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RADON DIAGNOSTICS AND MITIGATION IN A DIFFICULT TO MITIGATE SCHOOL

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ABSTRACT

This paper describes radon diagnostics and mitigation in a school the U.S. Environmental Protection Agency classified "difficult to mitigate." The school had a utility tunnel beneath corridors that served as the outside air and return air mixing chamber for the heating and ventilation (HV) system. The HV system depressurized the tunnel, sucked radon from the soil, and distributed it to school rooms. An initial radon reduction effort using block wall depressurization did not reduce radon concentrations below four picoCuries per liter. Extensive diagnostics, including continuous measurements of building and environmental variables, were conducted to test mitigation options and to provide design parameters for additional mitigation. The final radon mitigation technique involved pressurizing the utility tunnel. The findings indicate that: active soil depressurization systems can be overpowered by HV operations; in some cases, increased ventilation can increase radon entry and indoor concentrations; and, if properly implemented, additional ventilation can reduce indoor radon concentrations without significant energy penalties.

INTRODUCTION

Knowledge about radon levels and radon reduction techniques in schools was varied and divergent a decade ago. For example, Turk, et al. (1987) examined radon and other indoor air pollutant concentrations in 38 commercial and institutional buildings, including six "typical" schools, in the Pacific Northwest of the U.S. and reported radon as generally low. By contrast, others reported elevated radon concentrations in schools as well as early experience at radon mitigation in schools, e.g.: Fred and Stafford (1988) on an assessment of radon in three Florida schools; Leovic, et al. (1988) on characteristics of schools with elevated radon; Saum, et al. (1988) on school radon reduction efforts; and Witter, et al. (1988a & b) on radon resistant new construction techniques as well as heating, ventilation, and air conditioning (HVAC) pressurization techniques for radon control.

The Indoor Radon Abatement Act, signed into law in October 1988, authorized EPA to initiate a national survey of radon in schools. In 1989, following initial reports from early EPA radon surveys in 130 schools in 16 states (that were being used to develop the protocol for EPA's National School Radon Survey), EPA recommended that schools nationwide test for radon. Fifty-four percent of the 130 schools had one or more rooms with test results above EPA's four picoCurie per liter (pCi/L) threshold for action (Cox and Miro, 1989; Peake and Schmidt, 1990).

The 1991-1992 U.S. EPA national survey obtained short-term radon measurements from 927 randomly selected U.S. schools (Phillips, et al., 1992; Ratcliff and Bergsten, 1992). Nineteen percent of the surveyed schools, or about one in five, had one or more rooms that had radon concentrations of four picoCuries per liter or higher. Overall, about three percent of the schoolrooms in ground-contact had short-term results of four picoCuries per liter or higher which indicates that 73,000 U.S. schoolrooms have a potential radon concentration in excess of EPA's voluntary threshold for action.

During the early 1990s, radon reduction research and demonstration efforts in schools had different thrusts. On one hand, it was found that there were many advantages to using the same active soil depressurization (ASD) radon mitigation techniques in schools that had been used in houses. By contrast, it was found that many schools with elevated radon had heating, ventilation, and air conditioning (HVAC) deficiencies that should be corrected before other radon mitigation efforts (e.g., ASD) were attempted. These differing views had two important points of consensus:

- first, HVAC systems could overwhelm ASD mitigation if they were not considered and addressed; and
- second, increased ventilation in some schools could increase radon entry and indoor concentrations.

The latter variable became an important factor in EPA's identification of "difficult to mitigate" schools[a]. In all schools, EPA radon mitigation guidance recommends "... comprehensive investigations and diagnostics as the only effective way to determine what mitigation strategy to implement." (Ligman and Fisher, 1994; 3-2). EPA also notes, "Some areas over 10 pCi/L **might** be corrected with improved ventilation (emphasis original)." (ibid. 3-5). A flow chart in the Agency's guidance suggests consideration of ventilation-based mitigation when pre-mitigation radon concentrations are less than 10 pCi/L.

