BUILDING MATERIALS AS A SIGNIFICANT CONTRIBUTOR TO INDOOR RADON CONCENTRATIONS IN A LARGE APARTMENT COMPLEX MITIGATION: CASE STUDY

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ABSTRACT

The Florida Department of Health conducted an investigation to address reported difficulties in mitigating some units of a large apartment complex in Florida. The complex houses over 300 one and two bedroom apartments in over 40 three-story concrete structure buildings. Initial mitigation work successfully mitigated many of the first floor units to levels below 3.5 pCi/l using Active Soil Depressurization (ASD) systems. However, other units particularly those located at both ends of the buildings continued to exhibit elevated indoor radon concentrations. Since problematic units and successfully mitigated units can be found in the same building, radon entry contribution from building materials was not initially suspected as the cause of the problem. Modification and enhancement of ASD systems in problematic units demonstrated no effectiveness in reducing indoor radon levels. The investigation revealed that unexpected distribution of concrete mix materials inside the wall cavities can be responsible for the persistent elevated indoor radon concentrations. Wall cavities of the end apartment units were found to be filled with the concrete mix while no filling or inconsistent filling patterns were diagnosed in other wall cavities. It has been demonstrated that contributions of building materials can be accounted for the uncontrolled portion of the elevated average indoor radon concentration in the problematic units. Abnormality in structures such the one encountered in this investigation can be found occasionally. Therefore, it is recommended that radon mitigation work in large and complex structures should incorporate a practice of performing detailed building diagnosis prior to installation.

INTRODUCTION

In early 1997, the Florida Department of Health (DOH), Bureau of Environmental Toxicology received a request for assistance from a Florida licensed radon mitigation firm to help in solving unexplained, elevated indoor radon in a large apartment complex. The complex consists of more than forty, three-story buildings of one and two bedrooms apartments. A requirement of a commercial loan to finance expansion in the complex, as well as potential liability, resulted in the owner's decision to mitigate the radon problem. The original contract to remediate elevated levels of indoor radon was enacted to mitigate first floor apartments to a level below 3.5 pCi/l based on the owner's condition by installing Active Soil Depressuriztaion (ASD) systems. ASD systems were installed in the first floor apartments with one or two suction pit(s) depending on the size. Installation includes vertical, plasticized polyvinyl chloride (PVC) pipes extending through the second and third floors and the attic area to the outdoors. Typical soil-gas suction pumps were located in the attic area at the top of the building.

Post-mitigation measurements revealed that some of the apartment units were successfully mitigated to below 3.5 pCi/l while others failed. Some of the units did not experience any sizable change in pre- and post-mitigation tests while others exhibited increased levels of indoor radon concentration after installing the ASD system. Evaluation of the ASD systems in these units and measurements of pressure field extension (PFE) developed by the systems indicated appropriate design, installation, and performance. Additional suction pits and pumps were added into the problematic units to enhance ASD effectiveness but were not successful. PFE measurements indicated that depressurization under the slab is greater than ten pascal at approximately one foot from the slab edge and over fifty pascal at five feet from the suction point. Extensive sealing of concrete slab cracks, slab/wall joints, and further enforcement to the ASD system resulted in no noticeable difference in the indoor radon levels.

The majority of the problematic units are end units. This was the only consistent common factor among the non-mitigated apartments. Building materials were suspected as a cause of the elevated radon concentrations prior to the subsequent investigation by the Florida DOH, however, such suspicion was suspended due to the nature of observations. The fact that problematic units are only those which are end units and that the central units are successfully mitigated derived the solution approach toward PFE of the ASD systems. If building materials are the responsible source of the elevated indoor radon concentrations in the problematic units, elevated concentrations should have also persisted in the central units.

APPROACH

Investigation of the subject problem was conducted by the following sequence:

(1) Analyzing of available data prior to investigation. This includes radon measurement pre- and post mitigation results, ASD design and installation features, building construction plans, and consultation reports.

(2) Conducting building diagnosis, verification test, and site evaluation. The primary concerns are to determine the pressure patterns inside the units, among the units, and between the unit and outdoors; construction details of the wall, floor, and ceiling systems; and the soil system.

(3) Systematically analyzing indoor radon entry routes, and driving and removal forces with respect to occupational and environmental parameters.

(4) Minimizing unlikely driving forces to isolate likely forces responsible on the observed indoor radon level.

(5) Verification of isolated driving forces and development of optimized solutions.

BUILDING INFORMATION

The building construction includes poured concrete slab-on-grade and concrete foundation with grade beams. The second and third floor partitions are poured concrete slabs. The attic area was constructed by wood frame and sheeting. The building walls are made from standard two-cavity concrete masonry units and stucco on the outsides. Interior walls are standard dry boards installed on 0.75 inches wood panels placed on the concrete block. Insulation materials were applied in the cavity between the inner surface of concrete block and the inner surface of the wall boards. Internal walls and partitions were constructed from dry wall boards and standard wood and/or metal frames. The buildings house different floor plans of one and two bedroom apartments with square footage areas ranging from approximately 550 to 1000. Apartment distribution and corresponding floor plans are identical in the three stories of each building. Some of the units are served by ceiling mounted air handler units, in which the drop ceiling area houses the supply ducts. The rest of the units are served by air handler units located in a closet and a drop ceiling area to house the supply ducts. Investigation was conducted in a unit that has a suspended type air handler unit.

