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RADON DIAGNOSTIC MEASUREMENT GUIDANCE FOR LARGE BUILDINGS

Volume 1. Technical Report

By

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FOREWORD

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E. Timothy Oppelt, Director
National Risk Management Research Laboratory

ABSTRACT

The purpose of this study was to develop radon diagnostic procedures and mitigation strategies applicable to a variety of large non-residential buildings commonly found in the State of Florida. The investigations document and evaluate the nature of radon occurrence and entry mechanisms for radon, the effects of heating, ventilating, and air-conditioning (HVAC) systems configuration and operation on radon entry and dilution, and the significance of occupancy patterns, building height, and other building construction features. A primary focus of this project was the effect of the HVAC systems of a large building in influencing the transport, entry, and hopefully the minimization of indoor radon in the building. Two buildings were investigated, both of which showed an inverse relationship between dedicated ventilation air and indoor radon concentrations, as was expected. Both also showed signs of aberrant HVAC design, operation, and maintenance that presumably adversely affected indoor radon and other indoor air quality variables. The second building showed clear indications of foundation design elements that contributed to radon entry. Some recommendations relevant to building standards can be concluded from this project. First, design and construction should concentrate on elimination of major soil gas pathways such as hollow walls and unsealed utility penetrations. Second, HVAC system design should include strategies designed to minimize depressurized zones adjacent to the soil. Third, while increased supply ventilation is generally helpful for radon control, it is clearly not the most cost-effective solution or prevention tool once the requirements of occupant comfort and general indoor air quality have been met.

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METRIC EQUIVALENTS

Nonmetric units are used in this report for the reader's convenience. Readers more familiar with the metric system may use the following factors to convert to that system.

Nonmetric	Multiplied by	Yields Metric
cfm	0.0283	m^3/min
ft	0.305	m
ft^2	929	cm^2
^oF	(9/5) C + 32	^oC
in	2.54	cm
in WG	249	Pa
pCi/L	37	Bq/m^3
ton	907	kg (metric ton)

GLOSSARY

ACH	Air Changes per Hour
ACH50	Air Exchange Rate at ± 50 pascals
AH	Air Handler
CATS	Capillary Absorption Tube Samplers
CFM50	Cubic ft/min at ± 50 pascals
CMU	Concrete Masonry Units
CRM	Continuous Radon Monitor
ELA	Effective Leakage Area
EMS	Energy Management System
EPERM	High Sensitivy, Standard Chamber
EqLA	Equivalent Leakage Area
FCN	Financial Center North
FRRP	Florida Radon Research Program
FSEC	Florida Solar Energy Center
HRS	Health and Rehabilitative Services
HVAC	Heating, Ventilating and Air-Conditioning
LLC	Polk County Life and Learning Center
MBH	Million BTU/Hr
NEBB	National Environmental Balancing Bureau
NPP	Neutral Pressure Plane
OA	Outdoor Air
OAR	Outdoor Air Riser
PFT	Perfluorocarbon Tracer
PRV	Power Roof Ventilator
RPP	Radon Proficiency Program
TAB	Test and Balance
VAV	Variable Air Volume

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SECTION 1

INTRODUCTION

This report describes the results of a project conducted by Southern Research Institute and other organizations for the U.S. Environmental Protection Agency on behalf of the Florida Department of Community Affairs. The purpose of this study is to develop radon diagnostic procedures and mitigation strategies applicable to a variety of large non-residential buildings commonly found in the State of Florida. To accomplish this, it was necessary to perform detailed field investigations and parametric studies in a variety of buildings that have elevated levels of radon. The investigations document and evaluate the nature of radon occurrence and entry mechanisms for radon, the effects of heating, ventilating, and air-conditioning (HVAC) systems configuration and operation on radon entry and dilution, and the significance of occupancy patterns, building height, and other building construction features.

Elevated levels of radon have been found in large buildings in Florida. These have generally been in the same areas of the state that were identified by the Florida Statewide Radiation Survey (Nag 87) as having high radon potentials. To date, the greatest effort in the research of radon in large buildings has been to develop radon diagnostic and mitigation techniques for school buildings throughout the U.S. Experience in other types of large non-residential buildings was limited at this time, although there are a number of similarities between school buildings and other types of large buildings. Diagnostic and mitigation techniques developed by the U.S. EPA and used in school buildings were used as the basis for developing suitable diagnostic and mitigation techniques for large buildings in Florida.

A primary focus of this project was the effect of the HVAC systems of a large building in influencing the transport, entry, and hopefully the minimization of indoor radon in the building. The report contains a discussion of HVAC systems and their effects, followed by a description of case studies in two large buildings in the state of Florida. Conclusions and recommendations address elements of significance to proposed statewide standards for radon resistance in new large building construction.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

The two case studies in this report present some insight which can be generalized to other structures. The first building was a structure that had apparently been successfully mitigated by passive techniques, so would not normally be considered a "problem" structure. In this building, variations in outdoor air flow control dampers produced ventilation rate changes within the typical range [0.2 to 0.6 air changes per hour (ACH)] resulting in variations in indoor radon concentrations over a comparable range (a factor of 2.6). The second building had much higher radon levels, which could not be reduced below the 4 pCi/L radon standard without introducing outdoor air at a rate in excess of American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standard requirements, not to mention the energy management priorities of the owner. Both buildings demonstrated an inverse relationship between dedicated ventilation air and indoor radon concentrations, as was expected. Both also showed signs of aberrant HVAC design, operation, and maintenance which presumably adversely affected indoor radon as well as other indoor air quality variables. The second building showed clear indications of foundation design elements which contributed to radon entry; elimination of these entry paths at the time of construction would have been by far the most cost-effective remedy for the building.

Some recommendations relevant to building standards can be concluded from this project. First, design and construction should concentrate on elimination of major soil gas pathways such as hollow walls and unsealed utility penetrations. It is less clear from this study how much benefit can be derived from sealing of minor cracks and joints. Second, HVAC system design should include strategies designed to minimize depressurized zones adjacent to the soil. Such zones could be caused by flow imbalance in the air distribution system, inadequate sealing of major duct leaks, or imbalance of supply and exhaust ventilation airflow. The combination of depressurized areas and poor barriers is particularly undesirable, especially if the depressurizing element is the return air portion of the air handling system. Third, while increased supply ventilation is generally helpful for radon control, it is clearly not the most cost-effective solution or prevention tool once the requirements of occupant comfort and general indoor air quality have been met.

Further studies to extend the information base would be of value. In particular, future studies could include monitoring of the radon in new buildings constructed on high radon potential soil according to radon control guidelines.

SECTION 3

BACKGROUND: HVAC SYSTEMS AND RADON IN LARGE BUILDINGS

3.1 HVAC SYSTEMS BACKGROUND

Heating, ventilating, and air-conditioning (HVAC) systems have two distinct primary functions: a) provision and maintenance of specific environmental conditions; and b) occupant or space ventilation for the provision and maintenance of acceptable indoor air quality. Specified environmental conditions are typically for occupant comfort, but special environmental conditions can also be needed for a process or a product. In all cases, the HVAC system must provide the occupant or process with the proper conditions (dry-bulb temperature, relative humidity, etc.). The primary purpose of ventilation is the controlled introduction, and exhaust or recirculation of air in a given space. Research indicates that the required amount of outdoor air is dependent on the rate of contaminant generation and the maximum acceptable contaminant level. Understanding this is important to HVAC system designers since confusion can lead to designs that are energy wasteful (too much outdoor air) or that provide poor indoor air quality (too little outdoor air).

There exists a wide variety of design situations for these two basic functions. These include commercial and manufacturing applications, general office space, educational and institutional facilities, and special purpose space, such as laboratories and clean rooms. These diverse environmental conditions require a wide range of equipment types and sizes for HVAC systems for the creation and maintenance of a controlled environment. For purposes of simplicity, all HVAC systems fall into one of the following four major categories: ALL-AIR SYSTEMS, AIR-WATER SYSTEMS, ALL-WATER SYSTEMS, and UNITARY SYSTEMS. These system types are distinguished from one another based on their terminal-cooling medium:

> An **ALL-AIR SYSTEM** is defined as an HVAC system that provides complete sensible and latent cooling capacity in the cold air supplied by the system. No additional cooling is required at the zone. Heating may be accomplished by the same air stream either in the central system or at a particular zone. In some applications, heating is accomplished by a separate air, water, steam, or electric heating system.
>
> An **AIR-WATER SYSTEM** is one in which both the medium of air and water are distributed to each space to perform the cooling function. In virtually all AIR-WATER SYSTEMS, both cooling and heating functions are carried out by changing the air or water temperatures (or both) to permit control of the space temperature during all seasons of the year.
>
> An **ALL-WATER SYSTEM** is one with fan-coil units, unit ventilators, or valance-type room terminals having unconditioned ventilation air supplied by an opening through the wall or by infiltration. Cooling and humidification are provided by circulating chilled water or brine through a finned coil in the unit. Heating is

provided by supplying hot water through the same or a separate coil using a piping distribution system from a central boiler plant. Electric heating or a separate steam coil may also be used.

A **UNITARY SYSTEM** consists primarily of conditioning equipment that is factory-matched with refrigerant-cycle components for inclusion in air-conditioning systems that are field designed to meet the needs of the user. Heating is generally accomplished by the use of electric coils.

3.1.1 ALL-AIR SYSTEMS

ALL-AIR SYSTEMS may be briefly classified in two basic categories: a) single-path systems, and b) dual-path systems. Single-path systems are those which contain the main heating and cooling coils in a series flow air-path, using a common duct distribution system at a common air temperature to feed all terminal apparatus. Dual-path systems are those that contain the main heating and cooling coils in a parallel flow, or series parallel flow air-path, using either a separate cold and warm air duct distribution system, which is blended at the terminal apparatus (dual-duct systems), or a separate supply duct to each zone with blending of warm and cold air at the main supply fan. These classifications may be broken down as follows:

Single-Path Systems

Single Duct, Single Zone, Constant Volume
Single Duct, Variable Volume
Single Duct, Variable Volume Induction
Single Duct Zoned Reheat

Dual-Path Systems

Dual-Duct (including Dual-Duct, Variable Volume)
Multizone

The ALL-AIR SYSTEM may be adapted to all types of air-conditioning systems for comfort and ventilation. It is used in buildings requiring individual control of conditions within a multiplicity of zones, such as office buildings, schools and universities, laboratories, hospitals, stores, and hotels. An ALL-AIR SYSTEM is also used for many special applications where a need exists for close control of temperature and humidity, including clean rooms, computer rooms, hospital operating rooms, and textile factories. In general, ALL-AIR SYSTEMS offer the following advantages:

- Centralized location of major equipment allowing operations and maintenance in unoccupied spaces.

- Greatest number of potential cooling season hours when outdoor air can be used for cooling in lieu of mechanical refrigeration.

- Wide choice of zone-ability, flexibility, and humidity control under all operating conditions with simultaneous availability of heating and cooling to the extent required, even during off-season periods.

- Readily adaptable to heat-recovery systems.

- Best suited for applications requiring abnormal exhaust makeup.

- Adaptable to winter humidification.

Some of the disadvantages of ALL-AIR SYSTEMS are:

- Plenum space for the duct distribution system can be very expensive.

- System designs can be difficult to keep in air balance, requiring balancing as often as once a year.

- Accessibility to equipment and room terminal units can be difficult if not closely coordinated between the architect and the mechanical engineer.

- Some ALL-AIR SYSTEMS are not energy efficient.

Four types of ALL-AIR SYSTEMS that are commonly found in buildings today are:

Reheat Systems

The purpose of this system is to permit zone or space control for areas of unequal loading; or to provide heating or cooling of perimeter areas with different exposures; or for process or comfort applications where close control of space conditions is desired. These cases arise in some hospitals, laboratories, office buildings, or spaces where wide load variations occur.

Variable Volume Systems

The Variable Air Volume (VAV) system is a central HVAC system that compensates for varying cooling load by regulating the volume of air being supplied to the space through a single duct. Of significant advantage are the low initial and operating costs associated with the VAV system. The system is far lower in first cost in comparison to other systems that provide individual space control because it requires only single runs of duct and a simple control at the room terminal unit. Also, where diversity of loading occurs, smaller equipment can be used. Applications of VAV exist for office buildings, hotels, hospitals, apartments, and schools.

Dual or Double-Duct Systems

In a dual-duct system, the central station equipment supplies warm air through one duct and cold air through the other. The temperature in an individual space is controlled by a thermostat that mixes the warm and cool air in proper proportion. Many dual-duct systems are installed in office buildings, hotels, hospitals, schools, and large laboratories. With the simultaneous availability of warm and cool air from the room-terminal unit at all times, this system provides great flexibility in satisfying multiple loads and in providing prompt and opposite temperature response as required.

Multizone Systems

The multizone system provides a single supply duct for each zone and obtains zone control by mixing warm and cool air at the central unit in response to room or zone thermostats. For a comparable number of zones, this system provides greater flexibility than the single-duct system and involves lower cost than the dual duct-system, but it is physically limited by the number of zones that may be supported by the equipment.

3.1.2 AIR-WATER SYSTEMS

In ALL-AIR SYSTEMS, the spaces within the building are cooled and heated solely by the air supplied to them from the central air-conditioning equipment. In contrast, an AIR-WATER SYSTEM is one in which both air and water are distributed to each space to perform the cooling and heating functions. The water side of the system consists of a distribution system of piping and pumps that carries the hot and cold water to the space room terminal unit to perform the heating and cooling functions. The air side to the system consists of central air-conditioning equipment and a duct distribution system connected to the same space room terminal unit. The air side is constant volume and often referred to as primary air to distinguish it from room air which is recirculated over the coil in the room terminal unit. The common room terminal unit associated with these systems is the air-water induction unit. In virtually all AIR-WATER SYSTEMS, both cooling and heating are carried out by changing the air or water temperature (or both) to permit control of space temperature during all seasons of the year. A number of reasons exist for the use of this type of system:

(1) Water has a greater specific heat and density than air; consequently, the mechanical space required for the water-piping system to accomplish the same cooling effect as the air-duct system is much less.

(2) The air side of this type of system can be designed as a high velocity system further reducing the mechanical space required.

(3) Since the water side of this system does most of the heating and cooling, energy

consumption is reduced since pump horsepower is more efficient than fan horsepower.

AIR-WATER SYSTEMS are primarily applicable to multiple perimeter spaces where a wide range of sensible loads exist and where close control of humidity is not required. Systems of this type have been commonly applied to office buildings, hospitals, hotels, schools, some apartment buildings, and laboratories. The mechanical space savings associated with these systems make them especially beneficial for use in high-rise structures.

3.1.3 ALL-WATER SYSTEMS

ALL-WATER SYSTEMS are those with fan-coil, unit ventilator, or valance-type room-terminal units with unconditioned ventilation air supplied by an opening through the wall or by infiltration. Cooling is provided by circulating chilled water or brine through a coil in the room terminal unit. Heating is provided by supplying hot water through the same or separate coil. Heating could also be supplied by a separate electric or steam coil.

Most of the ALL-WATER SYSTEMS that are installed do not meet the criteria for this type of air-conditioning system as stated in ASHRAE Standard 55 (ASH 92) because they lack humidity control and because the quantity of outdoor air is limited by the effectiveness of mechanical exhaust fans within the room and by the size of the wall opening. These systems also fail to meet the ventilation requirements of ASHRAE Standard 62 (ASH 89). There is no positive ventilation unless wall openings are used, and the effect of these openings depends on wind pressures and stack action on the building.

The greatest advantage of the ALL-WATER SYSTEM is its flexibility for adaptation to many building module requirements. A fan-coil system applied without provision for positive ventilation or taking ventilation air through an aperture is one of the lower first-cost central-station perimeter systems in use today. It requires no ventilation air-duct work, is comparatively easy to install in existing structures, and (as with any central-station perimeter system utilizing water in pipes instead of air ducts) offers considerable space saving throughout the building.

On the other hand, maintenance and service work have to be done in the occupied areas, and as the units become older, the fan noise can become objectionable. Each unit requires a condensate drain line that periodically has to be flushed out and cleaned. It can be very difficult to limit bacterial growth in these units. In extreme cold weather, it is often necessary to close the outdoor air dampers to prevent freezing of coils, reducing ventilation air to that obtained by infiltration.

3.1.4 UNITARY SYSTEMS

UNITARY SYSTEMS include air-conditioning equipment consisting of factory-matched refrigerant cycle components for inclusion in air-conditioning systems that are field designed to meet the needs of the user. These fundamentally simple systems are characterized by the use of split-system configuration utilizing an air-cooled condensing unit. The nearly infinite combinations of coil configurations, evaporator temperatures, air-handling arrangements, refrigerating capacities, and variations thereof, which are available in central systems, are rarely possible with UNITARY SYSTEMS. Consequently, in many respects, a higher level of design ingenuity and performance is required to develop superior system performance using UNITARY SYSTEM equipment than for central systems.

UNITARY SYSTEM equipment tends to fall into a zoned system category with each zone being served by its own unit. For large single spaces, where central systems are at their best advantage, application of multiple units often finds advantage due to movement of load sources within the larger space, giving the flexibility of many smaller interlocked and independent systems instead of one large central system. Typical examples of systems in this category are:

Window Air Conditioners
Packaged Terminal Air Conditioners
Rooftop Split Systems
Unitary Air Conditioners
Water-loop Heat Pumps

Multiple-unit systems generally have the following advantages over central system alternatives:

- Individual room control provided simply and inexpensively.
- Individual air distribution system for each room, usually with convenient, simple adjustment provided by the occupant.
- Individual ventilation air provision, normally operating whenever the conditioner is operating.
- Manufacturer-matched components ensure consistent performance.
- Manufacturer assembly and connection of components allow easier quality control and improved reliability.
- Heating and cooling capability is provided at all times, independent of the mode of operation of other spaces in the building.
- Only one terminal zone or conditioner affected in the event of equipment malfunction.
- Usually some space saving.
- Usually lower initial cost.
- Equipment serving spaces that become vacant can be turned off locally without

affecting occupied spaces.

This class of HVAC system typically finds application in small to medium commercial buildings, some smaller multistory office buildings, and schools.

3.2 HVAC SYSTEM DEMANDS

An HVAC system is an assemblage of equipment components, such as fans, heating and cooling coils, filtration devices, and ductwork, with the primary function of:

(a) providing an acceptable level of indoor air temperature and control so that the occupants perceive that they are comfortable;

(b) maintaining relative humidity levels that are not detrimental to human health or processes, yet positively interact with temperature ranges to enhance comfort;

(c) effectively cleaning the indoor supply air of contaminants and odors generated outdoors and contaminants originating indoors;

(d) distributing and circulating the room air supply in such a way that air-flow patterns ensure mixing in all comfort zones; and

(e) providing building ventilation systems that distribute the required amounts of outdoor air to the comfort zones in a manner that ensures proper pressure relationships throughout the entire system.

Research has shown that the comfort and health of building occupants can be greatly impacted, depending on the ability of the HVAC system to perform according to each of the system's demands. Complete, properly designed and installed HVAC systems have the ability to meet and control all of these and many other factors. It is possible for a system to react accordingly to each system function.

Why then are many indoor air-quality problems associated with newly constructed or renovated HVAC systems? The answer to this question may well be found by investigating the planning, development, and selection process. Reports of investigations of large buildings indicate that many indoor air problems exist because of misapplication of the HVAC system, poor maintenance born out of faulty design, lack of system control, poor construction and installation techniques, or deficient commissioning practices.

Many problem systems can be associated with the lack of initial consideration of system demands and performance characteristics by the design engineer. Quite a few cases exist that indicate that the designer overemphasized first cost as the most important factor when evaluating and selecting the HVAC system, or failed to properly evaluate the quality of the system.

The practice of being guided primarily by first cost can prove to be false economy. Problem HVAC systems can cause future losses associated with worker productivity, possibly poor indoor air quality litigation, and costs associated with increased operation and maintenance. Additionally, considering first cost only ignores other important factors such as life expectancy, ease of maintenance, and even to some extent, energy efficiency, though most energy codes require a minimum efficiency rating.

Most professionals involved in the design, construction, and maintenance of HVAC systems would agree that prevention is the least expensive way to go. The expense and effort required to prevent indoor air quality problems is much less than the expense and effort required to resolve problems after they develop.

It seems that in many cases the design engineer is not aware of the important factors in the development and selection stage of HVAC system design. Technologies have changed greatly in the past few years. We now know more about the demands of HVAC systems and their ultimate effect on indoor air quality and energy usage if proper consideration is not given to design in the earliest steps of HVAC system development. As research is done, we continue to learn in this area. A more valued and complete approach to system development and selection is to consider and evaluate the following criteria:

(a) Comfort requirements must be evaluated, including indoor air quality. This primarily involves defining the goals and objectives of the indoor air requirements. Consideration should be given to the building type and number of occupants. A thorough knowledge of the activities of the occupants and equipment or devices they may employ in their everyday activities is necessary for thorough evaluation. These considerations can sometimes help in identifying possible indoor sources of contaminants and their classifications. Once this type of information and knowledge is gained, the design engineer can more expertly apply relevant codes and standards. Many problems can be anticipated and resolved using this technique, and HVAC system configuration options can be developed and evaluated for maximum impact. After the options are defined, the final decision concerning the type system needed can be made much more effectively.

Occupant comfort is generally easy to define and evaluate since this involves providing the occupants with proper temperature and relative humidity levels. Engineering procedures for accomplishing this are well defined in design manuals and textbooks. However, problems can arise when not enough detailed consideration is given to methods of providing and controlling relative humidity levels. Humidification can be a very serious cause of occupant health related issues. Low humidity results in eye and throat irritation. High humidity encourages biocontaminant growth, which is also a health hazard. Occupant comfort is closely tied to air movement and circulation. Many occupant-related problems occur when the design engineer performs insufficient design analysis to ensure good mixing and distribution of air.

(b) Energy usage actually refers to the efficient use of energy as it relates to the total building. Total building energy usage includes many factors, the most dominant being operation and maintenance aspects of HVAC systems. It is well known that certain aspects of HVAC systems can have a great impact on total building energy usage; two of these are ventilation and comfort control. Many concerns surface, and questions are raised when discussing the potential costs associated with increased outdoor air ventilation rates required by indoor air standards. Additionally, energy cost associated with comfort control (temperature and relative humidity) can be substantial, depending upon the systems application and building process. Total building energy usage is estimated to account for 30% of all energy consumed. Obviously, great initial savings, as well as life-cycle savings, can be realized by closely controlling energy costs associated with ventilation and comfort control. Energy savings at the expense of ventilation and comfort can result in a deterioration of indoor air quality. Design decisions that impact and reduce this usage and that are relative to the previous discussions are: construction of the building shell and its associated thermal and air-barrier performance, HVAC system type and class, and HVAC operational demands and duty cycle. A reasonable plan for evaluating energy aspects should be developed. The design engineer must look at the building, evaluate its use, determine the type and source of energy available, and develop an energy-reduction plan that maintains the best building environment for all anticipated circumstances.

(c) First cost and life-cycle costs are critical design variables. Providing the building owner with a well designed and efficiently operating HVAC system is the intent of all design engineers. Unfortunately, this is not enough. The systems must be economical. The best intentions of the design engineer will quickly be lost if the system is not economically balanced with respect to first-cost, operating cost, and maintenance cost. It is not easy to determine the economy of a system. The process of evaluation is wrought with many complex parameters, such as varying equipment costs related to different system types, various energy sources and usage rates, tax codes and structures, the time value of money, building-life expectancy, asset depreciation, and varying levels of insurance needs. As stated before, it is easy for the design engineer to overemphasize the importance of first-cost in evaluating different systems. It is imperative that a successful design include a thorough life-cycle analysis. Different systems can be realistically evaluated and compared by converting all system costs to "present worth values."

(d) System maintenance is a critical and important consideration in system selection and design. Very often design engineers give little thought to this factor even though the long term satisfaction of the owner and the occupants is at stake. A basis towards poor maintenance of a complex system can negate any potential for radon mitigation (Sau 93). It is the responsibility of the design engineer to determine the amount of space that will allow maintenance personnel to perform their job of maintaining the system. The design engineer must also make the architect aware of the importance of providing the proper space to meet these needs. This applies not only to the obvious spaces, such as mechanical equipment rooms, but also to ceiling plenums and interstices. This will allow proper maintenance of the control and distribution systems.

(e) System operations, along with system maintenance, is an important but often overlooked design and selection factor. The design engineer must consider and design HVAC systems that are easily understood and that can be operated in accordance with design intent. This means that, with proper training, the operating engineer(s) can operate the system to meet the demands for which it was designed. Simplicity is the rule that the design engineer should follow. Do not overly complicate the system or its controls. Additionally, simple systems are the easiest to commission. Commissioning involves testing and balancing the final installation to certify that it can meet the environmental design parameters that it was intended to fulfill, such as temperature, relative humidity, and air movement.

3.3 RADON ENTRY MECHANISMS RELEVANT TO LARGE BUILDINGS

Radon entry into large buildings can be influenced by the effect of either ventilation air or infiltration air. These are two important types of entry-influencing mechanisms that contribute to the driving forces causing soil gas to enter a building. Outdoor air is generally used to dilute indoor air contaminants, pressurizing the building interior thus creating a driving force that impedes entry, while the energy associated with heating or cooling this outdoor air can have a significant impact on space-conditioning, energy-loading factors.

The generally accepted definition of ventilation air is the intentional and controlled introduction of outdoor air into occupied space. Further, ventilation air can be either natural or forced. Natural ventilation is unpowered airflow through open windows, doors, and other intentional openings in the building envelope. Forced ventilation on the other hand is the intentional, powered air exchange by a fan or blower with intake and/or exhaust vents that are specifically designed and installed for the introduction of outdoor air. Designers of heating, ventilation, and air-conditioning systems utilize design standards to determine the correct amount of outdoor air to introduce into the occupied space. The current standard used by designers is The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 62-1989 (ASH 89), "Ventilation for Acceptable Indoor Air Quality." Under ASHRAE Standard 62-1989, the minimum ventilation rate can be defined by two approaches. The primary approach is a specification standard calling for the provision of minimum amounts of clean, conditioned, outdoor air. The alternative method is a performance standard whereby the minimum outdoor air quantities need not be met but the quality of the indoor air must conform to established guidelines. Either approach is acceptable; however, the alternative approach generally results in a lower ventilation rate. This means that less ventilation air (outdoor air) is being brought into the building, which could have an adverse impact on the HVAC system's ability to control radon entry. In building design, the key factors influencing radon entry from soil are the design and operation of the ventilation system, which affects pressures driving bulk airflow through soil, and the design and construction of the building substructure, which controls the degree of movement between the air in the soil and the air in the building.

Infiltration is the unintentional and uncontrolled introduction of outdoor air into the building through cracks and openings in the shell or envelope of the building. Infiltration is uncontrolled airflow through cracks, interstices, and other unintentional openings that occur in the envelope of the building and seem to be a general result of construction practices. Both infiltration and natural ventilation airflows are caused by pressure differences due to wind, indoor-outdoor temperature differences, and equipment operation.

3.3.1 Radon Entry

Most large buildings are built with the lowest floor made of poured concrete and in direct contact with underlying soil (basement or slab-on-grade), or in some cases, suspended above the soil (crawl space). The building substructure influences radon entry by the degree of coupling between indoor air and soil air, and the size and location of openings, penetrations, joints, and cracks in the slab, through the substructure. The degree of coupling is a result of the underlying layer, which can act to distribute soil gas (such as gravel) or provide minimum gaseous communication (such as clay or tight sand) beneath the slab and the building to subslab differential pressure providing the convective driving force. In addition to buildings with slab-on-grade or basement construction of the foundation, crawl space substructures can be well coupled when crawl space vents are not installed. Penetrations in the building shell of greatest importance are those in the floor and, in the case of basement substructures, openings in the wall below soil grade. In addition, the rate at which soil-gas moves through soil may be the limiting factor when slab openings are not minor in size.

In buildings, a possible additional source of entry are building materials, which can contribute to the total indoor radon concentrations but are easily controllable. Intended building materials should be investigated on the basis of their properties as sources of radon. Materials high in radon concentration should not be used.

3.3.2 Ventilation Air

In the previous discussion of heating, ventilating, and air-conditioning systems, it was stated that one of the primary purposes of HVAC systems is for space ventilation, specifically for the provision of acceptable indoor air quality. Ventilation is best described as the action of replacing indoor air with outdoor air; this occurs either naturally or intentionally. A primary use of ventilation air for acceptable indoor air quality is the introduction of outdoor air for the purpose of controlling building depressurization. Building depressurization occurs when the indoor building pressure is less than the outdoor atmospheric pressure.

Research has indicated that the infiltration of pollutants (e.g., soil gases) in large buildings increases as building depressurization increases. Building depressurization can be caused by a number of driving mechanisms. Wind pressure on the outside of the building, temperature differences between indoors and outdoors (stack effect), and the operation of combustion devices and mechanical ventilation systems are the primary factors affecting building depressurization. Building depressurization can also have a great impact on energy usage in a building, as well as on the general quality of the indoor environment. When a building experiences depressurization energy costs can rise since the air entering via infiltration is unconditioned. Additionally, infiltration air can also have an adverse effect on the indoor air quality since it is essentially untreated. Ideally, the designer of building systems will want to control the level of building depressurization; however, this is not an easy task since the driving forces are not easily controlled.

During the early 1970's, energy conservation was a primary goal of building designers. Buildings were built with airtight envelopes to lessen the intrusion of infiltrating air. We now know that this practice has led to poor indoor air quality since infiltrating air can help to dilute and remove indoor air pollutants.

3.3.3 Wind Pressure

Building depressurization can be caused by wind pressure when the wind impinges on a building, setting up a distribution of static pressures on the building's exterior surface. The degree of pressure difference is dependent on the direction of the wind and varies with the location on the building exterior. These static pressure distributions are dependent on the pressure inside the building. For large buildings that are very tall and have relatively porous exteriors, the effect of building depressurization due to wind pressure can be very significant. The static-pressure distributions will cause outdoor air to infiltrate the building through openings in the windward walls and exfiltrate through wall openings in the leeward wall of the building. In order to overcome the wind pressure infiltration, the HVAC design must be such that a positive pressure is maintained in the building with respect to outside the building. This, of course, is accomplished by using a system design that introduces outdoor air in a controlled and conditioned fashion. Not all HVAC systems meet both of these requirements. Even with HVAC systems that have outdoor air capability, wind pressure is not easily overcome.

3.3.4 Stack Effect

Stack effect is the term used to describe the entry mechanism of outdoor air into a building due to a temperature difference. The temperature difference is primarily between the indoor air temperature and the outdoor air temperature. These temperature differences between indoor and outdoor air tend to cause density variations between the indoor air and the outdoor air. The density variations are then translated into pressures differences that cause outdoor air to infiltrate the building structure. When the HVAC system is in the heating mode, it supplies warm air to the building. This warm air has less density than the colder outdoor air and will naturally tend to rise inside the building. In large and tall buildings, the warm air rises through stairwells, elevator shafts, and utility corridors. Flow has also been shown to occur through pipe penetrations in floor slabs. As it rises, warm air eventually will flow out of the building at the upper floors through openings and cracks in the building envelope or through mechanical penthouses located on the roof. As this air is exfiltrating at the upper floors, it is replaced by unconditioned, untreated, outdoor air at the bottom floors. This phenomenon occurs primarily at the base of the building. The air finds its way into the building through the action of opening doors, through the building loading dock, or through cracks and openings in the envelope.

During the cooling season, the flow directions are reversed, and air will enter at the top of the building and be exfiltrated at its base through the doors and other openings. During the cooling season, the stack effect is generally less than that found during the heating season. This is because stack effect is driven by a density variation caused by the indoor air and the outdoor air temperature differences. In the cooling season, this temperature difference is smaller than is experienced during the heating season.

There is a point in the height of the building where the exterior and interior pressures are equal. This point in the building is commonly referred to as the Neutral Pressure Plane (NPP). Above this neutral pressure plane, (during the heating season), the pressure inside the building is greater than the pressure outside of the building. Therefore, air will tend to flow from the building above the NPP. Below the NPP, the inside pressure is less than outdoors, and air will tend to flow into the building. The determination of the location of the NPP at zero wind speed depends upon a number of factors:

(1) The vertical distribution of openings along the shell of the building; are the openings and cracks in the shell evenly or unevenly distributed?

(2) The level of resistance of the openings to airflow; are the windows well sealed and caulked?

(3) The resistance to vertical airflow within the building; is the interior of the building constructed so that air can easily flow from one floor to another? Are stairwell doors well sealed and gasketed? Are utility penetrations in the floors well sealed?

If the openings in the building shell are uniformly distributed vertically, and there is no internal airflow resistance, the NPP is naturally found at the mid-height of the building. If there is only one opening, or an extremely large opening relative to any others, the NPP is at or near the center of this opening. Internal partitions, stairwells, elevator shafts, utility ducts, chimneys, vents, and mechanical supply and exhaust systems complicate the analysis of NPP locations. Chimneys and openings at or above the roof height raise the NPP in small buildings. Exhaust systems increase the height of the NPP, while outdoor air supply systems lower it.

3.3.5 System Operation

Previous studies have shown that radon entry into large buildings can be reduced by reducing the amount of building depressurization that occurs. By decreasing the building depressurization, entry mechanisms, such as wind pressure and stack effect, can be de-emphasized. The heating, ventilating, and air-conditioning system can play an important role in the depressurization of the building by controlled use of ventilation air. By introducing more outdoor air through the HVAC system than is removed through the building exhaust systems, the building can be pressurized with respect to the outdoors. Ideally, under building pressurization, indoor air exfiltrates rather than outdoor air infiltrating. A properly operating HVAC system with outdoor air provision need only maintain a pressure differential of 1-4 pascals. Not all HVAC systems encountered in large buildings are capable of providing a level of building pressurization that is required to mitigate radon entry. System configuration, type of HVAC system, building porosity, or some other factor may affect a desired degree of building pressurization. The ability to pressurize a space or a building depends upon the following factors:

Type of HVAC System

The system characteristics and features of various types and classes of HVAC systems were discussed in previous sections. From the discussion, it is obvious that not all HVAC systems will provide building pressurization. Many of the ALL-AIR SYSTEMS and some of the AIR-WATER SYSTEMS are desirable for building pressurization. These classes of systems can provide outdoor air in specific quantities to offset the forces that defeat pressurization. Many of the UNITARY SYSTEMS and all of the ALL-WATER SYSTEMS do not allow pressurization because outdoor air is not a feature of these types of systems.

Room or Building Porosity

Generally, the designs of building envelopes are successful in meeting structural and porosity requirements. However, poor envelope construction can adversely affect the ability of the HVAC system to maintain building pressurization. Many of these practices include inadequate sealing and caulking around window frames or the installation of window and door systems that do not meet tight construction standards. Another construction feature that can greatly affect envelope porosity is the air barrier. The purpose of the air barrier is to prevent air from flowing through the building shell itself. This means that outdoor air should be prevented from flowing into the building through the walls, roof, and fenestrations. Conversely, flow of indoor air to the outdoors should also be discouraged. These types of air leakages lead to excessive energy usage, poor thermal performance, and poor indoor air quality, as well as interfere with the normal operation of the HVAC system.

Ductwork System

Leakage in duct systems is responsible for most major problems in air distribution systems. Poor construction practices can cause leakage rates of up to 50%. This means that only half of the air that enters the supply duct will reach the intended occupied zone. With this level of loss, it is virtually impossible to maintain any degree of building pressurization. To avoid these leakage rates, HVAC systems should be designed to operate at the lowest acceptable supply pressure. High pressure in ducts only serves to encourage leakage. In existing systems, duct joints should be sealed. A number of accepted sealing techniques can be used.

Automatic Control Methodology

The degree of building pressurization achievable will be directly proportional to the HVAC system's ability to control and balance the introduction of outdoor air with the amount of air removed from the building. This can only be accomplished by satisfactory operation of the automatic control system for the HVAC system. There are three primary control methodologies in use today: pneumatic, electric, and digital. All three of these methodologies have proven to be effective as control systems. There are many advantages as well as disadvantages to each. It is incumbent upon the system designer to evaluate these and select the most advantageous system for pressurization, ventilation, and comfort control.

System Return-Air Fans

In some HVAC system configurations and designs, it is necessary to incorporate a return-air fan in the system. This is particularly true in variable air volume systems and dual-duct systems where the return-air system has a high pressure loss. The difficulties involved with return-air fans and the ability of the HVAC system to maintain building pressurization center around maintaining the synchronization of the return-air-fan operation and the system supply fan. If the supply fan and the return fan do not operate in harmony, imbalances in airflow can result. In the extreme case, these imbalances allow the building pressure to swing from positive to negative. Controlling these fans in order to eliminate imbalances in airflow is a difficult task. It is not enough to match fan speeds, since these fans operate with different characteristics, making speed an insufficient measure for balance. Usually, total flow or pressure is used to correct the imbalance. This practice is not without problems, however, because the question arises as to the best point in the total system at which to measure flow or pressure. The general design rule is to avoid using return-air fans if at all possible. However, as the building becomes larger in size, a return-air-fan will be required. Proper balancing of the return and supply air flows during the building commissioning, prior to first occupancy, is critical. Also, continued maintenance and regular calibration and testing of the return and supply fans and dampers are essential to avoid a negative pressurization.

Building Exhaust Fans

Powered exhaust systems are usually a requirement of building codes. Toilets, bathrooms, kitchens, workshops, and similar areas are required to be exhausted. In many buildings, the very nature and operation of individual exhaust systems defeat the HVAC system's ability to maintain building pressurization. The best practice is to design central exhaust systems. With central systems, the designer has the ability to provide some level of control over the operation of the exhaust systems.

Building Systems

The entire range of ALL-AIR category HVAC systems, by their very nature, will allow building pressurization. These systems have as a major feature the ability to provide and control wide ranges of outdoor air. It is not a difficult task to select and design an ALL-AIR system based upon the idea that it will provide building pressurization. It is an entirely different task to implement that design. Many of the obstacles that need to be considered and overcome were previously discussed.

The AIR-WATER SYSTEM is somewhat less acceptable for building pressurization. This is because the heating and cooling medium is a combination of air and water, and this means that the type of terminal units used will depend upon the amount of outdoor air used. If less outdoor air is used, then less control of building pressurization will be realized.

The ALL-WATER SYSTEM provides no means of outdoor air introduction. With this type of system, no means of providing pressurization for the building exists. Typically, buildings that are served by this type of system operate under depressurization, or negative pressure. Generally, this depressurization is the result of a combination of a lack of outdoor air and the operation of exhaust fans associated with toilets and bathrooms.

On the other hand, the UNITARY SYSTEM can be made to operate with the full range of outdoor air introduction and control available in the ALL-AIR SYSTEM.

