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# A COMPARISON OF RADON MITIGATION OPTIONS FOR CRAWL SPACE SCHOOL BUILDINGS

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## ABSTRACT

School buildings that are constructed over crawl spaces can present unique challenges to radon mitigation since they are often quite large (at least 4,000 $ft^2$ in area) and may contain support walls with footings that extend below the soil surface. The perimeter walls in the crawl space can also be extensive (on the order of 500 to 1,000 lineal ft). In this research project, natural ventilation using the existing vents in the foundation walls, depressurization and pressurization of the crawl space, and active soil depressurization under a polyethylene liner covering the soil were compared in a wing of a school building in Nashville, Tennessee. The wing has four classrooms constructed over a crawl space area of 4,640 $ft^2$. The building and crawl space were monitored throughout each mitigation phase with continuous sampling devices that recorded radon levels both in the crawl space and in the rooms above, in addition to environmental conditions such as temperatures and pressure differences in the building.

Results showed that active soil depressurization was the most effective technique for reducing radon levels in both the crawl space and the rooms above. Crawl space depressurization was also very effective in reducing radon levels in the rooms above the crawl space; however, radon levels in crawl space increased during depressurization.

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 AND BACKGROUND

This 29,266 $ft^2$ (refer to Table 1 for metric conversion factors) Nashville school building was originally constructed in 1954, with subsequent additions in 1957 and 1964. The original building and the first addition are slab-on-grade construction, and the 1964 four-classroom addition is constructed over a crawl space connected to the slab-on-grade section by a walkway. Initial charcoal canister measurements in this school in 1989 indicated that the 18 slab-on-grade rooms measured presented the most severe radon problems, averaging 34.1 pCi/L with a standard deviation of 7.5 pCi/L. In fact, levels over 100 pCi/L were subsequently measured in some of the slab-on-grade rooms. Radon levels in the four classrooms constructed over the crawl space were relatively much lower, averaging 9.7 pCi/L with a standard deviation of 0.7 pCi/L. As a result, initial remediation efforts during the summer of 1989 focussed on reducing levels in the slab-on-grade wings with active subslab depressurization (1,2). Post-mitigation measurements during February 1990 indicated that levels in the slab-on-grade rooms averaged below 2 pCi/L, and at this time plans were initiated to research the effectiveness of various mitigation techniques in the crawl space wing.

The crawl space is approximately 4,640 $ft^2$ in area, and the height ranges from 46 to 80 in. with a total air volume of approximately 25,500 $ft^3$. The plan view of the crawl space is shown in Figure 1. Access to the crawl space is excellent and the surface of the soil is not complex (i.e., no inaccessible areas, rock outcroppings, or large piles of soil). The floor of the classrooms over the crawl space is a suspended concrete slab poured over corrugated steel sheets supported by a network of steel trusses. There are two internal concrete block support walls in the crawl space that extend below the soil. These walls do not penetrate the slab overhead; however, the walls effectively subdivide the crawl space into three sections, as shown in Figure 1. This type of construction is quite different from that found in residential houses. In many existing houses, the floor is composed of wood decking (either 1 by 6 in. boards or plywood sheathing) supported by wooden floor joists. This type of house construction has been shown to be quite leaky and nearly impossible to seal all the openings between the crawl space and the rooms overhead (3,4). Since the crawl space does not contain any heating, ventilating, and air-conditioning (HVAC) ductwork or any asbestos, it was of interest to determine if the crawl space in this school building could be sealed well enough to permit pressurization or depressurization of the crawl space volume as a mitigation option.

The crawl space is ventilated naturally with eight block vents (four each on the east and west sides of the building). Each of these foundation wall vents has a screened opening with the same gross area as a concrete block (8 by 16 in.) or approximately 128 $in.^2$ Fan door leakage tests carried out on the crawl space according to ASTM E 779-87 resulted in an effective leakage area

(ELA) at 0.016 in. WC of pressure difference of 251 $in.^2$ with the vents open and 83 $in.^2$ with the vents sealed (using closed-cell foam board and caulking). Thus, the vents were providing approximately 168 $in.^2$ of total open area, or about 21 $in.^2$ per vent. This value is consistent with that measured in houses using similar techniques (5). The important point is that the leakage area independent of the block vents is very low (83 $in.^2$) compared to that measured in 15 houses in the same geographic area which ranged from 198 to 424 $in.^2$ with a mean of 262 $in.^2$ (5). Thus, this building was thought to be an ideal candidate to test a variety of possible mitigation techniques.

METHODOLOGY

Mitigation systems typically installed in crawl space houses include: isolation of the crawl space from the rooms above, isolation and depressurization or pressurization of the crawl space, isolation and ventilation of the crawl space (either natural or forced), and active soil depressurization either directly in the soil or under a plastic membrane (SMD) covering the exposed soil (4). Each of these mitigation techniques (with the exception of the forced ventilation and direct soil depressurization techniques) was tested in this school crawl space in an effort to compare their effectiveness when applied to a building having a larger size and a different construction type (concrete slab over the crawl space).

Initial baseline testing was carried out before any modifications were made to the building. Following the baseline measurements, the accessible openings (e.g., utility penetrations) from the crawl space to the upstairs rooms were sealed with a combination of closed-cell foam and urethane caulking. The block vents were also sealed with rigid closed-cell foam board and caulking. Following testing with the vents closed, a network of 4 in. PVC ducting was installed as shown in Figure 1. The fan installed is rated at 200 cfm at 1.5 in. WC. The fan and the air distribution network were used to test the effectiveness of crawl space pressurization and depressurization as mitigation options for the building. After the crawl space depressurization and pressurization tests were completed, two suction pits approximately 24 in. in diameter and 12 to 18 in. in depth were excavated in each of the three sections of the crawl space for a total of six suction pits as shown in Figure 1. Each suction pit was covered with a piece of 36 in. square by 1 in. thick marine grade plywood. The plywood covers were supported at the corners by four common bricks. Both the suction pits and the exposed soil were covered with two-ply high-density polyethylene sheeting. The plastic film was installed in three pieces, one in each section of the crawl space. No attempt was made to seal the plastic to the outer or inner foundation walls. The edges of the plastic were cut approximately 12 in. wider than necessary in the event that sealing to the walls was necessary. The excess material was then simply folded up the walls or allowed to fold back upon itself. The network of PVC ducting was connected to the suction pits to complete the active soil depressurization systems, as in previous house research (3).

