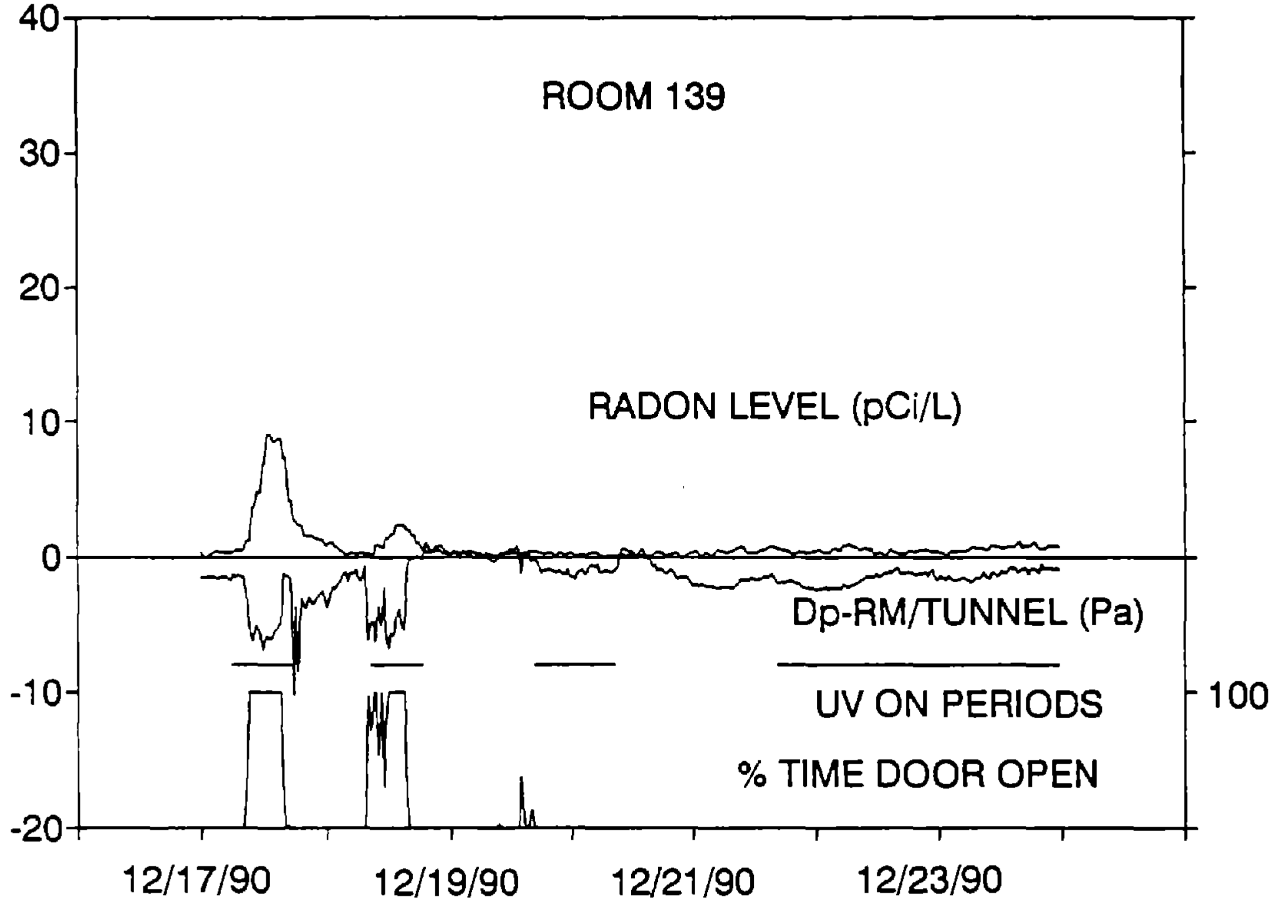


Figure 10.1.25. Summary of the data measured in Room 139 over the period December 17, 1990 through December 23, 1990.

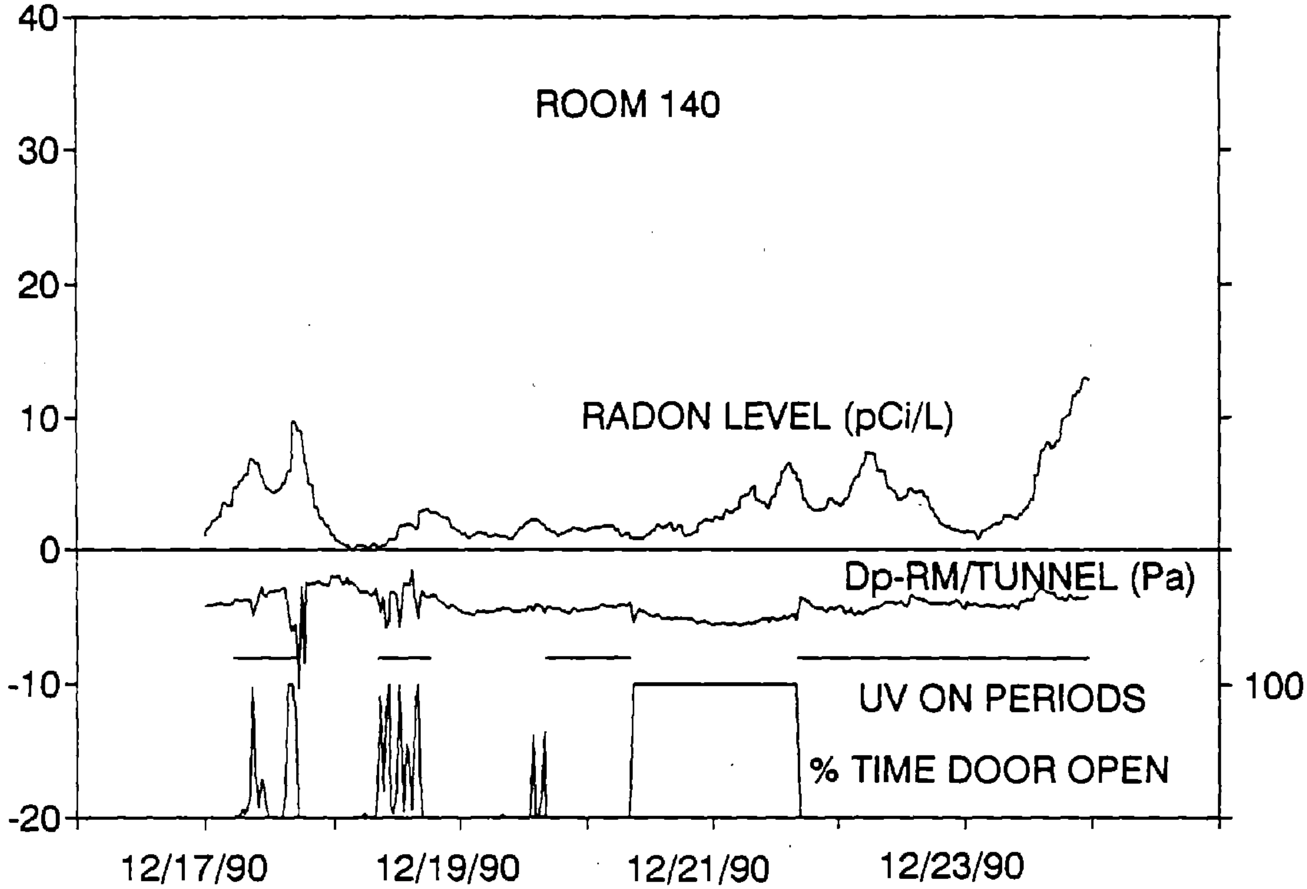


Figure 10.1.26. Summary of the data measured in Room 140 over the period December 17, 1990 through December 23, 1990.

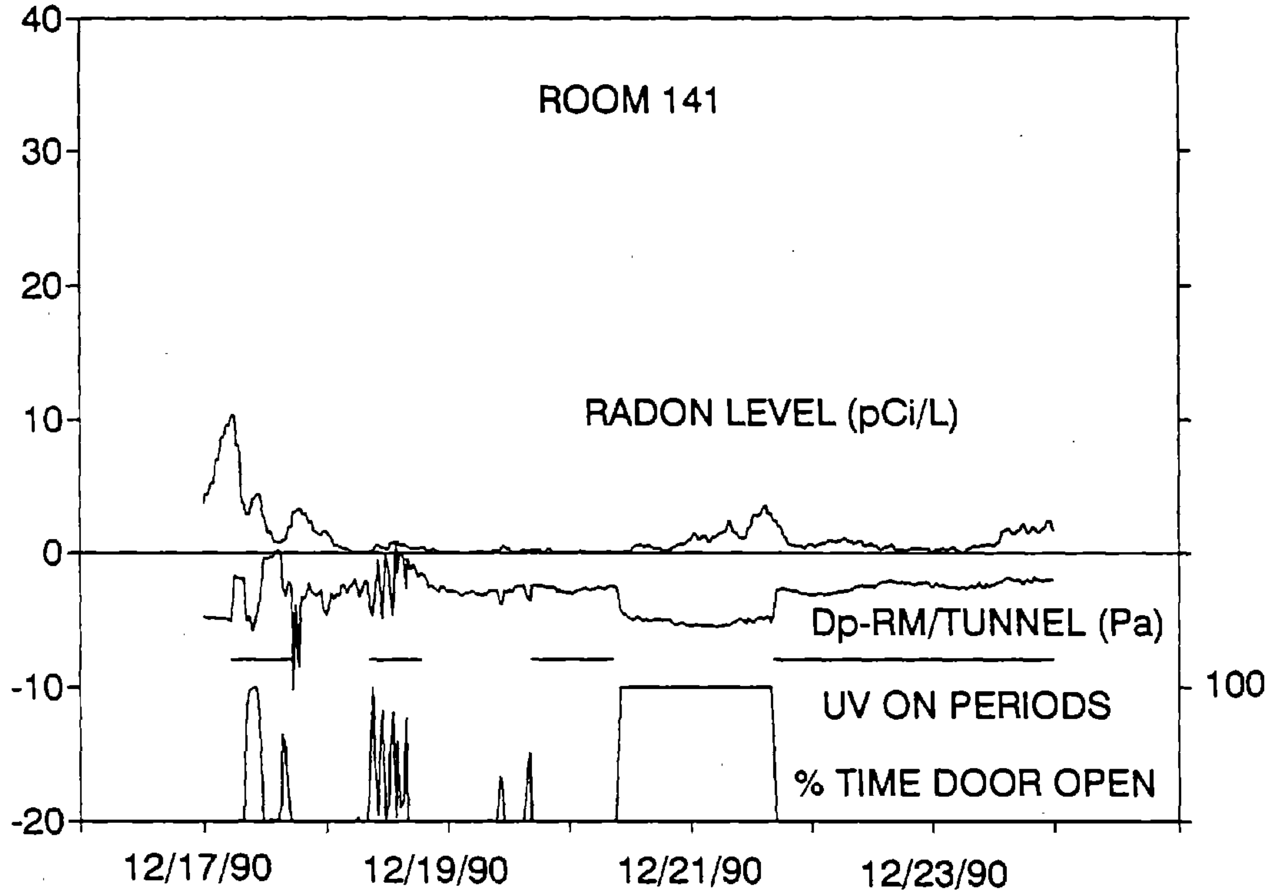


Figure 10.1.27 Summary of the data measured in Room 141 over the period of December 17, 1990 through December 23, 1990.

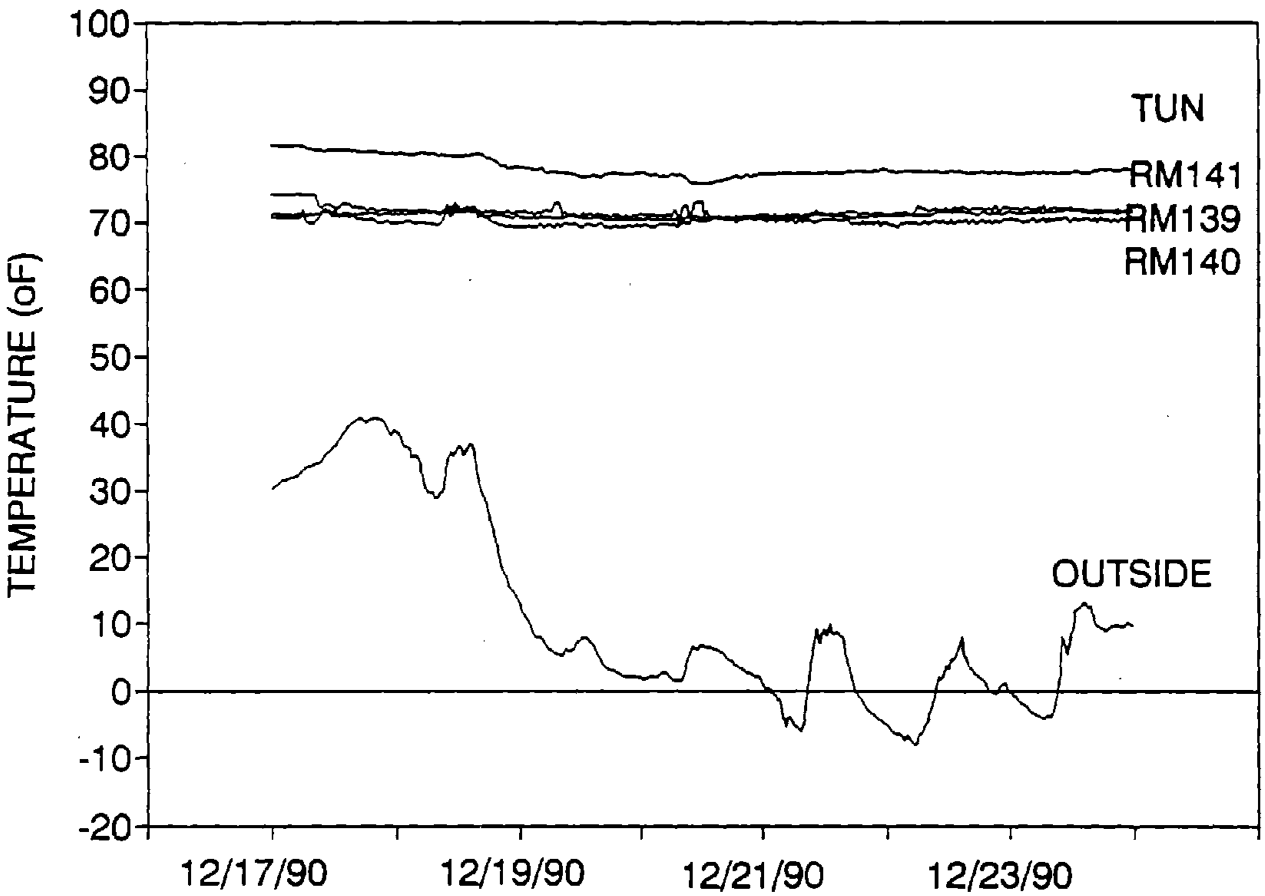


Figure 10.1.28. Summary of the temperature data measured in the classrooms over the period December 17, 1990 through December 23, 1990.

