A Multi-Pronged Approach to VI Mitigation of a Large Mixed-Use Building

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Abstract

A large, mixed-use industrial manufacturing and office building impacted by vapor intrusion (VI) of chlorinated volatile organic compounds (CVOCs) presented several challenges for improvement of indoor air quality. These challenges included 1) the presence of a CVOC source zone beneath the building floor slab, 2) dissolved-phase CVOC presence in the relatively shallow groundwater beneath the building, and 3) building infrastructure and mechanical systems that provided multiple advective pathways and drivers for VI. Beginning with initial assessment and continuing to final mitigation, this paper shows how a combination of modern investigative tools and custom-designed measures were employed to illuminate the challenges and inform appropriate response actions. Using a field-portable gas chromatograph-mass spectrometer (GC-MS) and other tools, the magnitude and extent of the VI impacts to indoor air were rapidly assessed, and the principal VI pathways were identified. An evaluation of mitigation options included source remediation, adjustments to the air handling units, and both passive and active VI cutoff/interception methods. Due to the relatively high strength of the sub-slab source and presence of multiple VI pathways, passive mitigation measures, such as sealing of preferential pathways, were combined with active ventilation of subsurface utilities and sub-slab vapor extraction to provide redundancy and performance assurance. The portable GC-MS was used to evaluate the relative effectiveness of the implemented remedies and to refine the overall mitigation strategy. To reduce energy consumption associated with the active mitigation measures, the electric-powered blowers were equipped with variable speed drives, which provide operations flexibility to achieve lower operating costs as CVOC mass flux rates are gradually reduced over time. Post-startup monitoring and sampling indicates that the VI mitigation measures have been successful in reducing indoor air CVOC concentrations consistent with performance objectives.

Introduction

VI assessment and mitigation of large, multi-use buildings can be challenging because these buildings often exhibit characteristics that are complex to evaluate and difficult to address. Such characteristics often include the size and volume of the building, the variability of subsurface contaminant presence beneath the building (including separate phase, dissolved phase, and/or vapor phase contaminants), complex building foundation and infrastructure components, and confounding influence of heating, ventilating, and air conditioning (HVAC) equipment and operations. This paper presents a project example of how these characteristics were assessed for a large, mixed-use building impacted by VI of CVOCs, principally trichloroethene (TCE), using a combination of evaluation tools and methods. In addition, the mitigation approach informed by the assessment findings is also presented.

In recent years, VI investigations have benefited from the use of field-portable gas chromatograph-mass spectrometer (GC-MS) instruments to obtain rapid, real-time indoor air quality data.[1,2,3] This paper will show how the portable GC-MS was used to establish baseline conditions, identify VI pathways, and inform and develop mitigation methods. Recent work on VI investigations of large buildings has also demonstrated how HVAC systems can influence VI by creating pressure gradients favorable to vapor entry and/or transferring vapor-phase contaminants throughout the building.[4,5] Therefore, large building VI assessments should also include an evaluation of HVAC system influence, as exemplified in this paper.

Once the VI causes and pathways are characterized, mitigation of large buildings can be accomplished by a variety of passive and active measures.[6,7] For this project, a combination of measures was employed to address the multiple sources and pathways that were identified. By describing the investigative methods, findings, and mitigation approach and results, we intend for others undertaking similar work to benefit from the experience of this large and complex project.

Background

The building is a three-story structure built in 1952 with a footprint of 100,000 square feet (SF) and a total area of 300,000 SF. The building is constructed with reinforced poured concrete foundation walls, floors, and columns. The exterior walls are constructed of concrete block with brick veneer. Figure 1 shows the layout/ footprint of the first floor.

Solvents, including TCE, were used in the building from the 1960s to early 1970s to support manufacturing of electronic components. Bulk solvent storage and handling included a TCE underground storage tank outside the west side of the structure, and underground solvent conveyance pipes to the building.

Historical subsurface investigations conducted in the 1990s under the Resource Conservation and Recovery Act (RCRA) indicated CVOC presence in sub-slab gas, soil, and groundwater beneath the building, with the highest concentrations in these media indicative of a source zone beneath the west-central area of the building as shown on Figure 1.