SECTION 4

PROJECT OBJECTIVES AND EXPERIMENTAL PLAN

In accomplishing the project objectives the following activities have been included: (1) identification of candidate buildings, (2) selection of a representative subset of buildings for diagnostics and mitigation research, (3) developing standard diagnostic protocols applicable to large buildings, and (4) conducting diagnostic measurements and research in two selected buildings. The elements of this study plan are described below.

In preparation for the field study, the EPA, Southern Research Institute, and GEOMET made contacts to identify candidate buildings and contact building owners and/or managers to obtain agreements with regard to study participation and availability of buildings. Only those buildings whose owners agreed to full and continued participation were considered for selection.

The following basic criteria were used to select candidate buildings for evaluation:

(1) Large buildings which are representative of the Florida building stock and have radon levels higher than 4 pCi/L.

(2) Buildings with a minimum area of 10,000 square feet or three floors (excluding basements).

(3) Buildings and HVAC systems characteristic of Florida building stock.

(4) Buildings with owners/mangers willing to participate in the study and support study activities.

Preference was to be given to buildings with:

- Radon levels significantly higher than 4 pCi/L.
- Facilities (or Energy) Systems which are computer based and from which HVAC operating parameters may be recorded and reported.
- Owners willing to support or cost share in measurement and/or mitigation activities.

Standardized information relative to each building's construction type, HVAC type and operating procedures was collected to aid in the screening process. Short-term radon measurements were made in these buildings to verify elevated radon conditions. Measurements were carried out in accordance with "Indoor Radon and Radon Decay Product Measurement Device Protocols" (EPA92). From these measurements, a subset of preferred candidates were determined.

The exclusion of many buildings was necessary to accomplish study results which could be meaningful and consistent. The screening of a large number of buildings produced three buildings recommended for inclusion in this research project. Of these, two were used for the case studies reported in Sections 6 and 7.

Southern Research and the EPA selected three buildings, screened as described above, for more detailed diagnostic and mitigation strategy research. A team of building researchers conducted a preliminary site assessment of each of these buildings. The visit consisted of a walk-through of the facility and a review of all available building information and plans.

The preliminary assessment provided: verification of previously obtained information, more detailed information on type of building and occupancy patterns, and specifics on HVAC system configuration, air handlers, air supply, and operating schedules. Further, the team attempted to identify potential radon entry routes, and noted information on possible sampling locations and procedures. In view of the limited number of buildings available for study, it was important to select buildings which gave complementary information regarding construction or HVAC type. The two buildings that were selected to be studied consist of one unitary constant-volume flow system (having 23 separate air handlers), and one variable air volume control system (having one air handler).

The diagnostic measurements were a part of an experimental plan to develop a diagnostic protocol, identify radon mitigation strategies, and provide test data for the calibration of the Florida Radon Research Program (FRRP) integrated radon entry and building performance model "Florida Software for Environment Computation - User's Manual Version 3.0" [FSEC 3.0] (FSE92). The following data as core measurements were gathered in each building during the early stages of the field study:

(1) Verification of building data collected during the first site visits.

(2) Radon subslab sniffs to evaluate the radon source strength and the relationship between subslab and indoor radon levels.

(3) Pressure differential measurements throughout the building (to the outdoors and to the subslab) for various HVAC system operating conditions, (e.g., outdoor damper open and closed, exhaust systems on and off).

(4) Ventilation rate measurements via flow hood and duct traverses to determine the effect that various operating conditions of the HVAC systems have on radon levels in the buildings.

(5) Infiltration rate measurements using tracer gas to determine the effects that air infiltration rates have on diluting radon that enters buildings.

(6) Determination of the operating parameters for HVAC systems and the data logging capabilities of the building Energy Management Systems (EMS), if available.

In preparation for the parametric evaluations, a thorough survey of the flow patterns and balance of the HVAC system was performed. The measurements of the HVAC system were made by a certified

Test and Balance (TAB) Contractor of the National Environmental Balancing Bureau (NEBB) or other equally qualified TAB company.

After each building was evaluated based on the core measurements, a detailed measurement plan was developed for that building. This plan consisted of systematic study of the building over a range of HVAC settings. Depending on the types of HVAC systems available in the study buildings, it was necessary to override the normal system operation in order to simulate various operating modes. These modes of operation include:

(a) Adjustment of outdoor air (OA) intake from 0 to as much as 20 cfm/person, if possible under equipment and operation limitations.

(b) Control of the duty cycle operation of HVAC fans, including air handlers (AH), OA, and exhaust fans. Defined periods of on, off, and intermittent operation are necessary to test conditions driving HVAC system employment.

These HVAC operation modes were coordinated with the building managers and thus limited to weekends only. Each of these operation modes was allowed to run for at least 4 full days. Each building was fitted with sensors and data collectors to collect the following information at each building:

(a) Pressure differentials across the building shell and the building slab.

(b) Radon levels in the building, subslab, and ambient air.

(c) Flowrate measurements of outdoor air or outdoor air damper positions (calibrated to the outdoor air flow).

(d) Indoor air quality measurements of temperature, relative humidity, and carbon dioxide.

(e) Ventilation rates using tracer gases.

(f) Data on the HVAC system fan duty cycle operations and flowrates (taken by TAB company). These data would include run schedules, setpoints, and input and output data (temperatures, control signals, etc).

(g) Data on weather conditions at the building location.

These measurements were made in order to identify radon entry points and sources of pressure driven flow, to quantify the overall ventilation rate of the space, and to measure the impact of the HVAC systems operation on radon levels, ventilation rate, and pressure differentials. Data from these measurements were provided to Florida Solar Energy Center (FSEC) to be used in the model analysis to verify model predictions.

Measurements were completed on two large buildings in Florida. Section 6 describes the first study at the Financial Center North (FCN) Building located in Deerfield Beach. This building has a unitary HVAC system with 23 separate AHs, two outdoor air intakes; and contains office areas on three floors. Multiple zone measurements of radon, carbon dioxide concentrations, temperature, humidity, pressure differentials across the building shell and subslab areas, and outdoor air intake flowrates were collected over an 8 week period. The outdoor air intake was adjusted from 0 to 20 cfm/person (ASHRAE recommended levels) as a modification of pressurization and dilution of the indoor air conditions. Passive perfluorocarbon tracer (PFT) gas emitters were placed in all rooms, and detector sets were placed in all zones for each outdoor air intake level. Short term EPERM detectors were also used as an integrated sampling for each outdoor air intake level.

The second case study, described in Section 7, was conducted at the Polk County Life and Learning Center (LLC), located in Bartow. The same conditions and measurements described above were also made at LLC, with five data stations and a weather station installed and operated for 6 months. All stations were downloaded by phone modem and are collecting data analogous to those collected at the Deerfield Beach site.

Obviously, the findings of two case studies must be generalized to provide useful conclusions for a broad range of large building types. In each case study, data synthesis must be performed to find if correlations are observed which provide implications for mitigative strategies and could be used to guide design or operation of HVAC systems. To apply this information to a better understanding of all large buildings a unifying comprehension of all dynamic conditions must be achieved. This comprehensive understanding can only be achieved through the application of a computer model to study the many types and variations of HVAC systems.

Computer modeling of building dynamics is a viable tool in completely understanding the actions and interactions of various building components on indoor air quality. The use of building models, including those for zonal transport, ventilation, soil gas entry, and energy, is desirable and could enhance and extend the results of this study. Models such as FSEC 3.0 (FSE92), CONTAM (Axl 90) and COMIS (Feu 90) require extensive data input to produce successful results. An effort in modeling the study buildings was conducted in a parallel study by the Florida Solar Energy Center for the Florida Department of Community Affairs (DCA). The data from our studies have been processed through the FSEC 3.0 model and the correlations between exhibited and predicted examined. The validation of the model to predict large building responses to changes in design or operational controls and the limits of the ability to predict these responses was investigated (Gu 96).

Results of the FSEC evaluation of the second case study of this project (LLC) are published in a separate report, "Analysis of the Polk Life and Learning Center (PLLC)," FSEC - CR-739-94 (Gu96). In view of the applicability of this model to this and other studies, it is described briefly below.

One of FSEC 3.0's major features is its ability to solve user-defined systems of governing equations. Up to 250 coupled differential equations and their corresponding boundary conditions may be either selected from libraries or defined by the user. The equations may be linear or nonlinear, spatially lumped or spatially distributed, steady-state or transient, ordinary or partial. The structure of the software also allows users to incorporate their own routines or programs. Thus, researchers may define a specific problem and incorporate it into general software that provides the numerical framework for detailed computer simulation.

The software allows combined heat, moisture, and contaminant transport and system simulations at different levels of detail. For example, in considering a building that is composed of several solid and air interfaces where the solids include the envelope, internal walls, or furniture, and the air is either indoor or outdoor, spatially lumped or distributed equations may be used to define the characteristics of the solid and air domains.

FSEC 3.0 incorporates the necessary macrolevel and microlevel models needed for simulating radon in large buildings. In addition, several component level models are available to assemble different HVAC systems. These include models built from manufacturers' data and those obtained from other codes. Models to simulate VAV box performance have been also added.

A unique feature of FSEC 3.0 is that the user is not limited to any specific type of HVAC system. Rather, the user has the option to assemble individual components such as ducts, fans, fittings, coils, chillers, VAV boxes, and control elements and construct the desired HVAC system to be simulated. This was seen as a critical feature for the type of modeling required in this large building radon study.

SECTION 5

EXPERIMENTAL PROCEDURES

This project is examining how radon concentration and indoor air quality levels are affected by building ventilation dynamics and building air system conditions, including mixing and leakage rates of typical residential, commercial, and public structures, and HVAC components. The ventilation dynamics inherent to a building to dilute radon and indoor air pollution, and overcome soil gas entry forces, are being analyzed in an effort to develop diagnostic and mitigation protocols.

Large buildings, being complex in character, raise imposing demands on data needs. Project demands to measure many data parameters over time made it necessary to either utilize numerous individual monitoring sensors or develop a new data collection station system. Individual sensor units would put large demands on field personnel in time and individuals needed to collect data, and would have created quality control concerns. A centralized data collection system was needed to reduce technical support time and streamline data collection. Extensive data collection microcontroller requirements consisting of four 12 bit channels, seven 8 bit channels, three pulse channels, and three switch channels, and the high cost of existing centralized data collection systems made the development of a new system important to the project success.

Measurements required for this project include radon and carbon dioxide concentrations, temperature, humidity, pressure within indoor building zones and subslab areas, and outdoor air intake flowrates. The general experimental procedure includes adjustment of the outdoor air intake from levels of no outdoor air to recommended ASHRAE levels while monitoring pressurization and dilution of the indoor air conditions. Weather station information was recorded continuously on a separate data logging system. Real time data from instruments are downloaded by computer modem connection to allow for prompt evaluation and analysis, and minimize on-site time demands.

5.1 DATA STATION EQUIPMENT

The Large Building Instrumentation System is based on the Blue Earth Research Micro-440 microcontroller system. This device is designed for compact, low power (or battery-operated) applications, and contains the core hardware and software in the main unit. The only additional required hardware units are the 4-input 12-bit A/D converter and a power supply. A 12-volt rechargeable battery pack is included in the power supply to provide for continued operation during brief power failures. The built-in memory is large enough to save 20 days of data. If a longer period between downloading of data is desired, an additional memory module may be added to the system to give an extra 28 days of data storage. The devices are installed in a metal cage to give mechanical protection.

Each instrumentation node serves as a stand-alone system, requiring only electrical power to operate. A built-in battery allows the system to withstand brief power failures without loss of operation. Data may be downloaded on site with a portable computer used as a terminal or by using the built-in modem; the data may be accessed by telephone.

The microcomputer controlling the Blue Earth system uses a 1-second clock interrupt to pace data acquisition. It counts to 7 seconds and then reads each A/D converter and samples the input switch lines. The readings are added to averaging buffers which hold the intermediate values. After 256 loops the contents of the buffer are averaged and converted to one or two bytes of data. The 12- bit A/D converter values result in two bytes of data each, the 8-bit A/D converters and the switch registers produce one byte of data each, and the counter registers which are read at this time produce two bytes each. The elapsed time for the loop is 1792 seconds (7 X 256), so an added delay of 8 seconds before beginning the next loop produces sampling periods of 30 minutes (1800 seconds).

The real time clock is read at this time and the month, day, hour, and minute values are used to form the header for the data block, which is stored in the battery-backed RAM which is available in the system. The 4 date/time numbers and the 20 data value numbers are stored as a block in the next available space in memory.

The system contains rechargeable batteries which will provide about 8 hours of operation with the external power off. This will permit data acquisition to continue during brief power outages. If the power is off for a longer interval, data acquisition will stop but the data taken up to that point will be saved in internal battery-backed RAM. When power is reapplied, the system will reset and start taking data from that time. The system will operate automatically without any operator intervention.

For system control and data downloading, a computer configured as a terminal is connected to the RS-232 connector. The terminal operates at 2400 baud. Any one of the data channels can be checked for operation or calibrated via the RS-232 input. The channel number and the number of repetitions of the test are entered, and then that channel is exercised and the results printed out, with a delay between each repetition of the test.

The blocks of data stored in memory are identified by the month and day of acquisition. The month and day of the first data block to be downloaded are entered at the prompts, then the system searches memory for the first data block for that month and day. There are 48 blocks in each full day of data. When downloading starts, all of the data from the entry date to the current block are downloaded.

Several input channels are dedicated to the internal instruments on the data station, including a continuous radon monitor (FemtoTech Model R210F), a carbon dioxide monitor, two differential pressure transducers (Modus, typically -25 to +25 Pa full-scale), and temperature and relative humidity transducers. Additional pulse counting, A/D, and switch monitoring channels are available for other instruments if required.

5.2 TRACER GAS MEASUREMENTS

A number of techniques both passive and active are available for characterizing airflow and transport in a building by use of tracer gas. Perfluorocarbon tracer (PFT), devised at Brookhaven National Laboratories, is a passive method of characterization of airflow patterns in residential, large industrial, commercial, and office buildings using five varieties of gas and common detectors. The five types of passive emitter gases allow five zones to be monitored simultaneously for interzonal mixing, yielding an integrated average for the sampling period. With this technique, natural and mechanical ventilation rates and efficiency, natural infiltration, and overall HVAC system performance can be measured. Capillary adsorption tube samplers adsorb the steady state gases and are analyzed at Brookhaven. This type of measurement technique was used in FCN.

The most widely used and simplest technique is the tracer gas decay method which was employed at LLC. In this method a tracer gas is injected into a well-mixed zone of the building. Once the sulfur hexafluoride (SF_6) concentration becomes uniform, the injection is stopped and the concentration of gas is periodically sampled over a period of several hours. From the decaying concentration information the zone (or building) ventilation rate can be calculated. This technique is simple to perform and requires little expensive equipment. However, the measurements are not continuous, and the assumption of a well-mixed zone (or building) is often not realized. Also, although it is possible to perform multizone decay tests, the amount of time required for a single tracer gas is often over 8 hours, and the analysis is difficult and prone to errors.

Active multigas analyzers can give comparable data, but on a real time basis, reporting information several times each hour in four or more zones. The time between buildup and decay of tracer gas is minimized allowing multiple tests to be run and variation in HVAC control to be incorporated.

The constant injection technique is a very powerful but complex method. In this method, several different tracer gases are constantly injected into the building with each gas going into a different zone. Simultaneously, the concentrations of all the gases are measured in all of the zones on a continuous basis. For the case where the building can be considered a single zone, the air infiltration rate is simply a function of the rate of change of the concentration and the tracer injection rate. When more than one zone is called for, the equations governing the level of tracer gases are a series of coupled first order differential equations. The advantage of the constant injection method is the ability to continuously measure the air flowrates (interzonal and infiltration) in a multizone building.

PFT measurements were used at the Florida Financial Center Building while active continuous measurements were used at the Polk County Life and Learning Center.

5.3 DIAGNOSTIC MEASUREMENTS

A series of tests were done by FSEC at the LLC to characterize building airtightness, air flowrates, and pressure differentials. These measurements assist in understanding the driving forces for radon entry (pressure differential) and dilution (infiltration/ ventilation rate), and form the basis for much of the LLC computer modeling effort. While this information is also included by FSEC in their project report (Gu 96), their participation provided significant input to these project goals. Accordingly, sections of their procedures will be reproduced here and some of their results in Section 7 of this report.

5.3.1 Airtightness

Building or zone airtightness was done using blower doors; FSEC, like Southern Research, uses Minneapolis Blower Door Model 3. These units come from the factory with a rated accuracy of ±5%. FSEC has performed calibration checks on their blower doors since the fall of 1993, and have found them to be within the factory specifications. One of the FSEC blower doors was sent to the factory for a more precise calibration in early 1994.

The "Fan Pressurization" test method is essentially that used in ASTM Standard E779-87 (AST87). However our tests are done exclusively in the depressurization mode, because we believe that this more typically represents the true airtightness characteristics of the building. If a building is pressurized to +50 pascals, it is common for windows, exhaust fan dampers, dryer dampers, skylights, etc. to push open and thereby overrepresent the true leak area of the building. Also, repeating the test in the pressurization mode consumes more time and yields little additional useful information.

We obtain six or more "pressure versus air flow" data points, and do a best-fit curve to those points. The FSEC test data are input directly to a Quattro Pro file, which automatically calculates and plots the $Q = C(\Delta P)^n$ curve, the goodness of fit (r), CFM50, ACH50, EqLA, and ELA. Sample data are shown in Section 7. Because the results are computed instantaneously, we are able to assess the goodness of the test and repeat the test if necessary.

5.3.2 Air Flows

Air flows are measured by air flow hood, pitot tube traverse, or tracer gas injection. The air **flow hood** used by both FSEC and Southern Research is a Shortridge ADM-860. The FSEC hood was calibrated during the third quarter of 1993 using a bench-top TSI wind tunnel as the standard. Air coming from supply registers or going into return or exhaust registers is measured by placing the hood over the register/grill.

We use a **pitot tube** in conjunction with the ADM-860 micromanometer/computer and sample in a matrix of 5 by 5 (25 data points for the rectangular outdoor air ducts). In the round supply trunk ducts we used a cross section sampling technique of 10 points vertically and 10 points horizontally (20 data points). These points are averaged to obtain an average velocity, and this is multiplied by the cross-section area of the duct to obtain the volumetric air flowrate.

Tracer injection is also used by FSEC as a method for measuring air flows within a duct. They used tracer injection to measure the airflow rate of outdoor air, the two major supply trunks, and the total supply air through the air handler. A Gilmont (Cole-Parmer cat.#L-03202-00) flow meter, calibrated to either nitrous oxide (N_2O) or SF_6, was used to inject gas into the air stream. A Miran 101 was used to read the concentration of tracer gas downstream.

The flowrate of air can be calculated by knowing the injection rate and the gas concentration downstream, assuming that the gas is well-mixed in the air. Mixing is enhanced by injecting the gas in a distributed manner. For example, when injecting gas into the outdoor air stream at the LLC, FSEC divided the gas stream four ways and injected at four sides of the outdoor air intake fan (the fan would provide further mixing, as well). As the test is run, FSEC inputs the data directly into a Quattro Pro program which immediately calculates the air flowrate. By repeating the test 3 to 5 times, they are able to check for internal consistency and then average the values to reduce inaccuracy.

5.3.3 Pressure Differentials

Digital micromanometers are used to measure pressure in various zones of the building. Two types of instruments are primarily used: single-channel micromanometers from the Energy Conservatory (EC) or EDM, Inc. and a six-channel micromanometer with computer interface. The EC micromanometers have several features which make them ideal for use in measuring the small pressures which exist in buildings. They have resolution to 0.1 pascal and they have time averaging: 5 seconds, 10 seconds, or long term. When pressure differentials are small, say less than 1 pascal and there is fluctuation in pressures due to the wind, then the long-term averaging feature is invaluable. It provides a running average from the time of turn-on. By watching the value displayed on the screen stabilize, the observer knows when a good value has been achieved, often after a period of 5 to 10 minutes. We last calibrated these micromanometers during the fourth quarter of 1993, against an inclined manometer, several ADM-860 micromanometers, and against each other (typically agree within $\pm$ 0.1 pascal). These instruments have been found to be very accurate, and stable over time.

The six-channel micromanometer can measure all six channels simultaneously, plot them to a real-time screen display, average over specified time increments, and record them to computer memory. Plastic tubing can be attached to each of the six pressure ports, and run to distributed locations which are of measurement interest. This six-channel uses Modus micromanometers. Because their zero is subject to thermal drift, the assembly has been designed to rezero at each reading, about every 15 seconds. This procedure is also used by Southern Research Institute (with a 30 minute zeroing frequency).

5.3.4 Infiltration Rate

FSEC uses tracer gas decay tests of the type discussed in Section 5.2 to determine the infiltration rate/ventilation rate of the building. The gas detectors are Miran 101s and Bruel and Kjaer 1305. Two Miran 101s are available which can read SF_6 and N_2O, respectively. The Bruel and Kjaer can read both SF_6 and N_2O, simultaneously. The tests at the LLC were done with N_2O as the tracer gas, with both the Bruel and Kjaer and the Miran instruments.

The FSEC test method is as follows. We inject the tracer gas into the return air side of the air distribution system with the air handler operating. This distributes the gas. We then leave the unit on for a period of about 30 minutes to achieve good mixing. At the end of this mixing period, we typically take readings of indoor air concentration at 10 minute intervals and at a representative number of locations throughout the building. Tests at the LLC were done with sampling at four distributed locations throughout the building.

The air exchange rate is calculated based on the formula

$$\mathrm{ach} = \frac{60}{\mathrm{min}} \ln\left(\frac{C_i}{C_f}\right)$$

where

ach = air changes per hour
min = length of test period, minutes
C_i = initial tracer gas concentration, ug/m^3
C_f = final tracer gas concentration, ug/m^3

SECTION 6

RADON CASE STUDY 1: FINANCIAL CENTER NORTH

The first large building selected for a radon case study is the Financial Center North (FCN) Building in Deerfield Beach, Florida. This is a privately owned building that is presently being leased to the General Services Administration (GSA) for purposes of housing Financial Center North of the Internal Revenue Service (IRS). The Crown Diversified Industries Corporation presently owns the building.

6.1 BUILDING AND HVAC SYSTEM DESCRIPTION

The building is a combination office and warehouse/maintenance facility. It is constructed in two wings that form the shape of an L. Each of the two wings is three floors, with each floor in the north wing measuring approximately 5600 gross square feet (112 x 50 feet), and approximately 6200 gross square feet (124 x 50 feet), in the east wing floors. The warehouse/maintenance portion of the facility is located in the crook of the L shape. It is predominantly a two-story high bay space. This area of the building is primarily used by a maintenance staff that services an adjacent apartment complex also owned by Crown Diversified Industries Corporation. The maintenance/warehouse area measures approximately 10,450 gross square feet (110 x 95 feet). The entire building measures approximately 46,000 gross square feet and houses approximately 125 occupants.

The HVAC systems are of the UNITARY SYSTEM type and rely on 22 separate direct expansion split systems for primary cooling to the office spaces. All of the condensers are frame mounted and located on the roof. The system evaporators are located in ceiling hung air handler (AH) units in/or near the comfort zone being served. In addition to housing the evaporator, all of the AHs contain electric reheat coils that provide space heating. The AHs are also provided with a system of distribution ductwork consisting of supply, return, and outdoor air connections. Cooling and heating of the occupied space is controlled by wall mounted thermostats. Each AH is provided with its own individual thermostat. The heating and cooling capacities of each split system range in size from 2.91 tons cooling/7.2 kW heating to 9.16 tons cooling/15 kW heating.

Air is exhausted from the building primarily by three roof mounted power roof ventilators (PRVs), as well as toilet exhaust fans. The original HVAC design called for the outdoor air to be provided through two outdoor air risers (OARs) that, through a system of ductwork, were connected to the suction side of each AH. None of the OARs were originally powered by a fan. The introduction of OA was reliant on the ability of the AH fan to inject OA from the roof level down the OARs and into the intake of the AH. The original design specified that a total of 4500 cfm of outdoor air be introduced to the building. This quantity of outdoor air represents 10% of the total building supply air.

The building was designed to operate under a slightly positive pressure; that is, the outdoor air is being introduced at a greater rate (4,500 cfm) than the quantity of air being exhausted (2,310 cfm). This is a desirable mode of operation since outdoor contaminants can not infiltrate the building (see Appendix I, Financial Center North Initial Engineering Report).

6.1.1 HVAC System - Diagnostics and Modifications

In May 1991, the building owner hired Bailey Engineering Corporation (BEC), a certified HVAC TAB firm, to perform the following evaluations of the HVAC systems:

(a) Compare the original design criteria to current standards for ventilation requirements.

(b) Determine if the systems conform to the design drawings and specifications.

(c) Evaluate the actual system performance against the design and current requirements of ventilation as related to indoor air quality.

From this evaluation the following observations were made by BEC:

(a) The installation of the HVAC systems closely follows the original design configuration.

(b) Most of the AH thermostats are not being operated in a proper mode. Most are in the "auto" mode which cycles the AH off when space conditions are satisfied. When the AH is off, no outdoor air can be introduced into the building. Obviously this condition can reverse the building from positive pressure to negative pressure. This is an undesirable condition.

(c) Dampers installed in the OARs are all in the open position.

(d) Outdoor air quantities appear to be more than sufficient to satisfy ASHRAE Standard 62-1989 "Ventilation for Acceptable Indoor Air Quality" (ASH89). The design quantities would support 100 occupants per floor. This population is never realized.

(e) All HVAC equipment operates 24 hours a day.

BEC reported the following conclusions:

(a) Operating the AHs in the "auto" mode will not allow the HVAC systems to perform as intended by the original design.

(b) The building actually operates in a negative mode rather than a positive mode. This creates a situation where unfiltered, untreated infiltration air is brought into the space along with unwanted humidity and contaminants.

(c) Without performing a complete test and balance of all components, it is not possible to determine how closely the systems are performing to the original design parameters.

(d) The exhaust systems may very well be exhausting more air than was designed.

(e) It is unlikely that the low static pressure produced in the return air plenum of the AHs is capable of overcoming the static resistance of the OARs. This would result in less outdoor air being brought in than was intended by the original design.

Based on these observations and conclusions, BEC made the following recommendations:

(a) Operate all systems with the AHs in the "ON" mode to ensure constant AH operation.

(b) Perform a complete test and balance of each of the systems to verify that design requirements are met.

(c) Install time clocks on the exhaust fans to prevent unnecessary ventilation during the unoccupied hours.

(d) Install motorized dampers on the fresh air intakes that operate in concert with the exhaust fans.

(e) Energy savings can be realized by putting all AH operation on a time clock. This would prevent after hours operations.

(f) BEC should be provided with the energy history of the building from the last 24 months for determination of the potential energy savings.

In June 1991 the building owner continued the services of BEC to perform item b of the recommendations cited above. The complete test and balance of the HVAC systems was to be carried out in three phases:

Phase I <u>Preliminary testing</u>

Each system AH was to be tested to determine the following:

- total air flow (cfm)

- return air flow (cfm)

- outdoor air volume (cfm/occupant)

Phase II Engineering of system modifications

Design criteria was to be determined from the results of Phase I for the following required system components:

- new outdoor air fans

- automated dampers and actuators

- control system to interlock all system components for balanced ventilation

Phase III Final testing and balancing

After all system modifications were complete, a final test and balance was to be performed to ensure that proper ventilation standards are maintained and that control strategies are functioning as designed.

In June 1991 BEC began Phase I, and their primary finding was that the outdoor air actually being introduced to the building by the AHs was 21% of the volume called for in the original design. This quantity of outdoor air satisfies the GSA lease requirements of 5 cfm per person occupancy. The actual tested volume of outdoor air would be sufficient for 192 occupants but not sufficient to meet the ASHRAE Standard 62-1989 requirement of 15 cfm/person occupancy. BEC also reported that the low volume of outdoor air is not sufficient to offset the volume of exhaust air. This creates the undesirable condition of building negativity mentioned previously. BEC recommended that the following additional engineering items be required before the systems could perform as designed:

(a) New outdoor air supply fans were to be installed on the OARs.

(b) Motor operated dampers were to be installed on the OARs to close when the supply fans are not in operation. This would prevent uncontrolled outdoor air from entering the building during unoccupied hours.

(c) The new outdoor air fans were to be controlled by time clocks to operate only during occupied hours. The existing exhaust fans were to be controlled by the same time clocks on the same operating schedule.

The building owner complied with all of these recommendations and in January 1992, the final test and balance was performed. BEC found that the new outdoor air fans that they recommended were not operating to specified catalog specifications. BEC measured the outdoor air quantities at about 3000 cfm total being introduced by the new outdoor air fans. The new outdoor air fans raised the level of outdoor air from 21% to about 66% of design. Using the ASHRAE Standard 62-1989, this new quantity of outdoor air would support 200 occupants (3000 cfm/15 cfm per occupant). BEC reports no more than 102 occupants in the building at any time (17 occupants per floor x 6 floors).

At the time of our study, the building was being operated in this mode (see Appendix II, Financial Center North HVAC System(s) Test and Balance Reports).

6.2 EXPERIMENTAL PLAN: OUTDOOR AIR VARIATIONS

For the purposes of this part of the study, it was agreed that the primary feature of the HVAC systems in mitigating radon is pressurization of the building.

It was decided to operate the HVAC systems in four different modes of building pressurization while collecting data. These modes of operation were determined by our ability to vary and control the amount of outdoor air allowed to be introduced into the building while maintaining supply and exhaust at known quantities.

The four modes are:

Mode 1 Operate the system(s) with no outdoor air from the outdoor air supply fans. No changes in the supply or exhaust air quantities.

Mode 2 Operate the system(s) so as to provide 5 cfm/occupant. No changes in the supply or exhaust air quantities.

Mode 3 Operate the system(s) so as to provide 15 cfm/occupant. No changes in the supply or exhaust air quantities.

Mode 4 Operate the system(s) so as to provide 20 cfm/occupant. No changes in the supply or exhaust air quantities.

These predetermined modes of operation describe situations from complete system shutdown of OA quantities to those recommended in ASHRAE Standard 62-1989. Mode 1, no OA, would be considered the worst case scenario. Under this mode of operation, the building is under complete negative pressure and all OA is through infiltration. As OA supplied to the AH increases, infiltration decreases resulting in no change in supply or exhaust quantities, although increasing OA causes increased pressurization throughout the building. Mode 2 would simulate the OA requirements illustrated in the Florida Administrative Code chapter 6A-2 (FAC94) that controls the amount of outdoor air to 5 cfm/occupant. Modes 3 and 4 would be variations on the ASHRAE Standard 62-1989 (ASH 89) using 15 and 20 cfm/occupant, respectively.

The following schedule indicates the time-frame of data collection for each mode of operation:

Mode 1 data were collected from July 3 to 6, 1992.

Mode 2 data were collected from July 6 to 15, 1992.

Mode 3 data were collected from June 16 to July 3, 1992.

Mode 4 data were collected from July 15 to 27, 1992.

For Mode 1, the BEC closed the outdoor air intakes with polyethylene to ensure a complete nonporous seal. Mode 1 was accomplished over a weekend since the building owner would not permit the HVAC systems to be operated without outdoor air during normal working hours.

For Mode 2, BEC balanced the HVAC systems so that the measured outdoor air intake was actually 5.5 cfm/occupant. Mode 3 was measured at 13.6 cfm/occupant. Mode 4 was 19.5 cfm/occupant (see Appendix II, Financial Center North HVAC System(s) Test and Balance Reports).

6.3 DATA AND ANALYSIS

Data were collected from the data stations by downloading data files through the internal modem by telephone connection. The information was converted into usable numbers, calibrated, and put into graphs and tables. Data files were analyzed and compared to other information, such as maintenance practices.

The FCN data are limited in scope due to instrumentation difficulties that were later corrected for the second case study. FCN results are limited to radon concentrations and some PFT tracer gas measurements. A description of part of the resulting data follows. The current extent of the data analysis is limited to a qualitative discussion of carbon dioxide levels and a quantitative comparison of radon levels and building HVAC activity. The FCN building is used as office space and as such was occupied largely during weekday periods from 8 AM to 5 PM. Carbon dioxide levels as expected peaked during the weekday periods. Radon correlated to outdoor air levels, temperature, pressure, and relative humidity, and PFT analysis from Brookhaven National Laboratory are included in graph and table form respectively in Appendix III.

6.3.1 Radon

The FCN had initially exhibited radon levels of approximately 10 picocuries per liter (pCi/L), during GSA screening measurements, which are above the EPA action level guideline of 4 pCi/L. In early 1992, Radon Environmental Testing Corporation was requested to provide radon measurement and mitigation service to the building management. Passive sealing of slab cracks and penetrations was provided as well as increasing the level of outdoor air by installing supply fans. This reduced radon levels to below the 4 pCi/L guideline and generally subjectively improved indoor air quality. By intentionally reducing the outdoor air intake an increase in radon concentrations was exhibited to a peak level above 4 pCi/L throughout the building (see Appendix III for all data). Distinct average levels of radon can be identified from the graphs for a consistent level of outdoor air intake. A comparison of radon levels versus outdoor air intake flowrate is evident in Figure 1. The building average concentration at 0 cfm (per occupant) was 2.6 pCi/L as compared to 1.8 pCi/L at 5.5 cfm, 1.2 pCi/L at 13.6 cfm, and 1.0 pCi/L at 19 cfm. These values are shown in Table 1.

TABLE 1. AVERAGE RADON MEASURED AT THE FCN UNDER RANGE OF OPERATING MODES

Outdoor Air Input (cfm/pp)	Building Ventilation (ACH)	Average 1st Fl. Radon (pCi/L)	Average 2nd Fl. Radon (pCi/L)	Average 3rd Fl. Radon (pCi/L)	Average Building Radon (pCi/L)
0	0.2	2.5	2.6	2.6	2.6
5.5	0.4	1.5	1.8	2.2	1.8
13.6	0.5	1.1	1.4	1.2	1.2
19.0	0.6	0.9	1.0	1.2	1.0

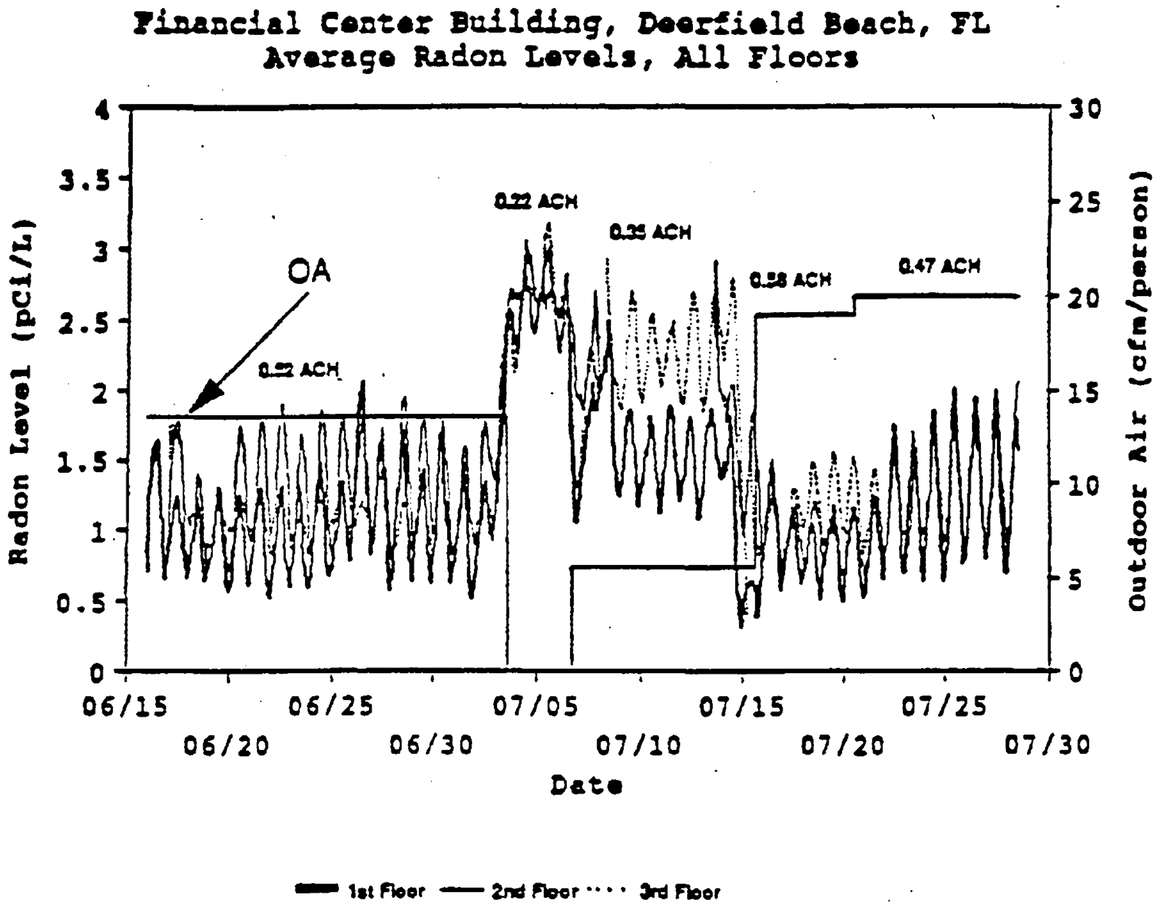


Figure 1. Average radon concentrations at Financial Center North during parametric study of outdoor air variations.

A reduction correlated with increased OA is present; however, due to imprecision in measurement and expected fluctuations in radon concentrations it is not possible to clearly use this result as a basis for forming conclusions. These results are shown in Figure 1 where the average radon values are plotted as a function of time (date) along with the levels of OA and the results of the tracer measurements (ventilation rates).

6.3.2 Tracer Gas

A number of techniques both passive and active are available for characterizing airflow and transport in a building by use of tracer gas. Perfluorocarbon tracer (PFT), devised at Brookhaven National Laboratories, is a passive method of characterization of airflow patterns in large industrial, commercial, and office buildings using five varieties of gas and common detectors. The five types of passive emitter gases allow five zones to be monitored simultaneously for interzonal mixing, yielding an integrated average for the sampling period. With this technique natural and mechanical ventilation rates and efficiency, natural infiltration and overall HVAC system performance can be measured. Capillary adsorption tube samplers (CATS) adsorb the steady state gases and are analyzed at Brookhaven.

Enclosed in Appendix III are the results of the six measurement periods performed in FCN plus a general description of the output data. The interzonal flow results in the building are of less interest than the overall building ventilation results. These are shown in Table 1. The ventilation in terms of building air changes per hour (ACH) correlate quite well with the measured OA flowrates.