BACKGROUND

This paper focuses upon radon testing, diagnostic experiments, and mitigation in an Ohio elementary school with elevated radon that EPA classified as "difficult to mitigate." The school is a one story, slab-on-grade building containing approximately 30 classrooms, offices, and related facilities serving about 410 students and 30 staff members in about 22,000 of square feet of floor area (see Fig. 1). The school was built in 1961 with additions in 1964 and 1966. The northern portion of the school receives conditioned and ventilation air through fan coil units (FCU) located in a six- by eight-foot utility tunnel located below hallways. The tunnel serves as the mixing chamber for outside air and return air. The FCUs draw conditioned air from the utility tunnel and deliver it through subslab clay tile ducts to the exterior perimeter of the classrooms and to the office area (see Fig. 2). The tunnel has a concrete floor and concrete block walls. The southern portion of the school is served by "packaged" or factory-fabricated air handlers that are designed to deliver conditioned air through ceiling mounted duct work as opposed to a utility tunnel and subslab ducts.

Initial and Follow-up Radon Measurements

Initial charcoal canister tests were conducted over a five-day period in December 1988 and results were[b]: 37 pCi/L in the multipurpose room; 25 pCi/L in the open classroom #17-21; 46 pCi/L in classroom #12; and 48 pCi/L in classroom #5. The latter two test sites with the higher results were served by the utility tunnel and subslab duct ventilation system while the other two were not. Follow-up testing using alpha track detectors during four months (February 15 - June 8, 1989) produced the following results[c]: 18 pCi/L in the open classroom; 18 pCi/L in the music room; 25 pCi/L in room #12; and 26 pCi/L in room #7. It was recommended that corrective action be taken within several weeks and the Superintendent was directed to the Ohio Department of Health for further assistance concerning mitigation. Sixty-four additional seven-day radon measurements were taken as part of EPA's school measurement protocol development study and EPA's national school radon survey. The average of the 64 EPA measurements was 28 pCi/L.

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[a] Henschel, B. (1993) ***Planning Document for Difficult to Mitigate Schools Project***, Research Triangle Park, NC, U.S. Environmental Protection Agency, Air and Energy Engineering Research Laboratory (unpublished).

[b] Stocker & Sitler (1989a) ***Correspondence to School Superintendent D. Dupps***, Newark, OH (January 4).

[c] Stocker & Sitler (1989b) ***Correspondence to School Superintendent D. Dupps***, Newark, OH (July 27).

Initial Radon Diagnostics and Recommendations[d]

A diagnostic team lead by Clarkin of Camroden Associates investigated conditions at the school in June 1992. He found block wall concentrations of radon were about 300 pCi/L. The soil under the tunnel contained concentrations of about 75 pCi/L while the tunnels had concentrations of about 70 pCi/L. Additional diagnostic measurements were made in several of the ducts connecting the tunnel fan coil units (FCU) to perimeter classroom diffusers. These measurements revealed radon concentrations similar to classroom concentrations. Pressure field extension (PFE) measurements were made in the utility tunnels, below the floor and in the block walls as well as below classroom #1. The soil below the utility tunnels was found to be relatively tight and, under existing conditions:

- a suction point every 18 feet would be required if an active subslab depressurization (SSD) system was installed through the tunnel floor to control radon entry;
- a suction point every 40 feet would be required for a tunnel block wall depressurization (BWD) system; and
- one suction point per classroom would be required if a subslab depressurization (SSD) system was installed.

Clarkin emphasized that the elevated radon in the school was predominately caused by the designed tunnel return duct/mixing plenum. Two approaches were presented to address this issue: 1) reduce radon concentrations in the tunnel; or 2) modify the heating and ventilation system so that tunnel air was not supplied to the classrooms. Due to costs, Camroden recommended that radon concentrations in the tunnel be reduced in a phased approach by:

- first, adjusting the delivery of outdoor air to schoolrooms to ensure that the rate complies with applicable codes or the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) Standard 62-1989;
- second, a block wall depressurization (BWD) system should be installed in the utility tunnels that served as the return air/mixed air plenum to reduced radon entry; and
- next, the school should be retested according to U.S. EPA protocols and the utility tunnel should be retested. The need for any further mitigation would be determined by these post-mitigation tests.

Also, Clarkin noted that an energy management firm had been contracted by the school district to install an energy management system and thus, it was recommended that school officials consult with the firm to increase outdoor ventilation rates. The energy management firm had proposed to check operation, calibrate, and adjust HVAC controls as well as replace defective controls and equipment. The firm was to be paid for such services through savings in the school's annual $13,381 gas and $10,701 electrical costs (1990). The energy management firm's proposal contained the recommendation, "Check indoor air quality for raydon [sic] levels," but did not reference EPA's threshold for action or ASHRAE Standard 55 or 62.

