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Update on Radon Mitigation Research in Schools

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ABSTRACT

EPA's Air and Energy Engineering Research Laboratory (AEERL) has conducted various levels of radon mitigation research in 47 schools since 1988. This paper is an overview of this research. The structural and heating, ventilating, and air-conditioning (HVAC) system characteristics of the research schools are presented, along with the mitigation techniques implemented in the research schools. Specific research discussed includes recent and on-going projects in Colorado, Maine, Maryland, Ohio, South Dakota, Tennessee, and Virginia.

Initial research focussed on the application of active subslab depressurization (ASD) to school buildings, and recent research has emphasized the ability and limitations of using HVAC systems to reduce radon levels in schools. A goal of future projects is to compare the effectiveness of the two techniques in the same building.

Slab-on-grade is the most prevalent substructure in the AEERL research schools and, depending on pressure field extension, ASD systems have been recommended for radon control in many of these buildings. In schools where they have been installed, ASD systems have performed well and are currently being evaluated for long-term performance. The distribution of HVAC system types in these research schools is about a third central air handling systems, a third unit ventilators, and a third that do not supply conditioned outdoor air (i.e., fan coil units or radiant heat). Building investigations and carbon dioxide measurements have indicated that many of these HVAC systems are not supplying adequate outdoor air.

This paper has been reviewed in accordance with the U. S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.

INTRODUCTION

EPA's Air and Energy Engineering Research Laboratory (AEERL) has conducted various levels of radon mitigation research in 47 schools in 12 states since 1988. A summary of these schools by state, the extent of radon diagnostics conducted, primary building characteristics, and the mitigation techniques implemented are presented in Table 1. This table, along with a background and general summary of AEERL's school research program, is discussed in the following section.

The remainder of the paper is an overview of AEERL's research on radon in schools with a focus on a few recent and on-going projects. Specific projects discussed include those in Colorado, Maine, Maryland, Ohio, South Dakota, Tennessee, and Virginia.

EPA RADON RESEARCH PROGRAM IN SCHOOLS

Schools are typically selected for inclusion in AEERL's school mitigation research program based on parameters such as: the extent of the radon problem, characteristics of the building construction and the heating, ventilating, and air-conditioning (HVAC) system, geographic region (geology and climate), and the willingness of school officials to participate in the radon diagnostics and to implement the recommended mitigation strategy. The diagnostics are typically performed by a team composed of AEERL scientists and engineers, EPA contractors, and at least one school official. Reference 1 discusses typical diagnostic measurements; however, note that the extent of diagnostics presented in Table 1 varies based on the goals of each project.

Initial AEERL research in schools focussed on the application of active subslab depressurization (ASD) to large buildings. Pressure field extension (PFE) measurements have been made in 40 (or 85%) of the buildings.

In addition to PFE measurements, recent school research by AEERL has also studied the ability of HVAC systems to reduce radon levels in schools. Depending on the characteristics and extent of the radon problem in each school, HVAC system evaluations typically include a combination of system inspection, differential pressure measurements, flow measurements, measurement of ventilation, and measurement of continuous radon levels in various HVAC operating modes. The HVAC system has been evaluated in 27 (or 57%) of the schools, and carbon dioxide levels have been measured in 12 (or 26%) of the schools. These data on the HVAC system are critical in determining if it is possible to use the current system to help control the radon problem. HVAC system investigations also help to determine if the HVAC system is contributing to the radon problem in the building. (See discussion of Colorado school below.)

In most cases the school is responsible for implementing the recommended mitigation strategy. Depending on the school district, funding for such work may lag diagnostics by more than a year. Unless stated otherwise, the discussion which follows applies to those schools presented in Table 1.

COMMON SCHOOL BUILDING CHARACTERISTICS

Other papers have generally discussed the common structural and HVAC characteristics of AEERL's initial research schools (2). Tables 2 and 3 quantify these structural and HVAC system characteristics for the 47 schools in Table 1. The results are detailed below.

Structural Characteristics

The primary structural characteristics of the AEERL research schools are presented in Table 2. A large majority of the schools have slab-on-grade substructures. Including the combination substructures (for example, a BSMT/SOG substructure would count both as a basement and a slab-on-grade), 91% of the 47 schools have slab-on-grade; 19% have basement; and 15% have crawl space.