Throughout the entire testing period, several parameters were monitored continuously using a datalogging device. The parameters monitored include: pressure differentials between Room 116 and outside the building on the east and west sides; pressure differentials between Room 116 and the crawl space interior; pressure differentials between Room 116 and the sub-poly region during the SMD testing; temperatures outdoors, in Room 116, in the crawl space, and in the soil; wind speed and direction; the outdoor relative humidity and rainfall; and the radon levels in both Room 116 and the crawl space. Each of these parameters was sampled every 6 seconds and averaged or totaled at the end of every 30 minute interval. These measurements and their locations are summarized in Table 2. The data were accumulated in the datalogging device and periodically downloaded to a personal computer and stored on magnetic disks for later analysis. Initial testing of the building began on March 1, 1990, and continued through July 20, 1990, for a total of 152 days (3648 hours). The datalogger was reinstalled from December 18, 1990, to January 17, 1991, in order to evaluate the mitigation systems during winter conditions. The most significant results are described in the following sections for both the spring/summer and winter measurements.

RESULTS OF SPRING/SUMMER MEASUREMENTS

Baseline Measurements

The baseline radon measurements made with the block vents open averaged 5.1 pCi/L in Room 116 and 10.8 pCi/L in the crawl space, as shown in Figure 2. Figure 3 shows the averaged pressure differences between the crawl space and outdoors and between Room 116 and outdoors during each phase of the mitigation. Also plotted in Figure 3 are the average temperatures outdoors, in the crawl space, and in Room 116 averaged over the testing period. Following closing and sealing of the block vents and sealing the major openings from the crawl space to the classrooms above, the average radon levels in the classroom increased by about a factor of 3.3 to 17.1 pCi/L and the crawl space levels by a factor of 8 to 87.2 pCi/L. During this time the average pressure difference in the classroom increased by a factor of 1.6 to -4.7 Pa, and the crawl space pressure increased by a factor of almost 4 to -3.9 Pa. It is obvious that closing up the crawl space greatly enhanced the depressurization produced mainly by the stack effect. Also, the temperature differences between the interior of the building and the outdoors were much larger than during the other testing periods, thus increasing the stack effect. These results clearly indicate the effect on radon when the vents of crawl spaces are closed for energy conservation purposes.

Crawl Space Pressurization

The next mitigation technique tested was crawl space pressurization using the fan installed near the roof level of the building and the network of PVC ducting to distribute the flow with the crawl space vents closed. During pressurization, the average fan flowrate was 234 cfm which was equivalent to about 0.6 air changes per hour (ACH). During this time the average crawl space pressure difference was reduced to -1.5 Pa and the average classroom pressure difference was reduced to -2.5 Pa as seen in Figure 3. The average radon levels in the classroom and crawl space were 10.6 and 29.1 pCi/L, respectively, as shown in Figure 2. It is apparent that the flowrate of outdoor air into the crawl space is not sufficient to raise the pressure in the crawl space above the outdoor pressure and could only negate about 60% of that produced by the stack effect in the crawl space and about 50% of that produced in the classroom. It is possible that by doubling the flowrate (to around 500 cfm) the crawl space and the classroom could have been pressurized above the outdoor conditions and the radon levels further reduced. However, this option did not appear as a desirable year-round solution in view of the fact that unconditioned air was being used for pressurization.

Crawl Space Depressurization

Following the crawl space pressurization testing, the fan was reversed so that air was withdrawn from the crawl space and exhausted above the roof of the building. In this configuration, the fan flowrate increased slightly to 279 cfm or about 0.7 ACH. The negative pressures in the classroom were similar. However, the pressure differential in the crawl space increased by approximately 73% (from -1.5 to -2.6 Pa). The radon levels in the classroom were reduced by about 94% (from 10.6 to 0.6 pCi/L) even though the levels in the crawl space increased by a factor 1.8 (from 29.1 to 53.6 pCi/L). Therefore, while depressurizing the crawl space lowered the levels in the classroom, it nearly doubled the levels in the crawl space. This was not unexpected since a similar technique applied to a residential house increased the levels in the crawl space by about a factor of 3 (4, 5).

Active Soil Depressurization

The third type of mitigation system implemented was active soil depressurization under a plastic membrane covering the exposed soil (SMD). The total flowrate exhausted from under the plastic liners was 260 cfm when using all six suction points shown in Figure 1. As seen in Figure 2, the radon levels in the classroom were reduced within a matter of hours to around background (0.5 pCi/L), and in the crawl space the levels decreased to 3.5 pCi/L. In an attempt to determine if fewer suction points could be used, the two suction points in the central sector of the crawl space were disconnected and the suction pipes to both the fan and the suction pits were capped. The results are shown in Figure 2. The decrease in the crawl space levels is probably not significant, and the levels in the classroom are the same within the level of uncertainty of the measurement. The results from the SMD mitigation technique are quite similar to those found when the same method is applied to residential houses (4, 5, 6), where the area of the exposed soil is typically in the range of 1,000 to 2,000 ft$^2$. In this building the area is much larger (4,640 ft$^2$); however, the resulting reduction in the radon levels using SMD is seen to be as good as that achieved in smaller crawl spaces. The next important research step is to apply the SMD technique to crawl space areas on the order 10,000 ft$^2$ or larger.