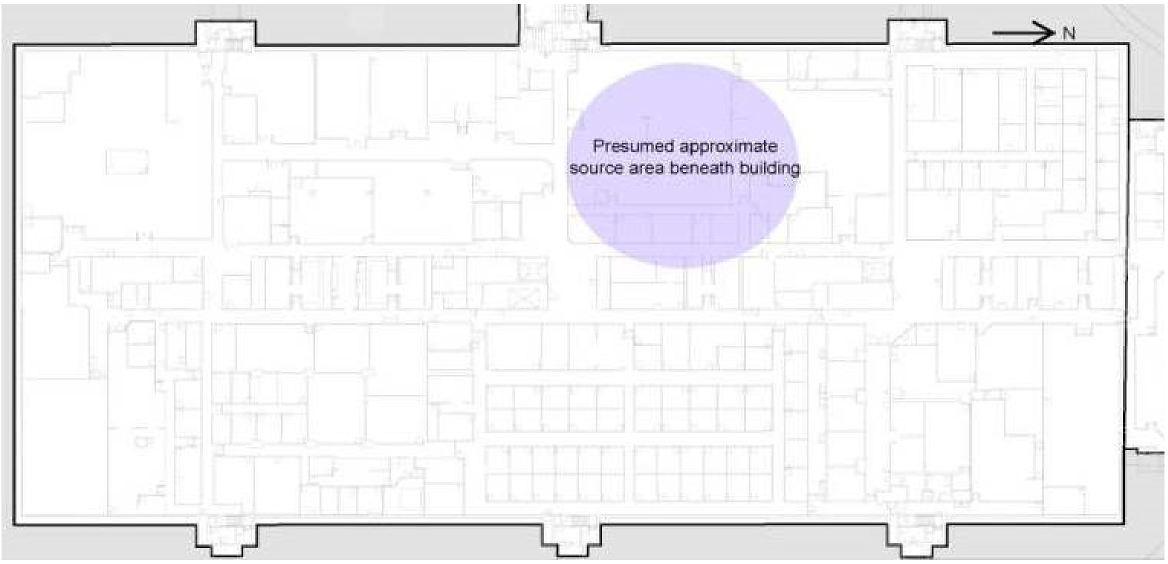

Figure 1: Layout of Building First Floor

The overburden soils beneath the building consist of about 6 feet of medium to coarse-grained fill overtop sand and gravel to the north, or sand and silt to the south. Groundwater is present in the overburden at depths of between 3 and 5 feet below the building slab. The bedrock surface beneath the building generally slopes down from south to north at depths of between 10 feet at the southern end to 35 feet at the northern end.

Investigative Approach and Findings

VI assessment of the building included the following:

- Review of HVAC system configuration and operations for possible unfavorable influence on VI and for potential capability to mitigate VI;

- Real-time baseline screening of indoor air using a HAPSITE® Smart Plus field-portable GC-MS, manufactured by Inficon of Syracuse, NY, for the target CVOCs, which included TCE, cis-1,2-dichloroethene (cDCE), trans-1,2-dichloroethene (tDCE), and vinyl chloride;
- Targeted screening of building structural features for VI preferential pathways using the portable GC-MS; and
- Sub-slab gas sampling and differential pressure assessment.

The details of these investigative methods and results are presented below.

HVAC System Review

For buildings with engineered HVAC systems, a basic assessment of HVAC configuration and operations can be invaluable when evaluating the effects of VI on indoor air quality. HVAC systems can exacerbate vapor intrusion when air handling systems impart a pressure gradient into the building proximate to the floor slab or at a potential pathway for VI, such as a utility penetration. In addition, once VOCs enter a building, the HVAC system can distribute the contamination far from the entry point(s) as a result of internal mixing and air flow patterns.

The subject building was equipped with 7 air handling units (AHUs) that serve 7 separate areas (zones) of the first floor. The AHUs were located in mechanical rooms located on the first floor. The second and third floors were served by AHUs located in mechanical space on the third floor. The AHUs were configured to draw in a combination of outside air and recycled air (return air) from the building space. The mixed outside air and return air is then conditioned (heated or cooled) and then discharged as supply air to the zone being served.

A summary of observed conditions and features of the AHUs and their implications for VI assessment and potential effects are presented in Table 1.

Observed Condition	Potential Implications
Outside air exchange rate (AER) for the 7 zones ranged from 0.4 to 2.9/hr, with an overall average of 0.9/hr based on a total outside air flow of about 15,600 cfm.	Average AER of 0.9/hr compares favorably to default value of 1/hr assumed by USEPA and many other state agencies.7 AER can be used to estimate VI mass load to building, as discussed below.
Return air flowed back to the AHUs through a common ceiling plenum (i.e., the space above the suspended ceiling).	Air from one zone could mix with air from neighboring zones in the ceiling plenum, thus allowing potential VI in one zone to affect indoor air quality in other zones.
The AHU mechanical rooms were at lower pressure than the zones they served.	Imposition of a pressure gradient in mechanical rooms can exacerbate VI through the slab or utility penetrations.
The AHU outside air dampers were 100% open and the fans were served by constant speed motors.	The AHUs did not have extra capacity to increase outside air exchange as a potential means to improve indoor air quality.
The first floor AHUs do not serve upper floors.	No direct, systematic air communication from first floor to upper floors – potential VI effects could be limited to first floor.