In some geographic areas, utilities in slab-on-grade schools are placed in tunnels under the slab. Of the schools listed in Table 1, 33% (15) have a utility tunnel in some portion of the building. The presence of utility tunnels can play an important role in radon entry and subsequent mitigation since they often have many openings to both the soil and the building interior (such as pipe risers to unit ventilators). Although utility tunnel depressurization has been considered in schools where the tunnel is a major radon entry route, asbestos in many of the tunnels limits the applicability of this technique.

As discussed above, PFE measurements have been conducted in 40 school buildings. The average maximum distance of PFE under the slab in 34 of these 40 schools where data were available was 12.5 meters with a standard deviation of 6 meters. A PFE radius of 12.5 meters implies an average coverage of 490 square meters per suction point. Assuming an average classroom size of 8 by 9 meters (72 square meters), these data imply that a single ASD point depressurizes an average of nearly seven classrooms. However, in addition to subslab permeability's being a determinant of PFE in these schools, the configuration of internal subslab walls (footings) also has a considerable influence on PFE since they reduce subslab communication between areas. A rough analysis of the footing structures in these 34 schools shows that approximately 40% of the schools have subslab walls between the classroom and the corridor and 20% have subslab walls between adjacent classrooms. Subslab walls are located both on the corridor and classroom sides in about 10% of the schools. As a result, it appears that subslab walls -- rather than subslab material -- are a limiting factor in PFE in a number of these schools. The various subslab wall (footing) configurations found in schools are discussed in detail in Reference 3.

HVAC System Characteristics

The distribution of the HVAC systems found in AEERL research schools is summarized in Table 3. Considering the combinations of HVAC systems within a given school, 45% of the 47 schools have central air handling systems; 43% have unit ventilators; 30% have radiant heat; and 11% have fan coil units. Of the schools, 17% have only radiant heat (11%) or only fan coil units (6%), indicating that the other 83% have some means of providing conditioned outdoor air. In practice however, most of these 83% are not designed or operated to supply at least 7 liters per second of outdoor air to each occupant as recommended in current ASHRAE guidelines (4).

To illustrate the ventilation in some of these schools, Figure 1 presents the average carbon dioxide measurements made in 67 rooms in seven South Dakota schools. The measurements were made in early May 1991, and all seven schools use typical unit ventilators (UV in figure) for HVAC. The data include only those rooms where the windows were closed and students were either in the classroom or had just left. The data do include some classrooms where the classroom-to-hallway door was open. (Note that carbon dioxide measurements will be made in a number of the other research schools over the next winter.)

As seen in Figure 1, the average carbon dioxide levels in all 67 classrooms is 1423 ppm. However, as would be expected, the average in the 32 classrooms where the unit ventilators were operating was 1118 ppm, compared with 1702 ppm in the 35 classrooms where there was no unit ventilator or where it was off. It is interesting to note that the carbon dioxide levels in the 32 classrooms where the unit ventilators were operating still exceeded the ASHRAE guideline of 1000 ppm (4). This is not surprising since the average carbon dioxide level in the unit ventilator air supply in these 32 rooms is 933 ppm. These results are typical of those found in many of the research schools, indicating that many of the unit ventilator outdoor air dampers are closed, only bringing in minimum amounts of outdoor air through leakage. One would expect that these carbon dioxide levels would be even higher during the colder winter months.

Study of School Building Characteristics

The AEERL research schools present a somewhat biased sample of the U.S. school population because of the selection criteria and because EPA does not have a national data base to use to randomly select schools that have measured elevated radon levels. To help gain a better understanding of the physical characteristics of schools throughout the U.S. and to help guide the selection of future research schools, AEERL is conducting a study of school building characteristics using a subsample of approximately 100 schools from the National School Radon Survey (5).

For this study, detailed structural and HVAC system characteristics are being collected at the National School Radon Survey schools which are located in 24 randomly selected areas. Depending on the population percentage, results should provide the percentage of various school building characteristics within plus or minus 5 to 10% at a 95% confidence interval. The results of the study will also be compared with those found in the AEERL research schools in order to identify any correlations.