RESULTS OF WINTER MEASUREMENTS

The above measurements were repeated during the winter (December 18, 1990, to January 17, 1991) in order to determine if the results were consistent with the spring and summer measurements. A brief analysis of the winter data supports the results of previous measurements and the integrity of the SMD system during cold weather. These data will be fully analyzed and documented in a future report. Based upon the initial analysis of the data, the average cold weather radon levels both in Room 116 and in the crawl space are shown in Figure 2.

Baseline Measurements

No attempt was made to reproduce the open vent (natural ventilation) condition as this was felt to be an unusual operating mode for wintertime conditions. The results for the closed vent mode in winter were much the same as those obtained in the spring/summer, with the possible exception that the winter radon levels in the crawl space were not as high as the previous values (63.4 pCi/L compared to 87.2 pCi/L). The lower readings could be due in part to the fact that the winter measurements were carried out after the soil was covered with the polyethylene liners. The presence of the plastic liners covering the soil could act as a partial barrier to soil gas exhalation. The lower readings could also be due to the fact that the winter measurement period was much shorter than the spring/summer measurement period.

Crawl Space Pressurization

The wintertime crawl space pressurization levels were much the same as obtained previously. These results indicate that, with the amount of unconditioned air used, the radon reductions achieved with this mitigation technique are still less than desirable.

Crawl Space Depressurization

Using this technique during cold weather conditions gave very similar results to those obtained in the spring/summer tests. The wintertime levels in both the classroom and the crawl space were somewhat higher and could be due to an increased stack effect normally expected during cold weather. In order for this technique to be successfully applied year-round, it is obvious that the installation and testing must be done during extreme temperature conditions in order to ensure that an adequate amount of air is exhausted from the crawl space.

Active Soil Depressurization

The wintertime radon levels measured with the SMD system operative were almost identical to the levels measured previously. The average level in the classroom was within the uncertainty of the measurement techniques, and the levels in the crawl space were slightly lower than before. These results clearly indicate that the SMB technique is not only effective but stable in its ability to lower the radon levels in both the classroom and the crawl space under varying weather conditions.

CONCLUSIONS

The results of this project indicate that the SMD technique is the most effective in reducing elevated levels in both the crawl space and the classrooms. In this application, the crawl space was large but fairly simple in geometry. Access to the exposed soil areas was excellent and, with the exception of the two internal support walls, did not contain a large number of obstructions such as support piers or utility pipes lying on the soil. The topology of the soil surface in this crawl space was relatively smooth. Other crawl spaces may have some or all of the complications that were absent in this application (7). Application of the SMD technique in these more difficult crawl spaces needs further investigation.

Depressurization of the crawl space is effective in reducing levels in the classrooms; however, the levels in the crawl space will be increased by at least a factor of 2 and perhaps as much as a factor of 3. This could pose a problem in buildings that have nonsealable openings from the crawl space into the occupied rooms above (e.g., HVAC ducts in the crawl space, wooden floors over the crawl space, or doors or other entry openings from the crawl space into the rooms above) or if the crawl space is occupied on a regular basis. In this building the overhead floor was a poured concrete slab with very few openings to the classrooms above that helped to contribute to the effectiveness of crawl space depressurization.

Pressurization of the crawl space was found to be less effective in reducing the radon levels than natural ventilation. This method may be more effective if larger quantities of air are supplied to the crawl space; however, this may result in increased energy losses and perhaps could increase the risk of damage to utility lines in cold weather.

Natural ventilation of the crawl space also appears to be ineffective in reducing the radon levels to acceptable levels. Increasing the ventilation through larger or more numerous vents may increase radon reduction; however, the effectiveness of this method depends to a large extent on the wind patterns outdoors. Also, this method can easily be defeated by closing vent openings during the colder periods.

The number of school buildings constructed over crawl spaces is not quantified at the present, although EPA research in over 40 schools has shown that only 7 of the buildings contain crawl spaces (in combination with slab-on-grade substructures). There is little information available regarding crawl space characteristics, such as floor construction, number of vents, number of piers and support walls, and the presence of HVAC ductwork or asbestos in the crawl space. While the SMD technique appears to be the method of choice for reducing levels in both the crawl space and the rooms above, further investigations need to be carried out in crawl spaces that are not as simple as the one used in this study to determine if it can indeed be applied successfully in non-ideal conditions.

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## TABLE 1. METRIC CONVERSION FACTORS

| Non-Metric | Times | Yields Metric |
|---|---|---|
| cubic foot ($ft^3$) | 28.3 | liters (L) |
| cubic feet per minute (cfm) | 0.47 | liter per second (L/s) |
| degrees Fahrenheit (°F) | 5/9 (°F-32) | degrees centrigrade (°C) |
| foot (ft) | 0.30 | meter (m) |
| inch (in.) | 2.54 | centimeters (cm) |
| inch of water column (in. WC) | 248 | pascals (Pa) |
| picocurie per liter (pCi/L) | 37 | becquerels per cubic meter ($Bq/m^3$) |
| square foot ($ft^2$) | 0.093 | square meter ($m^2$) |
| square inch ($in.^2$) | 6.452 | square centimeters ($cm^2$) |

## TABLE 2. SUMMARY OF MEASUREMENTS

| Parameter | Location |
|---|---|
| Differential Pressure | Room 116 to Outdoors<br>Room 116 to Crawl space<br>Room 116 to Subpoly |
| Radon | Room 116<br>Crawl Space |
| Temperature | Room 116<br>Crawl space<br>Soil<br>Outdoors |
| Wind Speed and Direction | Outdoors |
| Relative Humidity | Outdoors |
| Rainfall | Outdoors |