Initial Mitigation Effort

A contract for mitigation had not been awarded when U.S. Senate hearings on school indoor air quality were held in March 1993. The hearings stimulated national news media reports about the high radon levels in the Ohio school. The following week, radon mitigation began in the school although the contractor had no contract to do the work and there was no indication that the outdoor ventilation rates had been verified with the energy management firm. The initial mitigation work in the school included sealing openings between the utility tunnel and the soil and installation of a block wall depressurization (BWD) system that was intended to reverse the pressure-driven flow from the soil into the tunnel. The initial mitigation did not include sealing sump pit covers to tunnel footing drains. After the BWD system was installed, the contractor reported that the pressure-field extension was lost after several feet from each suction point. In an attempt to ameliorate this problem, the contractor increased the number of block wall suction points and increased the number of BWD system fans from two to four (Fantech model F-225; each capable of moving 520 cfm @ zero in. WC and 230 cfm @ 1 in. WC). The contractor reported that the additional work was insufficient. It was then discovered that the tunnel air pressure was more than one-third of an inch of water column (WC) negative in relation to the outdoors . . . which

[d] Clarkin, M. (1992) ***Report of Radon Diagnostics in (Unidentified) City Schools,*** Westmoreland, NY, Camroden.

was six times more negative than ten months earlier when the initial diagnostics had been completed! It was suspected that the energy management firm had replaced defective HVAC controls and equipment and made other changes that resulted in greater suction on the tunnel by classroom fan coil units (FCU) that drew conditioned and ventilation air from the tunnel.

Follow-up Radon Diagnostics and Recommendations[e]

In June 1993, investigators returned to the school to assess the performance of the block wall depressurization system. The investigation included measurements to determine: the impact of HVAC modifications and repairs upon the performance of the radon mitigation system; and the impact of the mitigation system upon radon concentrations in the school. There were three elements to the investigation:

1) continuous radon measurements were made during six days in three rooms to determine what effect there would be on the radon mitigation system when the outdoor air damper was completely open and when it was completely closed with the FCUs turned off;
2) air flow measurements for each FCU as well as pressure difference measurements between the tunnel, classrooms and outdoors with the outdoor air (OA) completely open, the OA completely closed, and with an emulation of additional return air openings to the tunnel were made; and
3) the strength and extent of pressure field extension associated with different radon mitigation fan flow rates were measured.

Based upon the investigation, it was concluded that modifications were required in the air handling system in order to meet the EPA's guideline of four pCi/L or lower. Furthermore, additional information that would be helpful in planning further mitigation was identified and requested, i.e., radon measurements in each classroom with the outdoor air completely open, the outdoor air completely closed, and the air handlers off. Two options for additional radon reduction were presented: 1) hard ducting the return air/outdoor air to the low pressure side of the classroom fan coils in order to isolate the ventilation system from the source of radon; or 2) a combination approach that reduced tunnel depressurization by adding return air/outdoor air grills and increased block wall suction by installing larger size mitigation system headers, further sealing of tunnel air leaks, and adding further exhaust fan capacity.

Request for Mitigation Proposals

Based upon the 1992 and 1993 diagnostic reports, a request for proposals (RFP) for additional mitigation was released by the University in early 1995. The RFP had the following elements: an objective, to reduce radon entry by pressurizing the utility tunnel make up air duct; a note that alternate proposals to the work statement would be accepted for consideration; design criteria including ASHRAE 62 and a minimum 0.05 inch WC positive pressure in the tunnel; and a request for a feasibility study addressing reduced air flow during periods of low building occupancy and heat recovery from exhaust air. It was expected the successful proposal would carry a price of about $40,000 to $50,000 and would involve about $2,000 per year additional energy costs on top of the existing $25,000 per year for all utilities.

The best construction proposal was in excess of $400,000 and the estimated increase in annual energy was about $25,000. Without the benefit of better detailed existing performance criteria, this response covered a variety of contingencies. An alternate proposal for the installation of sub slab depressurization was presented at a cost of $120,000. The alternate was, in concept, an extension of the BWD system. The BWD system had been evaluated in the second diagnostic investigation and was found to be insufficient by itself for the amount of radon reduction desired in this school. It was not clear which proposal was the best option for radon reduction: a) room or tunnel pressurization; b) increased outside air for additional dilution; or c) soil depressurization.

