DESIGN, EFFECTIVENESS, AND RELIABILITY OF SUB-SLAB DEPRESSURIZATION SYSTEMS FOR MITIGATION OF CHLORINATED SOLVENT VAPOR INTRUSION[1]

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INTRODUCTION

The use of sub-slab depressurization to mitigate homes with elevated radon gas levels is well established (e.g., EPA 1993). Performance data in the radon literature indicate that SSD's are typically able to reduce radon concentrations by 90 to 95% (e.g., from 40 or 80 pCi/L to 4 pCi/L, respectively), which is more than adequate for the levels found in most homes (EPA 1993). Mitigation of chlorinated solvent concentrations, however, may require far greater efficiencies, reflecting the need to reduce concentrations on the order of 100 ug/m3 (or higher) down to action levels that, for some compounds, are less than 1 ug/m3. Prior to work at the Redfield Site, no information was available indicating whether these reductions could be achieved by standard SSD systems.

Fortunately, experience at the Redfield Site over the past 4 and a half years shows that SSD's can readily achieve efficiencies of up to three orders of magnitude (99.9% reductions), although minor system enhancements are sometimes required (Folkes and Kurz, 2000, 2002). In some cases, sub-membrane depressurization (SMD) systems were required in crawl spaces, where a plastic liner is installed as a surrogate for the floor slab. This paper describes the design, installation, and performance of the Redfield Site SSD and SMD systems, the modifications required in approximately 30% of the homes to achieve the State of Colorado interim action level for 1,1-dichloroethene (1,1 DCE) of 0.49 ug/m3, and factors that may affect long-term system reliability.

BACKGROUND

Site Description

The Redfield site is located in Denver, Colorado. Historic use of solvents at a former manufacturing facility and other surrounding facilities resulted in a groundwater 1,1 DCE plume that extends over a mile off-site under residential properties. The maximum historic 1,1 DCE concentration was 1600 ug/L, with a mean plume concentration of 136 ug/L. Concentrations generally decrease with distance from the site. The solvent plume is migrating in shallow alluvium, including sand and fine gravel, silt, and sandy clay deposits. Weathered sandstone, siltstone and claystone deposits of the Denver Formation underlie the alluvial deposits; while silt and clay loess typically overlies the alluvium to depths of 10 feet or more. Groundwater is found at varying depths, ranging from 10 to 45 feet below ground surface.

Indoor Air Testing

At the time this evaluation of mitigation systems was conducted, the indoor air of 639 homes in the neighborhood had been tested over 24-hour periods using inert stainless steel containers (SUMMA canisters). SUMMA canister samples were analyzed at the laboratory in accordance with EPA Test Method TO-15 using a mass spectrometer operated in the Selective Ion Monitoring (SIM) Mode. For tests conducted after October 1998, equipment-tuning procedures met the requirements of CDPHE (1999) guidelines. The SIM Mode monitors a few compounds instead of the entire mass spectra, allowing a 1,1 DCE reporting limit of 0.04 ug/m^3. Measured concentrations of 1,1 DCE, the compound of concern, ranged from below the reporting limit (0.04 ug/m^3) to 131 ug/m^3 prior to mitigation.

Concentrations in 356 homes of the homes tested exceeded the interim action level of 0.49 ug/m^3 prior to mitigation. Access was granted for installation and adjustment of mitigation (SSD and SMD) systems at 337 of the homes that had pre-mitigation 1,1 DCE concentrations that exceeded the action level. Periodic performance testing was conducted in homes with mitigation systems. For purposes of this evaluation, performance testing had been received for 301 houses.