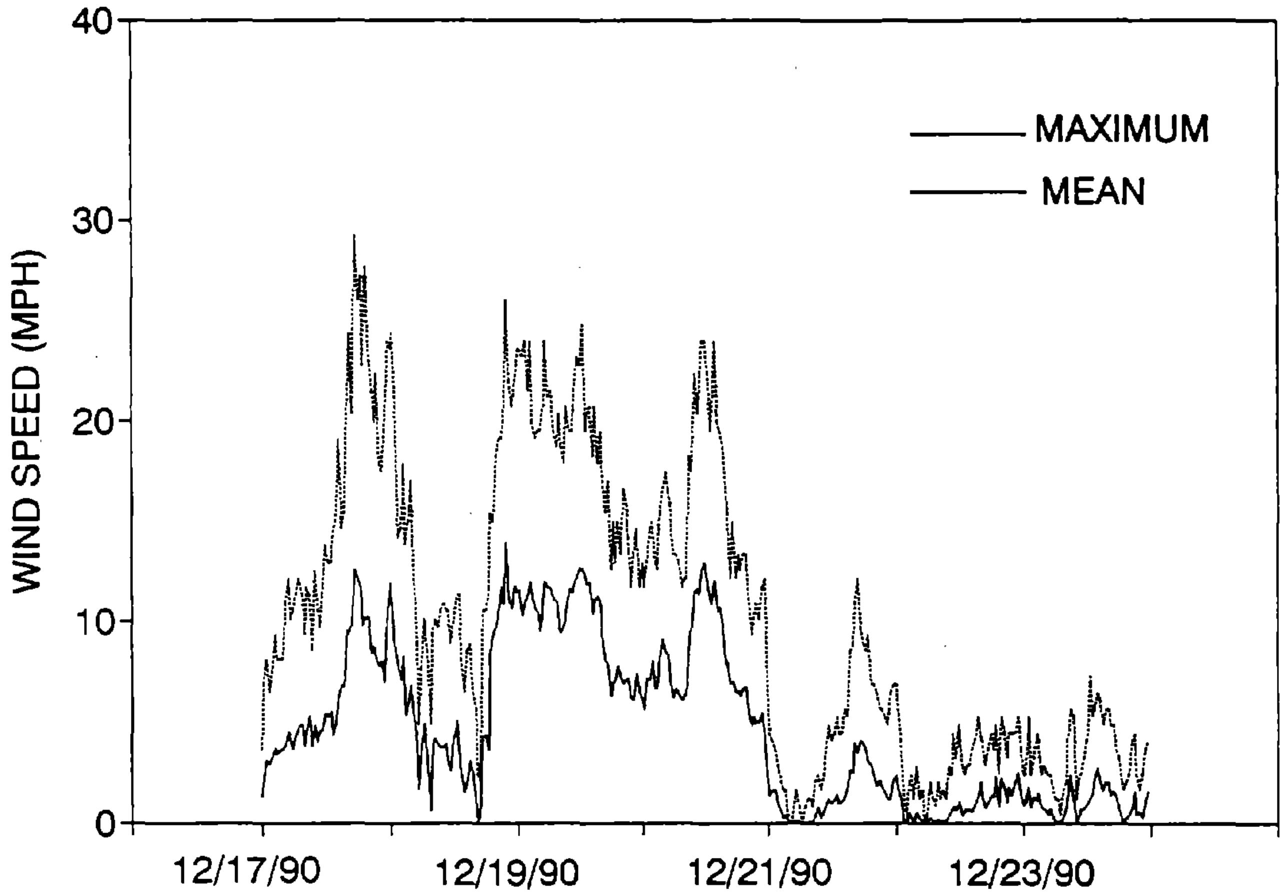


Figure 10.1.29. Summary of the wind data measured over the period December 17, 1990 through December 23, 1990.

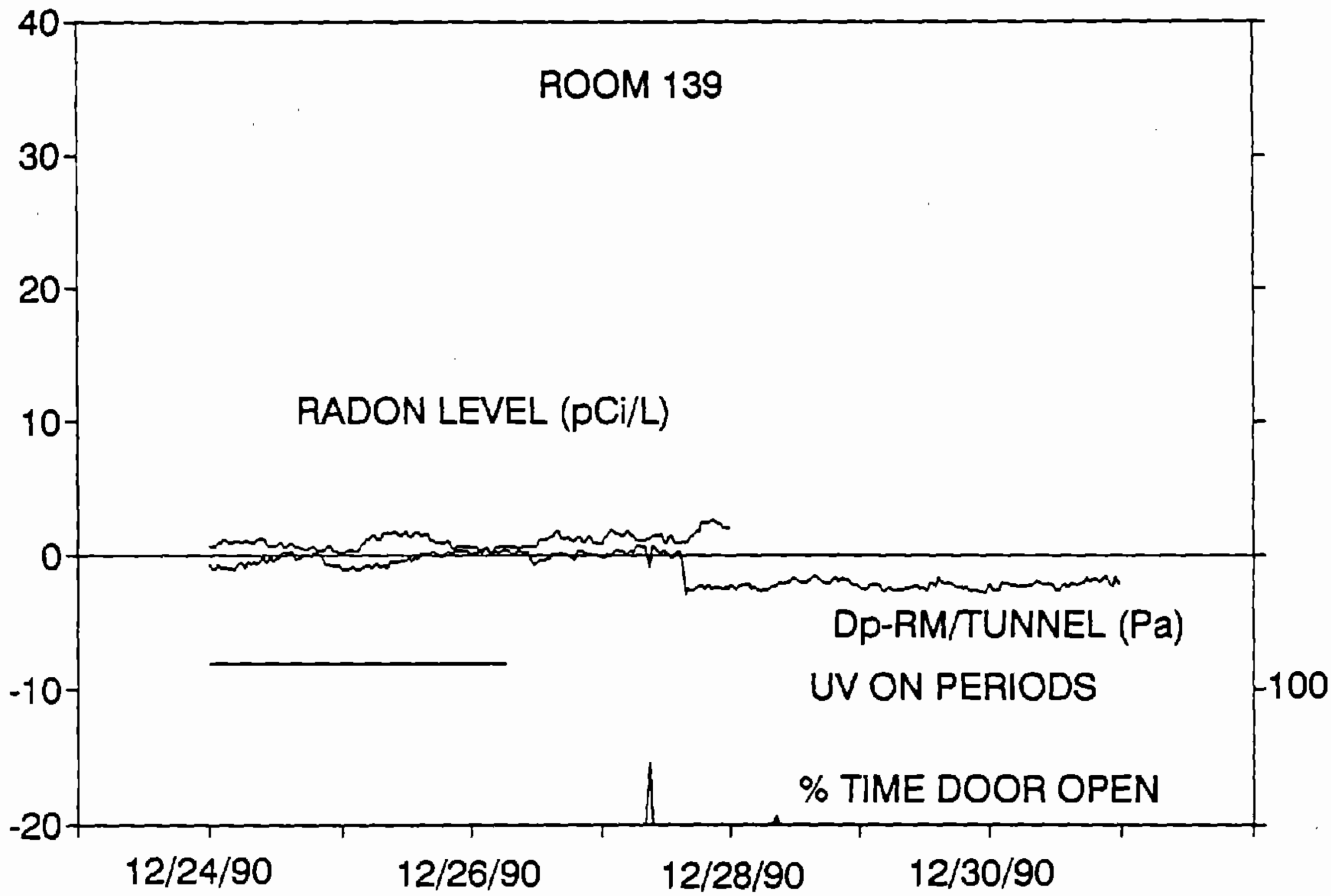


Figure 10.1.30. Summary of the data measured in Room 139 over the period December 24, 1990 through December 30, 1990.

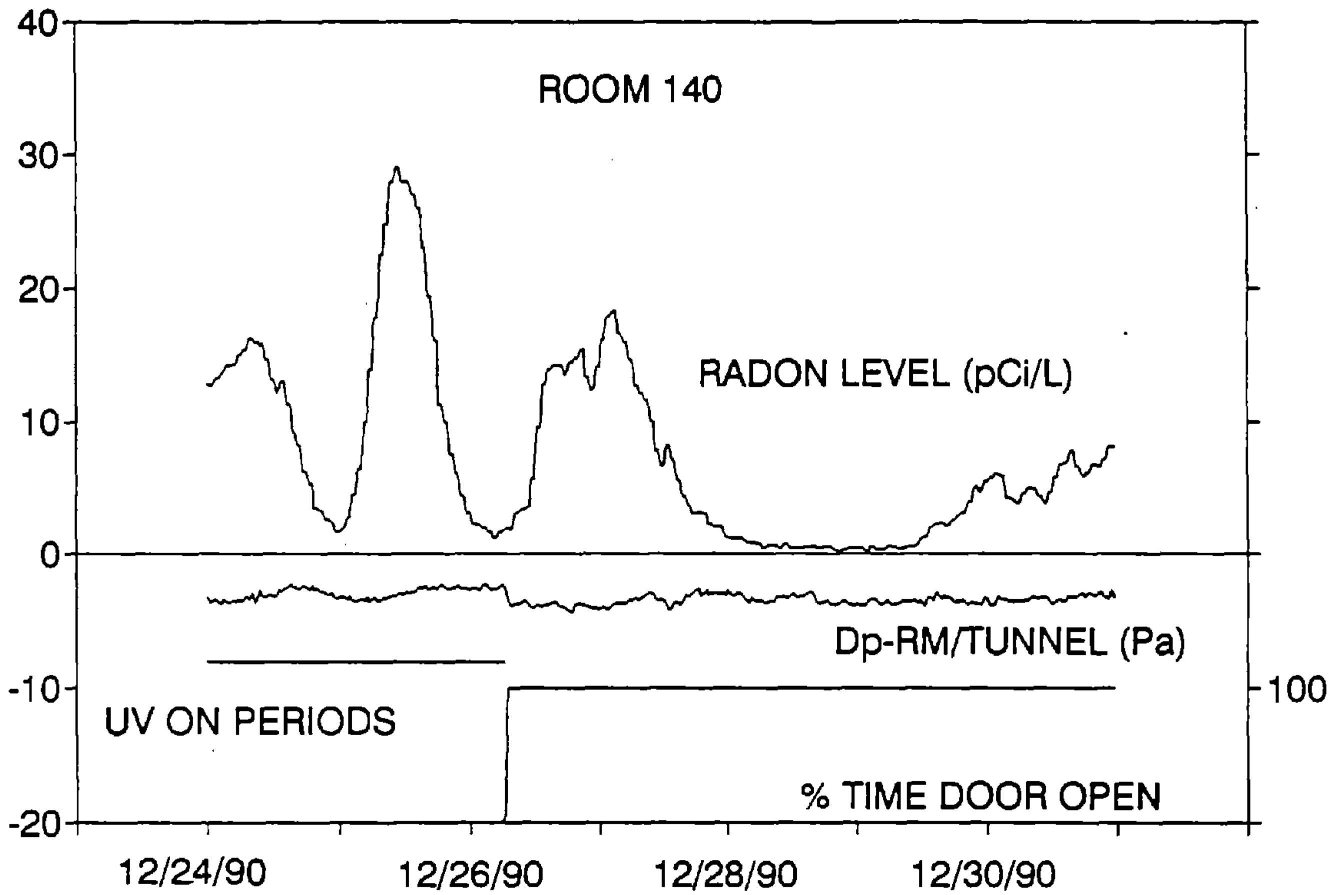


Figure 10.1.31. Summary of the data measured in Room 140 over the period December 24, 1990 through December 30, 1990.

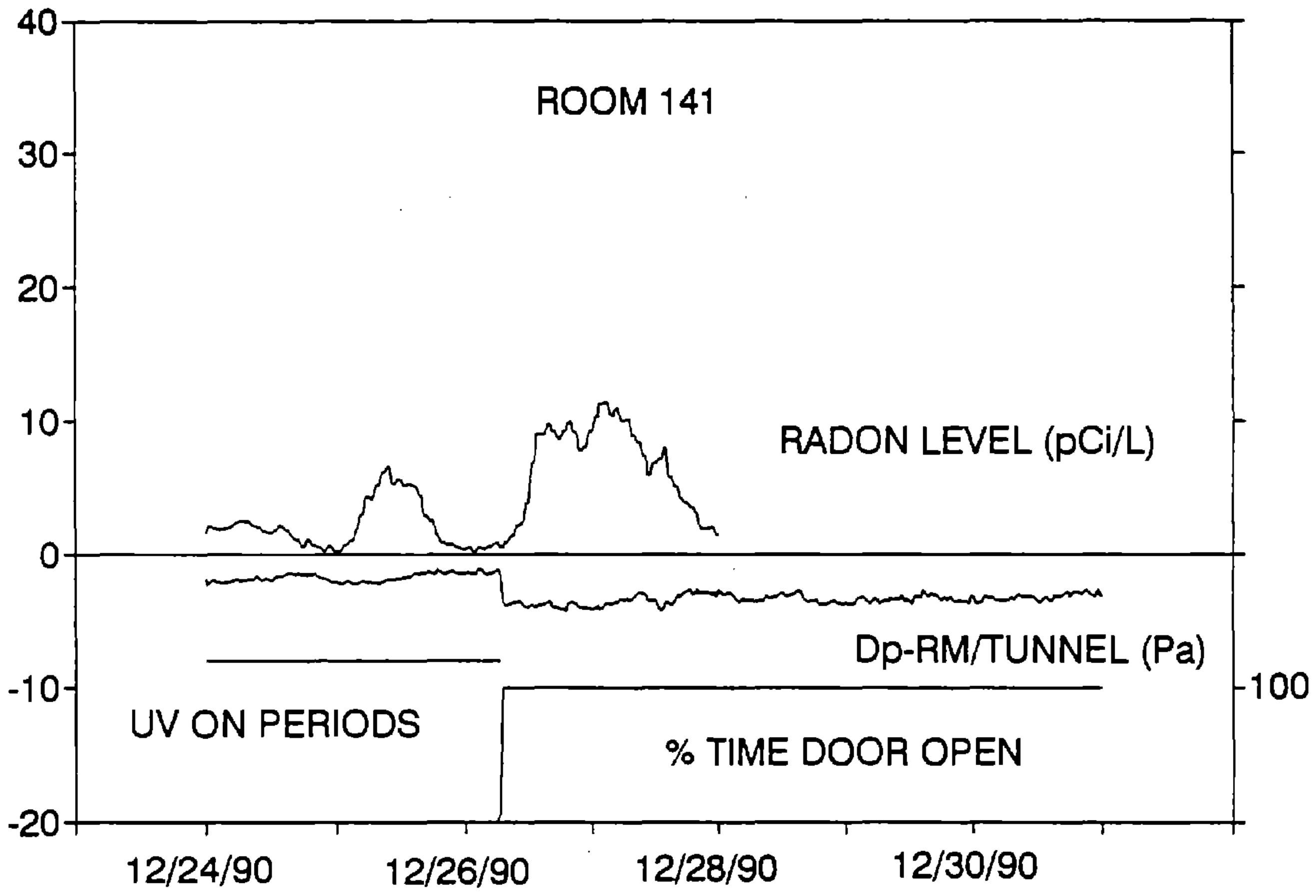


Figure 10.1.32 Summary of the data measured in Room 141 over the period of December 24, 1990 through December 30, 1990.