MITIGATION STRATEGIES

After conducting radon diagnostics in a school, AEERL recommends a mitigation strategy to appropriate school officials, with the school officials ultimately deciding what action to take. As summarized in Table 4, 28% of the 47 schools have installed ASD systems, 6% are using the HVAC system alone to control radon, and 13% are using a combined approach of ASD and HVAC control. Note that 36% of the schools are either being researched currently by AEERL or did not have resources available to implement the recommended mitigation strategy as of July 1991.

As mentioned above, experience has indicated that many school HVAC systems are not delivering adequate outdoor air to building occupants (2,4,6,7). In fact, many of the school officials have indicated that in most circumstances their preferred radon mitigation approach is to install an ASD system because of the complications involved with properly operating and maintaining an HVAC system for acceptable radon control. Causes of inadequate ventilation include HVAC system design, system operation, lack of maintenance, and energy conservation concerns. In order to achieve the long-term national goal of ambient indoor radon levels set forth in the 1988 Indoor Radon Abatement Act, it is likely that many schools with elevated radon levels will need to implement a combined strategy of ASD and optimal HVAC system operation. As a result, a future objective of the school research program is to compare the relative and combined effectiveness of the ASD and HVAC techniques in the same building. Improved design, operation, and maintenance of school HVAC systems will also help with indoor air quality problems such as elevated carbon dioxide levels.

MITIGATION RESEARCH IN EXISTING SCHOOLS

AEERL currently has school research projects in Maine, Ohio, South Dakota, and Virginia. Research projects were recently completed in Colorado, Maryland, and Washington State. In addition to evaluating the regional applicability of ASD by measuring PFE, these projects are typically designed to collect continuous data on the effects of HVAC system operation on radon levels. Data loggers are installed in the schools to continuously monitor parameters such as radon, differential pressure, HVAC system operation (e.g., amount of outdoor air supplied), opening/closing of classroom-to-corridor doors, and weather. One of the goals of these projects is to identify the conditions under which HVAC systems can be used to control radon levels. For example, by determining how long it takes to reduce radon levels by supplying a given quantity of outdoor air through the unit ventilators, school officials can determine how early they need to turn on the units in the morning in order to reduce radon levels that may have built up when the HVAC system was on night setback. Initial results indicate that such an approach to radon control is school (and possibly room) specific.

The following subsections briefly discuss the objectives, background information, and -- where available -- preliminary results from some specific AEERL school research projects in Colorado, Maine, Maryland, Ohio, South Dakota, and Tennessee. The details of these projects, along with other AEERL school research projects, will eventually be included in an EPA report.

COLORADO

In the summer of 1990, EPA initiated a research project with the assistance of the Western Regional Radon Training Center in Fort Collins. Data loggers were installed in selected areas of a 2576 square meter school building to determine the causes of elevated radon levels [ranging from 6 to 13 picocuries per liter (pCi/L) throughout the building]. The building has a central air handler with a single fan. Supply ducts are located under the slab, with the corridor serving as the return air plenum. From the hallway, the return air is ducted into a subslab return-air tunnel that pulls the air back to the air handler. During the building investigation it was noted that the outdoor air damper for the HVAC system was not opening properly, perhaps contributing to the radon problem in the school.

In January 1991, sensors were installed to continuously monitor radon, differential pressure, temperature, and the status of the HVAC system fresh air control damper which had been repaired. Data were collected for 3 months.

Results indicate that the position of the outdoor air damper had a significant influence on radon levels in the building. When the damper was closed, radon levels in the school were elevated for two reasons: 1) the fan was creating a large negative pressure in the return air tunnel, increasing levels in the tunnel, and 2) since minimal outdoor air was entering the HVAC system, the radon collected in the return air tunnel was distributed throughout the building with minimal dilution.

When the outdoor air damper was opened to 100%, the pressure differential was reduced, radon levels were diluted, and average radon concentrations in the building were less than 1 pCi/L. It appears that radon levels are still reduced even when the outdoor air damper is only partially open; however, radon concentrations rise rapidly when the damper is closed.

This research project is an example where the HVAC system was both a cause and a solution to the radon problem. The HVAC system will be fit with a device to monitor the position of the outdoor air damper to ensure that it is open while the building is occupied.