Table 1: HVAC conditions and implications for potential VI effects

Real-Time Baseline Screening of Indoor Air

Comprehensive baseline field screening of indoor air for the target CVOCs was conducted over two days using a portable GC-MS. The purpose of field screening was to 1) obtain a rapid understanding of the concentration and distribution of CVOCs in indoor air, 2) identify in real-time the building features that might be preferential pathways for CVOC entry, and 3) support the selection of sub-slab monitoring/sampling locations. Because the portable GC-MS provided real-time data, it was possible to follow-up on interesting results with additional screening of potential points of CVOC vapor entry into the building, such as utility penetrations, sumps, expansion joints, floor cracks, etc.

The screening samples analyzed by the portable GC-MS can be considered grab air samples collected over about a 1 minute interval; thus they represent a snapshot of CVOC presence. Since TCE was the predominant and principal CVOC of interest, this paper focuses on TCE. The results of screening for TCE in indoor air at 62 locations are presented on Figure 2, where each value represents the concentration detected in micrograms per cubic meter (µg/m3) at the location indicated.

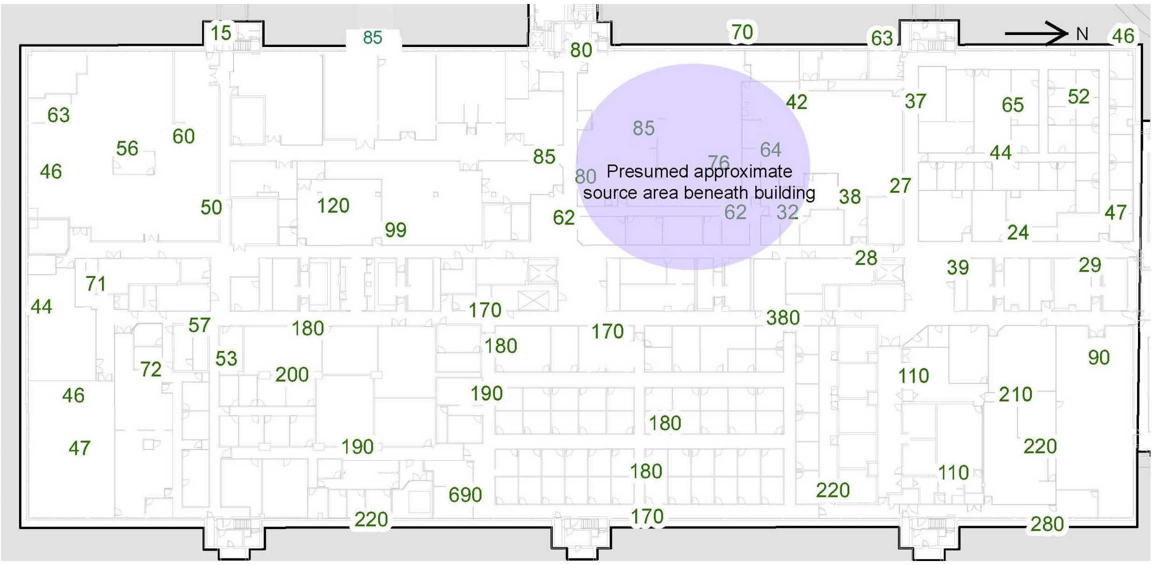

Figure 2: TCE Screening Result in Indoor Air (µg/m^3)

TCE was detected in every indoor air screening sample at concentrations ranging from 15 to 690 µg/m3, with an arithmetic mean of 120 µg/m3. Review of the data indicated that the highest concentrations were generally detected on the east side of the building, but other patterns, including clear "hot spot" areas, were not apparent. Notably, the indoor air data overlying the historical sub-slab source zone did not stand out from the balance of the building.

HVAC system features described in Table 1 that contribute to the widespread TCE presence in indoor air include the common ceiling plenum for return air flow, which allows air exchange across HVAC zones, and the AHU mechanical rooms imparting a negative pressure on the floor slab.

