EPA-600/R-97-051
May 1997

LARGE BUILDINGS CHARACTERISTICS AS RELATED TO RADON RESISTANCE: A LITERATURE REVIEW

by

Ronald A. Venezia, Consultant
1008 Askham Drive
Cary, NC 27511

EPA Purchase Order 4D2010NATA

EPA Project Officer: David C. Sanchez
U.S. Environmental Protection Agency
National Risk Management Research Laboratory
Research Triangle Park, NC 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

This report gives results of a literature review to determine to what useful extent buildings have been characterized and a data base developed in relation to radon entry and mitigation. Prior to 1993 most radon research in large buildings was focused on developing diagnostic and mitigation techniques for school buildings. The belief exists that those techniques developed for school buildings can be used as the basis for developing diagnostic and mitigation techniques for other types of large buildings. The complexity and diversity of large building designs is an added complexity in radon mitigation. Much in the available literature on large building characteristics is directed toward energy conservation and HVAC system design and operation. Data on floor space to footprint ratio, separation of lower level from upper floors, floor bypasses and building foundation design/construction is lacking. The development and application of energy conservation techniques for large buildings have been vigorously pursued since the mid 1970's and have resulted in significant energy savings. Some of these techniques may have contributed to Sick Building Syndrome, Building Related Illness and a general decrease in Indoor Air Quality. Radon diagnostic and mitigation strategies are lacking for large buildings. Studies are in progress to develop, validate and provide guidance for radon diagnostic procedures and radon mitigation strategies applicable to a variety of large buildings commonly found in the State of Florida.

TABLE OF CONTENTS

LIST OF TABLES

METRIC EQUIVALENTS

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

Nonmetric	Multiplied by	Yields Metric
cfm	0.000472	m^3/s
ft	30.5	cm
ft^2	929	cm^2
in.	2.54	cm
in. WC	249	Pa
mil	25.4	μm
mile	1.6	km
pCi/L	37	Bq/m^3

INTRODUCTION

Radon can enter a building in several ways. When there are no pressure differences radon can enter buildings by diffusion-driven transport. Radon can be emitted from well water directly supplied to a building from radium-bearing formations. Building materials can also be a source of radon. However, it is uncommon that any significant radon concentration would occur in large buildings by these mechanisms. Pressure-driven transport occurring when a lower indoor air pressure draws air containing radon from soil or bedrock into the building is the most common way radon enters large buildings. This occurs in many large buildings when they operate at an inside air pressure lower than that of the subsoil. The following four conditions must exist if radon is to enter a building through pressure-driven transport: 1) radon in the subsoil, 2) pathway from the source through the substructure into the building, 3) radon entry points, and 4) a driving force into the building.

Prior to 1993 most radon research in large buildings was focused on developing diagnostic and mitigation techniques for school buildings. The belief exists that those techniques developed for school buildings can be used as the basis for developing diagnostic and mitigation techniques for other types of large buildings (PYL 93). The complexity and diversity of large building designs is an added complexity in radon mitigation. Much in the available literature on large building characteristics is directed toward energy conservation and HVAC system design and operation. The development and application of energy conservation techniques for large buildings have been vigorously pursued since the mid 1970's and have resulted in significant energy savings (CHA 91). Some of these techniques may have contributed to Sick Building Syndrome (SBS), Building Related Illness (BRI) and a general decrease in Indoor Air Quality (IAQ). For example, tighter buildings with limited fresh air intake may result in poor indoor air quality. Efforts to improve IAQ through increased ventilation may create the driving force necessary to transport radon into the building if not properly balanced.

Radon diagnostic and mitigation strategies are needed for large buildings. Studies are in progress to develop, validate and provide guidance for radon diagnostic procedures and radon mitigation strategies applicable to a variety of large buildings commonly found in the State of Florida (MEN 93). To help meet these needs an understanding of existing characteristics of large buildings is necessary.

It is the purpose of this review to identify from the literature the data base for specific large building characteristics that is available regarding radon entry. The primary sources for the review were the Ei Compendix database (235 abstracts) and a database consisting of technical documentation related to indoor air work by EPA's Air Pollution Prevention and Control Division.

SUMMARY OF FINDINGS

Few large building studies have evaluated radon entry and/or mitigation. Most large building characterization studies are related to energy conservation. Environmental studies have centered on IAQ as it relates to Sick Building Syndrome and Building Related Illness. Large building characteristics of importance in relation to radon entry include: heating, ventilating, and air-conditioning (HVAC) system operation and maintenance, building foundation, floor space to footprint ratio, separation of lower level from upper floors, floor bypasses and location. Location has been suggested as the most important characteristic related to radon entry. The literature provided information on HVAC system operation and maintenance mostly in large building characterization studies that were related to energy conversation. There was minimal data on other radon related characteristics. One author concluded that "a significant body of knowledge exists about the infiltration, air leakage, and ventilation characteristics of residential buildings, however, little measured data exists on the quantities for commercial buildings" (SHA94).

Large buildings have diverse characteristics which make it difficult to place them into a manageable number of categories for radon mitigation studies. The DOE characterized nearly 4 million commercial buildings, 1 million of which may be considered to be large, greater than 10,000 ft^2. Average footprint size was available for buildings up to 3 stories. It was not possible to determine from the data the footprint size for buildings taller than 3 stories. This is significant because the building characteristic that is most strongly linked to radon entry is location. The much higher floor space to footprint ratio for large multistory commercial buildings over small buildings may account for the low incidence of high radon levels in large buildings. Ninety-five percent of 80,000 building measurements conducted in Federal buildings were under 4 pCi/L.

Approximately one-half of the commercial buildings (large and small) surveyed in the United States incorporate characteristics that could increase radon entry if the radon source was present and the pathway available. For example, basement substructures may significantly contribute to radon infiltration. The use of National Institute of Standards and Technology parameters for describing building and HVAC characteristics developed in conjunction with IAQ investigations may provide some insight relative to radon entry into large buildings especially as it relates to operation and maintenance of HVAC systems.

An extensive literature search regarding large buildings in Florida concluded that little information relevant to commercial building characteristics in regard to radon was available. Because of Florida's warm climate, high humidity, high water table and the scarcity of sources for aggregate for construction, large buildings in Florida generally differ from those built in other states.

HVAC systems have a significant impact, positive or negative, on radon concentrations in large buildings because of pressurization or depressurization, introduction of dilution air and air distribution.

Well designed and installed HVAC systems can be adjusted to effectively mitigate radon in large buildings. However, a bias towards energy conservation,poor maintenance and inefficient operation of these complex systems can negate any potential for radon mitigation. HVAC system performance characteristics are typically measured in terms of a number of different parameters such as air distribution, ventilation effectiveness, thermal comfort, building pressurization, energy and maintenance costs and outdoor air exchange rates. Experience has shown that a properly designed, well constructed, properly functioning and well-maintained HVAC system will minimize the majority of IAQ and comfort complaints, but may not be sufficient to solve all strong source/open pathway situations.

Energy use is a factor in radon entry as it relates directly to whether or not the building is under positive or negative pressure. Energy use is significantly influenced by: occupancy, building shell, mechanical equipment, and weather. Evaluation of end-use electrical consumption at commercial sites may give some insight to HVAC system operation and maintenance which can be inferred to impact on radon entry. Information may relate to energy conservation, ventilation and building depressurization. Protocols, standards, and codes which guide and regulate the design, installation, commissioning, operation and maintenance of HVAC systems considering both radon infiltration/mitigation and IAQ are needed.

LARGE BUILDING CHARACTERISTICS

The U.S.Department of Commerce, National Institute of Standards and Technology developed a series of parameters for describing building and HVAC characteristics of commercial buildings in conjunction with indoor air quality investigations (PER 93). Characterization included features considered essential to investigations intended to obtain baseline information on a test space within a building as opposed to a detailed research study or an effort to diagnose a specific problem. Check lists were provided for: 1)Whole Building Description (basic features), 2)Test Space Description (detailed information on area being studied which may be the entire building), 3) HVAC System Description (that serves the test space) and 4) HVAC System Performance (selected measurements). Because the parameters were defined to evaluate IAQ, not all information sought is applicable to radon entry. Those check lists relative to building characterization and radon entry are included for reference as Appendix A. The number of investigations using these check lists is not known. However, as a data base is developed it may provide additional insight to radon entry in relation to basic building characteristics and HVAC system operation and maintenance.

Common substructures in buildings include: 1)Basement construction, 2)Slab-on-grade, and 3)Crawl space. Basement construction is common in larger buildings except where a high water table prevails in which case a slab-on-grade substructure would be used. While crawl space substructures are common in some areas for houses they are not generally used for large buildings (GEO 91).

A representative sub-sample of 100 of the National School Radon Survey schools tested by the EPA Office of Radiation and Indoor Air was evaluated in regards to building characteristics (CHM 93). The survey form delineating the type of information requested is included as Appendix B. The report concluded, in part, that, "Commonly encountered structural characteristics include slab-on-grade with a conventional school building design with a single floor. Central HVAC is common, but often combined with other HVAC systems within a single school. Where applicable, central HVAC ductwork is usually located in the ceiling or suspended overhead. Radiant heat, using baseboard or radiator systems, is the second most common HVAC system. Unit ventilators and fan coils also present in many of the schools are most often located along outside walls, but may be in the ceiling, suspended overhead, along an inside wall, or on the roof."

The Department of Energy (DOE 92) characterizes large buildings in a comprehensive manner. The data include number of buildings and square footage. Building characteristics data include the type of building, structure characteristics such as wall and roof material, number of floors, and percent glass. Operating characteristics include: number of normal operating hours, additional operating hours, and months vacant. Energy sources include all fuels used, fuels used for heating, air-conditioning, water heating, cooking, manufacturing and generating electricity. Equipment characteristics include heating, refrigeration, and computers. Conservation characteristics include the use of an energy manager, participation in Demand-Side Management programs and energy audits. While these approaches to characterization may be adequate for energy related considerations, they generally lack the specifics necessary to relate meaningfully to radon entry and mitigation, i.e., identification of radon pathways and the magnitude and direction of driving forces.

The Department of Energy had previously characterized nearly 4 million commercial buildings by several characteristics (DOE 89). Those that are relevant to radon entry into large buildings include: 1)Building Floor space (25% had greater than 10,000 ft^2 and are considered large buildings, 2)Principal Activity (32% were mercantile and service;the next highest category was office at 15%), 3)Weekly Operation Hours (only 8% were open continuously), 4) 80% reported reduced heating and/or cooling during off hours, 5) 54% reported a HVAC energy conservation feature, and 6) 52% reported a HVAC preventive maintenance program. Other characteristics surveyed include HVAC production and distribution equipment. Of the building mix, 64% were one floor with an average footprint of 9,000 ft^2, 24% were two floors with an average footprint of 7,350 ft^2, 8% were three floors with an average footprint of 8,230 ft^2. Only 4% were over three floors. It was not possible to determine an average footprint for those buildings over three floors. Based on these data approximately one-half of the commercial buildings surveyed in the United States incorporate characteristics that could increase radon entry if the radon source was present and the pathway available, i.e., reduced heating and/or cooling during off hours, lack of HVAC preventive maintenance and incorporation of HVAC energy conservation features.

In regards to energy efficiency the State of Florida Energy Efficient Code for Building Construction (FLA 91) classifies commercial buildings by use type as shown in Table 1. This code is climate specific for Florida and information requested as part of the building permit process is generally not applicable to radon infiltration and mitigation.

As part of a study conducted for the Florida Department of Community Affairs, Geomet Technologies Inc. (GEO 91) provided recommendations to the Florida Radon Research Program (FRRP) with regard to radon in Florida's large buildings. As part of their "assembling a complete understanding of the extent of the problem", a literature review of radon in large buildings was conducted. It is included in this report as Appendix C. Their review was "heavily weighted toward research in schools, because there is very little literature on radon research in other types of large buildings." However, they did examine school data for relevance to other types of large buildings. Because of Florida's warm climate, high humidity, high water table and the scarcity of sources for aggregate for construction, which are relevant to the potential radon problem, large buildings in Florida generally differ from those built in other states.

In part Geomet reached the conclusion that "Large buildings have diverse characteristics which make it difficult to characterize them as a group. The building characteristic that is most strongly linked to radon is location (GEO 91). On an individual basis, buildings with residential-type HVAC systems are strongly influenced by the quantity of outside air intake and the overall pressure balance of the system."

Mitigation of large buildings typically involves sealing floors (particularly elevator shafts), pressure balancing the HVAC system and active subslab depressurization. The characteristics of large buildings in Florida that appear to be most significant for potential radon entry are: 1) the predominance of slab-on-grade construction, 2) the low porosity of the material under most slabs, 3)the potential for reverse stack effect pressures, and 4) the increased ventilation due to high outdoor humidity.

The University of Florida conducted research on reference building characteristics and building permit statistics and demographics. Their research report (SHA 94) presents building data as it directly relates to potential radon entry and mitigation. As part of their research they gathered statistical data on new commercial buildings recently constructed in Florida. The research produced a database containing the information from building permits of over 700 commercial buildings throughout Florida which was supplemented by data from over 200 survey questionnaires. A blank survey questionnaire is included as Appendix D. As part of the study a literature search was conducted at the University of Florida Science and Architecture Libraries and the database maintained by the University of Florida Department of Nuclear Engineering Sciences. Other public and professional agencies included Bureau of Census, Statistical Analysis Office, American Society of Civil Engineers, Florida Engineering Society, American Concrete Institute and the American Institute of Architects. The authors concluded that "Little information relevant to commercial building characteristics was obtained from these sources" and "The main findings were that most commercial buildings use monolithic slabs and spread or continuous footings. Commercial buildings are primarily made of steel and one-floor structures are predominant. Slab thickness of 4 inches and concrete strength of 3000 PSI are most commonly used. Typically, a 6 mil polyethylene vapor barrier is placed under the slab to prevent moisture from seeping through the structure. A 97% soil compaction level is commonly specified. The average saw cut spacing is about 20 feet, which is equivalent to a grid area of 400 ft^2. It is relevant to note that a large engineering consulting firm, RS&H, generally recommends a smaller saw cut grid area of about 225 ft^2. Less than 25% of respondents indicated that they use some type of sealant around pipes that penetrate the slab." Table 2 summarizes the database for 216 buildings responding to the survey questionnaire.

Air leakage, the flow of air through the building envelope in response to a fixed pressure, is an important characteristic in regards to radon entry. An evaluation of air leakage in a low-rise commercial building (SHE 94) showed that the air change rate due to leakage alone would satisfy ASHRAE Standard 62, Ventilation for Acceptable Indoor Air Quality, (ASH 89). Natural leakage can provide the driving force necessary for radon entry. The author stated that, "A significant body of knowledge exists about the infiltration, air leakage, and ventilation characteristics of residential buildings, however, little measured data exists on these quantities for commercial buildings." He goes on to rationalize that the lack of data is due in part to the larger technical effort required and the fact that suitable measurement techniques are not readily available.

In an attempt to gain an understanding of the parameters that affect radon in large buildings (SWA 94) testing was conducted in a one-story (16,700 ft^2) building located in Bartow, Florida. Tests were conducted to characterize building airtightness, air flow rates and pressure differentials. A parametric analysis was conducted using the FSEC 3.0 model (FSE 92). In part, it was concluded that, "a key factor that governs radon entry is indoor pressure; ratios of outdoor air to exhaust air have an important bearing on indoor pressure; OA/EA ratios of less that 1, generally cause negative pressures in the building and lead to increased radon levels; even with the building under overall positive pressures, lower ventilation rates tend to produce higher indoor radon levels; optimum ventilation for radon may not necessarily conform to ASHRAE guidelines; building tightness influences pressure differential regimes in a building; in a particular pressure regime (positive or negative) the indoor radon level varies almost linearly with source potential; across the pressure regime (negative to positive) the slope of the linear dependence changes drastically; and both the diffusion and advection mechanisms of radon entry across the slab are important factors that affect indoor radon level." The authors restricted their conclusions, noting that the building tested "may typify only a very narrow range of commercial building-system configurations."

The Bonneville Power Administration has monitored end-use electrical consumption at commercial and residential sites for the End-Use Load and Consumer Assessment Program (ELCAP) since 1983. ELCAP recorded building tenantry and use areas, thermal characteristics, building energy using equipment and central HVAC systems. Operational practices were also surveyed. Relationship to radon entry and/or mitigation was not evaluated. However, a review of the data generated by ELCAP may give some insight to HVAC system operation and maintenance which can be inferred to impact on radon entry through an analysis of effects on ventilation rate.

Atriums have found wide application for various purposes in multistory buildings. They present a complex interface between HVAC systems and building design which can lead to IAQ problems. Kainlauri and Vilmain have observed various kinds of atriums and conducted organized research in several since 1987 (KAI 93). They concluded that IAQ concerns were from sources both within (e.g.,smoking, food) and outside (e.g., pollen,dust)the atrium and that radon is seldom a problem.

Trends in building characteristics were evaluated in relation to energy demand (SUT 90). Regression analysis indicated that energy intensity for fuel oil and natural gas declines with building size. The trend of electricity substituting for other fuels was evident. Ventilation and cooling is done almost exclusively with electricity. Very few buildings cool with gas and almost none with oil. The study also showed that newer buildings are much more likely to be heated with electricity than are older buildings.

HVAC SYSTEMS

An HVAC system has been defined (FLA 91) as "A system that provides either collectively or individually the processes of comfort heating, ventilating, and/or air conditioning within or associated with a building." Some important parameters of large buildings relevant to HVAC operation and control of radon were identified at the Large Building Research Workshop held August 16-17, 1993 in Tampa, Florida (PYL 93). They include:

- Integrity of the slab
- Volume-to-soil footprint ratio
- Separation of lower level from upper floors
- Ventilation and depressurization
- Intake of outside air at higher levels
- Eliminate or seal bypasses such as elevator shafts
- Setback operation of HVAC systems.

HVAC systems have a significant impact on radon concentrations in large buildings because of pressurization or depressurization, introduction of dilution air and air distribution. In large buildings HVAC systems must contend with interrelated factors such as the building envelope, occupants, operation and maintenance. Major types of ventilation systems and their radon potential that are commonly used in large buildings include: 1)Passive systems which rely on stack effect and wind pressure can be found in older large buildings, 2) Exhaust-only systems may be found in older schools, but would not be expected in large commercial buildings, 3)Unit ventilators are in common use in schools and other large buildings, 4)Terminal air blenders, 5)Unitary heat pumps or fan coil units, 6)Heat Recovery Ventilators and 7) Central Station air handlers (GEO 91).

