EPA-600/R-97-124
November 1977

Large Building Radon Manual

by

Charles S. Fowler
Ashley D. Williamson
Bobby E. Pyle
Susan E. McDonough
Southern Research Institute
P. O. Box 55305
Birmingham, Alabama 35255-5305

EPA Contract No. 68-D2-0062
Work Assignment 3/63

EPA Project Officer:

Marc Y. Menetrez
Air Pollution Prevention and Control Division
National Risk Management Research Laboratory
Research Triangle Park, North Carolina 27711

Prepared for:

U.S. Environmental Protection Agency
Office of Research and Development
Washington, DC 20460

NOTICE

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and groundwater; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

E. Timothy Oppelt, Director
National Risk Management Research Laboratory

Abstract

Since 1992, the U.S. Environmental Protection Agency has worked with the State of Florida to evaluate the impact of heating, ventilation, and air conditioning (HVAC) systems on radon entry and mitigation in large buildings. The purpose for this manual is to summarize information on how building systems (especially the HVAC system) influence radon entry and can be used to mitigate a radon problem. Two chapters address the fundamentals of large building HVAC systems and the entry mechanisms for radon in large buildings. Another chapter provides a review of the different types of radon measurements and how to plan a deployment of instruments to obtain the desired results. A proposed diagnostic protocol for investigating a generic large building based on the investigations made in the State of Florida and other places is outlined. Another chapter summarizes the mitigation results reported in the previously cited papers and reviews some of the factors to consider in designing, installing, and evaluating the effectiveness of a mitigation system. The manual concludes with some recommended building design and operating practices for new construction large buildings.

This report was submitted in fulfillment of EPA Contract No. 68-D2-0062 by Southern Research Institute under the sponsorship of the United States Environmental Protection Agency. This report covers a period from 15 October 1995 to 31 July 1996, and work was completed as of 31 July 1996.

Contents

Tables

Chapter 1
Introduction and Background

Introduction

The U.S. Environmental Protection Agency's (EPA) Office of Research and Development's (ORD) Indoor Environment Management Branch (IEMB) has been involved with the evaluation of commercial and public building heating, ventilation, and air conditioning (HVAC) systems for a number of years. Since 1992, they have worked with the State of Florida to develop, validate, and provide guidance for radon diagnostic procedures and mitigation strategies applicable to a variety of buildings. This effort has produced reports applicable to Florida buildings and conditions. The purpose of this manual is to summarize the findings and reports of the work performed with the State of Florida and to integrate it with other previous and current national work.

The target audience includes architects, engineers, and building owners, operators, and maintenance staff. It was developed to assist such individuals to incorporate radon mitigation practices into building design, construction, operation, and maintenance. The evaluation of building ventilation dynamics, building air system balance (including leakage rates of typical residential, commercial, and public structures), and HVAC components and their effect to dilute radon and indoor air pollution is an example of the type of information this manual was written to communicate. The ultimate benefit of disseminating such information to both the above stated building professionals in the performance of their specific jobs or tasks and the public at large will be the improvement of indoor air quality (IAQ) and reduction of adverse health effects of radon and other indoor air contaminants.

Background

Many case studies of large buildings and their ventilation patterns and problems have been made over the years, especially in relatively recent times since indoor contaminants have been connected with phenomena such as "sick building syndrome" and other similar problems. Many of these studies have been initiated by various federal agencies with an interest in investigating or solving such problems. Some have had their bases in efforts prompted by activities of various individual states, and a few have their origins in the private or commercial sector. A listing of all such reports that have sprung from these studies would be too exhaustive for the purposes of this manual. Therefore, only those that have a direct link to radon contamination and a few that are representative of IAQ issues in general will be referenced.

Research Sponsored by the EPA

The U.S. EPA has been one of the primary sponsors of radon mitigation and prevention studies in residential structures, and much of that experience carried over to studies in larger buildings. The first such buildings to be studied were schools. Essentially two offices within the EPA have been involved with most of this work to date, the Office of Radiation and Indoor Air (ORIA) (formerly Office of Radiation Programs [ORP]) and ORD. Together they have been responsible for a large volume of research concerning radon in schools. Each of these offices has sponsored investigations dealing with the problem of radon in large buildings in general. Representative reports that have been the result of these research efforts will be mentioned in the following paragraphs.

Radon Measurement and Mitigation in Schools

When the EPA was expanding its fundamental research to include all types of residential construction, it began to identify some of the characteristics of schools with elevated radon concentrations (1,2). Radon diagnostics and mitigation procedures applicable to public school buildings were investigated (3,4,5). It was soon learned that the effects of HVAC system design and operation, which varied a great deal more in school buildings than it did in residences, potentially had a much greater impact on radon entry into school buildings than typically found in homes (6,7). Because of complicated foundations used in some school construction, it was discovered that certain schools were extremely difficult to mitigate with techniques developed for residences (8,9). ORP (later ORIA) began a coordinated radon in schools technology development effort in which a School Evaluation Team performed on-site evaluations of schools in eight regional locations throughout the United States (10). They later combined this information with research conducted by ORD to present the process of radon diagnostic and mitigation in schools to school decision makers (11).

School buildings that were constructed over crawl spaces were found to present unique challenges to radon mitigation not found in crawl space houses for a number of reasons (12). While the variety of HVAC systems in schools proved to lead to complications in their radon entry dynamics, ORD initiated research to determine the feasibility of using HVAC systems to pressurize the building interior with outside air to reduce radon concentrations in school buildings (13). They also began to collect information about types of HVAC systems commonly found in U.S. school buildings, their ability to pressurize and ventilate classroom spaces, and their operations and controls (14). The system of choice for many residential situations, active soil depressurization (ASD), was still found to be a very effective means to mitigate certain school buildings. Some of the design and application parameters naturally had to be based on the construction characteristics of the larger and more complicated buildings (15). Comparisons of radon reduction capabilities of ASD and HVAC system control in several school buildings (16,17) and the effectiveness of HVAC systems alone for radon control in schools (18,19) were conducted.

Because radon concentrations in schools have been found to vary significantly from room to room, the measurement approaches necessarily had to be modified somewhat from those used in the residential settings. ORIA conducted comprehensive studies of radon measurements in schools and has provided school administrators and facilities managers with instructions and recommendations on how to test for the presence of radon (20). Most of the discussion referenced above has dealt with mitigating radon in existing school buildings. Just as was the case in residential construction, once the problems of radon mitigation were beginning to be addressed, attention turned to preventing radon entry in new construction buildings. ORD has provided recommendations of radon prevention techniques for construction of schools and other large buildings in radon-prone areas and has updated these recommendations over time (21).

IAQ Studies in Large Buildings by ORIA

In addition to the large body of research for which ORIA was responsible concerning radon in residential structures and schools, it has placed a considerable amount of effort in characterizing IAQ in large buildings. It published a standardized protocol for taking the requisite measurements (22) and has worked with the University of Minnesota (23) and others on reviewing the transport of indoor air pollutants in large buildings. ORIA has also worked with the National Institute of Standards and Technology (NIST) (to be discussed in a subsequent paragraph) on the issues of contaminant transport. Some of this work arose from the Building Assessment Survey and Evaluation (BASE) Program, a multi year research effort to collect baseline information on indoor environmental performance of commercial buildings throughout the U.S.

Large Buildings Studies by ORD

ORD also sponsored work to compile information that might be used to develop standardized large building diagnostic protocols for IAQ investigations (24) and to summarize HVAC and IAQ evaluation techniques and results of testing (25). It initiated a research program to collect fundamental information on the key parameters and factors that influence IAQ and comfort in randomly selected General Services Administration (GSA) owned and operated large office buildings (26). ORD also was heavily involved with the research efforts in the State of Florida, which will be discussed in a later paragraph.

Research Conducted by NIST

NIST has conducted many studies over the years concerning the measurement of the indoor environment. The ones that will be mentioned here are just a few of those that most directly add to the current discussion. One was a performance evaluation of a new building including an assessment of the thermal integrity of the building envelope, long-term monitoring of ventilation system performance, and measurement of indoor levels of selected pollutants, including radon concentrations (27). In work performed for ORIA and the Department of Energy (DOE), NIST developed a series of parameters for describing building and HVAC characteristics of commercial buildings in conjunction with IAQ investigations (28) and described procedures for assessing ventilation system performance in commercial buildings (29). For DOE, NIST determined the local age of air and air change effectiveness in two office buildings using tracer gas techniques (30). For the U.S. Nuclear Regulatory Commission, they developed and implemented an IAQ commissioning program in a new office building (31). For ORIA they performed computer simulations of airflow and radon transport in four large buildings using the multi zone airflow and pollutant transport model CONTAM88 (32).

Research Sponsored by DOE

Just as DOE was involved in much of the early radon studies in residential construction, it has done a wide range of work in large buildings. Concerns of energy issues quite naturally are interlinked with areas of IAQ. Some of DOE's early work concerning radon in large buildings consisted primarily of developing measurement technologies (33). But many of its contributions to the field have been involved with determining ventilation and air leakage performance of large buildings (34,35). As mentioned earlier, DOE has worked with the EPA and NIST in many of these areas. DOE has also worked with other governmental agencies and entities that will be mentioned below.

Research Sponsored by State or Private Agencies

The California Healthy Building Study

One of the areas of cooperation between DOE and a state was the California Healthy Building Study that was conducted in 12 office buildings in two climate zones in the San Francisco Bay area to test the relationships between type of building ventilation, air quality, thermal comfort and occupant symptoms (36,37). This study was continued with the primary goal to identify the major characteristics of buildings, ventilation systems, jobs, and indoor environmental quality that are associated with building-related sick-building health symptoms (38).

The Florida Radon Research Program (FRRP)

The State of Florida, in partnership with the EPA and other contractors, initiated this research effort to develop standards for reducing the risk of radon entry in new residential and commercial construction and for mitigating radon in existing houses and other structures. In one of the Program's early efforts, GEOMET Technologies, Inc. was contracted to review the literature, survey the radon industry, and identify 10 to 15 buildings to be involved in follow-up diagnostic work to identify the extent of the problem of radon in large buildings (39). A large building research workshop was held to examine and exchange information on the conduct of current large building indoor air quality/radon studies and to develop recommendations regarding priorities for future research (40). One of the buildings identified by GEOMET and a second large building were used to develop radon diagnostic procedures and mitigation strategies applicable to a variety of large non-residential buildings commonly found in the state (41). A follow-on project entailed an extensive characterization and parametric assessment study of a single large municipal building in Florida with the purpose of assessing the impact on radon entry of design, construction, and operating features of the building, particularly, the mechanical subsystems (42).

Concurrently, the University of Florida (UF) conducted a study to document the construction design practices of large buildings' slab and foundation systems, to survey mitigation techniques implemented in large buildings throughout Florida, and to gather statistical data on new commercial buildings recently constructed in Florida (43). As a follow-on to this work, UF concentrated on the initial design and field work required to document the radon-resistant construction features of ten large buildings, some of which had been parts of other studies (44). In support of the development of buildings standards for radon-resistant large buildings for the FRRP, a study was conducted to evaluate the feasibility of implementing radon resistant construction techniques known to be effective in new construction houses in a new large building (45). Draft standards for radon-resistant construction in large buildings were prepared for the state of Florida in 1994 (46).

Private Companies

Since radon mitigation of large buildings is still a relatively new area of investigation, most of the information available through the literature has its origins in publicly funded research efforts. Although it is known that some private companies have been involved in the remediation of radon problems in large buildings, very little data from those occurrences are easily found. One exception is a report concerning a radon problem in a large commercial office building that was analyzed with a number of diagnostic techniques in an attempt to get a quick understanding of the nature of the problem while operating within a limited budget (47).

Scope and Content

The purpose for this manual is to bring together information to a wide audience of building professionals on how building systems (especially the HVAC system) influence radon entry and can be used to mitigate a radon problem in large buildings. Because the readers of this manual may vary in knowledge of details of building practices, familiarity with radon, and involvement with correcting existing or potential problems relating to them, not everyone will want or need to read it cover to cover in the order presented. It is divided into six chapters in addition to this introduction. The next two chapters address the fundamentals of large building air handling (AH) systems and the entry mechanisms for radon in large buildings, with a description and illustrations of how HVAC system operations affect ventilation and pressure differentials which in turn affect indoor radon concentrations. Some building professionals may find some or all of this information to be new or a useful review, while others may not feel it is necessary to give it more than a cursory perusal. Chapter 4 provides a review of the different types of radon measurements and how to plan a deployment of instruments to obtain the desired results. This chapter may answer many questions for professionals to whom radon is a new problem never before encountered, but it may not be necessary for an experienced radon contractor to read at all.

In many ways the last three chapters are the heart of this manual, but they build on the information presented in the first four. Chapters 5 and 6 deal with existing buildings, and Chapter 7 addresses new construction designs. A proposed diagnostic protocol for investigating a generic large building is outlined in Chapter 5, based on the investigations made in the State of Florida and other places. Once it has been determined that a large building has a radon problem, and a thorough diagnostic investigation has revealed the nature and cause of the problem, a mitigator must determine a good approach to solve the problem. Chapter 6 summarizes the mitigation results reported in the previously cited papers and reviews some of the factors to consider in designing, installing, and evaluating the effectiveness of a mitigation system. Chapter 7 concludes with some recommended building design and operating practices for new construction large buildings.

Chapter 2
Large Building HVAC Systems Overview

Most, if not all, large buildings being constructed today have some type of air distribution system designed and installed in them. Except in a few unique types of buildings such as warehouses, hangars, or some other type of building that consists primarily of large bay areas, most of these air distribution systems are central HVAC systems. Most of the following information was extracted from the 1992 ASHRAE Handbook on HVAC Systems and Equipment (48) and two reports by Persily (28,29), both of which were developed from this Handbook and other sources. Further applications of HVAC systems as a tool in controlling IAQ may be found in a literature review by Samfield (49).

Since radon is a gas and thus an airborne contaminant, the HVAC system is usually the single-most important building system in influencing the distribution, and sometimes the entry or abatement, of radon in a structure. The HVAC system usually creates the dominant pressure differentials within a building. These have the potential of either enhancing or retarding the entry of radon into a given space. The characteristics of a system's components and its operating schedule determine its effect on indoor radon concentrations and distributions. It is assumed that radon abatement by the HVAC system is the result of the pressurization of spaces whose shells are in contact with high radon concentration soil gas, the dilution by low radon concentration makeup outside air (OA), and the schedule of operation of the HVAC system. The effectiveness of radon removal by dilution is determined to some extent by the air distribution within the space itself. This space air distribution involves types and locations of air diffusers and return grills and the resulting entrainment, mixing, and stagnation which might occur within the space being served. Use of room air dilution will also assume that makeup OA is at typically lower ambient radon concentrations than the indoor air (14).

HVAC systems are categorized by how they control temperatures in the conditioned area. The 1992 ASHRAE Handbook (48) describes four specific types of systems, all-air, air-and-water, all-water, and unitary refrigerant-based systems. Persily (28) has produced forms to be used to describe other space conditioning systems that are sometimes used for special purposes in commercial buildings and usually contain features of one or more of the types of systems mentioned above. These include perimeter zone units that are not part of the central systems and are intended solely for perimeter applications, evaporative cooling systems that use water rather than refrigerants, and natural ventilation systems. The discussions that follow will deal with all-air systems and several subtypes of this system. A few key issues concerning the inspection and maintenance of HVAC systems will be summarized, followed by brief discussions of the influence of the design and operation of an HVAC system on its performance.

All-air Systems

An all-air system provides complete sensible and latent cooling, preheating, and humidification capacity in the air supplied by the system. All-air systems are classified in two basic categories, single-duct and dual-duct systems (48).

Single-Duct Systems

Single-duct systems contain the main heating and cooling coils in a series flow air path. A common duct distribution system at a common air temperature feeds all terminal apparatus. These systems may be further divided into constant volume and variable air volume (VAV) systems, each with some further subclassifications possible (48).

Constant Volume

While maintaining constant airflow, single-duct constant volume systems change the supply air temperature in response to the space load. The primary subclasses of these systems are single-zone, multiple zoned reheat, and bypass systems (48).

Single-zone systems are the simplest all-air system. They consist of a supply unit serving a single-temperature control zone or where all of the space or spaces have heating and cooling requirements sufficiently similar so that comfort conditions can be maintained by a single controlling device or thermostat. The unit can be installed within the space it serves or remote from it and may operate with or without distribution duct work. Single-zone systems can be shut down when not required without affecting the operation of adjacent areas. A return or relief fan may be needed, depending on the capacity of the system and whether 100% OA is used for cooling at some time during the year. Relief fans can be eliminated if provisions are made to relieve over pressurization by other means, such as gravity dampers (48).

The air handler (AH) supplies a constant volume of supply air to a single zone with minimum heating and cooling load variations. The load within the space is controlled by varying the temperature of the supply air. The supply air temperature is controlled by varying the quantity and/or temperature of the heating or cooling source, by varying the relative proportions of outdoor air intake and recirculation air, by modulating the position of face and bypass dampers within the AH, or by a combination of these approaches (28).

Very large spaces and large or multistory buildings usually require more that a single zone to maintain comfort in all spaces. In a single zone constant volume system the distribution of the air to the rooms is fixed by the design of the duct work, and can be modified only to some degree by the adjustment of dampers within the duct system or at diffuser outlets. In a zone with multiple rooms and with limited air returns with restricted air flow between rooms, a variation between rooms is highly probable, with the possibility of one or more rooms being below while others are above atmospheric pressure. As with any system, pressurization of all rooms can be attained only with the total rate of system intake of OA exceeding that of the exhaust (14).

Zoned reheat is a modification of the single-zone system. It provides zone or space control for areas of unequal loading, simultaneous heating or cooling of perimeter areas with different exposures, and close tolerance of control for process or comfort applications. Heat added as a secondary simultaneous process to either preconditioned primary air or recirculated room air. Relatively small low-pressure systems have reheat coils in the duct work at each zone. More sophisticated designs have high-pressure primary distribution ducts to reduce their size and cost, and pressure reduction devices to maintain a constant volume for each reheat zone (48). The AH provides a constant supply air flow rate to multiple zones with different thermal loads. The loads in the zones and the supply air temperature are controlled as described above for the single zone systems. Further temperature control in individual zones is provided by reheat coils in the ducts in the zones (29).

Bypass is a variation of the constant volume reheat system. It uses a bypass box in lieu of reheat. This system is essentially a constant volume primary system with a VAV secondary system. The quantity of room supply air is varied to match the space load by dumping excess supply air into the return ceiling plenum or return-air duct by bypassing the room. While this system reduces the air volume supplied to the space, the system air volume remains constant. This system is generally restricted to small systems where a simple method of temperature control is desired, a modest initial cost is desired, and energy conservation is less important (48). The AH provides a constant supply air flow rate to multiple zones with different thermal loads. The loads in the zones are controlled by varying the supply air temperature and the supply air flow rate to each zone. The supply air temperature is controlled as described earlier for the single zone systems. Further temperature control in individual zones is provided through the use of a bypass box in the zone which dumps some of the supply air as described above (29).

Variable Volume

A VAV system controls temperature within a space by varying the quantity of supply air rather than varying the supply air temperature. A VAV terminal device is used at the zone to vary the quantity of supply air to the space. VAV systems can be applied to interior or perimeter zones, with common or separate fan systems, common or separate air temperature control, and with or without auxiliary heating devices (48). The AH provides constant temperature supply air to VAV units located in the ceiling plenum. The supply air flow rate of the AH varies in response to space load variations in the building. A true VAV system provides cooling only, with perimeter zones heated by some other system (29). Energy conservation as well as improved controls and equipment have made VAV an increasingly popular option (14). VAV terminal devices are available in a number of different configurations, including reheat, induction, fan powered, dual conduit, and variable diffusers (48).

Reheat is a simple VAV system that integrates heating at the terminal unit. It is applied to systems requiring full heating and cooling flexibility in interior and exterior zones. The terminal units are set to maintain a predetermined minimum throttling ratio, which is established as the lowest air quantity necessary to offset the heating load, limit the maximum humidity, provide reasonable air movement within the space, and provide required ventilation air. Variable volume with reheat permits airflow to be reduced as the first step in control; heat is then initiated as the second step (48).

Induction systems use a terminal unit to reduce cooling capacity by simultaneously reducing primary air and inducing room or ceiling air (replaces the reheat coil) to maintain a relatively constant room supply volume. This operation is the reverse of the constant volume bypass box described earlier. The system primary air quantities reduce with load, retaining the savings of VAV, while the air supplied to the space is kept relatively constant to avoid the effect of stagnant air or low air movement (48). A VAV AH provides primary air to unpowered terminal units that induce plenum or room air into the supply airstream. The total air flow rate of the primary and induced air is roughly constant. Variations in space load are met by varying the relative proportions of the primary and induced air. Reheat coils or some other form of auxiliary heat is required when heat gain in the room and ceiling cannot balance envelope losses and cooling loads from the primary supply air (29).

Fan-powered systems are available in either series or parallel airflow. Fan-powered systems, both series and parallel, are often selected because they maintain a higher level of air circulation through a room at low loads while still retaining the advantages of VAV systems. As the cold primary air valve modulates from maximum to minimum (or closed), the unit recirculates more plenum air. Between heating and cooling operations, a dead band in which the fan recirculates ceiling air only is provided. During unoccupied periods, the main supply air-handling unit (AHU) remains not energized and individual fan-powered heating zone terminals are cycled to maintain required space temperature, thereby reducing operating costs (48).

In series units, the fan is located within the primary airstream and runs continuously when the zone is occupied. The constant fan VAV terminal can accommodate minimum (down to zero) flow at the primary air inlet while maintaining constant airflow to the space In a series arrangement with a constant fan, a constant volume fan-powered box mixes primary air with air from the ceiling space using a continuously operating fan; this provides a relatively constant volume to the space (48). Terminal units in exterior zones have heating coils for winter heating requirements. The heating coil is not activated until the primary air volume is reduced to a minimum value (28). In parallel flow units, the fan is located outside the primary airstream to allow intermittent fan operation. In these devices with an intermittent fan, primary air is modulated in response to cooling demand and energizes an integral fan at a predetermined reduced primary flow to deliver ceiling air to offset heating demand. The induction fan operating range normally overlaps the range of the primary air valve. A back-draft damper on the terminal fan prevents conditioned air from escaping into the return-air plenum when the terminal fan is off (48). The primary air and the induced air mix within a common plenum within the fan-powered unit (28).

Dual conduit systems are designed to provide two air supply paths, one to offset exterior transmission cooling or heating loads, and the other where cooling is required throughout the year. The first airstream, the primary air, operates as a constant volume system, and the air temperature is varied to offset transmission only (it is warm in winter and cool in summer). Often, however, the primary air fan is limited to operating only during the peak heating and cooling periods to further save energy. The other airstream, or secondary air, is cool year-round and varies in volume to match the load due to solar heating, lights, power, and occupants (48).

Variable diffusers reduce the discharge aperture of the diffuser. This keeps the discharge velocity relatively constant while reducing the conditioned supply airflow. Under these conditions, the induction effect of the diffuser is kept high. These devices are of two basic types--one has a flexible bladder which expands to reduce the aperture, and the other has a diffuser plate that is physically moved. Both devices are typically pressure-dependent, which must be taken into account in the design of the duct distribution system. They are system powered or pneumatically or electrically driven (48).

Dual-Duct Systems

Dual-duct systems contain the main heating and cooling coils in parallel flow or series-parallel flow air paths with either a separate cold and warm air duct distribution system that blends the air at the terminal apparatus (normal dual-duct system), or a separate supply air duct to each zone with the supply air blended to the required temperature at the main unit mixing dampers (multi zone variant) (48).