VI Mass Load/Flux

Under simplifying assumptions of well-mixed, steady-state conditions (which are reasonable assumptions for the subject building given the HVAC review), the VI mass load to the building can be estimated by the following equation:

Equation 1.

$M = (Q_{bldg}) \times (C_{mean}) \times$ (units conversion factor)

where:

M = mass load due to VI (lbs/day)

Q_{bldg} = outside air flow (cfm)

C_{mean} = mean indoor air concentration (µg/m3)

Units conversion factor = 9 x 10-9 for the above units

Using Equation 1, where Q_{bldg} = 15,600 cfm and C_{mean} = 120 µg/m^3, the VI mass load to the building was estimated as 0.17 lbs/day (0.077 kg/day).

The VI mass flux to the building, which represents the mass load per unit area, can be estimated by dividing M by the footprint of the building, which yields 8,300 µg/m^2/day.

The VI mass load or mass flux represents the amount of VOC entry responsible for sustaining the indoor air concentrations. It also represents a mitigation performance objective for intercepting or removing mass to prevent VI, which can be used to inform mitigation design, as discussed later in this paper.

Identification and Targeted Screening of CVOC Entry Pathways

Having established the baseline indoor air conditions, the next step was to determine how the CVOCs were entering the building. Targeted screening of features of the building infrastructure and floor slab was conducted using the portable GC-MS with the goal of evaluating them as potential pathways for CVOC entry. The selection of features to assess for VI vulnerabilities requires a detective's approach: research and review of building infrastructure, such as foundation plans and HVAC system configuration and operation, complemented by feet-on-the-ground inspection and sleuthing for potential VI pathways. This approach led to targeted screening of floor cracks, expansion joints, utility sumps, interior monitoring well covers, and various utility penetrations through the floor slab. Many of these features showed evidence of vapor entry based on the screening with the portable GC-MS, and mitigation involved sealing these features as discussed below; however, two infrastructure features stood out as particularly significant VI pathways.

Review of old foundation plans revealed that utility trenches were constructed along the entire length of the east and west sides of the building, and another trench segment bisected the building and connected the east and west trenches to a central pit. This trench network formerly carried steam condensate return pipes associated with the building's original heating system. The trenches were about 1.5 feet wide by 1.5 feet deep and constructed of poured-in-place concrete. The trench network was largely hidden because, over the years, their steel diamond plate covers were covered over by carpet or floor tile along most of their length. The steel plate was exposed in two of the mechanical rooms that house AHUs. Figure 3 shows the results of targeted screening of the trench cover in one of the mechanical rooms. The results indicate that CVOCs emanating from the floor trench were being drawn into the AHU through the return air intake (see Figure 3) and subsequently distributed to the area served by the AHU.

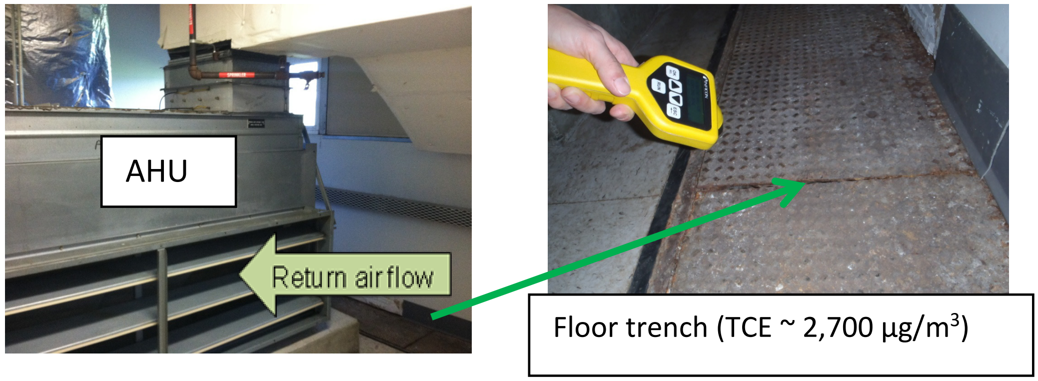

Figure 3: Targeted Screening of Utility Trench

The second significant feature contributing to CVOC vapor entry was the foundation under drain system, which was constructed beneath the floor slab and interconnected by several manholes inside the building. CVOC-containing groundwater had been entering the under drain system for many years, and the system had been converted in the 1990s to a groundwater capture system for subsequent treatment. Figure 4 shows the results of targeted screening of two of the manholes inside the building. Differential pressure readings also indicated a pressure gradient into the building from the manholes. The results demonstrated that the manholes were a pathway for CVOC vapor entry.

