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A REVIEW OF RADON MITIGATION IN LARGE BUILDINGS IN THE US

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INVITED PAPER

Abstract — The Environmental Protection Agency of the US carried out its initial research on radon mitigation in houses, both existing and new. A review of this work is presented in another paper at this workshop. Four years ago, this work was expanded to include the study of radon in schools, both new and existing, and now includes studies in other large buildings, as well. Factors affecting ease of mitigation of existing schools using active soil depressurisation (ASD) have been identified and quantified. Examination of the building and architectural plans makes it possible to predict the ease of mitigation of a specific building. Many schools can be easily and inexpensively mitigated using ASD. However, examination of a fairly large number of schools has shown that a significant percentage of existing schools will be hard to mitigate with ASD. In some cases, the heating, ventilating, and air conditioning (HVAC) system can be used to pressurise the building and retard radon entry. However, in some cases no central HVAC system exists and the school is difficult and/or expensive to mitigate by any technique. Prevention of radon entry is relatively easy and inexpensive to accomplish during construction of schools and other large buildings. It is also possible to control radon to near ambient levels in new construction, a goal which is much more difficult to approach in existing large buildings. The preferred method of radon prevention in the construction of large buildings is to design the HVAC system for building pressurisation, install a simple ASD system, and seal all entry routes between the sub-slab and the building interior.

BACKGROUND

Naturally occurring radon gas was first identified at high levels in houses in the US in 1984 in the Reading Prong area of Pennsylvania. Since that time houses with elevated radon levels have been found in every state of the union. Since radon was first identified in houses it is only natural that the first studies on radon mitigation techniques were in houses, both existing and new. Two papers are being presented at this workshop covering this work in the US.

Within two years of the discovery of radon in houses, school districts began to test schools for radon and, as expected, radon was about as prevalent in schools as it was in houses in the same geographic areas. Consequently, a need for mitigation technology for large buildings, both existing and new, began to emerge.

RADON MITIGATION IN EXISTING SCHOOLS AND OTHER LARGE BUILDINGS

As in houses, radon can best be controlled by keeping it out of schools and other large buildings rather than removing it after it has entered the building. The following three techniques have been the most effective in the control of radon in large buildings:

(1) *Active soil depressurisation (ASD).* Drill slab, dig out suction pit under the slab, and install vertical vent stack topped with external suction fan.
(2) *Building pressurisation.* Design and operate the HVAC system to meet ASHRAE Standard 62-1989[1] for ventilation *and* to keep all areas of the building under positive pressure during occupied periods.
(3) *Sealing radon entry routes.* Install physical barriers to block radon-containing soil gas by sealing all openings from the soil into the interior of the building.

A combination of all three techniques is recommended for maximum radon reduction and best overall indoor air quality.

Two major differences quickly became apparent between mitigation in houses and in schools. The first was that schools frequently have sub-slab walls extending down to undisturbed soil, dividing the slab area into 'boxes' and making mitigation by ASD more difficult and more dependent on architectural design than in houses. This was shown strikingly by two schools mitigated in Nashville, TN[2]. In one school, a 1200 m^2 wing was reduced from an average of 1200 $Bq.m^{-3}$ to 32 $Bq.m^{-3}$ with one suction point. In the second school, an area of 1200 m^2 required 16 suction points and 3 fan systems to get the same amount of reduction. Study of the architectural plans of the two schools showed that the difference was in the sub-slab walls. The easy-to-mitigate school had continuous aggregate under the slab with no sub-slab barriers, whereas all walls of the hard-to-mitigate school extended through the slab to undisturbed soil. In other words, there were as many compartments under the slab as there were rooms above the slab, and each sub-slab compartment needed at least one suction point.

Review of the architectural plans of many schools disclosed that most fall in one of the following four categories listed in order of increasing difficulty of mitigation:

Type 1. No interior walls extend through slab, with the roof load (and upper floor loads if multistorey) being carried by posts (steel or reinforced concrete) extending through the slab to footings.

Type 2. Walls between classrooms extend through slab to sub-slab footings. Hall walls do not.

Type 3. Hall walls extend through slab to sub-slab footings. Walls between classrooms do not.

Type 4. All walls extend through slab to sub-slab footings.

In this characterisation, the easy-to-mitigate school described in the Reference 1 paper was Type 1 and the hard-to-mitigate school was Type 4.

Another existing school of Type 1 design having a floor area of 5400 m^2 has more recently been mitigated to near ambient levels using just one suction point[3].