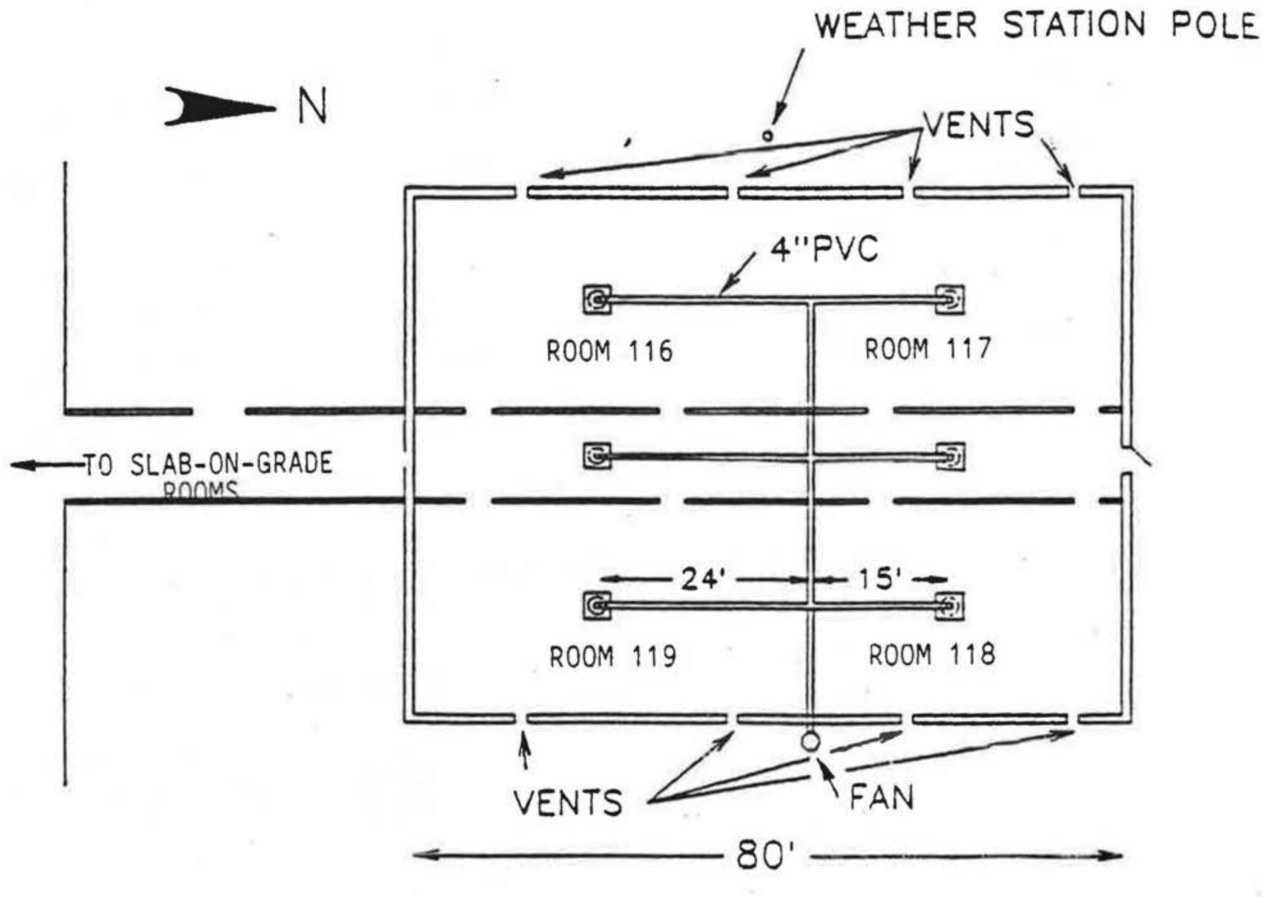


Figure 1. Plan view of the crawl space and installed ducting network.