SECTION 7

RADON CASE STUDY 2: POLK COUNTY LIFE AND LEARNING CENTER

The second case study in this project was conducted at the Polk County Life and Learning Center (LLC). While some of the same measurement techniques were used at this building as for the previous study at the FCN, the experimental and analytical sequences were much more detailed.

The LLC consists of three buildings: The Center for the Trainable Mentally Handicapped, the Severely Handicapped Center (two classroom addition), and the Greenhouse. The Center for the Trainable Mentally Handicapped and the Greenhouse were designed in 1974 and built in 1975. The Severely Handicapped Center was designed in 1984 and constructed in 1985. This study focuses entirely on the LLC Center for the Trainable Mentally Handicapped.

7.1 BUILDING AND HVAC SYSTEM DESCRIPTION

The LLC building is a single-story training/school building of approximately 18,000 gross square feet in size. It consists of staff office space, classrooms, a large multipurpose room, a kitchen, janitorial closets, and a woodshop. The facility houses 103 students daily along with 22 staff members for a total of 125 occupants. Architecturally, the building is constructed as a slab-on-grade. The slab is 4-inch reinforced concrete on compressed fill and provided with a vapor barrier. The vapor barrier is assumed to be polyethylene (the drawings are not specific). The walls of the Center are 8-inch CMUs (concrete masonry units; i.e., blocks) with stucco exterior and 5/8-inch gypsum board on 1- x 2-inch furring strips on the interior. The roof system consists of wood truss construction with asphalt shingle roof tiles over the majority of the roof. However, in some areas the roofing consists of rolled mineral roofing material. The interior ceilings are either lay-in tile or painted gypsum board. All windows are either aluminum frame single hung or bay windows. The interior walls are gypsum board on wood studs with interior ceiling heights of typically 9 feet except for the central area used as a cafeteria/auditorium. The LLC is divided into four fire control zones by means of rated 5/8-inch gypsum board that extends to the tectum decking below the roof. However, numerous openings between zones (some as large as 2 x 4 feet) tend to merge the separate zones into one or two larger zones. The floor plan of the LLC is shown in Figure 2, which shows the locations of the fire walls which divide the building into roughly four zones (although the zones appear to be well coupled).

The LLC is heated and cooled by an ALL-AIR system composed of a single main air handler (AH) unit. The AH provides cooling to the Center by means of a 21 ton (252.0 MBH) direct expansion split system and a distribution system of supply ductwork. The system is low pressure (2.5 inch WG) and utilizes a single supply duct and a ceiling plenum return air system. The individual rooms and zones are environmentally controlled by variable-air-volume (VAV) boxes mounted above the ceiling in the return plenum. Wall-mounted thermostats control the VAV boxes.

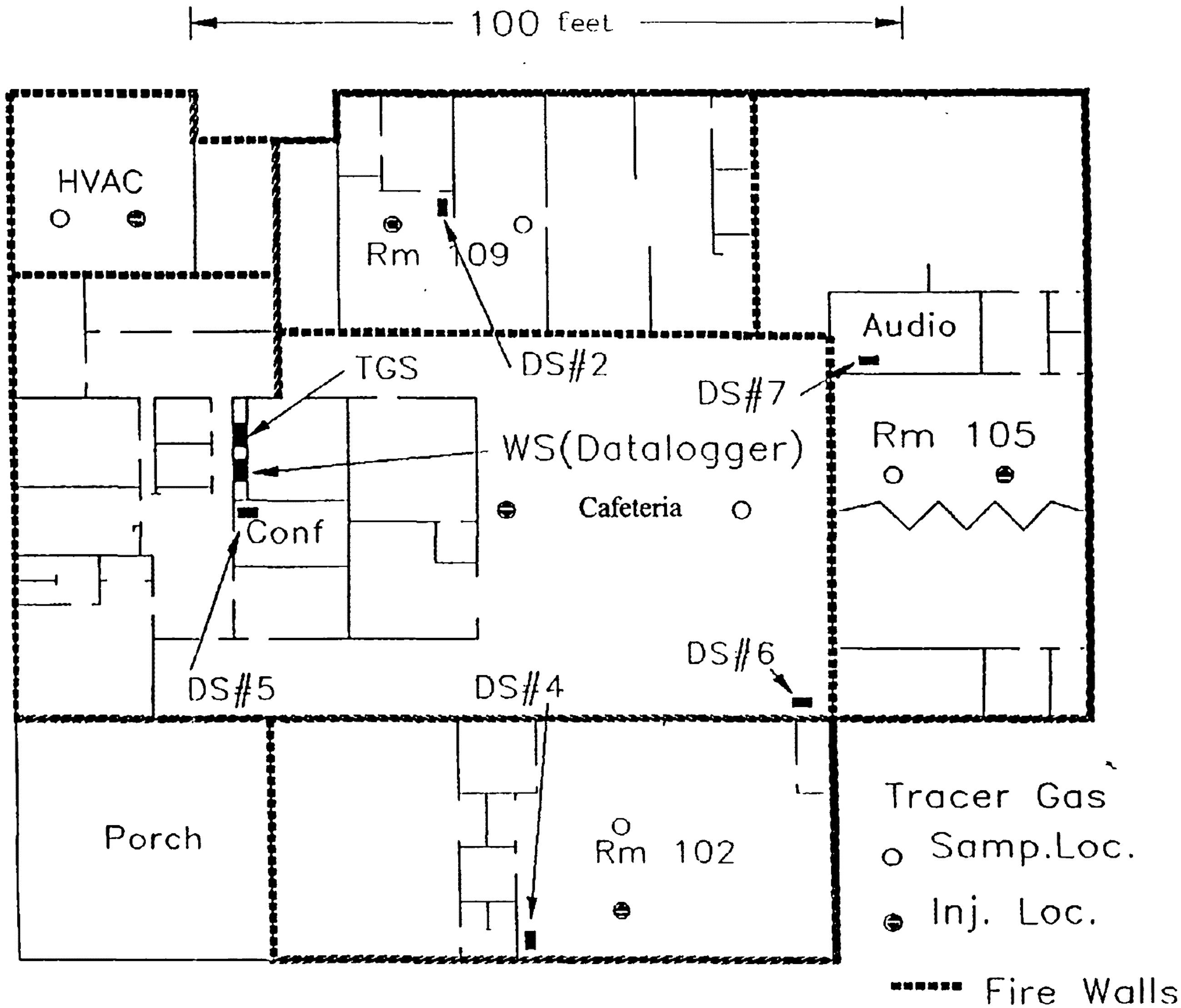


Figure 2. Floor plan of LLC showing locations of EPA data loggers (DS), tracer gas system (TGS), and weather station (WS) data logger.

The introduction of outdoor air is controlled by a roof-mounted supply fan (F-1). This fan initially could provide up to 1200 cfm of unconditioned outdoor air (OA) directly to the AH return air plenum. Refer to Appendix IV. The OA then mixes with the building return air. The AH has the capacity to supply 5620 cfm at conditions of 57°F dry bulb/56°F wet bulb which gives the machine a rating of approximately 21 tons. This is approximately 1.2 tons per 1000 ft^2 which constitutes a greatly oversized capacity. Based on the Florida Administrative Code, Chapter 6A-2 requirements of 5 cfm per occupant, the Center could house 240 occupants. The actual occupancy of 120 people increases the OA per occupant to 10 cfm per occupant (1200 cfm/120 occupants).

Heat for the LLC building (via AH) is provided with a 15 kW strip heater. In addition, each VAV box that serves a space that is adjacent to an exterior wall is provided with an additional strip heater. VAV box strip heaters are controlled by the room wall-mounted thermostat. The building is served by a total of 26 VAV boxes that are sized for a full air-conditioning load of 11,305 cfm. The boxes are set for a minimum setting of 40% of full load. The diversity factor (100 times the ratio of the sum of the individual VAV box capacities divided by the AH capacity, i.e., 100 x [5620/11,305]) is calculated to be approximately 50% for the VAV box operation.

Exhaust air from the LLC is through the use of 14 exhaust fans located in the toilets, bathrooms, janitor closets, workshop, and kitchen. The total design building exhaust from these 14 fans is 2350 cfm when all are operating.

Initial radon measurements were made at the LLC by the Polk County Health Unit during the 1990-91 and 1991-92 school years. The results are summarized in Table 2 and shown graphically in Figure 3. From Figure 3 it can be seen that the radon levels are fairly independent of the seasons and most always lie above the EPA guidelines. In Figure 4 the measured radon levels in the LLC building are plotted as a frequency histogram. It is seen in this figure that the average level shifts somewhat toward higher values during the Fall compared to the values measured in the Spring. However, overall the readings are fairly constant. The locations of the annual average radon levels listed in Table 2 are shown schematically in Figure 5.

7.2 INITIAL BUILDING INSPECTION AND HVAC MODIFICATIONS

Based upon inspection of the design plans for the building, it was easy to see that this building may have been operated in an undesirable HVAC negative pressure mode. Since the maximum outdoor air quantity was 1200 cfm and the exhaust quantity was 2350 cfm, the building may have been operated negative by about 1150 cfm or less. To compound this imbalance, the outdoor air fan was set to shut off when the return air temperature was below 70°F or above 80°F. The fan controls would only allow the outdoor air fan to operate when the return air temperature was in the range of 70-80°F. This condition of little or no outdoor air also violates the minimum outdoor air requirements of Chapter 6A-2 of the Florida Administrative Code, paragraph 6A-2.066 Ventilation, subparagraph (2)a-2 (FAC94), that calls for a minimum of 5 cfm of outdoor air per occupant at all times of occupancy.

TABLE 2. POLK COUNTY LIFE AND LEARNING CENTER
PHASE 3 TESTING RESULTS
1990-91 AND 1991-92 SCHOOL YEARS

Sample Location	Fall Radon Level (pCi/L)	Winter Radon Level (pCi/L)	Spring Radon Level (pCi/L)	Annual Average Radon Level (pCi/L)
1	12.9	10.9	8.3	10.7
2	12.2	9.9	9.2	10.4
3	11.1	9.6	8.5	9.7
4	11.7	9.9	10.2	10.6
5	*	*	*	*
6	14.0	8.4	8.9	10.4
7	12.6	8.1	9.0	9.9
8	12.3	9.8	8.2	10.1
9	11.4	8.5	9.1	9.7
10	12.7	5.7	7.4	8.6
11	14.0	7.6	8.8	10.1
12	14.4	7.9	8.8	10.4
13	*	7.5	8.6	*
14	12.8	9.6	8.4	10.3
15	12.4	9.3	8.9	10.2
16	13.6	10.8	9.5	11.3
17	18.7	19.1	13.1	17.0
18	11.6	9.0	8.7	9.8
19	13.2	10.5	7.1	10.3
20	11.4	9.7	8.0	9.7
21	12.0	10.0	10.0	10.7
22	12.6	10.9	8.8	10.8
23	12.8	9.3	8.9	10.3
24	11.7	8.7	7.6	9.3
Bldg. Average	12.8	9.6	8.9	10.4
High	18.7	19.1	13.1	17.0
Low	11.1	5.7	7.1	8.1
Std.Dev.	1.6	2.4	1.2	1.6
CV (%)	12.1	24.7	13.0	15.1

* Data not available.
CV - Coefficient of Variation

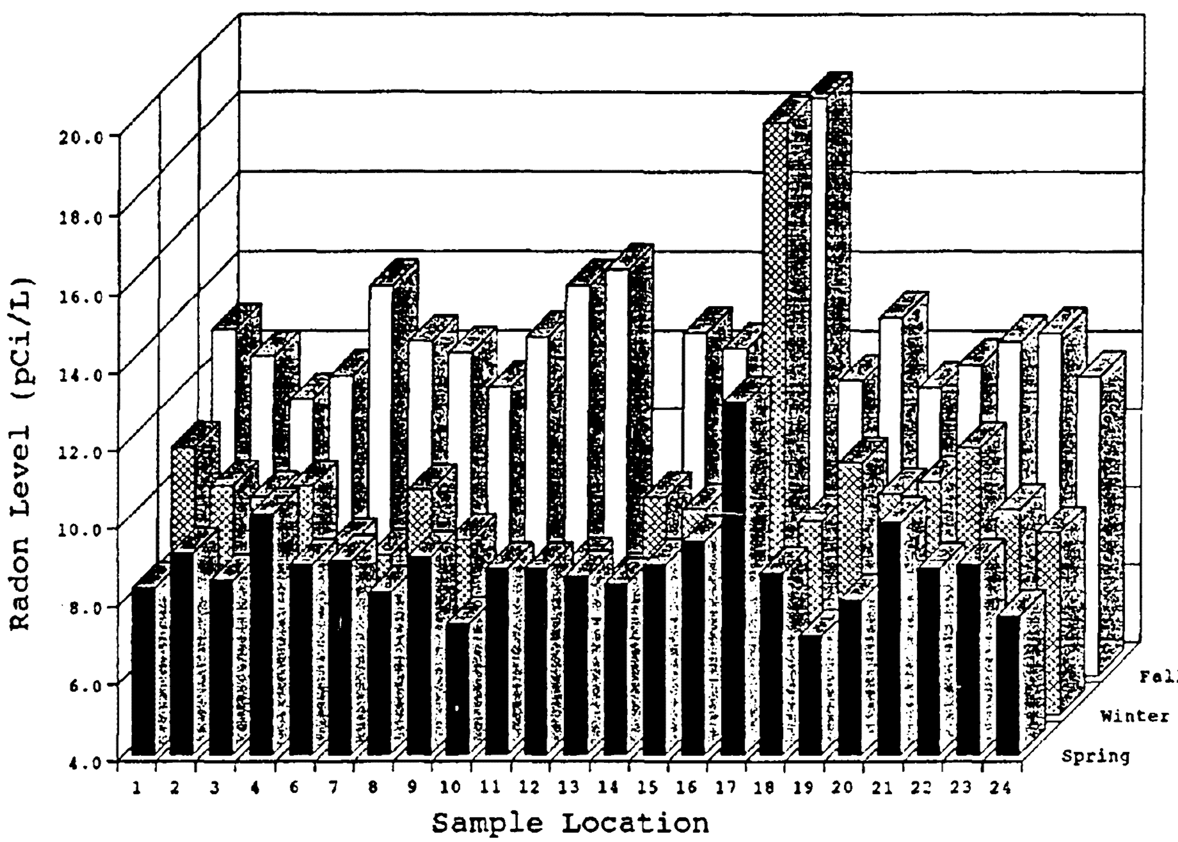


Figure 3. Results of the Phase 3 radon tests at Polk County Life and Learning Center as carried out by the Radiological and Occupational Health Section, Polk County Public Health Unit during the 1990-91 and 1991-92 school years.

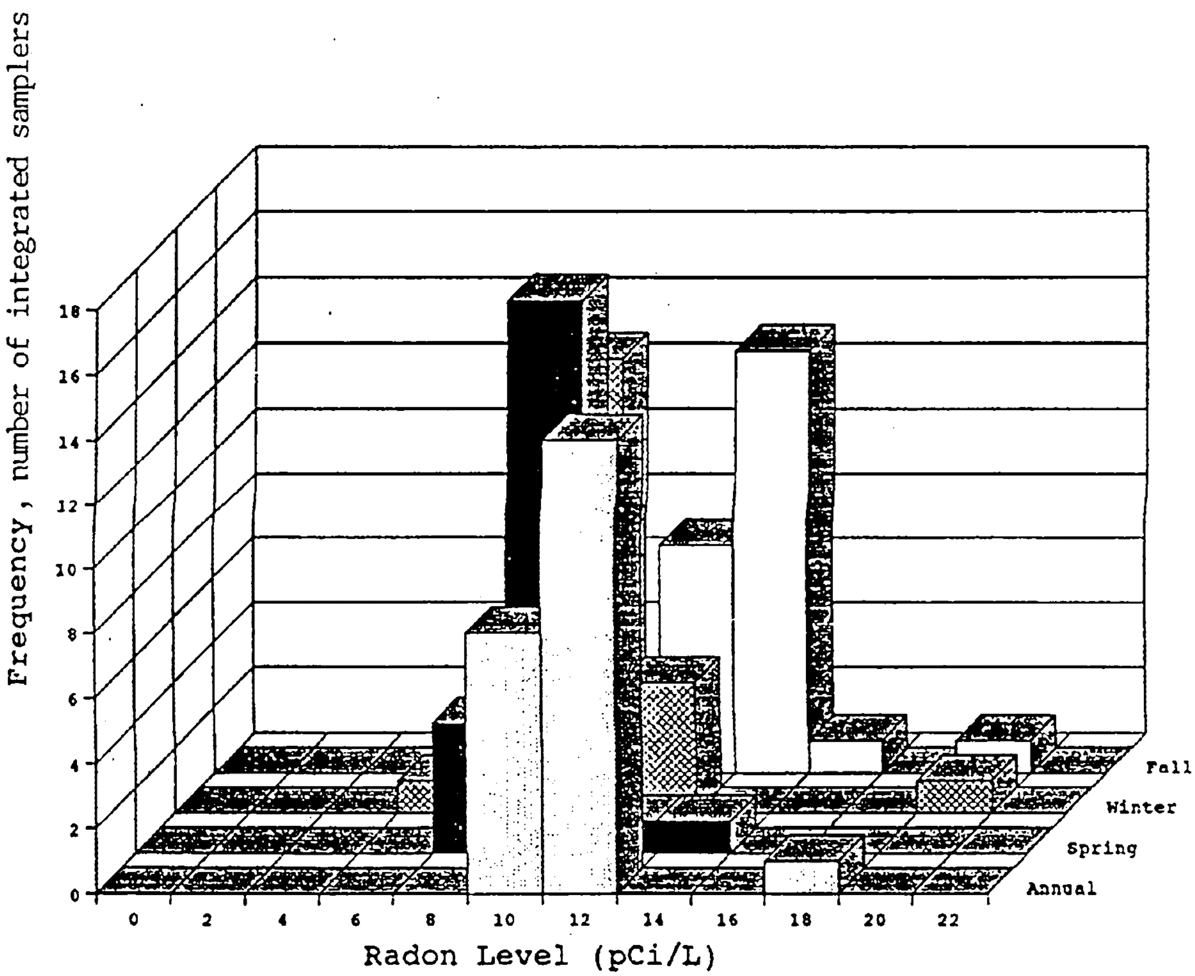


Figure 4. Frequency histogram of the radon levels measured at Polk County Life and Learning Center.

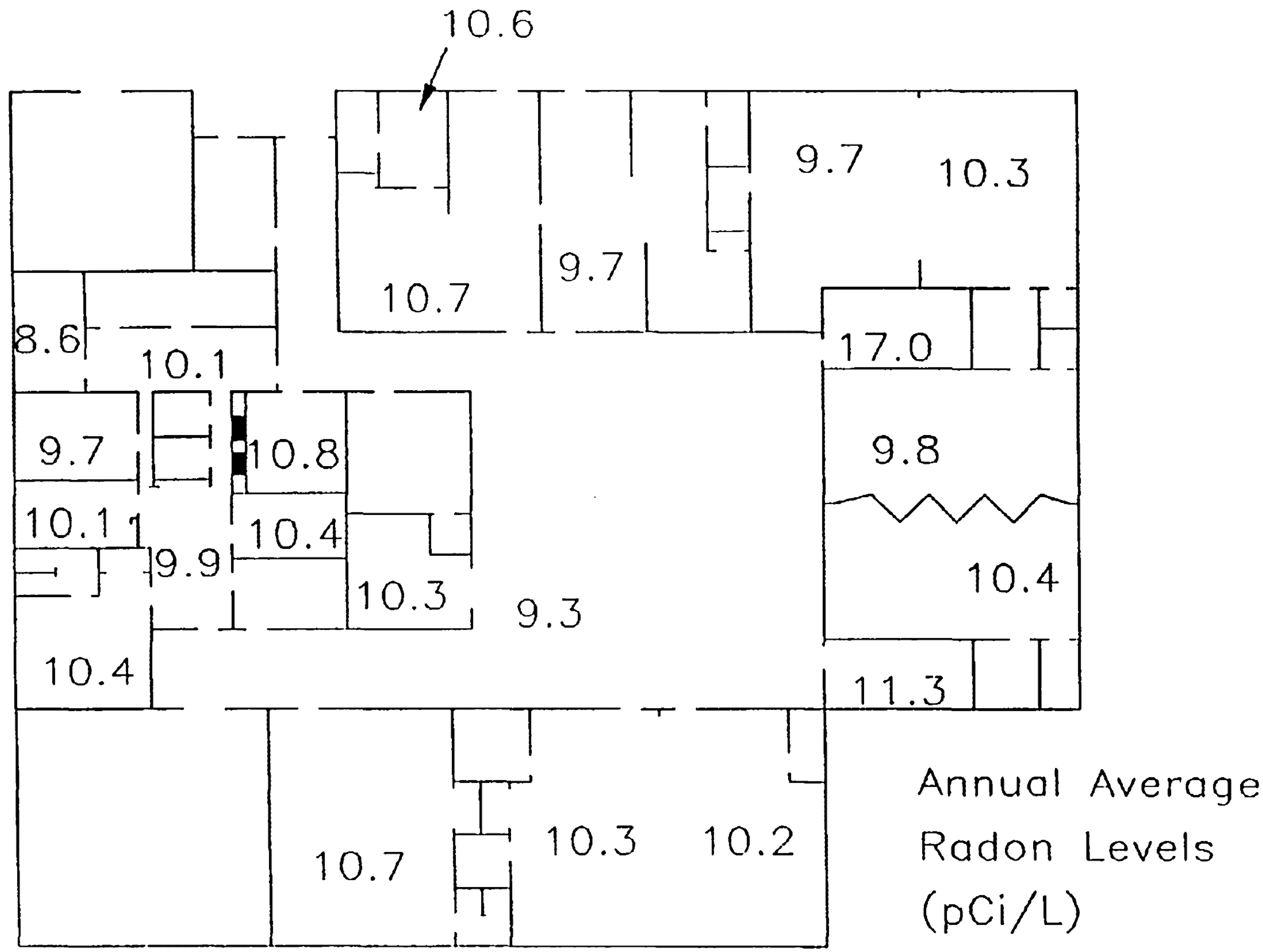


Figure 5. Locations of the radon values shown in Table 2 as measured in the LLC Phase 3 testing program.

In order to ready the LLC for instrumentation, a certified HVAC Test and Balance (TAB) firm was contracted (the Phoenix Agency, Inc.) to perform the following steps:

1. Building Pre-Balance Survey

    a. Review the design plans and become familiar with the design of the HVAC systems.

    b. Visit the site and evaluate the condition of the HVAC system and determine what components of the HVAC system are in need of replacement, repair, or renovation in order for the system to operate as desired.

    c. Develop a "punch list" of repair items for the Polk County authorities who will provide all repairs and maintenance.

2. Building Pre-Balance Survey: Re-visit the LLC after all repairs are made to confirm that the systems are ready for final air balancing.

3. Building Air Balancing: Air balance the HVAC systems.

On November 5, 1992, the Phase I System Survey was performed by the test and balance firm (The Phoenix Agency, Inc.) and the complete results of this survey are included as APPENDIX V. Some of the more serious deficiencies found were that the outdoor air fan (F-1) was installed backwards on the motor shaft, and the motorized damper for the OA fan was frozen in the closed position. Other deficiencies identified include: leakage from the supply air on both sides of the VAV boxes; in the main supply duct feeding all the VAV boxes, several of the VAV control mechanisms were inoperative; and four exhaust fans were inoperative. A list of the building deficiencies was sent to school officials on about November 10, 1992. It was agreed that the Polk County School System would fund all "punch list" items and the EPA would fund the TAB fee and fan replacement.

The LLC was instrumented with five of the EPA data logging systems on October 27-29, 1992. School maintenance personnel implemented a repair procedure at the LLC to correct the deficiencies detected in the building during the walk-through on November 5, 1992, and as described in the building pre-balance survey carried out by the TAB company. These repairs were completed during the latter part of January 1993. During December, the Phoenix Agency, Inc. (PAI) replaced the outdoor air supply fan and damper. The as-found condition of the building was such that little or no OA was being supplied to the building. The only ventilation was through openings in the building shell. This was evident from the odors that persisted in several of the rooms and in particular in Room 105. The new OA fan is capable of supplying 3000 cfm of outdoor air. Also during the last week of January, repairs were carried out to correct a problem in the EPA data loggers. This involved shorting out a base resistor in the solenoid-zero circuit in order to increase the current flow to the zeroing solenoids. Also during this time, an additional Campbell 21X data logger was installed in LLC to carry out parallel measurements of some of the parameters measured by the EPA data loggers. Additional parameters were also measured by this data logger.

The data taken at the LLC include:

- Data sampled as summarized in Table 3, which include continuous radon at six locations, subslab to room pressure differences at five locations, room to outdoor pressure differences at seven locations, ambient outdoor temperature, RH, wind parameters, local barometric pressures, temperatures in the building at seven locations, outdoor air (OA) flowrates into the HVAC system, and operation of bathroom exhaust fans in five locations.

- Air movements within the building and infiltration/exfiltration measurements using Southern Research's multi-gas tracer system.

TABLE 3. LOCATIONS AND DATA SAMPLED AT THE LLC

	Room 102	Room 104	Room 109	Cafe	Conf	Mech Room	RA Plenum[1]
Continuous Radon Levels	*	*	*	*	*	*	
Δp Room to RA Plenum	*	*	*	*	*	*	*
Δp Subslab to RA Plenum	*	*	*	*	*		
Δp to Outdoors				*			*
Temperature	*	*	*	*	*	*	*
Relative Humidity	*	*	*	*	*		
CO_2	*	*	*	*	*		
Exhaust Fan Operation	*	*	*	*	*		

[1]The RA Plenum includes the entire attic area above the suspended ceilings.

7.3 1993 PARAMETRIC STUDY

7.3.1 Experimental Sequence

Testing at the LLC was carried out using the matrix of conditions shown in Table 4. Generally, each OA flowrate condition occupied a week of testing. The exhaust-fan-on condition was maintained over 1-1/2 days of the weekend, and the exhaust-fan-off condition at nights and the remainder of the weekend. Typically, the HVAC fan operated on a 12 hour on/12 hour off cycle each day.

TABLE 4. TEST MATRIX FOR LLC EVALUATION

HVAC (ON/OFF)	BATHROOM FANS (ON/OFF)	OA FLOWRATE (CFM/PERSON)
OFF	OFF	0
OFF	ON	0
ON	OFF	0 5 10 15 20
ON	ON	0 5 10 15 20

Final balance of the HVAC system in the LLC was carried out on February 4, 1993, by The Phoenix Agency, Inc. Testing was begun on Friday, February 5th, with the Outdoor Air (OA) damper set to deliver approximately 3000 cfm (or 20 cfm/person based on an occupancy of 150 persons) OA into the building. The HVAC system was also set up to come on at 6:00 am and go off at 6:00 pm. Over the weekend days, Saturday and Sunday (the 6th and 7th of February), the exhaust fans in the restrooms of the building were set first to be off from Friday around 5 pm until Saturday about 3 pm at which time all operable fans were turned on until Monday morning when the teachers arrived and turned them off. This procedure was followed during each weekend of the testing period. On Friday, February 19th, the OA damper was closed and the OA fan turned off to create the condition of 0 OA intake. The exhaust fans were operated as described above. Data were downloaded from the five EPA data loggers and the Campbell 21X at least once per week for later analysis. The specific schedule of experiments is as follows:

Testing of the LLC building continued during March. On March 5th, the OA damper was set to provide roughly 750 cfm of outdoor air, or approximately 5 cfm/person. This test was plagued with problems with the data loggers, the tracer gas system, and the HVAC system itself. Consequently, the same test conditions were run the following week of March 12th. On March 19th, the OA damper opening was increased to 3000 cfm (20 cfm/person). The building was operated in this condition until March 26th when the OA damper opening was reduced to 2250 cfm or 15 cfm/person. The building was operated in this manner until April 2, 1993.

Jan 18-22

Polk County personnel complete repairs to the HVAC system in the Life & Learning Center (LLC).

Jan 29-Feb 1

Southern Research Institute work on EPA data loggers to improve Dp cell zero, and install Campbell based data logger to supplement EPA data loggers.

Feb 3-4

TAB company (PAI) return to LLC to carry out rebalancing of system.

Feb 5-12

Test Week #1, 20 cfm/person OA, HVAC on from 6 am to 6 pm seven days/week, run building with all exhaust fans off from 3 pm Friday (2/5) to 3 pm Saturday (2/6) and all fans on over the period from 3 pm Saturday (2/6) until about 7 am Monday (2/8), during weekdays (2/8-2/12) exhaust fans at normal operation, perform radon grabs under slabs in each data location on Friday and read EPERMs.

Feb 12-19

Test Week #2, 0 cfm/person OA, expose EPERMs (2/15-2/19), run tracer gas system, HVAC on from 6 am to 6 pm seven days/week, run building with all exhaust fans off from 3 pm Friday (2/12) to 3 pm Saturday (2/13) and all on over the period from 3 pm Saturday (2/13) until 7 am Monday (2/15), during weekdays (2/15-2/19) exhaust fans at normal operation, perform radon grabs under slabs in each data location on Friday and read EPERMs.

Feb 19-26

Test Week #3, 8 cfm/person OA, expose EPERMs (2/22-2/26), run tracer gas system, HVAC on from 6 am to 6 pm seven days/week, run building with all exhaust fans off from 3 pm Friday (2/19) to 3 pm Saturday (2/20) and all on over the period from 3 pm Saturday (2/20) until 7 am Monday (2/22), during weekdays (2/22-2/26) exhaust fans at normal operation, perform radon grabs under slabs in each data location on Friday and read EPERMs.

Feb 26-Mar 5

Test Week #4, 5 cfm/person OA, expose EPERMs (3/1-3/5), run tracer gas system, HVAC on from 6 am to 6 pm seven days/week, run building with all exhaust fans off from 3 pm

Friday (2/26) to 3 pm Saturday (2/27) and all on over the period from 3 pm Saturday (2/27) until 7 am Monday 3/1, during weekdays (3/1-3/5) exhaust fans at normal operation, perform radon grabs under slabs in each data location on Friday and read EPERMs.

Mar 5-Mar 12

Test Week #5, because of equipment failure the test from the previous week was repeated during this week.

Mar 12-Mar 19

Test Week #6, repeat the tests of Test Week #1, 20 cfm/person OA, expose EPERMs (3/15-3/19), run tracer gas system, HVAC on from 6 am to 6 pm seven days/week, run building with all exhaust fans off from 3 pm Friday (3/12) to 3 pm Saturday (3/13) and all on over the period from 3 pm Saturday (3/13) until 7 am Monday (3/14), during weekdays (3/15-3/19) exhaust fans at normal operation, perform radon grabs under slabs in each data location on Friday and read EPERMs.

Mar 19-Mar 26

Test Week #7, 15 cfm/person OA, expose EPERMs (3/22-3/26), run tracer gas system, HVAC on from 6 am to 6 pm seven days/week, run building with all exhaust fans off from 3 pm Friday (3/19) to 3 pm Saturday (3/20) and all on over the period from 3 pm Saturday (3/20) until 7 am Monday (3/22), during weekdays (3/22-3/26) exhaust fans at normal operation, perform radon grabs under slabs in each data location on Friday and read EPERMs.

Mar 26-Apr 2

Test Week #8, 15 cfm/person OA, HVAC on from 6 am to 6 pm seven days/week, run building with all exhaust fans off from 3 pm Friday (3/26) to 3 pm Saturday (3/27) and all on over the period from 3 pm Saturday (3/27) until 7 am Monday (3/29), during weekdays (3/29-4/2) exhaust fans at normal operation. This period was used to carry out special tests for Florida Solar Energy Center to assist in their model development and validation. This period was also used to validate data to determine if any tests needed to be repeated.

Apr 2-Apr 9

HVAC on from 6 am to 6 pm seven days/week, 15 cfm/person OA. This period was used to carry out special tests for Florida Solar Energy Center to assist in their model development and validation.

Apr 9-Apr 16

HVAC on from 6 am to 6 pm except for Saturday and Sunday, 4/10 and 4/11, when the HVAC was on continuously for testing purposes.

Apr 16-Apr 23

HVAC on from 6 am to 6 pm seven days/week, 15 cfm/person.

Apr 23-Apr 30

HVAC on from 6 am to 6 pm except for Saturday and Sunday, 4/24 and 4/25, when the HVAC was on continuously for testing purposes, 15 cfm/person.

Apr 30-May 7

HVAC on from 6 am to 6 pm, 15 cfm/person.

May 7-May 12

HVAC on from 6 am to 6 pm, 15 cfm/person, all equipment removed from building on 5/12/93.

7.3.2 Data and Analysis

The radon levels in the LLC building were significantly reduced from the levels first measured in December 1992. In Figure 6 the averaged radon levels measured in Rooms 102, 109, Cafeteria, and Conference room (excluding Audiology) with the Femto-Tech continuous monitors attached to the EPA data loggers located in those rooms are plotted as functions of time. Several aspects of the data are apparent. First, the levels measured during December 1992 and January 1993 were much higher than those measured by the Polk County Health Unit shown in Figures 3-5. The reasons for this large difference are not known. Second, the overall levels show a steady decrease as shown by the 5-day moving (un-weighted) average line. This is due primarily to the replacement of the OA fan and damper, and to the consistent operation of this fan. Also, the new OA fan has greatly reduced the level of offensive odors noticed in Room 105 in October 1992. The second interesting aspect of Figure 6 is the fine structure or daily variations in the radon levels. These are caused primarily by the daily cycling of the HVAC system from daytime use to nighttime setback.

Radon data from this test series are summarized in Figures 7 through 14. In Figures 7 through 14 are plotted the continuous radon levels as measured in Rooms 102, 109, the Conference room, the Cafeteria, and in the Audiology room over the 8 week testing period. Also shown in these figures are the outputs read from the x-type annubar installed in the OA duct (after conversion to cfm air flow). In Figures 15 through 22 the averaged radon levels in all rooms except Audiology are plotted along with the OA flowrates. Several aspects of these plots were readily apparent:

1. The radon levels generally increase overnight until the HVAC system comes on.

2. Once the HVAC system turns on, the levels drop rapidly.

3. As the HVAC system operates, the levels drop but seldom go below 4-5 pCi/L. The rate of drop and the limiting radon level depend as expected on the OA flowrate. The variation of average daytime radon levels with OA is shown is Figure 23.

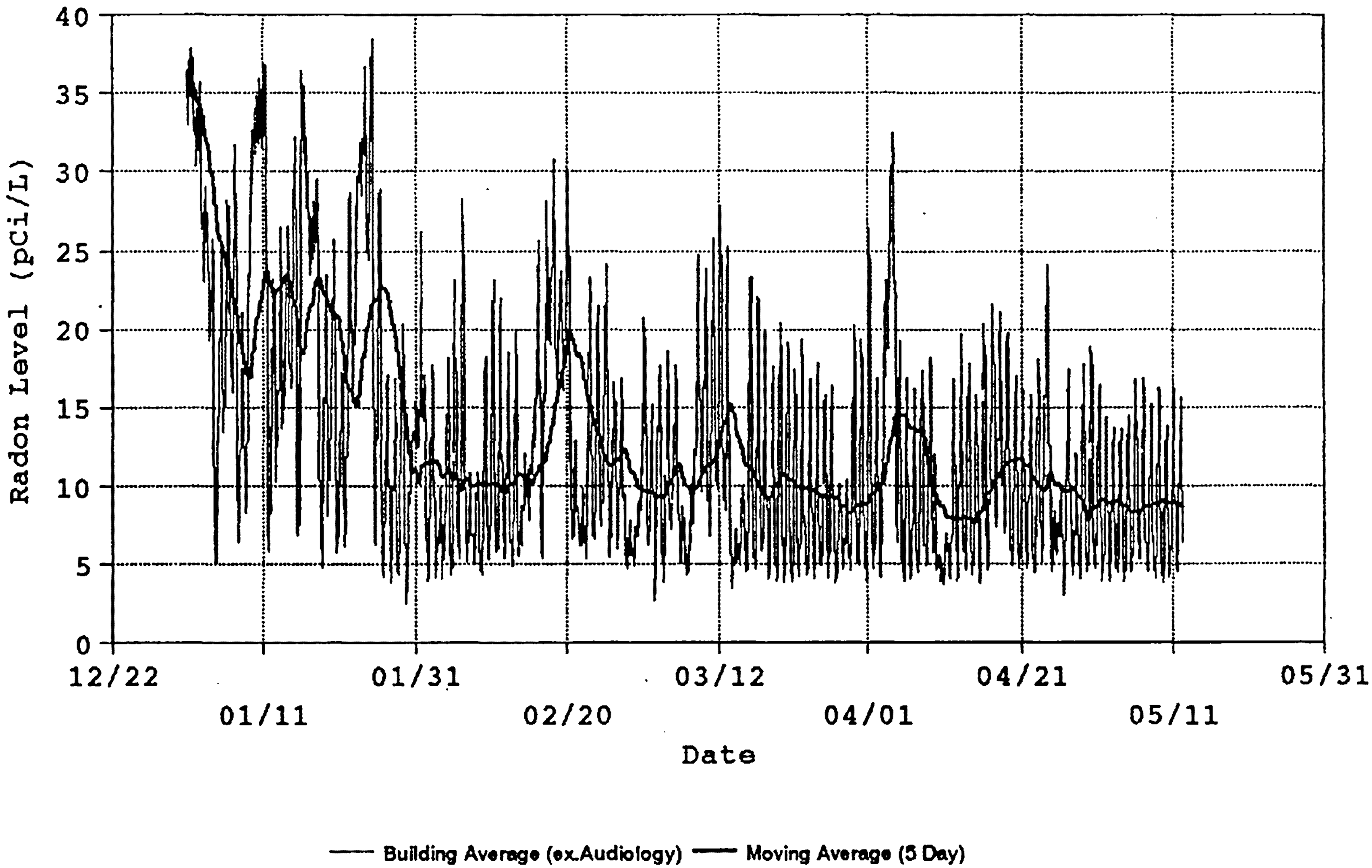


Figure 6 Polk Life & Learning Center, Lakeland, FL. Average of the continuous radon levels as measured in Rooms 109, 102, Cafeteria, and Conference Room (excluding Audiology) along with the 5-day moving average values over the testing period.