RESULTS AND DISCUSSION

Contributions to indoor radon can include sub-structure soil radon, building materials, potable water, and ambient air. In most cases, sub-structure soil radon is the primary source of elevated indoor radon. Radon gas can be transported from any of the above four sources into the occupied area by molecular diffusion, derived by concentration differences, and/or convective flow derived by pressure differences. Given a source and driving force for the gas movement, there must also be a path through which radon can move. The path can be any microscopic or macroscopic opening greater than the size of radon atom. Cracks in the slab, plumbing and electrical penetrations, construction joints, wall cavities, pores in concrete or other building materials can offer a path. The steady-state indoor radon concentration is developed from the mass balance between radon entry and radon removal from the building.

Measurements of radon concentrations in ambient air were performed at the site and indicated levels of 0.4 pCi/l. It was therefore ruled out as a possible cause of elevated indoor radon levels. Measurements of radon concentrations in potable water were not performed at the site, however, data from previous measurements in the area were reviewed and revealed no concentrations of concern. The mechanisms associated with releasing radon from water such as water activity (cooking, showering, ...etc.) in the apartment used during the investigation were minimal before and during the investigation but indoor radon concentration levels continued to exceed 4 pCi/l. With the consideration of the temperature-dependent radon dissolving coefficient in water for the associated ambient and indoor temperature patterns, potable water is ruled out as a possible cause of elevated indoor radon concentrations in these buildings.

The remaining sources and mechanisms of concern are diffusive and convective radon transport components of building materials and sub-structure soil system. The Florida DOH's investigation was conducted in a two bedroom unit that was vacant and represents a worse case scenario of the problem under investigation. Detailed building diagnostics were conducted concentrating on pressure relationships. This was done in order to quantify the driving forces responsible for radon entry from the sub-structure soil system and to determine the removal of indoor radon from the building. Differential pressure measurements were performed between the indoor and outdoor, the indoor/outdoor and sub-structure soil (SSS) system, the indoor/outdoor/SSS and wall cavity, the indoor/outdoor/SSS and the drop ceiling area of the air handling unit (AHU), among different areas of the indoor, and other combinations under all possible uses of the apartment. The latter included various operational configurations of the AHU, exterior door open/close, interior doors open/close, windows close/open, and the installed Active Soil Depressurization (ASD) on/off; at three different times (morning, afternoon, and evening).

The spatial and temporal variations of pressure differentials across the building slab (sub-structure - indoor) indicate maximum values of less than 0.75 Pascal (Pa) and 2.0 Pa (AHU on) for the configuration of ASD system off. The drop ceiling of the AHU contains supply ducts and is pressurized by up to 5 Pa with the AHU pressurizing the nearby wall cavity and depressurizing the occupied space by approximately 1.5 Pa. Indoor zones (when interior doors are closed) could develop up to 15 Pa pressurization in one of the two bedrooms while depressurizing the living area and kitchen. Measurements of SSS radon concentrations drawn immediately from beneath the slab revealed maximum concentrations of less than 500 pCi/l. With consideration of pressure differentials across the slab, these concentrations are unlikely to be the cause of the elevated indoor radon concentrations (above 3.5 pCi/l) that have not been successfully mitigated.

ASD systems mainly treat the SSS radon and the soil-gas convective flow component across the slab. To a lesser degree they can indirectly affect the diffusive component of radon transport from the SSS into the indoor by reducing the average concentration of radon immediately underneath the slab. Although relatively large pathways exist, due to a poor concrete job and cracks, the source (SSS radon) and the driving force (pressure differential across the slab) are insufficient to cause elevated indoor radon concentrations. Therefore, the convective transport component of radon (which is the main cause in most cases) is ruled out as the primary cause of the uncontrolled portion (not successfully-mitigated concentrations above 3.5 pCi/l) of the indoor radon concentrations in this investigation.

Inspection of the concrete slab and the interface between the slab and walls reveled a poor pouring job that resulted in long cracks developed across the building floor. The existence of substantial pathways that radon could seep through from the SSS system into the indoor is therefore considered. However, the process of molecular diffusion is derived by concentration differences (concentration gradient) between the two areas where the diffusion occurred. The measured concentration gradients are unlikely to be the cause of elevated indoor radon concentrations. Even though the path exists, the diffusive driving force is minimal when the radon diffusion length for low permeability soils and fill materials and concentration gradients are considered. Furthermore, the operation of the installed ASD system should further reduce the relatively small concentration gradients minimizing this component. Calculations of the radon diffusive fluxes possible, indicate only minimal contributions to indoor radon concentrations. This can not explain the elevated radon concentrations of concern. Therefore, despite the possibility that a small portion of the uncontrolled concentration may be developed from the SSS radon diffusive transport, this component is ruled out as the primary cause of the current elevated radon concentration in the apartment.