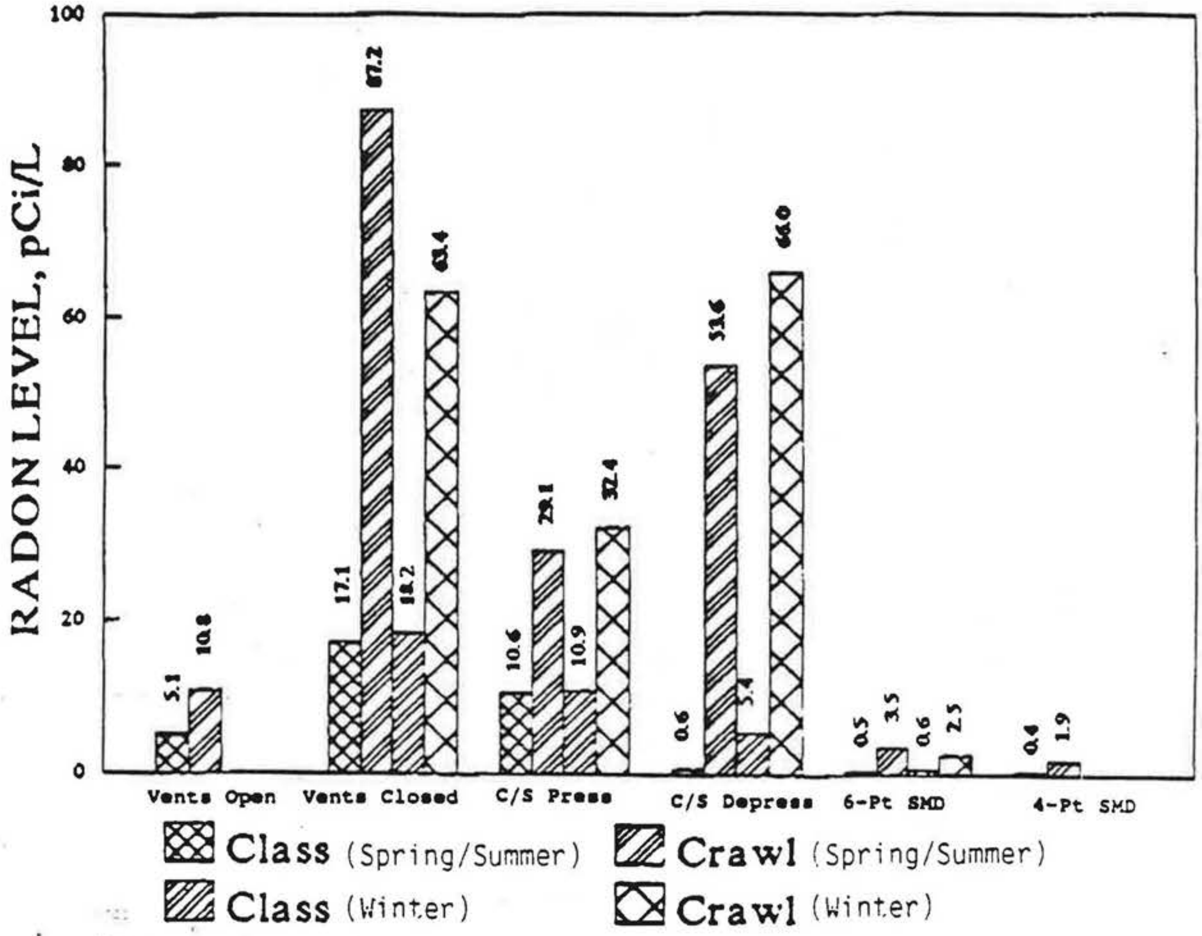


Figure 2. Average radon levels in the crawl space and in Room 116 during each of the mitigation testing periods (both spring/summer and winter).

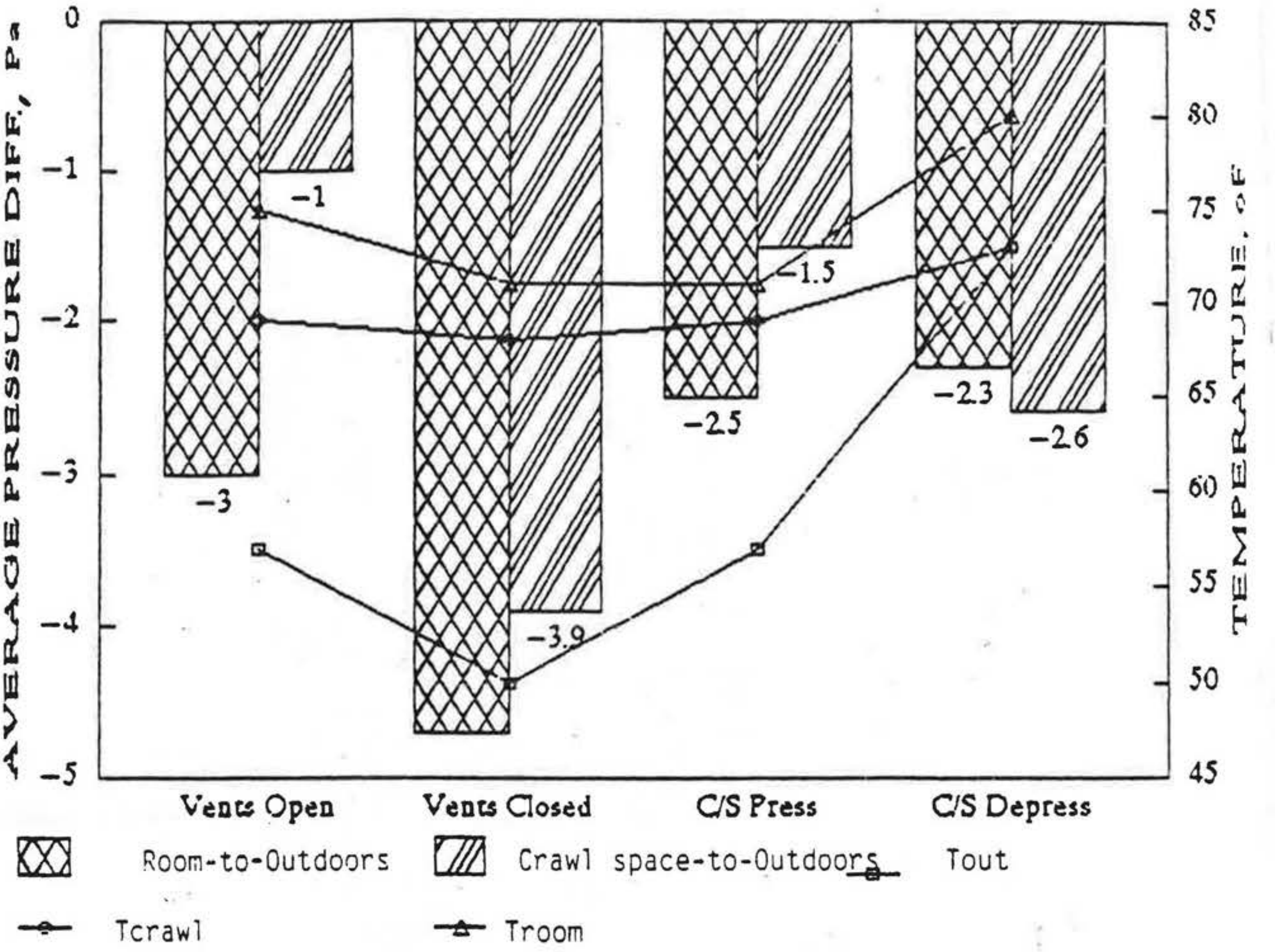


**Figure 3.** Average pressure differences between both the crawl space and outdoors and Room 116 and the outdoors during each of the mitigation testing periods.