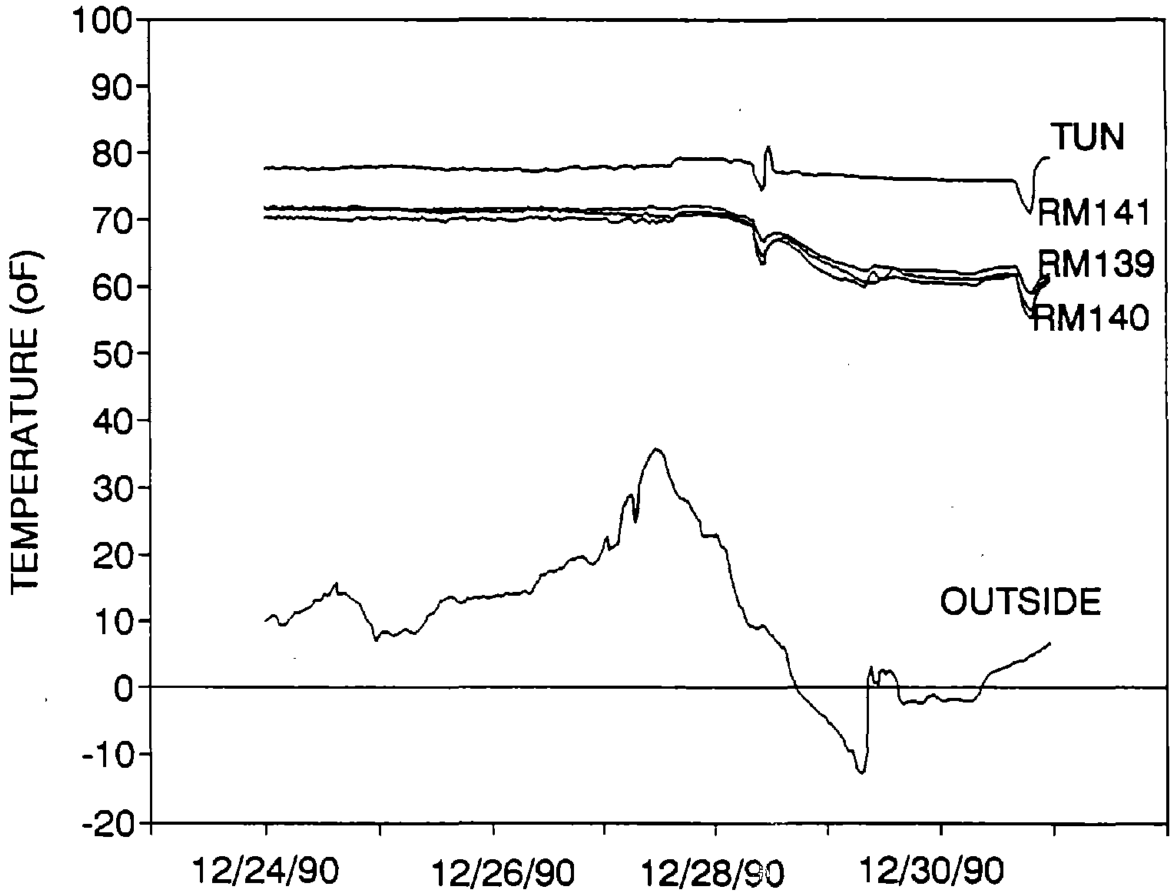


Figure 10.1.33. Summary of the temperature data measured in the classrooms and outside over the period December 24, 1990 through December 30, 1990.

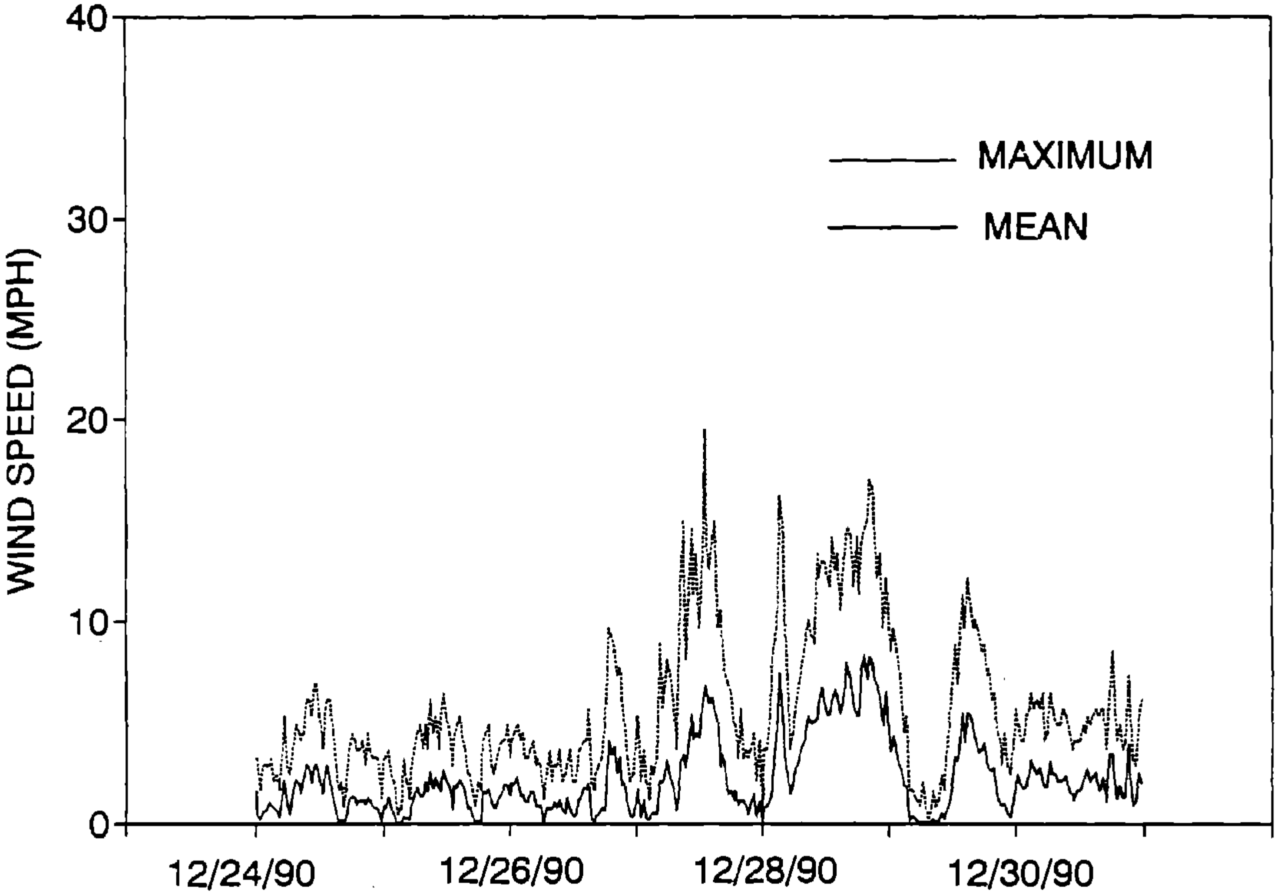


Figure 10.1.34. Summary of the wind data measured over the period December 24, 1990 through December 30, 1990.

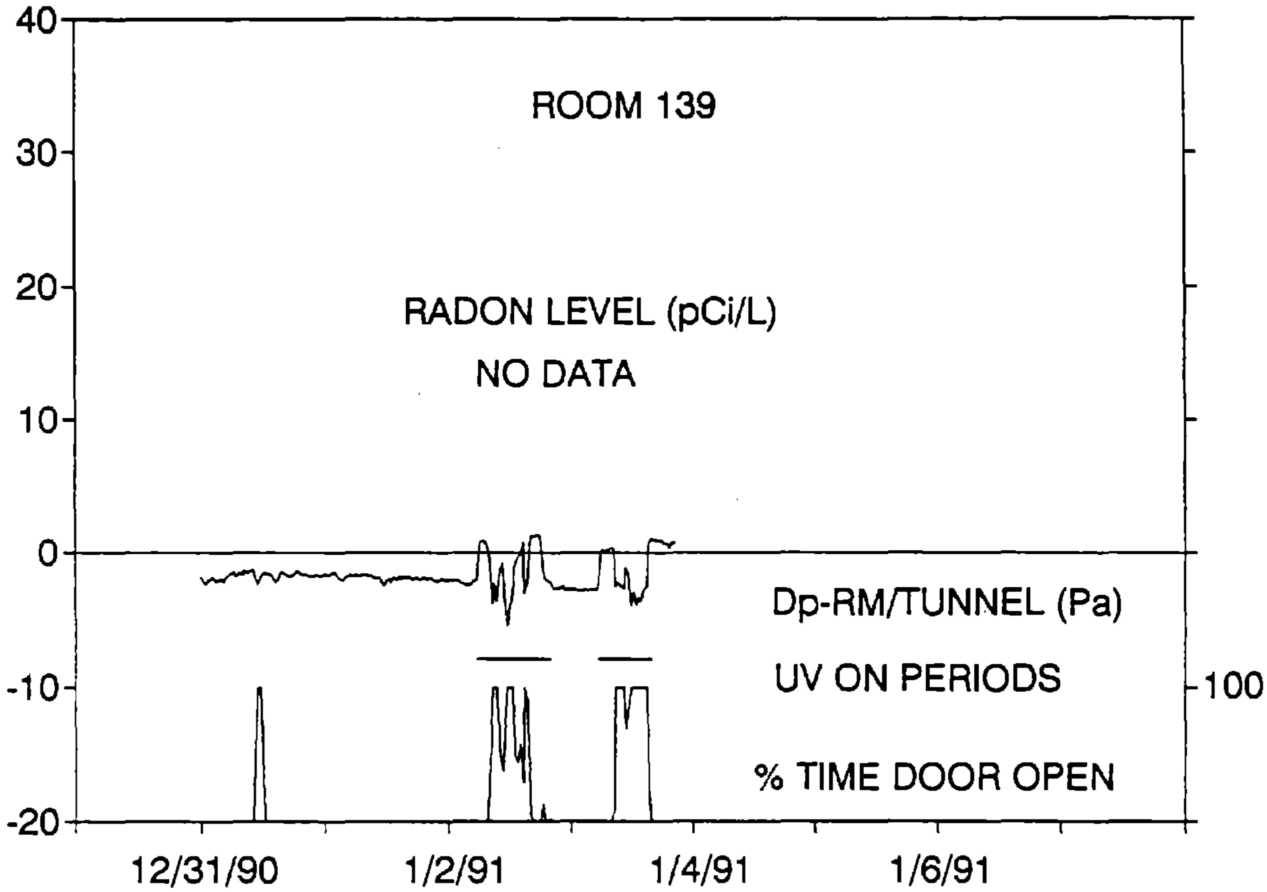


Figure 10.1.35. Summary of the data measured in Room 139 over the period December 31, 1990 through January 4, 1991.

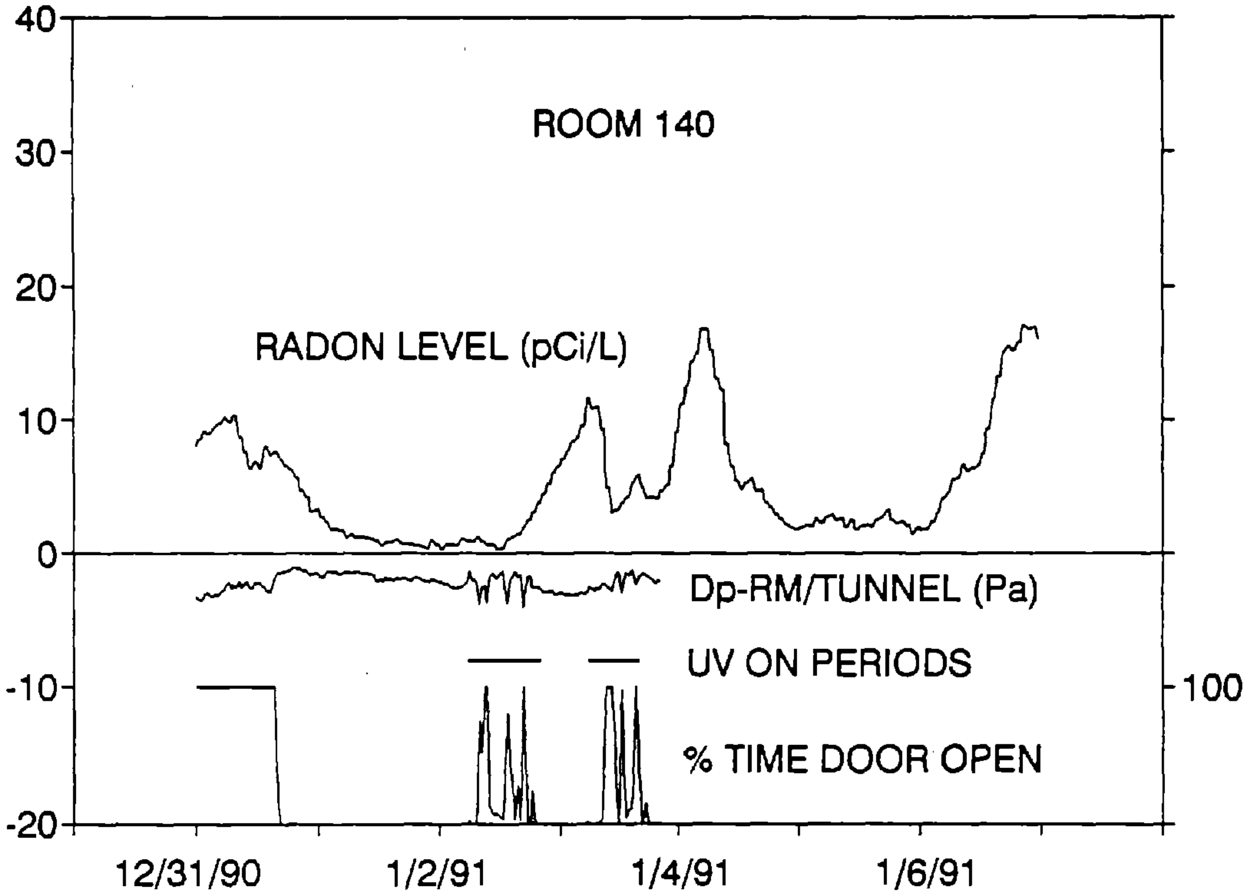


Figure 10.1.36. Summary of the data measured in Room 140 over the period December 31, 1990 through January 4, 1991.