MAINE

Data loggers were installed in three wings of a Maine school in November 1990. The school was initially studied as part of EPA's Office of Radiation Programs School Evaluation Program. Since the design and construction of each wing of the school are different and the radon source strength is relatively uniform, the school provides an excellent opportunity to compare different mitigation techniques.

During the winter of 1990-91, different mitigation techniques were evaluated -- ASD, unit ventilator pressurization/dilution, and heat recovery ventilation (HRV) -- independently in each of the three wings. Preliminary data indicate that radon levels in the ASD wing are below 4 pCi/L, with most rooms below 2 pCi/L. The HRV has also reduced radon levels to below 2 pCi/L in the one room where it is installed. However, the unit ventilators have thus far proven ineffective in consistently reducing radon levels to below 4 pCi/L and as a result, AEERL plans to install an ASD system in this wing for evaluation during the winter of 1991-92.

MARYLAND

The ability of unit ventilators to reduce radon levels is also being studied in a four classroom addition of a Maryland school. (The school had installed an ASD system in 1988 as their primary radon control strategy.) The unit ventilator damper positions were varied and continuous radon, differential pressure, and differential temperature data were collected. These data are currently being analyzed for comparison with radon reduction in the same rooms with the ASD system operating.

OHIO

Radon diagnostics were conducted in four Columbus schools during the spring of 1991. Data loggers were installed in two of the schools to determine if the HVAC systems can be used to control radon levels and, if they can, how the HVAC systems should be operated. One of the schools has a two fan central HVAC system with the return air located in a subslab tunnel. The other school has fan coil units located in a subslab tunnel, and outdoor air can be supplied to the fan coils in the tunnel.

Data collection in these two schools began in August 1991, and measurements will be repeated during the winter of 1991-92. The schools will be monitored with 0, 50, and 100% outdoor air, and 100, 50, and 0% return air, respectively. Each test will be run for a minimum of 48 hours, with a baseline re-established between each pair of tests.

SOUTH DAKOTA

PFE measurements and HVAC system evaluations were conducted in four Rapid City area schools during the summer of 1991. Carbon dioxide levels had been previously measured in eight area schools in the spring. One of the schools with unit ventilators was selected for continuous monitoring with a data logger since it consistently measured the highest radon levels. The opening of the unit ventilator dampers will be controlled to determine the units' ability to reduce radon levels in this cold climate. Other parameters that will be monitored with the data logger include: radon levels, differential pressure, opening/closing of the classroom-to-corridor door, and weather. In the long-term, school officials plan to install an ASD system, and the two techniques (ASD and HVAC system control) will be compared.

TENNESSEE

Radon levels were measured in February in two Nashville schools that were mitigated by AEERL in 1989 (8). Measurements made during the first winter after the systems were installed (1989-90) indicated that some system modifications were needed. Following these modifications, measurements made this past winter (1990-91) were all below 4 pCi/L in the mitigated areas of the buildings. (Premitigation levels had averaged 30 and 40 pCi/L in the two schools.) AEERL will continue to follow the long-term effectiveness of the ASD systems installed in these two schools.

VIRGINIA

One wing of a school constructed in 1987 with a variable air volume (VAV) central air handling system is being monitored to determine the optimal radon and indoor air quality control strategies. A one point ASD system was recently installed in one wing of the school, and a data logger is monitoring radon, differential pressure, and temperature in several locations. The parameters varied for the testing include: percent outdoor air (0, 50, and 100%), VAV box position (minimum and maximum), and ASD system operation (on and off). This is the first school where AEERL has studied the effects of a VAV system on radon levels and differential pressures.

RADON-RESISTANT NEW SCHOOL CONSTRUCTION

Although experience in radon-resistant new school construction is limited, AEERL has applied its findings in existing schools in making recommendations for large building construction. These recommendations will be detailed in an upcoming guidance document, and the major points are summarized as follows:

1) It is typically easier and less expensive to rough in a subslab depressurization system during building construction or, as a minimum, design the building so that an effective ASD system can be easily added if needed. Design and construction parameters that should be included are: at least 10 centimeters of clean, coarse aggregate should be placed beneath the slab; subslab walls should be minimized for improved PFE or a suction point should be placed in each area confined by subslab walls; and an adequate suction pit should be installed.