Normal Dual-Duct Systems

In each conditioned space or zone, a mixing valve mixes the warm and cold air from their respective ducts in proper proportions to satisfy the load of the space. These systems may be designed as constant volume or variable volume and, as with other VAV systems, certain primary air configurations can cause high space relative humidity during the spring and fall. Dual-duct systems use more energy than single-duct VAV systems but have certain advantages, like no pipes that could leak within occupied areas (48).

Constant volume systems are of two types, single fan with no reheat or single fan with reheat. A single fan system with no reheat has a cycle similar to a single-duct system, except that it contains a face-and-bypass damper at the cooling coil, which is arranged to bypass a mixture of outdoor and recirculated air as the internal heat load fluctuates in response to a zone thermostat. A problem with this system occurs during periods of high outdoor humidity, which the internal heat load falls, causing the space humidity to rise rapidly (unless reheat is added). It is identical in concept to bypass cooling coils. This system has limited use in most modern buildings because most occupants demand more consistent temperature and humidity conditions (48). The AH supplies a constant volume of supply air to multiple zones, with the supply fan blowing through cooling coil and bypass sections connected to cold and hot ducts respectively. These two ducts run through the building to unpowered mixing boxes in the ceiling plenum, which mix the warm and cold air in proper proportions to meet the loads in the zone (29).

A single fan with reheat system has a cycle similar in effect to a conventional reheat system. The only differences are that reheat is applied at a central point instead of at individual zones (48). The AH provides a constant supply air flow rate to multiple zones. The supply airstream is split into two flows, one blowing through cooling coils and the other blowing through heating coils. The hot and cold air decks are connected to unpowered mixing boxes in the ceiling plenum, which mix the hot and cold air to meet the loads in the zone. Interior zones mixing boxes may only be connected to the cold deck (29).

Variable air volume or dual-duct variable volume systems blend cold and warm air in various volume combinations. These systems may include single-duct VAV units connected to the cold deck for cooling only of interior spaces. In a single fan system, a single supply fan is sized for the coincident peak of the hot and cold decks. Control of the fan is from two static pressure controllers, one located in the hot deck and the other in the cold deck. The duct requiring the highest pressure governs the fan airflow. Usually the cold deck is maintained at a fixed temperature, although some central systems permit the temperature to rise during warmer weather to save refrigeration. The temperature of the hot deck is often adjusted higher during periods of low outside temperature and high humidity to increase the flow over the cold deck for dehumidification. Return-air quantity can be controlled by either flow-measuring devices within the supply and return duct systems or by static pressure controls which maintain space static pressure (48). The two decks run through the building to VAV mixing boxes in the ceiling plenum, which mix the hot and cold air to meet the loads in the zone. Interior zone boxes may be connected to only the cold deck (29).

In a dual fan system, the volume of each supply fan is controlled independently by the static pressure in its respective duct. The return fan is controlled based on the sum of the hot and cold fan volumes using flow-measuring stations. Each fan is sized for the anticipated maximum coincident hot or cold volume, not the sum of the instantaneous peaks. The cold deck can be maintained at a constant temperature either by operating the cooling coil with mechanical refrigeration when minimum fresh air is required or with a cooling economizer when the outside air is below the temperature of the cold deck set point. This operation does not affect the hot deck, which can recover heat from the return air, and the heating coil need only operate when heating requirements cannot be met using return air. Outdoor air can provide ventilation air via the hot duct system when the outdoor air is warmer than the system return air. However, controls should be used to prohibit the introduction of excessive amounts of outdoor air beyond the required minimum when that air is more humid than the return air (48). In this system, separate supply fans serve the cold and hot decks. The two duct systems run through the building to VAV mixing boxes in the ceiling plenum, which mix the hot and cold air to meet the loads in the zone. Interior zone boxes may be connected to only the cold duct, while exterior zones will be connected to both the hot and cold ducts (29).

Multizone Systems

The multizone system supplies several zones from a single, centrally located AHU. Different zone requirements are met by mixing cold and warm air through zone dampers at the central AH in response to zone thermostats. The mixed, conditioned air is distributed throughout the building by a system of single-zone ducts. The return air is handled in a conventional manner. In operation, it has the same potential problem with high humidity levels. Multizone packaged equipment is usually limited to about 12 zones, while built-up systems can include as many zones as can be physically incorporated in the layout (48). The space load of each zone is met through a mixture of the hot and cold air streams carried to the zone by a single duct. The hot and cold airstreams for each zone mix at the AH, with a set of dampers for each zone. The supply airflow rate to each zone is roughly constant (29).

In multizone systems, each zone may have a separate temperature control. Dampers in the AH are controlled by the zone thermostats to supply the proper air temperature and flow to each zone to meet that zone's individual load. The typical control system for a multizone system is the same as that for a constant volume dual-duct single fan system. Normally there is no provision for automatic control of either room or duct static pressure as these are set by system design and component adjustment. If room pressurization and control are to be added to a constant volume multizone system, it might be more easily accomplished by the addition of controlled relief dampers in the return duct of each zone and a corresponding reduction in return and central exhaust flow (14).

With this modification for pressure control there would be concern that the existing fan and duct system could provide sufficient air flow to all zones to meet comfort demands. The second concern is that additional quantities of hot and cold air would be used to maintain comfort during both occupied and unoccupied periods, and operating costs could be increased significantly. These concerns would be particularly valid if the building or parts of it have high leakage rates. Some multizone systems may have been modified to be VAV systems to conserve energy particularly where the major load is (49).

Constant Volume, Blow-through Bypass
The AH provides a constant supply air flow rate to multiple zones, with the supply fan blowing air through cooling coils or through a bypass section around the coils. The cold and bypass decks are split so that there is a cold duct and bypass air duct for each zone. The two supply airflows mix within the mechanical room, with a damper in the bypass air duct and a heating coil downstream of where the two flows merge. A constant quantity of air is supplied to each zone, and the supply air temperature to each zone is varied to meet cooling or heating loads by modulating the bypass damper and using the heating coil. The heating coil is not used unless all of the zone's supply air is bypass air. Interior zones may not have a heating coil in their ducts (29).

Design of HVAC Systems
From the material presented thus far, it is evident that although HVAC systems can offer a measure of control of indoor air quality (IAQ) (including radon concentrations), HVAC systems may also be the means of distribution of elevated radon concentrations or a major contributor to the driving force in bringing radon into a building unless the system is properly designed. For instance, the location of air inlets with respect to exhausts of mitigation systems or of other potential sources of elevated radon concentrations or of other pollution that may be entrained is an important item to be checked in the design of any ventilation system.

ASHRAE Standard 62-1989 (50) recommends a minimum of 15 cfm of OA per person. This amount is needed to control occupant odors and to guarantee that the concentration of carbon dioxide will not exceed 1000 ppm. Additionally, other recognized contaminants including formaldehyde, office products, building materials, and tobacco smoke will be maintained at acceptable levels. This standard includes an updated and revised IAQ procedure for which a model has been developed and equations are presented as part of the Air Quality Procedure for calculating the amount of recirculation needed. These are dependent on the type of flow (VAV or CAV), the supply temperature (constant or variable), and the use of OA (constant or proportional).

The Air Quality Procedure of the standard can be used to reduce the amount of OA required for given amounts of indoor contaminants over that required employing the prescriptive (alternate Ventilation Rate) procedure, thus reducing the associated energy cost for providing heating, cooling, humidifying of OA as well. Design and maintenance of HVAC systems should provide for comfortable and healthy indoor air consistent with energy optimization in buildings. Clearly the use of air recirculation in combination with adequate filtration (as a viable cost-effective alternative to increasing

OA rates in accordance with the Air Quality Procedure) provides the HVAC designer with means to substantiate decisions when dealing with client concerns with increased energy usage (49).

The importance of the location of components of the HVAC system within the structure is often overlooked. For example, in a building with a crawl space or utility tunnel that may not be well sealed in a high radon potential area, it is poor policy to locate the blower of the HVAC system in the crawl space or tunnel. Since the blower intake is under negative pressure, radon will be pulled into the duct system and distributed throughout the structure. Several school buildings have been found with crawl spaces or utility tunnels that contributed indoor radon contamination (12,17,51).

ASHRAE published in their standard a table listing OA requirements for ventilation for commercial facilities (50). Lizardos (52) discusses many HVAC design parameters that are critical to achieving adequate IAQ. Topics include location of building fresh air intakes and exhaust air outlets, economizer systems, air flow tracking, filtering systems, sound attenuation, humidification systems, room air distribution, coil drain pans and condensate traps, duct zoning, localized exhausts, and temperature and humidity control. He concludes that all the contributing factors to IAQ concerns can be minimized by following HVAC design guidelines that promote high IAQ while maintaining reasonable energy-efficiency.

The design of HVAC systems in commercial buildings is a complex process. The system design specifies airflow rates at various points in the ventilation system and how these airflow rates should change in response to weather conditions, internal loads and time of day. These specifications are based on the activities in the building zones, the thermal loads generated in these zones, the number of occupants, and recommended or minimum OA ventilation rates from appropriate building codes, ventilation standards ad guidelines. The specification of system airflow rates is often limited by uncertainties in how the building will be used and in the number of occupants in the zones. It is important to document the assumptions on thermal loads and occupancy levels used in the design. This information is very helpful when the ventilation system is evaluated and when space-use changes occur in the building. Persily (29) describes assessment procedures appropriate to ventilation evaluations of more limited scope and intensity than a test and balance (TAB) effort. He also describes how to determine how the ventilation system is intended to perform based on the design documentation.

Energy consumption is important as well as the effect of the HVAC system operation on IAQ. In his literature review of HVAC systems as a tool in controlling IAQ, Samfield (49) cites authors who have made energy analyses of buildings with different air supply and exhaust systems. The results he reports show that the air temperature distribution in the room is very important in the production of room energy consumption. For a VAV system, the energy required by the chiller and the ventilator with the displacement ventilation system is 26% less than with a well-mixed system. The air displacement system is recommended for practical applications for saving energy and obtaining better air quality.

Operation of HVAC Systems

Sliwinski et al. (53) acknowledged that existing HVAC operations activities center around maintaining building occupant comfort in terms of temperature and humidity. They suggested that operations procedures include a focus on aspects of existing protocols that impact the third factor in occupant comfort, IAQ. They asserted that new activities are not necessarily needed, but that problems arise when well known, accepted procedures are not followed. They identified and discussed in detail specific HVAC system components that have IAQ impacts. Included in their list were several items that are known to have impact on indoor radon concentrations, such as ventilation rates, filters, economizer systems, heat exchangers, sumps, and others. A checklist for some of these items was provided for both spring and winter startups. They also identified special operations for IAQ under certain conditions, such as commissioning of new buildings, retrofitting and refurnishing existing buildings, recovering after building structural damage due to storm, fire, or other cause, and mitigating certain IAQ problems such as asbestos. They provided a building commissioning procedure for IAQ. Their normal operation guidance focused on prevention of IAQ problems.

Mechanical ventilation system operation has significant impacts on OA change rates of buildings and airflows within buildings. Obviously, the system brings OA into the building through the AH and may be designed to move air from room to room. However, system operation can also induce pressure differences across exterior walls and interior partitions (29).

An imbalance between the OA intake and exhaust airflow rates for a building, will cause infiltration or exfiltration across the building envelope. Excess OA intake will cause the building to be at a positive pressure, and the excess air will be forced out of the building through openings in the building envelope. If the exhaust airflow rate is larger than the intake rate, then the building will be at a negative pressure and excess air will be pulled into the building through envelope openings. System-induced pressure differences can dominate stack and wind pressures, and depend on how the ventilation system is operating, i.e., the percent OA intake and the supply airflow rate. Under different modes of system operation, ventilation flow imbalances can vary in both magnitude and direction. Ventilation systems are often designed to maintain a positive pressure difference across the building envelope to reduce air infiltration. However, this excess supply air may not occur in practice if the system is not operated or maintained as designed (29).

In many large building HVAC units there are energy management systems (EMS) that may be mechanically operated based on timers or controlled by a microprocessor, microcomputer, or the like. These typically set back the thermostat or some other feature of the system during the building off hours. In this case there may be long periods when the fan is not running and pressurization is lost. Indoor radon concentrations can increase during such periods. A compromise between energy conservation and indoor radon concentration concerns would be to determine at what hour the fans could be activated so that through dilution and pressurization the radon in a space could be reduced to an acceptable level before the space is occupied. The specific time would depend on the indoor radon concentrations and the rates of pressurization and dilution effects (14).

Persily (28) developed a series of checklists to evaluate the performance of the operations of an HVAC system and its components. Many of these would be pertinent to the investigation of any building in which elevated indoor radon concentrations was a problem. Some of these forms are used to test the AH systems, including the supply airflow rate and the percent and rate of OA intake. Others test the exhaust fan operations, including the exhaust fan airflow rate. Persily's forms are used to record the airflow rates and other pertinent information for each space being investigated. He also provides forms and procedures to evaluate naturally as well as mechanically ventilated buildings by measuring air infiltration rates, supply airflow rates, percents and amounts of OA intakes. In addition to forms that instruct how to collect the data, others are provided to assist in the data analysis necessary to determine these air infiltration rates. Even forms to assist in the collection of data while conducting rectangular or round duct transverses are provided.

A ventilation strategy designed to reduce the energy cost of meeting the ventilation requirements of ASHRAE Standard 62-1989 while still meeting the IAQ objectives is called demand-control ventilation. An example of this strategy was given by Meckler (54), who presented the results of the application of a dynamic carbon dioxide prediction modeling methodology to a ten-story office building assumed to be located in five representative U.S. cities. Calculated hourly outdoor air flow rates at preset CO_2 concentrations of 800 ppm and 920 ppm were compared to a conventional approach in which a constant OA flow rate of 20 cfm per person was supplied during all occupied hours. The outdoor air flow control strategies used CO_2 sensors commercially available and took advantage of actual "variable-occupancy" levels in a building.

The impact of adjusting the OA flow rates based on CO_2 concentrations on indoor concentrations of radon and other potential contaminants was not addressed in this study. While CO_2 concentrations lag occupancy changes, radon concentrations tend to build before the HVAC systems are activated. Such a strategy based on CO_2 concentrations alone appears to have the potential to inhibit dilution or pressurization controls of indoor radon concentrations. However, if commercially available radon sensors could be used to activate the systems as well, then this strategy may have great potential for being effective in mitigating radon, controlling CO_2 concentrations, and cost and energy effective.

Dols et al. (31) developed and applied a pilot IAQ commissioning program to a new office building. Their first task was to compare the ventilation system design to the appropriate codes and standards to which it was built and to evaluate the design from an IAQ perspective. While their program was not presented as a candidate for a standardized protocol for IAQ commissioning, it was viewed as a program to provide experience and insight that will assist in the development of future IAQ commissioning protocols.

Inspection and Maintenance of HVAC Systems

One of the objectives of the report for the U.S. Army by Sliwinski et al. (53) was to provide maintenance personnel with useful background information on IAQ and basic preventive methods for use in representative Army facilities. In addition to the maintenance schedules presented in the technical manuals, other minimum maintenance activities with IAQ impacts are listed for spring and winter startup operations. Adequate ventilation using outdoor air of good quality is identified as a key factor in maintaining acceptable IAQ. A narrative description of inspection of a typical ventilation system is given, stressing the effective maintenance of air filters and its relation to acceptable IAQ. The maintenance of economizer cycles, requiring that dampers and linkages are properly maintained and that the controls function as intended is also emphasized. The use of air-to-air heat exchangers to promote energy-efficient building operation while allowing adequate ventilation for acceptable IAQ is reviewed. Several types of exchangers are described.

A properly designed, installed, operated, and maintained HVAC system should enhance IAQ and radon abatement. Some existing systems have inadequate provision for OA in their design. Some with adequate OA designs have had their mode of operation modified to minimize (or eliminate) OA to save on energy costs. In others OA damper units no longer operate properly due to poor maintenance (14). A review of documentation will usually only reveal the design status of a system. It will be necessary to conduct a thorough inspection, and perhaps a test and balance, to determine the impact of operation and maintenance actions performed (or neglected) in the past that affect the current performance of an HVAC system.

Persily (28) developed a number of forms and checklists to record information regarding HVAC system maintenance procedures and schedules. He recommended obtaining the information through discussion with the building manager and operator. Some of the components of the HVAC system that he included were the AH, filtration systems, heating and cooling coils, air distribution duct work, control systems, testing and balancing information, fan coil units, terminal units, and several others. He also developed other forms to record information obtained during the inspection of the HVAC system and its major components. Some of the additional information found on these forms include entries about the mechanical rooms, supply, return, and exhaust fans, OA intakes, and others.

HVAC system maintenance is crucial to reliable system performance over time. It involves many factors including inspecting and repairing system components, changing filters, cleaning system components such as coils, calibrating control sensors, and periodically evaluating ventilation system performance. If such maintenance procedures are not routinely employed, system performance will deteriorate, leading to the potential for increased energy consumption, reduced equipment life, poor thermal comfort and IAQ problems. Persily (29) has written a manual that describes basic procedures for ventilation system performance evaluation that could be used in a preventive maintenance program. Such a program should include an initial ventilation evaluation that encompasses a space-use analysis, design evaluation and a comparison between the two. Periodic follow-up assessments should be performed roughly once a year and after major space-use changes or ventilation equipment modifications.

Chapter 3
Entry Mechanisms for Radon in Large Buildings

Introduction

For radon to enter a building, there must be a source, a pathway, and a driving force. Once inside the building, radon is removed by air exchange with the outdoors. The indoor radon concentrations depend on the interaction of these factors. This section will review some essential elements of radon entry, especially those that may differ in magnitude or importance in large buildings. The objectives of this section are to provide a conceptual understanding of each significant mechanism, to give a semi-quantitative indication of the relative importance of different mechanisms, to indicate how the factors interact with one another (e.g., pressure differentials as a simultaneous driver for radon entry and removal by ventilation) and with other important building considerations (e.g., energy or occupant comfort). The goal of this treatment is to allow the reader a basis to visualize the likely effects of a given change of building structure or operating conditions. Therefore, each mechanism or element will be described in general illustrative terms; visual or other analogies will be presented if necessary. References to published literature will be included if the effect is not widely known. Some indication of magnitude of the effect will be provided for perspective.

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 sub-slab 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 (41).

Sources of Radon

Radon is a gas that is a radioactive decay product from radium, which is itself a decay product from uranium that occurs naturally (usually in trace quantities) in the earth's crust. Therefore, radon can be found existing in the gas between soil or rock particles, emanating from products made from soil components, dissolved in water taken from deep within the soil, or even remaining in the atmosphere above the soil. In isolated cases building products or well water has been implicated as significant indoor radon sources in homes, but these circumstances are rare for residential structures and even less common for large building construction and operating practices. Therefore, for most of the discussion to follow and throughout this manual, the source of indoor radon is assumed to be emanation from the soil adjacent to the building (55). A natural result of this assumption is that the areas of primary interest in most buildings found to have a radon problem will be those with the greatest contact with the soil. Basements, crawl spaces, ground level floors, and utility tunnels fall into this category.

Pathways for Radon Entry into Large Buildings from the Soil

The pathways by which radon must move to enter a building will be discussed from the perspective of three domains. The first is the path and mechanisms that radon follows in the soil before it reaches the building shell. The second is the path that radon may take as it diffuses through the shell itself (generally assumed to be the least significant entry). The last are paths that may exist in openings of the building shell.

Transport through the Soil

Radon transport is by two mechanisms: pressure driven flow of soil gas, and diffusion (radon flux due to concentration gradients). Pressure driven transport is thought to be governed by Darcy's law because small pressure and temperature gradients are assumed, resulting in laminar and incompressible soil gas flow (56,57). Darcy's law is usually written as $v = -(k/\mu)\nabla p$, where v is the Darcian velocity vector (i.e., the flux density of soil air divided by the total geometric area), k is the intrinsic permeability of the soil (usually in m^2), μ is the dynamic viscosity of the air in the soil pores, and ∇p is the gradient of the dynamic pressure (56,58). The radon diffusion coefficient for a homogeneous pore fluid is defined by a form of Fick's first law, $J = -PD(\partial C/\partial x)$, where J is the radon flux from the bulk soil, P is the total porosity of the soil, D is the diffusion coefficient for radon for radon in the pore fluid (m^2/s), C is the radon concentration in the total pore space of the material, and x is the dimension along which the concentration is varying (59).

There are a number of reports in the literature dealing with the transport of radon through soils, but just a few of the more recent ones will be reviewed here. Nielson et al. (59) developed a mathematical model for calculating radon diffusion coefficients from water contents and pore size distributions of soil materials. Researchers at Lawrence Berkeley Laboratory (LBL) (56,58) presented the transport mechanisms by which radon migrates in the soil air and through building substructures and derived the condition necessary to justify the assumption that diffusion may be neglected. Rogers and Nielson (60) defined soil gas permeability and its relation to other permeability units found in the literature, reviewed prior related permeability studies, and summarized predictive correlations with other measured fundamental soil properties, namely, total soil porosity, arithmetic mean grain diameter, and moisture saturation fraction. They extended this work to predict air permeabilities as well using these same properties (61). Yokel and Tanner (57) presented proposed measurement methods and test procedures and tentative protocols for the assessment of the radon source potential of building sites and fill materials. Their proposed protocols were based on repeatable measurements of invariant soil properties, one of which was the dry gas permeability.

The fundamental soil properties mentioned above to predict gas transport in soils indicate conditions that can significantly affect resistance to soil gas flow. One of these is the total porosity of the soil. A highly compacted soil will have a much smaller porosity, especially in the immediate vicinity of the compaction. If there is a very small volume for the soil gas to occupy, then it will take longer for a given volume of soil gas to pass through, given the same driving force is creating the flow. But total soil porosity is not the only determinant of resistance to soil gas flow. The distribution of the soil pores can be as important as their total volume. A series of very small tortuous pores will offer more resistance to gas flow than will an equal volume of large pores because of increased wall friction in the small pores. The pore size distribution is largely influenced by the soil particle size distribution. Interacting with both of these soil properties to influence resistance to soil gas flow is the moisture content of the soil. Generally a wetter soil will offer more resistance to soil gas flow than will a dry soil. If a large fraction of the soil pores is filled with water, then less gas will be able to pass. But if there are many small pores within the soil (influenced by the particle size distribution), then a smaller quantity of water may block enough of those small pores to offer effectively the same resistance to gas flow as a larger volume of water would in a soil with large pores.

Nazaroff and Sextro (58) focused on the characteristics of soil that influence the rate of radon emanation into the pore air of the soil. Radon's generation depends on the emanation coefficient (i.e., the fraction of radon atoms produced in the soil grains that enters the interstitial pore space before decaying), the density of the soil grains (commonly assumed to be constant for most soils), the radium content of the soil, the radioactive decay constant of radon, and the soil porosity. While the emanation coefficient, radium content, and porosity may vary from soil to soil, for a given soil, the generation rate will be fairly constant. In general, above some critical flow rate (caused by some pressure) which depends on the geometrical configuration and the soil conditions, the concentration of the entering soil gas tends to decrease with increasing flow (and pressure). Under most situations encountered in the field, this depletion will not be an important factor (34). There are two conditions that should be noted, however. First, surface soils generally have a depleted concentration of radon than deeper soils because of dilution with the atmospheric air unless the soil is highly anisotropic in one of the variables mentioned above. Second, if the soil gas is being evacuated by some mechanical means by one of a building's systems and the replacement air is coming from the atmosphere or some other place of lower radon concentrations, then the soil gas radon may be being depleted by that process.

Diffusion through Building Shell Surfaces

Because radon is an uncharged, nonpolar, chemically inert gas consisting of monatomic atoms, it will pass through any material that has pores no smaller than its atomic diameter. Concretes, plastic vapor barriers, wood, and most other common building materials are porous enough for radon to penetrate. The only driving force required to initiate soil gas movement through such a penetration is a concentration gradient. As discussed previously, almost all soils will have radon concentrations to produce at least a small concentration gradient. The larger the soil gas radon concentration the larger the concentration gradient, and the greater the radon diffusion through the material.