A study of one five story commercial building to determine the effect of HVAC operating cycles, including outdoor air level and exhaust ventilation (PYL 94) concluded that "the OA input into the HVAC systems was insufficient to pressurize the building and prevent radon entry into the building." Parameters evaluated during the study included building pressure, ventilation rate, radon concentration, and radon entry rate.

HVAC systems are being used that are responsive to building use. With adequate air distribution they should provide comfortable temperatures and acceptable indoor air quality. At times however, intake air, introduced by HVAC system operation directly or indirectly due to negative building pressure, can introduce pollutants such as radon and carbon monoxide to the indoor environment. It is important that HVAC systems be designed to be energy efficient and provide good indoor air quality, i.e., limit the outdoor air supply to conserve energy while providing sufficient outdoor air to prevent IAQ problems.

Poor IAQ and high radon concentrations are not necessarily synonymous. For example, building pressurization to eliminate the driving force into the building, and hence deter radon infiltration, may cause pollutants generated within the building to increase in concentration and hence decrease the IAQ. Higher exhaust ventilation rates in unbalanced systems can increase the driving force and hence radon entry if it is present in the subsoil. Clearly a balance is needed between in/exfiltration that considers both IAQ and radon entry.

The primary focus of a study to develop radon diagnostic procedures and mitigation strategies applicable to large non-residential buildings in Florida (MEN 93) was to determine the effect of the HVAC systems of a large building in influencing the transport, entry and minimization of indoor radon concentrations. Two buildings were studied. "Both showed signs of aberrant HVAC design, operation and maintenance which presumable adversely affected indoor radon as well as other indoor air quality variables." It was recommended that, "design and construction should concentrate on elimination of major soil gas pathways such as hollow walls, unsealed utility penetrations and the like; HVAC system design should include strategies designed to minimize depressurized zones adjacent to the soil," and the authors concluded that, "while increased supply ventilation is generally helpful for radon control, it is clearly not the most cost-effective solution or prevention tool once the requirements of occupant comfort and general indoor air quality have been met."

Experience in Montgomery County, MD, has shown that a properly designed, well constructed, properly functioning and well-maintained HVAC system will minimize the majority of IAQ and comfort complaints by building occupants (DAM 93). Particular attention should be given to the design of the air distribution system and the fresh air intake scheme. Poor air distribution can become the major source of IAQ problems.

It has been concluded that "One of the most significant factors contributing to elevated levels of radon in schools and influencing mitigation approach is the design and operation of the HVAC system. The complexities of large building HVAC systems present problems not previously encountered in house mitigation" (LEO 89).

Design and operation of HVAC systems are a factor in poor IAQ. A study conducted on a four story modern office building with a history of high occupant complaint rates (MCK 93) showed: delivery rates to the upper levels was low; basement contaminated air transported to upper levels; poor air distribution on each floor; considerable re-entrainment of exhaust at the air intake and evidence of past drip pan microbial amplification. This illustrates potential problems that may be associated with basement substructures. Some designers recommend demand-controlled ventilation to save energy. This approach can enhance radon entry.

One of the highest Research Priorities for Indoor Air Quality identified at the Ventilation and IAQ workshop (PRI 95) was to "develop checklists, protocols, standards and codes which guide and regulate the design, installation, commissioning, operation and maintenance of HVAC systems." These priorities apply equally well to radon infiltration and mitigation.

HVAC systems can be adjusted to effectively mitigate radon in large buildings. However, a bias towards energy conservation, poor maintenance and inefficient operation of a complex system can negate any potential for radon mitigation (SAU 93).

HVAC system control/operation are dominated by internal heat loads in large buildings, whereas smaller buildings are dominated by the envelope. The stack effect also has a significant effect on HVAC operation in large buildings.

The U.S.Department of Energy (DOE 91) recommends commercial sector energy conservation measures prepared in response to the need to conserve energy in the commercial sector (See Appendix E). The Bonneville Power Administration has also incorporated ASHRAE Standard 62-89, "Ventilation for Acceptable Indoor Air Quality" (ASH 89) into its commercial environmental requirements for mechanically ventilated buildings. Some conservation measures will directly affect radon infiltration. For example, the sealing of vertical shafts to reduce in/exfiltration will reduce the "stack effect" and help minimize radon infiltration while installation of an energy management system can at times lead to building depressurization and hence increase soil gas infiltration. All conservation measures would not be used in any given building. Various strategies and equipment should complement each other, not only for energy conservation but also for radon entry minimization and acceptable indoor air quality.

Diurnal occupancy cycles can affect radon entry and concentration in large buildings. For example, operating the HVAC system at a reduced level or turning it off at night may increase radon concentrations as the building depressurizes. However, all large buildings do not operate on the same diurnal cycle. Hotels may be the opposite of office buildings and hospitals may not significantly vary HVAC operation.

In a study of office and college buildings during daytime in the Pittsburgh area (COH 84) it was found that:

1. Average daytime commercial building radon levels may be an order of magnitude lower than home levels in the same area.

2. Colleges and universities seem to have higher daytime radon levels than commercial buildings.

3. Age of buildings did not seem to be an important factor in regard to radon levels.

4. There was little indication that radon levels in these buildings were higher in the winter than in the summer.

The impact of ASHRAE 62-1989 on building energy usage versus its impact on indoor air quality was analyzed (TAY 93). The scope of the study was limited to SBS as related to ventilation system operation and design. One hundred research studies were reviewed (25 were referenced, see Appendix F) and "in only two was the ventilation rate found to have a statistically significant correlation with SBS symptoms or even with the concentration of pollutants believed to be the cause of SBS." It was concluded that "much of the evidence to support the claim that increasing outside air improved IAQ is anecdotal. In some case studies, SBS symptoms were lessened by 'improved' ventilation, but the actual amount of outside air being distributed before and after the 'improvements' is seldom measured and documented. There is little evidence that 15 cfm/person is any better at maintaining high indoor air quality than 5 cfm/person." Eleven studies were cited as evidence that increasing outdoor air intake will have little impact on IAQ. The author concluded that "clearly there is some minimum ventilation rate required to dilute pollutants generated within buildings. But there do not appear to be any definitive studies that indicate what the minimum rate should be."

Ventilation rates have a direct effect on energy costs. The energy implication of ASHRAE 62-1989 was evaluated (STE 90). It was concluded that the standard had significant energy cost impacts and that the minimum outdoor air requirement will meet resistance with building contractors as being excessive. An evaluation of the impact of ventilation rate on IAQ and comfort (NAG 90) concluded that "although there was a two fold difference in mechanical air exchange rates for the two weeks of monitoring, measured air exchange rates (infiltra-tion/ventilation components) differed by only 25 to 30 percent."

Control of indoor air pollutants requires identification of pollutants and an understanding of emission mechanisms and rates. Microorganisms, volatile organic compounds, nitrogen dioxide, carbon monoxide, carbon dioxide, radon, and particulates have been measured in the indoor environment as well as comfort related indicators such as temperature, humidity, and odor. Physical symptoms have also been evaluated. However, while some studies show relationships between symptoms and lowering or raising the ventilation rate, there is an absence of data to correlate symptoms and pollutant levels with ventilation rates (MEZ 90).

The Indoor Radon Abatement Act of 1988 (USC 88) required all Federal agencies to test their buildings. Eighty-five percent of the 80,000 buildings measurements were under 2 pCi/L and 95% were under 4 pCi/L. One reason for the low incidence of high radon levels in large buildings may be that the floor space to footprint ratio is much higher for large multistory commercial buildings than it is for small buildings such as residences.

Pollutant concentrations and ventilation rates were measured in

38 commercial buildings in the Pacific Northwest during 1984 and 1985 (TUR 87). Only one building was found with a significant radon concentration, 7.8 pCi/L. In this instance the HVAC system's intake air came through a basement with an open soil floor and from a network of underground service tunnels. The study concluded that:

- In areas with high radon potential, radon problems might be expected in buildings with foundations allowing exposed soil and with HVAC systems that depressurize the foundation
- Service tunnels connected to buildings may allow entry of radon
- Ventilation rates varied widely in the buildings and the operators often did not understand the operation of the HVAC systems
- The mean radon measurement was 0.5 pCi/L similar to outdoor levels
- No indication of radon transport to upper floors was noticed in high-rise buildings
- Although ventilation rates were sometimes quite low, few air pollution problems were traced to this
- The correlation between pollutant concentrations and ventilation rates was weak, suggesting, as seen in past studies, that pollution is due primarily to the presence of strong pollutant sources and not ventilation rates.

Evidence of preferential pollutant flow from the lower levels of a seven-story building to the upper levels was shown in a Federal Office Building Study (GRO 89). Significant results include large variations in ventilation rates over the course of the year, very large uncontrolled air leakage, and transport of carbon monoxide from the garage and radon up the vertical shafts to the upper stories. Flows in the building shell and its HVAC systems are not well understood.

In an evaluation of the effectiveness of air change measurements (PER 94) noted that "the ability to evaluate the existence of short-circuiting in the field and to assess the performance of innovative approaches to air distribution is limited by a lack of validated measurement procedures to assess ventilation effectiveness."

REFERENCES

ASH 89 ASHRAE, Ventilation for Acceptable Indoor Air Quality. Atlanta, GA: The American Society for Heating, Refrigerating and Air-Conditioning Engineers, Inc., Standard ANSI/ASHRAE 62-1989, 1989.

CHA 91 Chaddock, J.B. and Todorovic, B. (Ed.) *"Heat and Mass Transfer in Building Materials and Structures,"* Hemisphere Publishing Corp. New York, NY, 1991.

CHM 93 Chmelynski, H.J., *"Characteristics of School Buildings in the U.S.,* U.S.Environmental Protection Agency report. EPA-600/R-93-218 (NTIS PB94-121704), November 1993.

COH 84 Cohen, B., et al., *"Radon Concentrations Inside Public and Commercial Buildings in the Pittsburgh Area,"* Health Physics, Vol 47, No 3, pp 399-405, September 1984.

DAM 93 Damiani, A.S. and Tseng, P., *"IAQ Strategies for Facilities Engineers,"* AIPE Facilities, Vol 20, No 5, pp 11-13, September-October 1993.

DOE 89 *"Commercial Buildings Consumption and Expenditures 1986,"* Energy Information Administration, DOE/EIA-0318 (86), Washington, DC, May 1989.

DOE 91 *"Environmental Assessment - Approaches for Acquiring Energy Savings in Commercial Sector Buildings,"* DOE/Bonneville Power Administration, DOE/EA--0513, Washington, DC, September 1991.

DOE 92 *"Commercial Buildings Energy Consumption Survey: Building Characteristics 1992."* Data File (for microcomputers), Department of Energy, Energy Information Administration, Washington, DC, 4 diskettes, 1992.

FLA 91 *"Energy Efficient Code for Building Construction 1991,"* Florida Department of Community Affairs, Tallahassee, FL, 1991.

FSE 92 FSEC, Florida Software for Environment Computation - User's Manual, Version 3.0. Cape Canaveral, FL: Florida Solar Energy Center Report FSEC-GP-47-92, 1992.

GEO 91 *"Assessment of Radon in Large Buildings,"* Germantown, MD; GEOMET Technologies, Inc., report IE-2552, September 1991.

GRO 89 Grot, R.A. and Persily, A.K., *"Environmental Evaluation of the Portland East Federal Office Building Pre-occupancy and Early Occupancy Results,"* National Institute of Standards and Technology, NIST 89-4066, Gaithersburg, MD, April 1989.

KAI 93 Kainlauri, E.O. and Vilmain, M.P., *"Atrium Design Criteria Resulting from Comparative Studies of Atriums with Different Orientation and Complex Interfacing of Environment Systems,"* ASHRAE Transactions, Vol 99, Pt 1, 1993. Published by ASHRAE, Atlanta, GA, pp 1061-1069, 1993.

LEO 89 Leovic, K.W., Craig, A.B. and Saum, D., *"Characteristics of Schools with Elevated Radon Levels,"* In: Proceedings: The 1988 Symposium on Radon and Radon Reduction Technology, Volume 1, EPA-600/9-89-006a (NTIS PB89-167480), pp 10-37 thru 10-47, March 1989.

MCK 93 McKnight, F.T., et al., *"Evaluation of 'Before' and 'After' Occupant, IAQ, and HVAC Parameters in a Building Remediated Because of Unacceptable IAQ,"* In: Proceedings of Indoor Air '93, Vol.6.

MEN 93 Menetrez, M.Y. and Kulp, R., *"Radon Diagnostic Measurement Guidance for Large Buildings,"* U.S.Environmental Protection Agency, Research Triangle Park, NC (in press) 1997.

MEZ 90 Menzies, R.I., et al., "Sick Building Syndrome: the Effect of Changes in Ventilation Rates on Symptom Prevalence; the Evaluation of a Double Blind Approach." In: Indoor Air '90, Proceedings of the 5th International Conference on Indoor Air Quality and Climate, Volume 1, pp 519-524, 1990.

NAG 90 Nagda, N., et al., *"Impact of Increased Ventilation Rates on Office Building Air Quality,"* Indoor Air '90: Proceedings of the 5th International Conference on Indoor Air Quality and Climate, Vol 4, pp 281-286. 1990.

PER 93 Persily, A.K., *"Building and HVAC Characterization for Commercial Building - Indoor Air Quality Investigations,"* National Institute of Standards and Technology, NISTIR 4979, Gaithersburg, MD, May 1993.

PER 94 Persily, A., et al., *"Air Change Effectiveness Measurement in Two Modern Office Buildings,"* Indoor Air '94, Vol 4, pp 40-55. 1994.

PRI 95 Priest, J.B., et al., "Ventilation Technology Systems Analysis," U. S. Environmental Protection Agency report EPA-600/R-95-065 (NTIS PB95-212767), May 1995.

PYL 93 Pyle, B.E. and Williamson, A.D., *"Review of FRRP Large Building Research."* In Proceedings: The Large Building Research Workshop, Southern Research Institute, Birmingham, AL, August 1993.

PYL 94 Pyle, B.E., et al.,"Florida Large Building Study Polk County Administration Building," Southern Research Institute, SRI-ENV-94-851-7400.93.41.1, Birmingham, AL (in press) 1997.

SAU 93 Saum, D.W., *"Case Studies of Radon Reduction Research in Maryland, New Jersey and Virginia Schools,"* U. S. Environmental Protection Agency report EPA-600/R-93-211 (NTIS PB94-117363), November 1993.

SHA 94 Shanker, A. and Hintenlang, D., *"A Research Study of Foundation Designs of Commercial Buildings for Radon Resistant Construction,"* University of Florida, Gainesville, FL (in press) 1997.

SHE 94 Sherman, M. and Dickerhoff, D.,*"Monitoring Ventilation and Leakage in a Low-Rise Commercial Building,"* Solar Engineering, ASME-JSES-JSME International Solar Energy Conference, 1994, ASME, New York, NY, pp 291-297.

STE 90 Steele, T. and Brown, M., *"Energy and Cost Implications of ASHRAE Standard 62-1989,"* Bonneville Power Administration, Washington, DC, May 1990.

SUT 90 Sutherland, R.J.,*"Demand for Energy in Commercial Buildings,"* Argonne National Laboratory, Energy and Systems Policy, Vol 14, No 4, pp 237-256, 1990.

SWA 94 Swami, M.V., et al., "Analysis of the Polk Life and Learning Center (PLLC), Draft Task-Final Report", Florida Solar Energy Center, FSEC-CR-739-94, Cape Canaveral, FL (in press) 1997.

TAY 93 Taylor, S., *"ANSI/ASHRAE 62-1989: Energy vs. IAQ Impact* Energy Impacts Subcommittee Report for June 1992 Meeting," Atlanta, GA. 1993.

TUR 87 Turk, B., et al., *"Indoor Air Quality and Ventilation Measurements in 38 Pacific Northwest Commercial Buildings,"* LBL 22315, Lawrence Berkeley Laboratory, Berkeley, CA, December 1987.

USC 88 15 U.S.C. 2601, Title III, Indoor Radon Abatement Act of 1988, Washington, DC. 1988.

Table 1. Commercial Building Characteristics

ZA Place of Assembly, Auditorium
ZB Bank or Savings and Loan
ZC Clinic
ZD Drug Store
ZE Schools
 1. Classroom
 2. Gymnasium (conditioned)
 3. Office (same as ZO)
 4. Laboratory
 5. Auditorium
 6. Dining
 7. Kitchen
ZG Supermarkets
ZH Hotel, Motel
ZL Library
ZM Mercantile
 1. Strip Shop (Stores smaller than 15,000 ft^2)
 2. Department Store (Stores larger than 15,000 ft^2)
 3. Mall (conditioned common areas of malls)
 4. Storage (conditioned common areas of malls)
ZN Nursing Home
ZO Office Building
ZP Hospitals
 1. Autopsy/Morgue
 2. Central Supply
 3. Operating Suite
 4. Emergency Department
 5. Intensive Care Unit
 6. Laboratory
 7. General Patient Care
 8. Dining
 9. Kitchen
 10. Office (Same as ZO)
ZR Restaurants
ZS Storage, Warehouse (conditioned)
ZT Theater
ZV Air Terminal
 1. Commercial Area
 2. Concourse
 3. Storage (conditioned) (Same as ZS)
 4. Dining
 5. Kitchen
ZW Place of Worship
ZX Bowling Alley
ZZ Special: Any building not listed above.

Table 2. Building Database Summary (SHA 94)				
Building Characteristics *	**ALL BLDGS**	**ONE STORY**	**> ONE STORY**	**WIDE BLDGS**
Avg. Number of Floors	1.7	1	3.3	1.5
Total Area (square ft)	33800	24000	54000	80800
Footprint Area (square ft)	21200	24000	14500	64600
Avg Bldg Length (ft)	174	176	168	352
Avg Bldg Width (ft)	123	136	86	183
Building Height (ft)	29	21	47	35
First Floor Height (ft)	15	16	14	18
Slab Thickness (in)	4.88	4.78	5.12	5.12
Slab Strength (PSI)	3213	3149	3357	3360
Barrier Thickness (mil)	5.9	5.9	5.9	6
Compaction Rate (%)	96.7	96.7	96.7	96.9
Air Handler/Floor	5.5	5.3	5.9	10.6
Saw Cut Spacing (ft)	21	21	19	21
NUMBER OF BUILDINGS	216	151	65	45

(*) for readers more familiar with metric units: 1 ft = 0.30m, 1 ft^2 = 0.093m^2, 1 in. = 2.54cm, 1 mil = 25.4 μm, and 1 psi = 6.89 kPa.