The principal investigators, Angell and Bridges, recommended that there was enough uncertainty about the benefit from tunnel pressurization that the over-budget proposed mitigation should not proceed. Also they noted, that experimentally, it would be possible to: vary the proportion of outside air using temporary fans; a

[e] Brennan, T. (1993) ***Follow-Up Report for Radon Control at (Unidentified) Elementary School, (Unidentified) City School District, (Unidentified City), Ohio,*** Westmoreland, NY, Camroden (July 6)

temporary duct could be installed to directly connect the mixed air source with one existing classroom fan coil unit to eliminate any air being drawn from the tunnel; and a temporary subslab depressurization system could be installed in one or more rooms served by the utility tunnel and one or more rooms not served by the tunnel to determine the effect of subslab depressurization by itself and in combination with other radon reduction techniques. The investigators recommended that experiments should be conducted over the summer to clarify the best mitigation techniques for the school.

METHODS

A matrix of 12 experiments for testing the effectiveness of: pressurizing the tunnel mixed air system; hard ducting the classroom FCUs; classroom SSD; tunnel BWD; and tunnel block wall pressurization, individually and in combination was defined. Due to time limitations, the matrix required a minimum of 24 hour baseline conditions (i.e., BWD off, mixed air fans to tunnel off, SSD off, no hard ducting of the FCU) before and after each 24-hour test. By using this flip-flop technique, the effects of one operational configuration would have little, if any, impact on the effect of a subsequent experimental configuration. Since the condition of greatest concern was during peak heating load, the system operation was set for that situation. This would happen during the occupied winter day. The fans would be on and the dampers set to bring in 15 CFM per student (ASHRAE Standard 62-89). This required about 20% outside air mixed with 80% return air. The test condition would run all the school fans (all FCU's and also three supply fans in the south end of the building) continuously with the outside air dampers set at the expected minimum of 20% outside air.

With a gross volume of 300,000 cubic feet in the portion of the school served by the tunnel fan system and air circulation of about 20,000 CFM, there were about four air changes an hour. Thus, only one or two hours would be needed to see changes, if any, in the classrooms and six to eight hours to approach a steady state condition due to the experiments. In addition, the BWD system removed about 1,000 CFM or one air change in five hours. In this case, a clear change should be seen in about 15 hours and thus, 24 hours between tests was expected to be sufficient for a valid measure of each trial's effect.

The preliminary findings at the end of the 12 tests appeared to support the conclusions that additional ventilation and pressurization of the tunnel would reduce radon. The experiment was expanded to include ten additional tests to determine the effects of FCU operation and to find if tunnel pressurization would force radon out of the ventilation system but move it into rooms (even those not served by the FCU's for example, the music room) through other pathways. The additional tests were run for several days without a "flip back" to the base case so that extended effects could be assessed. These added tests provided a picture of possible problems which would come from extended operation with the proposed ventilation changes.

Environmental conditions that were monitored included: subslab pressure between the music room and classrooms #2 and #7 with the hallways; room pressure between the paper supply room, tunnel, BWD system and outside with the hallway; continuous radon concentrations in classrooms #1, #2 and #7 and the Principal's office; temperature in the hallway, paper supply room and outside; and barometric pressure. Two blower door fans were installed in the mixed air shaft to simulate a mixed air fan. Subslab depressurization systems were installed in classroom #2 and the music room. A temporary duct was installed to connect the classroom #2 FCU to the mixed air shaft.

FINDINGS

<u>Experimental Phase</u>

The continuous radon measurements in the tunnel and in classroom #2 during the week prior to installation of testing systems showed a clear relation between the daily cycle of the FCUs in the utility tunnel with fans being started at 0700 and stopped at 1600. The radon concentration patterns were nearly identical in the tunnel and classroom, with the classroom values lower and slightly delayed. When the fans started, the radon concentration rose from about three pCi/L to about 25 pCi/L in two hours. When the fans stopped, the radon concentration dropped from 25 to three pCi/L over about six hours. Short term electret ion chamber (ES) readings, taken over four days periods several weeks before the installation of testing systems revealed classroom radon levels averaging in the 20 pCi/L range. Radon measurements made the week before and during the installation of the testing systems revealed radon concentrations of 10 pCi/L. One obvious change between these time frames was that the tunnel sump and footing drains had been physically connected to the block wall depressurization system and that the sumps had been sealed from the tunnel.