Several studies of diffusion through building shell surfaces have been conducted over time. A few will be referenced here as samples of what has appeared in the literature. Renken et al. (62) presented experimental measurements of radon diffusion coefficients of various concrete samples and analyzed other published results. Rogers and Nielson (63) identified the main properties of concrete that influence radon migration from the subsoil into dwellings, characterizing radon transport through concrete with the diffusion coefficient, the porosity, and the permeability coefficient. Rogers et al. (64,65) also determined the diffusion coefficients of older concrete samples and of five different brands of polyethylene sheeting used under concrete slabs. Gadd and Borak (66) developed a method for *in situ* determination of the effective diffusion coefficient and emanation fraction of ^{222}Rn in concrete that relied on the minimum number of assumptions about the concrete.

Throughout most of the literature, diffusion through the building shell surfaces is generally not considered to be a significant factor for most buildings. Most buildings will not be built over extremely high radon potential soils to provide the concentration gradient necessary to produce a significant diffusive flux. Generally the slabs for large buildings are required by specifications to be thicker and higher in quality (less porous) than those found in residential construction; so their diffusive contribution to the total radon entry should be less per unit area.

Pressure-driven Flow through Openings in the Building Shell

All buildings will have some breaks in the building shell, especially in the slabs and other portions in contact with the soil. Generally all the plumbing of a building comes through underground penetrations. Often other utility lines also enter the building shell through subterranean access. All concrete cracks, whether on a microscopic or a macroscopic scale. Usually the builder tries to control where and how it cracks, but because the curing process results in shrinkage, there will be some degree of cracking over time in almost all circumstances. Whenever there is an opening in the sub-grade shell of a building, soil gas may enter. Because the resistance to soil gas air flow is less for a crack than it is for intact concrete or even for most soils to be found around the building shell, such openings are felt to be the major pathways for radon entry into buildings.

Cracks

There are four types of cracks that will be discussed briefly in the light of their potential for being pathways for radon entry into buildings. The first are random shrinkage or settling cracks. These are unplanned cracks that occur as a result of the contraction of the concrete as it dries or of misalignment of the foundation caused by uneven settling of the supporting soil. Generally shrinkage cracks are not as important in terms of radon entry because they are usually small, and sometimes they do not penetrate the entire thickness of the slab. Settling cracks, however, usually do occur over the whole thickness and are characterized by a vertical displacement as well as a horizontal displacement of the slab. Therefore, they tend to be larger and have less resistance to gas flow. The second type of crack includes planned construction joints. These may be contraction joints cut into the slab so that the location of the shrinkage will be controlled. They may also be cold joints where one placement of concrete abuts an earlier one. The advantage of these and other controlled cracks is that their location is known, and they can and should be sealed more easily and thoroughly. In all of these cracks, they usually will be underlain by the vapor barrier; so their resistance to radon entry will be relatively high. If they are sealed, then they should be inconsequential.

The perimeter crack of a "floating" slab does not have this same advantage; therefore, it is usually of greater concern for radon entry. The vapor barrier under a floating slab will necessarily terminate close to the stem wall, usually in very close proximity to the perimeter crack. Therefore, there is usually less resistance to soil gas flow through this type of crack than through the others mentioned earlier. Because the perimeter crack usually occurs at the floor-wall intersection, it may be more difficult to seal effectively, especially if it continues to expand after finishing treatments have been installed on the walls or floors. This type of crack also has a shorter path length (and therefore less resistance) for makeup air to travel; so greater flow is allowed. However, that path usually traverses below the footings so that high radon concentration soil gas may be transported to the crack. The final type of crack that may be encountered is the sub-grade wall crack. This type has the same disadvantage of a perimeter crack in that there is usually no vapor barrier between it and the soil, but the path length to the atmosphere is usually shorter and more direct; so that the concentration of soil gas radon is usually not as high.

Penetrations in the Building Shell

These openings are usually of greater concern than most cracks (except for perimeter cracks). That is because the utility penetrations that cause these openings puncture the vapor barrier as well as penetrate the slab. Quite often the soil around these lines was disturbed when they were laid, and the second compaction may not have been as thorough either by omission or by design (less strenuous compaction to reduce the risk of stressing the line). Therefore, soil gas may have a more permeable conduit leading directly to the breach in the building shell. In addition to the penetrations of utility lines, there may be structural elements that break the seal of the building shell. For instance, load-bearing walls or pillars are constructed on their own interior footings. These structures therefore penetrate the ground floor, creating a perimeter crack on both sides of the wall or all around the pillar. Additionally, if they are constructed of hollow masonry blocks, those voids may form a direct pathway for soil gas to enter the interior of the building.

Usually, one would correctly assume that with a larger penetration, the rate of radon entry will increase proportionally. If the slab rests on compacted soil, then the amount of radon that may be drawn into the interior of the space may be limited by the resistance of the soil rather than the size of the opening. The greater the path length the soil gas has to travel, the greater will be the resistance it has to overcome. Therefore, the location of the opening may affect the amount of soil gas transported. If, however, the opening leads to a very porous material like a coarse gravel aggregate, then the soil gas has much less resistance to overcome and a much larger plenum to evacuate.

Relative Importance of These Various Pathways

In the preceding discussions, qualitative indications have been mentioned of the relative importance of some of these various radon entry pathways. Since the forces acting on a building are usually dynamic and changing in nature, it is difficult to fix absolute numbers or rules on some of these concepts. For instance, if there are pathways of low resistance between the soil and the building's interior, then the soil gas will naturally follow them. If there are very few of them, then diffusion through the building shell becomes a more significant source. If the spaces of the building bounded by the building shell are usually depressurized, then mass flow of soil gas through openings totally dominate diffusive flux. If, however, these spaces are typically neutral to positive in pressure compared to the soil gas, the diffusive component will be more significant. In order to attempt to quantify some of these complex interrelationships, several groups have done extensive modeling of building systems to be able to predict some of the relative importance of these various components.

Revzan et al. (67) developed a model that predicted the radon entry rate into a house using a set of soil and building substructure characteristics that were typical of Florida soils and houses. They found that if all openings in the vicinity of the stem wall were eliminated, then the radon entry rate reduced by at least two thirds. Nielson et al. (65) also developed a model by which the radon resistance effectiveness of different building construction features was ranked according to their usefulness for radon control. Four features of passive construction features were recommended. The first was the elimination of floating slab construction because of the floor-wall crack that resulted from this construction practice. The second was the use of improved concrete mixes, which reduced slab cracking and the porosity of the slab. The remaining two were the sealing of slab penetrations and of large openings and cracks. These two reports and many of their references (e.g., 68, 69), involved models designed primarily for residential structures. Most of the relative comparisons should be valid when extended to large buildings. Gu, et al., (70) performed a similar study of the relative effectiveness of various passive and active mitigation strategies in large buildings.

Driving Forces for Pressure-driven Radon Entry

If a building has any pathways between the high radon concentration soil gas and the inside of a building (and almost all do), then it does not require much of a driving force to pull radon into the structure. Indeed, around neutral pressures (throughout the range of ±2-3 Pa), Hintenlang and Al-Ahmady (71) demonstrated that maximum radon concentrations occurred. They attributed these elevated radon concentrations to the natural pumping of the soil gas from the sub-slab areas into building interiors. Nielson and Rogers (68) tested their model for radon entry by applying it to these data and compared the results with the perimeter crack and potential physical openings in the concrete-block stem walls.

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 is less dense 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, it eventually will flow out of the building at the upper floors through openings and cracks in the building envelope or out 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 (41).

The stack effect is generally less during the cooling season than 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 and reversed from what is experienced during the heating season (41). Sherman (34) contends that the ratio of the radon entry pressure to the pressure driving ventilation gives a good indication of how effective each driving force is at creating indoor radon. His calculations indicate that the winter stack effect (especially in basement structures) is much more efficient than other driving forces at inducing elevated radon concentrations. Since many large buildings will have greater heights than the residential structures that most of the models are simulating, the stack effect is likely to be even more significant in them.

Effects of Fluctuating Pressure Fields

While the stack effect is caused by temperature induced pressure differentials, there are other naturally occurring phenomena that also influence building pressures. The first to be discussed is wind pressure. This effect has had a considerable attention in the literature. The second, the effect of barometric pressure, has generally been dismissed as being insignificant. A few recent papers have presented evidence that this may not be the case.

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 of 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 OA 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 OA in a controlled and conditioned fashion. Not all HVAC systems meet both of these requirements. Even with HVAC systems that have OA capability, wind pressure is not easily overcome (41).

Sherman (34) states that wind-induced ventilation has about the same importance as stack-induced ventilation for most climates, unless the buildings are highly sheltered. For a crawl space whose leakage distribution mirrors the building, the wind pressure will be in between the pressures on the faces of the building, so that its effect of driving radon entry will be insignificant. This fact coupled with the fact the wind will dilute the radon in the crawlspace allows one to ignore wind-induced radon entry in such a building. Sherman's model for infiltration and radon entry gives radon sourse ratios which indicate that the wind effect is one half to one quarter that of the stack effect, though its variation may be twice as great. The highest radon concentrations usually occur during stack-dominated periods, and the lowest during wind-dominated periods. For example, the model's prediction for a leaky house attributes twice the infiltration rate to stack effect than to wind effect in the winter and eight times the induced radon concentrations. In the spring, the infiltration due to the wind is twice that of the stack effect and the induced radon concentrations are less than four times as great for the stack effect. Although the wind effect may be quite small in steady-state, it may contribute significantly under non-steady conditions - a case not analyzed by the model. Dynamic wind effects could be considerable.

Barometric Pressure

Because most of the simple models of radon entry use a steady-state analysis (34,67, 72), the effects of dynamic pressure changes such as induced by sudden changes in the barometric pressure are usually not taken into consideration. However, empirical data from structures build over low permeability soils (71,73,74) have shown that a 0.2 kPa drop in barometric pressure associated with a storm front increased the radon entry rate by more than an order of magnitude. Usually the building is influenced quite rapidly by a change in external pressure, whether it is caused by a change in temperature, wind speed, or barometric pressure. The soil or other aggregate under the building requires a considerably longer time to respond to the change than the building itself. Therefore, there will be a pressure difference between the building and the sub-slab environment. Such a driving force can pump soil gas through any opening in the building shell that is available. Even if such a differential exists for a relatively short time, just small quantity of high radon concentration soil gas can enter and quickly disperse into the indoor air. Mixing by the building's systems enhance the dispersion. If the pressure differential reverses itself, then it is much lower concentration building air that may be forced back through the opening.

Forced Air Handling Systems
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 HVAC system can play an important role in the depressurization of the building by controlled use of ventilation air. By introducing more OA 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 OA infiltrating. A properly operating HVAC system with OA provision need only maintain a pressure differential of 1-4 Pascal. 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 (41).

Type of HVAC System
Some system characteristics and features of various types and classes of HVAC systems were discussed in Chapter 2. Not all HVAC systems will provide building pressurization. Many of the all-air systems and some air-water systems are desirable for building pressurization. These classes of systems can provide OA in specific quantities to offset the forces that defeat pressurization. Many unitary systems and all all-water systems do not allow pressurization because OA is not a feature of these types of systems (41).

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. There are a number of accepted sealing techniques that can be used (41).

There can also be leaks in the return system that may cause major problems of radon entry and other IAQ circumstances. In some large buildings [see reference (42)] the return fans may be located in mechanical equipment rooms. In such cases, the whole space is often highly depressurized. If this is a ground floor room and there are any pathways at all for soil gas to enter that room, then that high radon concentration air is pulled into the return air and subsequently distributed to all the space covered by that AHU. Some large buildings have return plenums in the space above a false ceiling. One might surmise that such a location might be far enough removed from the soil so that this would be a safe practice. In one building (41) the load bearing walls resting on sub-slab footings terminated in such a ceiling plenum and had numerous open cells that communicated with the soil gas through small leaks in the sub-slab mortar joints and through the permeable concrete blocks. The high radon concentration soil gas was pulled into the plenum and distributed through the building every time the HVAC system operated.

Besides leaks in the ductwork, the positioning of supply registers and return intakes may lead to imbalances in the pressure regime of a building or a group of spaces therein. Quite often there are many more supply registers than return intakes. If one or more supply ducts terminate in a space that can be isolated from the appropriate return duct servicing that space by closed doors, partitions, renovations in the space, or the like, then it is conceivable that areas of localized depressurization can result. If there exists within such a space any pathway for soil gas to enter, then radon may also be pulled into the system and distributed to even pressurized spaces. Even if no such pathway exists, then there may still be areas of stagnant or poorly circulated air that could lead to other IAQ problems.

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 OA 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 (41).

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 centers 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 to measure flow or pressure. The general design rule is to avoid using return-air fans if at all possible. However, larger buildings require

return-air fans. 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 is essential to avoid a negative pressurization (41).

Exhaust Air Systems with Inadequate Make-up Air

Powered exhaust systems are usually a requirement of building codes. Toilets, bathrooms, kitchens, workshops, and similar areas are required to be exhausted. Many of the exhaust systems may not have the provision of adequate make-up air included in their design. Often their use cannot be avoided and code standards still be met. 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 (41). The rest of the HVAC system must be designed to compensate the loss of indoor air through the exhaust system with additional OA to ensure that the proper level of pressurization is still maintained.

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 OA. 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 OA used. If less OA is used, then less control of building pressurization will be realized. The all-water system provides no means of OA 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 OA introduction and control available in the all-air system (41).

Room or Building Porosity

Generally, the design of building envelopes is 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 effect 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 OA should be prevented from flowing into the building through the walls, roof, and fenestrations. Conversely, flow of indoor air to the outside should also be discouraged. These types of air leakages lead to excessive energy usage, poor thermal performance, and poor IAQ, as well as interfere with the normal operation of the HVAC system (41).

Radon Removal by Air Exchange with Outside

While the rest of this chapter has dealt with how radon enters a building, this section will address how radon is normally removed from a building. The primary mechanism is by air exchange with the outside. Air is exchanged with the outside through several mechanisms. One is by normal infiltration and exfiltration. This occurs through leaks in the building shell, whether they be doors, windows, utility accesses, cracks, pores, or other openings. Another is by forced air exchange such as designed OA intakes or exhaust system discharge, or by unplanned leaks in the HVAC system, which may introduce air through return leaks or exhaust air through supply leaks. While it is evident that the air lost or gained by the HVAC or powered exhaust systems moves by the pressure created by system fans, it is just as true that the air that moves through the unplanned leaks in the building shell does so under the influence of pressure differentials. These pressures are usually smaller, but they may be active continuously and over larger areas than those of the planned or designed systems.

Sextro reported at a large building research workshop (40) the results of a 40 commercial building study in Washington, Oregon, and Idaho that the measured air exchange rates varied from 0 to 0.5 air changes per hour (ACH) in three buildings (7.5%) to 4.0 to 4.5 ACH in one building (2.5%). The largest number of buildings, ten (25%), had exchange rates of 0.5 to 1.0 ACH. The next was nine (22.5%) at 1.0 to 1.5 ACH, followed by eight (20%) at 1.5 to 2.0 ACH, six (15%) at 2.0 to 2.5 ACH, and four (10%) at 2.5 to 4.5 ACH. With such a small sample, it would be difficult to say that these numbers would match the regional or national expected values, but the trends are probably represented of what one might find. While these numbers represent the whole building air exchange rates, they say nothing about how the air is transported or exchanged within the buildings.

In multi-story buildings, many of the same forces act on infiltration air in much the same manner as discussed as radon driving forces in the previous section, i.e., stack effect, wind pressure, HVAC system pressures, exhaust air systems, and building systems. One building system that influences infiltration air that was not explicitly discussed is how well or poorly the floors or zones of a building are coupled or uncoupled from one another. If floors have good communication with one another, then forces such as the stack effect may be especially strong on the top and bottom floors rather than evenly distributed over all the floors. This would induce greater infiltration where the forces were concentrated that the other areas. But radon concentrations pulled into the ground floor by such forces could be more easily transported to the upper floors if such good communications existed.

From these discussions, it may be apparent that both the ventilation rate and the radon entry rate respond to pressure differentials exerted on or by the building. If the pressure differential is negative, then both infiltration and radon entry rates increase. If, however, the pressure differential is positive (usually caused by forced introduction of OA), then both natural infiltration and the radon entry rates are low. If the ventilation rate is very high because of a high depressurization, then more OA dilutes the radon introduced by the high radon entry rate. It is usually near neutral to small depressurizations that create enough radon entry rates without sufficient infiltration to increase indoor concentrations (71).

Chapter 4
Radon Measurements

Types of Radon Measurements

Radon measurements may be classified in several different ways. For the purpose of this section, we will discuss radon measurements on the basis of the use of the data and make further distinctions within those general categories based on the types of devices used. The three functionally different realms of radon measurement discussed in the following subsections are grab, continuous, and integrating measurements.

Grab Measurements

Grab radon measurements may be used to determine indoor radon concentrations, but within the context of this manual they will seldom be used for that purpose. Grab measurements are generally "snapshots" of radon concentrations found in a relatively small volume over a relatively short time frame. Therefore, their greatest usefulness is in characterizing stable concentrations or in making diagnostic measurements of short time duration. Examples of situations in which grab measurements are typically used as the measurement type of choice are radon concentration determinations during radon entry investigations, site characterizations, slab crack analyses, sub-slab or soil gas radon measurements, and exhaust gas evaluations. The EPA's "Indoor Radon and Radon Decay Product Measurement Device Protocols" (75) gives protocols for three grab radon sampling methods: scintillation cell, activated carbon, and pump/collapsible bag. The protocols given are specifically for indoor radon concentration determinations, but the one for scintillation cells is directly transferable to the diagnostic measurements described. Therefore, it is the method for grab samples that will be used in this document. There are some other grab radon technologies currently on the market, such as one with a solid-state silicon detector, but since EPA protocols have not been published for them, they will not be included in the discussion that follows.

Number of Samples

For the purpose of quality assurance, at least 10 percent of the grab samples should have duplicate measurements made. However, for some measurement locations and situations, duplicates in excess of 10 percent of the time may be recommended. For instance, some radon entry measurements may be considered critical; so duplicate measurements of those locations are suggested. When taking duplicate measurements with grab scintillation cells, it is recommended that the two cells be placed in series so that the same gas is being pulled through both. The act of extracting a sample may alter the conditions of the environment being sampled, especially when there may be a limited gas volume in the measured space. For example, when measuring soil gas concentrations, repeated pumping in the same location may be extracting gas from a larger volume of soil, which may be more concentrated or more dilute than the initial volume just in contact with the probe. On the other hand, repeated sampling of a slab crack or other potential radon entry location may pull dilute ambient air into the volume being sampled after the initial gas has been evacuated.

Location of Samples

The question of what locations to sample must be determined on a case by case basis depending on the specific building, the conditions, and time and other limitations. When conducting diagnostic measurements, one should give priority to locations that are most likely to be radon entry routes. For instance, cracks around slab penetrations have high potential for being points of radon entry. Slab edge cracks of "floating" slabs are far more likely to be entry routes than are settling cracks or control joints in the slab, which in turn are more likely to be entry routes than are shrinkage cracks. Block "stem" walls or other block walls that penetrate the slab should be sampled, but block walls that rest on the slab need not be sampled at all.

Continuous Radon Measurements

A continuous radon monitor (CRM), for the purpose of this manual, will be considered to be a device (or system) that records radon concentrations on some fixed interval over a prolonged period of time. Because of the requirement to store or record the data over time, these devices will always require electrical power, whether provided internally by battery or externally. This fact, coupled with the inherent sophistication of these devices, makes them considerably more expensive than most integrating devices to be discussed later. The benefit of this sophistication (and expense) is that the investigator can determine periodic changes in radon concentrations with the use of the devices. For instance, they can be used for diagnostic purposes to determine if the radon concentrations depend on diurnal changes, operation of other systems (such as the HVAC), or other explained or unexplained factors. The influence of changes to the building's systems, installation of passive radon retarding features (such as sealing entry routes), and activation of radon mitigation systems can be documented with the use of CRMs. The EPA's measurement device protocol document (75) covers three types of CRMs, and the following descriptions are extracted from that reference.

Scintillation Cells

In this type of CRM, ambient air is sampled for radon in a scintillation cell after passing through a filter that removes radon decay products and dust. As the radon in the cell decays, the radon decay products plate out on the interior surface of the scintillation cell. Alpha particles produced by subsequent decays, or by the initial radon decay, strike the zinc sulfide coating inside the scintillation cell, thereby producing scintillations. The scintillations are detected by a photomultiplier tube in the detector which generates electrical pulses. These pulses are processed by the detector electronics and the data are usually stored in the memory of the monitor where results are available for recall or transmission to a data logger or printer. This type of CRM uses either a flow-through cell or a periodic-fill cell. In the flow-through cell, air is drawn continuously through the cell by a small pump. In the periodic-fill cell, air is drawn into the cell once during each preselected time interval, then the scintillations are counted and the cycle repeated. Often a CRM will be used in this mode to monitor sub-slab or ambient radon concentrations. The advantage of this mode is that the CRM can be located in the protection of the building while tubing is run to the sub-slab space or the outside to sample the gas there. A third variation operates by radon diffusion through a filter area with the radon concentration in the cell varying with the radon concentration in the ambient air, after a small diffusion time lag. A CRM with a passive radon detector (PRD) is an example of this type. The concentrations measured by all three variations of cells lag the ambient radon concentrations because of the inherent delay in the radon decay product disintegration process. Commercially available CRMs of this type tend to have greater sensitivity than those of the other two types discussed below; however, they also tend to be more expensive. Some of the more popular devices of this type are self-contained units with internal memories and do not require a data logger to store the data. The scintillation cells will increase in background counts because of the plate-out phenomenon; therefore, the background will have to be monitored periodically.

Ionization Chamber

A second type of CRM operates as an ionization chamber. Radon in the ambient air diffuses into the chamber through a filtered area so that the radon concentration in the chamber follows the radon concentration in the ambient air with some small time lag. Within the chamber, alpha particles emitted during the decay of radon atoms produce bursts of ions which are recorded as individual electrical pulses for each disintegration. These pulses are processed by the monitor electronics; the number of pulses counted is displayed usually on the monitor, and the data are available usually for processing by an optional data logger/printer. Commercial versions of this kind of detector tend to be not quite as sensitive as the scintillation type, but they are less expensive and generally have a more stable background. Generally, they do not have internal memory to store the data and therefore require a data logger or printer to perform the recording.

Solid-state Silicon Detector

A third type of CRM functions by allowing ambient air to diffuse through a filter into a detection chamber. As the radon decays, the alpha particles are counted using a solid-state silicon detector. The measured radon concentration in the chamber follows the radon concentration in the ambient air by a small time lag. These monitors are generally not as sensitive as the other two types, often requiring up to four hours of normal indoor radon concentration exposure before the counting statistics produce equivalently precise data. On the market there are several of these devices that range in price and complexity from units that monitor and display the average radon concentration detected to research-grade units with data memories and printout capabilities.

Location of Samples

Because of the cost and therefore limited number of CRMs that an investigator will typically have for use in a given building, strategic placement of the detectors available will be an important consideration. Specifics will vary by the building being studied, but a few general rules will apply most of the time. Because radon emanates from sources generally found in the soil beneath and occasionally surrounding spaces in a building, the ground floor is often the most critical location for sampling. Radon also needs an access to the building; so spaces with penetrations that may communicate with sub-grade soil gas volumes are good candidates for monitoring. Radon enters a building by diffusion through openings (whether they are micropores in what appears to be a solid barrier or obvious cracks or holes) or by induced mass flow caused by some type of driving force such as a pressure differential. Most of the time mass flow can easily be the dominant radon entry mechanism; therefore, spaces that are under negative pressures are important ones to monitor. The primary concern with radon is with its potential adverse health effects to humans. Therefore, there is a strong argument to make occupied spaces a priority in conducting some of the critical radon measurements. Ground floor air handling rooms with cracks or penetrations to spaces containing soil gas may also be good candidates for monitoring because they are often operated at negative pressure differentials to the outside, and they are integrally involved with the distribution of air to occupied spaces. Within any given building, all of these factors and perhaps others specific to that building will be taken into account in determining the placement of the CRMs available.