APPENDIX A

National Institute of Standards and Technology Check Lists (PER 93)

FORM A-1: BUILDING DESCRIPTION

Only one copy of Form A-1 is required for each building.

1 Building Age: ____________ 2 Floor Area: ____________ m^2 or ft^2

Number of Floors
3 Below Grade: ____________ 4 Above Grade: ____________

Space Use

		Floors	Floor Area (%)
5	Office	______	______
6	Retail	______	______
7	Public Assembly	______	______
8	Laboratory	______	______
9	Storage	______	______
10	Food Services	______	______
11	Employee-Use Kitchen	______	______
12	Parking	______	______

Occupancy

13 Number of Occupants: ____________
14 Days per Weeks: ____________

Hours per Day
15 Weekdays: ____________
16 Weekends: ____________

Climate and Site

17 Building Location: ____________
18 Heating Degree Days: ____________ °C-Day or °F-Day
19 Cooling Degree Days: ____________ °C-Day or °F-Day
20 Winter Design Drybulb Temperature (99%): ____________ °C or °F
21 Summer Design Drybulb Temperature (1%): ____________ °C or °F
22 Summer Design Wetbulb Temperature (1%): ____________ °C or °F

23 Site Characterization

Urban/Industrial: ____________ Suburban/Industrial: ____________
Urban/Residential: ____________ Suburban/ Residential: ____________
Urban/Commercial: ____________ Suburban/ Commercial: ____________

Rural/Near Urban: ____________ Rural/ Commercial: ____________
Rural/ Agricultural: ____________ Rural/ Industrial: ____________

Building Equipment

24 Ventilation: ______________________ Natural or mechanical

25 Cooling System

Air Conditioned: ______________ Y/N

Equipment

Central Chillers: ______________________ Y/N
Packaged Air Conditioning Units: ______________ Y/N
Heat Pump: ______________________ Y/N
Ducted Air Distribution: ______________________ Y/N
Fan Coil Units: ______________________ Y/N
Individual Room Air Conditioners: ______________ Y/N

26 Heating System

Heated: ______________ Y/N

Equipment

Steam or Hot Water Boiler: ______________________ Y/N
Central System with Heating Coils: ______________ Y/N
Reheat Coils in Air Distribution System: ______________ Y/N
Packaged Units: ______________________ Y/N
Forced Air Furnace: ______________________ Y/N
Heat Pump: ______________________ Y/N
Ducted Air Distribution: ______________________ Y/N
Fan Coil Units: ______________________ Y/N
Individual Space Heaters: ______________________ Y/N

Operating Schedule

Space Conditioning

27 Days per Weeks: ______________

Hours per Day

28 Weekdays: ______________
29 Weekends: ______________

Ventilation System

30 Days per Weeks: ______________

Hours per Day

31 Weekdays: ______________
32 Weekends: ______________

Building Envelope

33 Wall Construction: ______________________

34 Roof Construction: ______________________

Glazing

35 Glazing Elements: ______________ Single, Double or Triple
36 Operable Windows: ______________ Y/N
37 Shading Elements: ______________ Y/N

FORM C-1: CENTRAL AIR HANDLING AND DISTRIBUTION SYSTEM

One form is required for each central air handling system serving the test space.

1 Air Handler Number: ______________

2 Air Handler Location: ______________

3 System Type: ______________

Other System Information

4 Number of zones served by the air handler: ______________

5 Return air Fan: ______________ Y/N

6 Variable supply air temperature setpoint: ______________ Y/N

FORM C-2: PERIMETER ZONE UNITS

This form is used to describe the systems that provide space conditioning to perimeter zones. These systems are intended solely for perimeter applications, as opposed to central systems that also serve exterior zones. Only one copy of Form C-2 is required for the test space.

System Type: Select one of the following systems and answer the system specific questions.

1 Air-Water Induction Units: ______________________________Y/N

2 Condensate Drain Pan: __________Y/N

3 Filters for Secondary Airflow: _____Y/N

4 Fan-Coil Units: ______________________________________Y/N

5 Ventilation Air: _______________Y/N

6 Source of Ventilation Air: ______________________________

7 Condensate Drain Pan: __________Y/N

8 Filters for Secondary Airflow: _____Y/N

9 Fin-Tubed Radiator: ____________Y/N

10 Electric Baseboard: ____________Y/N

FORM C-3: UNITARY SYSTEMS

This form is used to describe any unitary air conditioning equipment that serves the test space. Only one copy of Form C-3 is required for the test space. If the test space is not served by a unitary system, this form is not required.

System Type: Select one of the following systems and answer the system specific questions.

1 Roof-Top Units: ____________________ Y/N

2 Number of Systems: __________

3 Zoning: __________

4 Constant or Variable: __________

5 Through-the-Wall Conditioner Systems: ____________________ Y/N

6 Ventilation Air: __________ Y/N

7 Ducted: __________ Y/N

8 Number of Systems: __________

9 Heat Pump Systems: ____________________ Y/N

10 Number of Systems: __________

11 Ventilation Air: __________ Y/N

12 Source of Ventilation Air: ____________________

FORM C-4: EVAPORATIVE COOLING SYSTEMS

This form is used to describe evaporative cooling systems used to condition the test space. If the test space has such a system, only one copy of Form C-4 is required.

System Type: Select one of the following systems and answer the system specific questions.

1 Direct Evaporative Air Cooler: ______________________________ Y/N

2 Direct System Type: ____

3 Indirect Evaporative Air Cooler: ___________________________ Y/N

FORM C-5: OUTDOOR AIR INTAKE

This form is used to describe the outdoor air intake strategy employed by the mechanical ventilation system serving the test space. Only one copy of Form C-5 is required for the test space.

Intake Strategy: Select one of the following options.

1 Conditioned Positive: ____________________

2 Unconditioned Positive: __________________

3 Unconditioned Suction: __________________

4 Unconditioned Suction, No Duct: ____________

Intake Control Strategy: Select one of the following options.

5 100% Outdoor Air Intake: ________________

6 Fixed Minimum Outdoor Air Intake: _________

7 Economizer Cycle: _____________________

8 Enthalpy Economizer Cycle: ______________

Means of maintaining minimum outdoor air intake: Select one of the following options.

9 Fixed Damper Positions: ______________

10 Supply/Return Fan Tracking: ___________

11 Intake Airflow Monitoring: ____________

Additional Intake Control Information

12 Morning Warm-Up Cycle: ______________Y/N

13 Morning Purge Cycle: _________________Y/N

14 Night Cool-Down Cycle: _______________Y/N

FORM C-6: NATURAL VENTILATION SYSTEM

This form is used to describe the ventilation strategy employed in naturally ventilated buildings. Only one copy of Form C-6 is required for the building, and only if it is naturally ventilated.

Select which of the following natural ventilation systems exist in the building and answer the system specific questions.

1 Operable Windows: ____________Y/N

2 Through-the-Wall Vents: ________Y/N

3 Number of Vents: ________________

4 Size of Vents: ___________ cm^2 or in^2

5 Central Shaft: _______________Y/N

6 Exhaust system: _______________Y/N

7 Area served by exhaust system: ____________________________

FORM C-7A: AIR HANDLER SPECIFICATIONS

This form is used to describe the specifications of the air handlers serving the test space. One copy of Form C-7A is required for each air handler serving the test space.

1 Air Handler Number: ______________
2 Location of Air Handler: ______________

3 Design Supply Airflow Rate Capacity: ______________ m^3/s or cfm
4 Source of Value: ______________

5 Design Minimum Outdoor Air Intake Rate: ______________ m^3/s or cfm
6 Source of Value: ______________

7 Space Served by Air Handler: ______________
8 Source of Value: ______________

9 Floor Area Served by Air Handler: ______________ m^2 or ft^2
10 Source of Value: ______________

11 Number of Occupants Served by Air Handler: ______________
12 Source of Value: ______________

13 Design Cooling Load: ______________ W/m^2 or W/ft^2
14 Source of Value: ______________

15 Existence of Return Fan: ________ Y/N

16 Return Fan Capacity: ______________ m^3/s or cfm
17 Source of Value: ______________

18 Space Served by Return System: ______________
19 Source of Value: ______________

20 Floor Area Served by Return System: ______________ m^2 or ft^2
21 Source of Value: ______________

FORM C-7B: EXHAUST FAN SPECIFICATIONS

This form is used to describe the specifications of the exhaust fans serving the test space. One copy of Form C-7B is required for each exhaust fan serving the test space.

1 Exhaust Fan Number: ____________

2 Location of Exhaust Fan: ____________________________

3 Design Exhaust Airflow Rate: __________________ m^3/s or cfm

4 Source of Value: ________________________________

5 Space Served by Exhaust Fan: _________________________

6 Source of Value: ________________________________

7 Floor Area Served by Exhaust Fan: ________________ m^2 or ft^2

8 Source of Value: ________________________________

Controls

9 Manual: _________________ Y/N

10 Time of Day: _______________ Y/N

11 Temperature: _______________ Y/N

12 Equipment Operation: __________ Y/N

FORM C-11: MAINTENANCE

This form is used to describe the HVAC system maintenance procedures and schedules. One copy of Form C-11 is required for the building.

Air Handler Inspections

1 Regularly Scheduled: ____________Y/N

2 Recorded in Logbook: ____________Y/N

3 Frequency: ______________________

Particulate Filtration Systems

Panel Filter Replacement

4 Regularly Scheduled: ____________Y/N

5 Recorded in Logbook: ____________Y/N

6 Frequency: ______________________

Manual Roll Filter Advancement

7 Regularly Scheduled: ____________Y/N

8 Recorded in Logbook: ____________Y/N

9 Frequency: ______________________

Automatic Roll Filter Inspection

10 Regularly Scheduled: ____________Y/N

11 Recorded in Logbook: ____________Y/N

12 Frequency: ______________________

Electronic Air Cleaners

Inspection

13 Regularly Scheduled: ____________Y/N

14 Recorded in Logbook: ____________Y/N

15 Frequency: ______________________

Cleaning

16 Regularly Scheduled: ____________Y/N

17 Recorded in Logbook: ____________Y/N

18 Frequency: ______________________

Heating and Cooling Coils

Inspection

19 Regularly Scheduled: ____________Y/N

20 Recorded in Logbook: ____________Y/N

21 Frequency: ________________________

Cleaning

22 Regularly Scheduled: ____________Y/N

23 Recorded in Logbook: ____________Y/N

24 Frequency: ________________________

Drain Pans

Inspection

25 Regularly Scheduled: ____________Y/N

26 Recorded in Logbook: ____________Y/N

27 Frequency: ________________________

Cleaning

28 Regularly Scheduled: ____________Y/N

29 Recorded in Logbook: ____________Y/N

30 Frequency: ________________________

Air Distribution Ductwork

Inspection

31 Regularly Scheduled: ____________Y/N

32 Recorded in Logbook: ____________Y/N

33 Frequency: ________________________

Cleaning

34 Regularly Scheduled: ____________Y/N

35 Frequency: ________________________

Humidifiers

Inspection

36 Regularly Scheduled: ____________Y/N

37 Recorded in Logbook: ____________Y/N

38 Frequency: ________________________

Cleaning

39 Regularly Scheduled: __________ Y/N

40 Recorded in Logbook: __________ Y/N

41 Frequency: __________________

42 Purge or Blowdown: __________ Y/N

43 Purge Frequency: ______________________________

44 Purge Duration: ______________________________

45 Purge Control: ______________________________

Evaporative coolers

Inspection

46 Regularly Scheduled: __________ Y/N

47 Recorded in Logbook: __________ Y/N

48 Frequency: __________________

Cleaning

49 Regularly Scheduled: __________ Y/N

50 Recorded in Logbook: __________ Y/N

51 Frequency: __________________

52 System Bleeding Frequency: ______________________

53 Water Treatment: __________ Y/N

54 Water Treatment Frequency: ______________________

55 Water Treatment Compound: ______________________

56 Biocide Treatment: __________ Y/N

57 Biocide Treatment Frequency: ______________________

58 Biocide Treatment Compound: ______________________

Air washers

Inspection

59 Regularly Scheduled: __________ Y/N

60 Recorded in Logbook: __________ Y/N

61 Frequency: __________________

Cleaning

62 Regularly Scheduled: __________ Y/N

63 Recorded in Logbook: __________ Y/N

64 Frequency: __________________

65 Tank Maintenance Frequency: ____________________

66 Eliminator Repainting Frequency: ____________________

67 Glass Media Cleaning Frequency: ____________________

68 System Bleeding Frequency: ____________________

69 Water Treatment: __________Y/N

70 Water Treatment Frequency: ____________________

71 Water Treatment Compound: ____________________

72 Biocide Treatment: __________Y/N

73 Biocide Treatment Frequency: ____________________

74 Biocide Treatment Compound: ____________________

Control System

Inspection

75 Regularly Scheduled: __________Y/N

76 Recorded in Logbook: __________Y/N

77 Frequency: ____________________

Sensor Recalibration

78 Regularly Scheduled: __________Y/N

79 Recorded in Logbook: __________Y/N

80 Frequency: ____________________

Testing and Balancing

81 Regularly Scheduled: __________Y/N

82 Frequency: ____________________

Cooling Towers

Inspection

83 Regularly Scheduled: __________Y/N

84 Recorded in Logbook: __________Y/N

85 Frequency: ____________________

86 Surface Cleaning Frequency: ____________________

87 Scale Control Treatment: __________Y/N

88 Blowdown or Chemical Treatment: ____________________

89 Blowdown or Chemical Treatment Frequency: ____________________

90 Scale Control Treatment Compounds: ____________________

91 Corrosion Treatment: __________Y/N

92 Treatment Frequency: ______________________________

93 Corrosion Treatment Compounds: ______________________

94 Biocide Treatment: ___________Y/N

95 Biocide Treatment Frequency: ________________________

96 Biocide Treatment Compounds: _______________________

97 Silt Treatment: ______________Y/N

98 Silt Treatment Frequency: ___________________________

99 Silt Treatment Compounds: __________________________

Fan coil Units

Inspection

100 Regularly Scheduled: __________Y/N

101 Recorded in Logbook: __________Y/N

102 Frequency: ____________________

Filter Replacement

103 Regularly Scheduled: __________Y/N

104 Recorded in Logbook: __________Y/N

105 Frequency: ____________________

Terminal Units

Inspection

106 Regularly Scheduled: __________Y/N

107 Recorded in Logbook: __________Y/N

108 Frequency: ____________________

INSPECTION

This form is used to record information obtained during the inspection of the HVAC system and its major components. One copy of Form C-12 is required for the building.

Mechanical Room

1 General Condition: ________________

2 Part of Return System: __________Y/N

3 Used for Storage: ______________Y/N

System Check-Out

Supply Fan

4 Operating: __________________Y/N

5 Correct Direction of Fan Rotation: __Y/N

6 Correct Airflow Direction: _______Y/N

Return Fan

7 Operating: __________________Y/N

8 Correct Direction of Fan Rotation: __Y/N

9 Correct Airflow Direction: _______Y/N

Exhaust Fan

10 Operating: __________________Y/N

11 Correct Direction of Fan Rotation: __Y/N

12 Correct Airflow Direction: _______Y/N

Outdoor Air Intake

13 Correct Airflow Direction: _______Y/N

14 Height: ____________________m or ft

Proximity to Pollutant Sources

15 Standing Water: _______________Y/N

16 Exhaust Vents: _______________Y/N

17 Sanitary Vents: _______________Y/N

18 Cooling Tower: _______________Y/N

19 Loading Dock: _______________Y/N

20 Parking Garage: _______________Y/N

21 Vehicle Traffic: _______________Y/N

22 Trash Dumpster: _______________Y/N

Air Handler Housing

23 General Condition: ______________

24 Sound Liner: ______________

Air Handler Components

25 General Condition: ______________

26 Intakes: ______________

27 Dampers: ______________

28 Coils: ______________

29 Drain Pans: ______________

30 Fan Belts: ______________

Air Distribution Ductwork

31 General Condition: ______________

32 Leakage at Seams: ______________

33 Liners: ______________

Exhaust Fans

34 General Condition: ______________

35 Fan Belts: ______________

Particulate Filtration Systems

36 General Condition: ______________

37 Accessibility: ______________

38 Filter Fit into Frames: ______________

39 Filter Condition: ______________

40 Evenness of Loading: ______________

41 Indicator of Resistance: __________Y/N

42 Time to Change Label: ______________Y/N

43 Pressure Indicator Reading ______________Pa or in. wg.

Humidifiers

44 General Condition: ______________

45 Drain Pans: ______________

Evaporative Coolers

46 General Condition: ______________

47 Water Pans: ______________

48 Water Clarity: ______________

Air Washers

49 General Condition: ______________

50 Water Pans: ______________

51 Water Clarity: ______________

52 Eliminators and Baffles: ______________

Control System

53 General Condition: ______________

54 Sensors: ______________

Cooling Towers

55 General Condition: ______________

56 Surfaces: ______________

57 Water Condition: ______________

Fan Coil Units

58 General Condition: ______________

59 Valves: ______________

60 Fans: ______________

61 Coils: ______________

62 Drain Pans: ______________

63 Air Filters: ______________

Terminal Units

64 General Condition: ______________

65 Dampers: ______________

FORM D-1A: SUPPLY AIRFLOW RATE

Four forms are required for each air handler serving the test space, with one form for each measurement of the supply airflow rate.

1 Date of Test: ______________ 2 Time: ______________
3 Air Handler Number: ______________ 4 Air Handler Location: ______________

5 Location of Duct Traverse: ______________

Measurement Device Information

6 Measurement Device Type: ______________
7 Manufacturer: ______________ 8 Model Number: ______________
9 Serial Number: ______________

Duct Dimensions

10 Rectangular or Round: ______________ 11 Duct Area: ______________ m^2 or ft^2

Traverse Data, Traverse Grid and Data on Form D-X1 or D-X2

12 Start of Traverse, time: ______________ 13 End of Traverse, time: ______________

Calculations

14 Root Mean Square Velocity Pressure

$\Sigma(p_v)^{1/2}$ / Number of readings: ______________ $(Pa)^{1/2}$ or $(in.\ w.g.)^{1/2}$

15 Average Air Speed

Air speed measurements, Σv_s / Number of readings: ______________ m/s or fpm

Velocity pressure measurements (Pa), 1.29 x #14: ______________ m/s

Velocity pressure measurements (in. w.g.), 4002 x #14: ______________ fpm

16 Airflow Rate, #11 x #15: ______________ m^3/s or cfm

FORM D-1B: PERCENT OUTDOOR AIR INTAKE

Four forms are required for each air handler serving the test space, with one form for each measurement of the percent outdoor air intake.