With the tunnel fans on and 0% outside air, the tunnel was about 0.45 inches WC negative to the outside and the BWD was about 0.4 inches WC negative to the tunnel. This pattern was consistent with the BWD fan curve which provided the measured 300 CFM exhaust at 0.8 inches WC. Total exhaust air flow from the four BWD system fans was about 1275 CFM.

Some system deficiencies were not corrected for the experiments. For example, the music room fan did not have any outside air duct, return air traveled above the ceiling tile and one of three fan wheels did not turn. As a result, about half of the delivered air short circuited the supply duct and was not delivered to the room. Also, infrequent operation of the multipurpose room fan during the school year and lack of outside air from the CORE fan limited dilution of radon in the southern part of the building to that from outside damper leakage (perhaps only to 5 to 10% of the supply air). Test criteria required continuous operation of the multipurpose room fan and operation of the CORE fan with OA to provide a supply temperature of 65 ^{0}F. These conditions were different from those present during premitigation radon measurements in the southern portion of the school and thus, may have masked the effects of some of the tests.

Experimental Phase Results

The 22 experiments and the resulting averaged radon concentrations are listed in Table 1. The radon concentration averages exclude the first two hours of each experiment to reduce the effects of any transients caused by changing the operating conditions of the building. The last four hours and the last 22 hours of each base condition test were compared and found to be virtually the same. Thus, base conditions were verified before each of the first 12 experiments. The greatest radon reductions were observed in the following experiments (percent in parentheses = radon reduction upstairs):

- 17. block wall depressurization (BWD) fans on and fan coil units (FCU)off (97%);
- 13. mixed air (MA) and BWD fans on with FCUs off (89%);
- 06. MA and BWD fans on with FCUs on (76%);
- 11. MA, BWD, and subslab depressurization (SSD) fans on with FCUs on (67%);
- 12. BWD and SSD fans on with FCUs on and duct mixed air supply to FCU (67%);
- 09. MA and SSD fans on with FCUs on (65%);
- 21. MA, block wall pressurization, and east tunnel BWD fans on with FCUs on setback (64%); and
- 03. MA fans on with everything else off (62%).

In all but two of these eight tests, mixed air fans were on and the utility tunnel was probably slightly pressurized although we do not have access to that data. Test 17 indicates that radon concentrations can be controlled by the BWD as long as the tunnel is not depressurized by the FCUs removing air from the tunnel. In test 02, the BWD fans in the west tunnel were reversed and the radon concentrations declined in the study area. During test 21, the west tunnel block walls were pressurized and the east tunnel block walls were depressurized with a 36% reduction of radon in the west classrooms and more than a 40% increase of radon in the east wing classrooms.

The tests that resulted in the least amount of tunnel depressurization also provided the greatest radon reduction, with only three exceptions (tests 12, 2 and 10). Increasing the amount of air flow removed from the block walls of the tunnel by the BWD system might help somewhat. However, the amounts of air needed would likely result in rather large pressure drops in the BWD system piping and greatly reduce the effectiveness of any reasonably sized fans that could be installed. These experimental findings provided the foundation for a mitigation plan involving adding MA fans to in the MA shafts to the tunnels and a corresponding reduction in the FCU suction. In concept, this plan involved shifting the energy load from the FCUs to the new MA fans as well as shifting the negative pressure from the soil to above grade.

HVAC Focused Mitigation Phase

The specific measured values of air pressure and flow rates provided a much clearer picture of the needed design criteria. Appropriately sized fans could be specified and installed as pressure make up fans. Specific construction details included the relocation of the filter racks, modification of the mixed air controls and addition of electricity for power and lighting. A local heating contractor prepared an estimate to provide and install a 10,000 cfm, ½ inch static pressure supply fan in each shaft (see Fig. 2). These fans would be located downstream of the mixed air dampers. The work required correction of the ventilation problems identified in the earlier test (addition of two fans, tunnel transition ducts, and filter system) and included control revisions and related mechanical and electrical connections which would provide full operation of increased ventilation at higher static pressure in the utility tunnel. The majority of the work was scheduled during the winter 1995-1996 holidays. Installation was completed in February 1996. From March through May, final acceptance activities were conducted and detailed testing and balancing of the HVAC system were performed on each FCU. For most of the fans, a 70% smaller drive wheel provided the correct flow. Because of the MA fan pressure, even slowing the FCUs still resulted with an air flow increase. The final cost of the HVAC focused mitigation, including testing and balancing, was $29,900.