Recommended Deployment

Once it has been determined in which locations the deployment of CRMs should occur, they should be placed with the building operating in its "normal" mode. Conditions should be monitored to ensure that nothing out of the ordinary is influencing radon concentrations during this measurement period. For instance, if unusual weather occurs, then enough measurements need to be made after conditions have returned to normal to allow the investigators to know what the expected concentrations are. Such baseline measurements need to be made across all of the building's usual operating cycle, including overnight and weekend "set back" periods, if they exist. Then the parameters that have been selected to be varied should be changed one factor at a time in large enough increments so that effects on the radon concentrations can be distinguished. Some of these parameters may be the sealing of suspected entry routes, the adjustment of OA intakes and exhaust fans, other variations of the building operating conditions, and the activation of a radon mitigation system, if one was installed. Once all of the desired data have been collected and reviewed with the building owner/manager, and a decision has been reached in what condition to leave the building, the monitors should remain in place for at least another normal full operating cycle of the building to ascertain the effectiveness of the adjustments made.

Integrating Measurements

For the purpose of this manual, devices termed as integrating will refer to those that passively collect "information" on the radon concentration in a given space while they are exposed. Analysis of the device indicates radiological activity that occurred during the exposure, but there is no way to determine specifically if changes occurred within the exposure period. Therefore, the results tell something about the overall "average" of the activity that occurred. There are many such devices on the market, but only three of the more commonly used classes will be discussed here. General information from the EPA's protocol document (75) will be used to describe these technologies.

Activated Charcoal (AC) Adsorption Devices (quasi-integrating)
These are passive devices requiring no power to function. The passive nature of the activated charcoal allows continual adsorption and desorption of radon. During the measurement period (typically two to seven days), the adsorbed radon undergoes radioactive decay. Therefore, the technique does not integrate uniformly radon concentrations during the exposure period. As with all devices that store radon, the average concentration calculated using the mid-exposure time is subject to error if the ambient radon concentration varies substantially during the measurement period. This technique is used by several groups and companies across the U.S., often taking different forms.

A device used commonly by several groups consists of a circular, 60- to 100-mm (2.4- to 3.9-in.) diameter container that is approximately 25 mm (1 in.) deep and filled with 25 to 100 g (0.9 to 3.5 oz) of activated charcoal. One side of the container is fitted with a screen that keeps the charcoal in but allows air to diffuse into the charcoal. These "open face" charcoal canisters are normally exposed two to five days. In some cases, the charcoal container has a diffusion barrier over the opening. For longer exposures, this barrier improves the uniformity of response to variations of radon concentration with time. Usually diffusion barrier canisters are exposed from five to seven days. Desiccant is also incorporated in some containers to reduce interference from moisture adsorption during longer exposures. Another variation of the charcoal container has charcoal packaged in a sealed bag, allowing the radon to diffuse through the bag. Several companies now provide a type of charcoal liquid scintillation (LS) device that is a capped, 20-ml liquid scintillation vial that is approximately 25 mm in diameter by 60 mm and contains one to three grams of charcoal. All ACs are sealed with a radon-proof cover or outer container after preparation. The measurement is initiated by removing the cover to allow radon-laden air to diffuse into the charcoal bed where the radon is absorbed onto the charcoal. At the end of a measurement period, the device is resealed securely and returned to a laboratory for analysis.

At the laboratory, the ACs are analyzed for radon decay products by placing the charcoal, still in its container, directly on a gamma detector. Corrections may be needed to account for the reduced sensitivity of the charcoal due to adsorbed water. This correction may be done by weighing each detector when it is prepared and then reweighing it when it is returned to the laboratory for analysis. Any weight increase is attributed to water adsorbed on the charcoal. The weight of water gained is correlated to a correction factor, which is derived empirically. This correction factor is used to correct the analytical results. This correction is not needed if the configuration of the AC is modified to reduce significantly the adsorption of water and if the user has demonstrated experimentally that, over a wide range of humidities, there is a negligible change in the collection efficiency of the charcoal within the specified exposure period. AC measurement systems are calibrated by analyzing detectors exposed to known concentrations of radon in a calibration facility.

Generally the most common use for AC devices is in making screening measurements, in which it is desired to see if an elevated radon problem exists or to check to see how concentrations have changed over time. If possible, it is usually recommended that each occupied space that has at least one of its shell faces in direct contact with the soil or with a space where soil gas may be trapped be screened. For occupied spaces in the building that are not directly linked to soil gas, it is a good idea to screen at least one that is served by each AHU. To ensure the data quality, at least 10 percent of the spaces screened should have duplicate (collocated) detectors placed in them, and least 5 percent of the deployed detectors should be field control detectors (field blanks) that are kept sealed in a low radon (less than 0.2 pCi/L) environment, labeled in the same manner as the field detectors to ensure identical processing, and sent back to the supplier in the same shipment as the field detectors for analysis. These control devices measure the background exposure that may accumulate during shipment or storage. If any of the field detectors seem to have results outside the norm of the others, that space should be monitored again if possible.

Alpha Track Detectors (ATD)
An ATD consists of a small piece of plastic or film enclosed in a container with a filter-covered opening or similar design for excluding radon decay products. Radon diffuses into the container and alpha particles emitted by the radon and its decay products strike the detector and produce submicroscopic damage tracks. At the end of the measurement period, the detectors are returned to a laboratory. Plastic detectors are placed in a caustic solution that accentuates the damage tracks so they can be counted using a microscope or an automated counting system. The number of tracks per unit area is correlated to the radon concentration in air, using a conversion factor derived from data generated at a calibration facility. The number of tracks per unit of analyzed detector area produced per unit of time (minus the background) is proportional to the radon concentration. ATDs function as true integrators and measure the average concentration over the exposure period. Many factors contribute to the variability of ATD results, including differences in the detector response within and between batches of plastic, non-uniform plate-out of decay products inside the detector holder, differences in the number of background tracks, and variations in etching conditions. Since the variability in ATD results decreases with the number of net tracks counted, counting more tracks over a larger area of the detector, particularly at low exposures, will reduce the uncertainty of the result.

Because of the longer time required to get enough tracks on the plastic to produce statistically significant results, ATDs are considered to be long-term measurement devices. Generally a month is the shortest time interval recommended for ATDs, and at low concentrations, the counting statistics may still not be good. Usually ATDs are deployed for three months to a year. Therefore, they are usually the devices of choice for long-term post mitigation monitoring, for studying seasonal effects, or for determining actual annual exposures. Because they are used after screening measurements have been made, they do not need as wide a deployment as was described for the screening measurements. It would generally be prudent to deploy them in the locations that were identified as having elevated concentrations by the screening measurements, and perhaps to monitor at least one occupied space served by each AHU so that it can be ascertained whether any unexpected increases in radon concentrations occurred because of any of the mitigation activities that were implemented. At least 10 percent of the spaces monitored should have duplicate (collocated) detectors to test the precision of the measurements. The pair of detectors should be treated identically in every respect. They should be shipped, stored, opened, installed, removed, and processed together, and not identified as duplicates to the processing laboratory. The samples selected for duplication should be distributed systematically throughout the entire population of measurements. Field control ATDs (field blanks) should consist of a minimum of 5 percent of the devices that are deployed. These should be set aside from each shipment, kept sealed and in a low radon (less than 0.2 pCi/L) environment, labeled in the same manner as the field ATDs to assure identical processing, and sent back to the supplier with the field ATDs for analysis. These control devices are necessary to measure the background exposure that accumulates during shipment and storage.

Electret Ion Chamber (EIC) Radon Detectors

Measurements made with EICs can produce either short-term or long-term measurements, depending upon the type of electret employed. They require no power and function as true integrating detectors, measuring the average concentration during the measurement period. The EIC contains a charged electret (an electrostatically-charged disk of Teflon®) which collects ions formed in the chamber by radiation emitted from radon and radon decay products. When the device is exposed, radon diffuses into the chamber through filtered openings. Ions which are generated continuously by the decay of radon and radon decay products are drawn to the surface of the electret and reduce its surface voltage. The amount of voltage reduction is related directly to the average radon concentration and the duration of the exposure period. EICs can be deployed for exposure periods of two days to 12 months, depending upon the thickness of the electret and the volume of the ion chamber chosen in use. These deployment periods are flexible, and valid measurements can be made with other deployment periods depending on the application. The electret must be removed from the chamber and the electret voltage measured with a special surface voltmeter both before and after exposure. To determine the average radon concentration during the exposure period, the difference between the initial and final voltages is divided first by a calibration factor and then by the number of exposure days. A background radon concentration equivalent to ambient gamma radiation is subtracted to compute radon concentration. Electret voltage measurements can be made in a laboratory or in the field.

Short-term electrets (two to seven days exposure) can be used in just about any setting in lieu of AC canisters. Long-term electrets (one to twelve months) can be used instead of ATDs. Duplicate (collocated) detectors should be placed in at least 10 percent of the measurement locations to test the precision of the measurements. The duplicated devices should be shipped, stored, exposed, and analyzed under the same conditions, and not identified as duplicates to any third party who may be processing the data. The samples selected for duplication should be distributed systematically throughout the entire population of samples. At least 5 percent of the electrets deployed should be set aside from each shipment and evaluated for voltage drift. They should be kept covered with protective caps in a low radon environment and analyzed for voltage drift over a time period similar to the time period used for those deployed in the building. EICs are sensitive to background gamma radiation. The equivalent radon signal per unit background radiation is determined by the manufacturer for each different type of chamber. Specific steps for determining this background are provided by the manufacturer.

Relative Advantages and Disadvantages of the Integrating Measurement Devices
ACs may be the least expensive and most widely understood of these devices. However, as mentioned, they are not true integrators and preferentially weight the end of the measurement period over the first of the time. They have to be mailed back to the source company for analysis so there is always a delay between the measurement and the discovery of the results. They are the most sensitive devices to moisture, which has potential of reducing the confidence in the results. ATDs are the most widely used long-term measurement devices, but they also have to be returned to the source laboratory for analysis. They tend to have less precision than the other devices. EICs are purported to be insensitive to humidity, but they are perhaps more sensitive to mishandling, as the charged electret can be discharged quite easily, giving false high readings. If the investigator owns an electret reader, then determinations of the measured radon concentrations can be done within minutes without shipping the electrets anywhere or waiting for an analysis laboratory. However, the surface voltage meter is the most expensive item in the system, and it has been shown to be somewhat temperature dependent. Some knowledge of the radon concentration is sometimes required when using EICs because if the space has a much higher than expected concentration, it is quite possible that the electret may discharge below the usable range if left exposed too long. Knowledge of the gamma background is necessary to achieving accurate results with the EIC.

Recommended Deployment
All three types of integrating detectors (and CRMs as well) should be placed in locations where they will not be disturbed during the measurement period and where there is adequate room for the device. The measurement should not be made near drafts caused by heating, ventilating, and air conditioning (HVAC) vents, doors, fans, and windows because ambient air sources may dilute radon in contact with the detectors while drafts of elevated radon concentrations may expose more radon to the detector than would otherwise come in contact and thus there would be the potential for measurements greater than the actual concentrations. Locations near excessive heat or in direct sunlight and areas of high humidity (bathrooms, kitchens, laundries, etc.) should be avoided because either heat or moisture may cause aberrations in the substrate being used or in some of the electronics or other mechanisms used in the collection or counting processes. The measurement location should not be within 0.9 m

(3 ft) of windows or other potential openings in the exterior wall because of possible dilution of results. If there are no potential openings in the exterior wall, then the measurement location should not be within 0.3 m (1 ft) of the exterior walls of the building. The detector should be at least 0.5 m (20 in.) from the floor, and at least 0.1 m (4 in.) from other objects. For those detectors that may be suspended, an optimal height for placement is in the general breathing zone, such as 2 to 2.5 m (about 6 to 8 ft) from the floor.

Uses of Radon Measurements

Most of the protocols concerning the use of the various technologies for measuring indoor radon referenced above were written in the context of single family residential housing. With the exception of schools (20), there has not been much published on extending these protocols to other buildings, at least on the national level. While most of the device protocols will not change depending on the type of building involved, measurement strategies may vary in larger structures.

Screening Measurements

As generally mentioned in the above paragraphs that dealt with the individual devices, screening measurements for indoor radon concentrations are usually conducted with short-term (2 to 90 days). Short-term measurements are most often made with AC devices, ATDs, EICs, and CRM detectors. Generally, the longer the test period, the more representative the measurement will be of the annual average of indoor radon concentrations. However, if a building is usually not occupied continuously and its HVAC system is operated differently during periods of low or no occupancy, then indoor radon concentrations may vary considerably depending on the system's functions. Measurements that cover extended periods of system setbacks may not represent accurately the concentrations to which people are exposed when the building is normally occupied. Therefore, a screening measurement of two to five days during a normal work week may be preferred to a longer term measurement that includes a weekend. Measurements of this duration are not usually made with ATD devices. Short-term measurements should be made in all frequently-occupied rooms (tested simultaneously) in contact with the ground. A follow-up measurement should be performed in every room whose initial test result was 4 pCi/L or greater (20). In large buildings with many rooms to be tested, CRMs are usually not feasible to use for screening measurements because of their expense.

Diagnostic Measurements

If screening measurements indicate that the building has a radon problem, then diagnostic measurements will need to be made to identify the source of the problem before any type of mitigation plan is designed. There are at least two types of these diagnostic measurements that give different kinds of information about the nature of the elevated indoor radon concentrations. Proper screening measurements will usually have identified the room(s) that seem to have the highest concentrations. It is usually a good idea to place a CRM in this room(s) to record the short-term (approximately hourly) changes in the concentrations. These measurements will give an indication if the radon entry is influenced to any great degree by the HVAC or other building system or operation. They will also give a better indication of the indoor concentrations during the hours when the room is actually occupied. The second type of diagnostic measurement normally employed is the taking of grab samples of suspected radon entry routes or of the potential source environments. Suspected entry routes may be cracks or other openings in floors or walls. Potential source environments would include sub-slab spaces, block wall voids, crawl spaces, utility tunnels, ventilation ducts in contact with the ground or other high radon environments, and other conduits that a specific building design may have.

Post-Mitigation Measurements

After measures have been taken to mitigate a radon problem, post mitigation measurements will need to be taken to quantify their effectiveness. Usually the device of choice would be a CRM so that changes of patterns in time of the radon concentrations as well as the concentrations themselves may be evaluated. Taking other short-term measurements as similarly as possible to the screening measurements is another alternative. It is usually a good idea to make long-term measurements (ATDs or EICs) to confirm that the measures put in place have durability, but usually the conduct of these measurements will be at the discretion of the building owner or operator.

Chapter 5
Diagnostic Protocol

Pre Mitigation Radon Measurements

The previous section discussed radon measurements in general and some of the pre mitigation measurement strategies in particular. A summary of some of the highlights of that discussion follows. Generally some type of screening radon measurement would normally have been made that identified the building in question as having a potential radon problem. Unless the screening measurements were made in a very systematic manner as described in the previous section, the investigator will probably want to conduct another thorough screening. Such a screening consists of measuring radon concentrations in all occupied spaces that have one or more faces of their shell in contact with sub-grade soil or a space likely to contain soil gas. At least one occupied space served by each AHU, even if it does not have a shell face in contact with soil or soil gas, should also be screened. Normally the device of choice for the screening measurements will be AC canisters or short-term EICs. In addition to placing these devices in accordance with the criteria discussed above regarding adequate coverage of the building and its physical characteristics and systems, the investigator should ensure that adequate numbers of replicate and blank devices are employed for good quality assurance (QA) and quality control (QC). Specific recommendations can be found in the EPA's protocol document (75), as reviewed in the previous chapter. If the results of these screening measurements confirm that there is indeed a radon problem in the building, then the spaces with the most elevated radon concentrations should be prioritized for closer study. CRMs should be placed in the highest priority spaces, and their results should be analyzed covering one or more complete normal operating cycles of the building, including times of overnight and weekend setbacks of the HVAC system. If unusual weather occurs during this cycle, then these measurements should be repeated until a reliable set of trends is ascertained.

General Information

Access, Security, and Key Personnel

Before, during, or after some of the radon measurements are being taken, some basic information about the building will need to be determined. One of the first issues that will arise will be that of access and/or security. More than likely some level of the subject will arise before any screening devices can be placed, and it would be expeditious to follow those discussions with a complete evaluation of anticipated access needs for the project duration so that the resolution of security problems can be initiated as early as possible to avoid delays that may be costly and inconvenient later in the project. Part of these efforts will undoubtedly begin the process of identifying and making contact with some of the key building personnel that will be essential to the completion of a successful project. Often the building owner may be an absentee individual or a corporation. The role he/she/it plays in the daily operation of the building and what level of communication needs to be established and/or maintained must be determined. Usually the building manager will be the contact person of greatest consequence that the investigator will have to inform, satisfy, and placate. If there are multiple tenants in the building, then their relationships with the project will have to be determined and documented. The expected level of information transmittal that will be required should be understood clearly by all. Issues of space, information, and material security will need to be addressed with all the parties involved. Material security relates to property belonging to both the building personnel and the investigator and others involved with the project.

Most of the contact individuals mentioned so far could be classified loosely as management personnel whose cooperation will be vital especially in the planning and communications of the project. For the actual execution of the measurements, technicians and maintenance staff will be of crucial importance. Individuals who set, control, maintain, adjust, and monitor the HVAC system will be needed for consultations on how the system normally functions and for making various adjustments to the outside air (OA) intakes, exhaust fans, and other system components. It is quite likely that, unless the building has had a recent history of maintenance on its HVAC system, it will be necessary to have a TAB company make a thorough assessment of the system. This may be a company that has worked on the system in the past, or it may be determined that an independent specialist needs to be consulted. While the HVAC system will commonly be the primary building component evaluated in the diagnostic visit, there will almost certainly be the need to communicate and cooperate with maintenance personnel from other trades as well. The plumbing system is typically responsible for many, if not most, of the penetrations of the building shell that enter spaces with high potential of having elevated soil gas levels. Electrical systems, structural features, and several other areas of the building's physical plant may affect indoor radon concentrations or be impacted by a proposed mitigation system; so personnel from these areas should be kept apprised of proposed activities.

Building and Component System Plans

The initial contacts with these various individuals concerning the proposed diagnostic and potential mitigation activities should be accompanied by a request for copies of various sets of the building plans. Specifically, the foundation details may indicate possible soil gas entry routes and will be essential to the planning and installation of any proposed sub-slab mitigation system. The importance of the HVAC system to the diagnosis and possibly the mitigation of the radon problem has been mentioned earlier; so detailed plans will be required of it as well. If the building has had any renovations or modifications that may have affected any of the systems of interest, then current plans that show these changes must be obtained.

Operating Schedule

Once plans for the various building systems have been received, reviewed, and evaluated, further contact with some of the HVAC operation technicians will need to be initiated for the investigator to obtain an understanding of the building's normal operating schedule. A key component to the operating schedule is usually the building's occupancy patterns. It needs to be established if any areas of the building are occupied for extended hours. If the building is used for a multiplicity of functions or by a variety of tenants, then the investigator needs to determine the occupancy patterns for these different functions or groups. If the building has one or more energy management systems, then the person or group who controls it (them) needs to be included in the plans and communications. If any of these complicating conditions exist, it will need to be determined if they will influence when or where access to the HVAC system may be limited.

Applicable Local Codes and Other Information

Because local building codes vary considerably around the country, the investigator needs to know before the planning of the building's mitigation system if there might be any problem with any of the recommendations that might be offered. Often the use of a knowledgeable and respected local contractor may make this step in the process a bit easier. Nevertheless, it pays to know whether a recommended approach may violate a local fire, energy, electrical, or other code before it is installed. Other crucial information to determine as early in the investigative and planning stages as possible is the history of any HVAC or other system modifications, tests, and evaluations. Depending on the age past management of the building, these may be extensive and possibly difficult to locate and document.

Preliminary Site Visit

When as much of this background information about the building as possible has been gathered and reviewed, a preliminary site visit will usually be scheduled. Often some of the items mentioned above will not be available until the site visit, but generally such information that can be learned before the visit has the potential to make the visit more profitable. The investigator knows better who to contact about what subject and where to focus attention for potential trouble spots.

Meeting with Key Personnel

It will be important to meet with as many of the key players as early in the site visit as possible to reinforce lines of communication opened during the planning that has occurred so far. A good understanding of the building and its operation will communicate thoroughness and professionalism to these individuals. This type of exchange increases the potential for them to respond in an accommodating manner. During this meeting it is important to outline the activities to be accomplished during this visit, the places to be investigated, the personnel to be seen, and the approximate schedule to be kept. It is a good idea to use this meeting to educate the participants in some of the principles involved with both the building's problem and possible solutions. Having and communicating some potential mitigation options will help to prepare them for future activities and solicit their input and participation in the project.

Building Tour

After the meeting with the key contact people, the next logical step in this preliminary visit to the building will be a tour of the facility. Although there are two crucial areas to be covered, the whole building is a system; so there may be areas where one would not expect to find that much useful information that may contain clues to the building's problem.

Soil Contact Surfaces

Because indoor radon ultimately comes from some radium source, usually in the soil, the spaces that border soil contact surfaces or other spaces containing open soil "communication" paths are primary locations to be inspected. Literally every such space, whether normally occupied or not, which may include mechanical rooms, closets, elevator shafts, stairwells, wiring or plumbing chases, or utility tunnels, should be examined for potential radon entry routes. Detailed notes should be recorded for the next (diagnostic) visit. Specific features to investigate include plumbing or electrical penetrations, slab edge cracks, shrinkage or settling cracks, construction or control joints, and construction elements that extend below the slab, such as posts (in post and beam construction), some load-bearing or fire walls that require separate footing, and special areas that may require a modified foundation support like elevator shafts or heavy equipment rooms.

Key Components of HVAC System

While the inspection of the spaces will hopefully reveal information about the radon pathways from the source, it is often the driving force and distribution capability of the HVAC system that influences the presence of radon in the occupied spaces. Therefore, the second major area where attention is focused during this visit is the HVAC system. Specific features of the system that should be investigated are the control rooms for each AHU, OA intakes, exhaust fans, and any crossover zones. Items to note about the control rooms are whether they are also soil contact spaces and if they are physically connected with spaces that may have access to soil gas. It is also of interest to discover if they normally operate at positive, negative, or neutral pressure and if this pressure changes when the system status changes. Of course, information such as the type and capacity of each AHU should be verified during the visit. The OA intakes for each AHU should be physically located and the damper mechanisms visually inspected. The location of these intakes sometimes is one of the most crucial parameters that can influence indoor air quality (IAQ). Their proximity to various exhausts could create a number of problems, and objects that restrict free flow of air into them reduces their effectiveness. A number of buildings investigated in the past have had OA control dampers that have been partially or totally inoperative (usually in the closed position) as a result of neglect or intentional misuse. Exhaust fans operating without adequate makeup air create unbalanced pressure differentials that contribute to the infiltration of soil gas into the building. Crossover zones could contribute to distribution of a pollutant in areas where it may not be expected or to unusual pressure balance problems.