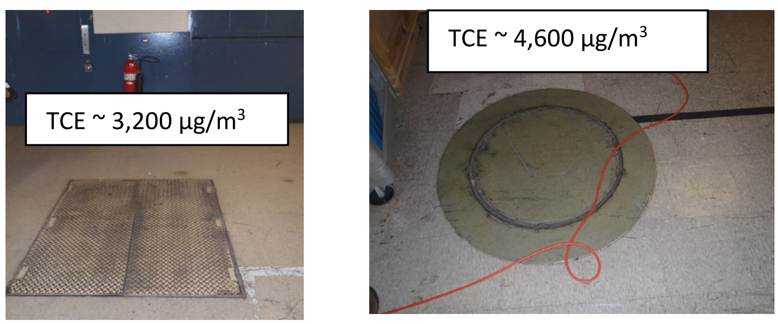

Figure 4: Targeted Screening of Interior Manholes

Sub-slab Gas Sampling and Differential Pressure Monitoring

Sub-slab gas sampling and differential pressure monitoring was conducted using a network of ports installed through the floor slab. Figure 5 shows the TCE concentrations detected in the sub-slab gas samples. The sample results show the highest concentrations beneath the west-central area of the building consistent with historical documentation that indicated this area as the source zone. Sub-slab-to-indoor air differential pressure monitoring indicated that most areas were near neutral to slightly positive, conditions which provide a driving force for VI.

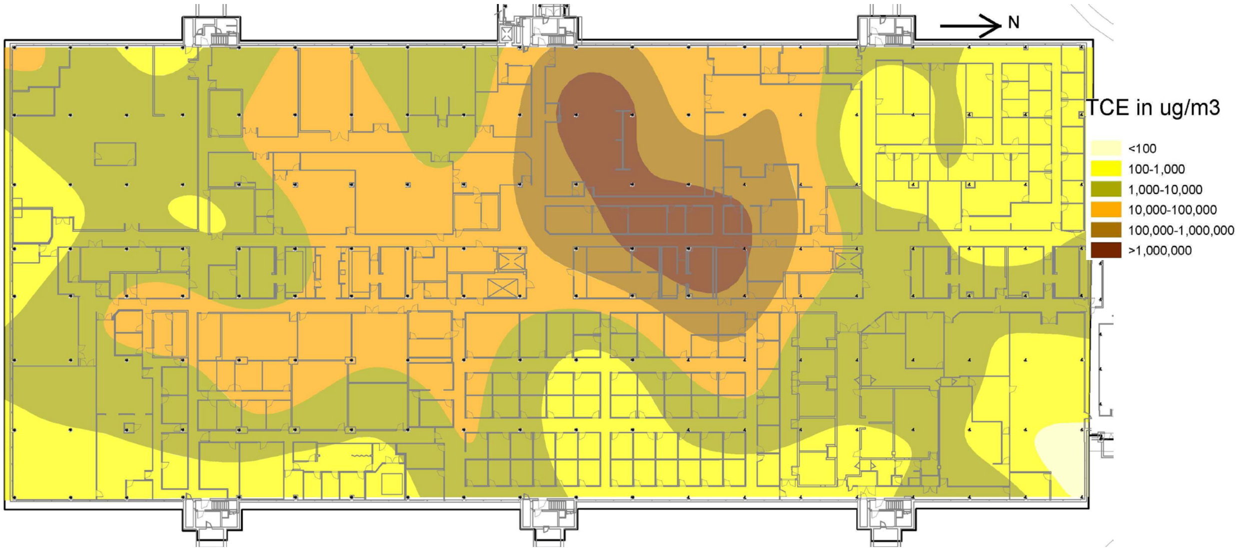

Figure 5: TCE Concentrations in Sub-slab Gas

Mitigation Approach and Results

The investigation findings revealed various pathways and mechanisms for VI, which suggested that a multi-pronged approach to mitigation would be required. The goal was to cut-off, or sufficiently intercept, vapor entry pathways to achieve a significant reduction in CVOC concentrations in indoor air. Mitigation methods included: 1) sealing of floor slab penetrations and features, 2) depressurization of the floor trench system and manhole headspaces, and 3) sub-slab vapor extraction. Each of these VI mitigation components is described below.

Sealing of Floor Slab Penetrations

Sealing of penetrations and other features associated with the floor slab represented simple, practical actions to cut off or reduce CVOC vapor entry to indoor air. These features had been indentified using the portable GC-MS as pathways for VI. The most prevalent features that were sealed included:

- Pipe and conduit penetrations through the floor slab;
- Condensate sumps in mechanical rooms;
- Expansion joints in the floor slab; and
- Cracks in the floor, particularly around building columns and footings.