AMOUNT OF SUCTION APPLIED

The amount of PFE also depends on the level of suction applied to the suction pit. The amount of vacuum which can be applied depends on fan size and the air leakage rate from all sources into the subslab area. Theoretically, if the subslab aggregate envelope is completely airtight, very little air will need to be moved to get very large PFE. The top and sides of the envelope can be well sealed, resulting in only a small amount of air leakage. However, the bottom of the envelope, the compacted soil under the aggregate, has variable permeability depending on composition and compaction. Consequently, the air infiltration into the envelope from this source is variable. Given a choice of subaggregate conditions, the underlayment should be made as impermeable as reasonably possible. For a given subaggregate, the more the soil is compacted, the less the resultant permeability. In areas where the subaggregate fill is highly permeable, such as with sand in Florida or with near-surface moraine in many areas, it may be necessary to overlay the permeable material with a compacted layer of impermeable clay.

The size of the suction fan needed can best be determined experimentally. Table 1 lists the performance characteristics of various sizes of one commercial exhaust fan (Kanalflakt). Note that the larger fans can achieve a higher negative pressure than the smaller ones. One wing of the Two Rivers Middle School (15,000 $ft^2$) was mitigated by a T3B fan which had a flow of 150 cfm at 1.97 in. WC when installed in this system. In choosing a fan size, it is better to err on the high side rather than the low side.

SIZE AND LOCATION OF OPENINGS IN SLABS

Expansion joints, pour joints, control saw cracks, and pipe penetrations are discussed in an earlier section. Several other types of slab penetrations can also affect radon entry. One such source is an open sump connected to perforated pipe installed under the slab for groundwater protection. All sumps must be sealed in order to keep out soil gas which may contain radon. One good solution for this is the use of a sewage ejector pit as a sump pit since they always have vaportight lids.

Floor drains can also be a source of radon entry if connected to a septic system (which is rare in the case of schools but they do exist). In this case, care should be taken in the design to make sure that the floor drain is trapped and will always be full of water. Lines of conventional sewer systems have not been found to contain radon since they are tightly sealed.

If electrical conduit is routed under the slab, care must be taken to make sure that any conduit connections under the slab are vaporproof. The same is true for any other subslab conduit.

## CONCLUSIONS

Study of the architectural features, diagnostic studies, and mitigation results for the existing schools that have been mitigated as part of the AEERL school mitigation program has resulted in identifying many factors which affect radon entry and ease of mitigation. Results of these studies have led to tentative conclusions on how to design new schools which are radon resistant and easy to mitigate. Many of these findings can be considered as sufficiently sound that they can be recommended for incorporation in new school buildings. Others need field verification in schools either currently under construction or in the design phase. Work is underway to accomplish this in the next 2 to 3 years.

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## CONVERSION FACTORS

Readers more familiar with the metric system may use the following factors to convert to that system.

| Nonmetric | Multiplied by | Yields Metric |
|---|---|---|
| cfm | 0.00047 | $m^3s$ |
| ft | 0.30 | m |
| $ft^2$ | 0.093 | $m^2$ |
| HP | 7.46 | W |
| in. | 0.025 | m |
| in. WC | 249 | Pa |

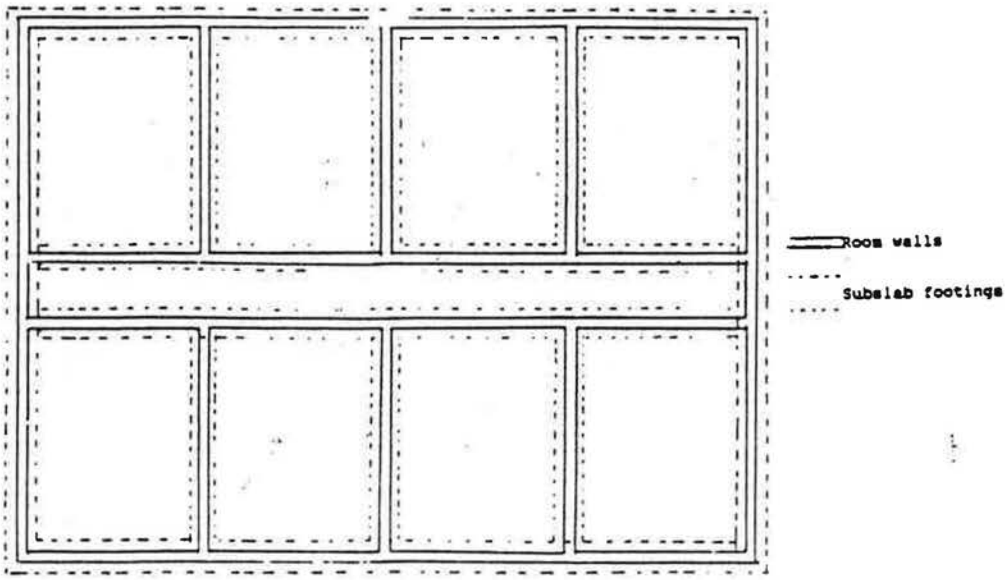


Figure 1. All walls are load-bearing.