1 Date of Test: ____________ 2 Time: ____________
3 Air Handler Number: ____________ 4 Air Handler Location: ____________

Air Sample Locations
5 Outdoor Air Intake: ____________
6 Supply Air: ____________
7 Return Air: ____________

Measurement Device Information
8 Manufacturer: ____________ 9 Model Number: ____________
10 Serial Number: ____________

Calibration Check

Span check	Zero check
11 Span Concentration: ____________	13 Reading: ____________
12 Reading: ____________	

Concentration Data
14 Start of Measurement, time: ____________

15 Outdoor Air	16 Return Air	17 Supply Air
________	________	________
________	________	________
________	________	________
________	________	________
________	________	________

18 End of Measurement, time: ____________

Calculations
Mean Concentrations

	Outdoor air	Return air	Supply air
Mean	19 ________ppm	21 ________ppm	23 ________ppm
Standard Deviation	20 ________ppm	22 ________ppm	24 ________ppm

Percent Outdoor Air Intake
25 Value, 100 x (#21 - #23) / (#21 - #19): ____________% OA

26 Error Estimate, 100 x #25 [$(\#22^2 + \#20^2)/(\#21 - \#19)^2 + (\#22^2 + \#24^2)/(\#21 - \#23)^2\ ]^{1/2}$
____________% OA

FORM D-1C: OUTDOOR AIR INTAKE RATE

Four forms are required for each air handler serving the test space, with one form for each measurement of the outdoor air intake rate.

1 Date of Test: ____________ 2 Time: ____________
3 Air Handler Number: ____________ 4 Air Handler Location: ____________

METHOD #1: TRAVERSE

5 Location of Duct Traverse: ____________

Measurement Device Information

6 Measurement Device Type: ____________
7 Manufacturer: ____________ 8 Model Number: ____________
9 Serial Number: ____________

Duct Dimensions

10 Rectangular or Round: ____________ 11 Duct Area: ____________ m^2 or ft^2

Traverse Data. Traverse Grid and Data on Form D-X1 or D-X2

12 Start of Traverse, time: ____________ 13 End of Traverse, time: ____________

Calculations

14 Root Mean Square Velocity Pressure

$\Sigma(p_v)^{1/2}$ / Number of readings: ____________ $(Pa)^{1/2}$ or $(in.\ w.g.)^{1/2}$

15 Average Air Speed

Air speed measurements, Σv_s / Number of readings: ____________ m/s or fpm

Velocity pressure measurements (Pa), 1.29 x #14: ____________ m/s

Velocity pressure measurements (in. w.g.), 4002 x #14: ____________ fpm

16 Airflow Rate, #11 x #15: ____________ m^3/s or cfm

METHOD #2: CALCULATION

17 Supply Airflow Rate from Form D-1A #16, same date and time of day

____________ m^3/s or cfm

18 Percent Outdoor Air Intake from Form D-1B #25, same date and time of day

____________ %

19 Outdoor Air Intake Rate, #17 times #18

____________ m^3/s or cfm

FORM D-1D: SUPPLY AIR TEMPERATURE AND RELATIVE HUMIDITY

Four forms are required for each air handler serving the test space, with one form for each measurement of the supply air conditions.

1 Date of Test: ____________ 2 Time: ____________
3 Air Handler Number: ____________ 4 Air Handler Location: ____________

5 Location of Measurements: ____________

Measurement Device Information

Temperature sensor
6 Measurement Device Type: ____________
7 Manufacturer: ____________ 8 Model Number: ____________
9 Serial Number: ____________

Relative humidity sensor
10 Measurement Device Type: ____________
11 Manufacturer: ____________ 12 Model Number: ____________
13 Serial Number: ____________

Data
14 Start of Measurement, time: ____________

15 Air Temperature	16 Relative Humidity
________ °C or °F	________ %
________	________
________	________
________	________
________	________

17 End of Measurement, time: ____________

Calculations

	Air Temperature	Relative Humidity
Mean	18 ________ °C or °F	20 ________ %
Standard Deviation	19 ________ °C or °F	21 ________ %

FORM D-2A: EXHAUST FAN OPERATION

One form is required for each exhaust fan serving the test space

1 Exhaust Fan Number: ______________ 2 Exhaust Fan Location: ________________

Day #1

AM
3 Time Operation Checked: ____________
4 Operating: yes or no: ______________

PM
5 Time Operation Checked: ______________
6 Operating: yes or no: __________________

Day #2

AM
7 Time Operation Checked: ____________
8 Operating: yes or no: ______________

PM
9 Time Operation Checked: ______________
10 Operating: yes or no: __________________

Day #3

AM
11 Time Operation Checked: ____________
12 Operating: yes or no: ______________

PM
13 Time Operation Checked: ______________
14 Operating: yes or no: __________________

Day #4

AM
15 Time Operation Checked: ____________
16 Operating: yes or no: ______________

PM
17 Time Operation Checked: ______________
18 Operating: yes or no: __________________

Day #5

AM
19 Time Operation Checked: ____________
20 Operating: yes or no: ______________

PM
21 Time Operation Checked: ______________
22 Operating: yes or no: __________________

FORM D-2B: EXHAUST FAN AIRFLOW RATE

One form is required for each exhaust fan serving the test space

1 Date of Test: ____________ 2 Time: ____________
3 Exhaust Fan Number: ____________ 4 Exhaust Fan Location: ____________

5 Location of duct traverse: ____________

Measurement Device Information
6 Measurement Device Type: ____________
7 Manufacturer: ____________ 8 Model Number: ____________
9 Serial Number: ____________

Duct Dimensions
10 Rectangular or Round: ____________ 11 Duct Area: ____________ m^2 or ft^2

Traverse Data, Traverse Grid and Data on Form D-X1 or D-X2
12 Start of Traverse, time: ____________ 13 End of Traverse, time: ____________

Calculations
14 Root Mean Square Velocity Pressure
$\Sigma(p_v)^{1/2}$ / Number of readings: ____________ $(Pa)^{1/2}$ or $(in.\ w.g.)^{1/2}$

15 Average Air Speed
Air speed measurements, Σv_s / Number of readings: ____________ m/s or fpm
Velocity pressure measurements (Pa), 1.29 x #14: ____________ m/s
Velocity pressure measurements (in. w.g.), 4002 x #14: ____________ fpm

16 Airflow Rate, #11 x #15: ____________ m^3/s or cfm

FORM D-3A: LOCAL VENTILATION PERFORMANCE - AIRFLOW RATE

One form is required

1 Date of Test: ______________________

Measurement Device Information

2 Measurement Device Type: ______________________

3 Manufacturer: ______________________ 4 Model Number: ______________________

5 Serial Number: ______________________ 6 Date of Last Calibration: ______________________

Data

7 Start of Measurement, time: ______________________

8 Units of Airflow Rate Measurement: ______________________

9 Airflow rate. For diffuser numbering, refer to test space floor plan.

#1________	#2________	#3________
#4________	#5________	#6________
#7________	#8________	#9________
#10________	#11________	#12________
#13________	#14________	#15________
#16________	#17________	#18________
#19________	#20________	#21________
#22________	#23________	#24________
#25________	#26________	#27________
#28________	#29________	#30________
#31________	#32________	#33________
#34________	#35________	#36________
#37________	#38________	#39________
#40________	#41________	#42________
#43________	#44________	#45________
#46________	#47________	#48________
#49________	#50________	#51________
#52________	#53________	#54________
#55________	#56________	#57________
#58________	#59________	#60________
#61________	#62________	#63________
#64________	#65________	#66________
#67________	#68________	#69________
#70________	#71________	#72________
#73________	#74________	#75________

10 End of Measurement, time: ______________________

FORM D-3B: LOCAL VENTILATION PERFORMANCE - SUPPLY AIR TEMPERATURE

One form is required

1 Date of Test: ____________________

Measurement Device Information

2 Measurement Device Type: ____________________

3 Manufacturer: ____________________ 4 Model Number: ____________________

5 Serial Number: ____________________

Data

6 Start of Measurement, time: ____________________

7 Units of Temperature Measurement: __________

8 Supply Air Temperature. For diffuser numbering, refer to test space floor plan.

#1________	#2________	#3________
#4________	#5________	#6________
#7________	#8________	#9________
#10________	#11________	#12________
#13________	#14________	#15________
#16________	#17________	#18________
#19________	#20________	#21________
#22________	#23________	#24________
#25________	#26________	#27________
#28________	#29________	#30________
#31________	#32________	#33________
#34________	#35________	#36________
#37________	#38________	#39________
#40________	#41________	#42________
#43________	#44________	#45________
#46________	#47________	#48________
#49________	#50________	#51________
#52________	#53________	#54________
#55________	#56________	#57________
#58________	#59________	#60________
#61________	#62________	#63________
#64________	#65________	#66________
#67________	#68________	#69________
#70________	#71________	#72________
#73________	#74________	#75________

9 End of measurement, time: __________

FORM D-4A: NATURAL VENTILATION - CONTINUOUS CARBON DIOXIDE

Two forms are required, one for each of two days

1 Date of Test: ______________________

Measurement Device Information

2 Manufacturer: ____________________ 3 Model Number: ______________

4 Serial Number: ____________________

Measurement Locations

5 Outdoor Air: ____

6 Occupied Space #1: ____

7 Occupied Space #2: ____

8 Occupied Space #3: ____

Data Analysis

Outdoor reading

9 6 am: ______________________ppm 11 2 pm: ______________________ppm

10 10 am: ______________________ppm 12 6 pm: ______________________ppm

Occupied space #1

13 6 am: ______________________ppm

Morning maximum	Afternoon maximum
14 Concentration: ______________ppm	17 Concentration: ______________ppm
15 Time: ______________________	18 Time: ______________________
16 Outdoor Concentration: __________ppm	19 Outdoor Concentration: __________ppm

Occupied space #2

20 6 am: ______________________ppm

Morning maximum	Afternoon maximum
21 Concentration: ______________ppm	24 Concentration: ______________ppm
22 Time: ______________________	25 Time: ______________________
23 Outdoor Concentration: __________ppm	26 Outdoor Concentration: __________ppm

Occupied space #3

27 6 am: ______________________ppm

Morning maximum	Afternoon maximum
28 Concentration: ______________ppm	31 Concentration: ______________ppm
29 Time: ______________________	32 Time: ______________________
30 Outdoor Concentration: __________ppm	33 Outdoor Concentration: __________ppm

FORM D-4B: NATURAL VENTILATION - TRACER GAS DECAY

One form is required

1 Date of Test: ____________ 2 Tracer Gas: ____________

Measurement Device Information

3 Manufacturer: ____________ 4 Model Number: ____________
5 Serial Number: ____________ 6 Concentration Units: ____________

Measurement Locations

7 Outdoor Air: ____________
8 Occupied Space #1: ____________
9 Occupied Space #2: ____________
10 Occupied Space #3: ____________
11 Occupied Space #4: ____________
12 Occupied Space #5: ____________
13 Occupied Space #6: ____________
14 Occupied Space #7: ____________
15 Occupied Space #8: ____________
16 Occupied Space #9: ____________
17 Occupied Space #10: ____________

Data

18 Initial reading
Outdoor
Time: ____________ Concentration: ____________
Temperature: ____________°C or °F Wind speed: ____________m/s or mph

	Time	Concentration		Time	Concentration
Location #1	______	______	Location #6	______	______
Location #2	______	______	Location #7	______	______
Location #3	______	______	Location #8	______	______
Location #4	______	______	Location #9	______	______
Location #5	______	______	Location #10	______	______

19 Second reading
Outdoor
Time: ____________ Concentration: ____________
Temperature: ____________°C or °F Wind speed: ____________m/s or mph

	Time	Concentration		Time	Concentration
Location #1	______	______	Location #6	______	______
Location #2	______	______	Location #7	______	______
Location #3	______	______	Location #8	______	______
Location #4	______	______	Location #9	______	______
Location #5	______	______	Location #10	______	______

20 Third reading
Outdoor
Time: ____________ Concentration: ____________
Temperature: ____________ °C or °F Wind speed: ____________ m/s or mph

	Time	Concentration		Time	Concentration
Location #1	____	____	Location #6	____	____
Location #2	____	____	Location #7	____	____
Location #3	____	____	Location #8	____	____
Location #4	____	____	Location #9	____	____
Location #5	____	____	Location #10	____	____

21 Fourth reading
Outdoor
Time: ____________ Concentration: ____________
Temperature: ____________ °C or °F Wind speed: ____________ m/s or mph

	Time	Concentration		Time	Concentration
Location #1	____	____	Location #6	____	____
Location #2	____	____	Location #7	____	____
Location #3	____	____	Location #8	____	____
Location #4	____	____	Location #9	____	____
Location #5	____	____	Location #10	____	____

22 Fifth reading
Outdoor
Time: ____________ Concentration: ____________
Temperature: ____________ °C or °F Wind speed: ____________ m/s or mph

	Time	Concentration		Time	Concentration
Location #1	____	____	Location #6	____	____
Location #2	____	____	Location #7	____	____
Location #3	____	____	Location #8	____	____
Location #4	____	____	Location #9	____	____
Location #5	____	____	Location #10	____	____

Data Analysis

23 Decay rates, air changes per hour

	Value	Standard Error		Value	Standard Error
Location #1	____	____	Location #6	____	____
Location #2	____	____	Location #7	____	____
Location #3	____	____	Location #8	____	____
Location #4	____	____	Location #9	____	____
Location #5	____	____	Location #10	____	____

24 Building Average Decay Rate: ________ ach
25 Standard Deviation: ____________ ach

Outdoor Conditions, Averages
26 Exterior temperature: ________ °C or °F 27 Wind speed: ____________ m/s or mph

FORM D-5A: AIR INFILTRATION RATE: TEST DESCRIPTION

One form is required.

1 Date of Test: ____________________ 2 Tracer Gas: ____________________

Tracer Gas Concentration Measurement Locations

3 Outdoor air: ____________________

4 Occupied Space #1: ____________________
5 Occupied Space #2: ____________________
6 Occupied Space #3: ____________________
7 Occupied Space #4: ____________________
8 Occupied Space #5: ____________________
9 Occupied Space #6: ____________________
10 Occupied Space #7: ____________________
11 Occupied Space #8: ____________________
12 Occupied Space #9: ____________________
13 Occupied Space #10: ____________________

14	#1	Air Handler Number: ________	Air Handler Location: ____________________
15	#2	Air Handler Number: ________	Air Handler Location: ____________________
16	#3	Air Handler Number: ________	Air Handler Location: ____________________
17	#4	Air Handler Number: ________	Air Handler Location: ____________________
18	#5	Air Handler Number: ________	Air Handler Location: ____________________
19	#6	Air Handler Number: ________	Air Handler Location: ____________________
20	#7	Air Handler Number: ________	Air Handler Location: ____________________
21	#8	Air Handler Number: ________	Air Handler Location: ____________________
22	#9	Air Handler Number: ________	Air Handler Location: ____________________
23	#10	Air Handler Number: ________	Air Handler Location: ____________________

FORM D-5B: AIR INFILTRATION RATE: SUPPLY AIRFLOW RATE

One form is required for each air handler serving the building.

1 Date of Test: ______________ 2 Time: ______________
3 Air Handler Number: ______________ 4 Air Handler Location: ______________

5 Location of Duct Traverse: ______________

Measurement Device Information
6 Measurement Device Type: ______________
7 Manufacturer: ______________ 8 Model Number: ______________
9 Serial Number: ______________

Duct Dimensions
10 Rectangular or Round: ______________ 11 Duct Area: ______________ m^2 or ft^2

Traverse Data, Traverse Grid and Data on Form D-X1 or D-X2
12 Start of Traverse, time: ______________ 13 End of Traverse, time: ______________

Calculations
14 Root Mean Square Velocity Pressure
$\Sigma(p_v)^{1/2}$ / Number of readings: ______________ $(Pa)^{1/2}$ or $(in.\ w.g.)^{1/2}$

15 Average Air Speed
Air speed measurements, Σv_t / Number of readings: ______________ m/s or fpm

Velocity pressure measurements (Pa), 1.29 x #14: ______________ m/s

Velocity pressure measurements (in. w.g.), 4002 x #14: ______________ fpm

16 Airflow Rate, #11 x #15: ______________ m^3/s or cfm

FORM D-5C: AIR INFILTRATION RATE: PERCENT OUTDOOR AIR INTAKE

One form is required for each air handler serving the building.

1 Date of Test: ____________ 2 Time: ____________

3 Air Handler Number: ____________ 4 Air Handler Location: ____________

Air Sample Locations

5 Outdoor Air Intake: ____________

6 Supply Air: ____________

7 Return Air: ____________

Measurement Device Information

8 Manufacturer: ____________ 9 Model Number: ____________

10 Serial Number: ____________

Calibration Check

Span check

11 Span Concentration: ____________

12 Reading: ____________

Zero check

13 Reading: ____________

Concentration Data

14 Start of Measurement, time: ____________

15 Outdoor Air	16 Return Air	17 Supply Air
________	________	________
________	________	________
________	________	________
________	________	________
________	________	________

18 End of Measurement, time: ____________

Calculations

Mean Concentrations

	Outdoor air	Return air	Supply air
Mean	19 ________ppm	21 ________ppm	23 ________ppm
Standard Deviation	20 ________ppm	22 ________ppm	24 ________ppm

Percent Outdoor Air Intake

25 Value, 100 x (#21 - #23) / (#21 - #19): ____________% OA

26 Error Estimate, 100 x #25 [(#22^2 + #20^2)/(#21 - #19)^2 + (#22^2 + #24^2)/(#21 - #23)^2]$^{1/2}$

____________% OA

FORM D-5D: AIR INFILTRATION RATE: OUTDOOR AIR INTAKE RATE

One form is required for each air handler serving the building.