Sealing was conducted using a combination of materials, including expanding foam, silicone and polyurethane sealants, non-shrinking grout, ready-mix concrete, and epoxy coatings. The effectiveness of the sealants was evaluated using the portable GC-MS, which allowed for real-time adjustments and improvements to the sealing methods.

While these actions were beneficial in reducing vapor entry, active measures were needed to further mitigate VI, as discussed next.

Depressurization of Building Infrastructure Features

As described above, the VI investigation identified the interior manholes and floor trench system as significant pathways for VI. Sealing alone was not a feasible long-term solution for the floor trenches because they consisted of 1,200 linear feet, most of which was inaccessible under floor tile and carpet. The manholes require occasional access for maintenance, which would necessitate re-sealing them after each service event.

To address VI from these features, an active depressurization approach was employed. For the trench system, this was accomplished by using a blower to maintain a vacuum of about 0.01 inches water column on the trench system. The air flow required to depressurize the 1,200 linear feet is about 500 cfm, or 0.4 cfm per foot of trench. As a result, the trench infrastructure was converted from an active VI pathway to an active VI capture system.

For the manholes, "headspace" depressurization was employed to achieve a vacuum of 0.01 inches water column beneath the manhole lids (same value used for the trenches) to intercept CVOCs off-gassing from the groundwater being collected by the foundation under drain system. To limit the amount of air flow (and energy) required to maintain the target vacuum beneath the manhole lids, interior covers were constructed beneath the manhole lids, and the vacuum was applied to the space between the internal cover and original lid. Figure 6 shows an internal cover installed beneath the double-hatch original cover, with vapor extraction using the open pipe between the covers. The air flow required to depressurize four manholes retrofitted in this manner was about 200 cfm, or about 50 cfm per manhole.

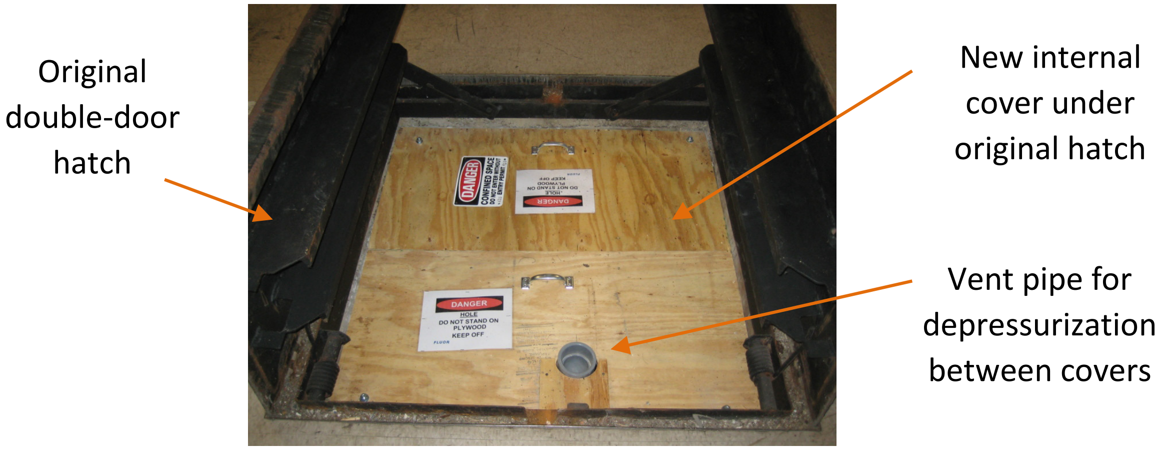

Figure 6: Manhole Retrofit for Depressurization

Sub-slab Vapor Extraction

The third component of the VI mitigation approach is sub-slab vapor extraction. The intended role of sub-slab vapor extraction is to depressurize the floor slab as a VI preventive measure, while also attaining CVOC source mass removal from the vadose zone beneath the building.

Pre-design sub-slab communications testing was conducted to assess the number of extraction ports required to achieve sub-slab depressurization, and to evaluate vapor flow and CVOC mass removal characteristics to support design of blower and treatment equipment. The pre-design testing indicated that about 5 extraction ports would effectively remove CVOC mass and depressurize the primary source area delineated by sub-slab TCE concentrations greater than 100,000 µg/m3. However, the final system design incorporated 26 ports to allow for depressurization of the entire building footprint, if desired, at a total flow rate of about 170 cfm.