Equipment and Instrumentation Requirements

Throughout this preliminary visit, and particularly during the tour, the investigator should be noting equipment and/or instrumentation requirements that will likely be needed during the full diagnostic visit and during the installation and/or operation of possible proposed mitigation strategies. The number and kinds of radon monitors, temperature, relative humidity, and pressure differential measurement devices, flow meters, weather station components (if required), CO_2 monitors, and data loggers should be determined based on the number of potential problem areas in the building and the number of simultaneous measurements to be made. The inspection of soil contact spaces should have indicated the extent of potential radon entry routes, which will be used to estimate how many radon grab samples will be necessary for an adequate characterization. The total number of AHUs and of AHUs serving soil contact spaces will influence how many sets of pressure differential stations will be needed. The number of OA intakes and exhaust fans and the size of the associated ducting will contribute to the number and kinds of flow measuring devices that will be needed. The interaction between the various building components determines whether individual sequential or simultaneous measurements will need to be made. This determination will influence whether one or more mobile data gathering stations or several somewhat permanent stations will be needed. The building layout and access issues will impact if long tubing runs will be required.

Additional Plans and Specifications

If the earlier request for building and component system plans did not yield all of the plans that would be helpful in planning for either the diagnostic visit or a potential installation, then either the meeting of the key personnel or the building tour should be used for discovering who has control of those plans and how to arrange obtaining the copies needed. Even if the plans were in hand, the building tour and subsequent follow-up excursions with the key individuals should be used to verify that the systems installed and used match the specifications listed on the plans. Such a careful review of the systems is especially important in any area where expansion, modification, repair, upgrade, or other changes have occurred.

Additional Radon Measurements in Suspected Entry Locations

Even if the full suite of radon screening measurements occurred before the preliminary site visit as described above, the tour of the building may have revealed spaces that might contain radon entry sites. These may include mechanical rooms, closets, chases, or other areas that would not have been monitored before because they are not normally occupied spaces. It may have been discovered in meeting with some of the people occupying spaces that were measured that something occurred during the measurement period that had potential for skewing the results outside what would normally be expected. In such a case, a retest of that space would be in order.

Necessary Preparations Before the Diagnostic Visit

As described above, some of the purposes of the preliminary site visit were to be able to project equipment and/or instrumentation needs, to confirm the building and systems layout and conditions, and to determine the correct chain of communications and the individuals that will be critical to the decision-making processes. This section will discuss some of the steps that will build on the information gathered during that visit to prepare for the diagnostic visit to follow.

Obtain and Calibrate Primary and Backup Equipment

As discussed in one of the sections describing the preliminary site visit, one of the functions of that visit was to estimate the equipment and/or instrumentation that would be required in the diagnostic visit to follow. This estimation needs to include both primary and backup equipment. The amount of backup depends on many factors, including age of the primary equipment, its reliability history, the harshness of the environment in which it will be used, the availability and reliability of sufficient power sources, and the overall demand on the devices. Once these determinations have been made, that equipment must be gathered and its condition evaluated. It should be tested to ensure that all components work according to specifications, and then plans should be made to have it calibrated, if appropriate. Guidance from the EPA's indoor radon protocols document (75) directs that every CRM should be calibrated before being put into service and after any repairs or modifications. Subsequent calibrations and checks should be done at least once every 12 months, with cross-checks to a recently calibrated instrument at least semiannually. All radon scintillation cells need individual calibration factors. Most of the other equipment to be used should be on similar calibration schedules. For instance, most of the pressure-measuring and flow-measuring devices should be calibrated at least once a year and after any repairs or modifications and checked against one another at least semiannually. Some of the differential pressure instruments have limited ranges. Enough primary and backup instruments in each of the ranges anticipated will need to be collected and checked. In addition to the actual instrumentation, the investigator must ensure that adequate tubing, wiring, and connectors to put together the measurements stations are gathered and stored for the diagnostic trip.

Prepare a Diagnostic Plan

Another purpose of the preliminary site visit was to gather all of the information needed to formulate and develop a viable diagnostic plan for the building. Input to this plan includes the screening radon measurements (including additional ones made or initiated as a result of the preliminary visit), features, specifications, and operating parameters of the HVAC system, and restrictions resulting from workers, tenants, or other individuals. The plan should specify how many spaces, areas, or zones of the building should be tested and the extent and duration of the testing for each one. For instance, a series of measurements may be made from a mobile station in some of the zones of a building, but longer-term continuous measurements over at least one operating cycle of the HVAC system may be needed in other zones known to have a more serious problem. The plan should also outline a realistic schedule of the events to occur during the diagnostic visit. This schedule should allow time for briefing all of the affected personnel, staging of the equipment, and conducting all of the needed measurements with enough flexibility to deal with unexpected problems. A draft of this diagnostic plan should be reviewed by all of the professionals participating in the visit. As soon as a draft diagnostic plan is ready, it should be sent to the appropriate liaison personnel that will be affected at the site. This action should be taken in enough time to receive meaningful feedback from all affected parties. This feedback should be encouraged and requested in the cover that accompanies the plan. As comments are returned, adjust the plan or communicate with the responding personnel so what needs to be done and what the best way to accomplish it is completely understood.

Either as part of the diagnostic plan or as a separate document, a written QA plan should also be formulated if one is not already in place. In this document the measurements that are being planned need to be assessed to determine whether they are critical or ancillary measurements. Critical measurements are generally considered to be those that directly impact the technical objectives of the project. Examples of critical measurements would normally be the measurements of indoor radon concentrations and perhaps the grab samples of soil gas or sub-slab radon concentrations. In some instances pressure differential measurements or flow rates may be classified as critical measurements. Some of the "non-critical," or ancillary measurements would be those that define the environmental conditions in which the critical measurements were taken. For instance, temperatures, relative humidity, weather station data, and other such measurements that may be taken to establish a frame of reference may be classified as ancillary measurements. In addition to a general description of the project, the QA plan will also define the data quality objectives for the critical measurements. Usually these objectives are set or discussed for precision, accuracy (bias), completeness, representativeness, and comparability. Then sampling and analytical procedures, and data reduction methods to ensure that these objectives are obtained are outlined. If they are not, then corrective action procedures for the various critical measurements should be described. Data collection protocols based on these procedures and corresponding data sheets for the recording of the results should be drafted and reviewed by experienced professionals who will be taking the data.

Reach a Formal Contractual Agreement

Although the foundations for this step in the process likely began with the first contact, it is likely that a formal agreement will not have been completed by this point. Both sides probably wanted to have the face-to-face meetings of the preliminary visit and a chance to evaluate the scope of the situation first-hand. At this point in the process, the building personnel will have at least a rough idea from their communications and the draft of the diagnostic visit plan. They may have required some contingency mitigation plans to accompany the diagnostic plan. Items including times and duration of the agreement, extent of work and areas affected, some degree of promised cooperation, and cost estimates should be included in this agreement. In preparing this agreement sufficient time should be allowed for several passes through both sides' contracting offices.

Diagnostic Visit

While the preliminary site visit was primarily an opportunity for face-to-face encounters with the key personnel (typically management level) and an opportunity to gather information about the building and its systems, this visit will focus on the collection of actual data. That typically one-day visit probably involved no more than one or two investigators; a team of knowledgeable technicians will be performing these tests for more than two days to a week. The steps outlined below indicate a projected framework of a few of the specific issues that will arise, but every building and situation may have variants on these themes. The first three mentioned deal with communications and coordination activities, while the last three deal more directly with the actual data collection.

Interview Key Operations Personnel

Whereas most of the time in the first visit was spent interacting with primarily management personnel, this visit will involve largely key operations personnel, those individuals who actually maintain and operate the various building systems. If the preliminary visit did not allow enough time for interviews with the staff that maintains the various building components and the technicians who know best the HVAC and related systems, then time must be taken with them at this point. If the earlier building tour did not allow time or opportunity for a full "hands-on" review of these systems, or if the person(s) who will be conducting those tests was (were) not present at the last visit, then a complete appraisal of these operations will need to occur. Specific information concerning the EMS, if present, including the exact sequence of events in a typical heating and cooling workday and weekend needs to be discussed. A complete review of the fresh air and exhaust systems also needs to be understood. Maintenance schedules of each system should be discussed, as well as any permanent or temporary settings at which the system or any component is customarily placed. For instance, the parameters that determine at what settings the system is run need to be communicated. If the outside temperature gets below or above certain levels, are the OA intakes automatically or manually closed? If so, it is necessary to know if someone is assigned the task of ensuring that they are opened again when the extreme temperature no longer exists.

Coordinate Test Activities

During the planning of this visit (as described earlier) the coordination of the various activities was taken into account as the tentative schedule was developed. Once inside the building, the realities of the situation may throw some of the plans askew. Generally there are two classes of measurements that will be being made that may not conflict with each another unless some of the same people are scheduled to make them. Radon entry determinations would normally not interfere with measurements made on the HVAC system. However, if there was going to be any drilling into slabs or block walls in spaces where the dust might be drawn into the ventilation system, then it would be prudent to do the drilling in those spaces during a time when the HVAC system was shut down. If the HVAC system tests will be done on one or more AHU at a time, then all of the pressure, temperature, relative humidity, CO_2, and other such measurements in spaces affected by that (those) system(s) should be made concurrently. Sufficient time for the space to respond and equilibrate must be allowed before the next change occurs. If such time allowances are not feasible, then the space measurements made while the systems are being changed might be meaningless and should be scheduled when other systems are being tested.

Alert Appropriate Personnel of Related Consequences

Part of the rationale for sending drafts of the proposed diagnostics visit schedule to the building personnel was to alert them of impacts the tests might have on their normal work schedules. It would not be surprising if some supervisors did not get, understand, or plan properly for the information that was disseminated. Therefore, it is a good idea and good for relations to contact all of the personnel managers to inform them of the approximate schedule that the tests may impact their work areas. Impacts may include the times when individuals are in their spaces making measurements or times when the HVAC system may be turned off or is being altered in some way. Indoor air quality or comfort levels may be affected for short periods of time, and this information should be transmitted to the managers as far in advance as possible. If there are some legitimate scheduling conflicts with the proposed plan, it should be altered to accommodate the needs of the occupants as much as is feasible.

Collect the Data

After all of the equipment has been unpacked and checked, all of the applicable people have been notified and any necessary approvals have been obtained, the measurement teams have been assigned and know their parts, the schedule has been approved, and everything else is in order, the data collection may be begun. Each team or investigator should be using the protocols developed and their corresponding standard forms. Such forms should specify the units to be used in each measurement, or these should be clearly marked by each measurement. The conditions specified in the protocols should be precisely followed, and any variation should be duly noted on the data sheets. The investigators should communicate any problems with each another, and if it appears that the proposed schedule will need to be adjusted in any way, this information should be disseminated among the investigating team and to any affected building personnel as soon as it is known.

Conduct the HVAC Evaluation

The HVAC evaluation may be conducted simultaneously with some of the other data collection, or it may occur either before or after the other activities. Unless the building's HVAC system has recently undergone an acceptably thorough evaluation, a TAB company will likely be required to conduct this phase of the test. If there has been a recent test, then a check of some of its findings may be administered by the investigating team. If the results are not comparable, then reasons for the discrepancies should be sought, and/or a follow-up test should be conducted by either the same or a different company. Throughout this process, assistance from the building's maintenance department and HVAC technicians will be necessary both for the information they know about the system and for their familiarity with its operation. Specific data that will be collected for each AHU will include pressure differentials (between that zone and outside, that and adjacent zones, and that zone and the sub-slab space if appropriate), air flow rates through OA intakes, exhausts, supply and return registers, and any crossover dampers or grilles that connect one AHU zone to another.

Conduct Soil/Interface Evaluation
The set of measurements that will probably have the least direct impact on most of the building personnel is the battery of soils' properties determinations. Generally these will consist of measurements of the soil permeability at 0.3 m depths down to 1.2 m. Soil gas radon grab samples are typically taken from the 1.2 m depth, and the counting of those scintillation cells should occur about 4 hr or later after the samples are extracted. If possible, two soil gas permeability and radon concentration probes should be made about 0.3 and 3 to 5 m from each face of the building. This pattern should indicate if the building site has a relatively uniform radon potential or if there may be areas of the site that have elevated soil gas radon concentrations. If the soil permeabilities are considerably less near the foundation, these may be preferential paths of soil gas movement. While these measurements generally do not interfere with any of the inside tests or occupants' normal routines, there is one coordination aspect to be taken into account before the test can be executed meaningfully. If the building's grounds are routinely watered, especially by some type of automatic sprinkling system, the individuals responsible for its operation should have been notified several days before the measurements are to be made to override the system so that the soil is not wet when the measurements are to be made. If significant rainfall has occurred, these measurements may have to be rescheduled.

While the soil radon concentrations measured outside the building indicate something about the source potential, within the building all accessible soil contact floors, walls, and spaces need to be inspected for possible entry routes. For floors and walls that are in direct contact with the soil, settling or shrinkage cracks, contraction or other joints, and any penetration openings are potential entry routes for soil gas radon. Most slab floors will be underlain with some type of vapor barrier; so that random cracks will usually be effectively blocked from transmitting the flow of soil gas. Perimeter cracks and other cracks occurring at changes in slab elevations may not have complete coverage by the vapor barrier; so their potential as entry routes is much greater. Walls may not have continuous vapor barriers adjacent to the soil surface; so any cracks occurring in soil contact walls may allow radon entry. If the soil contact wall has any kind of interior surface covering such as gypsum board, paneling, or other finish that may have a gap between it and the wall, then the entry path into the indoor space may be at any position along that plenum. Any penetration that breaches a soil contact barrier (floor or wall) has a very high probability of being a potential entry route. All such penetrations that are accessible should be investigated and tested for radon entry. All of the above examples of soil gas radon entry routes have dealt with some portion of the building shell in direct contact with a soil volume. However, one of the most potentially difficult situations to diagnose is the case of a plenum, chase, or other space that has some direct or indirect contact with the soil and then the potential for widespread access to some interior inhabited space(s) of the building. Some large buildings have utility tunnels, often containing major components of the air handling duct work, and electrical and/or plumbing chases. Even if there is no exposed soil in these tunnels or chases, there are almost always many and varied penetrations that penetrate their soil contact faces. The presence of vapor barriers may be less likely under these spaces. It is likely that there may have been little to no effort to seal some or any of the penetrations. Therefore elevated radon concentrations may be quite common in such tunnels, and the potential for direct or indirect communications between these spaces and a wide variety of indoor inhabited spaces is quite high and difficult to quantify.

Because time may be limited for a thorough examination of all potential radon entry routes, some type of prioritization will usually be required. Cracks and penetrations that appear to be well sealed by visual inspection may be eliminated from further consideration if there appear to be enough other candidates with higher potential as entry routes to occupy the available time of testing. Pipes, lines, or conduits that penetrate soil contact floors or walls are usually very likely possibilities for soil gas radon entry because the penetration is complete and direct from the soil space to the interior space. The presence or absence of a vapor barrier is immaterial because the pipe or other object penetrates all layers of the total barrier. Slab edge cracks, cracks caused by changes in slab elevations, any sub-grade exterior wall cracks, and settling cracks which exhibit major vertical or horizontal displacement are further candidates for investigation. The situation of plenums, chases, or other spaces with access to the soil volume is usually the most difficult to measure. Access to the specific location of the openings may be limited if they are able to be found. If the opening(s) to the soil cannot be identified, located, or accessed, then the openings from the plenum to the interior space may be the only location left to measure. The sampling of these locations is not always conclusive because they may be too numerous to sample, difficult to determine, and uncertain in their results. Even if one is certain that the measurement is sampling air from the plenum, it may not be a valid measurement of the radon potential of that space. There are times when the plenum may be flushed with air low in radon because of wind pressure, temperature or pressure differentials, or mechanical system interference. If the sampling is made at such a time, then a misleading low reading may be obtained. Different conditions may produce elevated radon concentrations in that space.

While locating all of the highest potential radon entry routes may be a formidable task, ensuring that a valid sampling of the prospective places occurs is often no easier. While individual companies may have certain procedures for sampling potential entry points, a few guidelines will be presented here as examples of issues to be considered. For the purpose of this discussion, radon grab samples using alpha scintillation cells will be used as the sampling method. For sampling suspected entry paths around penetrations, the end of the tube should be fixed as close to the crack being tested as possible. Some type of flexible seal such as rope caulking has been used successfully by several groups. This sealant should be placed all around the penetration crack so that dilute indoor room air will not be pulled through the penetration and into the cell. Care must be taken so that the caulk does not obstruct the opening in the sampling tube. The sampling tube should be as short as practical so that the flushing time for the system is minimal.

The tube leads first to a filter that prevents dust or radon decay products from entering the scintillation cell. The next segment of the tube leads to one pole of the cell, while the other pole is connected to a suction pump. If high radon concentration soil gas is expected to be exhausted from the pump, then an exhaust tube should be run from the pump to the outside or to some space where people will not be breathing the air. At least 10 complete air exchanges should be pulled through the scintillation cell(s) before the pump is turned off. If a penetration has any type of fixture or flashing over or around it, then ensuring that one gets a good sample of the soil gas becomes much more difficult. It the fixture or flashing can be temporarily moved or removed nondestructively, then that should be attempted. If it cannot, then as good a sample as possible may be extracted from around the obstruction, with efforts to seal potential leakage paths. That sample should be identified as suspect.

Very similar procedures should be followed when sampling cracks in the slab or wall. One added complexity that cracks introduce is the fact that they often extend for considerable distances. It is recommended that the sampled crack be sealed for at least 1 m in both directions from the sampling point. If the slab or wall surface can be cleaned well enough and if it is smooth enough, aluminized tape has been found to be an effective seal for these longer stretches. For the case in which there is some type of plenum created by a raised floor or an internal wall covering, the best sampling efforts will still produce a questionable sample. If it is possible to find a sealable opening in the plenum's shell, then similar sealing techniques may be used, with the understanding that the sample may easily not be representative. In the case of larger plenums such as chases or utility tunnels, it is a good idea to try to place a CRM in the space for at least one complete operating cycle (one day minimum) to see if the space may be a conduit for soil gas radon under any of the normal operating conditions of the building such as daytime vs. nighttime, AHs on vs. times of setbacks, etc.

Reporting

Upon completion of the diagnostic visit, the investigator should plan to present at least two levels of reports. First, there should be scheduled time for a compilation of the findings, even if some may be preliminary in nature. Then an exit interview with manager should be held, in which general assessments of the building's systems should be reviewed. If there are areas of immediate concerns, such as pressure imbalances detected in the air handling system (possibly caused by leaks in either supply or return ducts or by dirty filters, duct constrictions, etc.), inadequate OA volumes, insufficient exhaust flows, uneven temperature or ventilation distribution in occupied zones of the building, obvious radon entry routes, or any serious maintenance shortfall that could lead to indoor air quality problems or that could contribute to the indoor radon problem, these should be reported to the appropriate operations personnel as well as the building manager. If any of these conditions have relatively quick and easy solutions, then it should be recommended that they be addressed and a series of retests be scheduled to evaluate their impact on the quality of the building's indoor environment.

After all of the collected data have been analyzed and any reports from assisting entities such as the TAB company have been received, a written report should be prepared and sent to the building owner and other appropriate individuals. This report should contain most of what was discussed in the exit interview with supporting numbers and documentation. Included should be any measurements of components of the building's systems that could be compared with known specifications of performance criteria. If there were any areas where measurements were not able to be made, but were suspected of influencing either the indoor air problem or its solution, then these should be mentioned with recommendations for further investigation. While the design of the mitigation plan will be discussed in the next section, mention should be made of some of the more obvious or likely mitigation possibilities.

Chapter 6
Building Mitigation Alternatives

Design a Mitigation Plan

In the previous chapter it was mentioned that the reporting of the diagnostic visit should have included some of the mitigation options that may be open to the building owner or manager. If the contract calls for a mitigation design plan or if the decision makers request one, then its development will be the next step to take. While the direction that will be taken in developing such a plan will vary from building to building, some of the more common features likely to be incorporated in most such plans will be discussed below. The literature has been reviewed to ascertain the relative effectiveness of these features.

Sealing Entry Routes

If, during the course of the diagnostic visit, major soil gas entry routes were discovered, then the closure of them is a reasonable first action to take. In residential structures, where there are significantly more data available, the radon reductions that can be achieved by closing individual entry routes are highly unpredictable and sometimes nonexistent (76). In large buildings the effectiveness of such actions may be even less certain, but the closure of large and obvious openings is generally a practice of good workmanship and usually not a difficult or expensive action to take. In theory it should reduce the potential for soil gas to enter the building. If the room or area in which the opening is found is ever operated in a depressurized condition (a fan room, a room with a major air return, a room from which air is frequently exhausted, etc.), then the importance of closing the potential entry routes is even greater. If some type of active soil or sub-floor space depressurization system is going to be installed, then these openings may become areas where the system could be short-circuited and its effectiveness diminished. There is a great chance that some potential soil gas entry routes will not be accessible; so excessive efforts to seal minor ones may not be merited.

If the openings to be sealed are large enough to require a major patch, then it is usually a good idea to overlap any existing vapor barrier as much as possible and seal the interface as completely as is feasible. A poured sealant that is resistant to air flow when it sets up may be an acceptable alternative to a sheet barrier. Because a cold joint will be formed where future cracking is very likely to occur, practices should be implemented that will minimize this possibility. Roughing the interface and using products that help the new concrete adhere to the old are two examples. Openings in the form of cracks (whether planned joints or unplanned shrinkage, settling, or stress cracks) can usually be sealed with caulks or pourable sealants. Larger cracks may require a closed cell filler to be inserted before the caulk or sealant is applied. Urethane caulks, seals, and foams are usually recommended to be used for cracks and other small openings because of their adherence, flexibility, and durability. Adequate ventilation during and after application of these sealants is required to protect the health and comfort of workers and later building occupants.

Installing an Active Soil Depressurization (ASD) System

ASD systems have typically been found to the most effective radon mitigation technique in houses where this approach is feasible. Buildings with basements or those built with slabs directly on the grade have similar techniques for installation. These include penetrating the slab at selected locations, excavating a pit under the slab to improve the pressure field extension (PFE), running a pipe out of the space to a location that is out of the building envelope and sufficiently far from any opening that could lead to the radon-laden soil gas reentering the building, placing a fan to exhaust the gas, and activating the system. Soil in contact with basement walls is sometimes depressurized with a technique called block wall suction. Here the space depressurized are the voids in the block walls rather than a pit excavated under the slab, but otherwise the overall strategy is the same. In structures with crawl spaces, vapor barriers may be placed on the soil, and then the space below the barrier may be depressurized [sub-membrane depressurization (SMD)]. Several problems can easily arise when attempting to adapt this popular and generally effective technique to large buildings. First, the slabs or other barriers in large buildings are typically much larger than those found in houses. Larger slabs will require more construction joints that tend to defeat the PFE, and more suction holes may be required for effective pressure fields to be created. Second, the foundations are typically far more complex in larger buildings, with possibly thicker slabs, more footings and other reinforcements, and more impediments to the PFE. Third, the piping runs will be longer, will have more bends, and generally will be much more difficult to route to spaces suitable for fan and exhaust placements.

The advantages of ASD systems, and the reason for their popularity and effectiveness, are that they intercept the radon at its source to the building (the soil), bypass the interior of the structure, and exhaust the soil gas to the outside, where there is less chance for it to be breathed and thus increase someone's risk of an adverse exposure. Moreover, the systems are very reliable and require a minimal amount of active involvement with the building occupant. Normal operation of the building's systems typically has little to no effect on the ASD performance. ASD systems are relatively unobtrusive to the occupants.