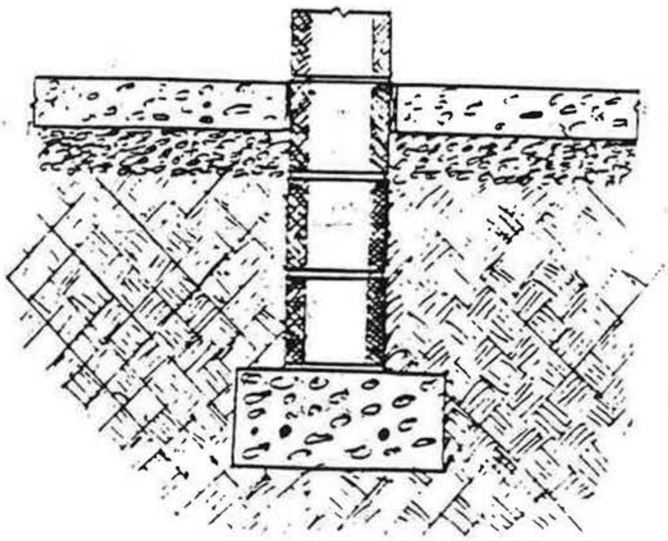

Figure 2. Section of load-bearing wall.

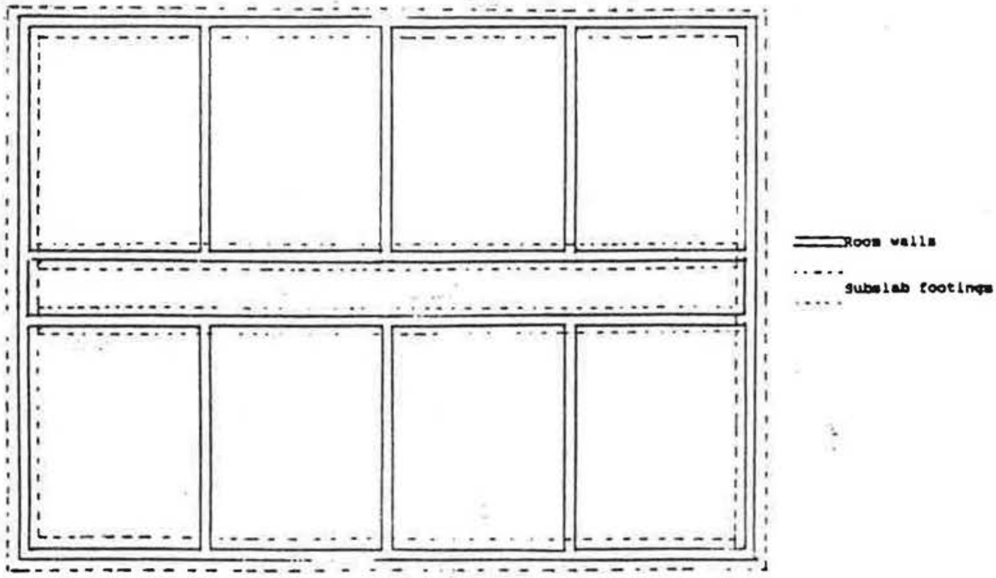


Figure 3. Hall and outside walls are load-bearing.

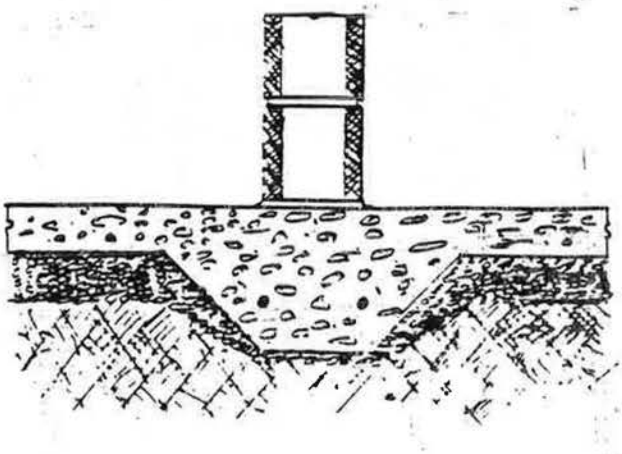

Figure 4. Section of wall resting on thickened slab footing.

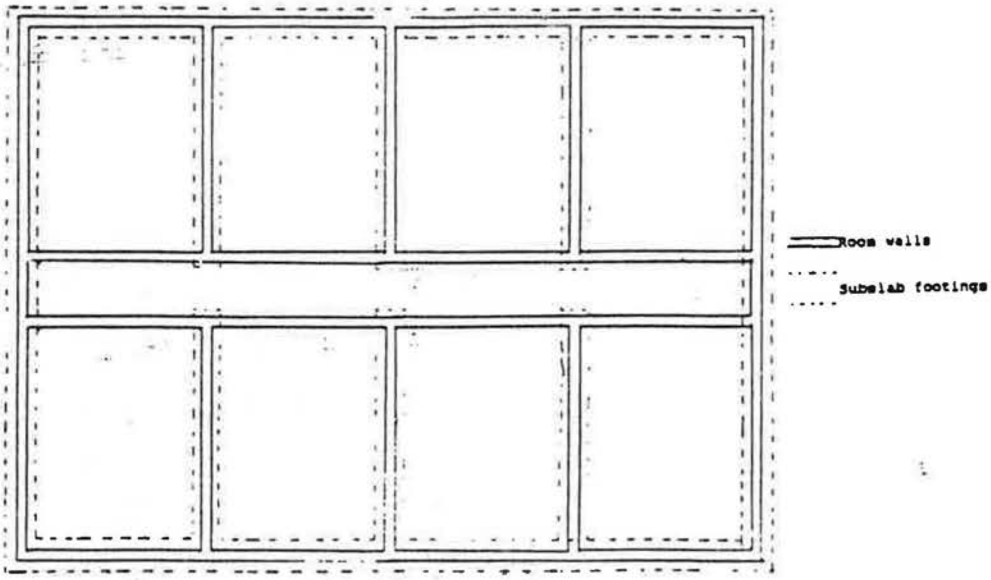


Figure 5. Walls between rooms and outside walls are load-bearing.