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DESCRIPTION OF MITIGATION SYSTEMS

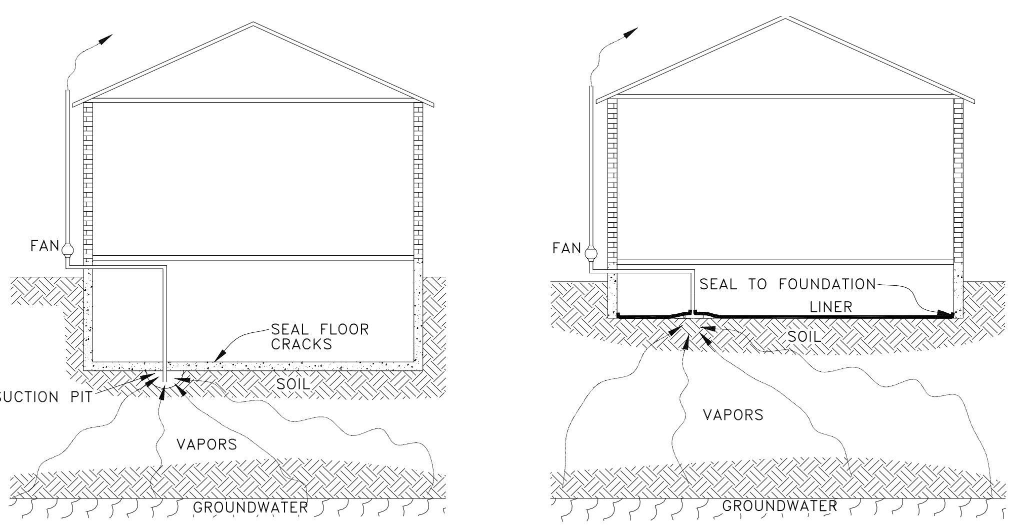
Vapor mitigation systems were installed generally following USEPA guidelines for radon mitigation (EPA 1993). SSD systems were installed in homes with basements, bi-levels, or slabs-on-grade, while SMD systems were installed in homes with crawl spaces, as described below. Combination systems were installed in homes with both basements and crawl spaces. Due to the large number of homes requiring mitigation in a short time period, systems were installed by different contractors, who used similar, but varying, methods and equipment (e.g., pipe and fans).

Sub-Slab Depressurization Systems

A typical SSD system installation is shown on Figure 1. Suction pits were created below the concrete floor slabs by drilling a 3.5 to 5 inch diameter hole through the slab, ideally but not necessarily located near the middle of slab, then hand-excavating a void approximately 1 to 3 cubic feet in volume to increase the effectiveness of the depressurization system (e.g., see Bonnefous et al., 1992). Either 3 or 4-inch diameter PVC pipe from the suction side of the fan was inserted in the hole. The annular space between the pipe and slab was sealed with acrylic latex caulk. In each home, one suction point was created in the floor slab. The fans were installed in the attic, garage, or outside the house. Pipe exhausts were located at least 10 feet above the ground and 10 feet from doors or windows, following EPA (1993) guidelines for radon systems. All visible cracks and joints in the floor were sealed with acrylic latex caulk; however, many of the homes had finished basements or garden levels, preventing identification or sealing of cracks.

Sub-Membrane Depressurization Systems

SMD systems were installed in crawl spaces by placing a 0.1 mm thick, cross-laminated polyethylene membrane or liner over the dirt surface and sealing the liner to the concrete foundation walls using acrylic latex adhesive (Figure 1). The end of the pipe (3 or 4 inch PVC) from the suction side of the fan was inserted through a hole cut in the liner. In some cases, the contractor simply put a short elbow or tee on the pipe to create one or two suction points; in other cases, the suction pipe was connected to a perforated, corrugated drain pipe that was snaked under the liner to extend the suction field. In one case, a non-woven geotextile was used to extend the suction field below the liner, providing a smoother surface for homeowners and workers to crawl on and cushioning the liner. All three methods were effective at achieving action levels. The liner was sealed to the pipe at the penetration hole using vinyl tape to prevent loss of vacuum. When concrete footings divided the crawl space, a separate suction point was generally installed in each separate area between the footings. The fan was installed outside the house and the pipe was routed up the outside wall to exhaust above the roofline.