There was some concern that a reheat system might be needed. However, based on boiler operation and some heating load experiments run by the investigators, it appeared that there was sufficient capacity in the boilers. An HVAC spreadsheet BIN model prepared for different system operating conditions estimated building energy for the proposed change at about $2,500 per year. This 10% increase in total energy cost was viewed as being reasonable.

HVAC Focused Mitigation Results

Occupants reported that the school was more comfortable after radon mitigation. School facilities personnel and occupants praised improvements in the overall perception of ventilation and heating uniformity. Measurements of average radon levels revealed radon concentrations were 0.8 to 3.3 pCi/L. Continuous radon monitoring showed that the indoor radon concentration dropped when the mixed air fans were started. This is the opposite of measurements taken prior to installation of the fans. Post mitigation radon testing was performed using short-term electret ion chambers (ES). The results of the ES's all were below the EPA level of four pCi/L. In addition, a continuous radon monitor was used in the principal's office that measured an average concentration of 1.2 pCi/L during the test period. Also, a continuous radon monitor (CRM), and three short term Electret Ion Chamber detectors (ES) were placed in the tunnel. The tunnel concentrations of radon were 1.1 to 1.6 pCi/L.

A review of energy use for both electricity and gas indicated no significant change. The time frame was not long enough to determined the exact effect, but it was clear that the change had, as predicted, shifted energy use from being less controlled to being more controlled. Also, energy use had not markedly increased. The system operated during some of the coldest weather experienced in many years and capacity was sufficient to meet peak load without adverse effects. The energy use remained constant even with the increased amount of outside air. It appeared that the initial evaluation of air circulation was correct. Uncontrolled ventilation, equal to about 20% outside air, was moving through the building. The total energy use was not expected to increase with the same air flow controlled in its delivery through the mixed air fans. The energy use of three similar schools within two miles of each other was compared. After mitigation, energy use in the mitigated school changed little and, if at all, it decreased.

CONCLUSIONS

While one cannot generalize from one case (e.g., a EPA classified "difficult to mitigate school" with an energy management system and BWD already in place as well as limited space for hard ducting), our findings suggest that:

1. The cost of school radon mitigation does not need to be expensive even in difficult to mitigate schools. In this case, the mitigation cost was about that of the school's annual energy costs. Thus, schools have no reason not to test for radon.

2. School radon mitigation must consider the operating characteristics of the HVAC system as recommended by EPA. In this case, an HVAC approach was required and it cost less than ASD.

3. It is important to invest resources in thorough diagnostics in order to acquire a detailed mitigation design that is effective and reasonable in cost. In this case, proper engineering application of simple HVAC design principals by a trained investigator resulted in an inexpensive radon mitigation solution that identified and corrected the problem without reinventing an entire HVAC system.

4. Pressurization of the occupied space may be more important than dilution and it does not necessarily increase energy use.

5. In other schools, it may be helpful to use a simplified version of the research matrix used in this school.

6. HVAC focused radon mitigation achieved radon reductions greater than those suggested by EPA guidance and thus, EPA should continue the Agency's research in radon reduction in schools using HVAC approaches.

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Figure 1 Floor plan of elementary school

