High-Frequency Continuous Monitoring to Track Vapor Intrusion Resulting From Naturally Occurring Pressure Dynamics

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Vapor intrusion characterization efforts can be challenging due to complexities associated with background indoor air constituents, preferential subsurface migration pathways, and response time and representativeness limitations associated with conventional low-frequency monitoring methods. For sites experiencing trichloroethylene (TCE) vapor intrusion, the potential for acute risks poses additional challenges, as the need for rapid response to exposure exceedances becomes critical in order to minimize health risks and associated liabilities. Continuous monitoring platforms have been deployed to monitor indoor and subsurface concentrations of key volatile constituents, atmospheric pressure, and pressure differential conditions that can result in advective transport. These systems can be comprised of multiplexed laboratory-grade analytical components integrated with telemetry and geographical information systems for automatically generating time-stamped renderings of observations and time-weighted averages through a cloud-based data management platform. Integrated automatic alerting and responses can also be engaged within one minute of risk exceedance detection. The objectives at a site selected for testing included continuous monitoring of vapor concentrations and related surface and subsurface physical parameters to understand exposure risks over space and time and to evaluate potential mechanisms controlling risk dynamics which could then be used to design a long-term risk reduction strategy. High-frequency data collection, processing, and automated visualization efforts have resulted in greater understanding of natural processes such as dynamic contaminant vapor intrusion risk conditions potentially influenced by localized barometric pumping induced by temperature changes. For the selected site, temporal correlation was observed between dynamic indoor TCE vapor concentration, barometric pressure, and pressure differential. This correlation was observed with a predictable daily frequency even for very slight diurnal changes in barometric pressure and associated pressure differentials measured between subslab and indoor regimes and suggests that advective vapor transport and intrusion can result in elevated indoor TCE concentrations well above risk levels even with low-to-modest pressure differentials. This indicates that vapor intrusion can occur in response to diurnal pressure dynamics in coastal regions and suggests that similar natural phenomenon may control vapor intrusion dynamics in other regions, exhibiting similar pressure, geochemical, hydrogeologic, and climatic conditions. While dynamic indoor TCE concentrations have been observed in this coastal environment, questions remain regarding whether this hydrogeologic and climatic setting represent a special case, and how best to determine when continuous monitoring should be required to most appropriately minimize exposure durations as early as possible. ©2017 Wiley Periodicals, Inc.

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BACKGROUND/INTRODUCTION

The U.S. Environmental Protection Agency (USEPA) describes vapor intrusion (VI) as "the general term given to migration of hazardous vapors from any subsurface vapor source, such as contaminated soil or groundwater, through the soil and into an overlying building or structure" (USEPA, 2015). Specific contaminants can include volatile organic compounds, select semivolatile organic compounds, select inorganic compounds such as elemental mercury and hydrogen sulfide, and methane (USEPA, 2015).

As a consequence of these TCE toxicity determinations, concerns about potential health and legal implications have resulted in a greater emphasis on vapor intrusion (VI) assessment as part of due diligence during property transactions and for legacy sites that have yet to undergo VI characterization.

VI is currently receiving considerable attention. A primary reason has to do with the fact that, for the majority of volatile contaminant releases, the vapor transport pathway was not initially afforded as much attention as the groundwater transport pathway. In addition, trichloroethylene (TCE) has received significant attention recently, as EPA has concluded that short-term low-dose exposures by pregnant women in their first trimester of pregnancy can result in risks to their unborn children. More specifically, 2 micrograms per cubic meter ($\mu g/m^3$) of TCE inhalation exposures for as little as 24 hours (hr) during a 21-day window of susceptibility can lead to fetal cardiac malformation and developmental disorders (USEPA, 2011). EPA Region 7 policy suggests that with higher concentrations, a single exposure of much shorter durations during the 21-day window of susceptibility can result in harm to the fetus (USEPA, 2016a). For instance, using equations presented in EPA Region 7 policy, residential exposure to 2 $\mu g/m^3$ TCE over 24 hr represents an acute risk, as does 6 $\mu g/m^3$ over eight hours (the commercial threshold), and 48 $\mu g/m^3$ for a one-hour duration. Since women do not always know if they are pregnant during the initial stages of pregnancy, many interpret this to imply that all women of child-bearing age should be protected from acute (short-term) TCE exposures.