The second difference between houses and large buildings such as schools is in the HVAC system. In houses, there is normally no means of bringing in outdoor air mechanically; whereas, in large buildings this is normally part of the HVAC system. Bringing in outside air under pressure can result both in pressurisation of the building keeping radon out and in dilution of any radon which has entered a building. Thus, the HVAC system can be used effectively to keep radon out of many buildings. This will be discussed in greater detail in another US paper given later in the programme.

Each of the mitigation techniques listed above has its drawbacks. ASD is ineffective if the substrate under the slab has very low permeability. Fortunately, in most parts of the US, crushed aggregate is used under the slab for moisture control. This aggregate has very high permeability and, if present, makes ASD highly effective. Occasionally, the return air ducts of the HVAC system are placed under the slab. Since these ducts are always under negative pressure, they result in radon entry when the HVAC system is in operation.

Under some circumstances, the HVAC system can be operated in such a way as to be an effective deterrent to radon entry. However, when the HVAC system is turned off at night for energy conservation, radon concentrations can build up, reaching levels where it takes a significant period of time to reduce the radon to acceptable levels once the system is turned back on the next morning.

Sealing used alone is not an effective radon mitigation technique but improves the performance of ASD and pressurisation techniques.

RADON MITIGATION IN DESIGN AND CONSTRUCTION OF LARGE BUILDINGS

In new construction, it is very easy and inexpensive to reduce radon to near ambient levels using ASD. This is readily accomplished by:

(1) Eliminating all major barriers to sub-slab pressure field extension, such as interior sub-slab walls.
(2) Placing a clean layer of coarse aggregate beneath the slab.
(3) Placing a plastic barrier between the aggregate and the slab.
(4) Installing properly designed suction pit(s) beneath the slab in the aggregate.
(5) Installing a vent stack from the suction pit to the roof.
(6) Installing a suction fan on the vent stack outside the building shell.
(7) Sealing all major slab and foundation penetrations.

If possible, the design should be Type 1 with no barriers to gas flow beneath the slab. If one of the other types is used it should be modified in such a way that all areas beneath the slab are interconnected with the aggregate layer.

A 10 to 15 cm layer of aggregate should be placed beneath the slab. Aggregate characteristics are very important to the mitigation of large slabs and have the following effects on pressure field extension (PFE):

(1) PFE is proportional to average aggregate particle size: the smaller the particle size, the less the PFE (assuming the same particle size distribution).
(2) The narrower the aggregate particle size distribution range, the greater the void volume and the PFE.
(3) The smoother the shape of the stone, the lower the void volume; hence moraine stone (with its rounded corners) has lower void volume and will give less PFE for the same average particle size and particle size distribution than crushed aggregate.

The preferred stone is a crushed aggregate which meets the specifications for size No. 5 as defined in ASTM C-33-86 'Standard Specifications for Concrete Aggregates'[4]. This stone has a nominal size of 1.25 to 2.5 cm with less than 10% passing a 1.25 cm screen. The stone should be a *minimum* of 10 cm deep (15 cm is preferable) over the *entire* area and should be placed in such a way that no dirt is mixed into it. The stone can be lightly compacted if required by code. However, if it is compacted at all, great care should be taken not to force any of it into the underlying strata, thus decreasing its effective thickness. If significant compacting is required, it may be desirable to place a layer of geotechnical fabric under the aggregate to keep dirt out of the aggregate. The stone should run under any thickened slab areas (footings, etc.) shown in the construction plans.

A plastic barrier is placed over the aggregate before the slab is poured. Although this serves as a partial soil gas barrier, its main function is to keep any of the wet concrete mix from penetrating the stone during pouring of the slab: this could result in partial binding of the stone and decreased PFE. Heavy polyethylene film is most commonly used. Wide widths should be used with 30 cm overlaps at the joints, which do not need to be sealed.

The design and placement of the suction pit are two of the most important aspects of ASD and increase in importance as the size of the building increases. The suction pit design shown in Figure 1 has been field tested and effectively mitigated a 6000 m^2 hospital to near ambient levels. PFE data indicated that a slab of much greater than 20,000 m^2 could have easily been mitigated by this single suction pit system. A suction pit of improved design is currently being field tested.

The key to the effectiveness of any suction pit is the area of the interface between the sub-slab void and the aggregate — the larger the area, the greater the PFE. This area in the suction pit shown in Figure 1 is 0.7 m^2.

If Type 1 construction is used, the suction pit should be located near the centre of the building to maximise the area which can be mitigated with a single suction point. In no case should it be located near an outside wall since this will decrease the PFE in the opposite direction. Under optimum sub-slab conditions, PFE can be as much as 100 to 150 m.