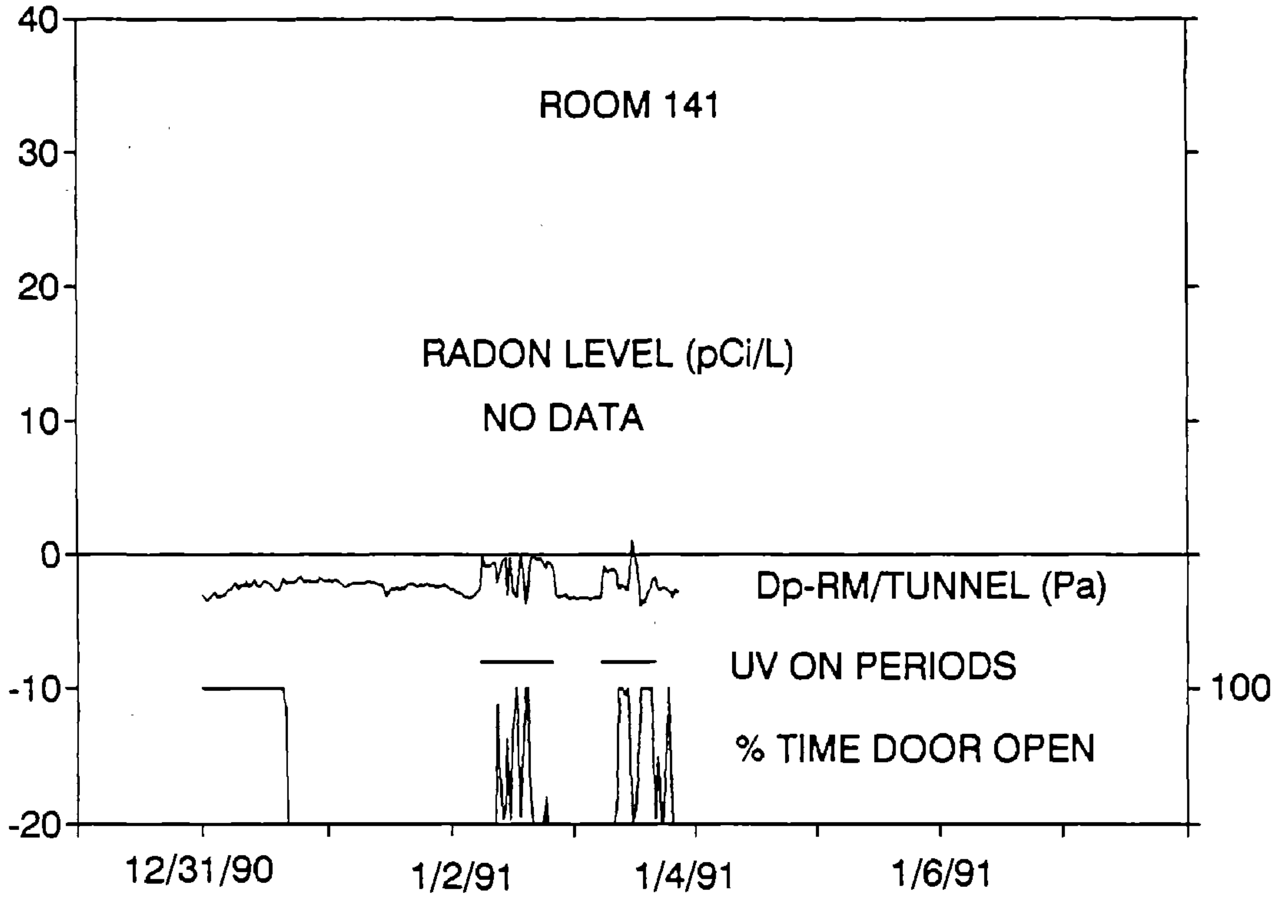


Figure 10.1.37. Summary of the data measured in Room 141 over the period December 31, 1990 through January 4, 1991.

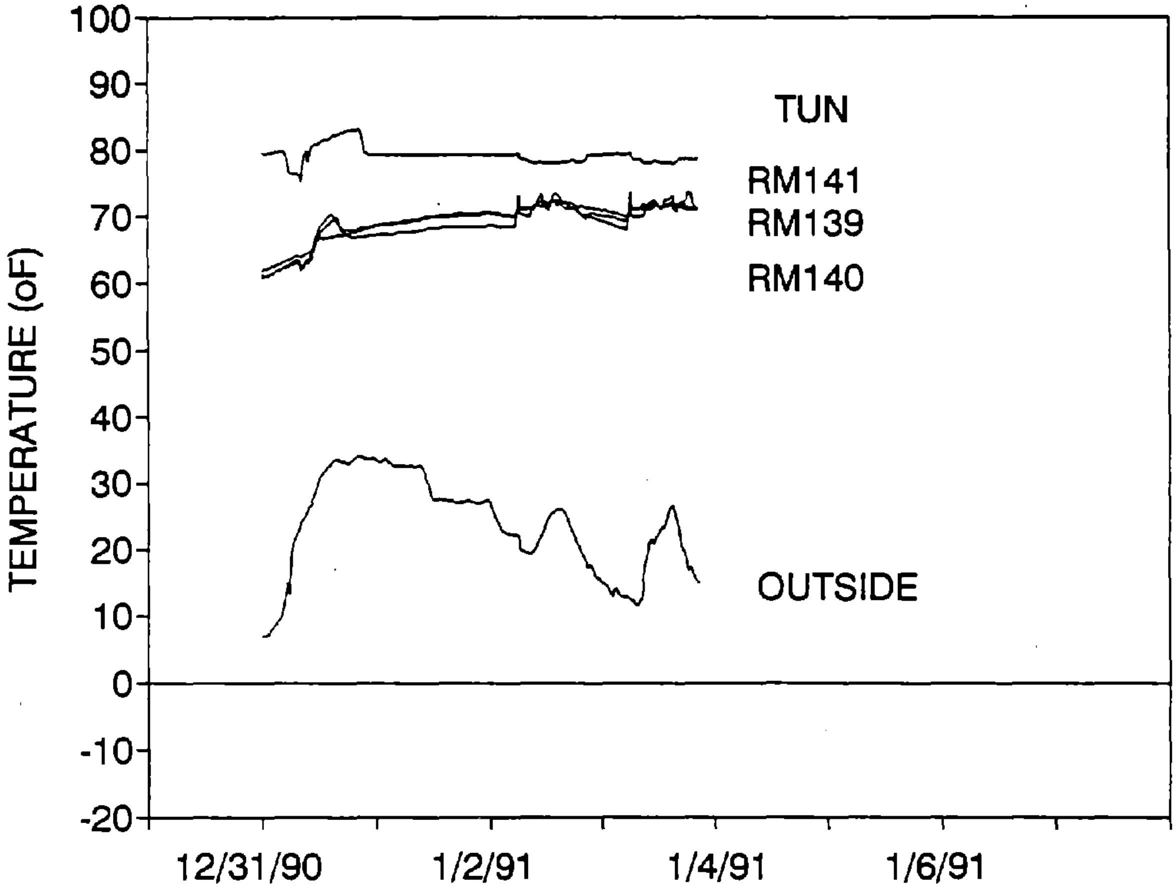


Figure 10.1.38. Summary of the temperature data measured in the classrooms and outside over the period December 31, 1990 through January 4, 1991.

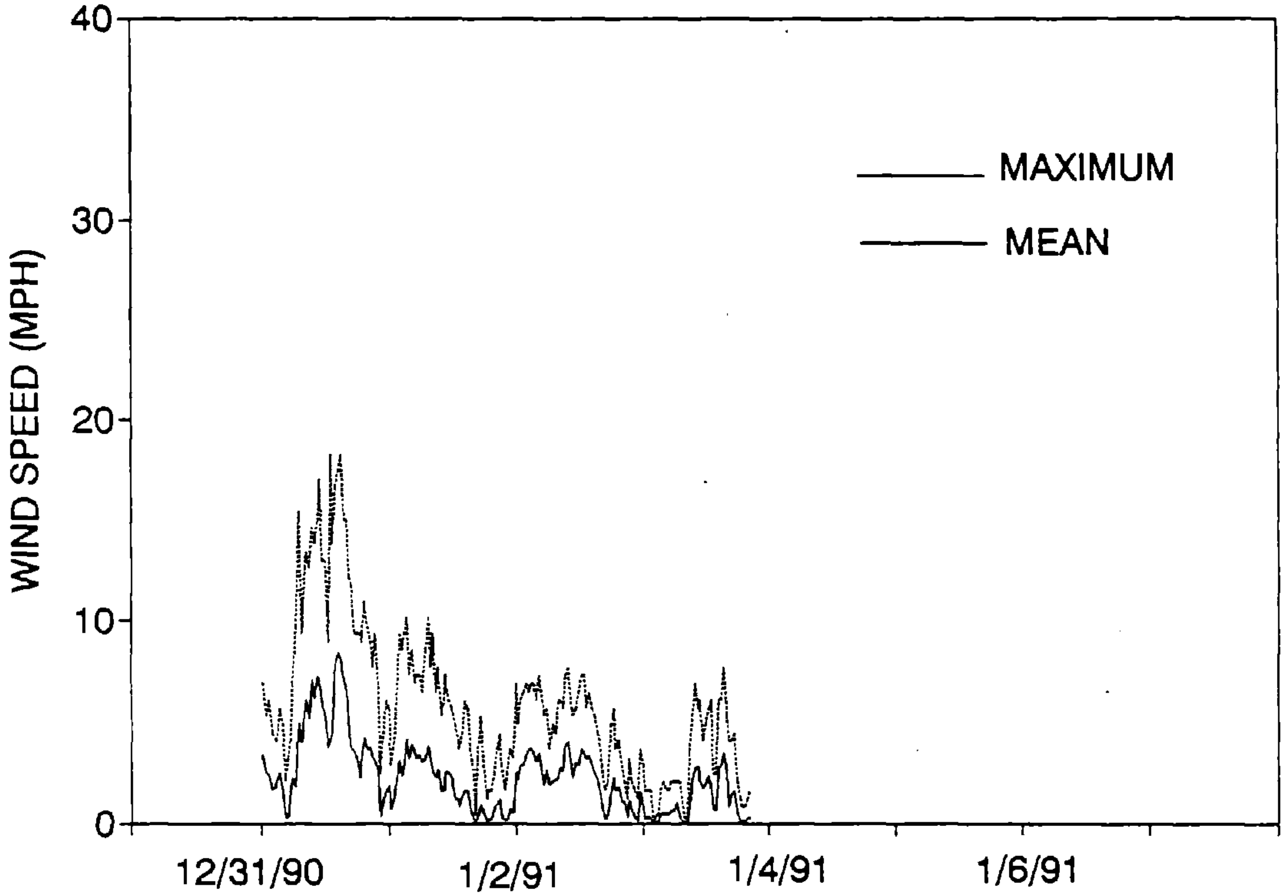


Figure 10.1.39. Summary of the wind data measured over the period December 31, 1990 through January 4, 1991.

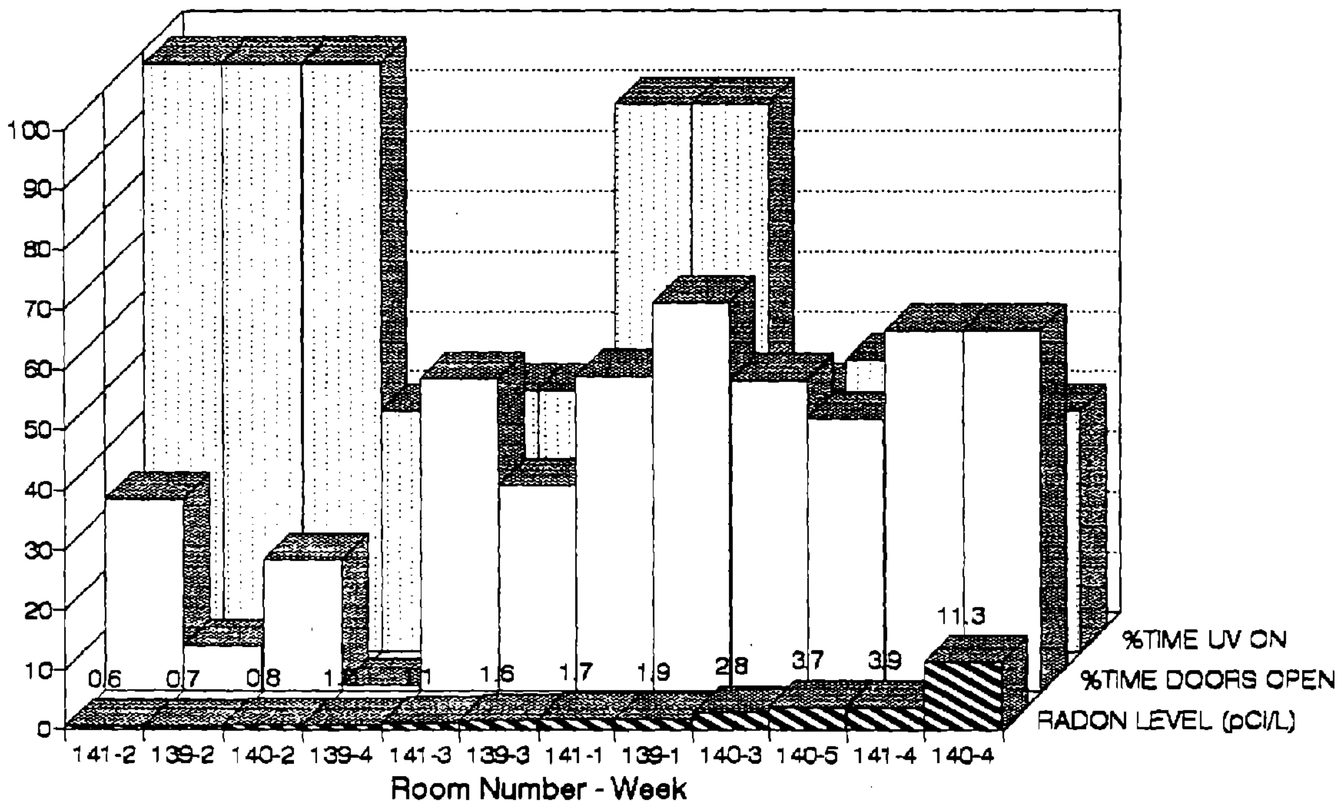


Figure 10.1.40. Correlation of the 8 hour averages of % time UV's on and % time doors open with radon levels averaged over same time period.

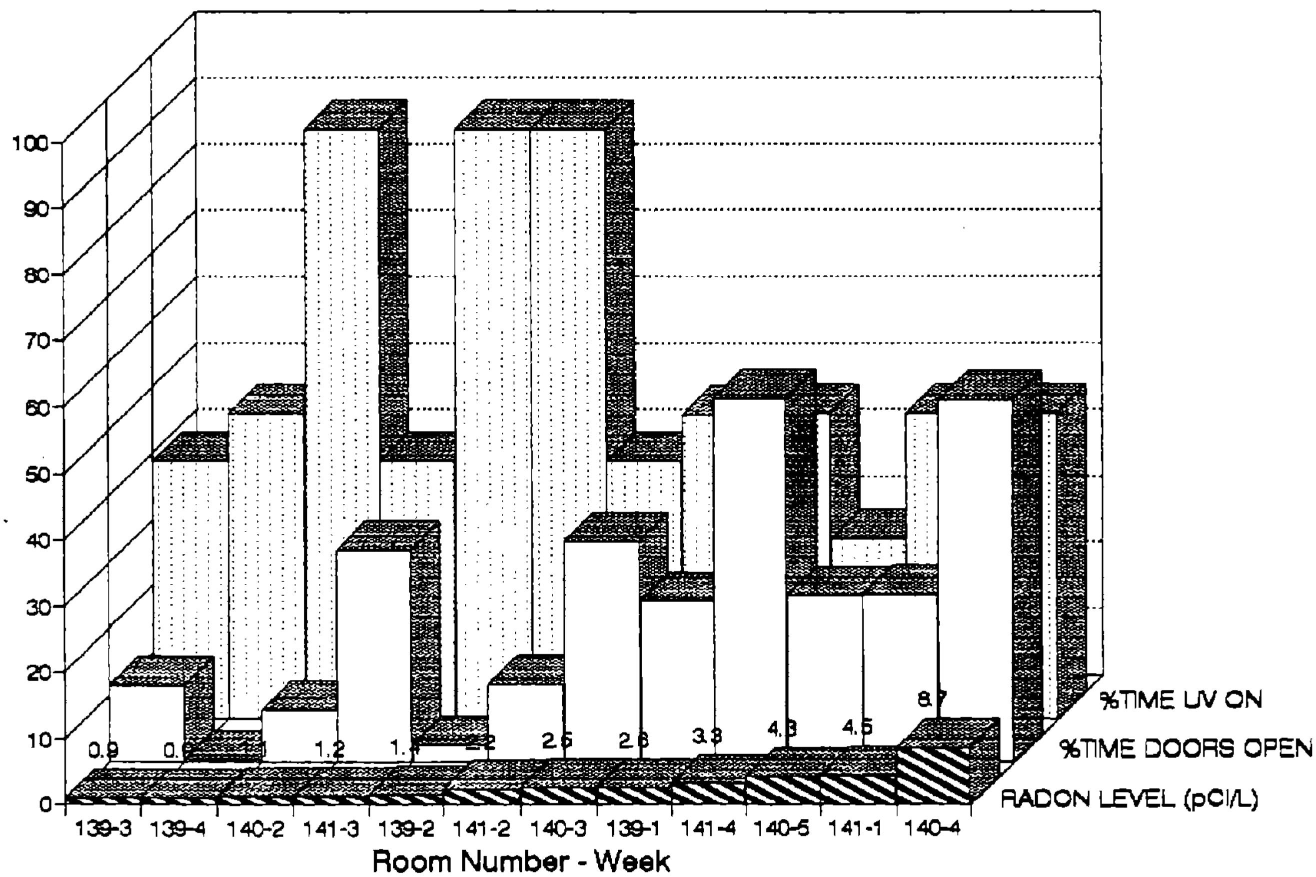


Figure 10.1.41. Correlation of the 24 hour averages of % time UV's on and % time doors open with radon levels averaged over same time period.