As a consequence of these TCE toxicity determinations, concerns about potential health and legal implications have resulted in a greater emphasis on VI assessment as part of due diligence during property transactions and for legacy sites that have yet to undergo VI characterization. For instance, in February 2016 EPA published rules in the Federal Registrar proposing to add VI to their Hazard Ranking System criteria that would be used to evaluate whether a site should be considered for the National Priorities List (USEPA, 2016b). In addition, states such as Massachusetts are currently evaluating sites classified as "no further action" prior to national recognition of the VI risk pathway and are in the process of contacting owners of sites they believe will require reopening. More specifically, Massachusetts Department of Environmental Protection stated that approximately 200 of the 1,000 closed sites it has reviewed to date may present a significant indoor TCE exposure risk (Grachuk, 2016).

Vapor concentrations can vary in both the subsurface and indoor environments due to barometric pumping, soil moisture dynamics, building ventilation, wind shear, tidal fluctuation, and other environmental and anthropogenic factors (ASTM International, 2013; Construction Industry Research and Information Association [CIRIA], 2007; Holton et al., 2013; Kram et al., 2011, 2013; USEPA, 2012, 2015). As such, it becomes important to measure concentrations using methods that are capable of detecting changes, the complete range of concentrations, and corresponding factors that contribute to concentration and exposure dynamics in order to best evaluate potential risks and to derive mitigation strategies based on patterns observed. By implementing continuous and high-frequency monitoring approaches, practitioners have concluded that several types of traditional VI monitoring and assessment methods (e.g., time-weighted passive samplers and point in time methods) can be susceptible to false negative and false positive conclusions and results that do not reflect worst-case exposure conditions (ASTM International, 2013; Holton et al., 2013; Kram, 2015; USEPA, 2015).

Time-integrated methods are not capable of revealing the entire range of concentrations as they yield a single sorbed or collected mass value estimate over the deployment duration. As such, without appropriate temporal resolution using traditional approaches, it is impossible to know when an episodic increase in concentration occurred, or the duration and dosage over that event. Most importantly, when acute TCE is of concern, traditional methods do not typically allow for response times sufficient to protect receptors from exposures of concern. Furthermore, mitigation measures such as subslab depressurization (SSD) are generally operated to maintain relatively low minimum pressure differentials (e.g., 0.02 inch, or approximately 5 pascal [Pa]; USEPA, 2008) to prohibit volatile constituents from entering buildings. Routine system checks do not typically include measurement of indoor air concentrations. Since naturally occurring pressure differentials can be much higher than induced pressure differentials, episodic increases in indoor concentrations during a pronounced naturally occurring barometric pressure drop could potentially overwhelm the induced SSD pressure differential. If concentration monitoring is not being performed during these episodic events, receptors could be exposed to acute TCE inhalation risk exceedances without their knowledge.

Atmospheric pressure is the force per unit area exerted against a surface by the weight of air above that surface in the earth's atmosphere. This pressure is often measured with a barometer at airports and other areas where barometric pressure can influence operations. Vapors typically flow from high pressure to low pressure. The phenomenon that describes vapor exchanges between the subsurface and ground level elevations is referred to as barometric pumping. When atmospheric pressure is higher than the subsurface pressure, air from the overlying atmosphere is induced to flow into the subsurface. When atmospheric pressure is lower than subsurface pressure, pore vapors can flow from the subsurface soils upward through the soil profile and discharge into the atmosphere, carrying with it entrained volatile gas-phase constituents. Therefore, when barometric pressures decrease at the ground surface through climatic and diurnal dynamics, soil vapors can migrate advectively through soil pores and conduits open to the surface, thereby impacting the chemical concentrations in the shallow subsurface as well as in the overlying atmosphere. It has long been known that barometric pumping occurs in the subsurface (Choi et al., 2002; Massmann & Daniel, 1992; Nilson et al., 1991; Rossabi, 1999; Tillman et al., 2001). These observations have been exploited by research teams deploying devices to induce passive contaminant vapor extraction (Riha, 2005). In addition, barometric pumping impacts on sample collection logistics have been acknowledged by the U.K. regulatory community for more than 10 years. More specifically, CIRIA (2007) states:

Time-integrated methods are not capable of revealing the entire range of concentrations as they yield a single sorbed or collected mass value estimate over the deployment duration.