1 Date of Test: ____________ 2 Time: ____________

3 Air Handler Number: ____________ 4 Air Handler Location: ____________

METHOD #1: TRAVERSE

5 Location of Duct Traverse: ____________

Measurement Device Information

6 Measurement Device Type: ____________

7 Manufacturer: ____________ 8 Model Number: ____________

9 Serial Number: ____________

Duct Dimensions

10 Rectangular or Round: ____________ 11 Duct Area: ____________ m^2 or ft^2

Traverse Data, Traverse Grid and Data on Form D-X1 or D-X2

12 Start of Traverse, time: ____________ 13 End of Traverse, time: ____________

Calculations

14 Root Mean Square Velocity Pressure

$\Sigma(p_v)^{1/2}$ / Number of readings: ____________ $(Pa)^{1/2}$ or $(in.\ wg.)^{1/2}$

15 Average Air Speed

Air speed measurements, Σv_s / Number of readings: ____________ m/s or fpm

Velocity pressure measurements (Pa), 1.29 x #14: ____________ m/s

Velocity pressure measurements (in. wg), 4002 x #14: ____________ fpm

16 Airflow rate, #11 x #15: ____________ m^3/s or cfm

METHOD #2: CALCULATION

17 Supply Airflow Rate from Form D-5B #16, same air handler

____________ m^3/s or cfm

18 Percent Outdoor Air Intake from Form D-5C #25, same air handler

____________ %

19 Outdoor Air Intake Rate, #17 times #18

____________ m^3/s or cfm

FORM D-5E: AIR INFILTRATION RATE: TRACER GAS DECAY

One form is required

1 Date of Test: ____________________

Measurement Device Information

2 Manufacturer: ____________________ 3 Model Number: ____________________

4 Serial Number: ____________________ 5 Concentration Units: ____________________

Data

6 Initial Reading

Outdoor

Time: ____________________ Concentration: ____________________

Temperature: ____________°C or °F Wind Speed: ____________m/s or mph

	Time	Concentration		Time	Concentration
Occupied Space					
Location #1	______	______	Location #6	______	______
Location #2	______	______	Location #7	______	______
Location #3	______	______	Location #8	______	______
Location #4	______	______	Location #9	______	______
Location #5	______	______	Location #10	______	______
Air Handlers					
Location #1	______	______	Location #6	______	______
Location #2	______	______	Location #7	______	______
Location #3	______	______	Location #8	______	______
Location #4	______	______	Location #9	______	______
Location #5	______	______	Location #10	______	______

7 Second Reading

Outdoor

Time: ____________________ Concentration: ____________________

Temperature: ____________°C or °F Wind Speed: ____________m/s or mph

	Time	Concentration		Time	Concentration
Occupied Space					
Location #1	______	______	Location #6	______	______
Location #2	______	______	Location #7	______	______
Location #3	______	______	Location #8	______	______
Location #4	______	______	Location #9	______	______
Location #5	______	______	Location #10	______	______
Air Handlers					
Location #1	______	______	Location #6	______	______
Location #2	______	______	Location #7	______	______
Location #3	______	______	Location #8	______	______
Location #4	______	______	Location #9	______	______
Location #5	______	______	Location #10	______	______

8 Third Reading

Outdoor

Time: ______________ Concentration: ______________

Temperature: ____________ °C or °F Wind Speed: ____________ m/s or mph

	Time	Concentration		Time	Concentration
Occupied Space					
Location #1	____	____	Location #6	____	____
Location #2	____	____	Location #7	____	____
Location #3	____	____	Location #8	____	____
Location #4	____	____	Location #9	____	____
Location #5	____	____	Location #10	____	____
Air Handlers					
Location #1	____	____	Location #6	____	____
Location #2	____	____	Location #7	____	____
Location #3	____	____	Location #8	____	____
Location #4	____	____	Location #9	____	____
Location #5	____	____	Location #10	____	____

9 Fourth Reading

Outdoor

Time: ______________ Concentration: ______________

Temperature: ____________ °C or °F Wind Speed: ____________ m/s or mph

	Time	Concentration		Time	Concentration
Occupied Space					
Location #1	____	____	Location #6	____	____
Location #2	____	____	Location #7	____	____
Location #3	____	____	Location #8	____	____
Location #4	____	____	Location #9	____	____
Location #5	____	____	Location #10	____	____
Air Handlers					
Location #1	____	____	Location #6	____	____
Location #2	____	____	Location #7	____	____
Location #3	____	____	Location #8	____	____
Location #4	____	____	Location #9	____	____
Location #5	____	____	Location #10	____	____

10 Fifth Reading

Outdoor

Time: ____________ Concentration: ____________

Temperature: ____________°C or °F Wind Speed: ____________m/s or mph

	Time	Concentration		Time	Concentration
Occupied Space					
Location #1	____	____	Location #6	____	____
Location #2	____	____	Location #7	____	____
Location #3	____	____	Location #8	____	____
Location #4	____	____	Location #9	____	____
Location #5	____	____	Location #10	____	____
Air Handlers					
Location #1	____	____	Location #6	____	____
Location #2	____	____	Location #7	____	____
Location #3	____	____	Location #8	____	____
Location #4	____	____	Location #9	____	____
Location #5	____	____	Location #10	____	____

Data Analysis

11 Decay Rates, air changes per hour

	Value	Standard Error		Value	Standard Error
Occupied Space					
Location #1	____	____	Location #6	____	____
Location #2	____	____	Location #7	____	____
Location #3	____	____	Location #8	____	____
Location #4	____	____	Location #9	____	____
Location #5	____	____	Location #10	____	____
Air Handlers					
Location #1	____	____	Location #6	____	____
Location #2	____	____	Location #7	____	____
Location #3	____	____	Location #8	____	____
Location #4	____	____	Location #9	____	____
Location #5	____	____	Location #10	____	____

12 Building Average Decay Rate: ________ach

13 Standard Deviation: ____________ach

Outdoor Conditions, Averages

14 Exterior Temperature: ________°C or °F 15 Wind Speed: ____________m/s or mph

FORM D-5F: AIR INFILTRATION RATE: DATA ANALYSIS

One form is required

1 Date of Test: ____________________

Outdoor Air Intake Rate, From Forms D-5D

2 Determined by Method #1 Traverse or Method #2 Calculation: ______

3 #1 Air Handler: ____________________ m^3/s or cfm
4 #2 Air Handler: ____________________ m^3/s or cfm
5 #3 Air Handler: ____________________ m^3/s or cfm
6 #4 Air Handler: ____________________ m^3/s or cfm
7 #5 Air Handler: ____________________ m^3/s or cfm
8 #6 Air Handler: ____________________ m^3/s or cfm
9 #7 Air Handler: ____________________ m^3/s or cfm
10 #8 Air Handler: ____________________ m^3/s or cfm
11 #9 Air Handler: ____________________ m^3/s or cfm
12 #10 Air Handler: ____________________ m^3/s or cfm

13 Total Outdoor Air Intake Rate, Add #3 through #12
____________________ m^3/s or cfm

14 Outdoor Air Intake Rate in air changes per hour, #13 divided by building volume
____________________ air changes per hour

15 Total Building Air Change Rate, From Form D-5E, #13
____________________ air changes per hour

16 Building Infiltration Rate, #15 minus #14
____________________ air changes per hour

APPENDIX B

Radon Mitigation Branch School Profile Sheet (CHM 93)

RADON MITIGATION BRANCH SCHOOL PROFILE SHEET (7/19/91 REVISION)

- USE ONE PROFILE SHEET FOR EACH BUILDING. USE ADDITIONAL SHEETS IF THERE ARE MORE THAN TWO SUBSTRUCTURES/ADDITIONS.
- THE ARCHITECTURAL PLANS AND SPECIFICATIONS MAY NEED TO BE EXAMINED TO ANSWER MANY OF THE QUESTIONS.
- GROUND CONTACT ROOMS INCLUDE SLAB-ON-GRADE, BASEMENT, AND ROOMS LOCATED DIRECTLY OVER THE CRAWL SPACE;

- PLEASE ATTACH A FLOOR PLAN OF THE SCHOOL (WITH RADON LEVELS IF AVAILABLE)
- A SECTION FOR COMMENTS IS PROVIDED ON THE LAST PAGE. PLEASE KEY THE APPROPRIATE LINE WITH EACH COMMENT (i.e., A1).

SCHOOL: ______________________ DISTRICT: ______________

STREET: ______________ CITY: __________ ST: ___ ZIP: ______________

NSRS CODE: ____________ COUNTY: ______________ DATE: ______________

CONTACT: ____________ POSITION: ______________ PHONE: ______________

YOUR NAME: ____________ POSITION: ______________ PHONE: ______________

A. THE FOLLOWING TABLE INCLUDES STRUCTURAL CHARACTERISTICS OF THE SCHOOL:

STRUCTURAL CHARACTERISTICS	ORIGINAL STRUCTURE	2nd STRUCTURE	3rd STRUCTURE
1) YEAR CONSTRUCTED			
2) SUBSTRUCTURE TYPE: BSMT/SLAB/CRAWL			
3) IF CRAWL SPACE, IS FIRST FLOOR: SLAB/WOOD			
4) TOTAL SQ. FT. OF BUILDING			
5) SQ. FT. OF GROUND CONTACT			
6) # 1st FL CLASSROOMS			
7) # OTHER 1st FL OCCUPIED ROOMS			
8) # OF FLOORS (INCL. BSMT)			
9) APPROX # OF BUILDING OCCUPANTS			
10) DESCRIBE GENERAL BUILDING DESIGN: CONVENTIONAL/OPEN CLASSROOMS/OTHER			
11) ARE SUBSLAB WALLS BLOCK OR POURED: BLOCK/POURED			
12) DO SUBSLAB WALLS SEPARATE EACH CLASSROOM: YES/NO/UNK			
13) ARE SUBSLAB WALLS UNDER THE CORRIDOR WALLS: YES/NO/UNK			
14) SUBSLAB MATERIAL ON PLANS: NA/GRAVEL/SAND/EARTH/OTHER			
15) SUBSLAB MATERIAL VERIFIED: NA/GRAVEL/SAND/EARTH/OTHER			
16) LOCATION(S) OF UTILITY LINES: TUNNEL/SUBSLAB (NO TUNNEL)/ OVERHEAD/BSMT/CRAWL/OTHER			
17) IF TUNNEL: WIDTH & HEIGHT			
18) TUNNEL LOCATION: OUTSIDE WALL/CORRIDOR/OTHER			
19) TUNNEL WALL: POURED/BLOCK			
20) TUNNEL FLOOR: DIRT/SLAB			

B. COMPLETE THE FOLLOWING TABLE IF ANY PART OF THE BUILDING HAS A CENTRAL HVAC SYSTEM:

CENTRAL HVAC SYSTEM	ORIGINAL STRUCTURE	2nd STRUCTURE	3rd STRUCTURE
1) # OF AIR HANDLING UNITS:			
2) SERVICES CLASSROOMS: YES/NO			
3) SERVICES MULTIPURPOSE: YES/NO			
4) SERVICES OFFICES: YES/NO			
5) SERVICES OTHER AREA: YES/NO			
6) LOCATION(S) OF AIR HANDLER(S): MECH ROOM/DROPPED CEILING/ ROOF/BSMT/CRAWL/OTHER			
7) SEPARATE RETURN FAN: YES/NO			
8) MINIMUM % OUTDOOR AIR			
9) MAXIMUM % OUTDOOR AIR			
10)AIR SUPPLY DUCTS LOCATION: CEILING/SUBSLAB(NO TUNNEL)/ TUNNEL/BSMT/CRAWL/OTHER			
11)LOCATION OF AIR RETURN: CEILING/SUBSLAB(NO TUNNEL)/ HALL/TUNNEL/BSMT/CRAWL/OTHER			
12)IS AIR RETURN DUCTED: YES/NO			
13)DOES SYSTEM HAVE A PRESSURE RELIEF: YES/NO			
14)BRIEFLY DESCRIBE ANY OTHER DETAILS ABOUT THE AIR HANDLING SYSTEM:			

C. COMPLETE THE FOLLOWING TABLE IF ANY PART OF THE BUILDING HAS UNIT VENTILATORS/FAN COILS:

UNIT VENTILATORS/FAN COILS	ORIGINAL STRUCTURE	2nd STRUCTURE	3rd STRUCTURE
1) SERVICES CLASSROOMS: YES/NO			
2) SERVICES MULTIPURPOSE: YES/NO			
3) SERVICES OFFICES: YES/NO			
4) SERVICES OTHER AREA: YES/NO			
5) TYPICAL LOCATION OF UNITS: OUTSIDE WALL/INSIDE WALL/ CEILING/TUNNEL/CRAWL/OTHER			
6) MINIMUM % OUTDOOR AIR			
7) MAXIMUM % OUTDOOR AIR			

D. COMPLETE THE FOLLOWING TABLE IF ANY PART OF THE BUILDING HAS RADIANT HEAT:

RADIANT HEAT	ORIGINAL STRUCTURE	2nd STRUCTURE	3rd STRUCTURE
1) TYPE: BASEBOARD/RADIATORS/ INTRA-SLAB PIPING/OTHER			
2) SERVICES CLASSROOMS: YES/NO			
3) SERVICES MULTIPURPOSE: YES/NO			
4) SERVICES OFFICES: YES/NO			
5) SERVICES OTHER AREAS: YES/NO			

E. COMPLETE THE FOLLOWING TABLE FOR BUILDING EXHAUSTS:

EXHAUSTS: IF KNOWN SPECIFY TOTAL CFM FOR FANS	ORIGINAL STRUCTURE	2nd STRUCTURE	3rd STRUCTURE

1) CLASSROOMS: NONE/GRAVITY/FAN			
2) CORRIDOR: NONE/GRAVITY/FAN			
3) MULTIPURPOSE: NONE/GRAVITY/FAN			
4) KITCHEN: NONE/GRAVITY/FAN			
5) CAFETERIA: NONE/GRAVITY/FAN			
6) RESTROOMS: NONE/GRAVITY/FAN			
7) LABS: NONE/GRAVITY/FAN			
8) OTHER: SPECIFY/GRAVITY/FAN			

F. THE FOLLOWING PERTAIN TO GENERAL QUESTIONS ABOUT THE BUILDING:

GENERAL INFORMATION	ORIGINAL STRUCTURE	2nd STRUCTURE	3rd STRUCTURE
1) DOES BUILDING HAVE WINDOW AC UNITS: YES/NO/PARTIALLY			
2) HVAC SYSTEM CONTROL: ENERGY MGT/ROOM CONTROLS/OTHER/ ELECTRONIC OR PNEUMATIC			
3) WERE BUILDING CONSTRUCTION PLANS AVAILABLE TO COMPLETE PROFILE SHEET? YES/NO			
4) HAVE "ENERGY CONSERVATION" MEASURES BEEN MADE: SPECIFY			
5) IS THE BUILDING WATER SUPPLY: WELL/PUBLIC			

G. IN THE SPACE BELOW, PLEASE PROVIDE ANY ADDITIONAL COMMENTS:

SECTION	COMMENTS

IF YOU HAVE ANY QUESTIONS OR NEED CLARIFICATIONS PLEASE CONTACT: KELLY LEOVIC, RADON MITIGATION BRANCH (MD-54), U.S. EPA, RESEARCH TRIANGLE PARK, NC 27711. PHONE: 919-541-7717; FAX 2157

APPENDIX C

Literature Review of Radon in Large Buildings (GEO 91)

Section 2.0

LITERATURE REVIEW OF RADON IN LARGE BUILDINGS

(NOTE: For maximum use to the reader, literature citations have been updated by EPA since their initial publication.)

2.1 INTRODUCTION

The problem of radon in large buildings has been under study by the United States Environmental Protection Agency (USEPA) since 1987 when schools with elevated radon problems were found. Many papers on large buildings have been presented at the last three USEPA Radon Symposiums, and radon in large buildings was the topic of a recent USEPA Forum. (USEPA 1990). The Indoor Radon Abatement Act of 1988 initiated several programs in schools and in work places. All Federal agencies were directed to test their buildings, and when these test results are released, they are expected to provide a nationwide data base on radon concentration in big buildings. Since 1987, research in schools has shown that the radon mitigation techniques developed for houses can often be used to mitigate large buildings. Large-scale school testing has revealed that the areas with elevated radon levels in schools are the same areas that have elevated levels in houses. The current USEPA research in schools is focusing on testing HVAC modifications for radon mitigation potential, and developing radon resistant construction techniques for new schools.

This literature review is heavily weighted toward research in schools, because there is very little literature on radon research in other types of buildings. The school data is examined for its relevance to other large buildings, and for its relevance to Florida large buildings.

2.2 LARGE BUILDING CHARACTERISTICS RELATED TO RADON

2.2.1 Definition of Large Building

If "large building" is defined as any habitable structure larger than a single-family detached house, then this is an extremely wide category. However, for the purposes of this study the term will be defined as structures that are over three stories in height or larger than 10,000 square feet in floor area, and which have HVAC systems that are more complex than home systems because they can generally provide ventilation air. The definition is meant to exclude single-story, multi-family buildings such as duplexes and condominiums because these buildings are generally considered to have radon problems that are similar to houses. The definition is intended to include most schools, office buildings, factories, and larger stores. Of course there are exceptions, such as older schools that do not have mechanical ventilation systems.

Large buildings in Florida generally differ from the stock of all large buildings in the United States because of several factors that are thought to be relevant to the potential radon problem. The factors include warm climate, the high humidity, the high water table, and the scarcity of sources of aggregate for construction. The warm climate may influence the pressure-induced radon entry. The outside temperature and high humidity increases the air-conditioning loads which provides an incentive to reduce building ventilation. The high water table limits the use of basements and makes slab-on-grade the predominant building substructure. The scarcity of aggregate makes it likely that the building substructure is constructed on sandy material with low permeability to air flow.

2.2.2 Major Determinants of Radon Entry into Large Buildings

Radon entry into buildings is generally considered to be dominated by convective flow caused by small pressure differences that draw soil gas through openings in the house substructure. Diffusion can be shown to be too small to account for the significant amount of radon found in many buildings (Nazaroff and Nero 1988), and most types of building substructure have many small openings through which soil gas can flow. The following four factors are generally considered to be the major determinants of elevated indoor radon concentrations in large buildings:

- Radon levels in the soil
- Soil gas entry routes
- Pressure differences
- Ventilation

Elevated levels of radon in the soil must be present near (typically within a meter) the building substructure. The inhomogeneity of the soil in most areas makes it very difficult to determine if a large building has a radon problem without testing all rooms that have contact with the soil. Site testing for radon before construction has generally not been proven to accurately predict the potential for radon problems in buildings subsequently constructed on the site. The best predictor for radon problems in large buildings has been the presence of nearby houses with radon problems.