SUB-SLAB DEPRESSURIZATION SUB-MEMBRANE DEPRESSURIZATION

Figure 1. Mitigation Systems (typical)

Fans

Inline centrifugal fans by various manufacturers (e.g., Fantech, RAM/GAM, AMG) were used to create the low-pressure zones below the concrete slabs and liners. In most cases a 90-watt fan was installed, with a flow rate of 2.5 m^3/min at 249 Pa. In situations where additional vacuum was desired (see Results and Discussion), a 150-watt fan with a flow rate of 5.7 m^3/min at 249 Pa was installed. The fans operate 24 hours per day and each SSD system has an oil-filled manometer in the pipe providing a visual indicator to the homeowner that the system is operating. The fans were hardwired with accessible on/off switches, in a few cases requiring larger electrical panels to meet code. All work was conducted by licensed contractors under electrical and mechanical permits, as required by the Denver Building Inspection Department.

MITIGATION SYSTEM PERFORMANCE

A total of 301 mitigation systems were evaluated for this study. Of these, 189 were SSD systems, 79 were SMD systems, and 33 were combined systems. In most cases, standard systems (i.e., with one suction point, a standard size suction pit, and a 90 watt fan) were installed and the need for modification, if any, was based on quarterly performance monitoring. Approximately 75% of the SSD systems, 68% of the SMD systems, and 70% of the combination systems met the CDPHE interim action level without requiring modification. SSD systems, SMD systems, and combinations were able to reduce indoor air concentrations of 1,1 DCE by up to two orders of magnitude and, in some cases, almost three orders of magnitude.

Modifications to the standard systems required to bring the remaining systems into compliance with the interim action level included enlargement of the suction pit, additional suction pits, and/or replacement of the 90 watt fan with a 150 watt fan were sufficient. The provision of outside combustion air in a few homes lacking these vents (now required by building code) was sufficient to allow the mitigation system to achieve the action level. In homes with SMD systems, typical modifications included sealing small gaps between the liner and foundation wall, adding more perforated pipe to extend the suction field under the liner, and installing a 150 watt fan were sufficient to meet the action level. As shown in Table 1, most systems were able to achieve the indoor air action level with the standard system or one modification. In a small fraction of homes (i.e., less than 10% of the total homes mitigated), more than one modification was required to meet the action level.

Table 1. Percentages of Systems Requiring Modification to Meet Action Level.

System	SSD	SMD	Combination
No Modifications	75%	68%	70%
One Modification	16%	27%	21%
More than one modification	9%	5%	9%
Totals:	100%	100%	100%

It would also be possible to initially install upgraded systems in all homes, including multiple suction points and 150-watt fans, at potentially lower cost (due to fewer mobilizations and less re-testing). This approach might be necessary if no performance monitoring was planned; however, at the Redfield Site a more iterative approach based on performance monitoring allowed installation of the most aesthetic and quiet system possible, consistent with typical radon systems installed in thousands of homes across the country, rather than overbuilt systems. It should be noted that the need for system modifications is not necessarily correlated to high initial concentrations, but is more a function of subslab soil and moisture conditions and house-specific factors.

LONG TERM RELIABILITY

SSD and SMD systems have proven track records based on radon mitigation experience (EPA 1993), and can be expected to continue to perform properly until the fan requires replacement (typical expected life span of 5 to 15 years, with 5 year warranty). Some fluctuations in concentrations should be expected over time, due to seasonal effects (e.g., thermal heat stack effect, furnace operation, and closed windows in the winter) and varying occupant activities (e.g., leaving doors and windows open). The long term Redfield Site data, however, indicate that these fluctuations are minor and remain within a relatively narrow range (see Figure 2, below). Occasional excursions over an action level should not be of concern, as long as the mean concentration remains below the action level, which is typically based on long-term average exposure. At the Redfield Site, compliance with the action level after the first three tests is based on the 95% upper confidence level of the mean concentration since system installation (or modification). In most cases, the need for system modification was determined within the first few months of operation.

Once the ability of a mitigation system to achieve action levels has been established, either over a period of four seasons or under worse case conditions (typically cold weather with the furnace operating), the mitigation system should be considered reliable, as long as it continues to operate normally. Occupants of buildings or homes can readily detect problems with the fan by silence (the fan stops operating), noise (bearing failure in fan), or lack of differential pressure in the manometer. As a result, inoperative fans can be replaced relatively quickly, ensuring no significant impact on long-term mean concentrations or system reliability.