> The key should be that the monitoring period for a specific site covers the "worst case" scenario. Such a "worst case" scenario will occur during falling atmospheric pressure and, in particular, weather conditions such as rainfall, frost and dry weather … Investigations concerned with soil gas are required to provide monitoring data sufficient to allow prediction of worst case conditions enabling the confident assessment of risk and subsequent design of appropriate gas protection schemes. (CIRIA, 2007, p. 59)

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Volatile contaminant vapors can migrate upward through the soil column and into buildings via advective and diffusive transport. In many cases, these vapors can accumulate just below the building slab. When buildings are in direct contact with the soil, barometric pumping can induce VI when a sufficient pressure differential between the subsurface and the building is established. Advection-driven pressure differentials between the building interior and the immediate subsurface can transport soil gas indoors through cracks, seams, utility penetrations in subsurface walls and floors, and through floors in contact with the ground surface.

A number of practitioners maintain that a relatively high minimum pressure differential is required for subsurface vapor transport sufficient to result in exposure and explosion risks.

The heat capacity of ocean water is typically higher than the heat capacity of the adjacent land. As such, toward the middle of the day in many coastal regions, air above the land that is heated by the sun during this time expands, rises, and creates a slight drop in barometric pressure relative to the pressure over the ocean. This slight drop in barometric pressure causes the midday onshore sea breeze commonly observed in many coastal regions throughout the globe on a daily basis. If the pressure drop over land is sufficient to induce vapor migration from the shallow subsurface into overlying buildings, this raises several critical issues and implications. For instance, if only a small and commonly occurring drop in barometric pressure (e.g., 50 Pa or less) is required to develop a pressure differential between the subsurface and ground surface sufficient to induce VI on a daily basis, risk conclusions derived could depend upon the time of measurement (e.g., early morning minimal upward oriented pressure differential vs. late morning and the middle of the day with an elevated upward oriented pressure differential). While these types of pressure patterns are very common, daily fluctuations can be disrupted by climatic anomalies and seasonal variations. As such, if these are not appropriately accounted for in the VI investigation design and planning phase, false negative and false positive readings could result from the field surveys. If a correlation between pressure and the potential for VI can be established, more effective risk conclusions, monitoring campaigns, and remediation strategies can be derived.

A number of practitioners maintain that a relatively high minimum pressure differential is required for subsurface vapor transport sufficient to result in exposure and explosion risks (ASTM International, 2016; California Department of Toxic Substances Control, 2005; Eklund, 2010; Interstate Technology & Regulatory Council, 2014). Mass flux is often relied upon to conclude whether conditions are conducive to exposure or explosion. For instance, some practitioners maintain that even with extremely high methane concentrations (e.g., double the upper explosive level), an explosion risk is not possible unless pressure differential exceeds 500 Pa (ASTM International, 2016). For reference, it is important to compare this to the 0.05 mbar (5 Pa) minimal requirements for SSD systems to prevent vapors from intruding into buildings (USEPA, 2008). While other high-frequency monitoring investigations have revealed dramatic increases in shallow subsurface methane concentrations temporally correlated with a relatively slight drop in barometric pressure (e.g., 100 Pa) along with a drop in shallow subsurface oxygen (Kram et al., 2011, 2013), it has also been suggested that shallow soil concentration extremes can be caused by approaching storm events that typically follow a relatively higher atmospheric pressure situation (CIRIA, 2007).

Previous investigations performed at a large industrial facility (see description below) were comprised of time-integrated sampling methods that did not provide sufficient temporal information required for a high level of confidence in cause-and-effect relationships that could impact pending decisions regarding remedial design options.

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Therefore, for this effort, a continuous analytical monitoring platform was deployed to answer key remaining questions. In the process, it was discovered that indoor TCE concentration dynamics temporally correlated with diurnal barometric pressure changes. Details and implications are presented below. While this observation suggests that the relationship between a slight drop in pressure and corresponding increase in VI could occur in other regions throughout the world, additional effort will be required using similar types of high-frequency monitoring systems before drawing such conclusions. At a minimum, given that these patterns have been revealed, designing field investigations around these relationships could result in superior site characterization campaigns, risk mitigation efforts, and system performance evaluation strategies.

Site Description

The site is located in Southern California adjacent to San Diego Bay, which is characterized by progradational—retrogradational sequences comprised of late Cretaceous and Eocene forarc stratigraphy (May et al., 1984). Soils are comprised of unconsolidated fluvial-deltaic, river stream, tidal influx (marine particulate), and dredge spoil depositional materials (Kram, 1988). The approximate present configuration was reached in Holocene time. The Silver Strand sandspit, which extends from Imperial Beach to North Island, developed in the early Holocene contemporaneously with shoaling and progressive filling of the bay as sediment load from local river fluxes moved oceanward and littoral drift transported sand toward the northwest (Inman et al., 1974). This elongated barrier separates most of the bay from the Pacific Ocean and is comprised of soils that range from coarse gravel and sand to lenses of fine clay.