APPENDIX B

TABLES

Table 4.1.1 Radon Concentrations Measured at Barton Elementary School, Ft. Collins, CO.

Room #	Meas #	January Screening Date	January Screening Level (pCi/L)	January Screening Type Det.	February Follow up Date	February Follow up Level (pCi/L)	February Follow up Type Det.	Post-Mitigation Follow up Date	Post-Mitigation Follow up Level (pCi/L)	Post-Mitigation Follow up Type Det.
Media Rm	1	01/15/90	7.0	EP	02/14/90	8.3	EP	12/23/91	3.4	EP
Media Rm Dup	2	•	7.3	•						
Work Rm	3	•	6.9	•	•	8.8	EP	•	2.9	•
4	4	•	7.2	•	•	7.1	•	•	2.9	•
3	5	•	6.9	•	•	8.2	•	•	3.0	•
2	6	•	6.0	•	•	7.5	•	•	3.0	•
5	7	•	7.0	•	•	7.6	•	•	3.2	•
1	8	•	5.5	•	•	7.7	•	•	3.0	•
Office #6	9	•	7.2	•						
Kindergarten	10	•	6.8	•	•	7.2	•	•	3.0	•
Kindergarten Dup	11	•	7.0	•						
Kitchen	12	•	4.8	•	•	6.1	•			
Kitchen Dup	13	•	5.1	•						
Gym	14	•	6.2	•	•	6.1	•	•	2.8	•
Gym	15	•	6.1	•	•	6.8	•	•	3.1	•
Nurse	16	•	6.4	•	•	10.3	•			
Teacher Aides	17	•	5.5	•	•	6.7	•			
6	18	•	7.0	•	•	8.3	•	•	2.7	•
7	19	•	6.0	•	•	7.7	•	•	2.7	•
8	20	•	7.1	•	•	7.9	•	•	2.7	•
9	21	•	6.8	•	•	9.0	•	•	2.9	•
10	22	•	5.0	•	•	8.5	•	•	2.9	•
11	23	•	6.8	•	•	7.9	•	•	2.7	•
12	24	•	6.1	•	•	7.6	•	•	3.0	•
Lounge	25	•	6.6	•	•	8.2	•	•	2.8	•
Main Off.	26	•	12.3	•	•	6.9	•	•	3.2	•
Principal	27	•	6.0	•	•	6.3	•	•	2.6	•
Principal Dup	28	•	6.3	•						
Coach Off	29	•	5.6	•	•	5.9	•			
Art Teach Off	30	•	6.1	•						
Nusic Rm #6	31				•	8.4	•	•	3.4	•
	Average		6.56			7.63			2.95	
	Minimum		4.84			5.86			2.60	
	Maximum		12.33			10.25			3.40	

Table 4.1.2 Subslab Communication Test Results at Barton Elementary School, Ft. Collins, CO.

Δp Suction Point Fa (in.W.C)	Suction Pt. Flowrate (cfm)	Δp Test Point Fb (1 ft from Fa) (in.W.C)	Δp Test Point Fc (11 ft from Fa) (in.W.C)	Δp Test Point Fd (22 ft from Fa) (in.W.C)
0.00	0.0	0.000	-0.001	-0.000
-0.75	28.	-0.095	-0.012	-0.002
-1.10	100.	-0.120	-0.014	-0.002
-1.60	>100.	-0.165	-0.019	-0.002
-2.60	>100.	-0.219	-0.024	-0.002

Table 4.2.1 Radon Concentrations Measured at Platteville Elementary School, Platteville, CO.

Room #	Meas #	March Screening Date (3day)	March Screening Level (pCi/L)	Type Det.	August Follow up Date (3day)	August Follow up Level (pCi/L)	Type Det.	1990 Alpha Track Date (3mo)	1990 Alpha Track Level (pCi/L)	Type Det.	Dec 90 HVAC On Date (3day)	Dec 90 HVAC On Level (pCi/L)	Type Det.	Dec 90 HVAC Off Date (3day)	Dec 90 HVAC Off Level (pCi/L)	Type Det.	Percent Increase w/HVAC On	March 91 Follow-up Date (3day)	March 91 Follow-up Level (pCi/L)	Type Det.
Inst Support	1	03/08/90	11.1	CC	08/08/90	1.9	CC	09/12/90	4.0	ATD	12/24/90	6.3	CC	12/28/90	7.9	CC	−20.3	03/15/91	6.6	CC
Classroom	2	•	5.3	•	•	2.8	•				•	6.7	•	•	0.5	•		•	4.7	•
Classroom	3	•	6.2	•	•	2.8	•				•	8.4	•	•	5.4	•	55.6	•	6.3	•
Classroom	4	•	5.6	•	•	3.4	•				•	8.5	•	•	4.6	•	84.8	•	4.9	•
Kindergarten	5	•	9.3	•	•	1.5	•	•	3.0	•	•	7.7	•	•	3.7	•	108.1	•	6.9	•
Kindergarten	6	•	9.5	•	•	1.7	•	•	3.5	•	•	8.6	•	•	3.5	•	145.7	•	6.9	•
Classroom	7	•	4.9	•	•	1.4	•				•	8.3	•	•	3.3	•	151.5	•	6.4	•
Classroom	8	•	7.7	•	•	1.4	•	•	4.0	•	•	7.4	•	•	3.1	•	138.7	•	6.6	•
Classroom	9	•	4.3	•	•	1.5	•	•	4.2	•	•	8.2	•	•	3.8	•	115.8	•	5.6	•
Inst Support	10	•	10.0	•	•	1.5	•				•	9.8	•	•	3.9	•	151.3	•	7.5	•
Classroom	11	•	7.5	•	•	1.4	•	•	4.4	•	•	7.6	•	•	3.4	•	123.5	•	6.5	•
Inst Support	12	•	6.1	•	•	1.6	•				•	6.8	•	•	3.0	•	126.7	•	5.8	•
Inst Support	13	•	5.8	•	•	1.7	•				•	6.5	•	•	3.5	•	85.7	•	5.7	•
Inst Support	14	•	6.8	•	•	1.8	•				•	7.5	•	•	3.4	•	120.6	•	2.7	•
Classroom	15	•	5.2	•	•	2.2	•				•	5.4	•	•	4.5	•	20.0	•	4.4	•
Classroom	16	•	3.0	•	•	1.7	•				•	3.4	•	•	2.5	•	36.0	•	2.5	•
Classroom	17	•	10.3	•	•	2.6	•	•	2.6	•	•	5.6	•	•	4.9	•	14.3	•	4.2	•
Classroom	18	•	10.3	•	•	2.2	•	•	3.1	•	•	8.4	•	•	5.3	•	58.5	•	3.2	•
Classroom	19	•	9.5	•	•	3.8	•	•	4.1	•	•	10.2	•	•	7.1	•	43.7	•	5.5	•
Classroom	20	•	6.0	•	•	2.1	•				•	7.8	•	•	6.1	•	27.9	•	4.6	•
Inst Support	21	•	0.5	•	•	1.1	•				•	1.5	•	•	1.1	•	36.4	•	1.4	•
Inst Support	22	•	1.2	•	•	0.9	•				•	1.8	•	•	1.3	•	38.5	•	1.7	•
Inst Support	23	•	2.2	•	•	1.2	•				•	1.7	•	•	1.7	•	0.0	•	1.4	•
Inst Support	24	•	2.1	•	•	1.1	•				•	1.7	•	•	1.2	•	41.7	•	1.4	•
Office	25	•	6.7	•	•	1.2	•				•	5.6	•	•	4.2	•	33.3	•	4.6	•
Office	26	•		•	•	1.1	•				•	10.8	•	•	10.0	•	8.0	•	7.0	•
Office	27	•	5.2	•	•	1.0	•				•	2.0	•	•	2.8	•	−28.6	•	1.4	•
Kitchen	28	•	5.8	•	•	1.0	•				•	2.1	•	•	1.7	•	23.5	•	1.6	•
Gym	29	•	7.4	•	•	1.2	•	•	4.1	•	•	6.4	•	•	4.0	•	60.0	•	5.2	•
	Average		6.3			1.8			3.7			6.3			3.8		64.3		4.6	
	Minimum		0.5			0.9			2.6			1.5			0.5		−28.6		1.4	
	Maximum		11.1			3.8			4.4			10.8			10.0		151.5		7.5	

Table 4.2.2 Pressure Field Extensions Measured During Diagnostic Tests at Platteville Elementary School, Platteville, CO.

	Suction Point #1	Test Point Location			Suction Point #2	Test Point Location		
	Fa Rm 16	Fb	Fc	Fd	Fa Rm 13	Fb	Fc	Fd
Distance (ft)	0.06	1	30	60	0.06	1	25	30
Dp (in.W.G)	10.0	0.500	0.005	0.000	27.0	1.200	0.002	0.000
	15.0	0.798	0.008	0.000	37.0	1.530	0.003	0.000
	20.0	1.024	0.010	0.000	44.0	1.750	0.002	0.000
	25.0	1.345	0.012	0.000				

Table 6.1.1. Test matrix for Nokomis Elementary, St. Paul, MN.

Test Number	UV (On/Off)	UV OA (%)	AHU (On/Off)	AHU OA (%)	ASD (On/Off)	Comments
1	On	Normal	On	Normal	On	
2	Off	Normal	Off	Normal	Off	
3	On	0	On	0	Off	
3A	On	0	On	0	Off	Filters Out
4	On	10	On	10	Off	
5	On	50	On	50	Off	
6	On	Normal	On	Normal	Off	
7	On	Normal	On	Normal	On	
8	On	Normal	On	Normal	On	Two Weeks Later

Table 6.1.2. Actual outdoor air flow (cfm) versus damper position for unit ventilators and AHU unit in Nokomis Elementary, St.Paul, MN.

Room	OA Damper Percent Open (%)	Total Unit Flow (cfm)	OA Flow (cfm)	Percent OA (%)
106 (UV)	0	900	0	0
	10	990	265	27
	50	1020	320	31
	100	950	358	38
107 (UV)	0	926	0	0
	10	1109	420	38
	50	1050	650	62
	100	1009	660	65
108 (UV)	0	1050	0	0
	10	1190	400	34
	50	1200	513	43
	100	1205	642	53
Office	0	2025	0	0
(AHU)	10	2160	420	19
	50	2280	500	22
	100	1960	1100	56

Table 7.1.1 Radon Concentrations Measured at Oakmont Elementary School, Columbus, OH.

Room #	Meas #	Winter(1990–91) Date	Level (pCi/L)	Type Det.	Screening(HVAC Off) Date	Level (pCi/L)	Type Det.	Subslab Source Strengths Date	Level (pCi/L)	Type Det.
6	1		15.4	EP	03/22/91	4.3	CC			
8	2		16.6	EP	03/22/91	5.3	CC	03/05/91	450	SSS
10	3		20.5	EP	03/22/91	6.3	CC	03/05/91	350	SSS
12	4		19.5	EP	03/22/91	7.2	CC	03/05/91	200	SSS
11	5		19.9	EP	03/22/91	7.2	CC			
9	6		17.2	EP	03/22/91	5.9	CC	03/05/91	100	SSS
7	7		15.5	EP	03/22/91	4.7	CC			
5	8		12.3	EP	03/22/91	4.7	CC	03/05/91	100	SSS
Office	9		11.3	EP	03/22/91	4.5	CC			
Boiler R	10		3.8	EP	03/22/91	2.6	CC			
3	11		11.1	EP	03/22/91	4.6	CC			
1	12		12.4	EP	03/22/91	4.9	CC			
2	13		11.2	EP	03/22/91	5.3	CC			
4	14		11.6	EP	03/22/91	5.8	CC			
H'Room	15				03/22/91	4.7	CC			
T'Lng	16		11.8	EP	03/22/91	4.7	CC			
G'Bath	17		10.3	EP	03/22/91	5.5	CC			
B'Bath	18		10.7	EP	03/22/91	4.0	CC			
19	19		5.4	EP	03/22/91	<0.5	CC			
20	20		4.5	EP	03/22/91	<0.5	CC			
21	21		3.7	EP	03/22/91	<0.5	CC			
22	22		5.9	EP	03/22/91	<0.5	CC			
23	23		5.7	EP	03/22/91	5.5	CC			
24	24		6.7	EP	03/22/91	<0.5	CC			
25	25		6.8	EP	03/22/91	<0.5	CC			
Gym	26		10.9	EP						
K'chen	27		10.9	EP	03/22/91	5	CC			
Counlser	28		10.2	EP	03/22/91	5.6	CC			
29	29		9.9	EP	03/22/91	6.4	CC			
W'Tunnel	30				03/22/91	5.3	CC	03/05/91	500	SSS
E'Tunnel	31				03/22/91	8.4	CC	03/05/91	730	SSS
C'Tunnel	32				03/22/91	6.2	CC	03/05/91	750	SSS
	33				03/22/91	6.3	CC			
	34				03/22/91	6.1	CC			
Averages =			11.1			4.5			398	
Highest Value =			20.5			8.4			750	

Notes: EP = E–perms
CC = charcoal canister
SSS = subslab sniff

Table 7.1.2. Fan coil unit flows at Oakmont Elementary, Columbus, OH.

Room Served by FCUs	Measured Airflow (cfm)	Design Airflow (cfm)
1	868 & 601	1700
2	705 & 816	1700
3	1305	1200
4	1260	1200
5	1170	1200
6	1435	1200
7	1407	1200
8	1335	1200
9	1192	1200
10	1210	1200
11	1269	1200
12	1318	1200
Multipurpose Room	3645	4000
Stage	839	1000
Teacher's Lounge	541	450
Music Room	568	700
Principal's Office	345	350
Supply Room	361	300
Conference Room	309	300
Office	476	350
Nurse's Office	308	200
TOTALS	23,283	23,050

Table 7.1.3 Data logger parameters measured at Oakmont Elementary School, Columbus, OH.