Soil gas entry routes through the building substructure must be present if radon can enter the building. Unfortunately only small cracks are apparently necessary in most cases and normal building construction provides sufficient opportunities for cracks to develop such as shrinkage cracks where the slab contracts with it cures, enlarged openings around pipe and/or electrical penetrations, and control joints in the slab that are designed to control the cracking of large slab areas. Even when all of these cracks are visible and are carefully sealed, there are often enough pathways left to result in poor radon mitigation results from sealing alone.

Pressure differences are generally necessary to drive the radon into the building. In houses, these pressures are generally very small and are most often caused by both imbalance in the air distribution system and the stack effect which is caused by temperature differences between the inside and outside of the building. In heating situations, the stack effect generally depressurizes the building substructure, increasing radon entry rates. In air-conditioning situations, the stack pressure would be reversed which should retard radon entry. In larger buildings, the HVAC system may be the dominant source of pressure, but at night the HVAC system is often operated less frequently, and the stack effect may be the dominant source of pressure on the building substructure.

Ventilation will tend to dilute the radon levels in buildings, and it may increase the pressure inside the building that will impede radon entry. In houses, ventilation is primarily due to uncontrolled leakage through unintended cracks in the building shell, and it is usually driven by a combination of pressures from air distribution system imbalances, stack and wind. In large buildings, there are generally code requirements to provide a minimum amount of mechanical ventilation. Tracer gas measurements in large buildings by researchers for the National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards) have recently shown that in many big buildings, the ventilation rate can vary substantially from the building design values.

2.2.3 Stack Effect

The stack effect (ASHRAE 1989) is a pressure gradient in buildings which arises from the difference in temperature between the inside and the outside of the building. When the internal air temperature is higher than the outer air temperature, then air enters through the lower building shell leaks in the building and escapes through the upper shell leaks. The level at which there is a transition between inflow and outflow is known as the "neutral pressure plane." In practice the neutral pressure plane is difficult to measure, but it can be predicted from the distribution of all the leaks over the surface of the shell.

If the building shell leaks are uniformly distributed over the shell, then the neutral pressure plane will be located approximately midway up the side of the shell, and under winter conditions, the stack pressure expelling air at the top of the building will be the same magnitude as the pressure drawing air in at the bottom. However, if all the leaks are on the bottom of the enclosure, then the neutral pressure plane will be at the bottom and all the stack pressure will be exerted at the top of the shell. This is the force that lifts a hot air balloon. In houses, the stack effect is generally small (a few pascals, or less), but in tall buildings the lower and upper doors and windows may be difficult to open if the stack effect is not compensated for by fan pressurization or depressurization.

In houses in the northern United States, the stack effect is often the dominant force that tends to depressurize the building substructure and draw radon in through the cracks. Under air-conditioning situations as might be expected in Florida, the stack effect would likely be reversed and radon entry may require other sources of depressurization such as air distribution system imbalances. In larger buildings, during the night the HVAC system is often adjusted to provide minimum ventilation and conditioning, and the stack effect may then be the dominant source of pressure in the building.

2.2.4 Ventilation and Ventilation Efficiency

Ventilation is defined as the introduction of outside air for the purpose of diluting the contaminants generated indoors under the assumption that outside air is cleaner than inside air. In the past, the acceptable levels of ventilation required for human comfort have been related to the removal of body odors, but more recently the acceptable rates have been related to pollution from smoking and chemicals out-gassing from materials in the large building. ASHRAE and BOCA codes have recommended ventilation rates that depend on the type of activity and materials that are expected to be found in the large building. Large building minimum recommended ventilation rates have risen from the 1981 recommendations of 5 cubic feet per minute (cfm) in a nonsmoking office space to 15-20 cfm in 1989 (ASHRAE 62-1989). A second aspect of ventilation is the evenness of the distribution of fresh air to the occupants of the space. This generally referred to as "ventilation efficiency" and if it is poor, some building occupants or building areas may not be receiving adequate ventilation even when the average ventilation meets the recommended levels.

Ventilation and ventilation efficiency are difficult to measure, so it is not a common practice to verify by test whether a building actually achieves its design ventilation levels. Even if the building was designed correctly, the equipment was installed correctly, it is properly maintained, and the building personnel understand how to operate it, it may be operated for the best energy conservation rather than adequate ventilation. Fortunately, there does not seem to be a correlation between indoor pollution problems and ventilation rates. This is probably due to the fact that although ventilation rates may vary by a factor of 10, the pollutant source strengths vary by much larger factors. For instance, the radon sources under problem buildings may be hundreds or thousands of times stronger than the radon under typical buildings.

2.2.5 HVAC Systems in Large Buildings

Large buildings vary greatly in size and also in their heating, ventilating and air-conditioning (HVAC) systems. HVAC systems can have a significant impact on the radon concentrations in a building because of their possible pressurization or depressurization on the ground contact rooms, the introduction of fresh air which can dilute any radon that is drawn in, and their distribution of radon throughout the building. The major types of large building ventilation systems and their radon potential (Turner and Greim 1988 and 1989) include:

- Passive Systems

- Exhaust Only Systems
- Unit Ventilators
- Terminal Air Blenders
- Unitary Heat Pumps or Fan Coil Units
- Heat Recovery Ventilators
- Central Station Air Handlers

Passive systems rely on stack effect and wind pressures to drive air through the building. This is the source of ventilation in most houses because the heating or cooling system is not designed to intentionally introduce fresh air into the building. Older large buildings often do not have mechanical ventilation. Note that the forced air circulation systems in houses and large buildings often induce considerable ventilation because of duct leakage and improper pressure balancing. Therefore, HVAC systems without mechanical ventilation may have ventilation by either stack/wind pressures or by defects in the air distribution system. It is impossible to predict in advance what effects will be dominant in determining the radon concentration in this type of building.

Exhaust only systems consist solely of exhaust fans which are often installed in halls, bathrooms and kitchens. Older HVAC systems sometimes incorporated window openings as a vital part of the ventilation system, but during extreme weather it will not be very comfortable to increase ventilation. These systems would be expected to increase radon entry because of increased depressurization of the building substructure, but they also increase ventilation, so the net impact on indoor radon concentrations is unclear. This type of HVAC system is common in houses and older schools.

Unit ventilators are small, wall-mounted HVAC units, usually consisting of a fan enclosure containing heating/cooling coils, and generally have a vent to the outside for ventilation air. Due to their low cost and easy architectural coordination, they are quite popular in many schools and other large buildings. When they are providing outside air, they provide some dilution and some pressurization of the room. However, they are generally controlled to save energy and not to provide ventilation, and this will lessen any radon reductions caused by pressurization or dilution.

Terminal air blenders are HVAC fan systems that use fresh air to modulate the heating requirements. As the outside temperature varies from the thermostat temperature, less fresh air is supplied until a minimum design ventilation rate is reached at an outside temperature that is selected to have a low probability of occurrence (about 10 percent). This type of HVAC system would be expected to provide overall pressurization of the building, although there could be local areas of depressurization.

Unitary heat pumps or fan coil units would not be expected to cause any pressure change in the school unless they have outside ventilation air ducted to the unit. If outside air is provided, then pressurization of the space is possible and radon entry may be reduced by the pressurization and the radon concentration indoors may be reduced by dilution provided by the fresh air. Again, if the air distribution system is imbalanced or leaky, then the radon concentration will be affected in an unpredictable way.

Heat Recovery Ventilators allow the supply of fresh air with less energy penalty because they allow the outside ventilation air to exchange heat with stale outgoing air. Since these systems require approximately balanced air flow, they would not be expected to change the net pressure balance in a building, but would increase the dilution thereby tending to reduce radon concentrations.

Central station air handlers consist of separate supply and return fans, tempering coils, dampers and controls. One type is the constant volume system where a two-position damper controls the fresh air supply depending on building and environmental conditions. One disadvantage is that the fan is always operating at full power. Another type is a variable air volume (VAV) control where the fresh air supply is continuously varied. This saves fan energy but ventilation rates are sometimes low when a zone in the building does not require conditioned air. Other variants are VAV with economizer or VAV with outside air control and heat recovery. All of these systems have the potential to provide an increase in enclosure pressurization and increased ventilation, but they are quite complex, and their performance depends on proper design, installation, balancing, and maintenance. The operators must have a good understanding of the system and must have performance goals that are consistent with good air quality and possibly not just energy conservation performance.

2.2.6 Building Substructure

The substructure of a building, the part that is in contact with the ground, may have a significant impact on its potential for radon problems. Most buildings have one (or a combination) of three types of substructures:

- Basement Construction
- Slab-on-Grade

- Crawl Space

Basement construction allows large areas of floor and walls to be in ground contact and generally has the greatest potential for radon entry. Most basements have cracks between the floor slab and the walls where radon can enter, as well as penetrations around pipes, and cracks in the slab or walls. Larger buildings often have basement substructures and may even have utility chases or tunnels which provide even more avenues for radon entry. Buildings in Florida do not generally have basements because of the high water table.

Slab-on-grade building substructures are common for houses in some areas, very common for schools, and are also used for many larger buildings. They have somewhat less radon entry potential than basements, but many houses and schools with this substructure have been found to have radon problems. This is the most common type of Florida building construction. In many parts of the United States, a layer of porous aggregate is placed under the slab for drainage, and this has proven to be very beneficial for future installation of radon mitigation system by the technique of active subslab depressurization (ASD). However, aggregate is not readily available in Florida, and sand is often used instead. This material is much less impermeable to air flow than aggregate and radon mitigation by ASD is much more difficult.

Crawl space building substructures are common in some areas for houses, and they are also found in schools and some larger buildings. In many cases they were designed with the intent that they could be passively ventilated by opening vents on all sides, but experiments have shown that air generally enters all of these vents, picks up any radon, and then the mixture is drawn up into the building by stack effect or ventilation depressurization. Many crawl space homes and schools have been found with radon problems. Crawl spaces are not a common building technique for Florida schools and large buildings.

2.2.7 Building Occupancy and Use

Building occupancy and use can have a major impact on radon levels in large buildings because of the HVAC system cycles. In larger buildings, there is a significant economic incentive not to provide the same level of heat, cooling or ventilation during unoccupied times (typically nights and weekends). Houses do not normally go through these radical ventilation cycles because they lack a mechanical ventilation system that can be turned on and off. It is not uncommon for large buildings to have lower radon levels when they are occupied because of high ventilation and building pressurization, but the radon concentration levels at night may increase because the HVAC system is off or operating at a reduced level. Since most radon tests integrate over several days, they may not show the temporal variations in occupant exposures.

2.3 PRECONSTRUCTION SITE SURVEYS

It is possible to identify areas with a high radon risk, or to test a specific site to estimate the risk? The USEPA and the U.S. Geological Service (Gunderson 1991) have developed a map summarizing the radon potential for each county in the United States. This might be used by builders and code officials in "hot" areas to consider using radon resistant construction techniques. *This map has been released by USEPA and was incorporated into EPA's development of a Map of Radon Zones (EPA 1993)*. The research in the area of site surveys is generally inconclusive because of the complexity of the problem and the difficulty of doing a sufficient number of controlled tests. One recent paper (Llewelleyn 1991) suggests that previous researchers did not measure enough locations for a long enough time. Some researchers (e.g., Hall 1988) report some successful correlations between soil surveys and indoor radon concentrations, but controlled studies with large numbers of samples are difficult to perform.

One example of the ambiguities of a large-building site survey is given by research on a school in Fairfax County, Virginia (Witter, Craig and Saum 1988). The site was surveyed by U.S. Geological Survey and some locations with high radon concentrations were found. Some radon-resistant features were built into the school, but no elevated concentrations were found when the school was first tested. After three years, the school was retested, and some elevated radon levels were found in one wing of the school. It is unclear what changes had taken place in the school, but the HVAC system was found to be operating in an energy-conserving night set-back mode rather than the recommended continuous-ventilation mode recommended for radon control. The elevated locations could not be clearly correlated with the soil test results. It appears that the inhomogeneity of the soil, the grading and fill at the site before construction, and the complexity of the school HVAC system and substructure, all tend to limit the precision of the initial site survey.

2.4 MODELING INDOOR RADON CONCENTRATIONS

Radon modeling has historically focused on either the building or the soil. Soil models have concentrated on predicting the radon entry rate from the dynamics of transport through the soil and foundation cracks without much consideration of the building physics or weather dynamics (e.g., Rogers and Nielsen 1990). Alternatively, building models have concentrated on predicting the indoor radon concentration from the above-ground characteristics of the buildings, the HVAC system action, and weather influences on the building (e.g., Saum and Modera 1991). Since radon concentrations in large buildings appear to be dominated by the HVAC system effects, it appears that a building model rather than a soil model would be most useful in understanding the radon concentration dynamics as the HVAC and weather change. Ideally, the two types of models should be integrated.

A simple building model was developed for slab-on-grade single-zone structures by Saum and Modera, but this model was limited to winter stack dominated or exhaust fan depressurization. Modera is currently working on an extension of this model. Saum is currently working on a simple model for indoor radon concentrations in the slab-on-grade single-zone situation for supply ventilation conditions (Saum and Leovic 1991). This model divides the radon mitigation effect into a pressure factor and a dilution factor. For instance, it can be used to evaluate the radon mitigation effect of changing building ventilation to meet ASHRAE Standard 62-1989.

Radon mitigation in Florida buildings has the special problem of low-permeability material under most slabs. One recent paper (Hintenlang and Furman 1990) models this type of soil-gas flow and provides experimental confirmation of some of the results.

2.5 HVAC EFFECTS ON RADON CONCENTRATIONS IN LARGE BUILDINGS

The use of HVAC systems for radon mitigation in large buildings has appeared to be attractive, especially when the subslab conditions are poor for an ASD system, and adjustments to the HVAC system may appear to be quite simple. The increased ventilation is often needed to bring the building up to modern ventilation standards. However, most of the studies have run into problems with poor maintenance, a bias toward energy conservation rather than ventilation, and a poor understanding of the operation of a complex system. For instance, the first new school that was built to operate with HVAC overpressurization (Witter, Craig and Saum 1988) was found, 2 years later, to be running in an energy conservation mode that defeated the radon control objectives (Saum and Leovic 1991). The energy management department who had control of this HVAC system did not follow through on the radon control plan that was decided during construction. Although this is only one case, it suggest that radon control by HVAC modifications can be politically as well as technically complex.

There are two USEPA projects on evaluation of HVAC radon mitigation in schools. Saum is investigating one school with unit ventilator systems and another school with a VAV system. These systems were modified/programmed for varying levels of ventilation, while radon and environmental parameters were monitored. Pyle is similarly investigating a school with unit ventilators. Both these reports will be available in the fall. A theoretical model for predicting the radon mitigation effects of increasing ventilation is being developed by Saum and will be included in the report. This model was discussed in the modeling section of this report.

2.6 RADON MEASUREMENTS IN LARGE BUILDINGS

Radon measurements in large building are more difficult than measurements in houses, if the goal is to accurately measure occupant exposure. In a house, the occupants are generally assumed to be in the house all day, and an integrating measurement over several days is acceptable. But in a large building, radon levels often change dramatically as the HVAC system changes the ventilation rates during occupied and unoccupied periods. In many cases, the ventilation rate is much higher during occupied periods and the radon concentrations are lower due to dilution and pressurization. This complicates the interpretation of integrated radon measurements that span several days. This problem led to the development of the radon measurement protocol for schools (USEPA 1989) which requires that integrated measurements be made with the HVAC system running continuously in the occupied mode. Perhaps the best technique to get an unbiased estimate of the actual occupant exposure is to use a continuous monitor (Wiggers, et al. 1990) and only integrate during occupied hours. Even this technique has problems because there are instrument time response lags in most types of continuous radon monitors that are difficult to remove.

The Indoor Radon Abatement Act of 1988 required all Federal agencies to test their buildings, and a report on these tests is currently undergoing internal review with the Federal government. Eighty-five percent of the 80,000 measurements were under 2 pCi/L and 95 percent were under 4 pCi/L.

One set of radon measurements for large buildings is from a study of indoor air quality measurement in 38 commercial buildings in the Pacific Northwest during 1984 and 1985 (Turk, et al. 1987). Measurements including ventilation rates and radon concentrations, as well as the concentration number of pollutants were measured. In general, the measured ventilation rates were high compared to design standards, and the pollutant concentrations were low compared to commonly recognized standards and guidelines. Only one building with a significant radon problem was found: it had radon levels of 7.8 pCi/L. This building had an HVAC system that drew "outside" air through a basement with an open soil floor and from a network of underground service tunnels. Conclusions related to radon testing from this study are as follows:

- In areas with high radon potential, radon problems might be expected in buildings with foundations allowing exposed soil and with HVAC systems that depressurize the foundation
- Service tunnels connected to buildings may allow entry of radon.
- Ventilation rates varied widely in the buildings and the operators often did not understand the operation of the HVAC systems.
- The mean radon measurement was 0.5 pCi/L similar to outside levels
- No indication of radon transport to upper floors was noticed in high-rise buildings
- Although ventilation rates were sometimes quite low, few air pollution problems were traced to this
- The correlation between pollutant concentrations and ventilation rates was weak, suggesting, as seen in past studies, that pollution is primarily due to the presence of strong pollutant sources and not ventilation rates.

Another study that combines radon and extensive indoor air quality measurements was performed by NIST at a new Federal office building in Portland, Oregon during 1986 and 1987 (Grot and Persily 1989). The building is seven stories tall with a one-story basement and a three-story underground parking garage. The occupied area is 495,000 square feet. It is served by three VAV-type HVAC systems and there are several elevator and stair shafts. Significant results include large variations in ventilation rates over the course of the year, very large uncontrolled air leakage, and transport of carbon monoxide and radon up the vertical shafts to the upper stories of the building. The ventilation rates vary from 0.4 to 2.2 air changes per hour (ach) which may be compared to the 0.7 ach which can be computed from the ventilation recommendations of the ASHRAE 62-1989 Ventilation Standard (20 cfm per person). This wide variation could lead to under or overventilation which would affect the dilution of pollutants such as radon. The building air leakage is the uncontrolled air leakage when the HVAC fans are off, and it was measured between 0.2 and 0.4 ach. This was equivalent to a house with a leakage of 1.2. to 2.4 ach which is several times leakier than most houses.