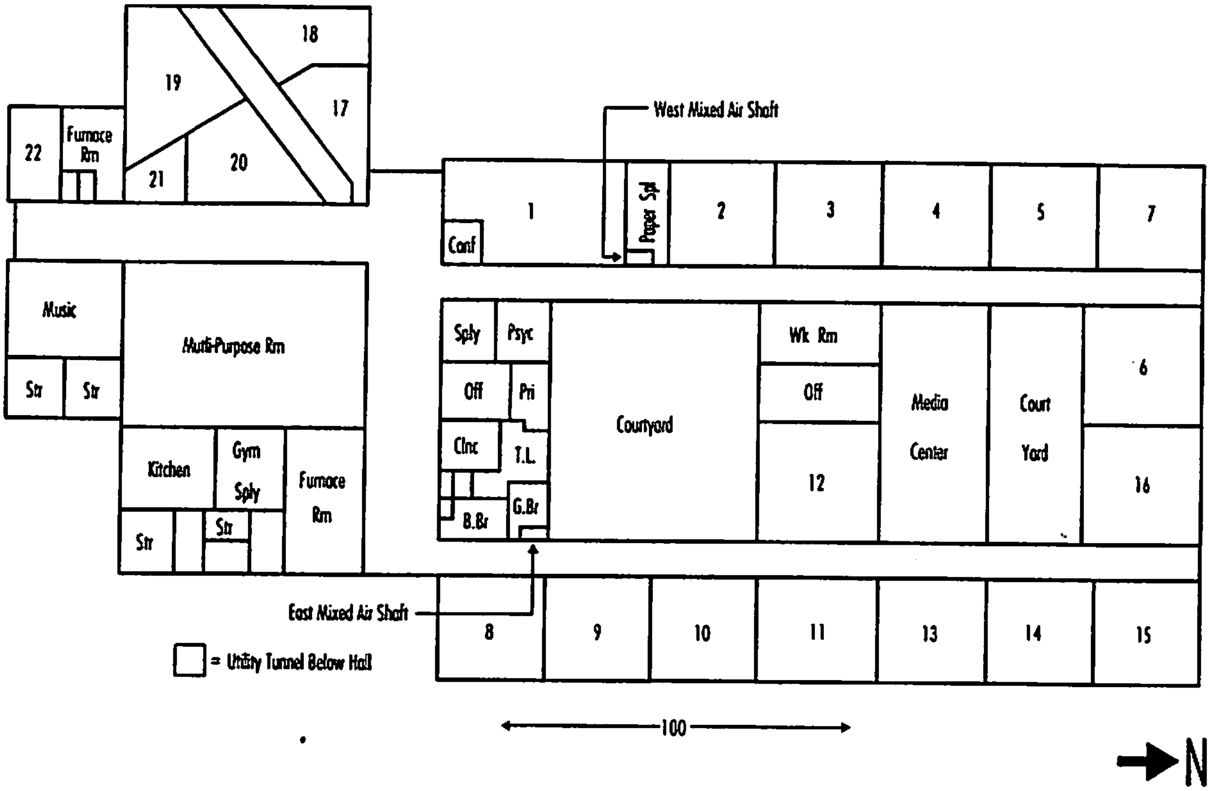
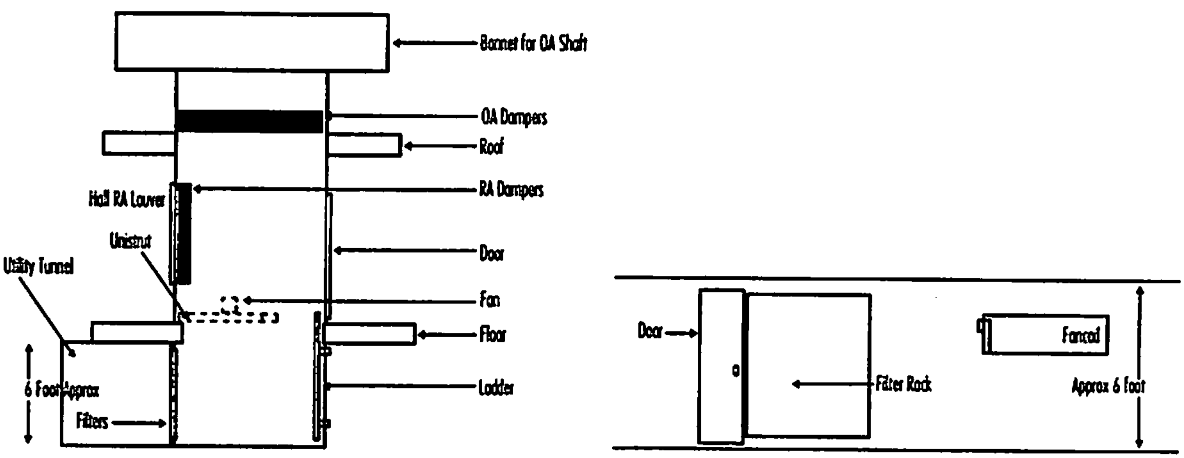


Figure 2 Utility tunnel east-west section and west elevation



Section

Elevation

Table 1 Average Radon Concentrations During Last 22 Hours of 24 Hour Trials and Percent Radon Reductions Compared to Previous Base Conditions[f]