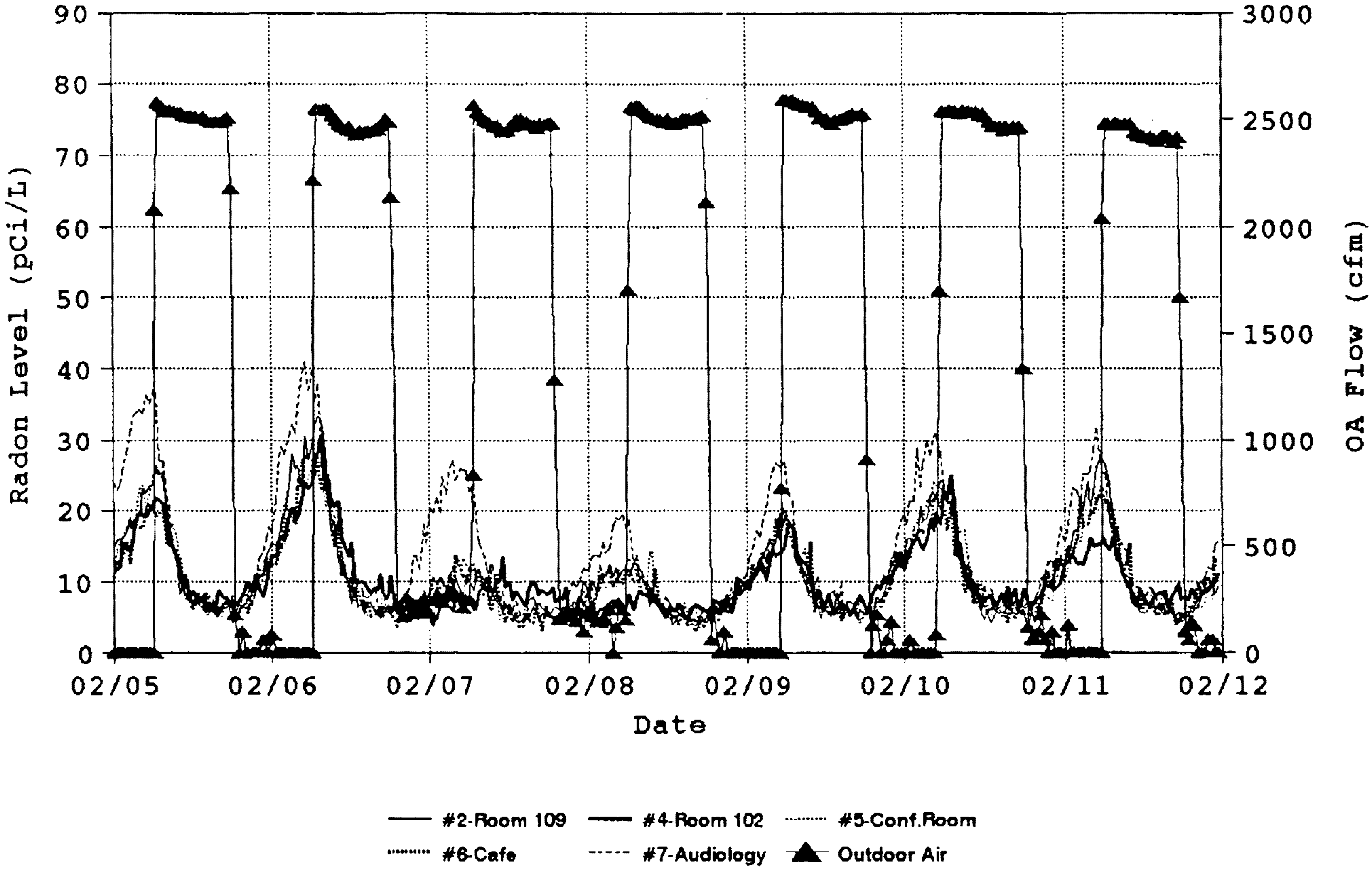


Figure 7. Polk Life & Learning Center, Lakeland, FL

Test Week #1 continuous radon levels, 20 cfm/person OA, HVAC on from 6am to 6pm seven days/week, all exhaust fans off from 3pm Friday (2/5) to 3pm Saturday (2/6) and all fans on over the period from 3pm Saturday (2/6) until about 7am Monday (2/8), during weekdays (2/8-2/12) exhaust fans at normal operation.

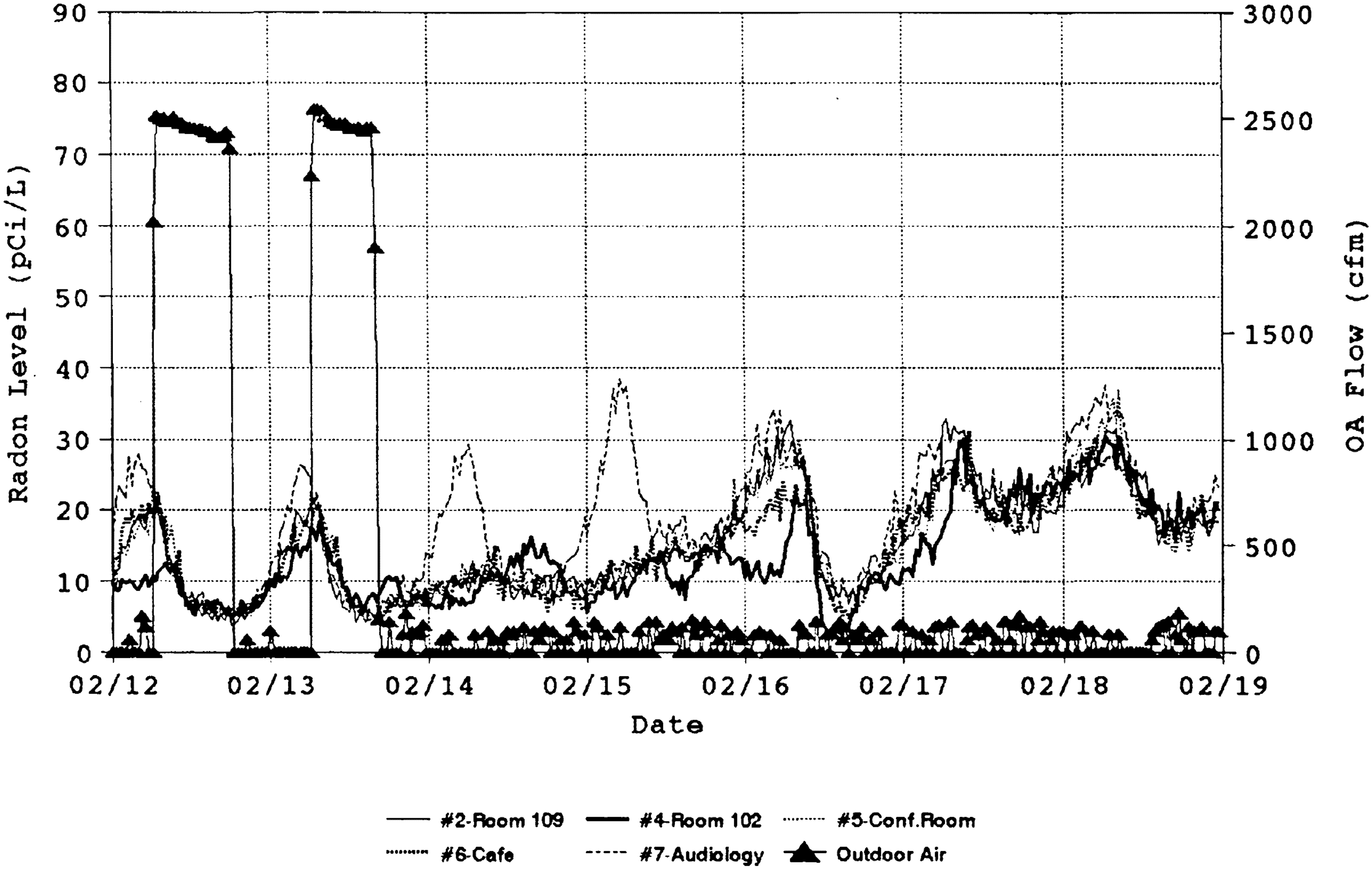


Figure 8. Polk Life & Learning Center, Lakeland, FL

Test Week #2 continuous radon levels, 0 cfm/person OA, HVAC on from 6am to 6pm seven days/week, all exhaust fans off from 3pm Friday (2/12) to 3pm Saturday (2/13) and all on over the period from 3pm Saturday (2/13) until 7am Monday (2/15), during weekdays (2/15-2/19) exhaust fans at normal operation.

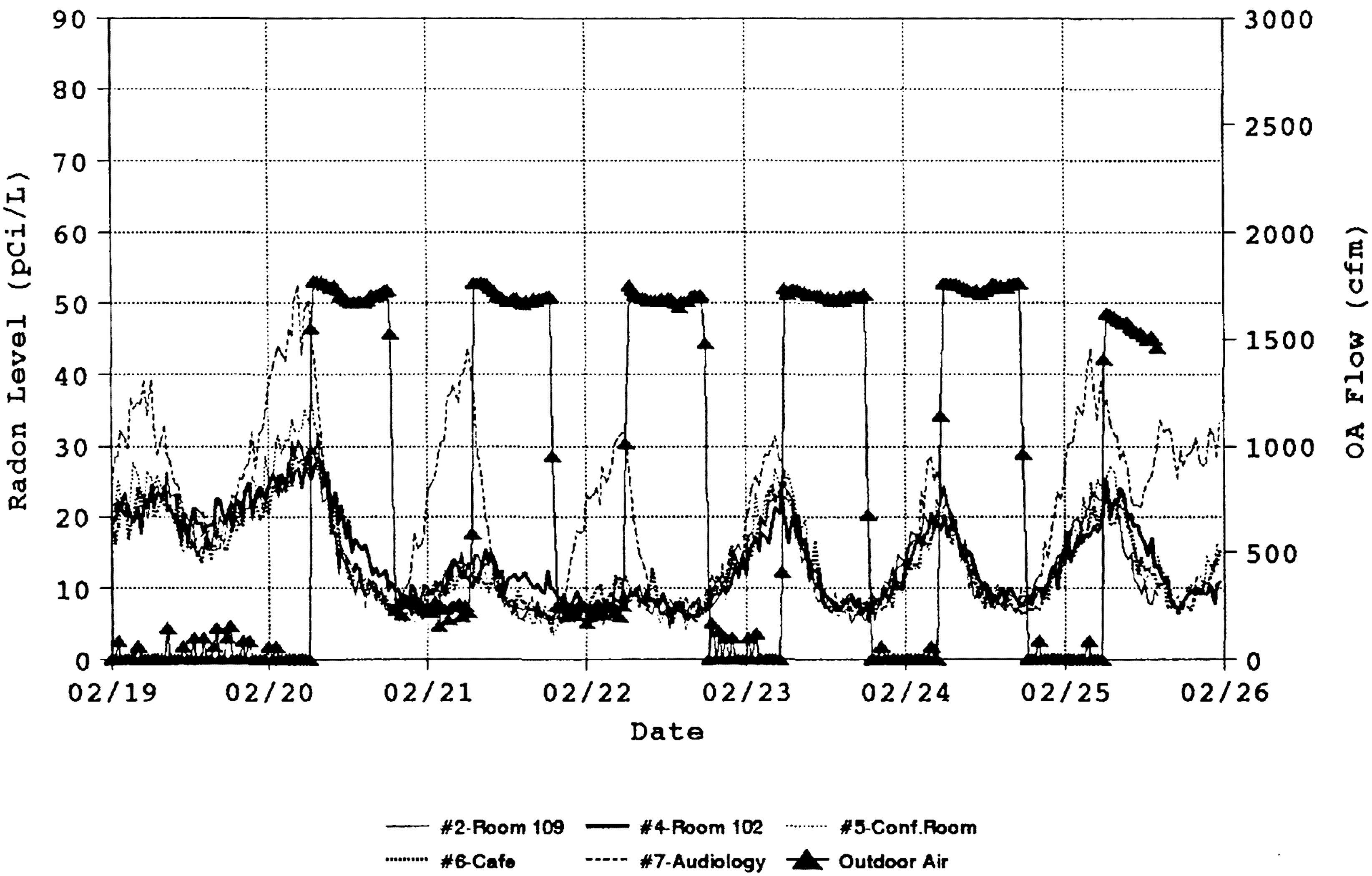


Figure 9. Polk Life & Learning Center, Lakeland, FL

Test Week #3 continuous radon levels, 8 cfm/person OA, HVAC on from 6am to 6pm seven days/week, all exhaust fans off from 3pm Friday (2/19) to 3pm Saturday (2/20) and all on over the period from 3pm Saturday (2/20) until 7am Monday (2/22), during weekdays (2/22-2/26) exhaust fans at normal operation.

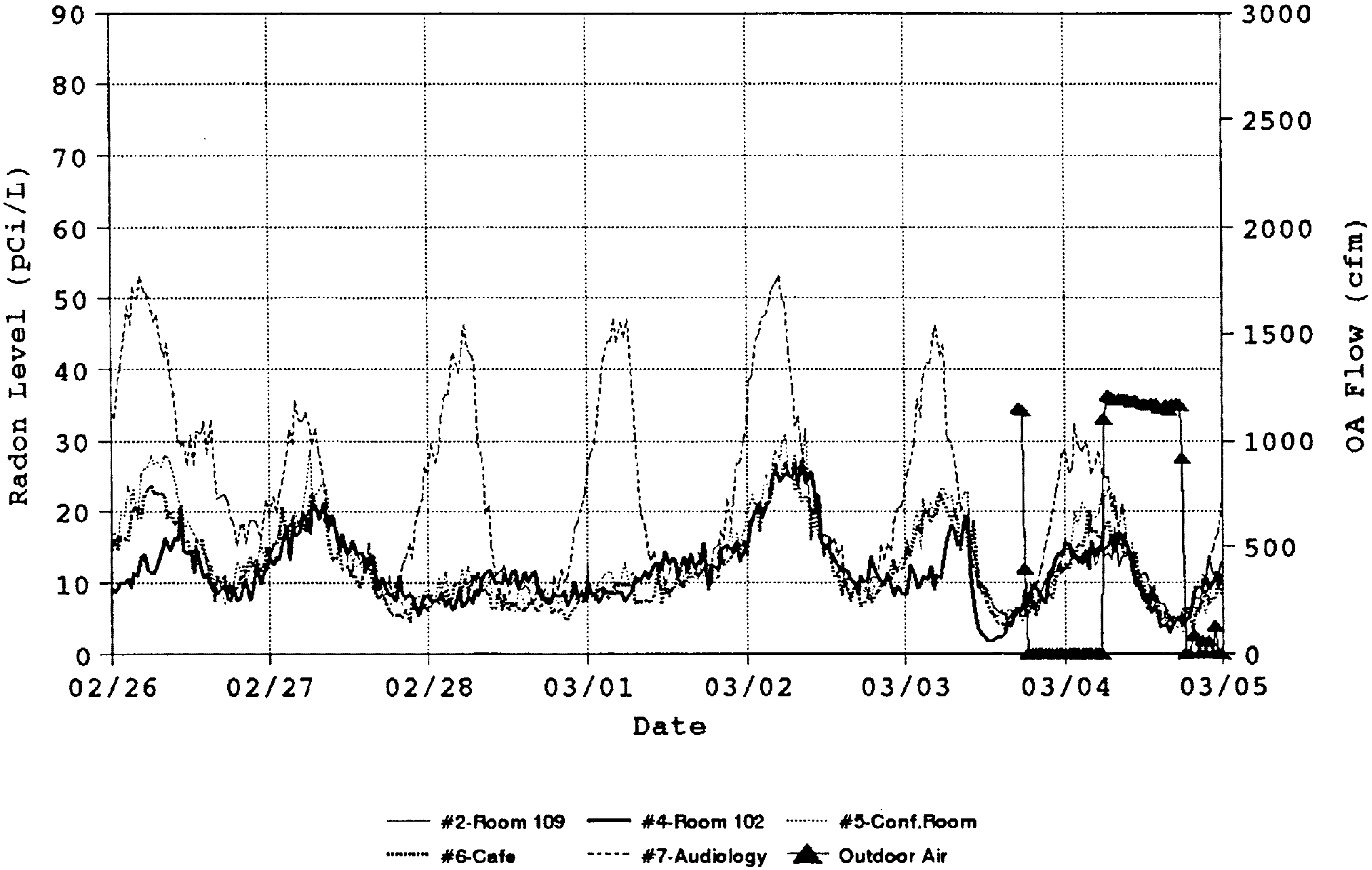


Figure 10. Polk Life & Learning Center, Lakeland, FL

Test Week #4 continuous radon levels, 5 cfm/person OA, HVAC on from 6am to 6pm seven days/week, all exhaust fans off from 3pm Friday (2/26) to 3pm Saturday (2/27) and all on over the period from 3pm Saturday (2/27) until 7am Monday 3/1, during weekdays (3/1-3/5) exhaust fans at normal operation.

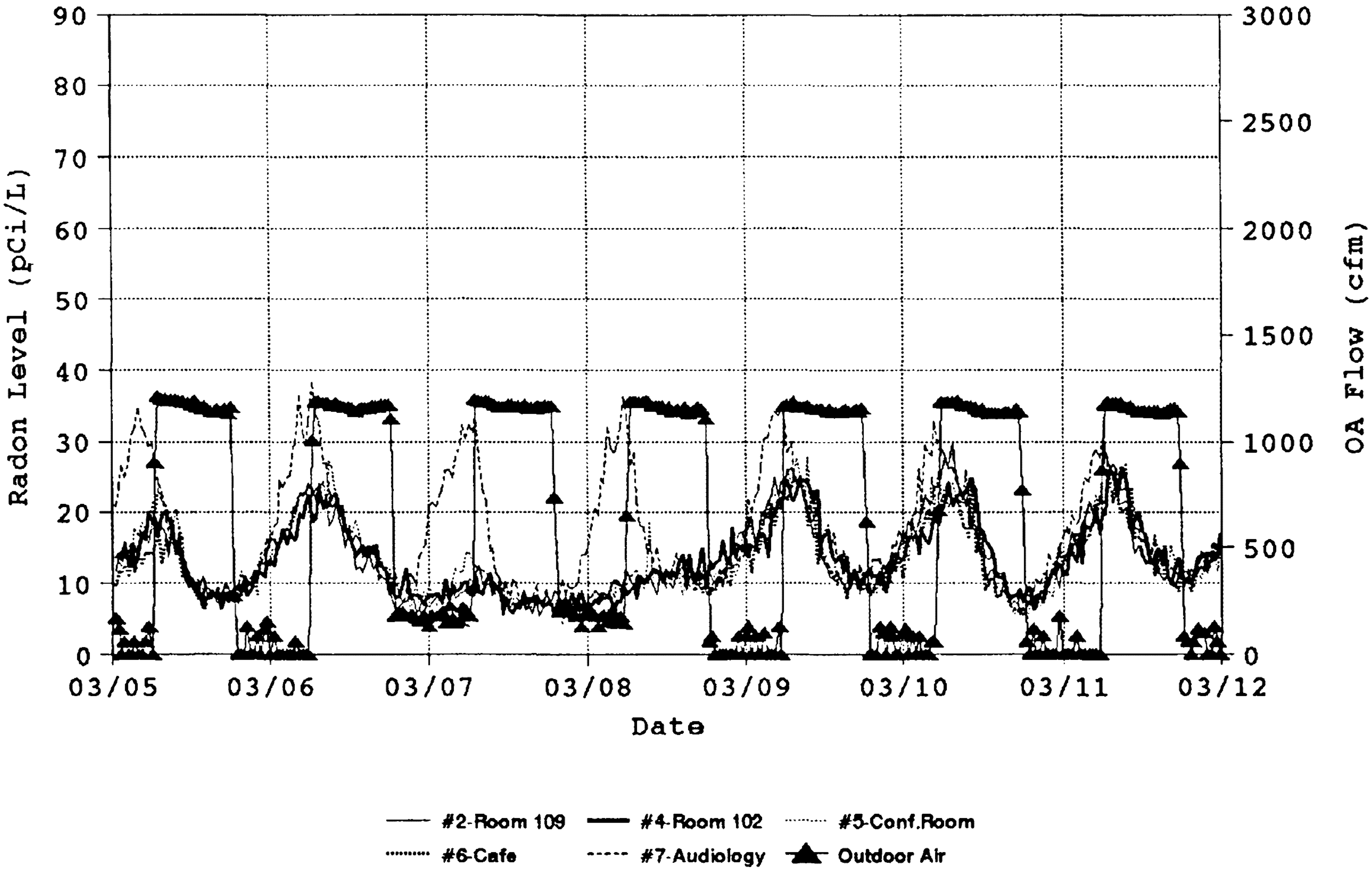


Figure 11. Polk Life & Learning Center, Lakeland, FL

Test Week #5 continuous radon levels, because of equipment failure the test from the previous week was repeated during this week.

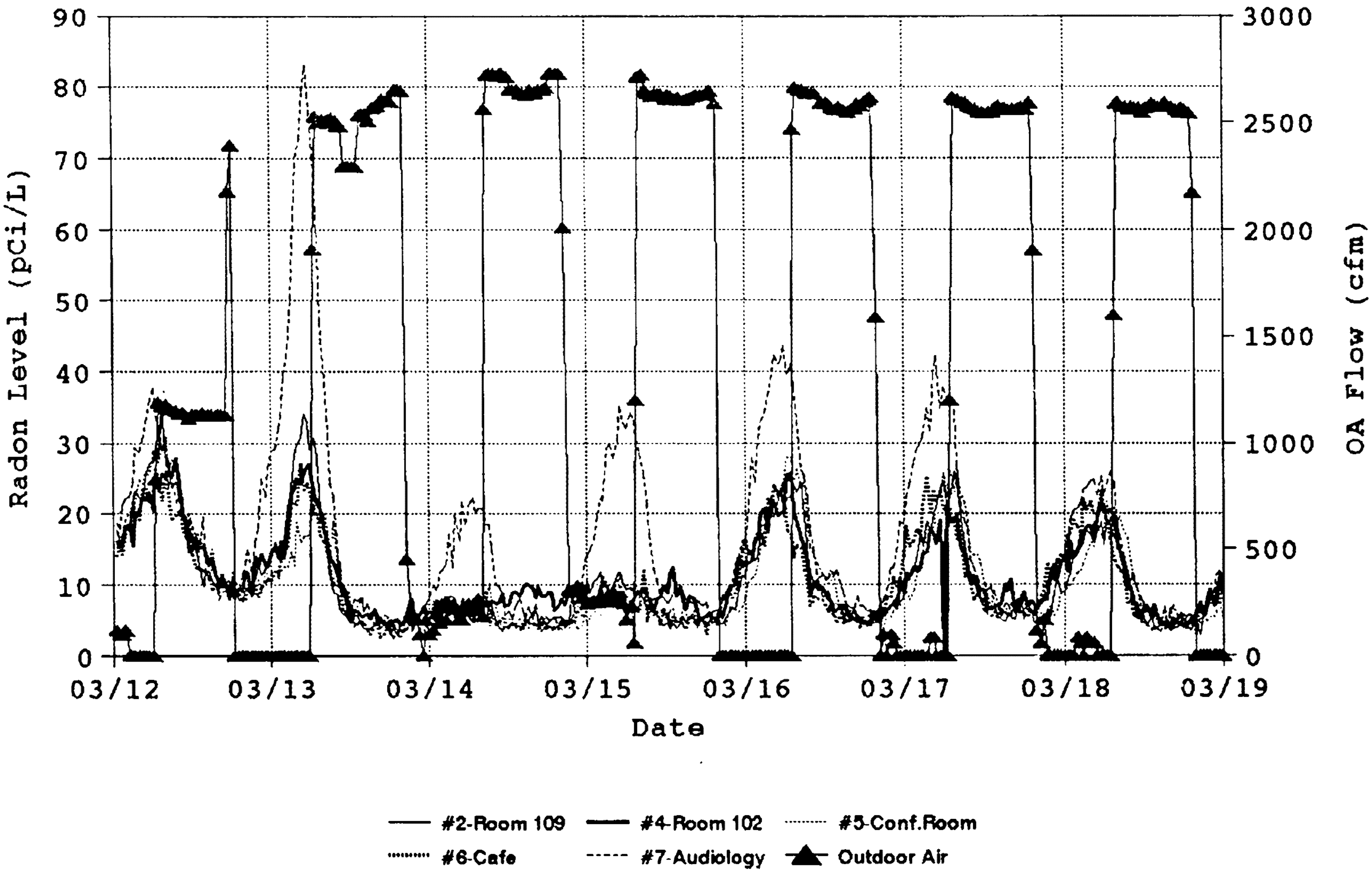


Figure 12. Polk Life & Learning Center, Lakeland, FL
Test Week #6 continuous radon levels, repeat the tests of Test Week #1, 20 cfm/person OA, HVAC on from 6am to 6pm seven days/week, all exhaust fans off from 3pm Friday (3/12) to 3pm Saturday (3/13) and all on over the period from 3pm Saturday (3/13) until 7am Monday (3/14), during weekdays (3/15-3/19) exhaust fans at normal operation.

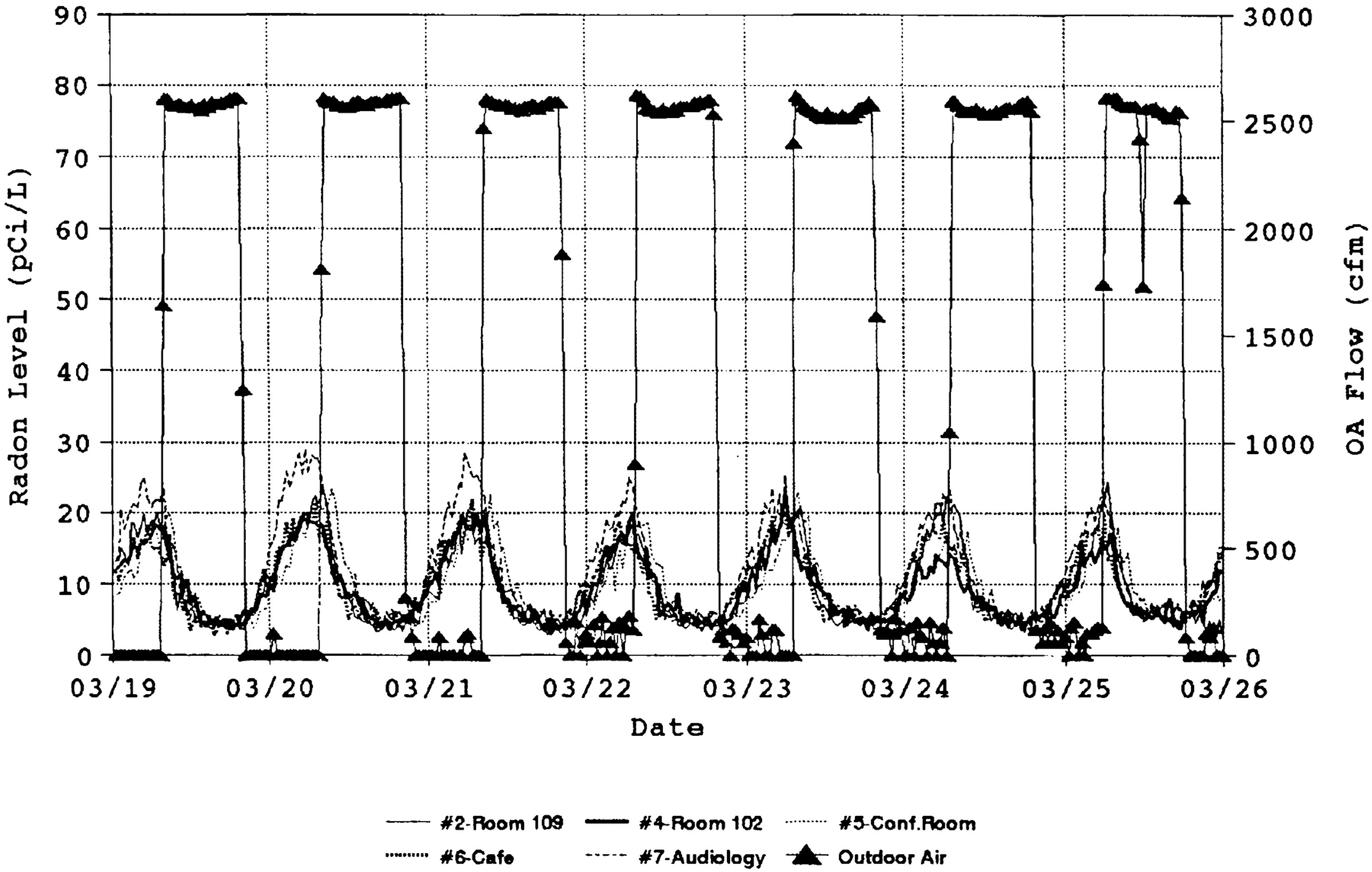


Figure 13. Polk Life & Learning Center, Lakeland, FL
Test Week #7 continuous radon levels, 15 cfm/person OA, HVAC on from 6am to 6pm seven days/week, all exhaust fans off from 3pm Friday (3/19) to 3pm Saturday (3/20) and all on over the period from 3pm Saturday (3/20) until 7am Monday (3/22), during weekdays (3/22-3/26) exhaust fans at normal operation.

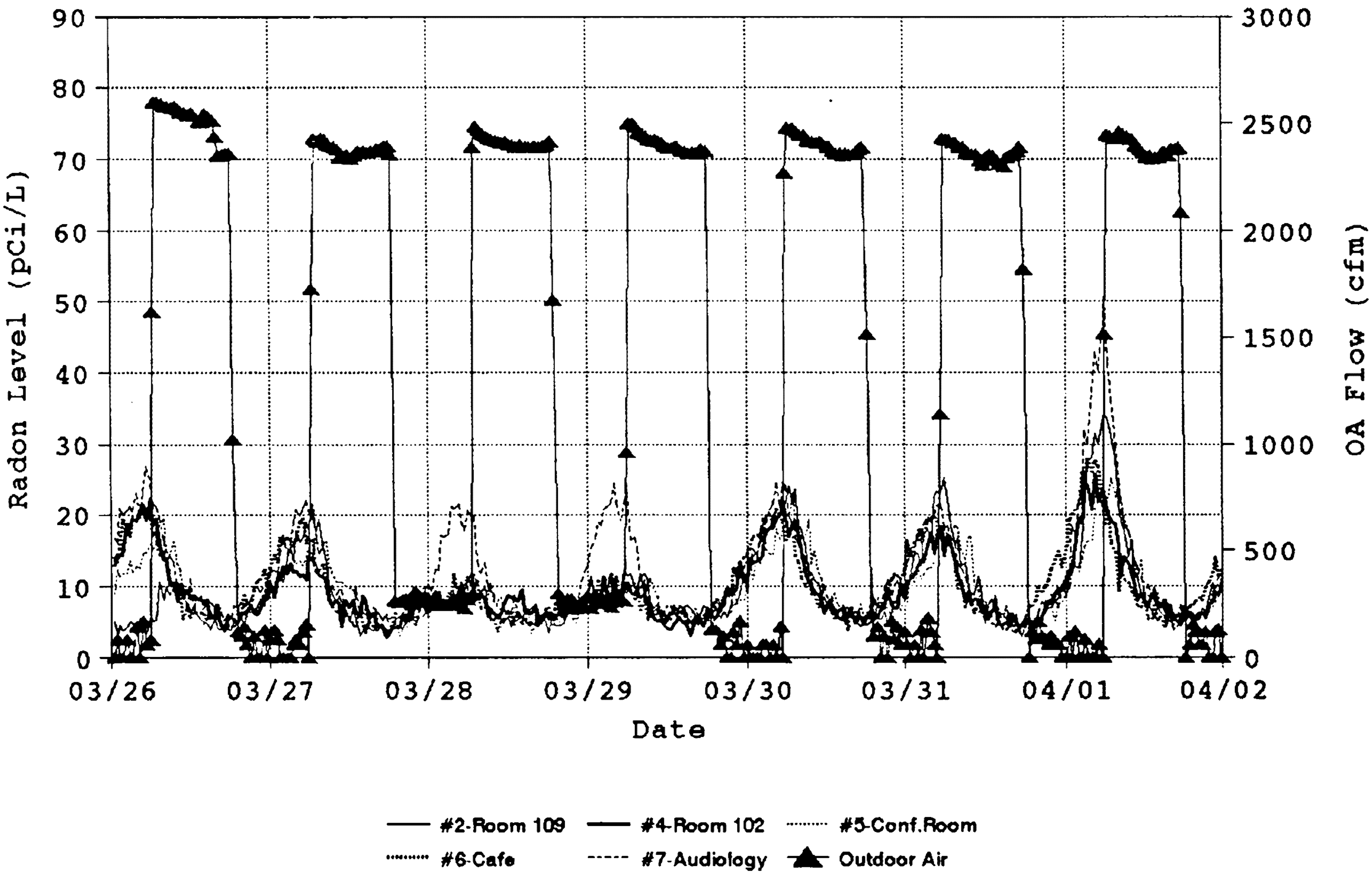


Figure 14. **Polk Life & Learning Center, Lakeland, FL**

Test Week #8 continuous radon levels, 15 cfm/person OA, HVAC on from 6am to 6pm seven days/week, all exhaust fans off from 3pm Friday (3/26) to 3pm Saturday (3/27) and all on over the period from 3pm Saturday (3/27) until 7am Monday (3/29), during weekdays (3/29-4/2) exhaust fans at normal operation.

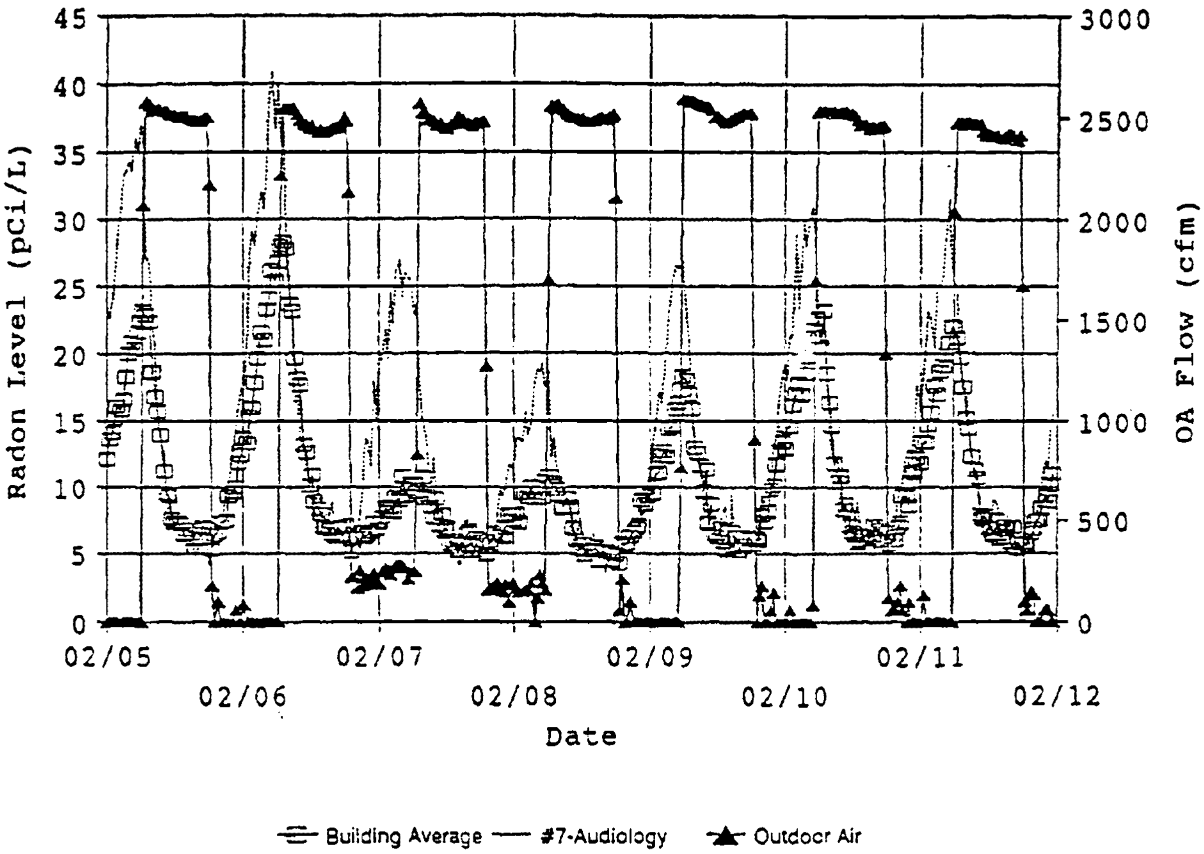


Figure 15. Polk Life & Learning Center, Lakeland, FL
Test Week #1 averaged continuous radon levels, 20 cfm/person OA, HVAC on from 6am to 6pm seven days/week, all exhaust fans off from 3pm Friday (2/5) to 3pm Saturday (2/6) and all fans on over the period from 3pm Saturday (2/6) until 7am Monday (2/8), during weekdays (2/8-2/12) exhaust fans at normal operation.

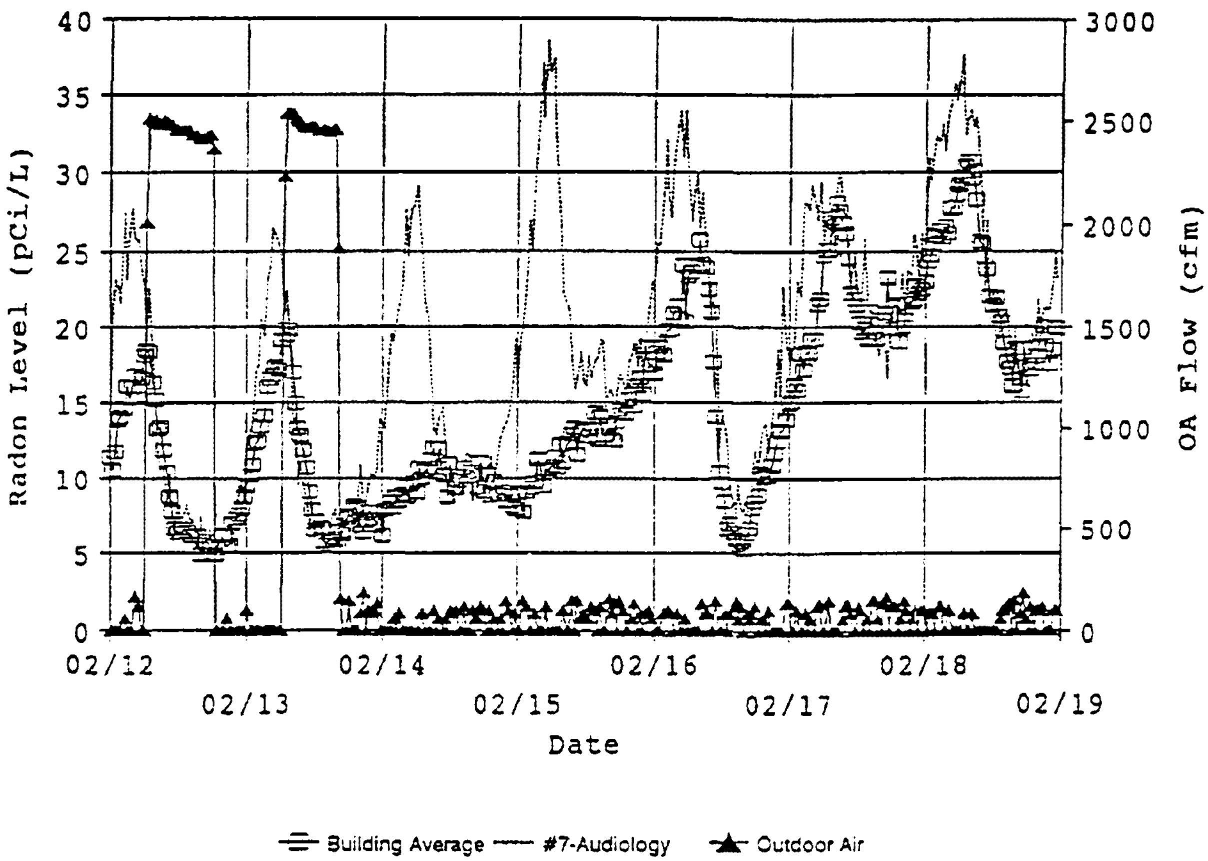


Figure 16. Polk Life & Learning Center, Lakeland, FL
Test Week #2 averaged continuous radon levels, 0 cfm/person OA, HVAC on from 6am to 6 pm seven days/week, all exhaust fans off from 3pm Friday (2/12) to 3pm Saturday (2/13) and all on over the period from 3pm Saturday (2/13) until 7am Monday (2/15), during weekdays (2/15-2/19) exhaust fans at normal operation.