2) The HVAC system should be designed and operated to pressurize the building interior.

3) Major radon entry routes such as utility penetrations and expansion joints should be avoided or sealed.

Research in radon resistant new school construction is focussing on evaluating the various approaches that different designers have used. Recent results have shown depressurization under a 5,500 square meter slab with only one ASD point. The additional cost of such a system was about $1 per square meter compared to costs of $3 to $11 per square meter in a study of commercial installations (9).

SUMMARY

AEERL has conducted various levels of radon diagnostics in 47 schools in 12 states. Most of the 47 schools have slab-on-grade substructures (91%), although some basement (19%) and crawl space (15%) substructures were found. (Note that this distribution includes combination substructures; for example, a BSMT/SOG substructure would count as both basement and slab-on-grade.) A rough analysis of PFE data collected in 72% of the 47 buildings, showed an average PFE radius of about 12.5 meters, implying an average coverage of 490 square meters per suction point. Assuming an average classroom size of 8 by 9 meters, these data imply that a single ASD point should depressurize an average of nearly seven classrooms in these schools. However, in addition to subslab permeability's being a determinant of PFE, it appears that subslab walls -- rather than subslab material alone -- are a limiting factor in PFE in a number of these schools. This not only has implications in the design of ASD systems in existing schools, but can also be applied in the design of easy-to-mitigate schools in radon prone areas.

The types of HVAC systems found in 47 AEERL research schools are relatively evenly distributed: 45% of the schools have central air handling systems; 43% have unit ventilators; 30% have radiant heat; and 11% have fan coil units. (Note that this distribution includes schools with combination HVAC systems; for example, a CENT/UV would count as both a central air handling system and a unit ventilator.) Of the schools, 17% have only radiant heat (11%) or only fan coil units (6%), indicating that the other 83% have been designed to provide conditioned outdoor air. In practice, however, most of these 83% are not designed or operated to supply at least 7 liters per second of outdoor air to each occupant as recommended by current ASHRAE guidelines. Providing adequate outdoor air should be considered in all schools both for radon reduction and for improved indoor air quality.

Because of the complications involved with using the HVAC system to control radon levels, ASD has been the preferred radon reduction technique in the mitigated schools. For maximum radon reduction and improved indoor air quality, a number of schools are using a combined approach of ASD and HVAC system pressurization. A third of the schools are either being researched currently by AEERL or did not have resources available to implement the recommended mitigation strategy as of July 1991. Since the school is typically responsible for implementing the recommended mitigation strategy, funding for such work may lag diagnostics by more than a year.

AEERL currently has research projects in existing schools in Maine, Ohio, South Dakota, and Virginia, and projects were recently completed in Colorado, Maryland, and Washington State. In addition to evaluating the regional applicability of ASD by measuring PFE, these projects are typically designed collect continuous data on the effects of HVAC system operation on radon levels to determine the conditions under which HVAC systems can be used to control radon levels. Data loggers are installed in the schools to continuously monitor parameters such as radon, differential pressure, HVAC system operation (e.g., amount of outdoor air supplied), opening/closing of classroom-to-corridor doors, and weather. Initial results indicate that HVAC system control of radon levels is school (and possibly room) specific.

AEERL's research on radon resistant new school construction is evaluating EPA's recommended approach (roughing in an ASD system) in addition to the various approaches that other designers have used. Recent results have shown depressurization under a 5500 square meter slab with only one ASD point. The additional cost of such a system was about $1 per square meter compared to costs of $3 to $11 per square meter in a study of commercial installations.