RADON LEVELS MEASURED WITH A FEMTOTECH:

Room 6
Room 7
Room 8
Room 10
Room 12
Teachers Lounge
East Tunnel
West Tunnel

PRESSURE DIFFERENTIALS MEASURED BETWEEN:

Room 8 and Tunnel(Central)
Room 8 Subslab and Tunnel (Central)
Supply Air to Room 8 and Tunnel (Central)
East Tunnel to Tunnel (Central)
Return Air Walkway to Tunnel (Central)
Tunnel Subslab to Tunnel (Central)
Outside Building to Tunnel (Central)

TEMPERATURES:

Room 8
Supply Room 8
Return Air
Air Mixing Chamber
Subslab in Tunnel
Outside Building

MISCELLANEOUS:

Wind Direction
Wind Speed
Ambient RH
Rainfall
Return Air Damper Position
Outside Air Damper Position

Table 7.1.4. Test Matrix for Oakmont Elementary School, Columbus, OH (HVAC operated only part of day).

Test No.	Duration	HVAC System Operation (hours)	Return Air (%)	Outdoor Air (%)
I	1 week	6:30 am - 4:30 pm	100	0
II	1 week	6:30 am - 4:30 pm	50	50
III	1 week	6:30 am - 4:30 pm	0	100

Notes: FCUs operate when HVAC system operates.
HVAC system hours of operation are approximate.

Table 7.3.1 PFE Measurements in Library Area at Fifth Avenue Elementary School, Columbus, OH.

Test Point	Approx. Distance to suction point (feet)	Subslab-to Room Baseline Pressure Differential at (in. WC)	Subslab-to Room Pressure Differential at 4 in. Vacuum on Suction at (in.WC)	Sub-slab Sniff pCi/L
b	1	0.000	-0.25	1600
c	66	0.002	0.001	100
d	50	0.001	0.000	200
e	41	0.002	0.000	na
f	71	0.002	0.002	2000
g	38	0.000 to 0.001	0.000 to 0.001	700

Table 7.3.2. PFE Measurements in Multi-Purpose Room at Fifth Avenue Elementary School.

Test Point	Approx. Distance to Suction Point (feet)	Subslab-to Room Baseline Pressure Differential at (in. WC)	Subslab-to Room Pressure Differential at 4 in.Vacuum on Suction at (In.WC)	Subslab Sniff (pCi/L)
h	65	0.000 to -0.001	-0.001 to -0.002	na
i	30	0.000 to -0.001	-0.000 to 0.002	na
j	1	na	na	100

Table 8.1.1 Radon Screening Measurements in the Rapid City Area School District, Rapid City, SD.

Site #	Room #	Detector #	Date Placed	Time Placed	Date Retrieved	Time Retrieved	Level (pCi/L)
Abraham Lincoln Elementary							
1	16	24587	11/07/90	07:31 PM	02/05/91	06:40 PM	36.7
2	11	24610	11/07/90	07:34 PM	02/05/91	06:42 PM	15.0
3	12	24612	11/07/90	07:36 PM	02/05/91	06:43 PM	20.4
4	4	24609	11/07/90	07:45 PM	02/05/91	06:49 PM	7.9
5	1 (Kndg)	22111	11/07/90	07:47 PM	02/05/91	06:48 PM	15.7
6	Boiler	24601	11/07/90	07:40 PM	02/05/91	06:44 PM	25.5
7	Prin Off	24611	11/07/90	07:42 PM	02/05/91	06:46 PM	10.4
Horace Mann Elementary							
1	Office	22139	11/05/90	06:24 PM	02/04/91	04:34 PM	3.9
2	15	17049	11/05/90	06:28 PM	02/04/91	04:38 PM	4.5
3	16	22155	11/05/90	06:31 PM	02/04/91	04:40 PM	5.6
4	7	22113	11/05/90	06:33 PM	02/04/91	04:35 PM	3.5
5	10	22148	11/05/90	06:36 PM	02/04/91	04:45 PM	6.2
6	17	24648	11/05/90	06:41 PM	02/04/91	04:46 PM	5.2
7	Mech.Rm	13442	11/05/90	06:43 PM	02/04/91	Missing	N/D
8	Kndg	22098	11/05/90	06:46 PM	02/04/91	04:48 PM	12.8
Annie Tallent Elementary							
1	16	24632	11/07/90	05:34 PM	02/05/91	05:02 PM	6.6
2	Boiler	24649	11/07/90	05:30 PM	02/05/91	05:05 PM	6.2
3	5	22151	11/07/90	05:27 PM	02/05/91	05:03 PM	5.7
Grandview Elementary							
1	12	22099	11/06/90	06:55 PM	02/05/91	04:33 PM	3.5
2	10	24617	11/06/90	06:53 PM	02/05/91	04:32 PM	3.8
3	8	24616	11/06/90	06:51 PM	02/05/91	04:31 PM	4.2
4	Health	22107	11/06/90	06:49 PM	02/05/91	04:28 PM	3.0
5	Kndg	24645	11/06/90	07:28 PM	02/05/91	04:25 PM	6.0
6	Boiler	24621	11/06/90	07:17 PM	02/05/91	04:20 PM	8.1
7	6	24635	11/06/90	07:30 PM	02/05/91	04:22 PM	5.6

(continued)

Table 8.1.1. Radon Screening Measurements in the Rapid City Area School District, Rapid City, SD. (continued)

Robbinsdale Elementary School

1	Boiler	N/D	N/D	N/D	N/D	N/D	17.7

E.B. Bergquist Elementary School

1	7	17076	11/06/90	05:48 PM	02/04/91	06:18 PM	1.1
2	6	24638	11/06/90	05:57 PM	02/04/91	06:26 PM	5.4
3	3	24631	11/06/90	05:45 PM	02/04/91	06:16 PM	5.2
4	12	24636	11/06/90	06:01 PM	02/04/91	06:29 PM	7.5
5	9	22029	11/06/90	05:59 PM	02/04/91	06:28 PM	2.1
6	Office	24628	11/06/90	05:37 PM	02/04/91	06:14 PM	7.0
7	A-3	22510	11/06/90	05:52 PM	02/04/91	06:21 PM	4.4
8	Kndg	24636	11/06/90	05:42 PM	02/04/91	06:32 PM	7.5

Valley View Elementary

1	3	24650	11/06/90	06:20 PM	02/04/91	06:44 PM	7.9
2	10	24646	11/06/90	06:23 PM	02/04/91	06:47 PM	12.7
3	Boiler	24640	11/06/90	06:25 PM	02/04/91	06:49 PM	10.6

Thomas Jefferson Elementary

1	1	24641	11/07/90	05:55 PM	02/05/91	05:30 PM	12.9
2	2	22132	11/07/90	05:49 PM	02/05/91	05:32 PM	Missing
3	4	24629	11/07/90	06:07 PM	02/05/91	05:35 PM	3.6
4	6	24634	11/07/90	05:52 PM	02/05/91	05:34 PM	3.9
5	9	22093	11/07/90	06:12 PM	02/05/91	05:17 PM	3.1
6	11	24647	11/07/90	06:17 PM	02/05/91	05:24 PM	3.3
7	16	22102	11/07/90	06:22 PM	02/05/91	05:28 PM	7.8
8	Lunch Rm	24643	11/07/90	06:10 PM	02/05/91	05:25 PM	2.6

Table 8.1.2 Radon concentrations measured at Abraham Lincoln Elementary School, Rapid City, SD.

Room #	Meas #	Winter(1990–91) Date	Level (pCi/L)	Type Det.	Screening(HVAC Off) Date	Level (pCi/L)	Type Det.	Screening(HVAC On) Date	Level (pCi/L)	Type Det.	Subslab Source Strengths Date	Level (pCi/L)	Type Det.
1	1	11/07/90	15.7	ATD	05/03/91	16.1	CC	05/17/91	3.2	CC			
2	2				05/03/91	6.9	CC	05/17/91	7.9	CC	07/30/91	2700	SSS
3	3				05/03/91	14.6	CC	05/17/91	6.0	CC			
4	4	11/07/90	7.9	ATD	05/03/91	6.6	CC	05/17/91	7.7	CC	07/30/91	1800	SSS
Office	5				05/03/91	8.5	CC	05/17/91	6.0	CC			
Gym	6				05/03/91	9.5	CC	05/17/91	5.1	CC			
P'Off	7	11/07/90	10.4	ATD	05/03/91	16.4	CC	05/17/91	9.3	CC			
T'Lng	8				05/03/91	8.5	CC	05/17/91	5.2	CC	07/30/91	4500	SSS
9	9				05/03/91	1.3	CC	05/17/91	2.4	CC			
B'Room	10	11/07/90	25.5	ATD	05/03/91	3.2	CC	05/17/91	11.2	CC			
11	11	11/07/90	15.0	ATD	05/03/91	15.8	CC	05/17/91	1.5	CC			
12	12	11/07/90	20.4	ATD				05/17/91	0.6	CC			
13	13				05/03/91	34.3	CC	05/17/91	12.2	CC			
14	14							05/17/91	4.7	CC	07/30/91	6600	SSS
H'Room	15				05/03/91	9.6	CC	05/17/91	3.8	CC			
16	16	11/07/90	36.7	ATD	05/03/91	35.9	CC	05/17/91	14.1	CC	07/30/91	5700	SSS
17–Lib	17				05/03/91	2.9	CC	05/17/91	3.5	CC			
18	18				05/03/91	1.5	CC	05/17/91	4.1	CC			
19	19				05/03/91	2.1	CC	05/17/91	2.2	CC			
20	20				05/03/91	1.9	CC	05/17/91	3.0	CC			
Averages =			18.8			10.9			5.7			4260	
Highest Value =			36.7			35.9			14.1			6600	

Notes: ATD = alpha track detector
CC = charcoal canister
SSS = subslab sniff

Table 8.1.3 Carbon Dioxide Levels Measured at Abraham Lincoln Elementary School.

Room #	Meas #	Date	Time Day	Corridor Door	Number Open Windows	Room Level (ppm)	UV Supply Level (ppm)	Comments
1	1	05/01/91	11:45 AM	Open	0	700	675	
2	2	05/01/91	11:45 AM	Closed	2	700	475	
3	3							
4	4	05/01/91	11:45 AM	Closed	0	1600	1500	
Office	5							
Gym	6	05/01/91	12:00 PM	Open	N/A	1400	N/A	
P'Off	7							
T'Lng	8							
9	9	05/01/91	12:00 PM	Open	0	800	625	
B'Room	10							
11	11	05/01/91	12:00 PM	Open	0	1200	650	
12	12	05/01/91	12:00 PM	Open	1	1050	675	Unoccupied
		05/01/91	12:30 PM	Open	0	1225	0	Occupied
13	13							
14	14	05/01/91	12:30 PM	Open	0	4000	Off	Initial Measurement
		05/01/91	12:35 PM	Open	0	3500	875	5 min later
		05/01/91	12:40 PM	Open	0	2800	N/A	10 min later
		05/01/91	12:50 PM	Open	0	1500	N/A	20 min later
H'Room	15							
16	16	05/01/91	01:00 PM	Open	2	1250	1050	
17-Lib	17	05/01/91	01:00 PM	Open	0	1075	1075	
18	18							
19	19	05/01/91	01:00 PM	Open	0	2500		
20	20							

Note: Unless noted otherwise, CO_2 measurements were made either while rooms were occupied or immediately after the students left.

Table 8.1.4. Test matrix for Lincoln Elementary School, Rapid City, SD.

Test No.	Test Dates	Class Room Doors	Unit Ventilator Operation	Exhaust Fan Operation	Outdoor Air-Damper Position	ASD System Operation
1	11/18 to 24/91	Normal[1]	Normal[2]	Off	Normal[3]	Off
2	11/25 to 29/91	Normal	Normal	On	Normal	Off
3	12/2 to 6/91	Closed[4]	Normal	Off	Normal	Off
4	12/9 to 16/91	Closed	Normal	On	Normal	Off
5	12/16 to 20/91	Closed	Normal	Off	Open[5]	Off
6	12/30 to 1/3/92	Closed	Normal	On	Closed[6]	Off
7	1/6 to 10/92	Normal	Normal	Off	Normal	On
8	1/13 to 17/92	Normal	Normal	On	Normal	On
9	1/20 to 24/92	Closed	Normal	Off	Normal	On
10	1/27 to 31/92	Closed	Normal	On	Normal	On
11	12/23 to 27/91	Closed	Off	On	Normal	Off

Notes: 1 Determined by teacher preference
2 On 4:00am - 8:00pm weekdays, off over weekend
3 Controlled by outside/inside temperature
4 Teachers asked to keep closed as much as possible
5 OA damper mechanically blocked open
6 OA damper mechanically blocked closed.

Table 9.1.1 Results of Blower Door Measurements at Glenview Elementary School, Nashville, TN, (in the crawlspace portion of the school).

Test Location	Test Conditions	Type Test (P/D)	ACH @ 4Pa	ACH @ 50Pa	Effective L.A. (sq.in.)	Equivalent L.A. (sq.in.)	Flow Equation C	n
Room 116	Closed	D	0.74	3.91	33.5	63.5	47.29	0.660
Room 116	Closed	P	0.45	10.06	20.5	65.5	13.18	1.228
Room 117	Closed	D	0.64	9.94	28.8	81.0	22.49	1.089
Room 117	Closed	P	0.71	4.21	32.4	63.8	43.17	0.702
Room 118	Closed	D	0.93	5.37	42.3	82.7	57.00	0.694
Room 118	Closed	P	0.51	3.85	23.2	50.0	27.08	0.798
Room 119	Closed	D	0.93	4.72	42.1	78.7	60.89	0.644
Room 119	Closed	P	0.76	2.95	34.5	58.4	57.79	0.537
Crawl	Closed	P	0.68	2.48	82.5	136.3	143.59	0.510
Crawl	Open	P	2.08	5.81	250.7	377.0	503.35	0.407
Room Averages			0.71	5.63	32.16	67.95		

*Notes: Rooms Closed implies Windows and Doors Closed
Crawl Closed implies Crawlspace Vents Closed
Crawl Open implies Crawlspace Vents Open
Test Type = D is Depressurization
Test Type = P is Pressurization

Table 9.1.2 Summary of parameters measured at the crawlspace part of Glenview Elementary, Nashville, TN.

Parameters	Locations
Differential Pressure	Room 116 to Outdoors
	Room 116 to Crawl-space
	Room 116 to Subpoly
Radon	Room 116
	Crawlspace
Temperature	Room 116
	Crawlspace
	Soil
	Outdoors
Wind Speed and Direction	Outdoors
Relative Humidity	Outdoors
Rainfall	Outdoors

TABLE 10.1.1 LIDGERWOOD SCHOOL SPOKANE, WA ROOM 139
DATA TAKEN: AUG 22, 1990

DIFFERENTIAL PRESSURE MEASUREMENTS (in.W.C.)