The uncontrolled leakage suggest flaws in the building shell and its ventilation that are not well understood. Although the radon levels were quite low (around 1 pCi/L) the levels on the upper floors were consistently higher than the lower above-grade floors, suggesting that the vertical shafts were transporting the basement pollutants to the higher floors. The carbon monoxide showed a similar transport up from the garage. In summary, the ventilation and air infiltration in this large building seem to be less well controlled than might be expected, and we have evidence of preferential pollutant flow from the lower levels of the building to the upper levels. Sever other NIST studies of "sick" office buildings include radon measurements (Persily, Dols, Nabinger and VanBronkhorst 1989), (Dols and Persily 1989) and (Persily, Dols, Nabinger and Kirchner 1991), but the radon levels are very close to background.

One report of radon measurements that suggest significantly lower measurement in large buildings during occupied periods involves surreptitious measurements of Pittsburgh office and college buildings (Cohen, et al. 1984). Students took samples of air from various commercial and school buildings that they visited during the day. These radon levels in these samples were compared with the home radon test data from the same areas. Conclusions from this study are as follows:

1. Average daytime commercial building levels may be an order of magnitude lower than home levels in the same area.

2. Colleges and universities seem to have higher daytime radon levels than commercial buildings, possibly related to better ventilation of commercial buildings.

3. Age of buildings did not seem to be an important factor.

4. There was little indication that radon levels in these buildings were higher in the winter than in the summer.

Note that this study may not have taken any measurements in the commercial buildings at night when the HVAC systems were off and the radon levels are probably highest. Of course there is a much lower occupancy at night.

2.7 RADON DIAGNOSIS AND MITIGATION IN LARGE BUILDINGS

2.7.1 Radon Diagnosis in Large Buildings

Radon diagnosis in large buildings can be quite complex. One report on radon diagnostic work in a large office building (Saum and Messing 1991) reports using the following types of measurements:

- Subslab radon grab samples

- Continuous radon in each HVAC zone

- Continuous differential pressure across the slab in each HVAC zone.

- Room-to-room pressure differential

- Integrated radon (EIC monitors) in several rooms of each zone.

This range of diagnostic measurements is not usually justified in a house, but may be essential in a large building were HVAC modification may seriously be considered as a mitigation option. Additional diagnostic measurements might include subslab communication tests and ventilation measurements.

School radon mitigation work is generally focused on making ASD systems work, and the primary diagnostic tool for ASD is the subslab communication or pressure field extension (PFE) test (e.g., Leovic, Craig, Harris, Pyle and Webb 1991). Experience has shown that most HVAC depressurization effects in big buildings can be ignored if the ASD system has an adequate PFE.

2.7.2 Radon Mitigation in Large Buildings

There is now extensive research literature on the excellent radon mitigation performance of ASD systems in slab-on-grade and basement schools where there is a porous material, such as aggregate, beneath the slab. For crawl space buildings, there is less experimental data, but the techniques of active soil depressurization and crawl space depressurization have been shown to provide significant radon mitigation (Pyle and Leovic 1991).

Most of the research literature on large-building radon mitigation is based on experience in schools using ASD. One office building was reported to have achieved a 50 percent reduction in indoor radon concentrations by increasing the fresh air supply to the VAV units (Saum and Messing 1991). This same office building has subsequently achieved an additional 50 percent decrease in radon levels by sealing some large cracks in areas where there was significant depressurization.

2.8 RADON RESISTANT NEW CONSTRUCTION

Major progress has been made in developing radon resistant new construction techniques for schools and other large buildings since USEPA research in this area was started in 1987. Although some of the initial new school experiments (Witter, Craig and Saum 1988) involved HVAC overpressurization, the most successful technique has been ASD. Laboratory work on aggregate effects on pressure field extension (Gadsby, et al. 1991) revealed the importance of the boundary conditions at the edge of the slab. The latest work involves an analysis of the costs of several ASD designs that have recently been built in the northeastern United States (Craig, Leovic and Saum 1991). This study suggests that radon contractors are installing effective, but over designed ASD systems. Work by Craig of USEPA Office of Research and Development (ORD) suggests that proper design of the subslab suction pit, optimum aggregate selection, and reduction of footing interference with pressure field extension can result in excellent radon mitigation with only one stack and fan for coverage of 50,000 or more square feet of slab area (Craig, Harris, and Leovic 1992).

For Florida new construction, the optimized ASD techniques may not be very useful if aggregate is not available. One alternative would be to incorporate an extensive perforated pipe (or drainage matting) network beneath the slab to make up for the lack of air flow through the sand. No experiments have been reported on large slabs with this type of ASD system. Alternatively, an HVAC overpressurization technique could be used. HVAC radon mitigation is under investigation in several schools (Saum and Leovic 1991). Both these options will be more expensive than the optimized ASD system, but the cost is a very small fraction of the cost of the building.

2.9 CONCLUSIONS OF THE LITERATURE REVIEW

The prevalence of radon problems in Florida large buildings is not precisely known, but problems may be expected in the same areas where elevated levels have been found in houses. Survey data from large Florida buildings will be available from the Federal Workplace Study, but this data has not been released yet.

The characteristics of large buildings in Florida that appear to be most significant for potential radon problem entry are: 1) the predominance of slab-on-grade construction, 2) the low porosity of the material under most slabs, 3) the potential for reverse stack effect pressures, and 4) the increased costs of ventilation due to high outdoor humidity.

Radon-resistant new construction techniques that have recently been successfully demonstrated for large buildings may be difficult to use in Florida because the primary technique relies on a layer of porous aggregate under the building slab. Florida construction may require either finding substitutes such as drainage matting, or be relying on alternative strategies such as sealing, avoidance of depressurization, and HVAC overpressurization.

Radon entry mechanisms in Florida buildings appear to rely less on stack effect depressurization of the building substructure (which should be reversed under air-conditioning situations), and more on HVAC-related depressurization.

Research in progress that is expected to be useful in the understanding of large building radon problems in Florida includes: 1) USEPA field research on HVAC radon mitigation in schools, 2) USEPA field research on pressures in Florida test structures, and 3) USEPA modeling of substructure pressures due to weather.

Data bases that may be useful for evaluation of the Florida Large-building radon problem include the forthcoming Federal Workplace Survey, and Federal Building Survey.

Section 6.0

REFERENCES FROM THE LITERATURE REVIEW

(NOTE: For maximum use to the reader, references have been updated by EPA since their initial publication.)

Introduction - Large Building Characterization

ASHRAE, 1989 Handbook of Fundamentals, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, 1989.

ASHRAE 62, "Ventilation for Acceptable Indoor Air Quality," ASHRAE Standard 62-1989, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, 1989.

Greim, C. and Turner, W., Guaranteeing Minimum Outside Air Quantities: Historical Methods and New Horizons, Harriman Associates, presented at ASHRAE Energy Seminar "Indoor Air Quality: Issues, Engineering, and the Future," Portland, ME, April 6, 1988.

U.S. EPA Office of Radiation Programs, Proceedings of the 1990 Forum on Radon Prevention in Large Buildings, prepared by SC&A, Inc., McLean, VA, June 1990.

Preconstruction Site Surveys

Gunderson, L., Geologic Radon Potential of the United States, U.S. Geologic Survey, Reston VA. *This map has been released by USEPA and was incorporated into EPA's development of a Map of Radon Zones (EPA 1993).*

Hall, S.T., "Correlation of Soil Radon Availability Number with Indoor Radon and Geology in Virginia and Maryland," In: Proceedings of the EPA/USGS Soil Gas Meeting, Washington, DC, September 1988.

Llewellyn, R.A., "Radon in Large Buildings: Pre-Construction Soil Radon Surveys," In: Proceedings: The 1991 International Symposium on Radon and Radon Reduction Technology Vol. 4, EPA-600/9-91-037d (NTIS PB92-115385), November 1991.

U.S. EPA, EPA Map of Radon Zones, Arizona, EPA-402-R-93-023, September 1993.

Witter (Leovic), K.A., Craig, A.B., and Saum, D.W., "New Construction Techniques and HVAC Overpressurization for Radon Reduction in Schools," In: Proceedings of ASHRAE IAQ'88, Atlanta, 1988, EPA-600/D-88-073 (NTIS PB88-196159).

Modeling Indoor Radon Concentrations

Hintenlang, D.W. and Furman, R.A., "Sub-Slab Suction System Design for Low Permeability Soils," In: Proceedings: The 1990 International Symposium on Radon and Radon Reduction Technology, Vol 3, EPA-600/9-91-026c (NTIS PB91-234468), July 1991.

Nazaroff, W. and Nero, A.V., editors, Radon and Its Decay Products in Indoor Air, John Wiley & Sons, New York, 1988.

Rogers, V.C. and Nielsen, K.K., "Benchmark and Application of the RAETRAD Model," In: Proceedings: The 1990 International Symposium on Radon and Radon Reduction Technology, Vol. 2, EPA-600/9-91-026b (NTIS PB91-234450), July 1991.

Saum, D.W. and Modera, M., Radon Mitigation Impact of Measures to Reduce Depressurization in New House Construction, Infiltec, Falls Church, VA, August 1991.

Saum, D.W., "Case Studies of Radon Reduction in Maryland, New Jersey, and Virginia Schools," EPA-600/R-93-211 (NTIS PB94-117363), November 1993.

HVAC Effects on Radon Concentrations in Large Buildings

Brennan, T., Fisher, G., Thompson, R., and Turner, W., "Extended Heating, Ventilating and Air-Conditioning Diagnostics in Schools in Maine," In: Proceedings: The 1991 International Symposium on Radon and Radon Reduction Technology, Vol. 2, EPA-600/9-91-037b (NTIS PB92-115369), November 1991.

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, Vol. 2, EPA-600/9-91-037b (NTIS PB92-115369), November 1991.

Leovic, K.W., Craig, A.B., and Saum, D.W., "The Influences of HVAC Design and Operation on Radon Mitigation of Existing School Buildings," In: Proceedings of ASHRAE IAQ '89, The Human Equation: Health and Comfort, San Diego, CA, EPA-600/D-89-015 (NTIS PB89-218762), 1989.

Leovic, K.W., Harris, D.B., Dyess, T.M., Pyle, B.E., Boradk, T., and Saum, D.W., "HVAC System Complications and Controls for Radon Reduction in School Buildings," In: Proceedings: The 1991 International Symposium on Radon and Radon Reduction Technology, Vol 2, EPA-600/9-91-037b (NTIS PB92-115369), November 1991.

Saum, D.W., "Case Studies of Radon Reduction in Maryland, New Jersey, and Virginia Schools," EPA-600/R-93-211 (NTIS PB94-117363), November 1993.

Turner, W. and Greim, C., Types of HVAC Systems and Their Possible Interaction with Radon Levels in Schools, Harriman Associates, Auburn, ME, July 1989.

Witter (Leovic), K.A., Craig, A.B., and Saum, D.W., "New-Construction Techniques and HVAC Overpressurization for Radon Reduction in Schools," In: Proceedings of ASHRAE IAQ'88, Atlanta, GA, EPA-600/D-88-073 (NTIS PB88-196159), 1988.

Radon Measurements in Schools

Belanger, W. and Pyles, M., "Prediction of Maximum Radon Concentrations in Schools Using Partial Sampling Methods," In: Proceedings: The 1990 International Symposium on Radon and Radon Reduction Technology, Vol. 3, EPA-600/9-91-026c (NTIS PB91-234468), July 1991.

Grodzins, L., "Radon in Schools of Massachusetts," In: Proceedings: The 1990 International Symposium on Radon and Radon Reduction Technology, Vol. 2, EPA-600/9-91-026b (NTIS PB91-234450), July 1991.

MacWaters, J., Mollyn, G., and Inge, T., Radon Measurement in Schools, SC&A, Inc. McLean, VA, EPA-402/R-92-014 (NTIS PB93-237493), July 1988.

Morth, T.H., Jacobson, A.L., Killingbeck, J.E., Lindsey, T.D., and Johnson, A.L., "Radon Measurements in North Dakota Schools," In: Proceedings: The 1991 International Symposium on Radon and Radon Reduction Technology, Vol. 4, EPA-600/9-91-037d (NTIS PB92-115385), November 1991.

Peake, R.T., Schmidt, A., MacWaters, J.T., and Chmelynski, H., "Radon Measurements in 130 Schools: Results and Implications," In: Proceedings: The 1990 International Symposium on Radon and Radon Reduction Technology, Vol 2, EPA-600/9-91-026b (NTIS PB91-234450), July 1991.

Schmidt, A.L., "The Results of EPA's School Protocol Development Study," Presented at The 1991 International Symposium on Radon and Radon Reduction Technology, Philadelphia, PA, April 1991.

Schmidt, A., Peake, R.T., Mac Waters, J.T., and Chmelynski, H., "EPA's Protocol Development Study - Phase II," In: Proceedings: The 1990 International Symposium on Radon and Radon Reduction Technology. Vol. 3, EPA-600/9-91-026c (NTIS PB91-2344668), July 1991.

U.S. EPA, "Radon Measurements in Schools: An Interim Report," EPA-520/1-89-010 (NTIS PB89-189419), March 1989.

Warren, H.E. and Romm, E.G., "The State of Maine School Radon Project: The Design Study," In: Proceedings: The 1991 International Symposium on Radon and Radon Reduction Technology, Vol. 4, EPA-600/9-91-037d (NTIS PB92-115385), November 1991.

Wiggers, K.D., Bullers, T.D., Zoske, P.A., Leovic, K.W., and Saum, D.W., "Electret Ion Chambers for Radon Measurments in Schools During Occupied and Unoccupied Periods," In: Proceedings: The 1990 International Symposium on Radon and Radon Reduction Technology, Vol. 3, EPA-600/9-91-026c (NTIS PB91-234468), July 1991.

Radon Measurements in Large Buildings (other than schools)

Boyd, M., Inge, T., and MacWaters, J., "Measuring Radon in the Workplace," In: Proceedings: The 1990 International Symposium on Radon and Radon Reduction Technology, Vol. 3, EPA-600/9-91-026c (NTIS PB91-234468), July 1991.

Cohen, B., et al., "Radon Concentrations Inside Public and Commercial Buildings in the Pittsburgh Area," Health Physics, Vol. 47, No 3, pp 399-405, September 1984.

Dols, S.W. and Persily, A.K., Ventilation and Air Quality Investigation of the U.S. Geological Survey Building, National Institute of Standards and Technology, NISAT 89-4126, Gaithersburg, MD, July 1989.

Grot, R.A. and Persily, A.K., Environmental Evaluation of the Portland East Federal Office Building Preoccupancy and Early Occupancy Results, National Institute of Standards and Technology, NIST 89-4066, Gaithersburg, MD, April 1989.

Llewellyn, R.A., "Radon Surveys in Large buildings: The UCF Radon Project," In: Proceedings: The 1990 International Symposium on Radon and Radon Reduction Technology, Vol. 2, EPA-600/9-91-026b (NTIS PB91-234450), July 1991.

Persily, A.K., Dols, S.W., Nabinger, S.J., and Kirchner, S., Preliminary Results of the Environmental Evaluation of the Federal Records Center in Overland, Missouri, National Institute of Standards and Technology, NISTIR 4634, Gaithersburg, MD, July 1991.

Persily, A.K., Dols, S.W., Nabinger, S.J., and VonBronkhorst, D.A., Air Quality Investigation in the NIH Radiation Oncology Branch, National Institute of Standards and Technology, NISTIR 89-4145, Gaithersburg, MD, August 1989.

Tuccillo, K. and Depierro, N., "Radon Levels in Non-Residential Buildings in New Jersey," In: Proceedings: The 1990 International Symposium on Radon and Radon Reduction Technology, Vol. 3, EPA-600/9-91-026c (NTIS PB91-234468), July 1991.

Turk, B., et al., Indoor Air Quality and Ventilation Measurements in 38 Pacific Northwest Commercial Buildings, LBL 22315, Lawrence Berkeley Laboratory, Berkeley, CA, December 1987.

Radon Diagnosis and Mitigation in Schools

Brennan, T., Fisher, G., Thompson, R., and Turner, W., "Extended Heating, Ventilating and Air Conditioning Diagnostics in Schools in Maine," In: Proceedings: The 1991 International Symposium on Radon and Radon Reduction Technology, Vol. 2, EPA-600/9-91-037b (NTIS PB92-115369), November 1991.

Craig, A.B., Leovic, K.W., Harris, D.B., and Pyle, B.E., "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, EPA-600/9-91-026b (NTIS PB91-234450), July 1991.

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, EPA-600/9-91-026c (NTIS PB91-234468), July 1991.

Fisher, E., Thompson, B., Brennan, T., and Turner, W., "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, Vol.2, EPA-600/9-91-037b (NTIS PB92-115369), November 1991.

Leovic, K.W., Craig, A.B., and Saum, D.W., "Radon Mitigation in Schools: Part 1," ASHRAE Journal, Vol. 32, No 1, pp 40-45, January 1990.

Saum, D.W., Craig, A.B., and Leovic, K.W., "Radon Mitigation in Schools: Part 2," ASHRAE Journal, Vol. 2, No 2, pp 20-25, February 1990.

Leovic, K.W., Craig, A.B., Harris, D.B., Pyle, B.E., and Webb, K., "Design and Application of Active Soil Depressurization (ASD) Systems in School Buildings," In: Proceedings: The 1991 International Symposium on Radon and Radon Reduction Technology, Vol. 4, EPA-600/9-91-037d (NTIS PB92-115385), November 1991.

Leovic, K.W., Craig, A.B., and Saum, D.W., "The Influences of HVAC Design and Operation on Radon Mitigation of Existing School Buildings," In: Proceedings of ASHRAE IAQ'89, The Human Equation: Health and Comfort, San Diego, CA, EPA-600/D-89-015 (NTIS PB89-218762), 1989.

Leovic, K.W., Craig, A.B., and Saum, D.W., "Characteristics of Schools With Elevated Radon Levels," In: Proceedings: The 1988 International Symposium on Radon and Radon Reduction Technology, Vol 1, EPA-600/9-89-006a (NTIS PB89-167480), March 1989.