To accommodate the wide range in potential operating objectives, the vacuum blower was equipped with a variable frequency drive (VFD). The VFD allows for flexibility and efficiency in blower operation at various conditions. For example, at system startup, flow and vacuum may be set higher to accomplish CVOC mass removal. Then, as source mass removal potential decreases with time, the system can be transitioned to a longer term operating mode of sub-slab depressurization at lower flow and vacuum, with lower energy consumption.

As described above, the VI mass load to the building can be estimated from Equation 1. This rate can also be thought of as the minimum mass capture rate required to prevent vapor intrusion. Further, it also provides an estimate of the long-term mass capture rate for vapor extraction systems. Initial higher recovery rates associated with removal of mass from storage in the soil pore spaces gradually transitions to a long-term rate that is limited by diffusion of CVOCs in the vadose zone, or by diffusion across the capillary fringe of underlying CVOC-containing groundwater. If vapor treatment is required or desired, it can be sized with the expectation that the long-term mass recovery rate will approach a diffusion-limited condition, which can be approximated by the VI mass load represented by Equation 1.

Performance Results

The performance of the VI mitigation components has been assessed by several measures, including monitoring of sub-slab depressurization, CVOC mass removal by the vapor extraction system, and most importantly, the CVOC concentrations in indoor air.

Indoor Air

Several weeks after startup of the sub-slab vapor extraction system, an extensive round of indoor air screening was conducted using the portable GC-MS. Screening was conducted at 24 of the locations that were screened prior to VI mitigation. In addition, 8-hour composite indoor air samples were collected into Summa® canisters at 10 representative locations on the first floor, including at least one sample in each of the 7 HVAC zones. Figure 7 summarizes the minimum, median, and maximum TCE concentrations in pre- and post-mitigation indoor air screening, as well as the TCE concentrations in the post-mitigation 8-hour samples. The results indicate significant reductions in TCE concentrations. For comparison, the post-mitigation TCE levels are less than the recent USEPA Region 9 guidance values for short-term (i.e., 21-day) TCE exposure in commercial/industrial settings of 7 µg/m3 (for 10-hr workday) and 9 µg/m3 (for 8-hr workday).[8]

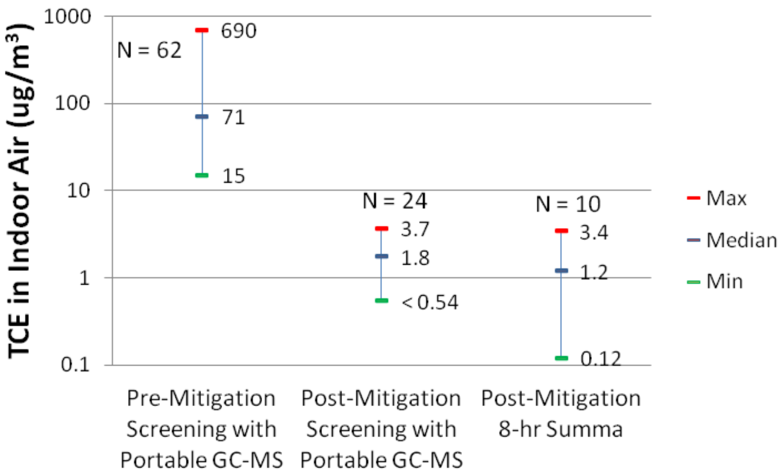

Figure 7: Pre- and Post-Mitigation TCE Concentrations in Indoor Air

The residual presence of low-level TCE in indoor air after VI mitigation has been attributed to bulk transfer of CVOC-containing air into the building through a corridor connected to an abutting building, which was confirmed by tracer smoke testing and portable GC-MS screening. This observation reinforces the premise that investigating indoor air quality in a large building can be complex and require a multi-dimensional approach.

Despite being collected over different durations, the post-mitigation portable GC-MS indoor air screening results and 8-hr Summa samples (analyzed by USEPA Method TO-15 in select ion monitoring mode) compared favorably, which highlights the value of the portable GC-MS as a VI investigation tool.

Sub-slab Depressurization

The sub-slab vapor extraction system has achieved depressurization across about 90% of the building footprint, including the entire source area beneath the west-central area. A sub-slab pressure differential of at least 0.004 inches water column (1 Pascal) was used to determine the extent of sub-slab depressurization sufficient to prevent VI, which is consistent with recent guidance[9] and the experience of the authors. Similarly, the floor trench network and manhole headspaces have been maintained under negative pressure sufficient to prevent CVOC vapor entry to indoor air.