Most other factors that could affect the long-term reliability of mitigation systems are the result of homeowner actions, including deliberately turning off the fan or ignoring an inoperative fan, knocking the suction pipes down, or damaging the crawl space liners. All of these events are readily mitigated as long as the homeowners contact the party responsible for system operation and arrange for repairs.

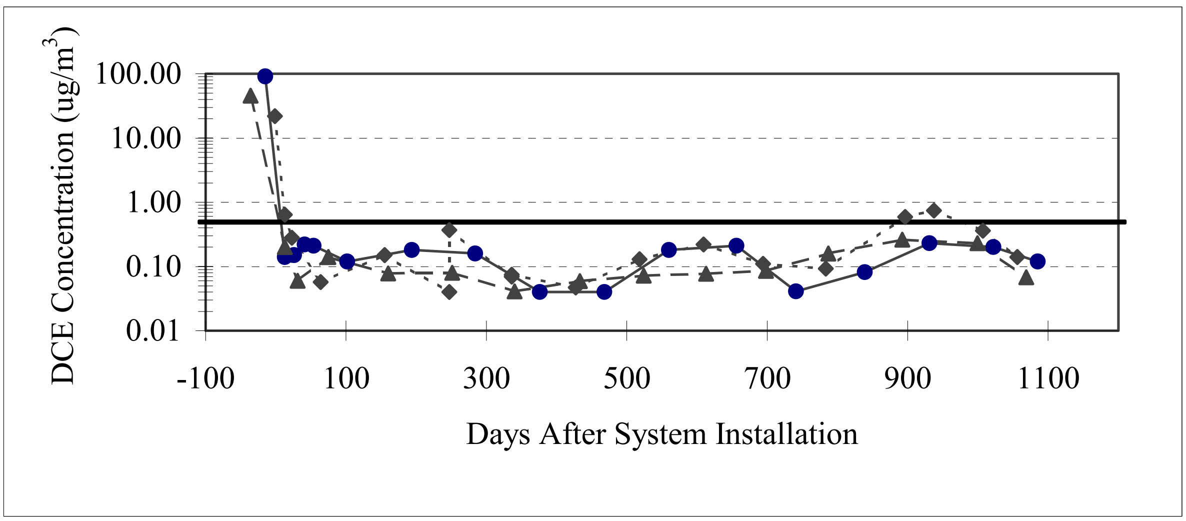


Figure 2. DCE Indoor Air Test Data For Homes with Mitigation Systems

RECOMMENDATIONS

Careful installation of standard radon mitigation system (SSD or SMD) can be expected to achieve up to three orders of magnitude reduction in concentrations approximately 70% of the time, depending on site-specific conditions. A standard system would include one suction point, a 90-watt fan, sealing of any visible cracks in the slab, and installing a liner in any crawl spaces. Crawl space liners should be carefully inspected for proper seals along foundation walls and intermediate footings, if any, with sufficient slack in the liner to reduce the potential for tearing. Smoke or pressure tests should be conducted at the far end of the slab or crawl space to ensure that an adequate suction field has been established. With periodic performance monitoring, relatively simple modifications can be made to the remaining 30% of the systems to achieve similar efficiencies, resulting in optimally designed systems for each house.

If performance monitoring is more limited, similar to the standard practice for radon systems (e.g., one or two post-mitigation tests), then it may be prudent to install enhanced mitigation systems from the beginning. Based on the Redfield Site experience, enhanced systems would include over-sized suction pits (e.g., 24" wide by 16" deep) in all SSD systems, 4 inch PVC to reduce pressure losses, and perforated pipe or non-woven geotextile below all SMD systems to extend the suction field. Second suction points should be installed when subsoils are wet or clayey, or when grade beams may be present below slabs (one suction point on either side of the beam), combined with larger (150 watt) fans. Combustion air vents should be added in any building lacking such vents that has forced air heating.

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