Leovic, K.W., Craig, A.B., and Saum, D.W., "Radon Mitigation Experience in Difficult-to-Mitigate Schools," In: Proceedings: The 1990 International Symposium on Radon and Radon Reduction Technology, Vol. 2, EPA-600/9-91-026b (NTIS PB91-234450), July 1991.

Pyle, B.E. and Leovic, K.W., "A Comparison of Radon Mitigation Options for Crawl Space School Buildings," In: Proceedings: The 1991 International Symposium on Radon and Radon Reduction Technology, Vol. 2, EPA-600/9-91-037b (NTIS PB92-115369), November 1991.

Sinclair, L.D., Dudney, C.S., Wilson, D.L., and Saultz, R.J. "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, EPA-600/9-91-026b (NTIS PB91-234450), July 1991.

Turner, W.A., Leovic, K.W., and Craig, A.B., "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, EPA-600/9-91-026b (NTIS PB91-234450), July 1996.

U.S. EPA, Radon Reduction Techniques in Schools, Interim Technical Guidance, EPA-520/1-89-020 (NTIS PB90-160086), October 1989.

Radon Diagnosis and Mitigation in Large Buildings (other than schools)

Messing, M., Diagnostic Analysis of Radon Remediation in the Germantown Building, Prepared for the U.S. Department of Energy by Infiltec, Falls Church, VA, August 1988.

Saum, D.W., and Messing, M., "Radon Diagnosis in a Large Commercial Office Building," In: Proceedings: The 1991 International Symposium on Radon and Radon Reduction Technology, Vol. 2, EPA-600/9-91-037b (NTIS PB92-115369), November 1991.

Radon Resistant New Construction

Meehan, T., "Major Renovation of Public Schools That Includes Radon Prevention: A Case Study of Approach, System Design and Installation; and Problems Encountered," In: Proceedings: The 1991 International Symposium on Radon and Radon Reduction Technology, Vol. 4, EPA-600/9-91-037d (NTIS PB92-115385), November 1991.

Craig, A.B., Leovic, K.W., and Harris, D.B., "Design of Radon Resistant and Easy-to-Mitigate New School Buildings," In: Proceedings: The 1991 International Symposium on Radon and Radon Reduction Technology, Vol. 2, EPA-600/9-91-037b (NTIS PB92-115369), November 1991.

Craig, A.B., Leovic, K.W., and Saum, D.W., "Cost and Effectiveness of Radon Resistant Features in New School Buildings," Presented at ASHRAE IAQ'91: Healthy Buildings, Washington, DC, September 2-5, 1991.

Craig, A.B., Harris, D.B., and Leovic, K.W., "Radon Prevention in Construction of Schools and Other Large Buildings - Status of EPA's Program." In:Proceedings: The 1992 International Symposium on Radon and Radon Reduction Technology, Vol. 2, EPA-600/9-93-083b (NTIS PB93-196202), May 1993.

Gadsby, K.J., Reddy, T.A., Anderson, D.F., Gafgen, R., and Craig, A.B., "The Effect of Subslab Aggregate Size on Pressure Field Extension," In: Proceedings: The 1991 International Symposium on Radon and Radon Reduction Technology, Vol. 2, EPA-600/9-91-037b (NTIS PB92-115369), November 1991.

Saum, D.W., Case Studies of Radon Reduction in Maryland, New Jersey, and Virginia Schools, EPA-600/R-93-211 (NTIS PB94-117363), November 1993.

Witter (Leovic), K.A., Craig, A.B., and Saum, D.W., "New-Construction Techniques and HVAC Overpressurization for Radon Reduction in Schools," In: Proceedings of ASHRAE IAQ'88, Atlanta, 1988, EPA-600/D-88-073 (NTIS PB88-196159).

APPENDIX D

Large Building Survey Questionnaire (SHA 94)

PERMIT NO: .... DATE: ....
ADDRESS: ....
ENGINEER/ARCHITECT: .... TEL: ....

1. NUMBER OF FLOORS: .... FLOORS
2. TOTAL AREA & FOOTPRINT AREA: .... S.F. .... S.F.
3. AVERAGE LENGTH & WIDTH: .... FT .... FT
4. HEIGHT OF BLDG & BOTTOM FLOOR: .... FT .... FT
5. TYPICAL SLAB THICKNESS: .... IN
6. CONCRETE COMPRESSIVE STRENGTH: .... PSI ... ADMIXTURE ... CURE C.
7. BUILDING USE ....
8. BUILDING TYPE: ... STEEL ... REINF CONCRETE ... WOOD ... STEEL/CONCRETE ... MASONRY ... OTHER
9. SLAB/FOUNDATION DETAILS: ... MONOLITHIC ... STEM WALL ... FLOATING ... OTHER
10. FOUNDATION TYPE: ... PILES ... SPREAD FOOTING ... RAFT FTG ... CONTINUOUS FTG ... COMBINED ... OTHER
11. TYPE/THICKNESS OF VAPOR BARRIER: ....
12. SUBSLAB SOIL COMPACTION LEVEL: ....
13. NUMBER OF AIR HANDLERS/FLOOR: ....
14. SLAB/PENETRATION SEALING TYPE: ....
15. LOCATION OF ELEVATOR SHAFT: ... CENTRAL ... SIDE ... OUTSIDE ... SHAFT NUMBER
16. TYPE OF LARGE SLAB OPENINGS: ... ELEVATOR ... INDOOR PLANTS ... WIDE PIPES ... EQUIPMENTS ... CRAWL SPACE ... OTHER
17. SPACING OF SAW CUTS: ....
18. TYPE AND SPACING OF JOINTS: ....
....
19. COMMENTS: ....
....

Return to: Dr. Shanker, School of Building Construction, FAC 101, Gainesville, Fl 32611

APPENDIX E

Commercial Sector Energy Conservation Measures (DOE 91)

I.1 LIGHTING SYSTEMS

- Remove lamps and fixtures; disconnect ballasts and leave in-place
- Install efficient fixtures including heat recovery fixtures, T8, and parabolic reflectors (remove old fixtures)
- Install efficient ballasts, including electromagnetic ballasts, and high frequency electronic ballasts
- Install efficient lamps - replace incandescent or low efficiency mercury vapor lamps with high pressure sodium, low pressure sodium, metal halide, T8, or fluorescent or low watt fluorescent lamps
- Install energy efficient exterior lighting Use only necessary illumination levels through microprocessor control
- Use natural light and daylighting, including perimeter dimming systems
- Install automatic dimming control systems
- Install photocells or timeclocks to control exterior lighting
- Install switching for selective control illumination
- Install occupancy sensors
- Install corridor light timers
- Install self-powered exit lights
- Install low voltage (tungsten) lighting

I.2 POWER SYSTEMS

- Disconnect lightly loaded transformers, leave in-place
- Replace transformers (economic replacement criteria)
- Convert primary distribution system to higher voltages
- Replace (resize) oversized motors
- Use high efficiency motors and transformers (replacement)
- Use variable speed motors and drives for pumps
- Use variable speed motors and drives for fans
- Install solid-state motor drives on elevators
- Install demand-type elevator controls
- Install energy management system (EMS)

I.3 BUILDING ENVELOPE[a]

- Install wall insulation
- Install roof insulation
- Install ceiling insulation
- Install floor insulation
- Install foundation (crawl space) insulation
- Install slab perimeter insulation
- Reduce space load from outside air infiltration (caulk, weatherstrip)
- Install window and skylight insulation (curtains)
- Install storm windows
- Install sash-mounted storm windows
- Install low-E glass
- Install multiple glazed windows
- Reduce solar heat gain with solar film, window tints, overhangs, awnings, louvers or other screening/shading devices
- Install storm doors
- Install double pane sliding doors
- Install screen doors
- Replace existing doors with insulated doors
- Enclose loading docks with shelters and seals
- Install vestibules to reduce infiltration/exfiltration
- Seal vertical shafts (elevators, stairwells) to reduce in/exfiltration
- Install air curtains
- a = Assume that new buildings would be designed to provide the prescribed ventilation rate.

I.4 HVAC SYSTEMS

Heating/Air Conditioning

- Install automatic condenser cleaning
- Increase evaporator and/or decrease condenser water temperatures and modify controls
- Replace air-cooled condenser with cooling tower
- Install spot cooling
- Install earth cooling tubes
- Install roof spray system
- Install high efficiency air-conditioning unit
- Install chiller economizer (water-side)
- Install economizer (air-side)
- Install air-side heat recovery system (ventilation air tempering), including packaged systems)
- Isolate off-line chillers and cooling towers
- Prevent simultaneous use of heating/cooling via automatic controls
- Reset hot deck temperature via automatic controls
- Reset cold deck temperature via automatic controls
- Zone optimize reheat systems
- Use duty cycling for fan control
- Install dead band thermostats
- Install warm-up cycle controls/optimum start
- Install automatic night setback/set up
- Reduce pump energy by reducing resistance and flow rates
- Insulate ducts
- Insulate piping
- Replace forced air heating system with (spot) radiant heaters
- Replace resistance heating with heat pump
- Install air/ground/water source heat pumps
- Install pool heat recovery
- Install high efficiency air handler
- Convert existing constant volume air distribution system to a variable air volume (VAV) system
- Install energy management system to control HVAC

Ventilation

- Install CO_2-controlled ventilation
- Install CO-controlled covered parking ventilation
- Automatically reduce ventilation during unoccupied periods
- Reduce minimum outside air
- Recirculate exhaust air using activated carbon filters
- Install vortex hoods for restaurants
- Use separate make-up air for exhaust hoods
- Employ evaporative cooling of outdoor air
- Employ desiccant dehumidification
- Reduce energy consumption for fans by reducing air flow rates and resistance to air flow
- Install high efficiency fans with larger ductwork
- Install dual speed fans
- Install attic ventilation
- Install low leakage dampers
- Install an air destratification system (ceiling fans)
- Install outside air reset controls
- Automatically reduce or minimize outside air intake by control modifications

Refrigeration

- Reset chilled water temperature
- Chiller optimization
- Optimize defrosting control through new controls
- Optimize capacity control via new controls
- Increase condensing unit efficiency
- Optimize cooling tower control (i.e., coolant/air flow modulation) via new controls
- Install variable speed chiller motor
- Install high efficiency chiller
- Install timeclocks on circulating pumps
- Install efficient compressors
- Reduce heat gains to refrigerated space
- Install efficiency-of-use improvements (strip curtains, etc.)
- Employ heat recovery from exhaust air
- Install thermal storage (ice, chilled water, hot water)
- Install variable speed drive (VSD) on pumps
- Install floating condenser head pressure control

I.5 DOMESTIC HOT WATER SYSTEMS

- Insulate hot water storage tank with wraps, bottom boards, convection loops
- Insulate hot water piping
- Install flow restrictors to limit water use
- Install chemical dishwashing system
- Use heat recovery systems, including packaged systems, to heat water
- Replace central system with local, tankless, point-of-use heating units to eliminate storage and/or separate summer dehumidification
- Use a heat pump water heater system
- Install a timer on electric systems
- Turn off domestic hot water pumps during off hours
- Install a timeclock to turn off water heater during unoccupied periods
- Install circulating pump control
- Use solar water heating systems

VS5-RMC-4366c

APPENDIX F

References from "ANSI/ASHRAE 62-1989 - Energy vs. IAQ Impact" (TAY 93)

1) Anderson L.O., Frisk P., Lofstedt B., Wyon D.P., 1975. "Human Response to Dry, Humidified and Intermittently Humidified Air", Swedish Building Research D11.

2) Berglund B., et al., 1984. "Characterization of Indoor Air Quality and Sick Buildings", ASHRAE Transactions, Vol 90, Part 1B, pp. 1045-1055.

3) Berglund L.G., Cain W.W., 1989. "Perceived Air Quality and the Thermal Environment", IAQ '89: The Human Equation: Health and Comfort, pp. 93-99.

4) Burge H.A., 1988. "Environmental Allergy, Definition, Causes, Control". Engineering Solutions to Indoor Air Problems, pp. 3-9.

5) Burge P.S., Jones P., Robertson A. S., 1990. "Sick Building Syndrome - Environmental Comparisons of Sick and Healthy Buildings", Indoor Air '90, Proceedings of the 5th Intl. Conference on Indoor Air Quality and Climate, Vol 1, pp. 479-484.

6) Cain W.S., Leaderer B.P., 1983. "Ventilation Requirements in Buildings-I: Control of Occupancy Odour and Tobacco Smoke Odour", Atmospheric Environment, Vol 17, pp. 1183-1197.

7) Eto J., Meyer C., 1988. "The HVAC Costs of Increased Fresh Air Ventilation Rates in Office Buildings, ASHRAE Transactions, Vol 94, Pt 2, No. 3166.

8) Eto J., 1990. "The HVAC Costs of Increased Fresh Air Ventilation Rates in Office Buildings, Part 2", Indoor Air '90 Proceedings of 5th Intl. Conference on IAQ and Climate, Vol 4, pp. 53-58.

9) Fanger P.O., Lauridsen J., Bluyssen P., Clausen G., 1987. "Air Pollution Sources in Offices and Assembly Halls, Quantified by the Olf Unit", Energy and Buildings, Vol 12 (1988), pp. 7-19.

10) Fanger P.O., 1988. "The Olf and the Decipol", ASHRAE Journal, Oct. 1988, pp. 35-38.

11) Green G. H., 1985. "The Effect of Ventilation and Relative Humidity Upon Airborne Bacteria in Schools", ASHRAE Transactions, Vol 91, Part 2.

12) Grot R. A., et al., 1988. "Ventilation and Indoor Air Quality in a Modern Office Building", Proceedings of the 9th AIVC Conference, pp. 303-326.

13) Hedge A., Sterling E., Sterling T., 1986. "Building Illness Indices Based on Questionnaire Responses". Proceedings IAQ '86.

14) Hedge A. et al., 1989. "Indoor Air Quality and Health in Two Office Buildings with Different Ventilation Systems". Environment International, Vol 15, pp. 115-128.

15) Jaakkola J.J.K., et al., 1990. "The Effect of Air Recirculation on Symptoms and Environmental Complaints in Office Workers: a Double Blind, Four Period, Cross-over Study", Indoor Air '90: Proceedings of the 5th Intl. Conference on Indoor Air Quality and Climate, Vol 1, pp. 281-286.

16) Jaakkola J.J.K., et al.,1991. "Mechanical Ventilation in Office Buildings and the Sick Building Syndrome. An Experimental and Epidemiological Study", Indoor Air, Vol. 1, No. 2, July 1991, pp. 111-121.

17) Lui R.T., Raber R.R., Yu H.H.S., 1991. "Filter Selection on an Engineering Basis", Heating, Piping, Air Conditioning, May '91.

18) Menzies R.I., Tamblyn R.M., Tamblyn R.T., Farant J.P., Hanley J., Spitzer W.O., 1990. "Sick Building Syndrome: the Effect of Changes in Ventilation Rates on Symptom Prevalence; the Evaluation of a Double Blind Approach", Indoor Air '90, Proceedings of the 5th Intl. Conference on Indoor Air Quality and Climate, Vol 1, pp. 519-524

19) Nagda N., Koontz M., Lumby D., Albrecht R., Rizzuto J., 1990. "Impact of Increased Ventilation Rates on Office Building Air Quality", Indoor Air '90, Proceedings of the 5th Intl. Conference on Indoor air Quality and Climate, Vol 4, pp.281-286.

20) Pejtersen et al., 1989, "Air Pollution Sources in Ventilation Systems", Proceedings of CLIMA 2000.

21) Rajhans G., 1983. "Indoor Air Quality and CO_2 Levels", Occupational Health in Ontario, Vol 4, No 4, pp. 160-167.

22) Seppanen O., Jaakkola J., 1989. "Factors That May Affect the Results of Indoor Air Quality Studies of Large Office Buildings", Design and Protocol for Monitoring Indoor Air Quality, ASTM STP 1002, pp. 51-62.

23) Sterling E.M., Sterling T.D., 1984. "Baseline Data: Health and Comfort in Modern Office Buildings", Proceedings of the 5th AIC Conference, pp. 17.1 - 17.13.

24) Turk B.H., et al., 1989. "Commercial Building Ventilation Rates and Particle Concentrations", ASHRAE Transactions, Vol 95, Pt 1, pp. 422-433.

25) Ventresca J.A., 1991. "Operation and Maintenance for Indoor Air Quality: Implication from Energy Simulations of Increased Ventilation", Proceedings of IAQ 91: Healthy Buildings, pp. 375-378.

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before com[pleting])

1. REPORT NO. EPA-600/R-97-051	2.	
4. TITLE AND SUBTITLE Large Buildings Characteristics as Related to Radon Resistance: A Literature Review		5. REPORT DATE May 1997
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Ronald A. Venezia		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Ronald A. Venezia (Consultant) 1008 Askham Drive Cary, North Carolina 27511		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO. EPA PO 4D2010NATA
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 Literature Review; 11/95-3/96
		14. SPONSORING AGENCY CODE **EPA/600/13**

15. SUPPLEMENTARY NOTES APPCD project officer is David C. Sanchez, Mail Drop 54, 919/ 541-2979.

16. ABSTRACT The report gives results of a literature review to determine to what useful extent buildings have been characterized and a data base developed in relation to radon entry and mitigation. Prior to 1993, most radon research in large buildings was focused on developing diagnostic and mitigation techniques for school buildings. The belief exists that techniques developed for school buildings can be used as the basis for developing diagnostic and mitigation techniques for other types of large buildings. The complexity and diversity of large building designs is an added complexity in radon mitigation. Much in the available literature on large building characteristics is directed toward energy conservation and heating, ventilation, and air-conditioning (HVAC) system design and operation. Data on floor space to footprint ratio, separation of lower level from upper floors, floor bypasses, and building foundation design/construction are lacking. The development and application of energy conservation techniques for large buildings have been vigorously pursued since the mid-1970s and have resulted in significant energy savings. Some of these techniques may have contributed to sick building syndrome, building related illness, and a general decrease in indoor air quality. Radon diagnostic and mitigation strategies are lacking for large buildings.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Data Processing	Pollution Control	13B	09B
Radon		Stationary Sources	07B	
Commercial Buildings		Large Buildings	13M	
Analyzing		Characterization	14B	
Review		Indoor Air Quality	05B	
Properties			14G	

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Release to Public	**Unclassified**	96
	20. SECURITY CLASS *(This page)* **Unclassified**	22. PRICE

EPA Form 2220-1 (9-73)