In order to be most effective, ASD systems require quality materials and good workmanship in their installation. A suction pit should be excavated (at least 0.03 m^3 [1 ft^3, 7.5 gal., or 29 L]) so that the exposed surface area is large enough to allow sufficient air flow through the soil pores to create an adequate PFE. The suction hole in the slab (or other barrier) needs to be sealed well to ensure that room air is not pulled into the system, thereby reducing the pressure field. The system piping needs to be sturdy, leakproof, and durable. Usually PVC works well. The size of the piping depends on the amount of air flow anticipated in the system (usually estimated by diagnostic measurements and/or a knowledge of the sub-barrier medium). The piping must not have dips or low spots that can collect condensation and therefore reduce or eliminate system air flow. All horizontal runs of piping should have a slope of at least 1/8 in. per foot so that water that condenses in the pipe will drain to the soil. The routing of piping through fire walls will require special attention so that all fire code requirements are met.

Joints in the pipes need to be well sealed, both the ones on the depressurized side of the fan (to improve system effectiveness) and especially the ones on the pressurized side of the fan (to minimize reentry of the radon-rich soil gas). The fans must be sized properly to make certain that they will produce an adequate suction and will have the required capacity for the expected air flow. For instance, if the sub-membrane soil is very tight, a high-suction fan with a relatively low flow rate may be required. On the other hand, a very porous medium will require a fan capable of handling high flows at relatively low pressures. In general, the ASD systems need to be fairly robust, because climatic conditions or building systems may change over time, thereby requiring an increase in the operating parameters of the system to maintain the designed level of effectiveness. With the fans required to be located outside the building envelope, they may be subjected to extreme environments. It must be determined that they are rated for the temperatures and other environmental factors to which they will be exposed. The system exhaust must be directed away from any openings or intakes that lead back into the building air. System components should be plainly marked and labeled to prevent accidental compromises to the system, and some type of visual or audible checks and/or alarms that indicate system performance or faults should be installed and documented.

Optimizing the HVAC System

Buildings are generally designed with specific ventilation goals, and the HVAC systems installed are selected to meet these goals. Installation flaws, system deterioration over time, modifications to system components or the spaces they serve, adjustments to the system or some of its components, and ineffective maintenance activities can all defeat even an optimal HVAC system. Moreover, one or more of these factors will occur in any given building, if enough time elapses. The overall effect of such an event's happening on a building's indoor radon concentrations could be significant. If the HVAC system gets out of balance, then some space will likely be depressurized relative to an adjacent space that may contain high concentrations of soil gas. If there is a pathway (and there usually is), then that soil gas will be transported into the depressurized space. If there is inadequate ventilation in a space, then high concentrations of radon could even diffuse through entry routes and build up in that space. Elevated indoor radon concentrations or other IAQ problems could arise. HVAC systems should be tested and balanced on a regular basis, and if a space seems to have a high potential for allowing radon entry into the building, then there are a few conditions that may be set to minimize this possibility.

Building Pressurization

If a building or an area within a building has known or suspected radon entry openings that are inaccessible for sealing, then pressurizing that space will have the effect of reversing the driving force that pulls radon in. This effect may be accomplished by having a more powerful supply fan than the exhaust fan, introducing OA to the return air plenum, adjusting dampers to allow more supply flow than return flow, or moving air from a low radon-potential (upper floor) space to the high radon-potential (soil contact) space. Spaces that are relatively tight (minimal leakage areas) and small are the best candidates for pressurization. Rooms with leaky envelopes or very large or open spaces are very difficult to pressurize to any extent without very large quantities of air.

Ventilation with OA
High concentrations of radon gas within a room or building may be diluted by ventilating with OA that is at a much lower concentration of radon. Pressurization techniques that use OA to supply the increase in pressure are also ventilating the space. There are limits to the effectiveness of ventilation to control indoor radon concentrations. If the room air is conditioned, then ventilation in excess of ASHRAE Standard 62-1989 may cost a significant energy penalty. Because doubling a room's air changes per hour (ACH) will only halve the indoor concentration of radon or some other contaminant, high initial concentrations cannot normally be efficiently mitigated using this technique. Ventilation with OA in areas of high humidity may introduce more moisture than the air handling system is designed to remove and thus substitute one problem with another.

Adjust the HVAC Setback to Lower Radon Concentrations
Often the HVAC systems in large buildings that are not occupied around the clock will be set so that they are shut down or reduced in operation during periods of no or reduced occupancy as an energy conservation measure. If the building is located in a high radon potential area and there is no ASD system operating, then indoor radon concentrations could (and often do) build significantly over the time periods when the ventilation system is off. If the automatic setback time is adjusted so that the HVAC system is activated earlier, then the pressurization that the system causes or the resulting increased ventilation will tend to lower the radon concentrations before the occupants arrive. Brennan et al. (4) estimated for one set of measurements in a school that the dose delivered to the occupants could be reduced 37% by starting the unit ventilator three hours earlier. Pressurization of the space where the radon entry occurs usually results in a relatively rapid decrease in indoor concentrations, but increased ventilation alone may take quite a while longer to reduce the indoor concentrations, especially if they increased appreciably when the system was off. The relative effectiveness of such an attempt must be weighed against the energy cost of activating the HVAC system for the required longer time.

Material and Performance Requirements
All materials and workmanship used in the installation and modifications of HVAC systems must meet ASHRAE standards and other local or national codes. Diffusers, filters, screens, baffles, and any bends, obstructions, or constrictions in duct work will alter flow rates; so the system must be tested to ensure that any modifications made have not changed flows or pressures from what the design target is. If a system is left in an optimum state once the installers have completed their work, any action by occupants, maintenance workers, or future repair personnel that reduces or blocks air

flow can alter the system performance. Even inaction such as failure to change filters or keep intakes clean can result in reduced flows and pressure imbalances.

Examples of Radon Mitigation Designs for Large Buildings

Table 1 lists large buildings reported in the literature in which some type of radon mitigation was installed. In many of these examples, multiple or mixed systems were part of the overall mitigation strategy. For those instances in which measurements were made for various phases of mitigation installation, separate lines are included in the table. As can be seen from a review of this table, most of the large building data reported comes from research in schools. In addition to building type, the table also lists the problem(s) identified in the building, the mitigation system(s) installed and tested, and the pre- and post-mitigation measurements made and reported. Literature references are listed where more detail may be obtained.

Sealing Effects

As can be seen from analyzing the results listed in Table 1, sealing alone was attempted in five of the schools and one administration building. It produced hardly any change at all in two of the schools and measurable reductions in two schools and the administration building (but not below 4 pCi/L when used alone). In one school room or wing where there was an obvious large entry route identified and sealed, this action resulted in a reduction in indoor radon concentrations from more than 10 to less than 4 pCi/L. These results seem to reinforce the trend mentioned earlier that was found in houses that if a major entry route is able to be identified and sealed, significant reductions in indoor concentrations may be made, but usually these will not be sufficient unless the initial concentrations are not much greater than 10 pCi/L. In one school, the administration building, and a library, sealing was used as a part of the installation of an ASD system with very good results. Two of the schools in Table 1 had utility tunnels suspected of being leaky enough to allow significant quantities of radon gas to enter the AH system. Some of the major leaks were sealed, and in one the walls were painted. When these efforts were combined with adjustments to the HVAC systems, improvements in the indoor radon concentrations occurred. However, in the school with more than 20 pCi/L initial concentrations, the reductions were not enough;

Table 1. Effectiveness of Radon Mitigation Alternatives

Building	Problem	Mitigation	Rn conc. Initial pCi/L	Final	Reference
School A	Floor/wall crack	Sealed crack	40+	Less	(77)
	Room at -15 Pa	Return air fan off	40+	< 2	
School B	Rn w/HVAC off	Continuous HVAC	80	< 4	
	High sub-slab Rn	Basement ASD	80	~ 40	
	PFE < 30 ft	Enlarged pit	40	Less	
	Inadequate PFE	Larger suction fan		Less	
	1st floor radon	1st floor ASD hole	40	10	
	Incomplete PFE	More ASD holes	10	> 4	
	Night Rn>4 pCi/L	More ASD holes	> 4	< 4	
School C	Rooms negative	Two ASD holes	~ 6	< 4	
	Rn in classrooms	Cont. ventilator	20	< 2	
	w/ventilators off	Two ASD holes	20	< 4	
School D	Rn in classrooms	Cont. ventilator	20	< 2	
	w/ventilators off	Four ASD holes	20	< 4	
	Exhaust fans only	One suction hole	17	< 2	
	Separate addition	One suction hole	17	< 2	
School E	Exhaust fans only	2 ASD holes/seal	19	< 4	
Admin.	Elevated radon	Seven ASD loops	24	< 1	(78)
Building	Leaky conduits	Sealed/ASD	17	< 1	
School A1	Floor cracks	Sealed cracks	82	29	(3)
	High sub-slab Rn	Four ASD holes	10	0.8	
School B1	Poor PFE	Twelve ASD holes	28	2	
School A2	Floor/wall cracks	Sealed cracks	12	7	(8)
	Poor PFE	Three ASD holes	7	< 2	
	Floor/wall cracks	Sealed cracks	> 4	> 4	
	Utility tunnel	Depress. tunnel	5	1.2	
School B2	SS return ducts	O/H return ducts	> 4	3.5	
	Ducts open	Two ASD holes	3.5	1.3	
School C2	High Rn C/S	Depressurize C/S	> 4	< 4	
School B3	Returns blocked	Returns cleared	> 4	< 4	(79)
	Slab opening	Foamed opening	> 10	< 4	
School D3	High Rn C/S	Operate AH longer	11	2	
Library	Cracks, no OA	Seal/4 ASD holes	1850	10	(9)

(Continued)

Table 1. Continued

Building	Problem	Mitigation	Rn conc. Initial pCi/L	Final	Reference
School A1	High Rn crawl space	Blocked vents	5	17	(12)
		Pressurization	17	11	
		Depressurization	11	0.6	
		Six SMD holes	5	0.5	
School A4	Sub-slab supply	Open OA	7.1	4.6	(13)
School B4		Operate UVs	> 20	< 2	
		Operate ASD	> 20	< 1	
School D4	Utility tunnel	Pressurize rooms	5.3	3.2	
School A5	Poor PFE	High suction fan	~7	< 3	(15)
School B5	Utility tunnel	Depressurize	5.3	1.8	
	Wing w/o tunnel	One ASD hole	8.2	1.3	
School A6	Low ventilation	Opened windows	14	0.5	(80)
		Pressurize room	38	3	
School A7	Low air exchange	Operate UVs	10.9	5.7	(16,17)
	Low air exchange	UV & exhaust on	~ 19	~ 5	
	Inconsistent	Six ASD holes	~ 19	~ 2	
School B7	Low air exchange	OA 10% open	~ 6	< 3	
		OA 50% open	~ 6	< 1	
		OA 20-50% open	~ 6	< 2	
	Poor PFE	ASD only	~ 6	~ 1	
		UVs/AHUs & ASD	~ 6	< 1	
School A8	Leaky utility tunnel and HVAC not optimum	50% OA	> 20	> 5	(17,18)
		Seal/adjust	> 20	< 15	
		50% OA	< 15	~ 4	
		100% OA	< 15	2.5	
Hospital	High Rn potential	Continuous HVAC	52.7	16.1	(81)
		HVAC & ASD	16.1	< 0.5	
School A9	High Rn potential	Continuous HVAC	~7	< 4	
	HVAC on setback	One ASD hole	~7	< 1	
School A10	Low air exchange	Solar OA ventilator	~ 5	< 2	(82)

(Continued)

Table 1. Continued

Building	Problem	Mitigation	Rn conc. Initial pCi/L	Final	Reference
School A11	High radon	ASD system	~ 20	< 1	(19)
	Assess	Daytime ventilation	~ 8	~ 7	
	ventilation effects	Cont. ventilation	~ 7	< 2	
	Assess	400 cfm	~ 5	< 2	
	ventilation effects	0 cfm	< 1	~10	
		100 cfm	~10	~7	
		200 cfm	~7	~ 5	
	Passive stacks	Open stacks	~8	~ 6	
School C11	Elevated radon	One ASD hole	> 4	~ 1	
	Ventilation effects	Weekend/weekday	~ 3	< 1	
	Winter ASD test	Turn on ASD	1.9	0.9	
School A12	Leaky tunnel	Repair OA intake	7.6	2.9	(17)
School C12	Poor PFE	Two ASD holes	> 4	< 2	
School D12	No ventilation	HRV	> 20	< 2	
	Poor ventilation	Repair/adjust UVs	> 20	less	
	Powered	ASD @ -2.5 in. WC	~ 17	< 4	
	exhausts	ASD @ -4.5 in. WC	~ 17	< 3	
		ASD @ -6.0 in. WC	~ 17	< 2	
School K12	Rn over slab	Install ASD system	34.1	< 2	
	Rn over crawl	Open C/S vents	~ 18	5.1	
	space	Pressurize C/S	~ 18	~ 11	
		Depressurize C/S	~ 18	~ 3	
		SMD	~ 18	~ 0.5	
School L12	Elevated Rn	Operate UVs	> 4	< 4	
School M12	Elevated Rn	Pressurize w/AH	> 4	< 2	
School B13	High Rn potential	11 holes/4 fans	13.4	~ 1	(51)
Financial	Cracks/low OA	Seal/increase OA	~ 10	< 4	(41)
center	0 cfm/person OA	5.5 cfm/person OA	2.6	1.8	
		13.6 cfm/person	2.6	1.2	
		19.0 cfm/person	2.6	1.0	
Special	Minimal OA	~11 cfm/person OA	~ 20	~ 13	
school		~20 cfm/person OA	~ 20	~ 8	

(Continued)

Table 1. Continued

Building	Problem	Mitigation	Rn conc. Initial pCi/L	Final	Reference
Admin. building	Insufficient OA	Max. OA (original)	8.2	7.4	(42)
		Min. OA(corrected)	8.2	7.9	
		3 OA 1st floor fans	8.2	5.6	
	1 OA fan failed	2 OA 1st floor fans	8.2	6.6	
		Replaced OA fan	8.2	4.8	

while in the school with less than 8 pCi/L initial concentrations, they were. In the one office building in which cracks were sealed and the OA was increased, the indoor concentrations reduced from about 10 to less than 4 pCi/L.

ASD Effects

In at least 19 schools and one administration building listed in Table 1, ASD systems were installed to mitigate high indoor radon concentrations. Some of these schools had multiple buildings that were treated with separate ASD systems. While sealing or some other mitigation activities may have been used to enhance these systems, these actions were not emphasized in the referenced reports, or the effects of the ASD systems were evaluated separately from those of the other enhancements. In all 23 of the cases reported, the indoor concentrations were reduced to below 4 pCi/L. In 18 of these cases the final concentrations were reported to be about 2 pCi/L or less. In eight of the 23 buildings reported, the initial concentrations were between 20 and 80 pCi/L. In six others, they were between 10 and 20 pCi/L, and in the others they were less than 10 pCi/L. In five of the buildings reported in which ASD systems were installed, six or more suction holes were installed. In most of these cases, the diagnostic measurements indicated that the PFE was poor, usually due to restricted air flow through tight soils or gravel layers with fines mixed with the gravel or to interior footings or other impediments to air flow under the slabs.

In one of the schools, the ASD stacks were left open, but the fans were deactivated, leaving a passive soil depressurization system in place. This system failed to reduce the indoor concentrations much below 6 pCi/L. In another of the schools the introduction of significant quantities of OA had been found to be an effective radon control measure, but there were great concerns about the system's ability to maintain comfort levels without excess energy consumption during the winter; so the ASD system was installed. When tested under a variety of configurations, the ASD system was found to enhance the HVAC system adjustments to a greater extent than did the HVAC system affect the ASD system's performance. In the hospital reported in Table 1, running the HVAC system continuously reduced the indoor radon concentrations from 53 to 16 pCi/L, and the installation and activation of an ASD system brought the concentrations down to less than 0.5 pCi/L.

Four of the schools in Table 1 had crawl spaces under the buildings that had elevated indoor radon concentrations, and five had utility tunnels. In three of the crawl space schools and two of the tunnel schools, depressurization of the crawl space/tunnel resulted in reducing the indoor concentrations to less than 4 pCi/L. This action was accepted as sufficient by one of the crawl space and both tunnel schools, but in the other two crawl space schools, the facts that the crawl space radon concentrations increased significantly when they were depressurized and that there was a fear that the crawl space temperatures might drop low enough in the winter to damage pipes caused the investigators and school officials to pursue other options. Ventilating and pressurizing the crawl spaces reduced indoor radon concentrations in two of the schools, but only to about 5 and 11 pCi/L. Placing a membrane over the soil surface in one of the crawl spaces also reduced the indoor concentrations to about 5 pCi/L, but installing an ASD system to evacuate the soil gas under the membrane dropped the indoor concentrations to about 0.5 pCi/L in both schools.

HVAC Effects

As mentioned earlier, the HVAC system can have a great effect on indoor radon concentrations. However, thorough diagnostics may be necessary to determine what that effect might be or if it has any effect at all. In most of the large buildings reported in the literature that had such diagnostics performed, some problem with the HVAC system was discovered. A few times they were design problems, such as the HVAC duct work's being located beneath the slab as found in at least two schools mentioned in Table 1. The use of leaky utility tunnels as part of or as the location of the return air system was found in several other schools. Even the use of an overhead return plenum was found to be part of the radon entry problem in a school because the interior load bearing walls that were in direct contact with the high radon concentration soil gas were not capped and thus became the conduit by which radon was pulled into the return air system and then distributed throughout the building. In several other cases the design was adequate, but the installation of the HVAC system was faulty. In at least one school some returns were blocked and in an administration building one of the OA intakes had been covered when the exterior stucco had been applied. But by far the most commonly discovered problems with the HVAC systems were those of incorrect operation or faulty maintenance. In a great number of cases OA louvers or dampers had been closed as part of energy conservation measures or did not operate properly because of lack of knowledge, attention, or maintenance. Quite often the system flows were far below their design specifications either because the proper fan size had not been installed, the fans were no longer operating up to their capacity, ducts or diffusers had been altered, or screens, ducts, or filters were blocked or had not been cleaned or changed. In almost all cases in which they were checked, the HVAC systems were not properly balanced.

Even when such problems as discussed above are found, sometimes the costs of changing the design or correcting the fault are determined to be too great to repair, especially if there have been no complaints about the operation of the system as it is currently installed and functioning. In other circumstances, the corrections to the system may produce no or inadequate changes to the indoor radon concentrations. In one of the schools mentioned above that had its return air ducts located under the slab, the modification of this system to overhead return air ducts did result in reducing the indoor radon concentrations to less than 4 pCi/L. The cost of changing the sub-slab supply ducts in another school was considered to be too great; so another option was attempted. In another school that had some of the returns blocked, the correction of this problem resulted in an adequate reduction in indoor radon concentrations. But in the administration building that had one of the OA intakes completely blocked, its opening only resulted in a reduction in indoor radon from about 8.2 to 7.9 pCi/L. The building owners/operators were not willing to make the additional modifications to bring the system up to its design specifications. The indoor radon concentration in a school that had a faulty OA intake dropped from 7.6 to 2.9 pCi/L after a relatively simple fix. Another school in a cold climate had its UVs repaired or adjusted to allow the specified OA introduction, and this effort seemed to be successful at reducing the indoor concentrations during mild weather. However, when winter came and the thermostats closed the OA intakes as they were designed to do, the UVs proved to be ineffective at mitigating indoor radon concentrations.

Building or Room Pressurization Effects

One of the schools in Table 1 had a room that was operating at a -15-Pa depressurization. When the return air fan was turned off, the severe depressurization was relieved, and the indoor radon concentrations dropped from more than 40 to less than 2 pCi/L. Whether this was a temporary fix or a permanent solution to the problem was not discussed. In another school with a utility tunnel, it was determined, at least in the short run that the sealing of the tunnel was not feasible and/or too costly to attempt, especially with the uncertainty of whether the effort could produce the desired effect. The entry routes from the tunnel to the rooms were largely inaccessible; so the likelihood of being able to seal them reliably was small. The rooms were pressurized to reduce the amount of tunnel air entering the classrooms, and the radon concentrations in the classrooms dropped from 5.3 to 3.2 pCi/L. Another school had one room with indoor concentration of 38 pCi/L and low ventilation. That room was pressurized, and the concentrations dropped to 3 pCi/L. The HVAC system was adjusted in a school that had just slightly elevated indoor radon concentrations so that it was pressurizing the building. The concentrations dropped to less than 2 pCi/L.

From these four illustrations, it seems that building or room pressurization is quite effective if the interior space is tight enough. However, the more leakage the space has, the more air will have to be supplied for pressurization to work as effectively. If the building is located in a climate of extreme temperature or high humidity, then pressurization with outside air can have significant energy costs if large volumes of air are introduced. If sufficient pressurization can be achieved by reducing the exhausted air rather than increasing the supply air, then the energy cost may not be an issue. However, IAQ issues such as CO_2 or humidity buildups may begin to create a problem. Spaces with lower indoor radon concentrations would require less of a pressure change and therefore less makeup air to be conditioned than rooms with high concentrations would have.

Effects of Ventilating with OA

In a large building, it will likely not be possible to detect much pressurization from the introduction of a reasonable quantity of OA to the whole building. However, the addition of low radon concentration OA will still have the effect of reducing indoor concentrations, not only of radon but also of CO_2 and other contaminants that have their source from the closed building. The opening of windows is the simplest means of introducing OA to a space, and one of the schools in Table 1 reported that as a short-term solution, reducing indoor radon concentrations from 14 to 0.5 pCi/L. However, extreme temperatures in most areas of the country would prevent this option as a long-term solution. Usually the introduction of OA in large buildings is accomplished by adjusting the HVAC system. Table 1 lists at least five schools and three other buildings in which the HVAC system was adjusted to increase the OA input. The officials at the school with sub-slab supply ducts mentioned earlier opted to open the OA intakes to reduce the radon concentrations being delivered to their classrooms by the HVAC system. This action did reduce the concentrations from 7.1 to 4.6 pCi/L, which was still above the recommended action level.

Another school with even higher initial concentrations (~19 pCi/L) in one of its rooms had a UV as its ventilation system. Even when this was adjusted to allow the designed OA, the indoor concentrations were not reduced enough. The school officials and investigators used the room exhaust to increase the ventilation in the room, and they were able to reduce the concentrations to about 5 pCi/L. An ASD system was finally installed to bring the concentrations to about 2 pCi/L. In a school with low air exchange rates and about 6 pCi/L indoor radon concentrations, the OA dampers were set at a number of openings and the concentrations were reduced to less than 3 pCi/L with them set at only 10% open. Their normal settings of 20-50% open yielded concentrations of less than 2 pCi/L. In a school with ducts in a leaky utility tunnel and an HVAC system not up to its design specifications, the initial indoor concentrations were measured to be more than 20 pCi/L. Adjusting the HVAC system and sealing and painting the tunnel dropped the indoor concentrations to less than 15 pCi/L; so the OA was adjusted to try to reduce the concentrations further. With the OA set at 50%, the concentrations were reduced to about 4 pCi/L, and it took the dampers to be set at 100% OA to bring the concentrations to 2.5 pCi/L. This amount of OA was considered to be too great for acceptable energy and comfort levels.

The fifth school mentioned above also had initial radon concentrations of about 20 pCi/L. An ASD system was installed and reduced the indoor concentrations to less than 1 pCi/L, but the investigators wanted to assess the effectiveness of using the ventilation system to attempt to mitigate the radon concentrations instead. The normal ventilation practices produced daytime radon concentrations of about 7 pCi/L; so the ventilation system was left on continuously. This operation reduced the concentrations to less than 2 pCi/L but was considered too costly in energy consumption. Therefore a fan was installed to assess how much additional OA would be required to produce comparable results. An additional 400 cubic feet per minute (cfm) (189 L/s) was required to reduce the indoor concentrations to this level.