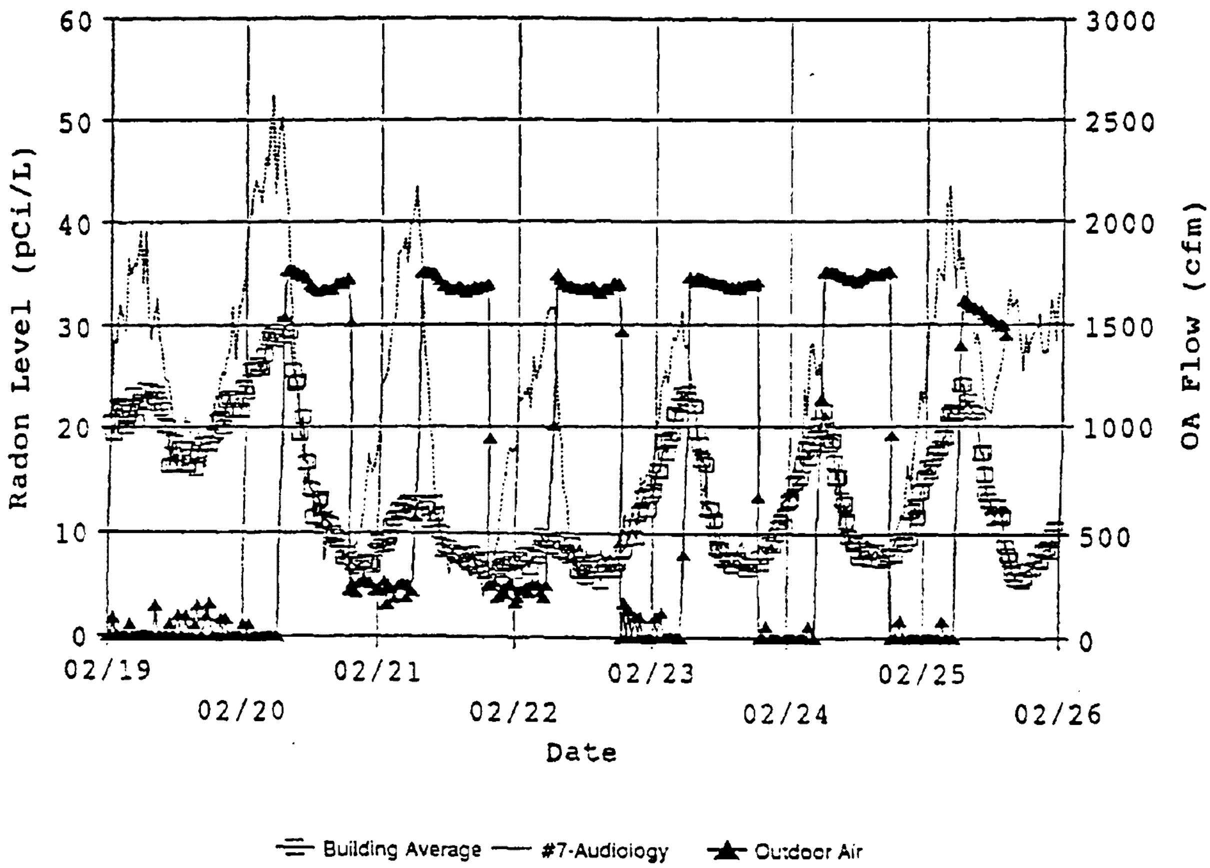


Figure 17. Polk Life & Learning Center, Lakeland, FL
Test Week #3 averaged continuous radon levels, 8 cfm/person OA, HVAC on from 6am to 6 pm seven days/week, all exhaust fans off from 3pm Saturday 2/20) and all on over the period from 3pm Saturday (2/20) until 7am Monday (2/22)m during weekdays (2/22-2/26) exhaust fans at normal operation.

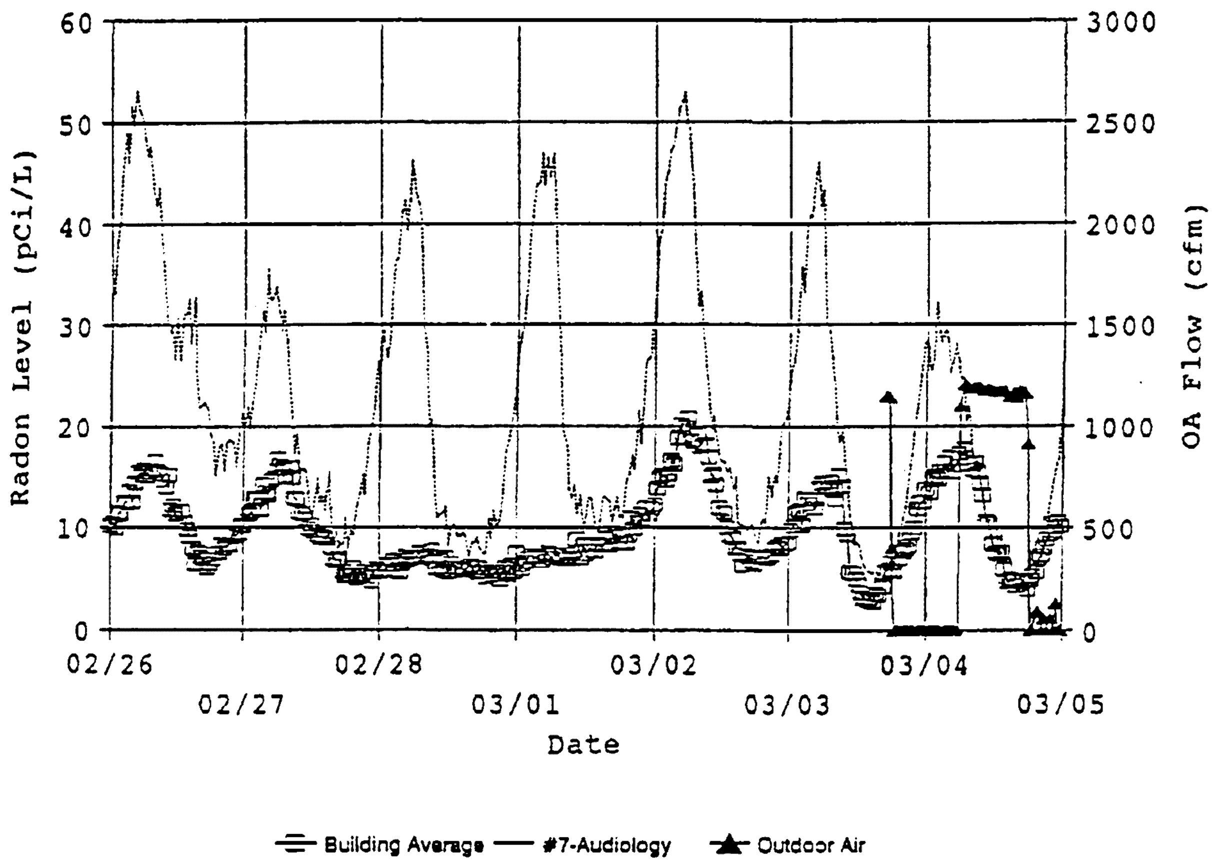


Figure 18. Polk Life & Learning Center, Lakeland, FL
Test Week #4 averaged continuous radon levels, 5 cfm/person OA, HVAC on from 6am to 6pm seven days/week, all exhaust fans off from 3pm Friday (2/26) to 3pm Saturday (2/27) and all on over the period from 3pm Saturday (2/27) until 7am Monday 3/1, during weekdays (3/1-3/5) exhaust fans at normal operation.

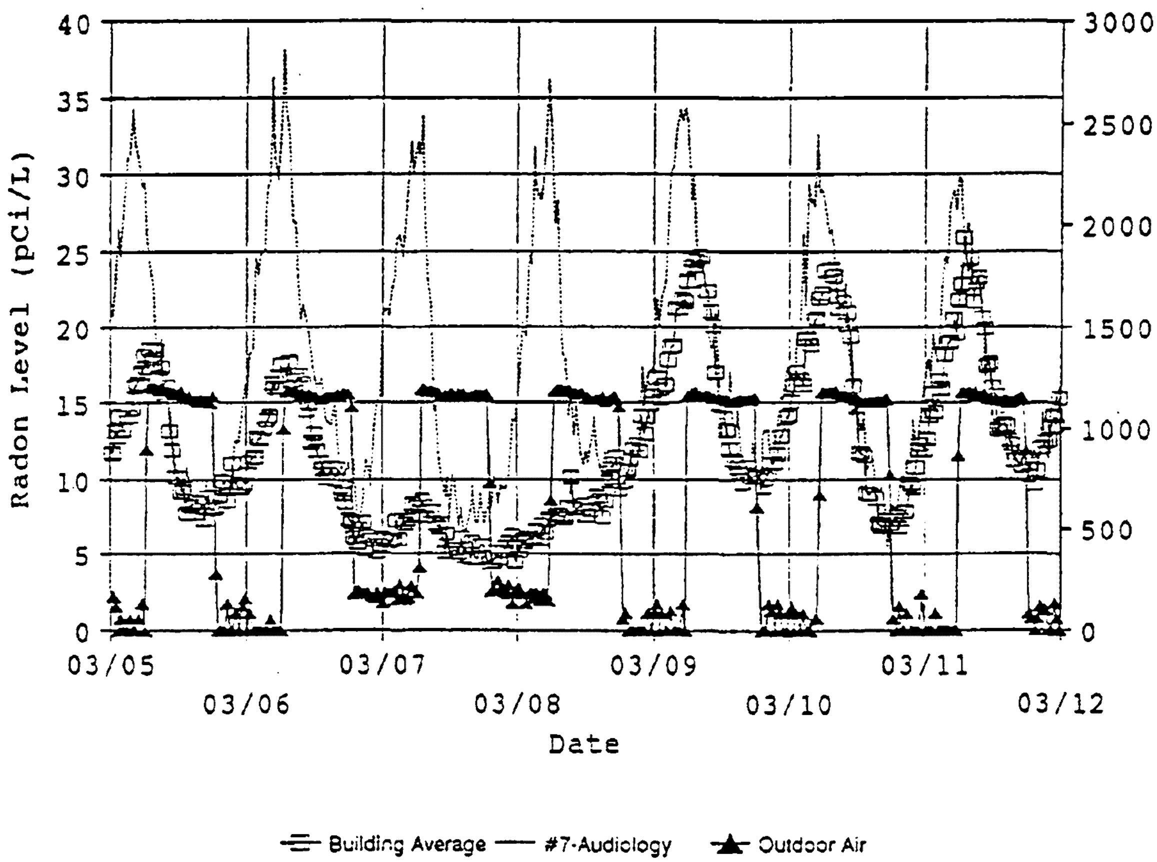


Figure 19. Polk Life & Learning Center, Lakeland, FL
Test Week #5 averaged continuous radon levels, because of equipment Failure the test from the previous week was repeated during this week.

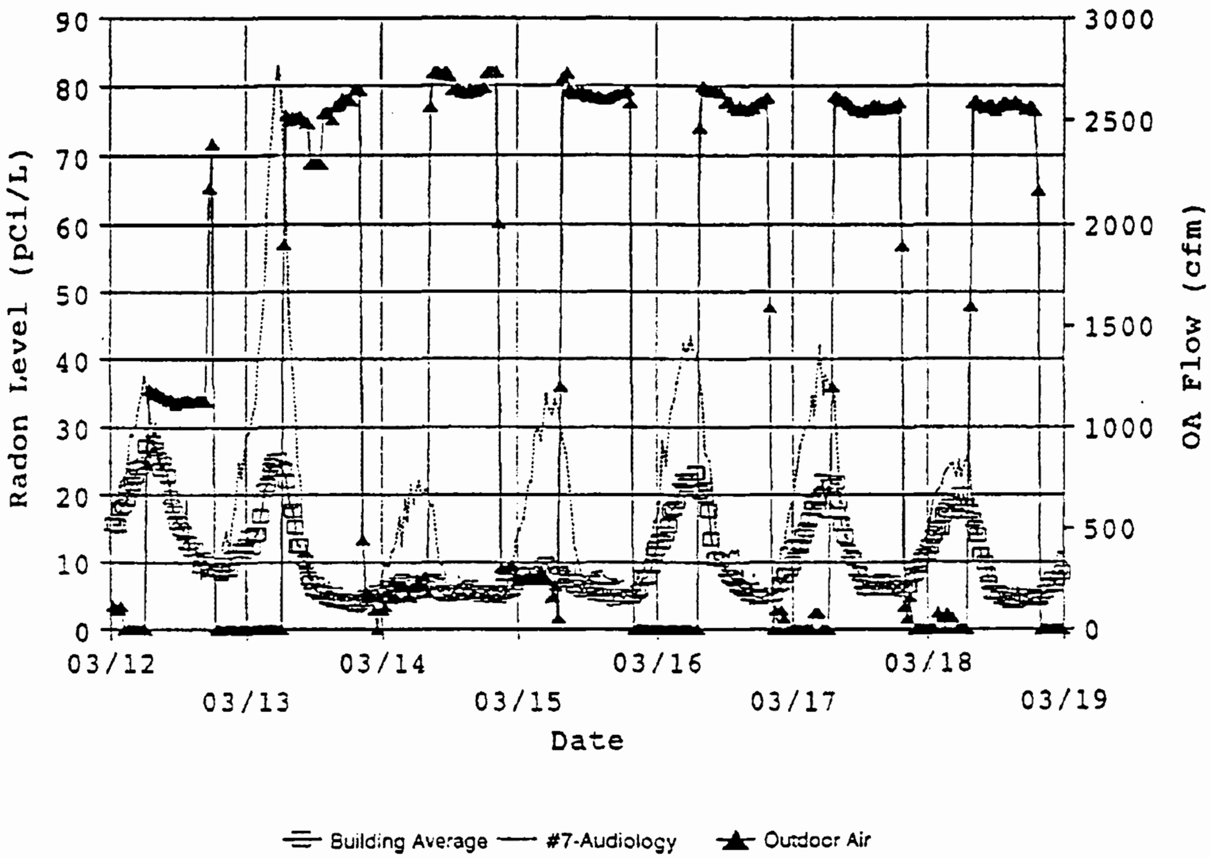


Figure 20. Polk Life & Learning Center, Lakeland, FL
Test Week #6 averaged continuous radon levels, repeated the tests of Test Week #1, 20 cfm/person OA, HVAC on from 6am to 6pm seven days/week, all exhaust fans off from 3pm Friday (3/12) to 3pm Saturday (3/13) and all on over the period from 3pm Saturday (3/13) until 7am Monday (3/14), during weekdays (3/15-3/19) exhaust fans at normal operation.

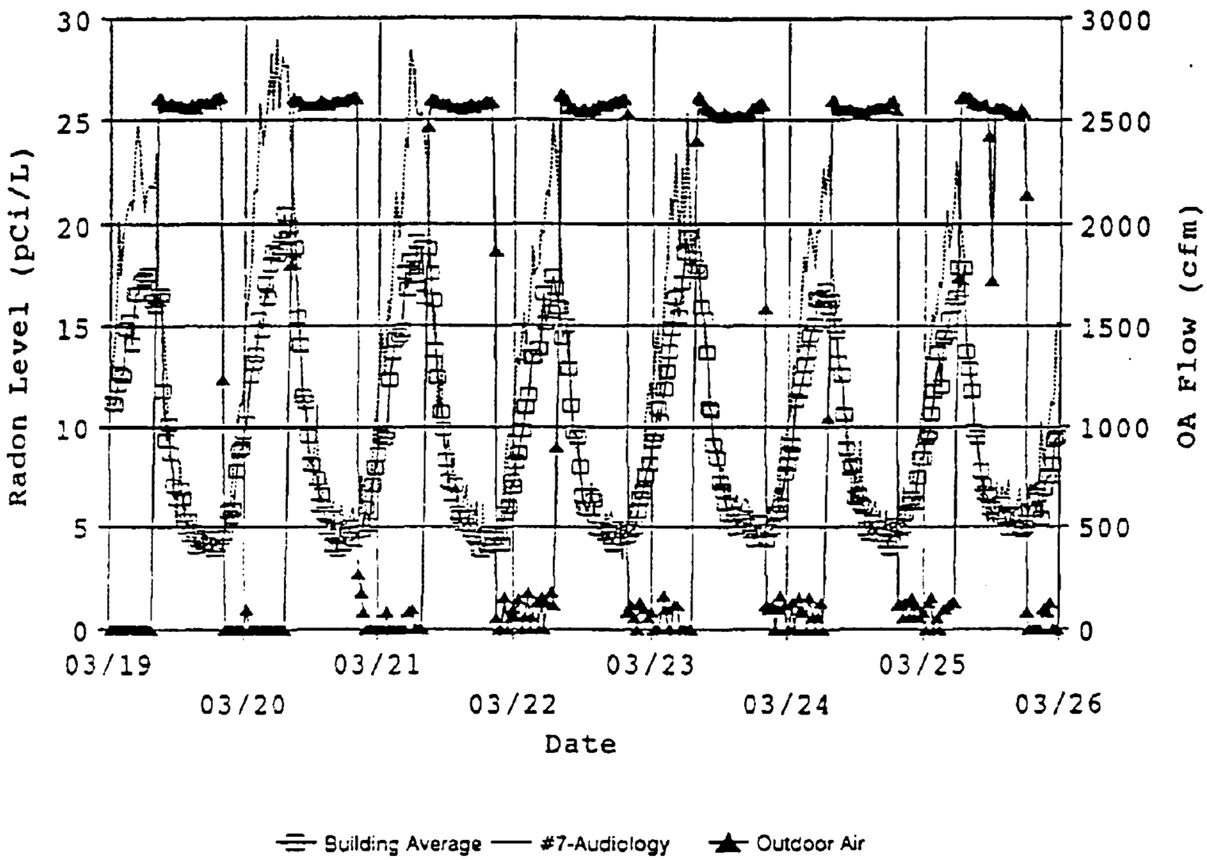


Figure 21. Polk Life & Learning Center, Lakeland, FL
Test Week #7 averaged continuous radon levels, 15 cfm/person OA, HVAC on from 6am to 6pm seven days/week, all exhaust fans off from 3pm Friday (3/19) to 3pm Saturday (3/30) and all on over the period from 3pm Saturday (3/20) until 7am Monday (3/22), during weekdays (3/22-3/26) exhaust fans at normal operation.

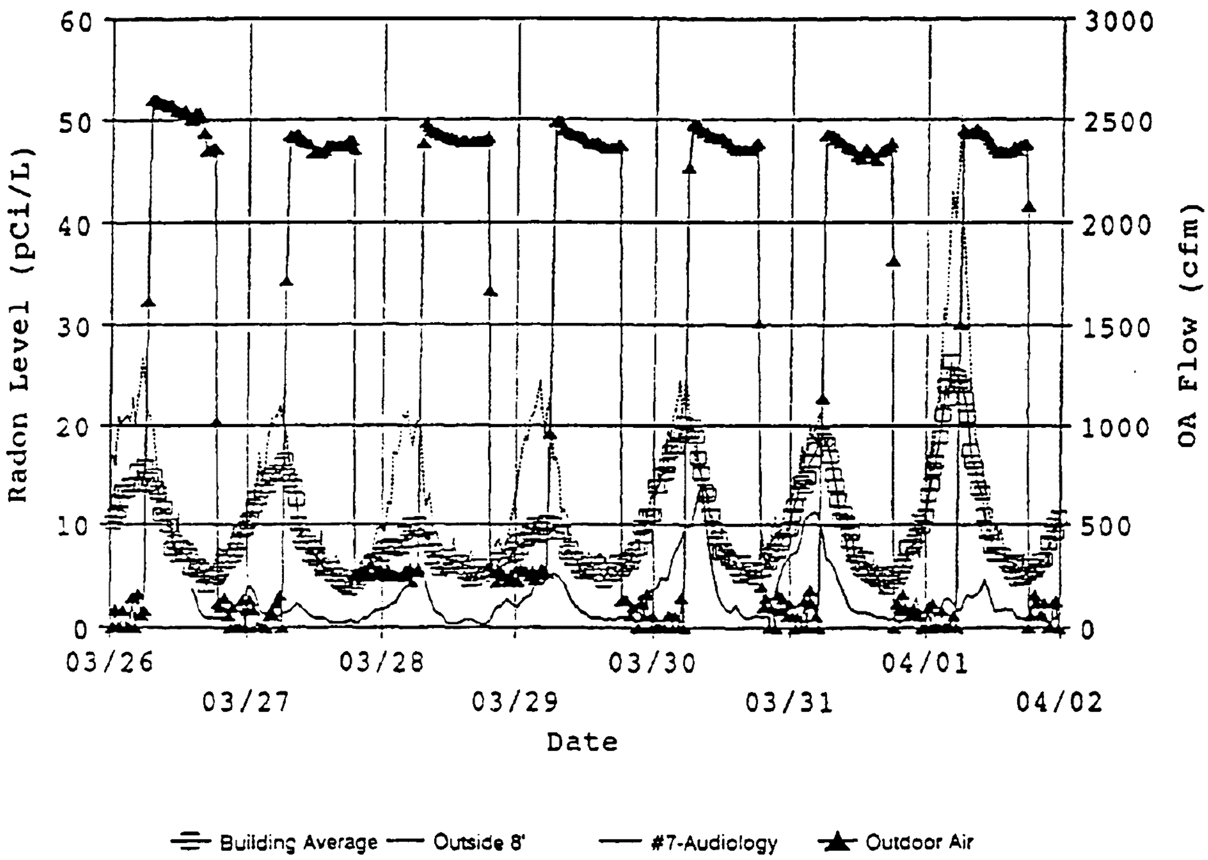


Figure 22. Polk Life & Learning Center, Lakeland, FL
Test Week #8 averaged continuous radon levels, 15 cfm/person OA, HVAC on from 6am to 6pm seven days/week, all exhaust fans off from 3pm Friday (3/26) to 3pm Saturday (3/27) and all on over the period from 3pm Saturday (3/27) until 7am Monday (3/29), during weekdays (3/29-4/2) exhaust fans at normal operation.

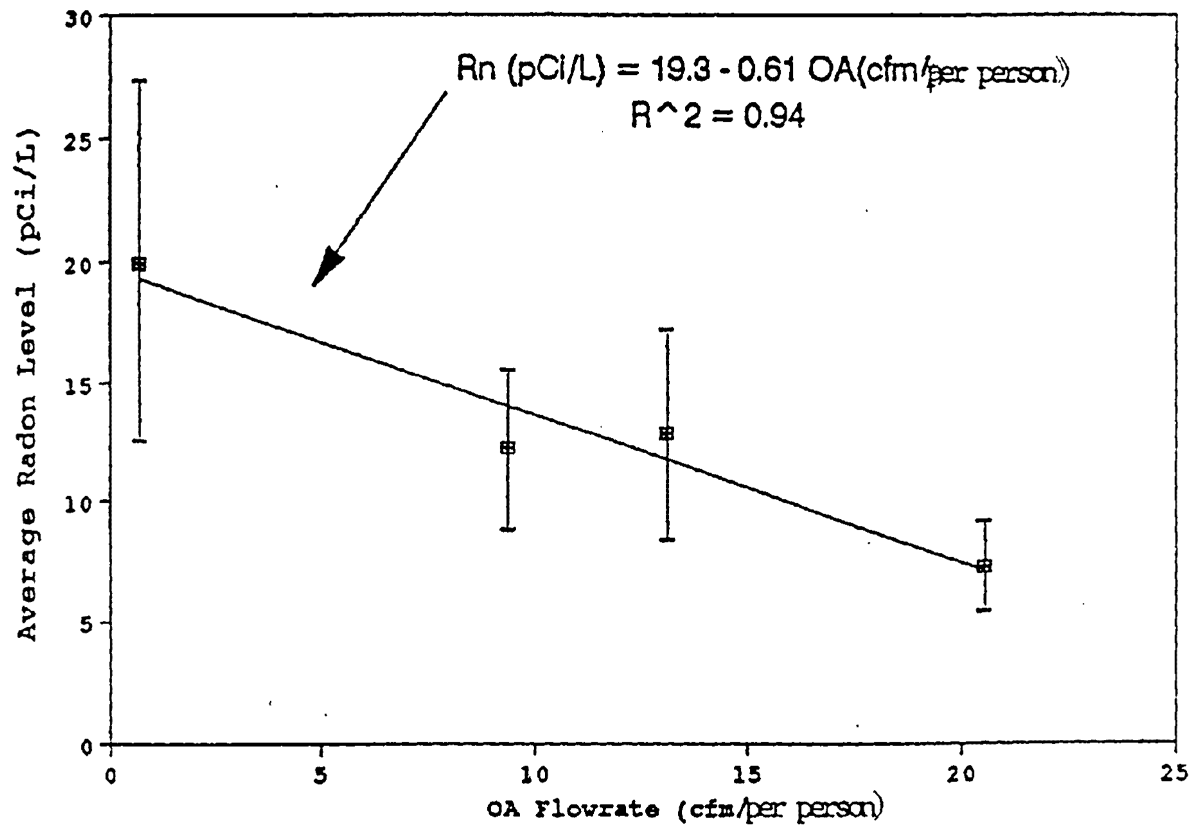


Figure 23. Polk Life & Learning Center, Lakeland, FL
Average building daytime (8 am - 4 pm) radon levels in LLC as a function of the outdoor air flowrate.

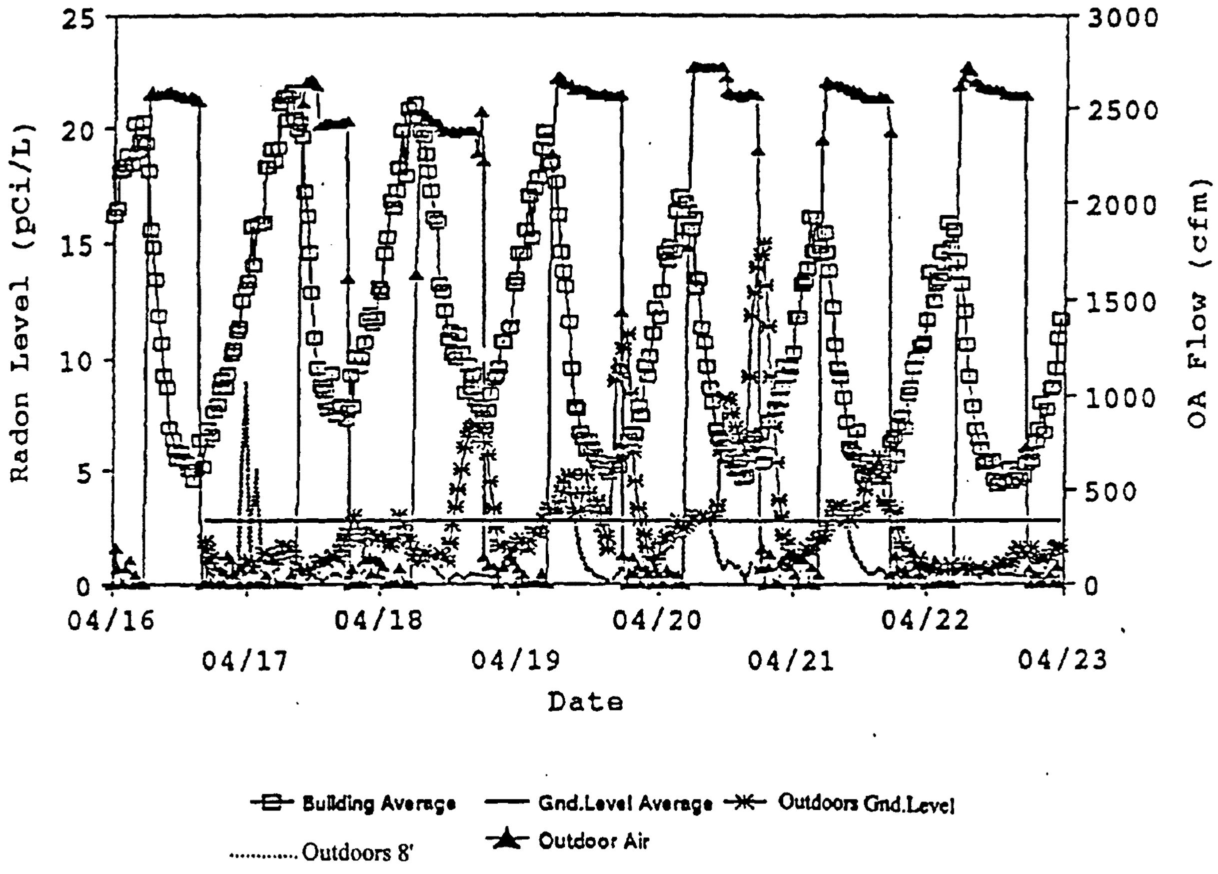


Figure 24 Polk Life & Learning Center, Lakeland, FL. Comparison of indoor average radon levels with those measured outdoors at ground level and 8 ft above the ground for the period form 4/16/93 to 4/23/93. HVAC on from 6 am to 6 pm, 15 cfm/person.

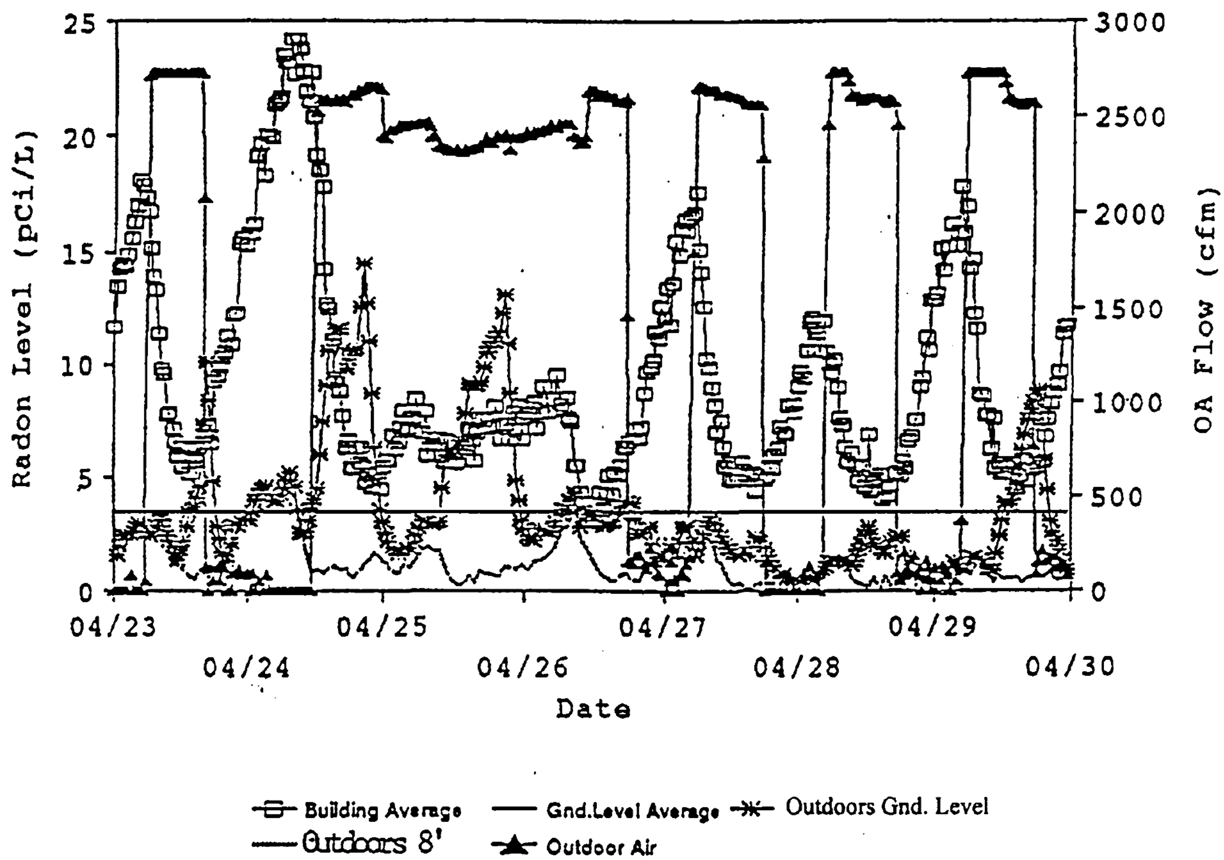


Figure 25 Polk Life & Learning Center, Lakeland, FL. Comparison of indoor average radon levels with those measured outdoors at ground level and 8 ft above the ground for the period from 4/23/93 to 4/30/93. HVAC on from 6 am to 6 pm except for Saturday and Sunday, 4/24 and 4/25, when the HVAC was on continuously for testing purposes, 15 cfm/person.

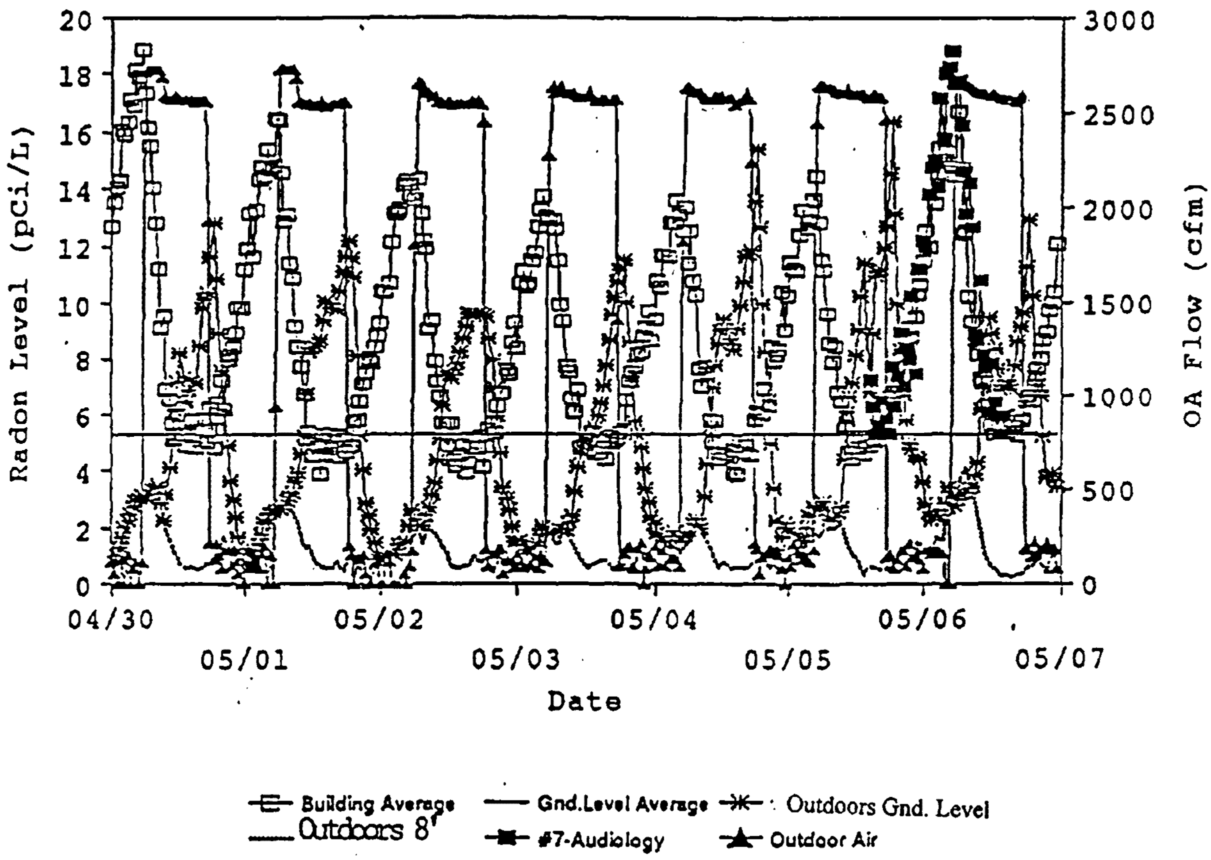


Figure 26 Polk Life & Learning Center, Lakeland, FL. Comparison of indoor average radon levels with those measured outdoors at ground level and 8 ft above the ground for the period from 4/30/93 to 5/7/93. HVAC on from 6 am to 6 pm, 15 cfm/person.