The only remaining cause is the diffusive and convective transport components from building materials. As discussed in the Building Information section above, inspection of the building structure revealed that the walls are constructed from standard concrete masonry units (CMU) with two cavities, concrete slabs for the floor and ceiling, and some combination of metal and wood framing for interior walls and dividers. Inspection of the attic area revealed that CMU cavities were filled with a concrete mix up to the last unit at the top of the walls. Inspections of walls in this apartment reveled that most of the CMU cavities were filled with the same mix. The procedure (which included vibration) used to fill the cavities was not properly done and some of the cavities did not get filled.

The most important observation is that not all the wall cavities were filled. It was discovered that walls of the end units were filled with the concrete mix and a few other walls that bear construction loads also appear to be filled. Wall cavities separating apartment units, that do not bear much load, appear to have been left empty. The latter walls are those of the central apartment units. The reason for filling the cavities up to the top of the walls is not clear, and no construction plan revels that CMU cavities at the end unit apartments are filled. However, filling may be exercised due to structural needs or code requirements. Furthermore, the investigation did not reveal a consistent pattern of filling wall cavities between the central apartment units.

Upon the above observation, gamma field measurements were conducted using a portable survey meter to provide a preliminary indication for building materials contribution. The background gamma field at the soil surface was established to be approximately 4.5 microR/hr average by a survey conducted at 60 points in the open field, adjacent to the apartment complex and away from parking lots and buildings. Measurements of gamma field inside the building at the floor level and near the walls indicated levels from 12-14 microR/hr and averaged approximately 12.7 microR/hr. Measurements taken at about three feet above the floor were slightly lower and averaged approximately 11 microR/hr.

Background gamma radiation is mainly generated from cosmic rays and the building envelop provides a slight reduction to the field compared to outdoors. The gamma field level inside the apartment under investigation was at least twice the established background level. Although gamma measurements can not quantify the contribution of diffusive radon transport from building materials, they provide an indication of such contribution. Quantitative assessment is performed by conducting flux measurement and a radon exhalation rate from building materials. Samples were taken from the concrete slab, the CMU, and the concrete fill mix used in some walls.

Measurements of radon flux exhaled from a clean, visually uncraked slab surface indicated an average flux of approximately 70 pCi/ft^2 hr. Results of testing the concrete slab core sample indicated an exhalation of approximately 11 pCi/ft^2 hr. Similar average radon flux was also found to be exhaled from the filling mix sample. Testing of the CMU concrete itself reveled no measurable radon emanation. Further, moisture saturation and solar heating (temperature difference) on the exterior surfaces of the building could result in a significant vapor pressure towards the interior spaces.

Based on the results of the radon flux measurement, the apartment's ventilation rate is needed to verify if flux entry rate, as related to the ventilation rate, could account for the observed elevated indoor radon concentrations. Testing of the ventilation rate, using carbon dioxide as a trace gas in the unoccupied unit indicated air changes rate per hour (ACH) of approximately 0.04. Further, testing of indoor radon concentrations in second floor units (conducted during the Florida DOH investigation) revealed levels greater than 3.5 pCi/l and are comparable with the first floor problematic units. Results of indoor radon testing in the third floor units showed lower levels than the second floor units. Although testing of second and third floor units is a logical step that should be performed in approaching radon remediation actions in concrete structures, such testing was not possible at an earlier stage of this project due to owner refusal.

Using the ventilation rate figures, calculation of the steady-state indoor radon concentrations based on building materials radon exhalation flux entry rate from the two slabs (floor and ceiling) and the external walls indicate levels comparable to the uncontrolled portion of the indoor radon concentrations found in the problematic units. Further, these concentrations are comparable with the levels found in the second floor units. Indoor radon levels in the third floor are expected to be lower due to two reasons. Third floor units have only one concrete slab since the ceiling is made of wood and they experience higher ventilation rate due to the attic area.

CONCLUSIONS

Investigation of problematic radon mitigation cases should be approached through detailed building diagnosis especially in large and complex buildings. In the current case, elevated indoor radon concentrations in the first floor apartments were primarily due to radon entry of convective flow from the sub-structure soil system and diffusive and convective flow from building materials. The balance between building material contribution and SSS contribution is related to the distribution of concrete mix materials used to fill some CMU walls. Throughout the structure, the filling of the CMU cavities is inconsistent but is primarily observed in higher load bearing walls. The filling pattern was sufficient to provide radon entry into the indoor air, which causes unsuccessful mitigation using ASD systems. Extensive enhancement of the ASD system is not effective in improving indoor radon reduction levels in configurations that may have substantial radon entry contribution from building materials. ASD systems can not control the building material source and associated driving forces responsible on such radon entry. Although the average radon exhalation rate from the complex walls is not substantial, the condition of very tight buildings provides extremely minimal dilution to the radon entry from building materials causing radon accumulation that could reach steady-state levels greater than 4 pCi/l with ASD system in operation.

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