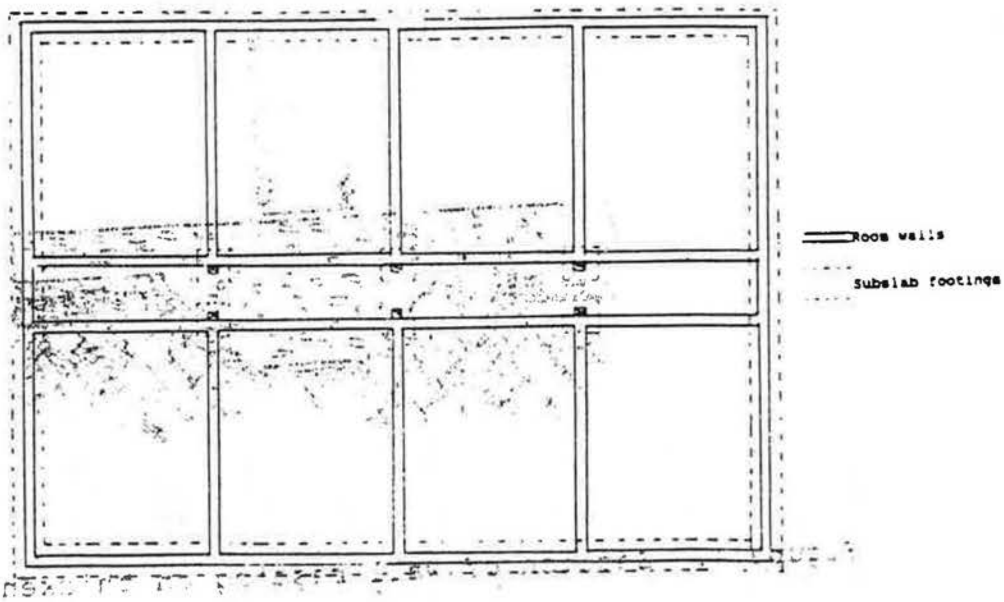


Figure 6. Outside walls and posts are load-bearing.

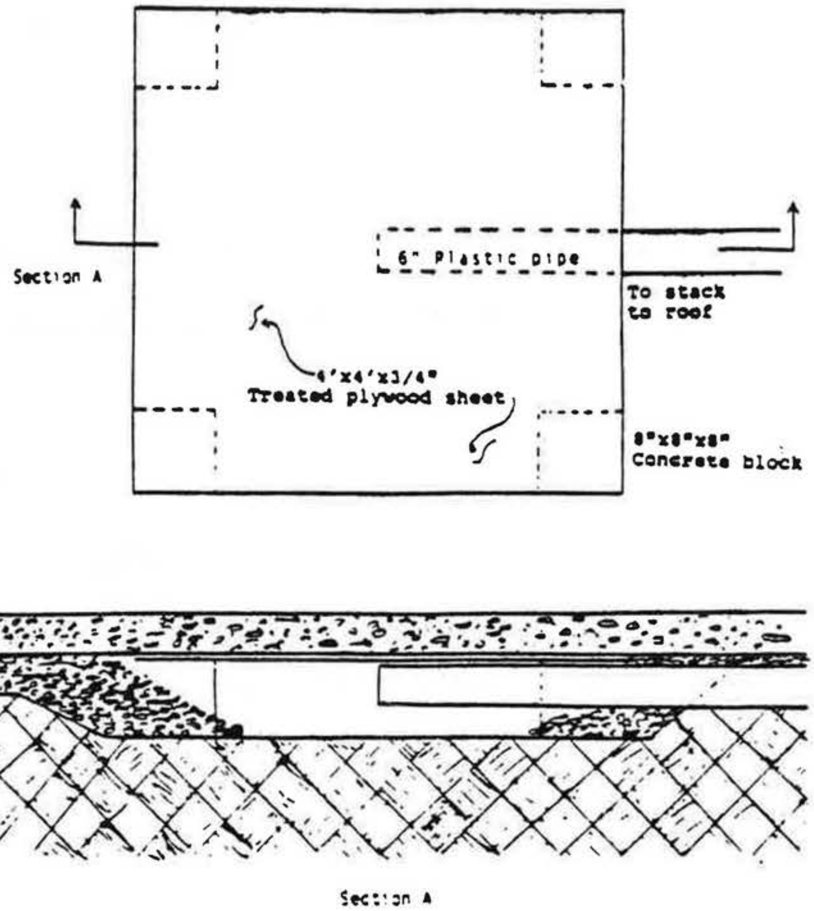


Figure 7. Design for large suction pit.

## TABLE 1. KANALFLAKT FAN PERFORMANCE

| MODEL | HP | FAN RPM | AIR FLOW (cfm) VS STATIC PRESSURE (in. WC) 0 | 1/8 | 1/4 | 3/8 | 1/2 | 3/4 | 1 | 1-1/2 | 2 | PIPE DIA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T1 Turbo 5 | 1/40 | 2800 | 158 | 143 | 125 | 114 | 90 | 45 | | | | 5" |
| T2 Turbo 6 | 1/20 | 2150 | 270 | 255 | 235 | 200 | 180 | 140 | 110 | | | 6" |
| T3A Turbo 8 | 1/15 | 2150 | 410 | 375 | 340 | 285 | 225 | 180 | 135 | | | 8" |
| T3B Turbo 8 | 1/10 | 2300 | 520 | 500 | 470 | 445 | 415 | 310 | 230 | 200 | | 8" |
| T4 Turbo 10 | 1/6 | 2400 | 700 | 670 | 640 | 612 | 582 | 470 | 410 | 250 | 115 | 10" |
| T5 Turbo 12 | 1/8 | 1250 | 900 | 801 | 718 | 624 | 557 | 456 | 359 | 254 | | 12" |