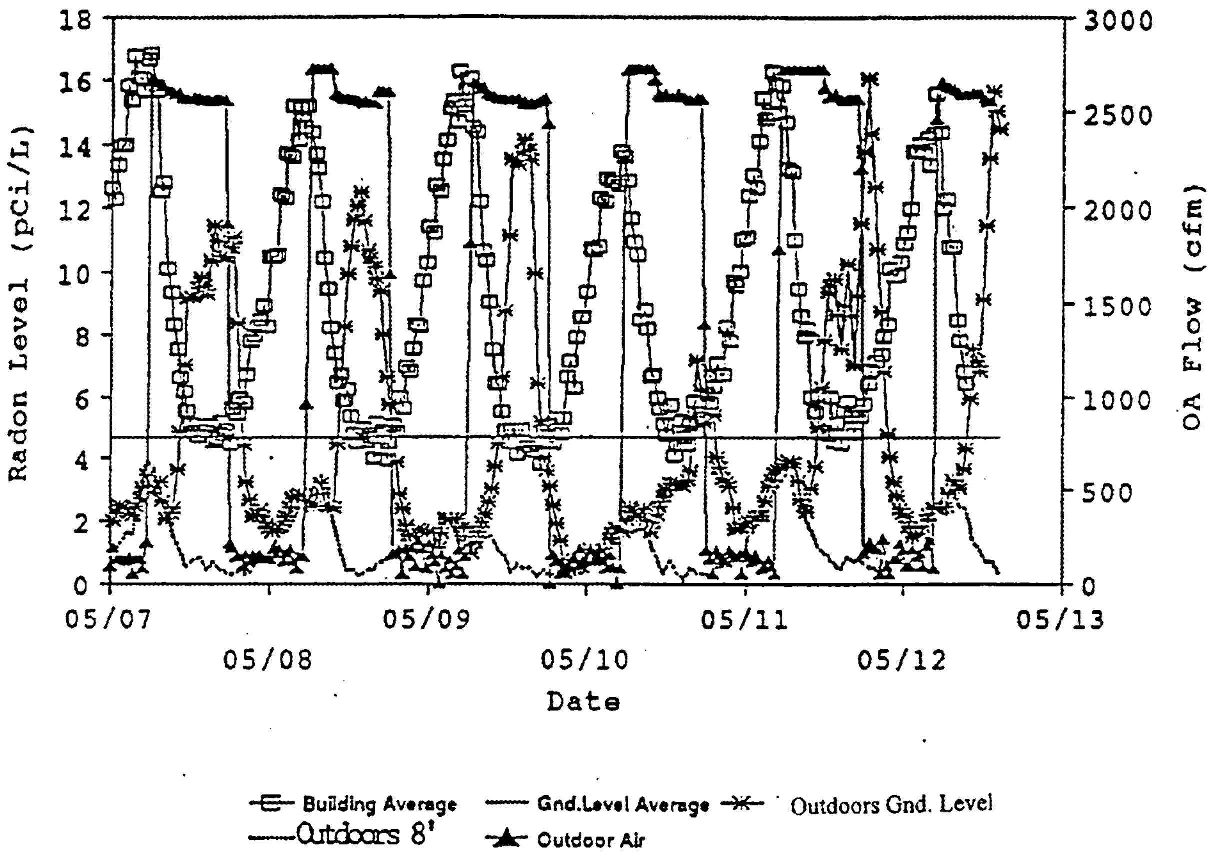


Figure 27 Polk Life & Learning Center, Lakeland, FL. Comparison of indoor average radon levels with those measured outdoors at ground level and 8 ft above the ground for the period from 5/7/93 tto 5/12/93. HVAC on from 6 am to 6 pm, 15 cfm/person.

4. When the exhaust fans are run continuously, the radon levels do not increase to nearly as high levels with the HVAC system off as they do when the fans are left off.

5. The radon levels in the Audiology room do not always follow the rest of the building. The levels here are usually higher than the building as a whole.

From these observations several conclusions appear obvious. The HVAC system is assisting in lowering the radon levels even without the intentional introduction of OA. A significant factor is almost certainly the enhanced ventilation rate induced by the system. Pressure differences across the building shell will enhance infiltration through shell openings, especially when exhaust fans are operating. This infiltrating air is difficult to measure and changes the definition of "no OA" to mean, "no OA actively supplied by the OA supply fan." The peak radon levels reached in the building just before the HVAC system comes on do depend somewhat on the amount of OA introduced into the system during the previous HVAC operation cycle and on the length of time that has transpired since the HVAC system was last operated.

In an effort to understand why the radon levels remain at 4 pCi/L or greater, two additional Pylon AB5 continuous radon monitors with PRD-1 passive cells were placed outside the building in the sheltered workshop area on the North side of the building. One of the monitors was located at ground level and the other approximately 8 feet off the ground. The locations were open and sheltered only from rain. The results are shown in Figures 24 through 27 where the building average radon levels (excluding Audiology) are plotted along with the levels measured outside the building. Also shown in these figures are the OA flowrates and the average (5 day) ground level radon value. Over the 4 week period the ground level radon averaged 4.1 pCi/L with a weekly high of 5.3 pCi/L (4/30-5/7) and a weekly low of 2.8 pCi/L (4/16-4/23). Some summary statistics of the data taken over these 4 weeks are shown in Table 5. These results were of obvious concern since, if the radon source strength is sufficiently high, the indoor levels can never be reduced below the average ground level outdoor levels.

TABLE 5. COMPARISON OF RADON LEVELS INSIDE AND OUTSIDE THE LLC BUILDING OVER THE PERIOD APRIL 16, 1993 TO MAY 12, 1993			
	Ground Level (pCi/L)	8' Above Ground (pCi/L)	Building Avg. (pCi/L)
Average Level	4.06	1.21	9.46
Highest Level	16.35	9.00	24.14
Lowest Level	0.31	0.08	2.99
Standard Dev.	3.36	0.93	4.36

The main reasons for the persistently higher radon levels in the Audiology room were thought to be due to the isolation of the room combined with a major entry path such as an open (or extremely leaky) expansion joint located under the room.

Results of the 1993 study were modeled using FSEC 3.0 (Gu 96). While they were able to reproduce some features of the data, certain aspects were difficult to fit from the information provided. The observed drop in indoor radon concentration was slower than predicted from the measured air flowrates. The limiting concentrations of about 4 pCi/L were difficult to explain without a significant radon source; moreover, since the building was apparently pressurized, the source would appear to be diffusive transport or radon in outdoor air above levels reasonably expected for either contribution.

7.4 1994 PHASE II STUDY

In order to address some of the uncertainties in the 1993 results, permission was obtained for a series of follow-up tests at the LLC. These tests occurred during April and May 1994, and involved further measurements by Southern Research and by James Cummings and coworkers from FSEC. This study involved two phases: a series of intensive characterization measurements by FSEC during March 29-April 1, followed by a 2 month set of continuous measurements by Southern Research which replicated some of the measurements performed in the 1993 study. The objective of these studies was to address some of the following unresolved questions:

- What exactly was the pressure balance in the LLC? Under what conditions was the building pressurized? To what infiltration flowrates do these pressure differences correspond?

- What is the source of the residual radon during daytime operation? Is it outdoor air? Locally depressurized areas? Failures in the foundation barrier?

The results of these experiments are presented in sections 7.4.1 and 7.4.2. The experimental study by FSEC was reported with their further modeling results in "Analysis of Polk Life and Learning Center (PLLC)" (Gu 94). The results in section 7.4.1 are reproduced, in part, from that report.

7.4.1 FSEC Study of HVAC System

7.4.1.1 Building Airtightness Tests

Blower door tests were done to characterize the building airtightness. A total of four blower doors were used to depressurize the building to as much as -59 pascals (Figure 28). Two were located in the north entrance, and one each was located in east and north classroom exterior doors. The building airtightness, as a whole, is 18,047 CFM50 with an airtightness curve of $Q = 1621.2\ (DP)^{0.62}$. The ACH50 is 4.9 (that is, the air exchange rate of the building when it is depressurized to -50 pascals). This indicates that the LLC is tighter than the average non-residential building.

7.4.1.2 Tracer Gas Infiltration Tests

Infiltration tests using tracer gas decay were done to characterize the infiltration/ventilation rate of the building under various HVAC conditions. [The length of each test is indicated in brackets.]

1) When the air handler was set to VAV max (maximum flowrate) and OA (outdoor air) was set at maximum, the building ventilation rate was 0.856 ach (air changes per hour), or 3132 cfm. [77 minutes]
2) When the air handler was set to VAV min (minimum flowrate) and the OA was still at full open, the ventilation rate was 0.498 ach, or 1822 cfm. [60 minutes]
3) When the air handler was again set to VAV max but the OA was set to "750" cfm , ventilation dropped to 0.340 ach, or 1244 cfm. [71 minutes]
4) When the air handler and exhaust fans were turned off (passive building), the ventilation rate dropped to 0.080 ach, or 293 cfm, during an overnight period when there were very light winds. [13 hours]

Building Airtightness

Building Description

16700	Floor Area [sqft]
13.1	Ave Building Height [ft]
219529	Building Volume
20	Max Building Height [ft]
0.7	Height Factor
23930	Surface Area

	80	Inside Temp
	80	Outside Temp
	1.000	Air Density Factor
a	ave	Wind Shielding (a)ve, (m)in, ma(x)
	28.6	"N"

Blower Door Data

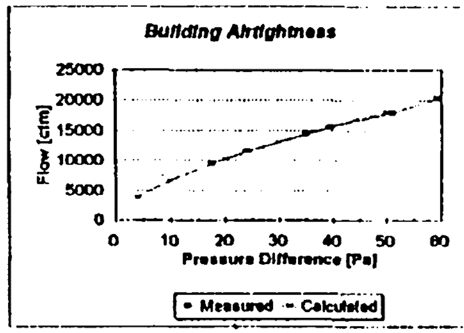
Door Location		front door			front door			north classroom			east classroom				
	BD Id. #	3512		BD Id. #	3510		BD Id. #	3511		BD Id. #	100				
Building Press	Fan Press	Fan Config	Fan Flow	Fan Press	Fan Config	Fan Flow	Fan Press	Fan Config	Fan Flow	Fan Press	Fan Config	Fan Flow	Sum Flows	Temp. Comp.	Calc cfm
1 59.3	109.1	o	4990	126	o	5604	114	o	5099	103	o	4608	20301	20301	20047
2 51	62.5	o	3788	75	o	4336	116	o	5143	106	o	4674	17942	17942	18269
3 39.4	0	o	0	121.8	o	5511	124	o	5316	110	o	4761	15587	15587	15584
4 35	0	o	0	73.9	o	4304	128	o	5358	110	o	4761	14423	14423	14487
5 24	0	o	0	40.4	o	3193	93	o	4611	70	o	3807	11611	11611	11483
6 17.5	0	o	0	27.5	o	2640	55	o	3558	51	o	3255	9452	9452	9453

Calculations

0.62	.....n
1621.18	C
0.9972	.....r

18047	...CFM50
2346.2	...FLA
6696	...CFM10
1968.1	...EqLA
3808	...CFM4
1079.6	...ELA
0.07	...C/SurfaceArea

4.9	...ACH50
0.17	...ach (ACH50/N)
632	...cfm (estimated)
4.5	...SLA
1950	...cfm needed for 15cfm / person
1281	...cfm @ 0.35 ach
1.1	...CFM50 / sqft



Notes:
Passive building, all exhausts covered and outside air closed.

03.30.94

Figure 28. Blower door test results on Life and Learning Center using four blower doors. Airtightness is 18,047 CFM50 and 4.9 ACH50 (Gu94).

Figure 29 shows tracer gas decay over a 13 hour period when all mechanical systems were turned off. It also shows the increase in interior radon levels from about 2 to 10 pCi/L over the same period.

7.4.1.3 HVAC System Assessment: Air Flowrates

FSEC measured air flowrates of the air distribution system using tracer gas injection (nitrous oxide) and sampling with a Miran 101 gas analyzer. The following flowrates were obtained by FSEC staff (measurements made by Phoenix Test and Balance are also indicated):

TABLE 6. SUPPLY AIRFLOWS AT LLC	
Air Handler	**Flow**
VAV max, OA @3000	7350 cfm
VAV min, OA @3000	5250 cfm
VAV max, OA @3000 (Phoenix)	7047 cfm
Supply Trunk Ducts (tracer injection; VAV max)	**Flow**
larger trunk	4822 cfm
smaller trunk	2744 cfm
total	7566 cfm

Outdoor air flows were measured under various VAV settings and outdoor air damper settings. Outdoor air flow does not vary significantly between VAV max and VAV min, because OA is forced into the building (into the outdoor air duct) by a large fan.

Outdoor air flow **does change** significantly with various OA damper settings. Note that, when the air handler flow is at **VAV max** and OA is at full open ("3000"), 35% of the total system air flow is from outdoors. When the air handler is at **VAV min** and OA is at full open ("3000"), 48% of the total system air flow is from outdoors. This amount of outdoor air represents significantly more ventilation than would normally be required for a building with this occupancy; and therefore, it significantly increases cooling loads and indoor humidity.

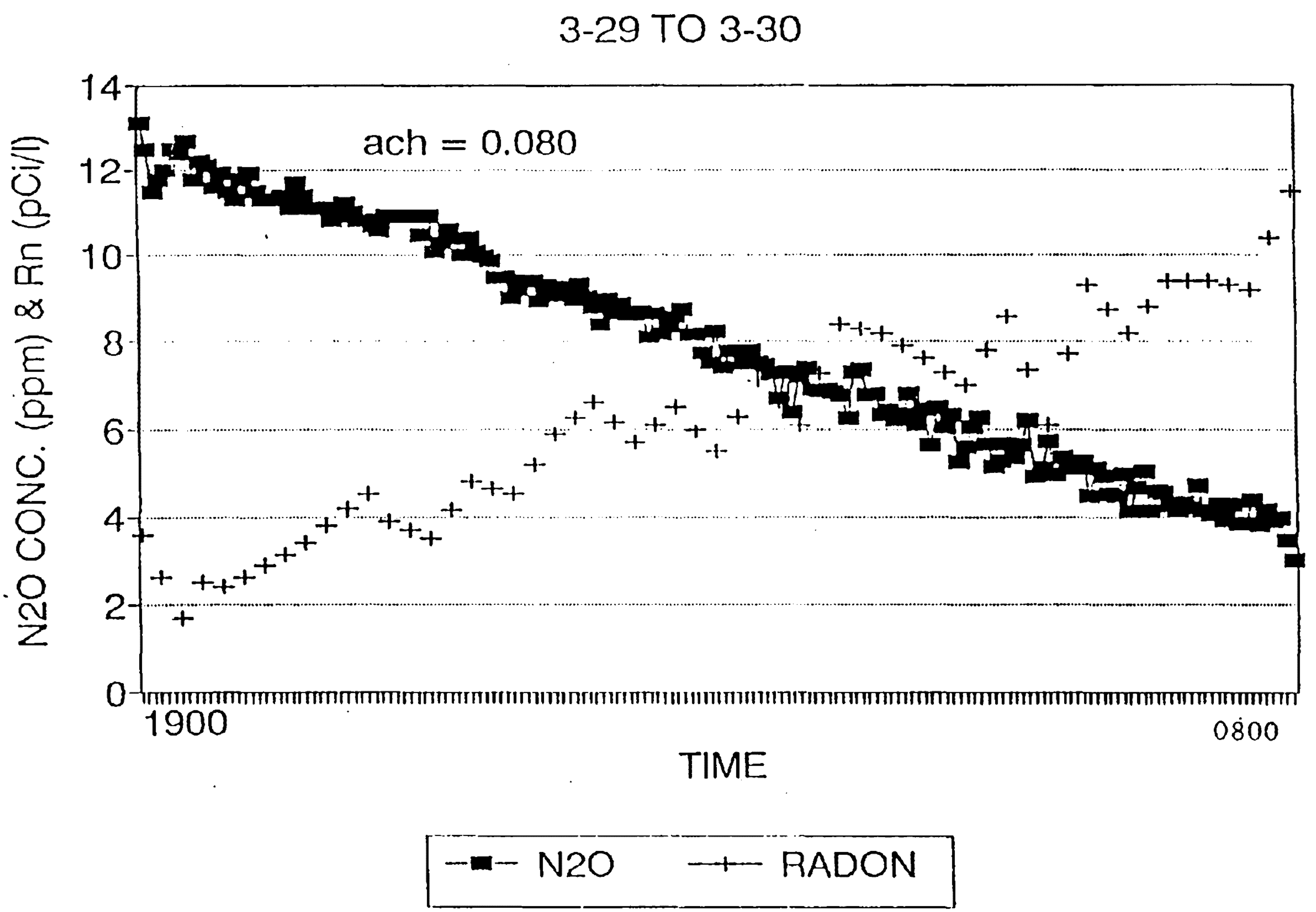


Figure 29. Infiltration rate of the building with all mechanical air moving systems turned off is 0.08 ach. Radon levels increase from about 2 pCi/L to about 10 pCi/L during this 13 hour period (Gu94).

TABLE 7. OUTDOOR AIRFLOWS AT LLC		
Outdoor Air	**VAV max (cfm)**	**VAV min (cfm)**
@3000	2550	2500
@3000 (Phoenix)	3072 (+20.5%)	
@2250	2520	2400
@2250 (Phoenix)	2249 (-10.8%)	
@1200	1990	1950
@1200 (Phoenix)	1200 (-39.7%)	
@750	1400	1400
@750 (Phoenix)	750 (-46.4%)	

Exhaust fans are all controlled by manual switches. The bathroom exhausts are tied into the light switch, so they operate whenever the light is on. Since the exhaust fans are manually controlled, we have no indication, based on our testing, of how much exhaust air occurs in this building under typical operation.

FSEC measured the following airflows at the indoor grills using a Shortridge flow hood. They did not measure any of the exhaust discharges at the roof level, so we do not have any indication of possible exhaust duct leaks.

TABLE 8. EXHAUST AIRFLOWS AT LLC	
Exhaust Fans	**Flow**
all operating	2649 cfm
as operated night 3/31	2174 cfm

7.4.1.4 Airtightness of the Mechanical Room and Ceiling Return Plenum

In order to properly model air flows and pressure differentials in various building zones/cavities, it is essential to know the airtightness of those spaces. FSEC had already done airtightness tests on the entire building, but they needed to characterize the airtightness of the mechanical room and return plenum.

An airtightness test was done on the mechanical room. Two blower doors were installed in the exterior door of the mechanical room, and the space was depressurized to a range of pressures from -60 to -10 pascals. $CFM50_{total}$ for the mechanical room was 4783. This represents its leakiness to "the universe." The test was repeated with the building depressurized to the same extent as the mechanical room, to yield the leakiness of the mechanical room to outdoors only. $CFM50_{out}$ was only 633, indicating that 87% of the zone leakiness was to the building and only 13% was to the outdoors.

An airtightness test was done to characterize the airtightness of the ceiling return plenum. This test was done by installing two blower doors in the building exterior door and two in the mechanical room exterior door. Ceiling tiles were removed from the ceiling of the mechanical room to make the ceiling plenum and the mechanical room one zone. Then a multi-point blower door test was done with each zone depressurized to the same extent. We checked that each zone was at identical pressure by measuring ΔP between the two zones with a micromanometer having resolution to 0.1 pascal.

The results of the blower door tests are shown in Figure 30. The ceiling return plenum has a CFM50 of 8867 while the downstairs space has a CFM50 of 9688. Since we know that the mechanical room by itself has a CFM50 of 633 to outdoors, we then can calculate that the plenum by itself is CFM50 = 8234. Therefore, we find that the return plenum has 44% of the entire building leak area to the outdoors. It is truly amazing that a building cavity that is so leaky is used as a portion of the air distribution system. It is interesting to note that the sum of the two CFM50 (ceiling plenum and downstairs) is 18,555, or very nearly identical to the entire building blower door test result of 18,047 CFM50 that was done on the previous day.

7.4.1.5 Pressure Differentials

Operation of the air handler is expected to pressurize the building because of outdoor air (following pressures are with exhaust fans off). Note that all pressures are "with respect to" outdoors (wrt outdoors) unless otherwise specified. At VAV max and full OA, the building was found to be about +2.2 pascals (wrt outdoors). At VAV min and "750" OA, the building was measured at about +0.9 pascal. Pressure in the ceiling return plenum typically runs about 0.6 pascal less than in the occupied space. Thus, in all cases the plenum was at positive pressure with respect to outdoors. The range of pressures produced by the operation of the air handler and OA blowers is presented in Table 9.

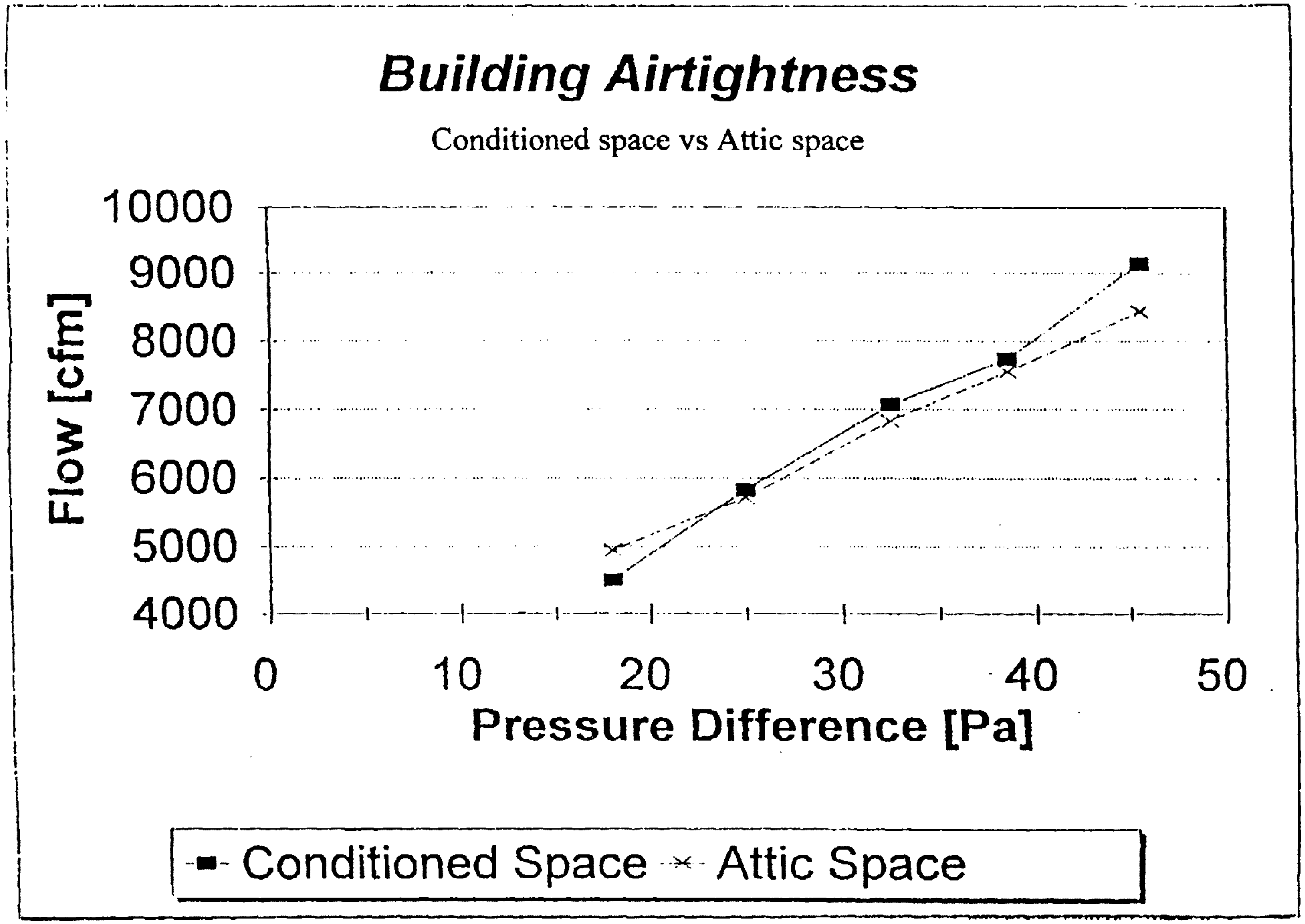


Figure 30. Airtightness curves for the Conditioned Space and the Attic return Plenum space (including the mechanical room). Building leakiness is approximately evenly split between the conditioned space and the attic plenum (Gu94).

TABLE 9. BUILDING AND CEILING PLENUM PRESSURES (EXHAUST FANS OFF)			
VAV OA Setting	**Zone Setting**	**Plenum Pressure (Pa)**	**Pressure (Pa)**
MAX	3000	+2.2	+1.8
MAX	2250	+2.0	+1.2
MAX	1200	+1.0	+0.5
MAX	750	+1.3	+0.8
MIN	3000	+1.7	+1.5
MIN	2250	+0.9	+0.6
MIN	1200	NA	NA
MIN	750	+0.9	+0.2

Zones of buildings can sometimes experience serious pressure imbalances, related to poorly designed return air, or operation of exhaust equipment within closed zones. Therefore, FSEC measured pressure differences in various zones of the building with interior doors closed.

Pressure differentials resulting from closing of interior doors were found to be small. With VAV max, pressures across closed doors ranged primarily from 0.2 to 0.4 pascal. This is very small compared to most commercial buildings. The small pressure imbalances were attributed to the ceiling return plenum. Since it can draw evenly from all rooms, there is little potential for imbalance.

However, when exhaust fans were also turned on, significant pressure differences were noted. For example, the janitor's room near the front door goes to -17.3 pascals when the exhaust fan (513 cfm) is turned on (door closed) and the classroom area across the hall from the janitor's room goes to -8.0 pascals when six exhaust fans (763 cfm) are operated (door closed).

The mechanical room was found to be depressurized relative the rest of the building. This indicates that return leaks are greater than supply leaks in the mechanical room, which is typical of both commercial and residential buildings.

- While the building was running at about +2.0 pascals with VAV max and full OA, the mechanical room averaged 0.0 pascal.

- Cutting OA back to the "750" setting reduced building pressure to about +1.2 pascals and mechanical room pressure dropped as well to about -1.5 pascals.

- It appeared then that the mechanical room runs typically about 2 pascals negative compared to the rest of the building.

7.4.2 Continuous Measurements

Continuous measurements by Southern Research Insitute replicated some of the conditions studied in 1993 and during the FSEC 1994 study. Significant changes included the following:

- Three outdoor air radon monitors were installed to investigate the distribution and time variability of outdoor radon.

- Since the indoor radon was known to be well-mixed outside the audiology room, only one indoor radon monitor (in the Cafeteria) was used. An additional monitor was installed in the mechanical room.

- In order to investigate the significance of the load-bearing block walls as an entry route, a pumped radon monitor was used to sample the air within one section of the block wall cavity. Another pumped radon monitor was used to sample subslab radon concentrations.

- Pressure differentials (with respect to the Cafeteria) were monitored in the following zones: the mechanical room, outdoors, subslab, and the block wall section.

- SF_6 was continuously injected into the Cafeteria (and generally found to be uniformly distributed in the building).

- In addition to operation of the HVAC during several week-long periods at each of the OA damper positions used previously, several periods of depressurization (using the exhaust fans) were scheduled on weekends. One period of pressurization (with the HVAC off) was performed using a blower door. Out of deference to the energy management concerns of the school district, the customary setback schedule (8 hr on/16 hr off, 5 days/week) was used in the 1994 study.

Some results of the outdoor radon experiment are illustrated in Figure 31. The monitor sampling at ground level (3 inches) failed early in the study and was removed. The other monitors (at 4 ft and on the roof level at the OA intake) continued to operate throughout the study period. Both monitors showed low values during the day (typically ≤ 0.5 pCi/L) followed by peaks of 2-6 pCi/L or higher at night, when turbulent mixing is low. The roof level monitor peaked at a higher value than the lower monitor, which was not expected. The possibility exists, however, that these levels may in fact be partly caused by radon leaving the building during the periods when the OA fan is off. In order to check for other artifacts, a charcoal filter was placed alternately in front of the inlet to each monitor. As seen in Figure 31, the measured radon in each monitor dropped to background levels during the period that the filter was installed. An inadvertent leak to the mechanical room demonstrated that the monitor used for 4 ft measurements responded normally to indoor levels.

Continuous data during 5 weeks of the 1994 study are summarized in Figures 32-46. Figures 32-36 illustrate pressure differences monitored during the experimental periods. Figure 32 covers depressurization experiments during the evening of April 14 and 15, and the blower door pressurization experiments of April 16-18. Figures 33-36 cover week-long periods of normal operation with the OA damper set at positions corresponding to nominal flowrates of 3000, 750, 2250, and 1250 cfm, respectively. Also included are depressurization experiments (using some or all exhaust fans) on 4/24-5, 5/8-9, 5/14, 5/15, and 5/23.

Examination of Figures 32-36 confirms some trends seen by FSEC in their short-term study, and suggest further insights into the normal operating state of the building. First, the cafeteria runs at positive pressure with respect to outdoors when the air handler is operating. The mean pressurization varies from about 0.3 Pa at 750 cfm nominal OA to about 1 Pa at 3000 cfm nominal OA. During weekdays, this pressure differential undergoes dramatic fluctuations. These may partly be due to changes in the building load (VAV operation), or in the OA fan operation, as they are not present during periods with the HVAC off, even when the building is mechanically pressurized or depressurized. However, since these fluctuations are also characteristic of occupied periods (note that they are greatly reduced on the weekend of 5/14-15), they may result from occupant activity (i.e., opening doors or windows).

During HVAC off periods, the cafeteria-outdoor pressure drops to low values, and a slight depressurization is observed on many nights. This depressurization is most likely explained by the observation that a few exhaust fans were often left in operation after the staff left at the end of the day. These unmonitored changes in building operation were unfortunate, since they leave some uncertainty as to the exact operating mode of the building.

As noted by FSEC, the mechanical room is depressurized relative to the cafeteria by 1.5-2.0 Pa when the air handler is operating. This difference is greater than the pressurization of the cafeteria, so the mechanical room is negative with respect to the outdoors for all but brief portions of the normally occupied periods. Pressures in the other zones monitored (subslab, block wall, and mechanical room during periods without air handler operation) track the cafeteria pressure, but tend to be slightly lower in magnitude during mechanical pressurization or depressurization.

Figures 37-46 illustrate radon levels during the four operating conditions and the pressurization/depressurization experiments. Figures 37-41 contain radon concentrations

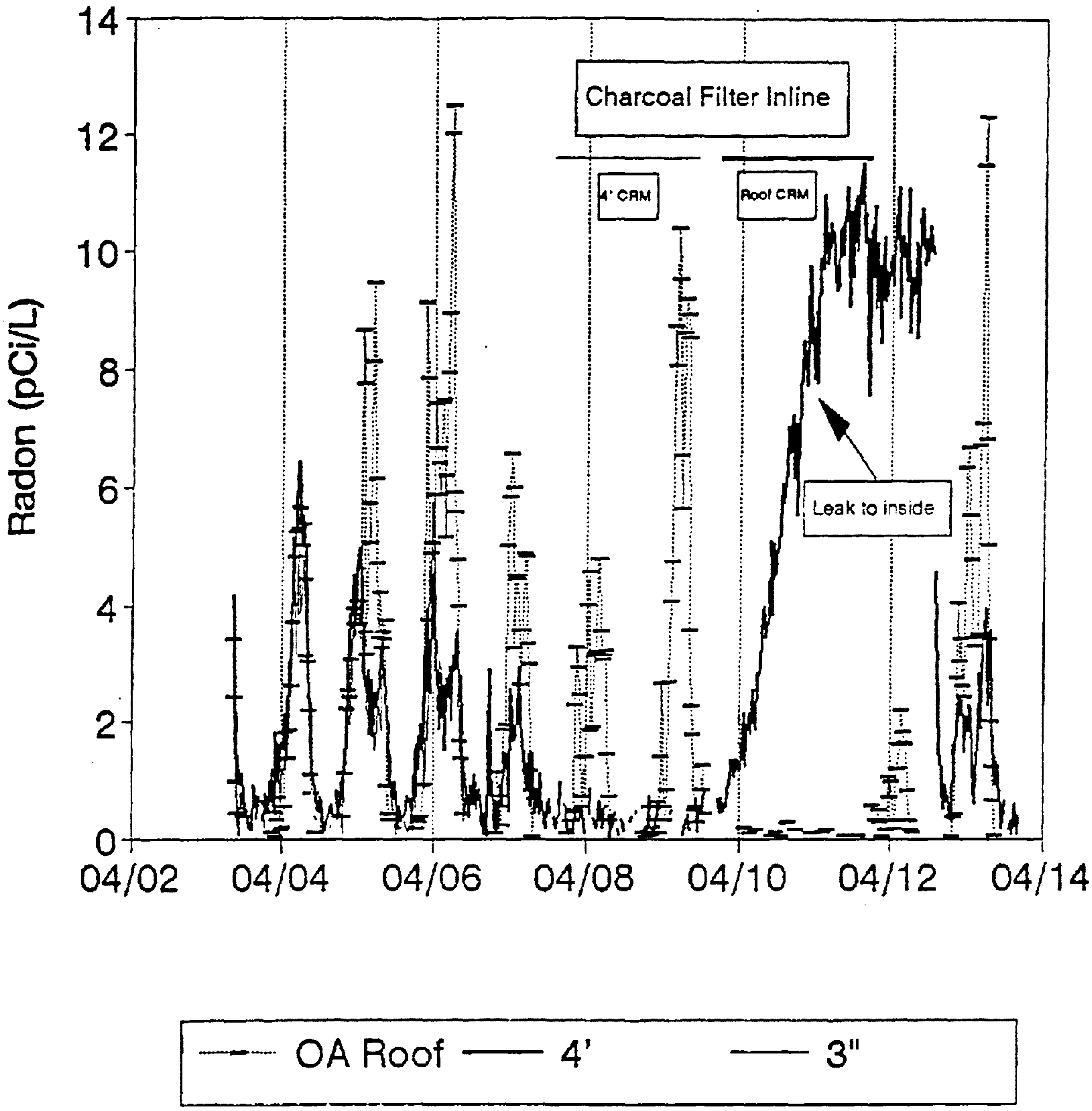


Figure 31. Outdoor air radon levels during the LLC radon experiments at three locations: roof level at the OA intake, 4 feet above the ground, and at ground level (3 inches). A charcoal filtler was placed at the inlet to the 4 foot CRM for 2 days and then removed and placed at the inlet of the roof CRM for 2 days.

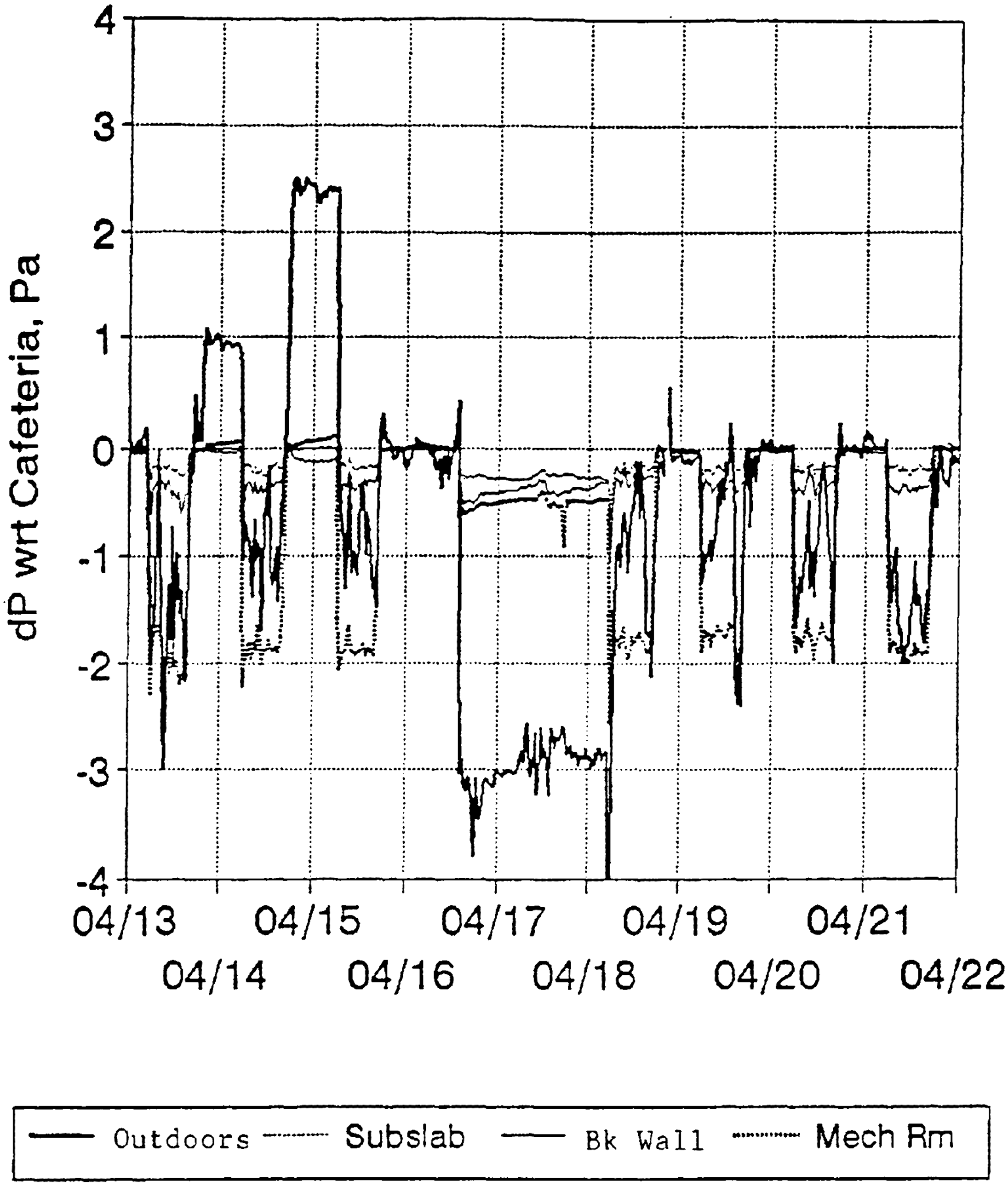


Figure 32. Differential pressure of LLC zones to cafeteria during the period 4/13-4/22/94.