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TABLE 1. SUMMARY OF AEERL RADON RESEARCH SCHOOLS BY STATE

ST	#	PFE	HVAC EVAL	UTL TUN	CO_2	PRIMARY STRUCTURES	PRIMARY HVAC	MITIGATED
AL	3	3	0	0	0	2 SOG 1 BSMT	3 FCU	1 ASD 2 LOW
CO	2	2	2	1	0	2 SOG	1 CENT 1 UV	1 HVAC 1 TBD
KY	6	5	2	1	0	5 SOG 1 BSMT/SOG	2 CENT 4 UV	3 ASD 1 COMB 2 TBD
MD	7	7	7	1	1	5 SOG 1 BSMT/SOG 1 SOG/CS	4 CENT 1 CENT/UV 2 UV/RAD	5 ASD 2 COMB
ME	2	2	1	0	1	1 SOG 1 BSMT	1 UV/RAD 1 UV	1 ASD 1 COMB
NC	2	1	1	1	0	2 SOG	1 CENT 1 CENT/FCU	1 ASD 1 HVAC
NY	1	1	1	0	1	1 BSMT/SOG	1 UV	1 COMB
OH	4	4	3	2	0	4 SOG	3 CENT 1 CENT/FCU	4 TBD
SD	8	4	4	7	8	7 SOG 1 BSMT	4 UV/RAD 1 CENT/UV 2 UV 1 CENT/UV/RAD	5 TBD 3 LOW
TN	9	9	3	1	0	3 SOG 1 BSMT/SOG 3 SOG/CS 1 BSMT/CS 1 BSMT/SOG/CS	2 CENT 5 RAD 1 RAD/CENT 1 FCU	2 ASD 4 TBD 3 LOW
VA	1	1	1	0	1	1 SOG	1 CENT	1 COMB
WA	2	1	2	1	0	1 SOG 1 SOG/CS	1 CENT 1 UV	1 TBD 1 HVAC
	47	40	27	15	12			

KEY TO ACRONYMS IN TABLES 1, 2, 3, AND 4:

ST state in which schools are located
\# number of schools investigated
PFE number of schools where pressure field extension measurements made
HVAC EVAL number of schools where HVAC system evaluated
UTL TUN number of schools with utility tunnel(s)
CO_2 number of schools where CO_2 levels measured
SOG slab-on-grade
BSMT basement
CS crawl space
FCU fan coil units
CENT central air handling system
UV unit ventilators
RAD radiant heat
ASD active subslab depressurization
LOW follow-up radon measurements relatively low; no action taken
HVAC HVAC system primary control of radon levels
TBD to be determined
COMB radon control strategy combines ASD and HVAC

TABLE 2. DISTRIBUTION OF STRUCTURE TYPES IN RESEARCH SCHOOLS

PRIMARY STRUCTURE(S)	# OF SCHOOLS	% OF SCHOOLS
SOG ONLY	33	70
BSMT ONLY	3	6
CS ONLY	0	0
COMBINATION BSMT/SOG	4	9
COMBINATION BSMT/CS	1	2
COMBINATION SOG/CS	5	11
COMBINATION BSMT/SOG/CS	1	2
TOTAL SOG	43	91
TOTAL BSMT	9	19
TOTAL CS	7	15

(Note that the total distribution of structure types is summarized in the bottom three lines. For example, a BSMT/SOG combination counts as both a basement and a slab-on-grade in the total lines.)

TABLE 3. DISTRIBUTION OF HVAC SYSTEMS IN RESEARCH SCHOOLS

PRIMARY HVAC SYSTEM(S)	# OF SCHOOLS	% OF SCHOOLS
CENT ONLY	15	32
UV ONLY	10	21
RAD ONLY	5	11
FCU ONLY	3	6
COMBINATION CENT/UV	2	4
COMBINATION UV/RAD	7	15
COMBINATION CENT/RAD	1	2
COMBINATION CENT/FCU	2	4
COMBINATION CENT/UV/RAD	1	2
TOTAL CENT	21	45
TOTAL UV	20	43
TOTAL RAD	14	30
TOTAL FCU	5	11

(Note that the total distribution of HVAC system types is summarized in the bottom three lines. For example, a CENT/UV combination counts for both central air handling systems and unit ventilators in the total lines.)

TABLE 4. SUMMARY OF MITIGATION TECHNIQUES APPLIED

MITIGATION TECHNIQUE	# OF SCHOOLS	% OF SCHOOLS
ASD ONLY	13	28
HVAC CONTROL ONLY	3	6
COMBINATION ASD AND HVAC	6	13
TBD	17	36
LOW (NONE PLANNED)	8	17

Figure 1. Carbon Dioxide Measurements