ROOM TO OUTDOORS
HALLWAY DOOR: CLOSED

		UNIT VENTILATOR SPEED SETTING:		
OA DAMPER POSITION	OFF	LOW	MEDIUM	HIGH
OPEN (100%)	-0.001	0.053	0.054	0.056
CLOSED (10% Open)	-0.001	0.01	0.009	0.012

HALLWAY DOOR: OPEN

		UNIT VENTILATOR SPEED SETTING:		
OA DAMPER POSITION	OFF	LOW	MEDIUM	HIGH
OPEN (100%)	-0.001	-0.001	-0.001	0
CLOSED (10% Open)	-0.001	-0.002	-0.003	-0.001

AIR QUANTITY MEASUREMENT (cfm)

OA DAMPER POSITION	LOW	MEDIUM	HIGH
OPEN (100%)			
OUTDOOR AIR	460	470	500
SUPPLY AIR	1175	1306	1285
CLOSED (10% Open)			
OUTDOOR AIR	30	47	109
SUPPLY AIR	NA	NA	NA
PERCENT OUTDOOR AIR			
OA DAMPER OPEN	39%	36%	39%
OA DAMPER CLOSED	3%	4%	8%
OA PER STUDENT (CFM - BASED ON 20 STUDENTS)			
OA DAMPER OPEN	23	24	25
OA DAMPER CLOSED	2	2	5

LEAKAGE AREA (M^2)=	0.046	0.047	0.049
AVG LEAK AREA(M^2)=	0.047		
AVG LEAK AREA (IN^2)=	73.2		

OBSERVATIONS: Room 139 could be pressurized with the unit ventilator, regardless of the OA damper position, but only when the hallway door was closed. This room is the library and it does not have an exhaust vent like the other rooms, thus it is easier to pressurize, however pressurization was not possible with the hallway door open.

TABLE 10.1.2 LIDGERWOOD SCHOOL SPOKANE, WA — ROOM 140

DATA TAKEN: AUG 22, 1990

DIFFERENTIAL PRESSURE MEASUREMENTS (in.W.C.)

ROOM TO OUTDOORS

HALLWAY DOOR: CLOSED

OA DAMPER POSITION	OFF	UNIT VENTILATOR SPEED SETTING: LOW	MEDIUM	HIGH
OPEN (100%)	0	0.02	0.021	0.024
CLOSED (10% Open)	0	-0.002	-0.001	-0.002

HALLWAY DOOR: OPEN

OA DAMPER POSITION	OFF	UNIT VENTILATOR SPEED SETTING: LOW	MEDIUM	HIGH
OPEN (100%)	0.001	0	-0.003	-0.001
CLOSED (10% Open)	0.001	-0.004	-0.002	-0.008

AIR QUANTITY MEASUREMENT (cfm)

OA DAMPER POSITION	LOW	MEDIUM	HIGH
OPEN (100%)			
OUTDOOR AIR	361	438	449
SUPPLY AIR	1200	1263	1380
CLOSED (10% Open)			
OUTDOOR AIR	45	23	44
SUPPLY AIR	1090	1135	1197
PERCENT OUTDOOR AIR			
OA DAMPER OPEN	30%	35%	33%
OA DAMPER CLOSED	4%	2%	4%
OA PER STUDENT (CFM - BASED ON 20 STUDENTS)			
OA DAMPER OPEN	18	22	22
OA DAMPER CLOSED	2	1	2
LEAKAGE AREA (M^2)=	0.059	0.070	0.067
AVG LEAK AREA(M^2)=	0.065		
AVG LEAK AREA (IN^2)=	101.1		

OBSERVATIONS: Room 140 could be pressurized with the unit ventilator, only with the OA damper in the fully open position, and only when the hallway door was closed. This room has a passive vent and is more difficult to pressurize.

TABLE 10.1.3 LIDGERWOOD SCHOOL SPOKANE, WA ROOM 141
DATA TAKEN: AUG 22, 1990

DIFFERENTIAL PRESSURE MEASUREMENTS (in.W.C.)

ROOM TO OUTDOORS
HALLWAY DOOR: CLOSED

	UNIT VENTILATOR SPEED SETTING:			
OA DAMPER POSITION	OFF	LOW	MEDIUM	HIGH
OPEN (100%)	0	0.03	0.034	0.036
CLOSED (10% Open)	-0.003	-0.002	-0.001	-0.003

HALLWAY DOOR: OPEN

	UNIT VENTILATOR SPEED SETTING:			
OA DAMPER POSITION	OFF	LOW	MEDIUM	HIGH
OPEN (100%)	-0.002	-0.005	0.001	-0.001
CLOSED (10% Open)	-0.002	-0.002	-0.003	-0.003

AIR QUANTITY MEASUREMENT (cfm)

OA DAMPER POSITION	LOW	MEDIUM	HIGH
OPEN (100%)			
OUTDOOR AIR	495	580	657
SUPPLY AIR	1001	1097	1160
CLOSED (10% Open)			
OUTDOOR AIR	72	87	94
SUPPLY AIR	NA	NA	NA
PERCENT OUTDOOR AIR			
OA DAMPER OPEN	49%	53%	57%
OA DAMPER CLOSED	7%	8%	8%
OA PER STUDENT (CFM - BASED ON 20 STUDENTS)			
OA DAMPER OPEN	25	29	33
OA DAMPER CLOSED	4	4	5

LEAKAGE AREA (M^2)= 0.066 0.073 0.080
AVG LEAK AREA(M^2)= 0.073
AVG LEAK AREA (IN^2)= 113.0

OBSERVATIONS: Room 141 could be pressurized with the unit ventilator, only with the OA damper in the fully open position, and only when the hallway door was closed. This room has a wind turbine exhaust and is more difficult to pressurize.

TABLE 10.1.4 LIDGERWOOD SCHOOL SPOKANE, WA ROOM 142

DATA TAKEN: AUG 22, 1990

DIFFERENTIAL PRESSURE MEASUREMENTS (in.W.C.)

ROOM TO OUTDOORS

HALLWAY DOOR: CLOSED

OA DAMPER POSITION	OFF	UNIT VENTILATOR SPEED SETTING: LOW	MEDIUM	HIGH
OPEN (100%)	0	0.03	0.034	0.036
CLOSED (10% Open)	-0.003	-0.002	-0.001	-0.003

HALLWAY DOOR: OPEN

OA DAMPER POSITION	OFF	UNIT VENTILATOR SPEED SETTING: LOW	MEDIUM	HIGH
OPEN (100%)	-0.002	-0.005	0.001	-0.001
CLOSED (10% Open)	-0.002	-0.002	-0.003	-0.003

AIR QUANTITY MEASUREMENT (cfm)

OA DAMPER POSITION	LOW	MEDIUM	HIGH
OPEN (100%)			
OUTDOOR AIR	226	230	251
SUPPLY AIR	1123	1218	1362
CLOSED (10% Open)			
OUTDOOR AIR	150	160	184
SUPPLY AIR	1078	1250	1306
PERCENT OUTDOOR AIR			
OA DAMPER OPEN	20%	19%	18%
OA DAMPER CLOSED	14%	13%	14%
OA PER STUDENT (CFM - BASED ON 20 STUDENTS)			
OA DAMPER OPEN	11	12	13
OA DAMPER CLOSED	8	8	9

LEAKAGE AREA (M^2)= 0.030 0.029 0.031

AVG LEAK AREA(M^2)= 0.030

AVG LEAK AREA (IN^2)= 46.2

OBSERVATIONS: Room 142 could be pressurized with the unit ventilator, only with the OA damper in the fully open position, and only when the hallway door was closed. This room has a wind turbine exhaust vent is more difficult to pressurize, although the turbine was inoperable during these measurements. The OA damper appears not to fully open.

Table 10.1.5 Subslab Communication Test Results At Lidgerwood Elementary School, Spokane, WA on August 21, 1990.

Fa Suction Pressure (in.W.C.)	Flow Rate at Fa (cfm)	Fb 1' from Fa (in.W.C.)	Fc 20' from Fa (in.W.C.)	Fd 32' from Fa (in.W.C.)	Fe 35' from Fa (in.W.C.)
0.0	0	0.00	-0.003	0.005	0.005
-3.0	8	-0.50	-0.020	0.003	0.002
-6.5	14	-1.00	-0.035	0.002	0.003
-8.0	17	-1.15	-0.036	0.003	0.003
-16.0	24	-1.76	-0.056	0.003	0.003
-24.0	123	-2.43	-0.075	0.002	0.003

Table 10.1.6 Radon levels and percent time classroom doors were open at Lidgerwood School, averaged over both the school day (8 hours) and over the 24 hour period.

		Room 139						Room 140						Room 141					
		(%)Door Open		(%)UV On		Avg. Radon Level (pCi/L)		(%)Door Open		(%)UV On		Avg. Radon Level (pCi/L)		(%)Door Open		(%)UV On		Avg. Radon Level (pCi/L)	
Day	Date	24Hrs	8Hrs	24Hrs	8Hrs	24Hrs	8Hrs	24Hrs	8Hrs	24Hrs	8Hrs	24Hrs	8Hrs	24Hrs	8Hrs	24Hrs	8Hrs	24Hrs	8Hrs
Fri	11/30/90	19.0	100.0	52.1	100	1.6	0.6	20.2	56.1	52.1	100	N/D	N/D	15.8	46.9	52.1	100	2.2	0.8
Sat	12/01/90	0.0	52.1	0.0	0	16.2	19.4	0.0	0.0	0	0	N/D	N/D	0.0	0.0	0	0	17.8	19.4
Sun	12/02/90	0.0	0.0	0	0	6.2	4.7	0.0	0.0	0	0	N/D	N/D	0.0	0.0	0	0	2.5	4.7
Mon	12/03/90	17.2	49.3	35.4	66.7	2.1	1.5	30.0	58.0	35.4	66.7	N/D	N/D	39.7	39.2	35.4	66.7	5.1	1.0
Tue	12/04/90	30.1	79.3	52.1	100	7.6	4.2	21.8	55.4	52.1	100	N/D	N/D	23.4	68.9	52.1	100	8.6	2.7
Wed	12/05/90	21.6	63.9	52.1	100	0.4	0.3	27.2	75.6	52.1	100	N/D	N/D	17.8	33.6	52.1	100	0.1	0.1
Thu	12/06/90	27.0	80.9	43.6	94.4	1.2	1.7	19.6	45.9	43.8	94.4	N/D	N/D	27.8	76.1	43.8	94.4	2.5	2.9
Fri	12/07/90	24.8	49.7	45.5	94.4	1.7	1.6	33.5	63.7	45.8	94.4	N/D	N/D	18.6	44.0	45.8	94.4	6.3	2.0
Averages=		24.2	64.6	45.8	91.1	2.6	1.9	26.4	59.7	45.8	91.1			25.4	52.4	45.8	91.1	4.5	1.7
Sat	12/08/90	0.0	0.0	0	0	8.2	9.0	0.0	0.0	0	0	N/D	N/D	0.0	0.0	0	0	N/D	N/D
Sun	12/09/90	0.0	0.0	0	0	10.6	10.3	0.0	0.0	0	0	N/D	N/D	0.0	0.0	0	0	17.4	17.0
Mon	12/10/90	1.9	4.1	77.1	100	5.3	1.6	5.1	12.6	77.1	100	N/D	N/D	16.3	43.7	77.1	100	7.5	1.6
Tue	12/11/90	1.5	4.4	100	100	0.3	0.2	8.2	24.3	100	100	N/D	N/D	16.5	47.5	100	100	0.1	0.1
Wed	12/12/90	3.0	8.8	100	100	0.5	0.6	7.5	20.2	100	100	N/D	N/D	9.0	18.7	100	100	0.4	0.4
Thu	12/13/90	3.5	10.3	100	100	0.5	0.7	8.0	23.3	100	100	1.9	1.3	11.8	34.7	100	100	0.5	0.7
Fri	12/14/90	3.4	10.0	66.7	88.9	0.3	0.3	10.4	28.8	66.7	88.9	3.7	2.8	5.4	15.4	66.7	88.9	2.5	0.4
Averages=		2.6	7.5	88.6	97.8	1.4	0.7	7.9	21.9	88.8	97.8	1.1	0.8	11.8	32.0	88.8	97.8	2.2	0.6
Sat	12/15/90	0.0	0.0	0	0	0.8	0.7	0.0	0.0	0	0	9.8	10.4	0.0	0.0	0	0	18.7	19.9
Sun	12/16/90	0.0	0.0	0	0	0.4	0.4	0.0	0.0	0	0	1.3	0.9	0.0	0.0	0	0	3.9	2.8
Mon	12/17/90	28.2	84.4	50	100	2.8	5.6	13.1	21.2	50	100	4.6	5.4	14.4	39.1	50	100	3.9	2.4
Tue	12/18/90	28.2	84.5	43.8	94.4	0.8	1.3	17.4	43.1	43.6	94.4	1.3	1.0	13.0	38.7	43.8	94.4	0.3	0.5
Wed	12/19/90	1.2	2.8	31.3	5.6	0.2	0.2	3.0	4.9	31.3	5.6	1.4	1.6	3.0	5.8	31.3	5.6	0.1	0.2
Thu	12/20/90	0.0	0.0	37.5	11.1	0.2	0.1	65.0	88.6	37.5	11.1	1.5	1.3	60.9	76.4	37.5	11.1	0.3	0.3
Fri	12/21/90	0.0	0.0	31.3	5.6	0.4	0.5	67.9	100.0	31.2	5.6	3.8	4.6	67.9	100.0	31.3	5.6	1.5	2.2
Averages=		11.5	34.3	38.8	43.3	0.9	1.6	33.3	51.6	38.8	43.3	2.5	2.8	31.8	52.0	38.8	43.3	1.2	1.1
Sat	12/22/90	0.0	0.0	100	100	0.5	0.4	0.0	0.0	100	100	4.1	4.4	0.0	0.0	100	100	0.5	0.6
Sun	12/23/90	0.0	0.0	100	100	0.7	0.7	0.0	0.0	100	100	5.6	4.6	0.0	0.0	100	100	1.0	1.0
Mon	12/24/90	0.0	0.0	100	100	0.8	0.9	0.0	0.0	100	100	10.8	13.6	0.0	0.0	100	100	1.5	1.9
Tue	12/25/90	0.0	0.0	100	100	1.1	1.6	0.0	0.0	100	100	15.5	26.7	0.0	0.0	100	100	3.1	5.5
Wed	12/26/90	0.0	0.0	29.2	0	1.0	1.0	73.0	100.0	29.2	0	8.0	7.5	73.0	100.0	29.2	0	5.0	5.0
Thu	12/27/90	1.3	3.9	0	0	1.7	1.3	100.0	100.0	0	0	8.6	8.2	100.0	100.0	0	0	6.7	7.1
Fri	12/28/90	0.1	0.4	0	0	N/D	N/D	100.0	100.0	0	0	0.6	0.6	100.0	100.0	0	0	N/D	N/D
Averages=		0.3	0.9	45.8	40.0	0.9	1.0	54.6	60.0	45.8	40.0	8.7	11.3	54.6	60.0	45.8	40.0	3.3	3.9
Sat	12/29/90	0.0	0.0	0	0	N/D	N/D	100.0	100.0	0	0	1.9	1.4	100.0	100.0	0	0	N/D	N/D
Sun	12/30/90	0.0	0.0	0	0	N/D	N/D	100.0	100.0	0	0	5.8	5.7	100.0	100.0	0	0	N/D	N/D
Mon	12/31/90	5.4	16.3	0	0	N/D	N/D	65.0	100.0	0	0	7.4	7.6	66.1	100.0	0	0	N/D	N/D
Tue	01/01/91	0.0	0.0	0	0	N/D	N/D	0.0	0.0	0	0	1.2	1.0	0.0	0.0	0	0	N/D	N/D
Wed	01/02/91	24.0	71.0	62.5	100	N/D	N/D	15.6	35.1	62.5	100	2.0	0.9	16.0	46.6	62.5	100	N/D	N/D
Thu	01/03/91	31.3	80.1	45.8	94.4	N/D	N/D	19.7	46.7	45.8	94.4	6.6	5.3	32.6	68.9	45.8	94.4	N/D	N/D
Averages=		15.2	41.8	27.1	48.6			25.1	45.4	27.1	48.6	4.3	3.7	28.7	53.9	27.1	48.6		

Table 10.1.7 Weekly average values of percent time classroom doors open, percent time UV's were on and radon levels at Lidgerwood School over the testing period.