Another large office building that had been identified for study of the HVAC system effects on elevated indoor radon concentrations (~10 pCi/L) was instrumented to monitor indoor radon concentrations, pressure differentials, infiltration rates, etc. However, in between the initial measurements and the instrumentation, the building owners/managers had sealed some obvious entry routes and adjusted the HVAC system to increase OA inputs. Therefore, the building was averaging only 2.6 pCi/L in a worst case mode of operation. The OA was increased incrementally, and the indoor concentrations decreased in like fashion to 1 pCi/L. A special school facility for physically and mentally challenged children was located on a very high radon potential site and had indoor concentrations of 20 pCi/L. Although it was known that there were numerous entry routes from the soil to the HVAC system (block wall concentrations rose to 600-1000 pCi/L when the AH was in operation), it was decided to determine how increasing ventilation with OA could influence indoor concentrations. Rates of 11 cfm/person OA dropped indoor concentrations to about 13 pCi/L and greatly improved IAQ. Twenty cfm/person resulted in about 8 pCi/L. If the school system chose to seal some of the major entry routes, it was believed that the concentrations could be lowered considerably more. However, the radon source strength at this facility was very high (soil gas radon concentration of ~14,000 pCi/L), and the ambient radon concentrations were sometimes elevated as well.

A large five-story administration building with an open interior design was located on a high radon potential site. The building was found to have inadequate OA and unbalanced pressure differentials in various parts of the building, especially the ground floor. When the maximum OA that the ventilation system could produce in its original state at the start of the investigation was set, the indoor radon concentrations dropped from 8.2 to 7.4 pCi/L. When one of the OA inlets was opened and the system was balanced, the indoor concentrations were 7.9 pCi/L with minimum OA. It was obvious that insufficient OA was being drawn into the system; so temporary OA fans were installed to increase the OA intake in each of the three first floor AHs. This dropped the indoor concentrations to 5.6 pCi/L. One of the fans malfunctioned. With only two OA fans on the first floor, the concentrations averaged 6.6 pCi/L. When a larger fan was installed to replace the failed one, the building average dropped to 4.8 pCi/L. These were temporary installations with flexible ducts which suffered from considerable pressure loss and thus reduced air flows. It was strongly believed that permanent installations with properly sized fans had the potential for reducing the indoor concentrations even further.

All of the cases mentioned since the anecdotal case of opening the windows used the HVAC system to introduce OA for ventilation. Two schools listed in Table 1 used a different means of introducing OA into the areas of elevated radon concentrations. One with greater than 20 pCi/L radon concentration in a space used a heat recovery ventilator to bring in the OA. This system was quite successful in bringing the concentrations to less than 2 pCi/L; however, some of the occupants complained when cold weather came that the supply air was uncomfortably cool. Part of the reason was that its humidity was much lower. A reheat system had to be added, and different diffusers were used to deflect some of the direct drafts. The second school had only 5 pCi/L of radon initially. A solar OA ventilator was used for dilution of the indoor radon concentrations, and it seemed to work quite well with no reported complaints.

Effects of Adjusting the HVAC Operating Schedule
In ten schools and one hospital listed in Table 1, it was noted that the radon concentrations were lower in the day when the HVAC system was operated. This fact usually indicates that the system is introducing OA which mitigates the radon concentrations either by dilution or by some degree of pressurization or a combination of both. In nine of these eleven cases the comparisons were made of the system off to the system on continuously. In seven of these nine cases continuous operation of the system produced acceptable radon reductions; four of them brought concentrations to less than 2 pCi/L. However, in six of these seven successful applications, the management of the buildings chose to install ASD systems, largely because of the cost of running continuously the HVAC systems when the building was not occupied. In the two buildings in which the HVAC system alone could not reduce the indoor concentrations below 4 pCi/L, ASD systems were installed to complete the task. In one school extending the hours of the AH operation reduced the indoor concentrations from 11 to 2 pCi/L, and this practice was accepted as a sufficient mitigation of the problem. The other case reported was merely an observation that the weekday system operation schedule further reduced the indoor concentrations after an ASD system was operating from 3 pCi/L on the weekends to less than 1 pCi/L.

Install the Mitigation System
Most of the specific material requirements for radon mitigation systems were mentioned in the earlier paragraphs that dealt with the various features of the mitigation designs. It is important for the mitigator to ensure that all of the materials (with spares) required for the job are obtained before the mitigation is to begin. General installation procedures for some of the mitigation options were also mentioned earlier. Additional information may be found in the radon mitigation literature (11,76,83,84). Although these were written predominantly with houses and schools in mind, most of the materials and procedures referenced will apply to other large buildings as well. Individual states may have additional guidance published. State departments of health and/or radiation safety or home builder associations, the ten EPA regional offices, and the four EPA Regional Radon Training Centers are other resources of information. It is of utmost importance that all applicable local codes, especially the fire, electrical, and energy codes, are consulted and applied to the installation. If any existing building systems, such as the HVAC, electrical panels, or drainage, have been changed or affected by the installation, the proper documentation needs to be made in all the appropriate manuals, operating procedures, and diagrams. New systems that have been installed (ASD, HRV, etc.) need also to be documented, outlining parts, operations, performance specifications,

maintenance, wiring and piping diagrams, failure indications, and persons to call in case of problems. In addition to the written documentation, verbal instructions should be passed to the facility manager, maintenance personnel, and anyone else who may be required to deal with the installed or modified systems. If there were other changes that might enhance the system but were not installed at this time, this information also needs to be passed to the appropriate individuals or groups.

Follow-up Measurements

If there are time and access to the building after the mitigation system is installed, it is always a good idea to make post-mitigation measurements of the indoor radon concentrations to get an idea of the effectiveness of the system. Usually a continuous monitor is the device of choice, if one is available, because it can show the radon concentrations as a function of time. The monitor(s) should be placed in the location(s) that had the highest concentrations before mitigation. If there is a space remote from the mitigation system or for some other reason there may be a question about the system's effectiveness there, then a measurement device should be placed there as well. After the mitigator is satisfied with the post-mitigation measurements, it is a good practice to encourage the owner/manager to have independent measurements made. It is also a good idea to provide the appropriate party with some long-term integrating monitors or to place them for the building personnel. These devices, when collected after about a year, will give an indication of whether the system continued to perform over all four seasons at the equivalent level that the short-term post-mitigation measurements indicated. There are other post-mitigation measurements that are usually good to conduct. If the HVAC system was altered as part of the mitigation design, then several pressures and flows may be taken to ensure that it is still operating as it should. Differential pressures in spaces over the ASD system may indicate whether too much room air is being drawn into the system. Artificial smoke devices can also indicate places where room air is being lost, where sealing was not effective, or where pipes or fans may not have been sealed properly. All areas of an ASD system should be checked for leaks, especially on the positive pressure side of the fan. Samples should be taken of the exhaust stack to ensure that the expected flow is exiting and to get an idea of the exhaust concentrations of the system. Samples should be taken of any nearby intakes to ensure that there is no or minimal reentry of the exhausted radon gas.

Chapter 7
Recommended Building Design and Operating Practices

The preceding two chapters of this manual dealt primarily with mitigating indoor radon concentrations in existing buildings. This chapter addresses recommended building designs and operating practices in new construction large buildings. While the literature contains a reasonably large number of citations for new construction homes (see references 85 and 86 and their references), there is relatively little published concerning radon resistant large building construction. On April 12, 1993, the EPA published a notice in the Federal Register concerning its "Proposed Model Standards and Techniques for Control of Radon in New Buildings" (87) whose title suggests its applicability to all buildings, but whose content seems to be emphasizing newly constructed homes. Indeed, the EPA later published basically this very document as "Model Standards and Techniques for Control of Radon in New Residential Buildings" as referenced above (86).

In August 1993, Southern Research Institute organized a Large Building Research Workshop for the EPA and the Florida DCA to examine and exchange information on the conduct of current large building indoor air quality/radon studies and to develop recommendations regarding priorities for future research in the large building study being conducted as part of the FRRP (40). In 1994, the EPA published the third printing of "Radon Prevention in the Design and Construction of Schools and Other Large Buildings" with an addendum that addressed increasing PFE by modifying sub-slab walls and improved suction pits (21). The University of Florida conducted "A Research Study of Foundation Designs of Commercial Buildings for Radon Resistant Construction" (43) and an "Evaluation of Radon-Resistant Construction Features for Large Buildings" (44) as parts of the FRRP large building study. Also working within the FRRP, Pugh and Grondzik (46) prepared a "Draft Florida Standard for Radon-Resistant Construction" for the Florida DCA and the U.S. EPA. Southern Research conducted an "Active Soil Depressurization (ASD) Demonstration in a Large Building" (45) for the FRRP.

As described by Pugh and Grondzik (46), there are three general principles of radon control in large buildings: structural barriers, pressure barriers, and building ventilation. Structural barriers refer to continuous vapor barriers, intact slabs or walls that are in direct contact with high radon potential soils, and well-sealed cracks or openings that penetrate the building envelope of conditioned spaces. These barriers reduce or eliminate radon entry routes to the occupied space. These are generally considered to be passive measures to prevent radon entry.

Pressure barriers deal with techniques designed to reduce, eliminate, or reverse the driving force that draws radon from the high concentrations in the soil surrounding a structure into the occupied space of the building. This can be accomplished by increasing the pressure inside the occupied space or by reducing the pressure in the space outside the building envelope that contains the high concentration radon gas. Building or space pressurization is usually accomplished by adjusting the air handling system so that more low radon concentration air is supplied to the space than the amount of exhaust air that is withdrawn. ASD systems, crawl space depressurization systems, and block wall depressurization systems are all examples of techniques that reduce the pressure in the spaces outside the building envelope that contain high concentration radon gas. These systems are usually considered to be active radon mitigation systems.

Building ventilation attempts to reduce the indoor radon concentrations by supplying low radon concentration OA while exhausting higher concentration indoor air. Ventilation is usually accomplished by active means, but passive ventilation may exist anywhere there are openings to areas of either higher or lower radon concentrations. The following paragraphs deal with the installation of systems that deal with one or more of these principles of radon control. The order of their presentation differs from that given above in order to represent the decision making process and the timing required for installation of these systems.

ASD Systems

Both the EPA (87) and Florida (46) standards base their recommendations on radon potential maps that divide the country or state into three zones based on predicted indoor radon measurements. Under either standard, structures that are being built in the zone that has the highest radon potential are recommended to have the most reliable and effective mitigation options installed. Under the EPA standard this is an open vent pipe stack that carries radon from the area beneath the slab or from under the plastic sheeting covering the crawl space floor to an exit point above the roof and electrical wiring to facilitate future installation of both a fan in the vent stack and a system failure warning device, if radon tests indicate that further radon reduction is necessary. The installation of an ASD system for radon mitigation is part of one of the two options open for builders in the highest potential zone under the Florida proposed standard. It is understood in both standards that a specific site may have a higher radon potential than its zone indicates. Therefore, there is nothing to prevent a builder or owner from having an ASD system designed for the structure if there is any question about the possible radon potential of the site.

Advantages of Installing a System During Construction

The cost of incorporating an ASD system into the design of the building is usually quite low, and doing so gives the flexibility of activating the system if elevated indoor radon concentrations are found in the building. Such elevated concentrations may be measured soon after construction or years later when the building's barrier may fail or be compromised. Usually the sub-barrier ventilation system (gravel layer, pits, matting, pipes, etc.) can be designed so that an adequate PFE is reasonably ensured, while problem areas such as interior footings, plumbing, or sub-barrier obstructions can be avoided or accommodated. Incorporating the design of the system into the structure as it is being built can also allow for the exhaust piping to be routed up existing conduits or in walls, closets, or other structural features so that the finished system offers minimal unsightliness or interference with any other building function. Having the vented exhaust piping in place when the roof is installed eliminates the cost of cutting additional holes and reduces the risk of leakage.

The cost of adding an entire system at a later time will usually be quite a bit greater. Cutting or drilling an existing slab or wall requires a greater expenditure of time, trouble, labor, and money than installing the same features as the structure is being built. Just the costs of the displacement of workers in order to accomplish the task and the ensuing cleanup may be significant. The risk of cutting through existing plumbing or electrical systems always exists when slabs or walls are penetrated. Unless the building has a uniform layer of clean aggregate under the slab, a good PFE can never be assumed. The digging of suction pits through a hole in the slab is a time consuming and costly job that results in waste materials that will have to be disposed properly.

The presence of interior footings or other obstructions may require additional suction holes, pits, and piping and all of the associated inconveniences. The placement of these components of the ASD system in an existing building in unobtrusive places that also enable the mitigator to establish an effective PFE is usually a very complicated puzzle that almost always will involve some compromise from an ideal design. The more unobtrusive places usually are more difficult to access, and additional efforts to cover or hide the systems almost always translate to higher costs of installation. Cutting holes in existing roofs always have a potential of introducing leaks, and the very act of doing so may invalidate some warranties.

Elements of an ASD System Design

An ASD system operates effectively when the suction from the exhaust fan is communicated to all areas of the sub-barrier region. Leovic and Craig (21) suggest that the most effective way of assuring that this occurs is to ensure that a continuous layer of clean, course aggregate [preferably crushed aggregate meeting Size #5 specifications as defined in ASTM C-33-90, "Standard Specification for Concrete Aggregates" (88)] is used beneath the barrier. Some of the factors that complicate such a continuous layer are the presence of interior footings or other such obstructions to the layer and fine soil or other material that block the void spaces in the gravel layer.

If interior load bearing walls extend down to the interior footings, then Leovic and Craig (21) suggest at least three possibilities for enhancing the PFE past such obstructions: eliminating these sub-slab walls under interior doors, using sub-slab 'pipe sleeves' to connect areas separated by sub-slab walls (especially useful if the walls are of poured concrete), or, if the walls are constructed of concrete masonry units (CMU), turning every other CMU in the first row of block below the slab on its side to allow soil gas to pass through its core holes. If none of these options seem feasible or desirable, or if the expanse of the slab is so great that the effectiveness of the PFE is in question, then the installation of additional suction points in remote or isolated areas of the slab is always a reliable possibility.

In some areas of the country well graded crushed stone is not readily available, is prohibitively expensive, or is not customarily used beneath barriers. This may often be the case in crawl space structures. In such occurrences the use of ventilation mats, perforated pipes (46), or pits dug into the underlying soil to extend the pressure field is usually recommended. Ventilation mats are relatively easy to install and have been found to be quite effective (44, 45). Most of the specifications for their installation are given by Pugh and Grondzik (46), but a few practical features will be highlighted here. Trenches should be dug for the matting to be placed so that neither the mat nor any other part of the system will be above the grade of the prepared sub-slab soil. As Pugh and Grondzik (46) emphasize, the radon vent pipe should join to the mat in a manner that does not restrict the full airflow capacity of the pipe. This may require enlarging the diameter of the vent pipe at the connection with a suitable flange, or increasing the net free area of the mat by installing additional layers of mat or a layer of gravel beneath the connection point. The trench should be deep enough where the radon vent pipe joins to the mat to accommodate any connecting flange and any additional layers of mat or other substance added under the pipe connection.

These activities ensure that the slab thickness is uniform with the surrounding area over the trench and connections. If the mat or connections sit on top of the soil, there is a possibility that the slab will be thinner there, and such an occurrence increases the possibility of a crack's forming in that location. The trench also increases the soil to mat contact area, which should enhance the PFE. [The use of a trench in a crawl space application where only a soil gas retarder membrane (no slab) will be overlying the mat is not as necessary.] The placement of the mats should occur as close to the time of the placement of the vapor barrier as is feasible within the schedule of the project. The reason for delaying as late as possible is that repeated foot traffic on the mats tends to get soil particles imbedded in the matting, which has distinct possibilities of reducing the subsequent air flows and PFE of the system. Another technique that reduces the introduction of soil particles into the mats is to place a strip of vapor barrier over the mats. This additional barrier should decrease the possibility of leakage should the slab crack (or the upper soil gas retarder membrane be punctured in a crawl space application) over the mat. In all cases the soil gas retarder membrane should be fully sealed to the radon vent pipe.

If the use of perforated pipe is chosen rather than a ventilation mat system, then Pugh and Grondzik (46) detail most of the information needed to ensure a successful installation. Perforated pipe usually have a limited number of holes; so some care must be taken that they are not blocked by compacted soil. One method mentioned to accomplish this state is to place them in gravel or a similar porous medium that provides an adequate air flow connection between the pipe and the sub-slab soil. One of the designers used by Hintenlang and Shanker (44) proposed horizontal gravel filled channels that were laid in a pattern similar to what would be used for a ventilation mat or perforated pipe pressure distribution system. Suction pits similar to those used in the mitigation of existing buildings are another option, but their effectiveness is enhanced by using mat, pipes, or trenches to extend their influence. However, as mentioned above, the use of some type of pit to increase the net free area of the system directly under the exhaust vent pipe location is a recommended procedure.

Structural Barriers

In both standards, the installation of an effective soil gas retarding barrier is recommended for houses in all zones. The draft Florida standard (46) specifically requires that all structures be isolated from the soil by an approved structural barrier and that no crack, joint, duct, pipe, conduit, chase, or other opening in the building foundation or floor be allowed to connect soil gas to a conditioned space or to the interior space of an enclosed space that is adjacent to, or connected to, a conditioned space. This requirement encompasses the recommendations in the EPA's proposed model standards (87) that air handling ducts not be placed in or beneath a concrete slab floor, in other areas below grade and exposed to earth, or in crawl spaces.

Soil Gas Retarding Membrane

The first element of the barrier is a soil gas retarding membrane. A minimum 6 mil (0.006 in. or <0.2 mm) polyethylene or equivalent flexible sheeting material that does not deteriorate and is not porous should be put on top of the prepared base prior to placing the slab or closing the crawl space. The sheeting should be continuous over the entire floor area, and any seams should be overlapped at least 0.3 m (12 in.). At all points where pipes, conduits, reinforcing bars, or other objects pass through the soil gas retarding membrane, the membrane should be fitted to within 100 mm (0.5 in.) of the penetration. When penetrations occur within 0.6 m (24 in.) of a soil depressurization system mat, pipe, trench, or pit, the gap between the penetration object and the membrane should be sealed completely. A second layer of membrane may be used to ensure that the system is adequately covered and that the penetrating object is adequately sealed. All punctures or tears in the membrane should be sealed or covered similarly.

Slabs

To limit the uncontrolled cracking of floor slabs, all concrete slabs spanning exposed soil should be designed, mixed, reinforced, placed, finished, and cured in accordance with the American Concrete Institute publications (89,90). The draft Florida standard (46) gives specific guidance relating to soil compaction, compressive strength of the concrete mixes, mix design, slump and workability, hot weather placing and finishing, and curing. Both standards (46,87) address the necessity of sealing openings through concrete slabs in contact with the soil or soil gas containing areas. Acceptable sealants and their methods of application are also reviewed as well as other specifications for water stops, joint configurations, cracks and other openings, and sumps.

Walls in Contact with Soil Gas

Walls separating below-grade conditioned space from the surrounding earth or from a crawlspace or other enclosed volume in direct contact with the soil should be constructed to minimize the transport of soil gas from the soil into the building. Foundation walls containing cavities that create an air space within the wall should be capped at the first finished floor they intersect. Such caps should provide air flow resistance equal to, or greater than, the adjacent floor. Joints, cracks, or other openings around all penetrations of surfaces of walls in contact with soil gas should be sealed using similar materials and guidance as that given for floors in contact with soil gas. The exterior surfaces of all such walls should be constructed with a continuous water proofing membrane to resist soil gas entry as well as water.

HVAC Systems

Meeting Ventilation Standards

The draft Florida standard (46) specifically requires that all HVAC systems be designed, installed, inspected, and maintained in accordance with ASHRAE 62-1989 (50). The purpose of this ventilation standard is to specify minimum ventilation rates and indoor air quality that will be acceptable to human occupants and are intended to avoid adverse health effects. It specifies alternative procedures to obtain acceptable air quality indoors. The first is a ventilation rate procedure whereby acceptable air quality is achieved by providing ventilation air of the specified quality and quantity to the space. The second is an indoor air quality procedure whereby acceptable air quality is achieved within the space by controlling known and specifiable contaminants. This second procedure could result in a ventilation rate lower than would result from the first procedure, but the presence of a particular source of contamination in the space may result in increased ventilation requirements.

Indoor air quality is a function of many parameters including outdoor air quality, the design of enclosed spaces, the design of the ventilation system, the way this system is operated and maintained, and the presence of sources of contaminants and the strength of such sources. It should be noted that providing the minimum OA requirements for ventilation recommended by ASHRAE 62-1989 may not be sufficient to pressurize a given space. If the total air volume of the exhaust fan is greater than that of the recirculated air and the OA supplied to the space, then that space will be depressurized to some extent.

Preventing Localized Pressure Imbalances

The air distribution system needs to prevent localized pressure imbalances. Both the EPA (87) and Florida (46) standards recommend that HVAC systems supplying spaces that have floors or walls in contact with soil or soil gas be designed and installed to minimize air pressure differences that cause significant flow of soil gas through the structural barrier and into the building. If at all possible, any such space should be maintained at an air pressure greater than the air pressure of the adjacent soil or crawl space. In order to meet this requirement, it may be necessary to increase the OA supply, balance the HVAC system supply/return, seal ducts, install balanced flow exhaust hoods, and/or duct combustion or make up air directly to equipment or appliances that exhaust room air from that space. Additionally, any mechanical equipment room containing a wall or floor in contact with the soil or a crawl space should be pressurized relative to the air pressure of the adjacent soil or crawl space.

Returns designed to serve more than one room should not be located in a space which can be closed from other portions of the building served by the same return without provision for return air passing to the space where the main return is located. Such provisions may include return ducts, transfer grilles, transfer ducts, door undercuts, or other applications. If return ducts are provided to individual rooms, then they should be sized to carry the same air flow as the supply ducts. Continuous operation exhaust fans should not be used in rooms of buildings that are adjacent to spaces containing soil gas, unless the design of the HVAC system can maintain the space at positive pressure with respect to the adjacent soil or crawl space.

Since high humidities can support the growth of pathogenic or allergenic organisms, ASHRAE 62-1989 recommends a relative humidity in habitable spaces to be maintained between 30 and 60% to minimize this growth. In very humid climates, if additional OA is being supplied to a space, then sufficient steps should be taken to ensure that the air-conditioning system is capable of keeping the relative humidity within these ranges. Supply air from one zone should not be provided to portions of the building which are in another zone, if the zones can be separated, unless provisions are made for properly sized return. Supply air should not be provided to remote spaces without provision for an equal amount of OA, in addition to the OA needed to satisfy ASHRAE 62-1989.

Minimizing Soil Gas Entry Routes

All air ducts, plenums, fan enclosures, or fans that are part of a building's HVAC system should be completely isolated from the soil gas by a structural barrier as discussed above. Because return plenums are typically operated in a depressurized condition, they should be constructed with materials which produce a continuous air barrier. Joints should be sealed with durable and approved materials. Construction of the return plenum should be done such that a continuous air barrier completely separates the plenum from adjacent building structures to ensure that these building structures do not become pathways for radon to be drawn into the building. A closet should not be used as a return plenum if the floor or a wall of the closet is in contact with the soil, slab, or crawl space. The return pathway from the return grille to the AH should be a continuous air barrier. If the return grille passes through a wall cavity, that cavity should be sealed in all directions to prevent the flow of soil gases into the return air stream. The junction of supply boxes to supply registers should be airtight and durable.

References

1. Leovic, K. W., A. B. Craig, and D. W. Saum. "Characteristics of schools with elevated radon levels." In *Proceedings: the 1988 Symposium on Radon and Radon Reduction Technology, Volume 1, pp. 10-37 - 10-47,* EPA-600/9-89-006a (NTIS PB89-167480), Denver, CO, 1989.

2. Chmelynski, H. J. *Characteristics of school buildings in the U.S.,* EPA-600/R-93-218 (NTIS PB94-121704), Research Triangle Park, NC: U.S. Environmental Protection Agency, 1993.