CVOC Mass Removal

Figure 8 shows the TCE capture rate and cumulative mass removed versus time by the sub-slab vapor extraction system. The mass capture rate exhibits a classic exponential decay with the mass removal rate approaching an asymptote that represents mass transfer limitations in the subsurface. For a vapor extraction system, mass transfer is commonly limited by the rate of volatilization from non-aqueous phase liquid, if present, and by the rate of diffusion into soil gas from CVOCs in the vadose zone or underlying groundwater.

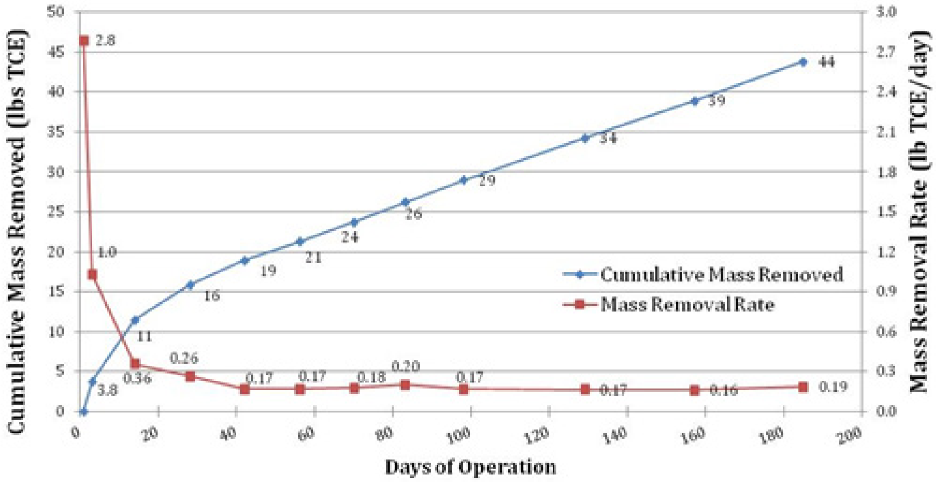

Figure 8: TCE Mass Removal

Note that the TCE mass removal rate has leveled off at about 0.17 lbs/day, which is equivalent to the original estimate of the VI mass load to the building obtained from Equation 1. This result suggests that by estimating the potential VI mass load, or mass flux, to the building, Equation 1 can be rearranged to predict indoor air VI impacts, if information can be obtained or assumed about the air exchange rate. Methods to independently estimate VI mass flux potential were presented by Green et al.[10]

Summary

The challenges of VI assessment and mitigation of a large, mixed-use building were addressed using a combination of modern investigative tools and custom-fit mitigation methods. First, an assessment of building HVAC configuration and operations identified several conditions that could exacerbate VI. These conditions included a common return air plenum and AHUs in ground floor mechanical rooms that imposed negative pressure in close proximity to VI pathways. Rapid screening of indoor air using a portable GC-MS identified widespread CVOC presence. These results were used to support focused investigation and sleuthing for VI pathways in real-time, which revealed multiple points and mechanisms for vapor entry. Subslab gas sampling confirmed a CVOC source beneath the western portion of the building with lower concentrations beneath the entire building footprint, including in proximity to VI pathways. Sub-slab-to-indoor air differential pressure monitoring indicated that most areas were near neutral to slightly positive - conditions which provided a driving force for VI. The highest sub-slab CVOC concentrations were not located in the areas of the highest indoor air concentrations, which demonstrated the complexity of VI investigations in large buildings and the need to carefully evaluate the factors contributing to VI when designing mitigation systems.

To address the multiple means of VI, a combination of passive and active mitigation methods was employed, including sealing of preferential VI pathways, depressurization of building infrastructural features such as utility trenches and manholes, and sub-slab vapor extraction. These methods were successful in reducing CVOC indoor air impacts attributable to VI to appropriate levels. The use of a VFD on the sub-slab vapor extraction blower allows this system to efficiently transition between operating objectives, from initial focus on CVOC mass removal from the source area to longer-term sub-slab depressurization as a VI preventive measure. This work also demonstrated how estimates of VI mass loading, or mass flux, can be used as a predictor of VI impacts to indoor air, and can also be used to size treatment equipment for captured soil vapor when appropriate or desired.

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Keywords

Vapor intrusion, commercial, industrial, HVAC, flux, gas chromatograph, mass spectrometer, Hapsite, depressurization, TCE, VFD.