A 15 cm vent pipe is run from the suction pit to the exterior of the building, normally through the roof. The preferred placement of this pipe within the suction pit is shown in Figure 1. With this arrangement, the stack can be remote from the suction pit location (in a planned pipe chase) or in a corner where it can readily be boxed in. It should be located near the suction pit to minimise vacuum loss in long runs of pipe. The pipe under the slab should be schedule 40 plastic rather than steel because of corrosion concerns. The type of pipe used above the slab will depend on local code requirements. In many areas, steel is required by code.

A high performance in-line centrifugal fan is mounted on the end of the vent pipe. The size of the fan will depend on a number of factors some of which cannot be determined until the system is completed. An optimum size fan for an installation with a well sealed slab and low permeability soil beneath the aggregate will pull about a 350 Pa head when operating on the ASD system. High performance fans of this type are available from a number of companies, some with guarantees of continuous operation for a number of years. The fan should be on a carefully labelled dedicated circuit in order to minimise the possibility of its being inadvertently turned off.

The fan should be mounted outside the building, since any pipe beyond the fan is under positive pressure and a leak in it would result in the inadvertent introduction of radon-containing soil gas into the building. The end of the stack should be located at least 10 m from any air intake for HVAC systems, doors, or windows. This must be carefully checked on roofs where HVAC systems are frequently installed.

It is important to remember that ASD system fans should be operated continuously; otherwise, elevated levels of radon may accumulate when the fan is off. The cost of operating the fan continously is comparable to the cost of operating any other exhaust fan in the building (such as a rest room exhaust fan).

Because concrete is a relatively good barrier against radon, it would appear that poured concrete floor slabs and foundation walls would seal out radon. But the problem with concrete is that it cracks. Many factors (e.g. the water/cement/aggregate ratio, humidity, temperature, curing and construction practices, and settling) influence how much cracking occurs in a poured concrete slab and foundation. Cracking can be minimised by following good design and placement procedures, as documented by the American Concrete Institute.

Cracking can also be controlled by the judicious use of pour joints and control saw joints. The edges of pour joints should be tooled (rounded) when poured to facilitate sealing. All pour and control saw joints should be carefully cleaned and sealed with a polyurethane caulking. This caulking is recommended over any other in that it is flexible and sticks tenaciously to concrete. If expansion joints are used in any slab, the top 1 to 2 cm should be removed (several types of expansion joints are made to facilitate this) and the opening carefully sealed with polyurethane caulking. Expansion joints

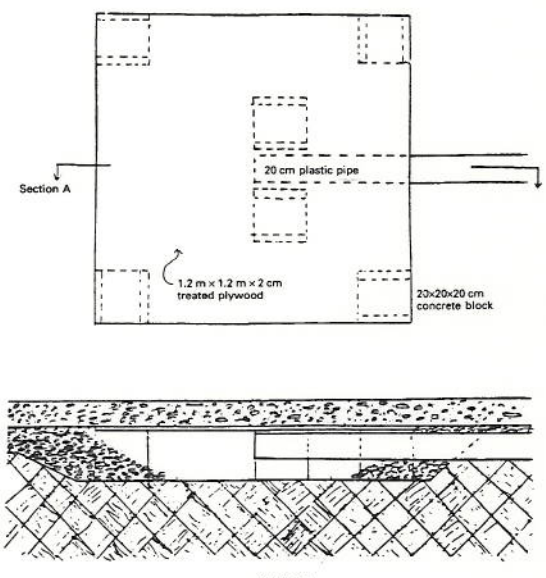

Figure 1. Sub-slab suction pit.

should be minimised or eliminated if code allows, since they are more difficult to seal than are pour joints. Areas around utility lines which penetrate a slab are potential radon entry points and should be carefully sealed. Any wrappings placed around copper water pipes to protect them from the concrete should be removed to below the slab surface and carefully sealed. Sealing is particularly important where several pipes come up near each other such as at pipe chases where it is difficult to finish the concrete and to seal between closely spaced pipes.

MITIGATION COSTS

Incremental costs of the mitigation system installed in a 5400 m^2 hospital were easily ascertained since the contract for the building had been let before the mitigation system was added to the design. The cost of the addition of the radon mitigation system was covered by four change orders for which the construction contractor charged an additional $5300. Thus the system cost was $1.03 per m^2 of floor space. Other installations can run significantly higher if the building is more complicated than the hospital.

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