	Variables						Average Radon Concentration in pCi/L						Radon Reduction	
Experiment	BWD Fans	MA Fans	SSD Fans	MA Source	Fan Coils	East BWD	Tunnel	Room #1	Room #2	Room #7	Princ. Office	Music Room	Tunnel	Upstairs
00. Base Condition Average	off	off	off	tunnel	on	off	30.3	10.7	6.8	11.4	9.3	0.3		
01. Orginal Operation with BWD	ON	off	off	tunnel	on	off	30.0	8.3	6.8	10.2	6.9	0.3	7%	19%
02. Blockwall Pressurization (BWP)	REV	off	off	tunnel	on	off	7.6	6.0	3.3	5.0	4.3	0.2	75%	52%
03. Tunnel Pressurization	off	ON	off	tunnel	on	off	8.7	3.0	2.3	4.4	2.9	0.2	61%	62%
04. Subslab Depressurization	off	off	ON	tunnel	on	off	28.2	9.9	5.4	9.8	8.0	0.5	-9%	9%
05. Hard Duct Mixed Air (MA)	off	off	off	DUCT	on	off	28.5	9.3	5.3	10.1	7.7	0.3	6%	12%
06. BWD + MA Fans	ON	ON	off	tunnel	on	off	7.4	2.1	1.4	3.2	2.0	0.2	76%	73%
07. BWD + SSD Fans	ON	off	ON	tunnel	on	off	23.6	5.8	3.2	7.3	4.3	1.3	5%	41%
08. BWD + MA Duct	ON	off	off	DUCT	on	off	29.9	8.3	5.4	10.6	7.3	0.4	11%	12%
09. MA Fans + SSD Fans	off	ON	ON	tunnel	on	off	8.1	2.4	1.8	4.1	2.6	0.2	63%	65%
10. MA Fans + MA Duct	off	ON	off	DUCT	on	off	14.3	6.1	4.7	7.6	5.5	0.6	63%	38%
11. BWD + MA + SSD Fans	ON	ON	ON	tunnel	on	off	10.2	3.8	3.8	6.6	3.6	0.6	74%	67%
12. BWD + SSD Fans + Duct	ON	off	ON	DUCT	on	off	28.6	3.4	1.1	6.9	2.1	0.3	27%	67%
13. BWD + MA Fans on, FCUs off	ON	ON	off	tunnel	OFF	off	3.4	1.2	0.8	3.4	1.1	1.3	89%	80%
14. BWD + FCUs on Setback	ON	off	off	tunnel	SET	off	24.6	9.6	5.3	9.0	6.4	1.3		
15. BWD + Duct + FCU Setback	ON	off	off	DUCT	SET	off	33.0	6.5	3.7	8.4	4.7	0.6		
16. BWD + MA Fans + FCU Setback	ON	ON	off	tunnel	SET	off	16.6	6.9	5.0	7.9	6.1	1.8		
17. BWD on + FCUs off	ON	off	off	tunnel	OFF	off	1.1	0.8	0.7	0.6	0.8	1.0	96%	90%
18. BWD + Outside Air @ 20%	ON	off	off	tunnel	on	off	28.2	11.8	6.1	11.9	7.3	0.2		
19. BWP + FCU Setback	REV	off	off	tunnel	SET	off	20.8	7.4	3.8	8.6	4.9	1.0	31%	33%
20. BWP + MA Fans + 6 of 12 FCUs	REV	ON	off	tunnel	6 on	off	5.4	5.3	5.6	5.9	5.2	6.6	82%	25%
21. BWP + MA Fans + FCU Setback	REV	ON	off	tunnel	SET	ON	2.0	1.8	1.8	1.8	1.7	6.7	94%	64%
22. BWP + FCU Setback	REV	off	off	tunnel	SET	off	13.5	9.2	6.0	8.4	6.7	2.4		

[f]Pyle, B.E., Williamson, A.D. and Menetrez, M. Y. (1995) ***Difficult to Mitigate Schools: (Unidentified School) Demonstration,*** Birmingham, AL, Southern Research Institute, SRI Project 7722.2.50/EPA Contract 68D20062/Work Assignment 2/050 (September)

BWD = block wall depressurization
BWP = block wall pressurization
FCU = fan coil units
MA = mixed air
PRINC = principal's
REV = reversed
SET = setback at night and week-ends
SSD = subslab depressurization