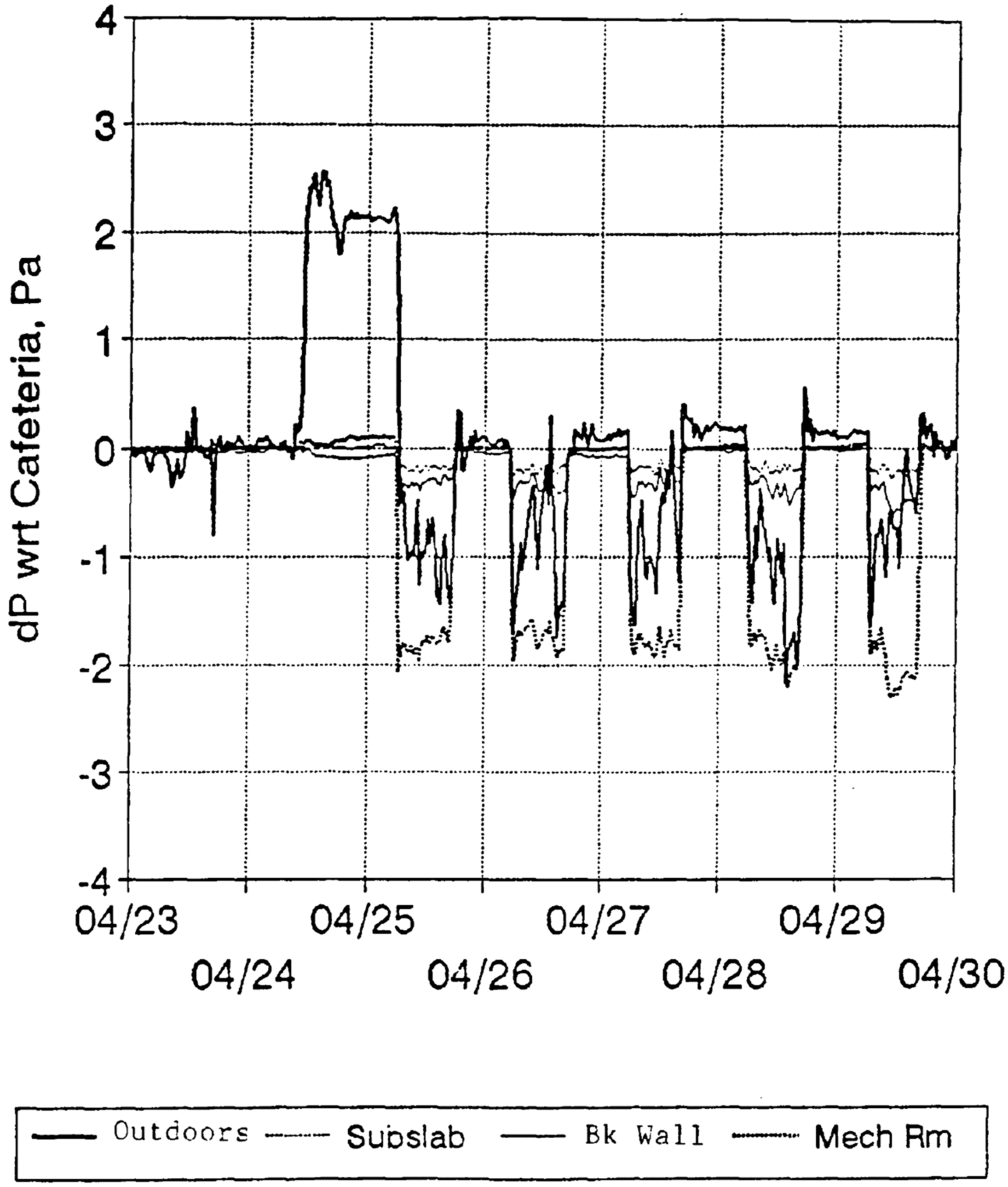


Figure 33. Differential pressure of LLC zones to cafeteria during the period 4/23-4/30/94.

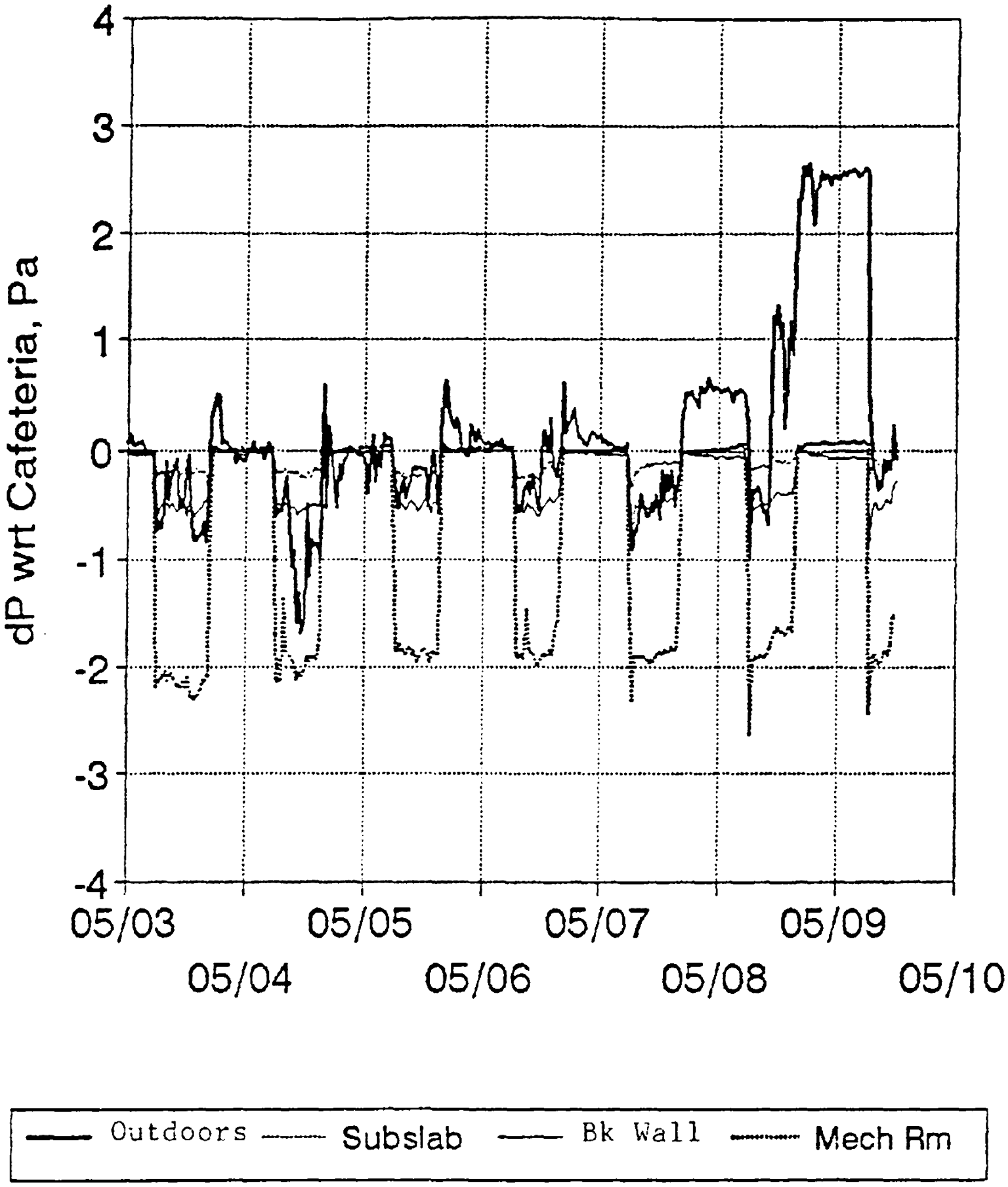


Figure 34. Differential pressure of LLC zones to cafeteria during the period 5/3-5/10/94.

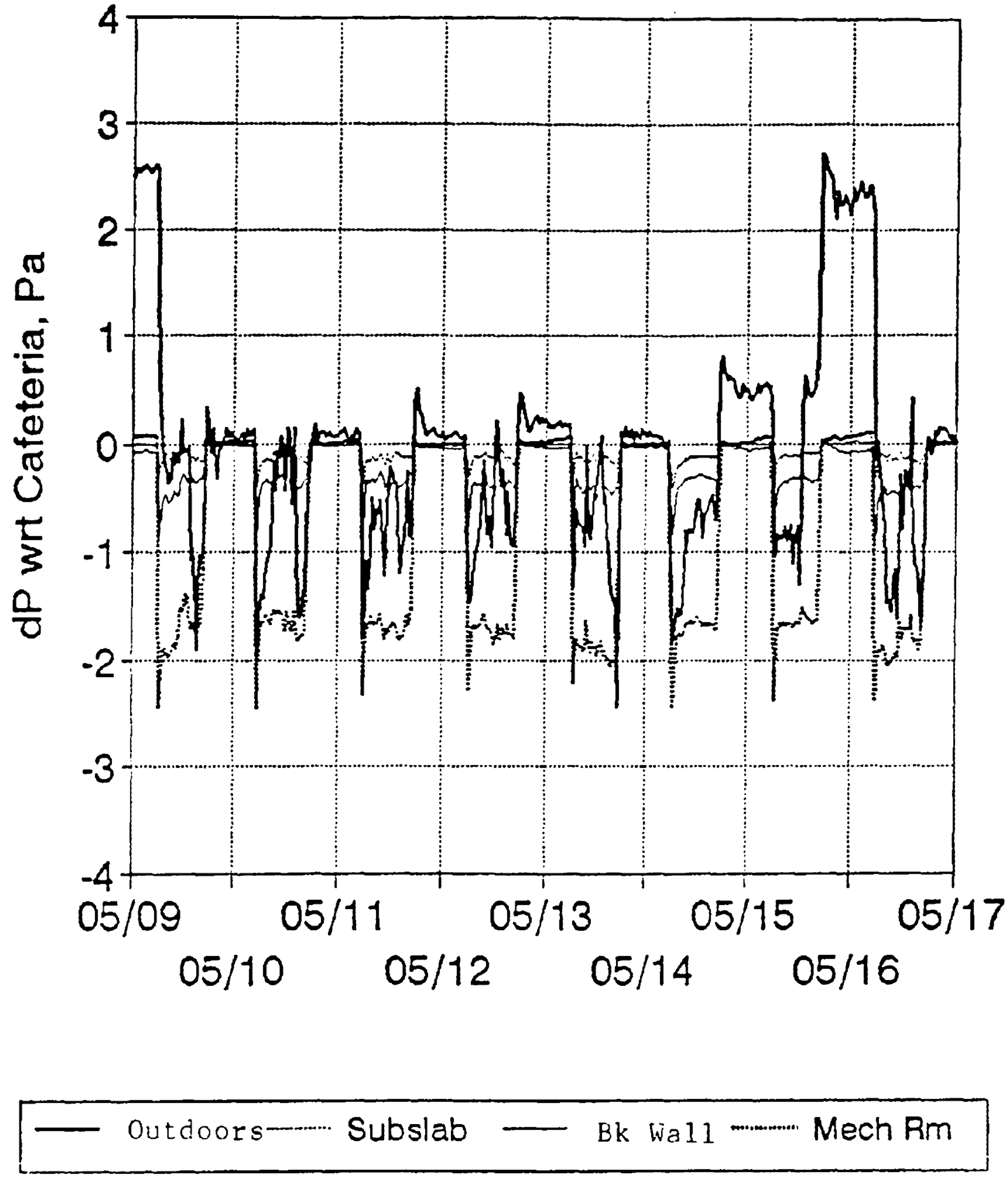


Figure 35. Differential pressure of LLC zones to cafeteria during the period 5/9-5/17/94.

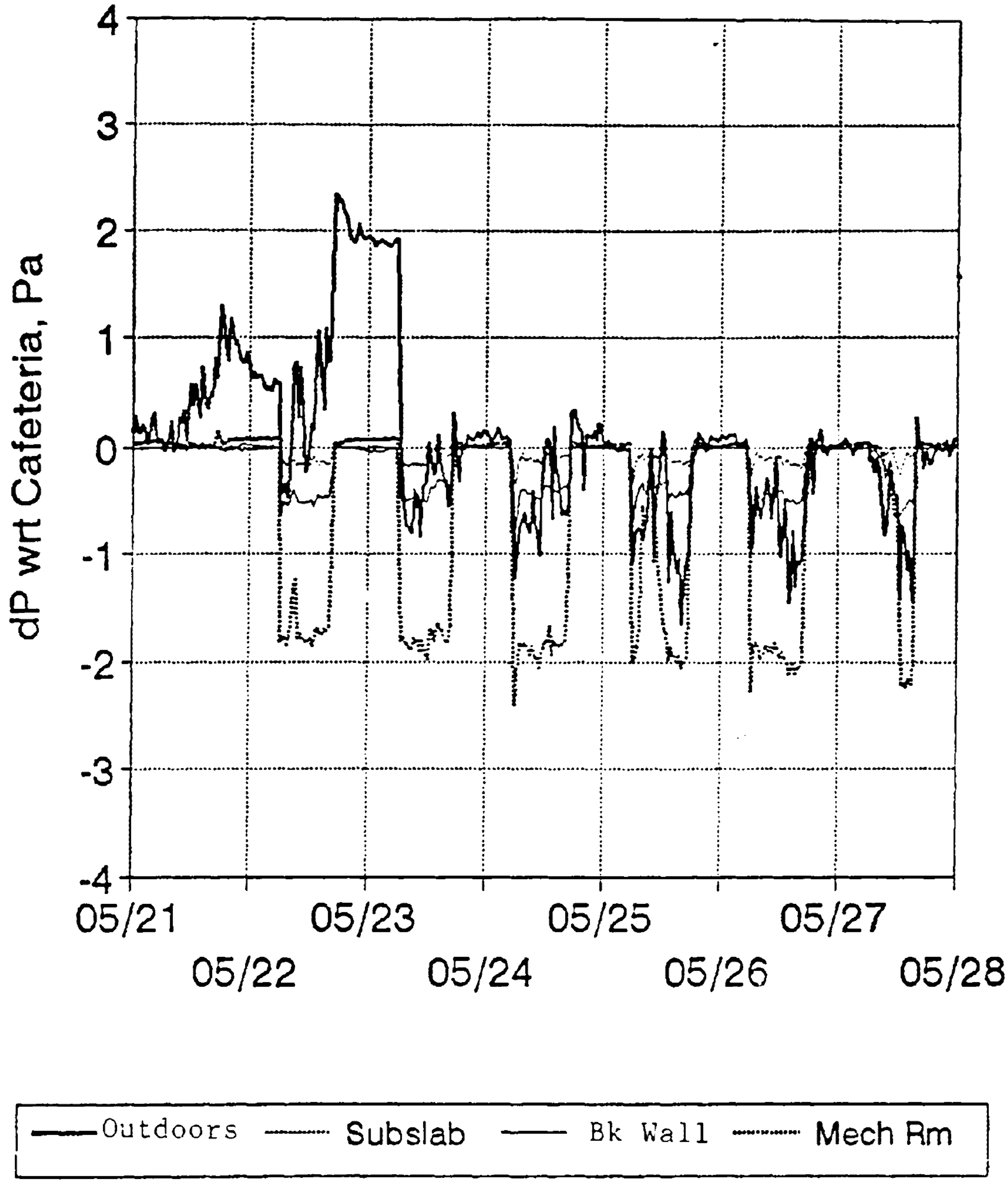


Figure 36. Differential pressure of LLC zones to cafeteria during the period 5/21-5/28/94.

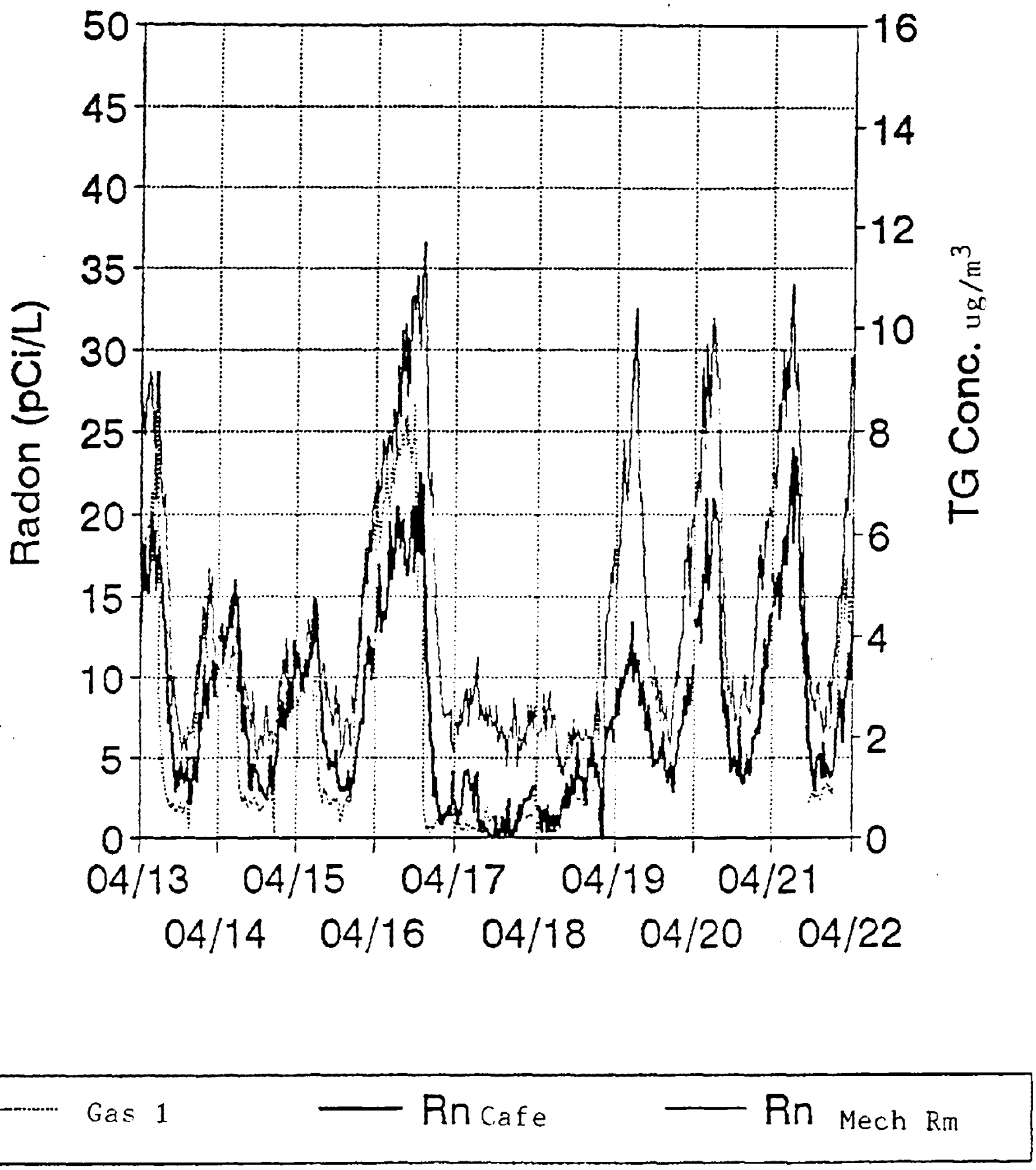


Figure 37. Radon in cafeteria and mechanical room during the period 4/13-4/22/94. Also plotted is SF_6 concentration in cafeteria.

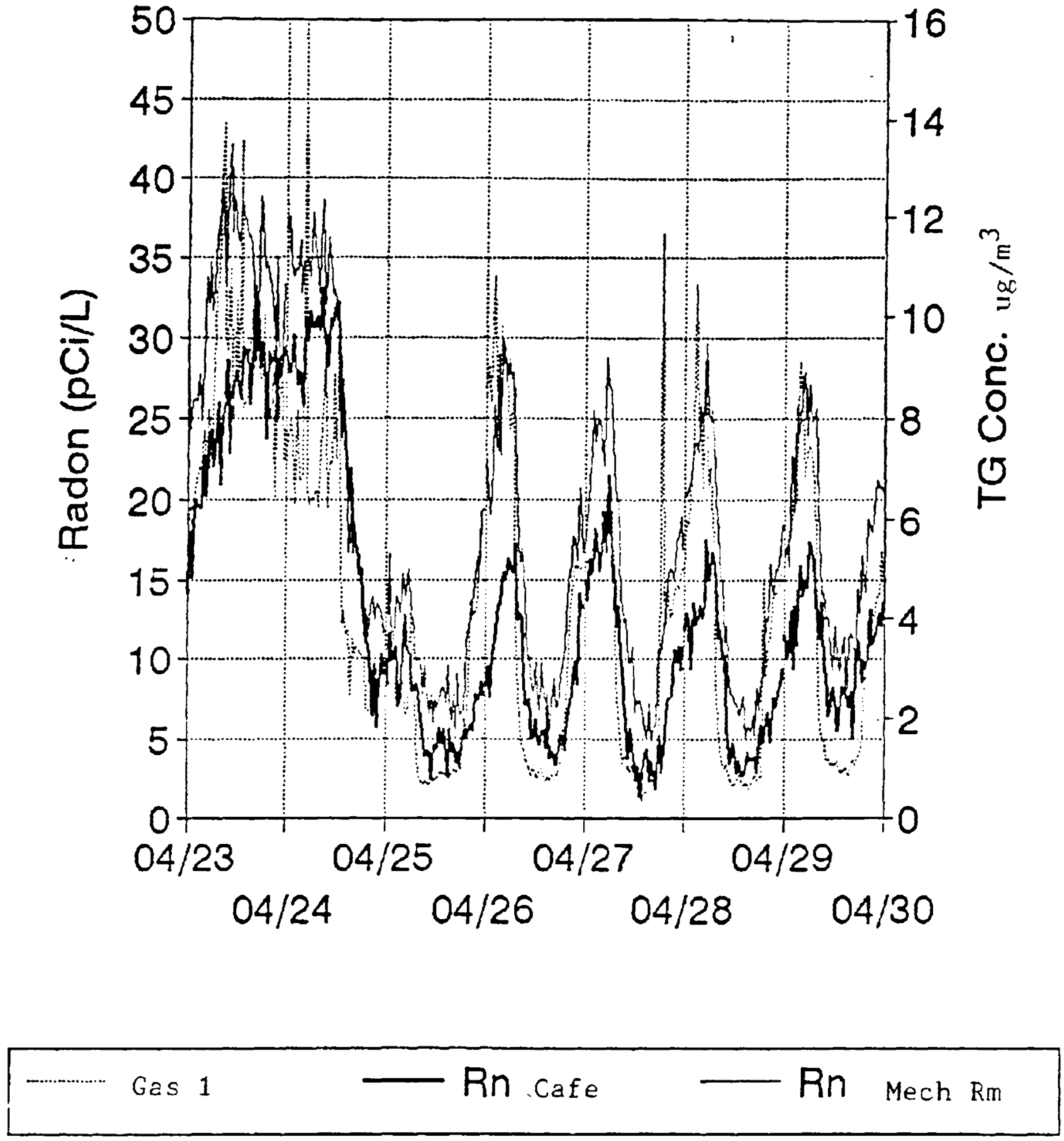


Figure 38. Radon in cafeteria and mechanical room during the period 4/23-4/30/94. Also plotted is SF_6 concentration in cafeteria.

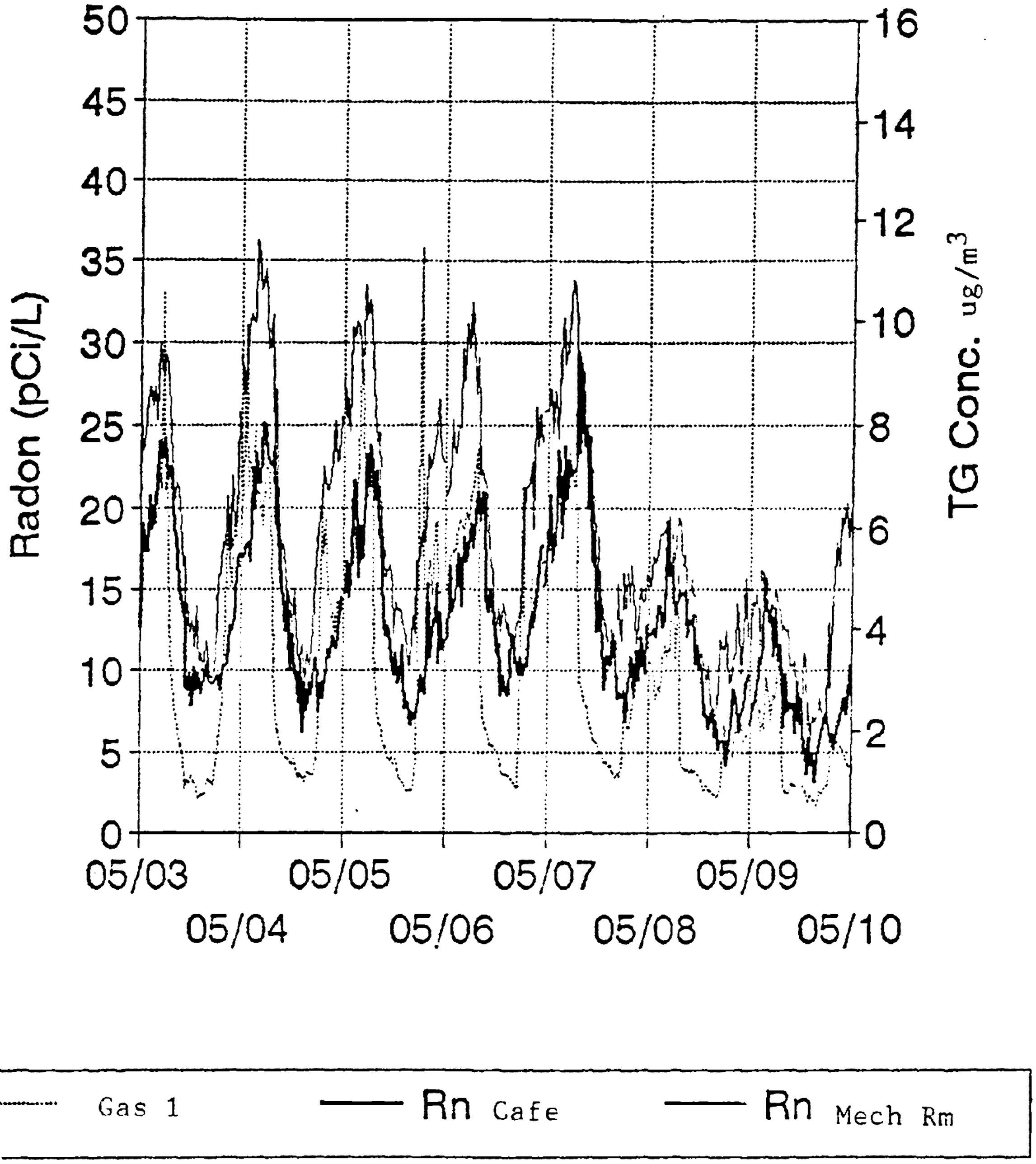


Figure 39. Radon in cafeteria and mechanical room during the period 5/3-5/10/94. Also plotted is SF_6 concentration in cafeteria.

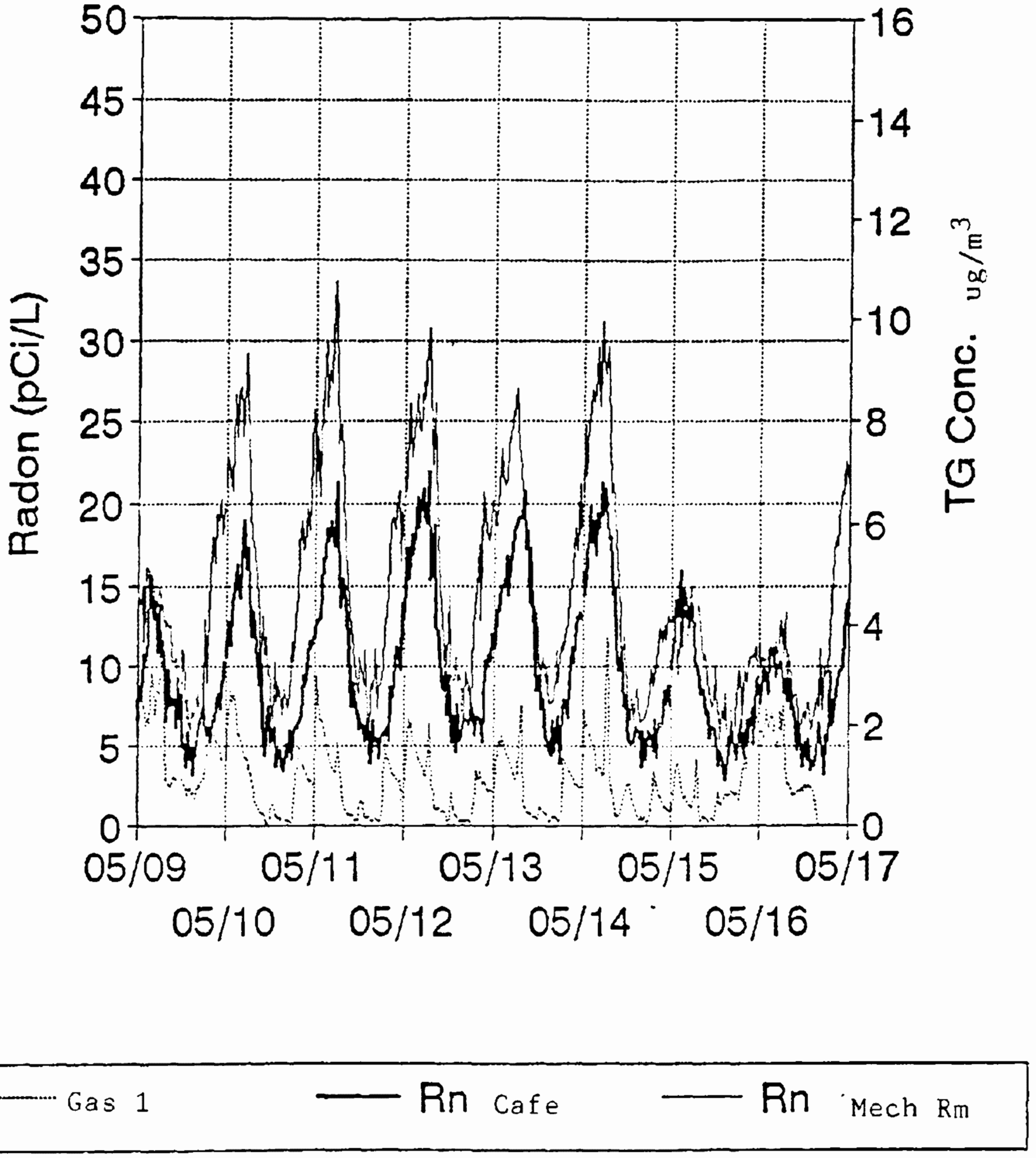


Figure 40. Radon in cafeteria and mechanical room during the period 5/9-5/17/94. Also plotted is SF_6 concentration in cafeteria.

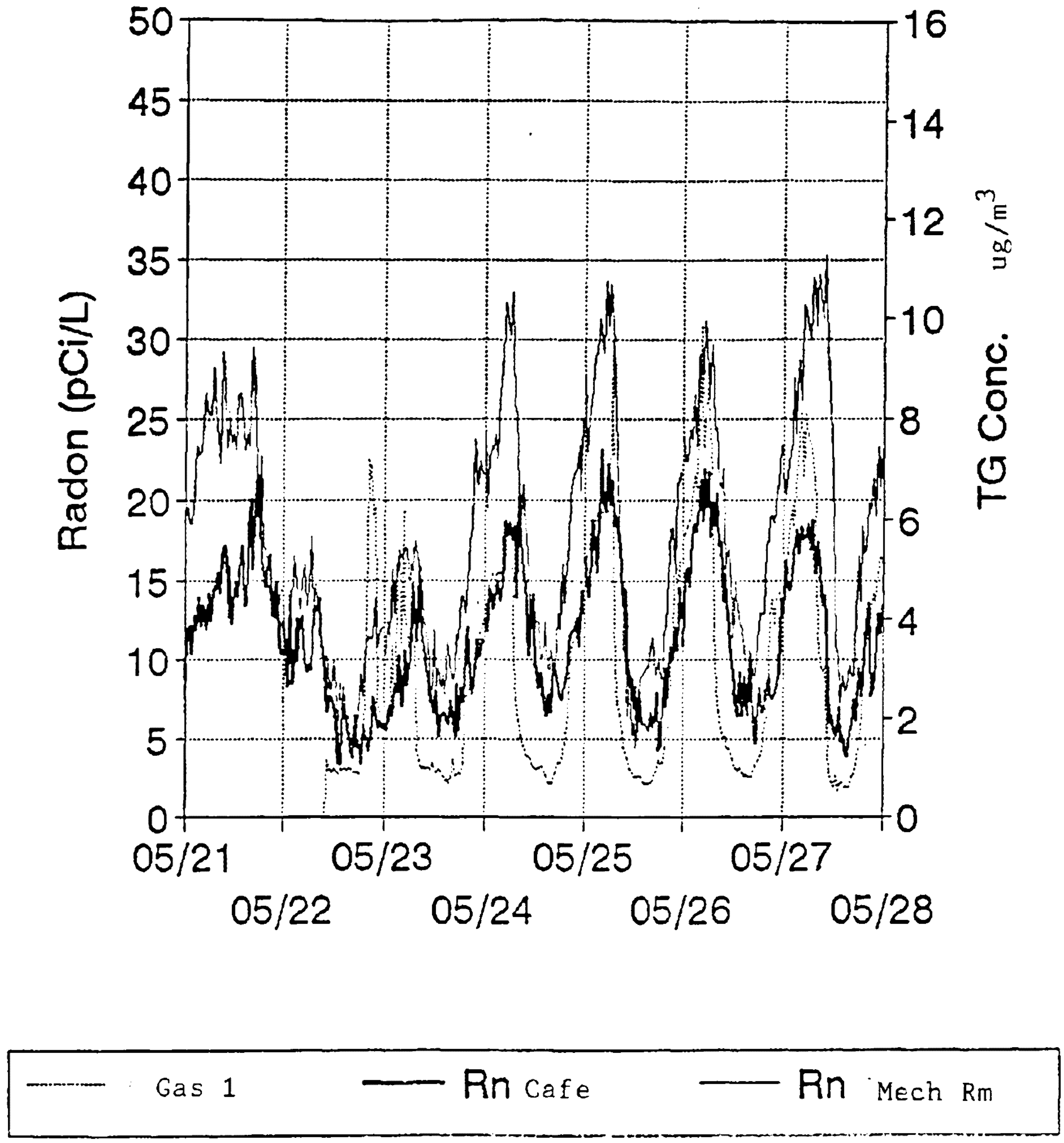


Figure 41. Radon in cafeteria and mechanical room during the period 5/21-5/28/94. Also plotted is SF_6 concentration in cafeteria.

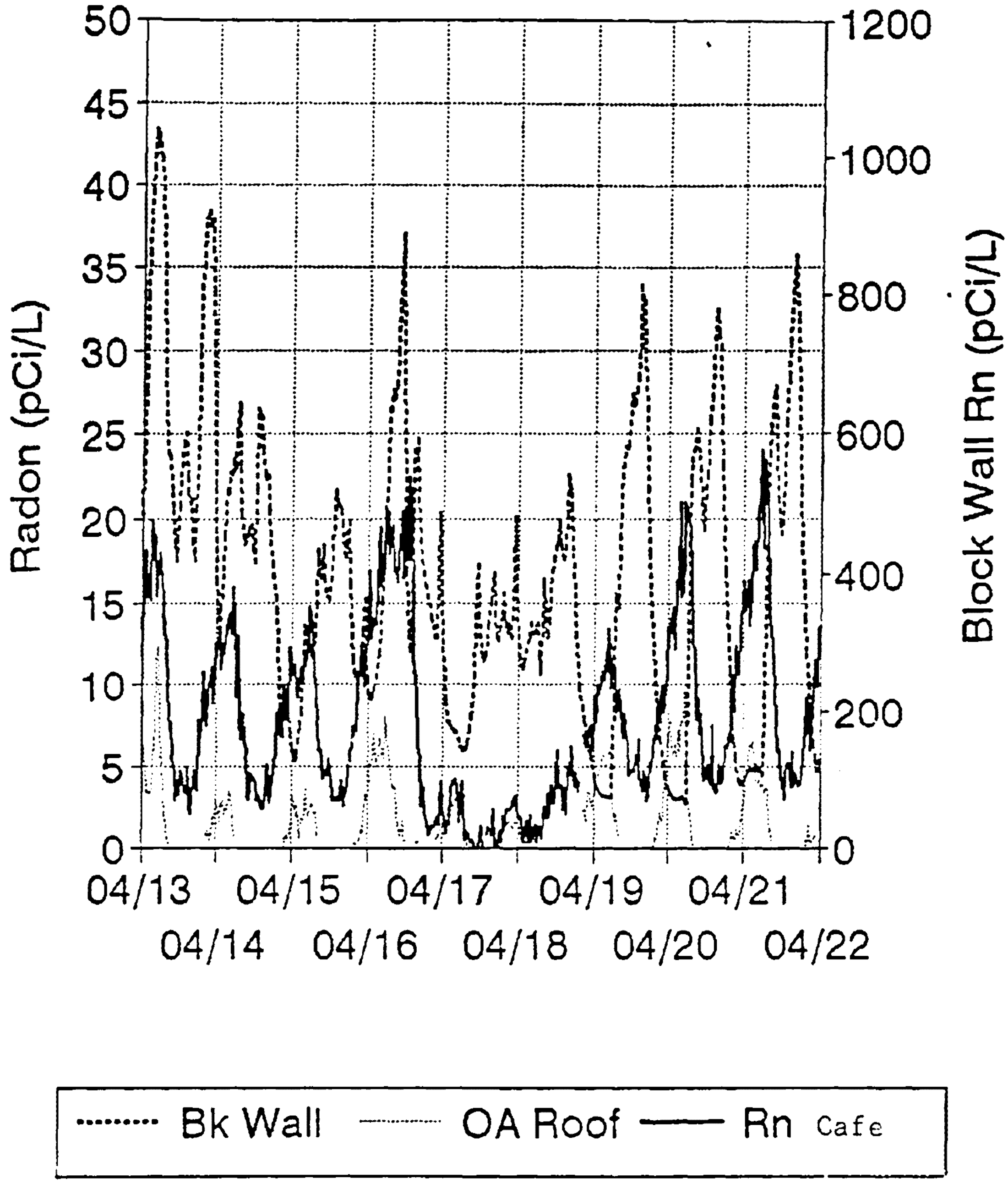


Figure 42. Radon concentrations in block wall section and outdoor air at roof level during the period 4/13-4/22/94.