Week of	Week #	Room–Week	(%)Door Open 24Hrs	(%)Door Open 8Hrs	(%)UV On 24Hrs	(%)UV On 8Hrs	Avg.Radon Level (pCi/L) 24Hrs	Avg.Radon Level (pCi/L) 8Hrs
Sorted by Room Number								
12/03/90	1	139–1	24.2	64.6	45.8	91.1	2.6	1.9
12/10/90	2	139–2	2.6	7.5	88.8	97.8	1.4	0.7
12/17/90	3	139–3	11.5	34.3	38.8	43.3	0.9	1.6
12/24/90	4	139–4	0.3	0.9	45.8	40.0	0.9	1.0
12/31/90	5	139–5	15.2	41.8	27.1	48.6	N/D	N/D
12/03/90	1	140–1	28.4	59.7	45.8	91.1	N/D	N/D
12/10/90	2	140–2	7.9	21.9	88.8	97.8	1.1	0.8
12/17/90	3	140–3	33.3	51.6	38.8	43.3	2.5	2.8
12/24/90	4	140–4	54.6	60.0	45.8	40.0	8.7	11.3
12/31/90	5	140–5	25.1	45.4	27.1	48.6	4.3	3.7
12/03/90	1	141–1	25.4	52.4	45.8	91.1	4.5	1.7
12/10/90	2	141–2	11.8	32.0	88.8	97.8	2.2	0.6
12/17/90	3	141–3	31.8	52.0	38.8	43.3	1.2	1.1
12/24/90	4	141–4	54.6	60.0	45.8	40.0	3.3	3.9
12/31/90	5	141–5	28.7	53.9	27.1	48.6	N/D	N/D
Sorted by 8 hr Radon Values								
12/31/90	5	139–5	15.2	41.8	27.1	48.6	N/D	N/D
12/03/90	1	140–1	28.4	59.7	45.8	91.1	N/D	N/D
12/31/90	5	141–5	28.7	53.9	27.1	48.6	N/D	N/D
12/10/90	2	141–2	11.8	32.0	88.8	97.8	2.2	0.6
12/10/90	2	139–2	2.6	7.5	88.8	97.8	1.4	0.7
12/10/90	2	140–2	7.9	21.9	88.8	97.8	1.1	0.8
12/24/90	4	139–4	0.3	0.9	45.8	40.0	0.9	1.0
12/17/90	3	141–3	31.8	52.0	38.8	43.3	1.2	1.1
12/17/90	3	139–3	11.5	34.3	38.8	43.3	0.9	1.6
12/03/90	1	141–1	25.4	52.4	45.8	91.1	4.5	1.7
12/03/90	1	139–1	24.2	64.6	45.8	91.1	2.6	1.9
12/17/90	3	140–3	33.3	51.6	38.8	43.3	2.5	2.8
12/31/90	5	140–5	25.1	45.4	27.1	48.6	4.3	3.7
12/24/90	4	141–4	54.6	60.0	45.8	40.0	3.3	3.9
12/24/90	4	140–4	54.6	60.0	45.8	40.0	8.7	11.3
Sorted by 24 hr Radon Values								
12/31/90	5	139–5	15.2	41.8	27.1	48.6	N/D	N/D
12/03/90	1	140–1	28.4	59.7	45.8	91.1	N/D	N/D
12/31/90	5	141–5	28.7	53.9	27.1	48.6	N/D	N/D
12/17/90	3	139–3	11.5	34.3	38.8	43.3	0.9	1.6
12/24/90	4	139–4	0.3	0.9	45.8	40.0	0.9	1.0
12/10/90	2	140–2	7.9	21.9	88.8	97.8	1.1	0.8
12/17/90	3	141–3	31.8	52.0	38.8	43.3	1.2	1.1
12/10/90	2	139–2	2.6	7.5	88.8	97.8	1.4	0.7
12/10/90	2	141–2	11.8	32.0	88.8	97.8	2.2	0.6
12/17/90	3	140–3	33.3	51.6	38.8	43.3	2.5	2.8
12/03/90	1	139–1	24.2	64.6	45.8	91.1	2.6	1.9
12/24/90	4	141–4	54.8	60.0	45.8	40.0	3.3	3.9
12/31/90	5	140–5	25.1	45.4	27.1	48.6	4.3	3.7
12/03/90	1	141–1	25.4	52.4	45.8	91.1	4.5	1.7
12/24/90	4	140–4	54.6	60.0	45.8	40.0	8.7	11.3

TABLE 11.3.1 Collocated Duplicate Charcoal Canister Results

School ID	Room No.	Canister Number	ZIP Code	Start Date	Stop Date	Level (pCi/L)	Percent Cnt.Err (2 Sigma)	Dup. Average (pCi/L)	Std. Dev. (pCi/L)	CV (%)
KWLSD10101	1	117825	57701	05/03/91	05/05/91	18.2	2.6			
KWLSD10101	1	117855	57701	05/03/91	05/05/91	18	6.1	18.1	0.1	0.6
KWLSD10104	4	118115	57701	05/17/91	05/19/91	7.9	3.8			
KWLSD10104	4	118068	57701	05/17/91	05/19/91	7.5	3.9	7.7	0.2	2.6
KWLSD10116	16	117806	57701	05/03/91	05/05/91	33.6	1.6			
KWLSD10116	16	117805	57701	05/03/91	05/05/91	38.2	1.7	35.9	2.3	6.4
KWLSD10116	16	118127	57701	05/17/91	05/19/91	14.1	2.4			
KWLSD10116	16	118167	57701	05/17/91	05/19/91	14.1	2.4	14.1	0.0	0.0
KWLSD10201	1	118248	57701	05/03/91	05/05/91	1.5	13			
KWLSD10201	1	118247	57701	05/03/91	05/05/91	1.6	13.1	1.6	0.1	3.2
KWLSD10201	1	118047	57701	05/17/91	05/19/91	1.7	9.2			
KWLSD10201	1	117998	57701	05/17/91	05/19/91	1.8	10.8	1.8	0.0	2.9
KWLSD10219	19	118227	57701	05/03/91	05/05/91	8.5	3.9			
KWLSD10219	19	117767	57701	05/03/91	05/05/91	8.7	3.6	8.6	0.1	1.2
KWLSD10219	19	118108	57701	05/17/91	05/19/91	17.4	2.2			
KWLSD10219	19	118066	57701	05/17/91	05/19/91	16.5	2.4	17.0	0.4	2.7
KWLSD10301	1	118204	57701	05/03/91	05/05/91	2.2	9.9			
KWLSD10301	1	118256	57701	05/03/91	05/05/91	2	10.6	2.1	0.1	4.8
KWLSD10301	1	117991	57701	05/17/91	05/19/91	1.1	15			
KWLSD10301	1	117990	57701	05/17/91	05/19/91	0.9	17.7	1.0	0.1	10.0
KWLSD10318	16	118210	57701	05/03/91	05/05/91	0.5	0			
KWLSD10318	16	118193	57701	05/03/91	05/05/91	0.5	0	0.5	0.0	0.0
KWLSD10318	16	118000	57701	05/17/91	05/19/91	0.5	0			
KWLSD10318	16	118001	57701	05/17/91	05/19/91	0.6	28.5	0.6	0.1	9.1
KWLSD10406	6	118197	57701	05/03/91	05/05/91	1	19.7			
KWLSD10406	6	118203	57701	05/03/91	05/05/91	0.9	18.9	1.0	0.1	5.3
KWLSD10406	6	118069	57701	05/17/91	05/19/91	0.8	21.4			
KWLSD10406	6	118062	57701	05/17/91	05/19/91	0.7	20.3	0.8	0.1	6.7
KWLSD10412	12	118213	57701	05/03/91	05/05/91	1.4	14.8			
KWLSD10412	12	118186	57701	05/03/91	05/05/91	1.2	17.6	1.3	0.1	7.7
KWLSD10412	12	118061	57701	05/17/91	05/19/91	0.6	32.3			
KWLSD10412	12	118060	57701	05/17/91	05/19/91	0.8	22.4	0.7	0.1	14.3
KWLSD10413	13	118009	57701	05/17/91	05/19/91	0.6	26			
KWLSD10413	13	118029	57701	05/17/91	05/19/91	0.6	29.7	0.6	0.0	0.0
KWLSD10506	6	118272	57701	05/03/91	05/05/91	1.6	12.7			
KWLSD10506	6	118273	57701	05/03/91	05/05/91	1.6	11.3	1.6	0.0	0.0
KWLSD10508	8	118034	57701	05/17/91	05/19/91	0.5	0			
KWLSD10508	8	118014	57701	05/17/91	05/19/91	0.5	0	0.5	0.0	0.0
KWLSD10511	11	118264	57701	05/03/91	05/05/91	0.5	0			
KWLSD10511	11	118263	57701	05/03/91	05/05/91	0.5	0	0.5	0.0	0.0
KWLSD10511	11	117993	57701	05/17/91	05/19/91	0.5	0			
KWLSD10511	11	118033	57701	05/17/91	05/19/91	0.5	0	0.5	0.0	0.0
KWLSD10518	18	118215	57701	05/03/91	05/05/91	3.4	6.4			
KWLSD10518	18	118236	57701	05/03/91	05/05/91	3.7	6.7	3.6	0.1	4.2
KWLSD10518	18	118016	57701	05/17/91	05/19/91	4.5	5.5			
KWLSD10518	18	117986	57701	05/17/91	05/19/91	4.1	8	4.3	0.2	4.7
KWLSD10523	23	117996	57701	05/17/91	05/19/91	0.5	0			
KWLSD10523	23	118026	57701	05/17/91	05/19/91	0.5	0	0.5	0.0	0.0
KWLSD10524	24	118218	57701	05/03/91	05/05/91	0.5	0			
KWLSD10524	24	118276	57701	05/03/91	05/05/91	0.8	21.2	0.7	0.2	23.1
KWLSD10710	10	117869	57701	05/31/91	06/02/91	18.4·	5.6			
KWLSD10710	10	117849	57701	05/31/91	06/02/91	17.6	5.8	18.0	0.4	2.2
KWLSD10810	10	118094	57701	05/31/91	06/02/91	8	10.2			
KWLSD10810	10	118039	57701	05/31/91	06/02/91	9.1	8.9	8.6	0.6	6.4
KWLSD20101	1	118437	57790	05/10/91	05/13/91	0.9	14.6			
KWLSD20101	1	118466	57790	05/10/91	05/13/91	0.9	17.9	0.9	0.0	0.0
KWLSD20108	8	118417	57790	05/10/91	05/13/91	1	18.2			
KWLSD20108	8	118363	57790	05/10/91	05/13/91	1.1	16.8	1.1	0.1	4.8
KWLSD20115	15	118427	57790	05/10/91	05/13/91	5.3	4.5			
KWLSD20115	15	118426	57790	05/10/91	05/13/91	5	4.7	5.2	0.2	2.9
KWLSD20121	21	118478	57790	05/10/91	05/13/91	0.5	0			
KWLSD20121	21	118364	57790	05/10/91	05/13/91	0.5	0	0.5	0.0	0.0
KWLSD20134	34	118394	57790	05/10/91	05/13/91	1.5	11.2			
KWLSD20134	34	118415	57790	05/10/91	05/13/91	1.5	9.7	1.5	0.0	0.0
KWLSD20150	50	118474	57790	05/10/91	05/13/91	1.2	11.7			
KWLSD20150	50	118473	57790	05/10/91	05/13/91	1.4	11.6	1.3	0.1	7.7
KWLSD20157	57	118403	57790	05/10/91	05/13/91	0.5	0			
KWLSD20157	57	118401	57790	05/10/91	05/13/91	0.5	0	0.5	0.0	0.0
KWLSD20158	58	118431	57790	05/10/91	05/13/91	1.9	9.5			
KWLSD20158	58	118402	57790	05/10/91	05/13/91	1.8	10.1	1.9	0.1	2.7
KWLSD20173	73	118440	57790	05/10/91	05/13/91	2.2	6.8			
KWLSD20173	73	118441	57790	05/10/91	05/13/91	2.4	8	2.3	0.1	4.3

Total Number of CCs = 72	Average for all Measurements	=	0.2	3.9
Number of Collocated Pairs = 36	High	=	2.3	23.1
	Low	=	0.0	0.0
	Average for Values > 4 pCi/L	=	13.5	3.0
	High	=	35.9	6.4
	Low	=	4.3	0.0
	Pooled Estimate of Variances	=	0.59	

TABLE 11.4.1 Calibrations of the Continuous Radon Monitors

Model No.	Serial No.	Cal. Date	Cal. Factor (cpm/pCi/L)	+− 1 sigma (cpm/pCi/L)	Cal. Date	Cal. Factor (cpm/pCi/L)	+− 1 sigma (cpm/pCi/L)	Percent Change Cal.Fact.
R210F	88R210F0165	07/21/89	0.28	0.01	11/01/91	0.28	0.01	0.0
R210F	88R210F0172	08/31/89	0.27	0.01	11/01/91	0.29	0.01	−7.4
R210F	91R210F0413	02/21/91	0.30	0.01	11/23/91	0.31	0.01	−4.0
R210F	91R210F0414	02/21/91	0.28	0.01	10/27/91	0.29	0.01	−3.2
R210F	91R210F0415	02/21/91	0.30	0.01	11/24/91	0.29	0.01	2.0
R210F	91R210F0416	02/21/91	0.30	0.01	10/28/91	0.29	0.01	3.3
R210F	91R210F0417	02/21/91	0.30	0.01	10/29/91	0.30	0.01	−1.4
R210F	91R210F0418	02/21/91	0.29	0.01	10/29/91	0.29	0.01	0.7
R210F	91R210F0419	02/14/91	0.30	0.01	10/27/91	0.30	0.01	0.7
R210F	91R210F0420	02/23/91	0.29	0.01	11/24/91	0.31	0.01	−5.8
R210F	91R210F0421	02/23/91	0.28	0.01	10/29/91	0.28	0.01	−1.4
R210F	91R210F0422	02/23/91	0.29	0.01	11/24/91	0.28	0.01	1.8
R210F	91R210F0423	02/23/91	0.27	0.01	11/27/91	0.31	0.01	−17.0
R210F	91R210F0424	02/23/91	0.29	0.01	11/26/91	0.31	0.01	−6.5
R210F	91R210F0425	02/23/91	0.30	0.01	11/26/91	0.28	0.01	5.4
R210F	91R210F0426	02/23/91	0.30	0.01	11/26/91	0.32	0.01	−5.6
R210F	91R210F0427	02/23/91	0.30	0.01	10/29/91	0.30	0.01	−1.4
R210F	91R210F0428	02/27/91	0.28	0.01	10/29/91	0.29	0.01	−5.1