3. Craig, A. B., K. W. Leovic, D. B. Harris, and B. E. Pyle. "Radon diagnostics and mitigation in two public schools in Nashville, Tennessee." In *Proceedings: the 1990 International Symposium on Radon and Radon Reduction Technology, Vol. 2, pp. 9-15-9-34, EPA-600/9-91-026b (NTIS PB91-234450),* Atlanta, GA, 1991.

4. Brennan, T., E. J. Fisher, R. Thompson, and W. A. Turner. "Extended heating, ventilating and air conditioning diagnostics in schools in Maine." In *Proceedings: the 1991 International Symposium on Radon and Radon Reduction Technology, Volume 2, pp. 10-37 - 10-55,* EPA-600/9-91-037b (NTIS PB92-115369), Philadelphia, PA, 1991.

5. Hall, S. T. "Mitigation diagnostics: the need for understanding both HVAC and geological effects in schools." In *Proceedings: the 1991 International Symposium on Radon and Radon Reduction Technology, Volume 2, pp. 10-57 - 10-71,* EPA-600/9-91-037b (NTIS PB92-115369), Philadelphia, PA, 1991.

6. Turner, W. A., K. W. Leovic, and A. B. Craig. "The effects of HVAC system design and operation on radon entry into school buildings." In *Proceedings: the 1990 International Symposium on Radon and Radon Reduction Technology,Vol. 2, pp. 9-35-9-44, EPA-600/9-91-026b (NTIS PB91-234450),* Atlanta, GA, 1991.

7. Sinclair, L. D., C. S. Dudney, D. L. Wilson, and R. J. Saultz. "Air pressure distribution and radon entry processes in east Tennessee schools." In *Proceedings: the 1990 International Symposium on Radon and Radon Reduction Technology, Vol. 2, pp-9-61-9-68, EPA-600/9-91-026b (NTIS PB91-234450),* Atlanta, GA, 1991.

8. Leovic, K. W., A. B. Craig, and D. W. Saum. "Radon mitigation experience in difficult-to-mitigate schools." In *Proceedings: the 1990 International Symposium on Radon and Radon Reduction Technology, Vol. 2, pp 9-45-9-60, EPA-600/9-91-026b (NTIS PB91-234450),* Atlanta, GA, 1991.

9. Davidson, J. G. "Commercial mitigation techniques used in remediating a 2200 pCi/L public building." In *Proceedings: the 1990 International Symposium on Radon and Radon Reduction Technology, Vol. 3, pp. 9-19-9-24, EPA-600/9-91-026c (NTIS PB91-234468),* Atlanta, GA, 1991.

10. Fisher, E. J., R. Thompson, T. Brennan, and W. A. Turner. "Diagnostic evaluations of twenty-six U.S. schools - EPA's school evaluation program." In *Proceedings: the 1991 International Symposium on Radon and Radon Reduction Technology, Volume 2, pp. 10-25 - 10-36,* EPA-600/9-91-037b (NTIS PB92-115369), Philadelphia, PA, 1991.

11. Ligman, B. K., and E. J. Fisher. *Reducing radon in schools: a team approach,* EPA-402/R-94-008. Washington, DC: U.S. Environmental Protection Agency, 1994.

12. Pyle, B. E., and K. W. Leovic. "A comparison of radon mitigation options for crawl space school buildings." In *Proceedings: the 1991 International Symposium on Radon and Radon Reduction Technology, Volume 2, pp. 10-73 - 10-84,* EPA-600/9-91-037b (NTIS PB92-115369), Philadelphia, PA, 1991.

13. Leovic, K. W., D. B. Harris, T. M. Dyess, B. E. Pyle, T. B. Borak, and D. W. Saum. "HVAC system complications and controls for radon reduction in school buildings." In *Proceedings: the 1991 International Symposium on Radon and Radon Reduction Technology, Volume 2, pp. 10-85 - 10-104,* EPA-600/9-91-037b (NTIS PB92-115369), Philadelphia, PA, 1991.

14. Parker, J. D. *HVAC systems in the current stock of U.S. K-12 schools,* EPA-600/R-92-125 (NTIS PB 92-218338), Research Triangle Park, NC: U.S. Environmental Protection Agency, 1992.

15. Leovic, K. W., A. B. Craig, D. B. Harris, B. E. Pyle, and K. Webb. "Design and application of active soil depressurization (ASD) systems in school buildings." In *Proceedings: the 1991 International Symposium of Radon and Radon Reduction Technology, Volume 4, pp. P10-3 - P10-14,* EPA-600/9-91-037d (NTIS PB92-115385), Philadelphia, PA, 1991.

16. Pyle, B. E., K. W. Leovic, T. M. Dyess, and D. B. Harris. "Comparison of ASD and HVAC system control in school buildings." In *Proceedings: the 1992 International Symposium on Radon and Radon Reduction Technology, Vol. 2, pp. 10-111-10-134,* EPA-600/R-93-083b (NTIS PB93-196202), Minneapolis, MN, 1993.

17. Pyle, B. E., and A. D. Williamson. *Case studies of radon reduction research in 13 school buildings,* EPA-600/R-93-225 (NTIS PB94-130010), Research Triangle Park, NC: U.S. Environmental Protection Agency, 1993.

18. Leovic, K. W., A. B. Craig, T. M. Dyess, and B. E. Pyle. "Effectiveness of HVAC systems for radon control in schools." In *Proceedings: the 1992 International Symposium on Radon and Radon Reduction Technology, Vol. 2, pp. 10-135-10-150,* EPA-600/R-93-083b (NTIS PB93-196202), Minneapolis, MN, 1993.

19. Saum, D. W. *Case studies of radon reduction research in Maryland, New Jersey, and Virginia schools,* EPA-600/R-93-211 (NTIS PB94-117363), Research Triangle Park, NC: U.S. Environmental Protection Agency, 1993.

20. U.S. Environmental Protection Agency. *Radon measurement in schools - revised edition,* EPA-402/R-92-014 (NTIS PB93-237493), Washington, DC, 1993.

21. Leovic, K. W., and A. B. Craig. *Radon prevention in the design and construction of schools and other large buildings,* EPA-625/R-92-016. Research Triangle Park, NC: U.S. Environmental Protection Agency, 1994.

22. U.S. Environmental Protection Agency. *A standardized EPA protocol for characterizing indoor air quality in large office buildings.* Washington, DC, 1994.

23. Grimsrud, D. T., and D. E. Hadlich. *The transport of indoor air pollutants in large buildings.* St. Paul, MN: University of Minnesota, 1995.

24. Fortmann, R. C. *Survey of protocols for conducting indoor air quality investigations in large buildings,* EPA-600/A-92-226 (NTIS PB93-119865). Research Triangle Park, NC: U.S. Environmental Protection Agency, 1992.

25. McKnight, F. T., W. A. Turner, M. J. Hodgson, and V. R. Highsmith. "Evaluation of "before" and "after" occupant, IAQ, and HVAC parameters in a building remediated because of unacceptable IAQ." In *Proceedings of Indoor Air '93,* 1993.

26. Fortmann, R. C., R. Clayton, V. R. Highsmith, and C. J. Nelson. *The U.S. EPA/ORD large buildings study: Results of the initial survey of randomly selected GSA buildings,* EPA-600/A-94-157 (NTIS PB94-203775). Research Triangle Park, NC: U.S. Environmental Protection Agency, 1994.

27. Persily, A. K., W. S. Dols, and S. J. Nabinger. *Environmental evaluation of the Federal Records Center in Overland Missouri,* NISTIR 4883. Gaithersburg, MD: U.S. Department of Commerce, 1992.

28. Persily, A. K. *Building and HVAC characterization for commercial building indoor air quality investigations,* NISTIR 4979. Gaithersburg, MD: U.S. Department of Commerce, 1993.

29. Persily, A. K. *Manual for ventilation assessment in mechanically ventilated commercial buildings,* NISTIR 5329. Gaithersburg, MD: U.S. Department of Commerce, 1994.

30. Persily, A. K., W. S. Dols, and S. J. Nabinger. Air change effectiveness measurements in two modern office buildings. *Indoor Air 1994* 4: 40-55 (1994).

31. Dols, W. S., A. K. Persily, and S. J. Nabinger. *Indoor air quality commissioning of a new office building,* NISTIR 5586. Gaithersburg, MD: U.S. Department of Commerce, 1995.

32. Fang, J. B., and A. K. Persily. *Computer simulations of airflow and radon transport in four large buildings,* NISTIR 5611. Gaithersburg, MD: U.S. Department of Commerce, 1995.

33. Harley, N. H. Radon levels in a high-rise apartment. *Health Physics* 61 (2): 263-265 (1991).

34. Sherman, M. "Simplified modeling for infiltration and radon entry." In *Proceedings: the 1992 International Symposium on Radon and Radon Reduction Technology, Vol. 1, pp.6-57-6-78, EPA-600/R-93-083a (NTIS PB93-196194),* Minneapolis, MN, 1993.

35. Sherman, M., and D. Dickerhoff. "Monitoring ventilation and air leakage in a low-rise commercial building." In *Proceedings of the 1994 ASME-JSES-MSME International Solar Engineering Conference, pp. 291-297,* San Francisco, CA, 1994.

36. Daisey, J. M., W. J. Fisk, A. T. Hodgson, M. J. Mendell, D. Faulkner, M. Nematollahi, and J. M. Macher. *The California healthy building pilot study: I. Study design and protocol*, NTIS DE92-000658. Berkeley, CA: Lawrence Berkeley Laboratory, 1990.

37. Fisk, W. J., M. J. Mendell, J. M. Daisey, D. Faulkner, A. T. Hodgson, M. Nematollahi, and J. M. Macher. Phase I of the California healthy building study: a summary. *Indoor Air 1993* 3: 246-254 (1993).

38. Fisk, W. J., D. Faulkner, M. J. Mendell, D. Sullivan, A. T. Hodgson, J. M. Macher, M. Boyle, K. Chow, J. M. Daisey, F. J. Offermann, and S. Loiselle. *Phase 2 of the California healthy building study: a status report*, NTIS DE95-004819. Berkeley, CA: Lawrence Berkeley Laboratory, 1994.

39. GEOMET Technologies, Inc. *Assessment of radon in large buildings,* IE-2552. Germantown, MD, 1991.

40. Pyle, B. E., and A. D. Williamson. *Proceedings of the large building research workshop*. Birmingham, AL: Southern Research Institute, 1993.

41. Williamson, A. D., B. E. Pyle, S. E. McDonough, and C. S. Fowler. *Radon diagnostic measurement guidance for large buildings (with appendices),* SRI-ENV-94-850-7722.1.37. Birmingham, AL: Southern Research Institute, 1996.

42. Williamson, A. D., S. E. McDonough, B. E. Pyle, and C. S. Fowler. *Florida large building study: Polk County Administration Building,* SRI-ENV-94-851-7400.93.41.1. Birmingham, AL: Southern Research Institute, 1996.

43. Shanker, A., and D. E. Hintenlang. *A research study of foundation designs of commercial buildings for radon resistant construction*. Gainesville, FL: University of Florida, 1994.

44. Hintenlang, D. E., and A. Shanker. *Evaluation of radon-resistant construction features for large buildings: Interim status report*. Gainesville, FL: University of Florida, 1995.

45. Williamson, A. D., B. E. Pyle, S. E. McDonough, and C. S. Fowler. *Active soil depressurization (ASD) demonstration in a large building,* EPA-600/R-96-147 (NTIS PB97-133805), Research Triangle Park, NC: U. S. Environmental Protection Agency, 1996.

46. Pugh, T. D., and W. T. Grondzik. *Draft Florida standard for radon-resistant construction*. Tallahassee, FL: Florida A & M University, 1994.

47. Saum, D. W., and M. Messing. "Radon diagnosis in a large commercial office building." In *Proceedings: the 1991 International Symposium on Radon and Radon Reduction Technology, Volume 2, pp. 10-105 - 10-115,* EPA-600/9-91-037b (NTIS PB92-115369), Philadelphia, PA, 1991.

48. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. *1992 ASHRAE handbook: heating, ventilating, and air-conditioning systems and equipment*. Atlanta, GA, 1992.

49. Samfield, M. M. *HVAC systems as a tool in controlling indoor air quality: a literature review,* EPA-600/R-95-174 (NTIS PB96-140561), Research Triangle Park, NC: U.S. Environmental Protection Agency, 1995.

50. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. *ASHRAE standard: ventilation for acceptable indoor air quality,* ASHRAE 62-1989. Atlanta, GA, 1989.

51. Pyle, B. E. *Study of radon remediation approaches for "difficult-to-mitigate" schools,* SRI-ENV-94-778-7722.1.35.10. Birmingham, AL: Southern Research Institute, 1994.

52. Lizardos, E. J. Designing HVAC systems for optimum indoor air quality. *Energy Engineering* 90 (4): 6-29 (1993).

53. Sliwinski, B. J., D. Kermath, M. R. Kemme, and M. R. Imel. *Indoor air quality management for operations and maintenance personnel,* TR P-91/42. Champaign, IL: U.S. Army Construction Engineering Research Laboratory, 1991.

54. Meckler, M. Demand-control ventilation strategies for acceptable IAQ. *Heating/Piping/Air Conditioning* (May): 71-74 (1994).

55. Nero, A. V. "Radon and its decay products in indoor air: an overview." In *Radon and Its Decay Products in Indoor Air,* by W. W. Nazaroff and A. V. Nero, eds., New York: John Wiley & Sons, 1988, 1-53.

56. Nazaroff, W. W., B. A. Moed, and R. G. Sextro. "Soil as a source of indoor radon: generation, migration, and entry." In *Radon and Its Decay Products in Indoor Air,* by W. W. Nazaroff and A. V. Nero, eds., New York: John Wiley & Sons, 1988, 57-112.

57. Yokel, F. Y., and A. B. Tanner. *Site exploration for radon source potential,* NISTIR 5135. Gaithersburg, MD: U.S. Department of Commerce, 1992.

58. Nazaroff, W. W., and R. G. Sextro. Technique for measuring the indoor ^{222}Rn source potential of soil. *Environmental Science & Technology* 23 (4): 451-458 (1989).

59. Nielson, K. K., V. C. Rogers, and G. W. Gee. Diffusion of radon through soils, a pore distribution model. *Soil Science Society of America Journal* 48: 482-487 (1984).

60. Rogers, V. C., and K. K. Nielson. *Correlation of Florida soil-gas permeabilities with grain size, moisture, and porosity,* EPA-600/8-91-039 (NTIS PB91-211904), Research Triangle Park, NC: U.S. Environmental Protection Agency, 1991.

61. Rogers, V. C., and K. K. Nielson. Correlations for predicting air permeabilities and ^{222}Rn diffusion coefficients of soils. *Health Physics* 61 (2): 225-230 (1991).

62. Renken, K. J., and T. M. Rosenberg. Laboratory measurements of the transport of radon gas through concrete samples. *Health Physics* 68 (6): 800-808 (1995).

63. Rogers, V. C., and K. K. Nielson. "Data and models for radon transport through concrete." In *Proceedings: the 1992 International Symposium on Radon and Radon Reduction Technology, Vol. 1, pp.6-41-6-56, EPA-600/R-93-083a (NTIS PB93-196194),* Minneapolis, MN, 1992.

64. Rogers, V. C., K. K. Nielson, and R. B. Holt. Radon diffusion coefficients for aged residential concretes. *Health Physics* 68 (6): 832-834 (1995).

65. Nielson, K. K., R. B. Holt, and V. C. Rogers. *Residential radon resistant construction feature selection system,* EPA-600/R-96-005 (NTIS PB96-153473), Research Triangle Park, NC: U.S. Environmental Protection Agency, 1996.

66. Gadd, M. S., and T. B. Borak. *In-situ* determination of the diffusion coefficient of ^{222}Rn in concrete. *Health Physics* 68 (6): 817-822 (1995).

67. Revzan, K. L., W. J. Fisk, and R. G. Sextro. *Modeling radon entry into Florida houses with concrete slabs and concrete-block stem walls,* EPA-600/R-92-119 (NTIS PB92-201128), Research Triangle Park, NC: U.S. Environmental Protection Agency, 1992.

68. Nielson, K. K., and V. C. Rogers. *Feasibility of characterizing concealed openings in the house-soil interface for modeling radon gas entry,* EPA-600/R-95-020 (NTIS PB95-178414). Research Triangle Park, NC: U.S. Environmental Protection Agency, 1992.

69. Nielson, K. K., R. B. Holt, and V. C. Rogers. *Lumped-parameter model analyses of data from the 1992 new house evaluation project - Florida radon research program,* EPA-600/R-95-090 (NTIS PB95-243077). Research Triangle Park, NC: U.S. Environmental Protection Agency, 1995.

70. Gu, L., M. T. Anello, and M. V. Swami. *Effectiveness of large building radon mitigation strategies,* FSEC-CR-861-95. Cocoa, FL: Florida Solar Energy Center, 1995.

71. Hintenlang, D. E., and K. K. Al-Ahmady. "Building dynamics and HVAC system effects on radon transport in Florida houses." In *Proceedings: the 1992 International Symposium on Radon and Radon Reduction Technology, Vol. 1, pp. 6-93-6-106, EPA-600/R-93-083a (NTIS PB93-196194),* Minneapolis, MN, 1993.

72. Nielson, K. K., V. C. Rogers, and R. B. Holt. *Development of a lumped-parameter model of indoor radon concentrations,* EPA-600/R-94-201 (NTIS PB95-142048). Research Triangle Park, NC: U.S. Environmental Protection Agency, 1994.

73. Fowler, C. S., A. D. Williamson, and S. E. McDonough. "Radon entry studies in test cells." In *Proceedings: the 1992 International Symposium on Radon and Radon Reduction Technology, Vol. 1, pp. 6-107-6-122, EPA-600/R-93-083a (NTIS PB93-196194),* Minneapolis, MN, 1993.

74. Williamson, A. D., C. S. Fowler, and S. E. McDonough. *Test cell studies of radon entry,* EPA-600/R-96-010 (NTIS PB96-153549). Research Triangle Park, NC: U.S. Environmental Protection Agency, 1996.

75. U.S. Environmental Protection Agency. *Indoor radon and radon decay product measurement device protocols,* EPA-402/R-92-004. Washington, DC, 1992.

76. Henschel, D. B. *Radon reduction techniques for detached houses: Technical guidance (second edition),* EPA-625/5-87-019 (NTIS PB88-184908). Research Triangle Park, NC: U.S. Environmental Protection Agency, 1988.

77. Saum, D. W., A. B. Craig, and K. W. Leovic. "Radon reduction systems in schools." In *Proceedings: the 1988 Symposium on Radon and Radon Reduction Technology, Volume 1, pp. 10-49 - 10-62,* EPA-600/9-89-006a (NTIS PB89-167480), Denver, CO, 1989.

78. McKelvey, W. F. "Radon remediation of a Pennsylvania school administration building." In *Proceedings: the 1988 Symposium on Radon and Radon Reduction Technology, Volume 2, pp. 4-105 - 4-118,* EPA-600/9-89-006b (NTIS PB89–167498), Denver, CO, 1988.

79. Grodzins, L. "Radon in schools of Massachusetts." In *Proceedings: the 1990 International Symposium on Radon and Radon Reduction Technology, Vol. 2, pp.9-69-9-86, EPA-600/9-91-026b (NTIS PB91-234450),* Atlanta, GA, 1991.

80. Cohilis, P., P. Wouters, and P. Voordecker. "Radon reduction in a Belgian school: from research to application." In *Proceedings: the 1992 International Symposium on Radon and Radon Reduction Technology,* Vol. 2, pp. 10-69-10-82, EPA-600/R-93-083b (NTIS PB93-196202), Minneapolis, MN, 1993.

81. Craig, A. B., D. B. Harris, and K. W. Leovic. "Radon prevention in construction of schools and other large buildings--status of EPA's program." In *Proceedings: of the 1992 International Symposium on Radon and Radon Reduction Technology, Vol. 2, pp. 10-151-10-171,* EPA-600/R-93-083b (NTIS PB93-196202), Minneapolis, MN, 1993.

82. Holmes, M., and K. W. Leovic. "Solar fresh air ventilation for radon reduction." In *Proceedings: the 1992 International Symposium on Radon and Radon Reduction Technology,* Vol. 3, pp. P10-3-P10-18, EPA-600/R-93-083b (NTIS PB93-196210), Minneapolis, MN, 1993.

83. Fowler, C. S., A. D. Williamson, B. E. Pyle, F. E. Belzer, and R. N. Coker. *Design and installation of a home radon reduction system--sub-slab depressurization systems in low-permeability soils,* EPA-625/6-91-029 (NTIS PB93-116234), Research Triangle Park, NC: U.S. Environmental Protection Agency, 1991.

84. U.S. Environmental Protection Agency. *Radon mitigation standards,* EPA-402/R-93-078. Washington, DC, 1994.

85. Clarkin, M., and T. Brennan. *Radon-resistant construction techniques for new residential construction,* EPA-625/2-91-032. Cincinnati, OH: U.S. Environmental Protection Agency, 1991.

86. U.S. Environmental Protection Agency. *Model standards and techniques for control of radon in new residential buildings,* EPA-402/R-94-009. Washington, DC, 1994.

87. U.S. Environmental Protection Agency. Proposed model standards and techniques for control of radon in new buildings. *Federal Register* 58 (68): 19097-19106 (1993).

88. American Society of Testing and Materials. *Standard specification for concrete aggregates,* ASTM C-33-90. Philadelphia, PA, 1990.

89. American Concrete Institute. *Guide for concrete floor and slab construction,* ACI 302.1R. Detroit, MI, 1989.

90. American Concrete Institute. *Building code requirements for reinforced concrete,* ACI 318. Detroit, MI, 1992.

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before compl

1. REPORT NO. EPA-600/R-97-124	2.	3. PB98-123995
4. TITLE AND SUBTITLE Large Building Radon Manual		5. REPORT DATE November 1997
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Charles S. Fowler, Ashley D. Williamson, Bobby E. Pyle, and Susan E. McDonough		8. PERFORMING ORGANIZATION REPORT NO. SRI-ENV-96-463-7722.3.63.10
9. PERFORMING ORGANIZATION NAME AND ADDRESS Southern Research Institute P.O. Box 55305 Birmingham, Alabama 35255-5305		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO. 68-D2-0062, WA 3/63
12. SPONSORING AGENCY NAME AND ADDRESS **EPA, Office of Research and Development Air Pollution Prevention and Control Division Research Triangle Park, NC 27711**		13. TYPE OF REPORT AND PERIOD COVERED Task Final; 3/96-9/96
		14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES APPCD project officer is Marc Y. Menetrez, Mail Drop 54, 919/541-7981.

16. ABSTRACT The report summarizes information on how building systems--especially the heating, ventilating, and air-conditioning (HVAC) system--influence radon entry into large buildings and can be used to mitigate radon problems. It addresses the fundamentals of large building HVAC systems and the entry mechanisms for radon in large buildings. It reviews different types of radon measurements and how to plan a deployment of instruments to obtain desired results. A proposed diagnostic protocol is outlined for investigating a generic large building based on invesigations made in Florida and other places. It summarizes mitigation results reported in previously cited papers and reviews some of the factors to consider in designing, installing, and evaluating the effectiveness of a mitigation system. It concludes with some recommended building design and operating practices for new-construction large buildings. (NOTE: The U.S. EPA has worked since 1992 with the State of Florida to evaluate the impact of HVAC systems on radon entry and mitigation in large buildings.)

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Ventilation	Pollution Control	13B
Radon	Air Conditioning	Stationary Sources	07B
Measurement		Indoor Air	14G
Diagnosis			06E
Buildings			13M
Heating			13H, 13A

18. DISTRIBUTION STATEMENT **Release to Public**	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 94
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)