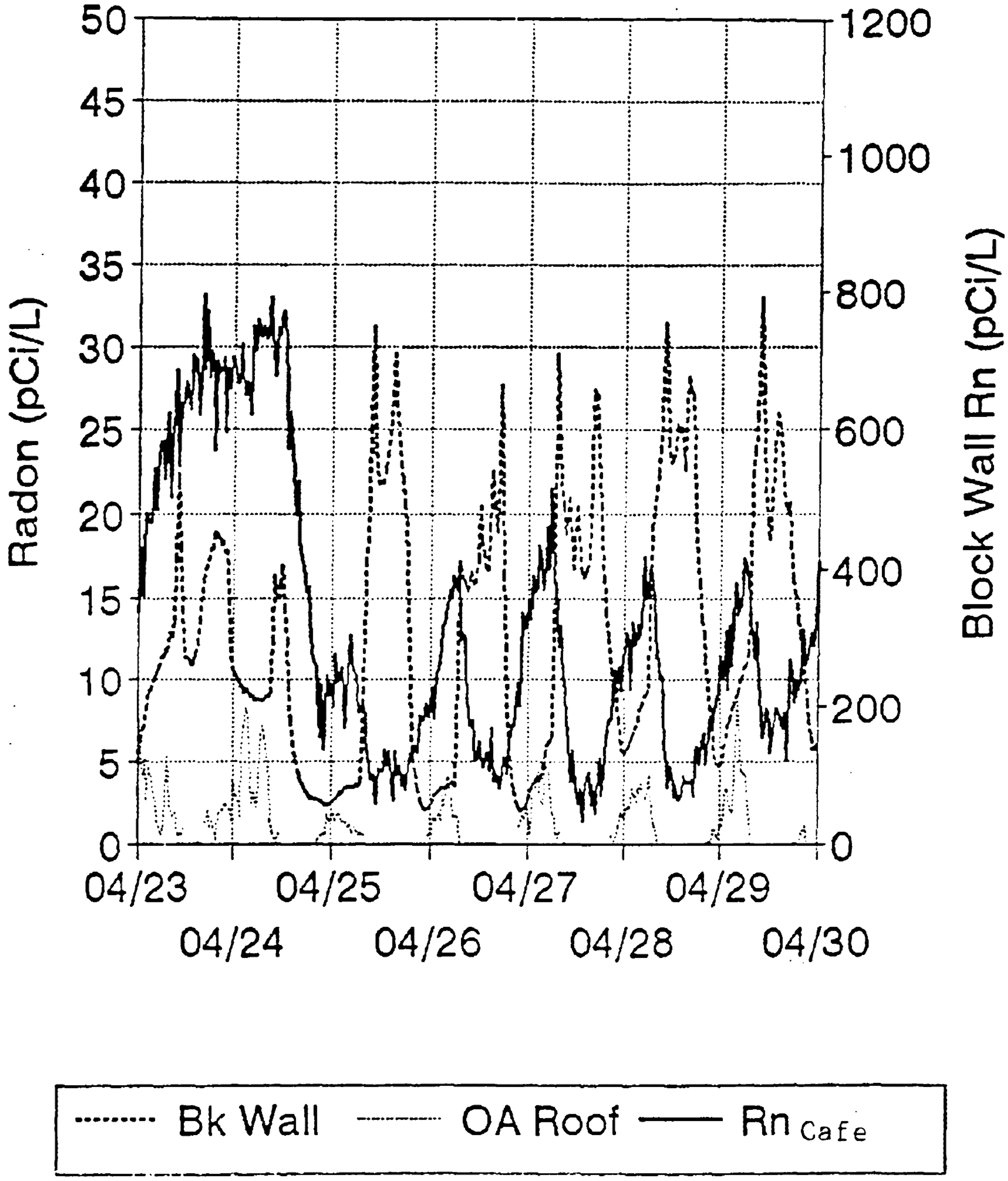


Figure 43. Radon concentrations in block wall section and outdoor air at roof level during the period 4/23-4/30/94.

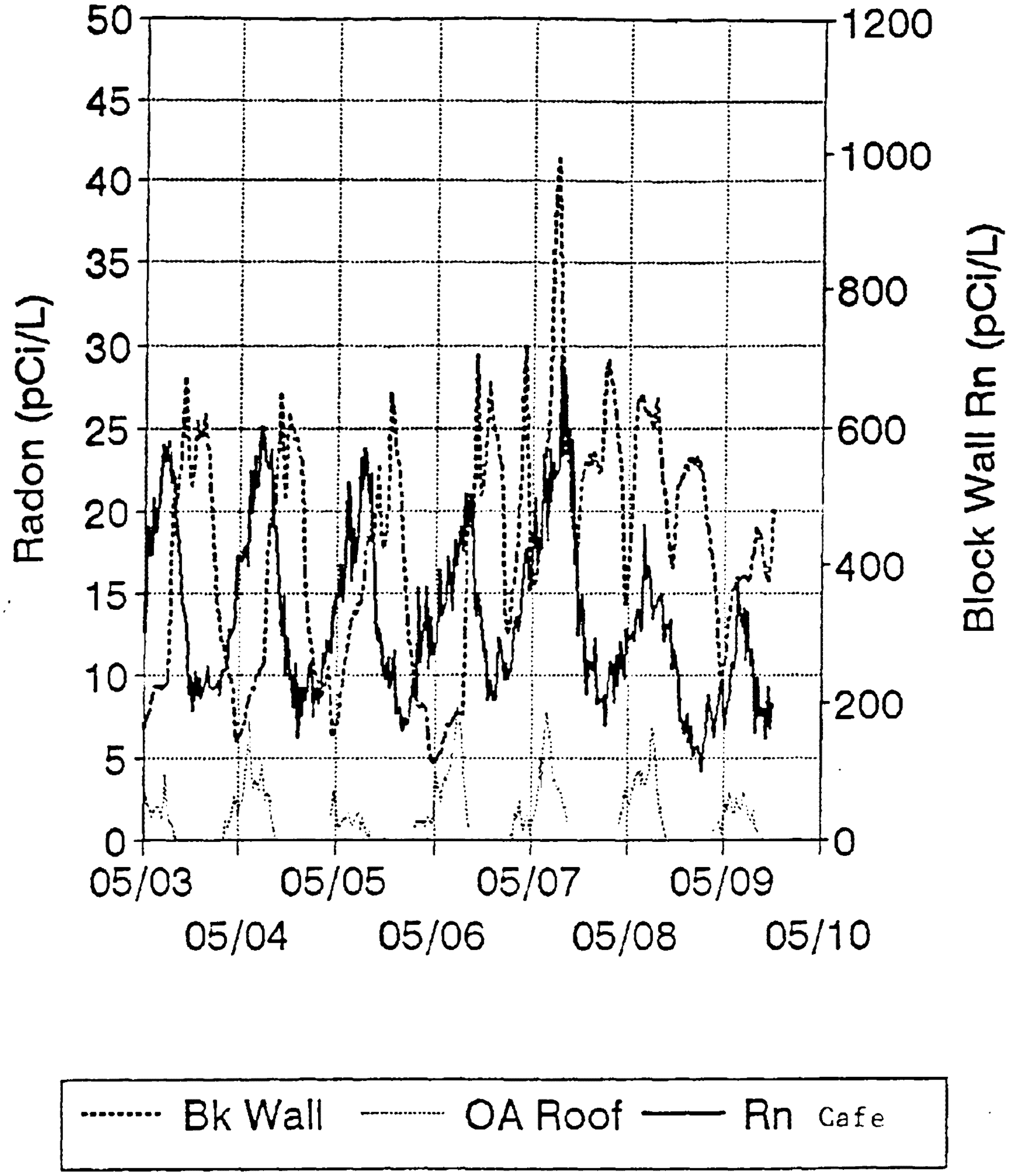


Figure 44. Radon concentrations in block wall section and outdoor air at roof level during the period 5/3-5/10/94.

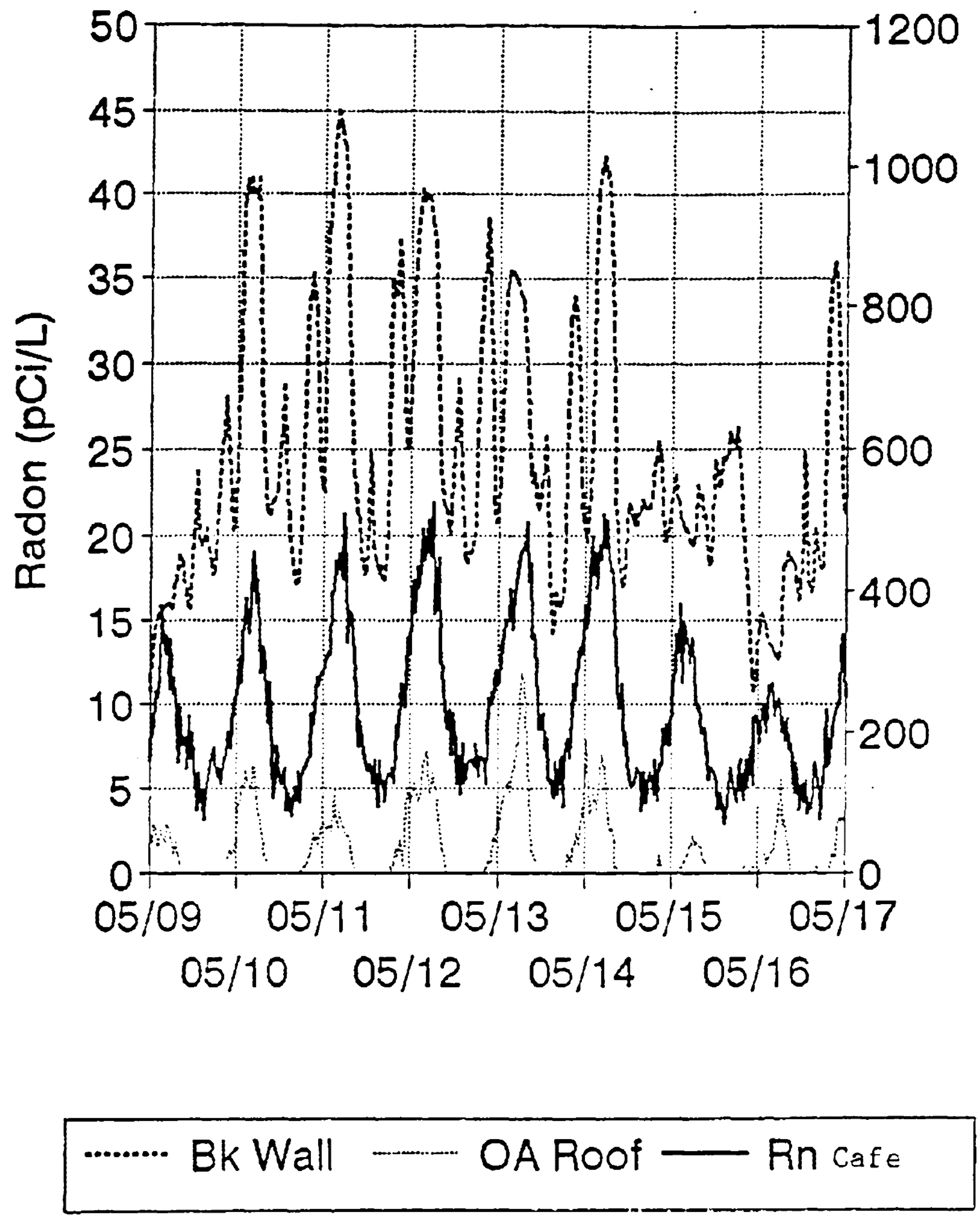


Figure 45. Radon concentrations in block wall section and outdoor air at roof level during the period 5/9-5/17/94.

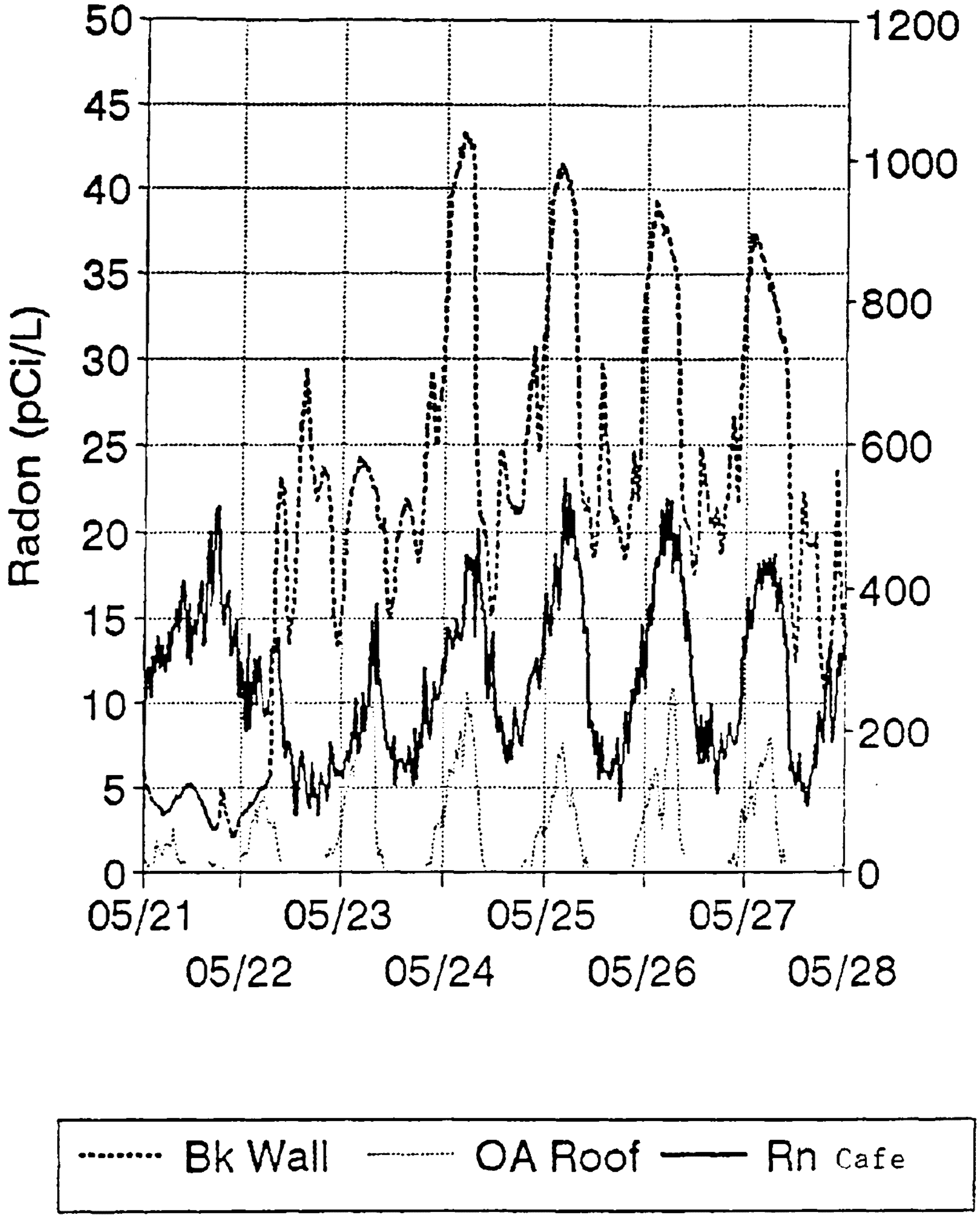


Figure 46. Radon concentrations in block wall section and outdoor air at roof level during the period 5/21-5/28/94.

in the cafeteria for each period. The three data sets show similar time trends, as would be expected, with a few significant differences. First, the radon concentrations in the mechanical room are consistently higher than in the cafeteria under all HVAC and mechanical ventilation conditions, although the differences grow smaller for periods of mechanical depressurization or of low OA damper setting. Since interzone ventilation rates between the two zones are expected to be high, and inleakage of outdoor air is expected to be much higher into the mechanical room as compared to the cafeteria, the higher concentration suggests a significantly higher radon entry rate into the mechanical room. This is not surprising in light of the pressure measurements showing the mechanical room to be the most highly depressurized portion of the building.

A second observation is that the ratio of indoor radon to SF_6 tracer is significantly higher in the daytime (with HVAC in operation) and during depressurization, indicating higher radon entry rates during those periods. (Since the ventilation rate is also increased, these periods tend to be periods of lower radon concentrations.) The increased entry rate when the air handler is turned on also helps explain the slower rate of fall of radon concentration than would be expected from the air change rate. Indeed, the SF_6 tracer gas does drop much more rapidly to its limiting daytime value. The slower decay time of the radon is partially explained by the larger measurement time constant of the radon monitors due to decay times of the radon progeny, but is also an indication of the change in entry rate as the HVAC cycles between normal and setback operation.

One portion of the added radon source becomes more clear in view of Figures 42-46, in which the concentrations of radon in the outdoor air and block wall cavity are plotted with the cafeteria concentrations during the study period. The outdoor air contribution is seen to be minimal, since the outdoor air concentration is at background levels during the day when the building ventilation rate is significant. In the early morning hours when the outdoor radon concentration is highest, the indoor concentrations are several times higher; furthermore, the infiltration rate is quite low at these times. The one period when the outdoor air radon may be a factor is the pressurization period of April 16-18, in which the indoor radon levels are low and track the daily pattern of the radon in the outdoor air.

In contrast, the block wall radon concentrations suggest this to be a major pathway for radon entry. During periods of air handler operation, the block wall radon rapidly rises to levels of 600-1000 pCi/L, then drops back to lower levels during the evening setback period. Inspection of Figures 32-36 indicates that, while the block wall pressure at the section tested is generally positive with respect to outdoors during HVAC on periods, it is generally negative with respect to both the subslab test point and the cafeteria. As hypothesized by FSEC, this depressurization may be due to coupling with the plenum, and would suggest some path for transport of radon into the return air system.

The pressure coupling would explain the rapid influx of soil gas into the block wall cores as the air handler activates in the morning, as is clearly seen in Figures 43 and 44. The rapid drop in block wall radon as the air handler goes off in the afternoon can be attributed to the relief of this driving pressure gradient combined with transport of the accumulated radon back into the soil or, more probably, into the building. The likelihood that the block walls provide a major entry path has been discussed before, since the cores of these walls penetrate the slab to the block courses in direct contact with the soil. Since the pores of the block are highly permeable, a low resistance pathway exists directly from the soil to indoors.

Two cautions must be observed regarding any quantitative interpretations from these results, however. The block wall section tested was a 4 foot wide interior wall segment bordering the cafeteria and Room 109. Horizontal communication within the wall segment will presumably be limited by the reinforced filled core sections specified every 4 feet in this building. There are exhaust fans in Room 109, which may enhance entry in this section over walls adjacent to rooms with no mechanical exhausts. On the other hand, entry into the walls of the mechanical room might easily be much higher, and could represent the major source of radon entry into the building. In any event, the results of the present study clearly indicate that the wall construction detail used in the LLC is highly vulnerable to radon entry, and alternatives must be provided for a radon-resistant building standard.

SECTION 8

QUALITY ASSURANCE

In 1993, the EPA approved a Quality Assurance (QA) Project Plan (QAPP) (#93012) for the "Study of Radon Entry and Control in Large Foot-Print Structures" to develop suitable diagnostic and mitigation techniques for existing large buildings in Florida. It was under this QAPP that the 1993 parametric study was conducted. In early 1994, the EPA approved a similar QAPP (#94036) for this and other Large Building 1994 Demonstrations that was used to guide the collection and analysis of the 1994 Phase II study. The radon measurements were made according to procedures found in the EPA's "Indoor Radon and Radon Decay Product Measurement Device Protocols" (EPA 92). The differential pressure measurements were made using MODUS Instruments, Inc. pressure transducers according to their operating instructions.

8.1 DATA QUALITY OBJECTIVES AND ACHIEVEMENTS

The primary objective of this project was to determine the effect of the HVAC systems of large buildings in influencing the transport, entry, and reduction of indoor radon in the buildings. The 1993 parametric study showed that in two buildings the HVAC system assisted in lowering the radon concentrations by inducing enhanced ventilation rates in the building and that the rate of their decline and the limiting radon concentrations depend on the OA gas flow rate. The peak radon concentrations reached in the second building (LLC) (just before the HVAC system was activated) depend somewhat on the amount of OA introduced during the previous HVAC operation cycle and on the length of time that had transpired since the HVAC system was last operated. However, two questions remained unresolved: why the radon concentrations in one room did not follow those of the rest of this building and why the minimum concentrations achieved were so high. Therefore, the 1994 Phase II study was implemented at LLC. Its objectives were to address questions not satisfactorily answered by the first study. These included: the pressure balance in the building; the conditions under which it was pressurized; the flow rates to which those conditions correspond; and the source of the residual radon concentrations below which it seemed impossible to reduce the indoor levels with the HVAC system (outdoor air, locally depressurized areas, or failures in the foundation barrier). The occupied portion of the building was found to be pressurized whenever the HVAC system was operated and neutral to slightly depressurized when it was not. However, the mechanical room was usually depressurized with respect to the outdoors when the building was occupied and the radon concentrations are consistently higher there, suggesting a significantly higher radon entry rate into the mechanical room. Although the outdoor air averages a higher than expected radon concentration, it does not account for the high indoor radon concentrations. High block wall concentrations suggest that they may be major pathways for radon entry.

8.2 DATA QUALITY INDICATORS

The data quality indicator (DQI) goals for precision, accuracy, and completeness are described in the QAPPs (#93012 and #94036) of 1993 and 1994, respectively. The precision goals for radon concentrations of 4 pCi/L or greater are given in terms of a coefficient of variation (CV) or relative standard deviation and are the 10% levels listed as achievable in the EPA's protocols. The precision goal for differential pressure of 25% CV was set higher because many of the measurements are expected to be in the range of ±1 Pa, and this level of precision will be quite adequate in this range of measurements. The accuracy goal for radon concentrations was the criterion for a pass in the EPA's Radon Proficiency Program (RPP), ±25% bias for concentrations above 4 pCi/L. This bias was also considered adequate for the differential pressure measurements. The target completeness goal was 90% for each measurement parameter.

8.2.1 Continuous Radon Monitors

8.2.1.1 Precision

As part of Southern Research Institute's ongoing QA/QC program, and before any continuous radon measurements were started in the LLC building in December 1992, six of the CRMs were placed in two locations and measured the radon concentration there simultaneously for about 2 days. [The remaining monitors (most belonging to the EPA) were treated similarly, with equally successful results, but the actual data were not provided.] Several times during the measurements, two or more monitors were collocated and measured radon concentrations in the same location over the same time intervals. Once again after the study's conclusion the monitors were again placed in the same locations and set to measure the indoor radon concentrations there. The resulting measurements from each of these replications are given in Table 10. The DQI goal

TABLE 10. RESULTS FROM REPLICATE PLACEMENT OF CRMS

	CRM								
Time Period	**1**	**2**	**3**	**4**	**5**	**6**	**165**	**172**	**CV**
11/25-11/26/91	5.8		5.8		5.1				7%
11/25-11/26/91		18.7		18.5		18.5			1%
04/14-04/15/93	16.5	16.3	16.1	15.2	17.8	17.0			5%
03/02-03/04/94	18.5	17.1	16.5	19.1	18.9	17.6	17.2	16.2	6%
04/11-05/03/94				12.8			13.4		3%
06/14-06/16/95	9.3	9.9	10.0	9.8	9.3	9.2			4%
06/16-06/19/95							9.3	9.8	3%

for the precision of the CRMs was a CV of 10% for radon concentrations greater than 4 pCi/L. The CVs listed in Table 10 range from 1 to 7%, all less than this DQI goal. Therefore, the precision of the CRMs was considered quite acceptable.

8.2.1.2 Accuracy

During the last calibration check in the EPA radon chambers at the National Air and Radiation Environmental Laboratory (NAREL) in Montgomery, Alabama, prior to the commencement of measurements in 1992, a calibration factor (CF) was calculated for the six CRMs that used alpha scintillation for radon measurement. The two ionization chamber (IC) CRMs were sent to the manufacturer for calibration checks. Twice during the study, the six scintillation monitors were returned to NAREL for subsequent calibration checks, during the second of which the two IC monitors were also calibrated. After the study was over, the eight CRMs were returned to NAREL for a final calibration check. The measurements of the radon in the NAREL chambers were calculated for each monitor as would have been done in the field.

After the exposures, NAREL sent the actual chamber concentrations so that the relative errors (REs) and the new CFs of the monitors could be calculated. The RE is the difference between the measured value and the actual concentration divided by the actual concentration, given as a percentage. The DQI goal for accuracy (or bias) was ±25% RE for concentrations greater than 4 pCi/L. Table 11 lists the results of the bias determinations made for the CRMs based on these calibration checks. The mean absolute relative error (MARE) (the mean of the absolute values of

TABLE 11. RESULTS OF THE BIAS DETERMINATIONS FOR THE CRMS

CRM	CF-92	RE-93	CF-93	RE-94	CF-94	RE-95
1	1.204	- 1%	1.194	1%	1.208	1%
2	1.193	- 2%	1.174	- 7%	1.098	7%
3	1.111	- 3%	1.080	-10%	0.972	8%
4	1.162	- 8%	1.066	5%	1.114	7%
5	1.082	7%	1.160	3%	1.197	1%
6	1.174	2%	1.268	- 4%	1.222	- 1%
165	0.295	- 6%	0.278	- 6%	0.234	7%
172	0.281	-12%	0.249	-13%	0.230	3%
MARE		4%		6%		4%

each of the individual REs) of each set of calibration measurements is also given in the table. Each of the individual REs and the MAREs were well within the target bias of ±25%; therefore, the accuracies of the CRMs were considered quite adequate. Even though the QAPP did not include ambient or sub-slab concentrations as critical measurements, the pumped (quasi-continuous) mode of making these measurements employed in this study was tested at the NAREL. A CRM was set up in this mode and sampled the air from one of the chambers for 5 days. The RE of these measurements was found to be about 1%. Other measures that were routinely taken to ensure that the bias of the measurements was kept to a minimum included measuring the background of each CRM before it was deployed in a different location.

8.2.1.3 Completeness
Of the roughly 42,100 half hourly indoor radon concentrations measured with the six CRMs over this study, 38,700 of these were considered valid measurements. This represents a completeness rate of 91.9%, greater than the DQI goal of 90%. The goal was not met for every experimental subset of the data, however. Due to monitor failures during the Case Study at the FCN, 74.2% CRM data capture was achieved from the four monitors in that set. Likewise, one of the three outdoor radon monitors described in Section 7.4.2 failed early, and a second developed a leak to indoors. These failures resulted in a 57% data capture for this segment and difficulty in extending conclusions to the spatial distribution of outdoor radon near the LLC. The indoor radon measurements for the 1993 and 1994 LLC tests achieved data completeness of 95.6% and 99.9%, respectively.

8.2.2 Integrative Radon Monitors

The integrative radon monitors used in this study were electret ion chambers (EICs).

8.2.2.1 Precision
Duplicate EICs were placed for 189 of the 190 integrative radon measurements made during this study. Of these, 162 (86%) had CVs of less than the 10% DQI goal. Twenty of the 27 measurements that had greater CVs measured indoor concentrations of less than 4 pCi/L and had standard deviations (STDs) of 0.4 pCi/L or less; so these were also considered to have met the DQI goal (total of 95%). Six of the seven remaining duplicate pairs had one of the EICs with a greater than normal voltage drop, which indicated that it was touched, had dust neutralize some of its charge, or for some other reason had lost excess voltage. The remaining EIC had a lower than expected voltage drop, for which there was no obvious reason, unless one of the building occupants had closed or covered it for some period of time. The average CV for those measurements greater than 4 pCi/L (including two with high CVs) was less than 5%, and the average STD for those duplicate pairs that averaged less than 4 pCi/L (including five high ones) was less than 0.4 pCi/L. This level of precision was considered quite adequate for the EIC measurements.

8.2.2.2 Accuracy
Several steps in our standard operating procedures for making EIC measurements are included to ensure that the bias of those measurements is minimal. Before reading any of the electrets on the surface voltage meter on a given day, an uncharged cap is usually placed over the sensor. Never did the voltage differ from zero by more than 2 V, which was considered acceptable. Reference electrets are normally read at least once each week that any measurements are made. Never was there greater than 2 V difference in the reading of a reference electret from its previous reading or greater than a 4 V change within a month. This was considered to indicate sufficient electrets reader stability.

Periodically, control electrets are placed in EIC chambers, and they are treated exactly like the measurement electrets, except that the chamber lids are not opened. Eight times during the study control electrets were so placed. Three of these showed no change in the voltages; one had a 1 V change; and two each had 2 and 3 V changes. These were considered acceptable voltage drops because of the handling to which these devices were subjected. The initial and final electret readings are made at as close to the same temperatures as possible. When the electrets are read, they are placed as nearly as possible in the same orientation for each reading. Each electret is read in the same manner, with repeated openings of the voltmeter shutter until a stable voltage is read on two consecutive openings.

A selected number of EICs were sent to the U.S. EPA NAREL in Montgomery, Alabama, for exposure for at least 2 days in a 13.5 pCi/L chamber in 1991 before the first of the measurements reported in this study and in a 16.6 pCi/L chamber in 1993 after the last of this study's measurements. There, procedures identical to those employed in the field were followed to make measurements of the chamber concentration. During the 1991 exposures, five control and two reference electrets were read. Two dropped 2 V, one dropped 1 V, two remained the same, and one each read 1 and 2 V higher. Thirty-three of the readings were performed with both our and NAREL's readers, and the EPA reader averaged 0.8 V higher. All of these checks were within acceptable ranges. Table 12 lists the results of these calibration checks of the exposed EICs. They all measured low, probably because 2 days is the minimum exposure time recommended for these devices, but all were within the ±25% DQI goal (the largest RE was -16%). Therefore, the accuracy for the EICs was considered adequate for this study. (The CVs for these measurements were 2 and 4%.)

8.2.2.3 Completeness

Of the 379 EICs used for measurements during this study, only seven produced questionable results that were not used, for a 98% completion rate, easily exceeding the 90% DQI goal. Therefore, the completeness of these measurements was considered quite adequate.

8.2.3 Radon Grab Samples

8.2.3.1 Precision

During this study, 40 grab samples were taken, 30 of which had duplicate samples made. Of these duplicate samples, 25 (83%) had CVs less than the DQI target of 10%. The five duplicate measurements that exceeded the 10% DQI goal were made with sequential rather than simultaneous samples, which could have easily allowed fresh air to infiltrate and dilute the duplicate sample. Therefore, this procedural inconsistency was corrected in later samples. Even with the five duplicates whose CVs exceeded the 10% DQI goal, the average CV for these 30 duplicate samples was less than the 10% goal. Therefore, the precision of the radon grab samples was considered adequate.

TABLE 12. RESULTS OF THE EIC CALIBRATION CHECK				
Electret Chamber	**1991 Radon**	**1991 RE**	**1993 Radon**	**1993 RE**
1	12.6	- 7%	14.4	-14%
2	12.1	-10%	15.9	- 4%
3	13.0	- 4%	15.8	- 5%
4	12.8	- 5%	14.6	-12%
5	12.6	- 6%	14.9	-11%
6	12.9	- 4%	14.8	-11%
7	12.9	- 4%	14.0	-16%
8	12.8	- 5%	15.0	-10%
9	13.0	- 3%	14.7	-12%
10	12.8	- 5%	15.8	- 5%
11	12.7	- 6%	*	*
Mean/MARE	12.7	6%	15.0	10%

* No data

8.2.3.2 Accuracy

In late November 1991 before any of the grab samples were taken for this study, and again in April 1993 after the grab sampling was completed, most of the grab cells were taken to the NAREL in Montgomery, Alabama, for checks of their calibration. (Such calibration checks were usually performed annually, but NAREL could not schedule us before April 1993.) Air from one of the environmental control chambers was sampled by each of the cells. They were returned to Southern Research Institute (SRI) , Birmingham, AL, where they were counted at least twice. The average detected concentrations were calculated for each cell using the most recently determined calibration factor (CF) for that cell. Later NAREL sent the actual concentrations that were maintained in the chambers at the time of sampling. The relative error (RE), expressed as a percent, was calculated. Then new CFs were calculated for each of the cells based on the actual chamber concentrations. Table 13 lists the calibration results for these two sets of calibration checks. As was the case with the CRMs, the measure that is used to compare the REs is the MARE. The individual REs for the various cells ranged from -22 to 20%, with MAREs for both calibration runs of 9%. All of these error measures were within the DQI goal of ±25%; so the bias of the grab samples was considered acceptable.

Before a cell was used in the field, a background count was generally made and recorded to

TABLE 13. CALIBRATION RESULTS FOR THE GRAB CELLS FROM 1991 AND 1993				
Cell Number	**RE 1991**	**CF 1991**	**RE 1993**	**CF 1993**
EPA 1.1	-13%	0.607	2%	0.616
EPA 1.2	2%	0.686	- 9%	0.625
EPA 1.3	-12%	0.615	14%	0.784
EPA 1.4	14%	0.796	12%	0.889
EPA 1.5	-15%	0.593	2%	0.606
EPA 2.1			- 9%	0.616
EPA 2.2	- 7%	0.654	9%	0.749
EPA 2.3	-14%	0.602	2%	0.612
EPA 2.4	2%	0.701	3%	0.713
EPA 2.5	- 8%	0.644	19%	0.818
SRI 283	14%	0.795	12%	0.889
SRI 291	- 4%	0.672	- 3%	0.649
SRI 292	17%	0.818	- 5%	0.779
SRI 293	- 5%	0.663	- 1%	0.655
SRI 294	- 2%	0.690	- 5%	0.653
SRI 295	13%	0.794	10%	0.872
SRI 296	10%	0.766	12%	0.858
SRI 297	- 1%	0.694	8%	0.750
SRI 300	1%	0.705	19%	0.838
SRI 301	-12%	0.614	19%	0.824
SRI 495	- 7%	1.203	14%	1.422
SRI 500	-22%	1.009	12%	1.399
SRI 501	-16%	1.087	20%	1.494
SRI 567	- 7%	1.206	- 3%	1.168
MARE	9%		9%	

ensure that the cell was relatively "clean." After a sample was collected and counted, the cell was flushed with clean ambient air and allowed to "relax" to allow the residual decay products to decay away before another background check was made. With the relatively high radon concentrations sampled in this study when taking soil and sub-slab samples, the cells were subjected to large potentials for increased backgrounds.

8.2.3.3 Completeness
Of the 70 individual grab samples taken over this study, 65 produced valid measurements, for a 93% completion rate, exceeding the 90% DQI goal for this measure of data quality.

8.2.4 Differential Pressure Measurements

As described in Section 5, continuous differential pressure measurements were made with the Modus pressure transducers in the EPA or Southern Research data logging stations. Confirmation measurements were taken using digital micromanometers. Due to concerns regarding possible zero drift, the 1993 pressure data from both the FCN and the LLC were not used for this study, and are considered questionable. The data reported in Section 7.4 were taken using instruments with automatic zero reference, and are considered reliable. For 5 minutes at the beginning of each half hour's measurements the pressure signal sent to the transducers was of zero pressure drop between the ports, and these readings were recorded by the data logger. The calculations of the measured pressures each half hour were made with this zero correction.

8.2.4.1 Precision
Before the pressure transducers were placed in the FCN and the LLC, another EPA contractor (Acurex) checked their precision, and found it to be acceptable. Unfortunately, these data were not supplied to us, and are not considered relevant in this study since measurements with these instruments were not used. After the Southern data station was removed from the LLC, the transducers were used to measure seven known pressures that spanned their ranges. CVs of 21, 21, 10, 18, and 12% were calculated from the higher absolute pressures (5 to 25 Pa). The measurements of pressures closest to zero had standard deviations of 1 to 2 Pa. These measures of precision (except for measurements close to zero) were all within the 25% DQI goal; therefore, the precision of these monitors was considered acceptable.

8.2.4.2 Accuracy
Digital micromanometers, which were routinely sent back to the manufacturer for their calibrations to be certified with the National Institute of Standards and Technology (NIST) traceable test equipment, were used to check the calibrations of the pressure transducers. In late 1992, before the LLC measurements were begun, all three micromanometers were so certified. In late 1993 and again in late 1994 and early 1995 after the building measurements were completed, the instruments were sent back to have their calibrations certified again. All three instruments were checked over 6 to 10 pressure ranges, and at no pressure did any of the three devices have a RE outside the ±6% range.

As mentioned above, Acurex calibrated the pressure transducers before placing them in the LLC, but those data were not provided to us. After the building measurements began, the Southern

Research pressure transducers used were calibrated with a micromanometer, using seven pressures that spanned their ranges. These measurements were made with the data acquisition system configured exactly as it was installed in the building; so that any bias introduced by a component of the system would be corrected by the calibration procedure. As the transducers were exposed to the known pressures, they sent to the data logger corresponding DC voltages, which were recorded and stored. Regressions were run over the pressure range measured, yielding slopes of pascals/volts and intercepts of calculated pressures in pascals.

8.2.4.3 Completeness
As described above, pressure data from both the 1993 field studies were discarded as questionable, leaving the 90% completeness DQI goal unmet for these tests. Of the 13,645 half hourly differential pressure measurements with the five Southern Research transducers reported in Section 7.4 for the 1994 LLC study, 13,573 are considered valid. This represents a completeness rate of 99.5% for this subset of the study.

8.3 DATA REVIEWS

Before the study, all of the radon and pressure measuring equipment was calibrated as described above. Generally QA personnel not directly involved with the actual field measurements checked the calibration of the equipment. Some of the CRMs and most of the pressure transducers came from the EPA, and one of their contractors performed the calibrations. The remaining CRMs, the EICs, the radon grab cells, and the micromanometers used to perform the pressure checks belonged to Southern. The calibration of these radon measuring devices was checked at the EPA's NAREL in Montgomery, Alabama, by SRI technicians and/or scientists. The calibration of the micromanometers was certified by the manufacturer. The results of all the calibration checks were reviewed by the project manager and the principal investigator and passed to the on-site project coordinator for use in the field. This individual kept detailed project logs, copies of which were sent to SRI at least monthly. There they were reviewed by both the manager and investigator for completeness. At least twice during the project, SRI personnel from Birmingham visited the NAREL to review the data setup and collection.

8.4 IDENTIFICATION OF CORRECTIVE ACTIONS

The data from the data logger were retrieved within the next working day of any changes to the system to ensure that their collection was complete and accurate as planned. If any data appeared to be faulty or missing, the system was checked immediately. For instance, if no data appeared in the output where some was expected, then the wiring and connections were inspected. If unreasonable data were detected, then sampling lines were checked for blockage, crimping, or leaks. Once the data retrieval appeared to be complete, then downloads were conducted approximately weekly, and another thorough review of the collected data was performed to ensure that the measurement and collection systems were operating as planned. Because both study buildings were occupied most of the time the measurements were being made, there were numerous potential interferences with consistent and continuous data collection. Moreover, frequent thunder storms and severe weather caused power fluctuations. Generally the system was inspected as soon as possible after each such event occurred.

SECTION 9

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16. ABSTRACT The report discusses the development of radon diagnostic procedures and mitigation strategies applicable to a variety of large non-residential buildings commonly found in Florida. The investigations document and evaluate the nature of radon occurrence and entry mechanisms for radon, the effects of heating, ventilation, and air-conditioning (HVAC) system configuration and operation on radon entry and dilution, and the significance of occupancy patterns, building height, and other building construction features. A primary focus of the project was the effect of the HVAC systems of a large building on the transport, entry and (hopefully) the minimization of indoor radon in the building. Two buildings were investigated, both of which showed an inverse relationship between dedicated ventilation air and indoor radon concentrations, as was expected. Both also showed signs of unusual HVAC design, operation, and maintenance that presumably adversely affected indoor radon and other indoor air quality (IAQ) variables. The second building showed clear indications of foundation design elements that contributed to radon entry. Among recommendations relevant to building standards that can be concluded from the project is that design and construction should concentrate on elimination of major soil gas pathways such as hollow walls and unsealed utility penetrations.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution Control	13B
Radon	Stationary Sources	07B
Measurement	Indoor Air Quality	14G
Air Conditioning		13A
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