The project was designed to evaluate potential VI risks associated with a documented TCE release known to exist under Building 379 on Naval Air Station North Island; a 172,000-square-feet facility used for industrial purposes including carpentry, machining, and similar operations. The building is over 60 feet (ft) tall with two main floors each having a height of at least 20 ft. The building was built in the 1940s, and the concrete floor is in poor condition, with over 15,000 ft of cracks which have recently been sealed. Numerous floor drains are also present. Most of the rooms and areas in the building are open (i.e., they do not have walls). There is an antiquated ventilation system that uses nine fans to continuously intake outside air and force it into the building. A number of windows are permanently open, and there are multiple openings in the walls. Based on previous investigations and changes in operational protocol, no TCE is currently in use in the building.

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The depth to groundwater is approximately 24 feet below ground surface (bgs), with modest or typically no fluctuation due to tidal influence under the building (Michael Pound, personal communication, 2016). The plume is comprised of nonaqueous, solute and vapor phase components extending 10 acres with the deepest contamination detected at 80 ft below ground surface. TCE has been detected as a constituent of a comingled light nonaqueous phase liquid dominated by petroleum hydrocarbons. Depth to the top of the nonaqueous phase liquid, which includes TCE, 1,1,1-trichloroethane (1,1,1-TCA), JP-5, and Stoddard solvent, is approximately 22 ft below grade. Subsurface solute concentrations as high as 100 milligrams per liter (mg/L) have been observed, whereas soil vapor concentrations as high as 6,000,000 $\mu g/m^3$ of TCE in subslab soil gas have been documented. Owing to the proximity to San Diego Bay, shallow groundwater contains very high levels of total dissolved solids.

Experimental Methods

For this project, a new sample was analyzed every four minutes as analyses were focused on measuring TCE concentrations. Six indoor sampling locations were monitored continuously. As such, each cycle was comprised of six monitoring locations and required approximately 25 min to complete.

The analytical instrumentation employed included a gas chromatograph (GC) equipped with an electron capture detector (ECD) and is described in greater detail in Kram et al. (2016). The system has been multiplexed with a 16-port valve component to allow for sample collection at multiple locations with a single analyzer. The sampling component is equipped with continuous vapor collection capabilities that draws from sampling lines connected to each port. The sample collection distal ends of each sampling line are surveyed for global position. Each port is subsequently aligned with the analyzer at a preset schedule, the sample is run for the desired analytes, and the values are automatically delivered to a remote processing Cloud-based software platform, where the information is processed and becomes available within one minute (min) of detection. As each sample is analyzed, all other ports are continuously purged to avoid carryover and ensure that subsequent samples in the multiplexing sequence represent air aliquots collected from corresponding locations just prior to analysis. Samples are typically run within ten minutes of collection. For this project, a new sample was analyzed every four minutes as analyses were focused on measuring TCE concentrations. Six indoor sampling locations were monitored continuously. As such, each cycle was comprised of six monitoring locations and required approximately 25 min to complete.

The Cloud-based automated data management, processing, and response software platform is comprised of several components described in greater detail in Kram et al. (2016). In summary, a web dashboard was employed to track time series analyses, contour images of live and selected time-stamped data, contour images of user-selected moving averages, and automated alerting and controls (Exhibit 1). Alerts are based on rules engaged to automatically contact designated recipients within one minute of an observation that meets key criteria. For instance, any time the analyzer measures a TCE concentration exceedance, an alert is automatically delivered to responders and the message is archived in a project tracking record accessible to project team members.

Each of the six data collection points were continuously monitored for indoor TCE vapor concentrations and automatically compared to a preset action level concentration threshold. The locations were selected based on previous observations, potential for inhabitant inhalation exposures, as well as a screening effort that included GC/ECD sample analysis performed with the analyzer set to batch mode. Once the six monitoring locations were selected, sample lines were deployed and connected to the analytical instrumentation, and continuous analytical processing from these locations commenced in a user-defined sequence. The analytical protocol, sequencing and multiplexing valve controls, and web integration and data upload timing were programmed during the project setup using instrumentation software and a local computer. The computer was directed to deliver each analytical result to a file transfer protocol site, where it was automatically posted and archived in the Cloud-based software platform, evaluated for concentration threshold exceedances, and if a threshold had been exceeded, an alert was immediately emailed to designated recipients. Account holders tracked results via Internet access in near real-time through time series charts, contour images of the most current results, and by observing contour images of time-weighted average results displayed for

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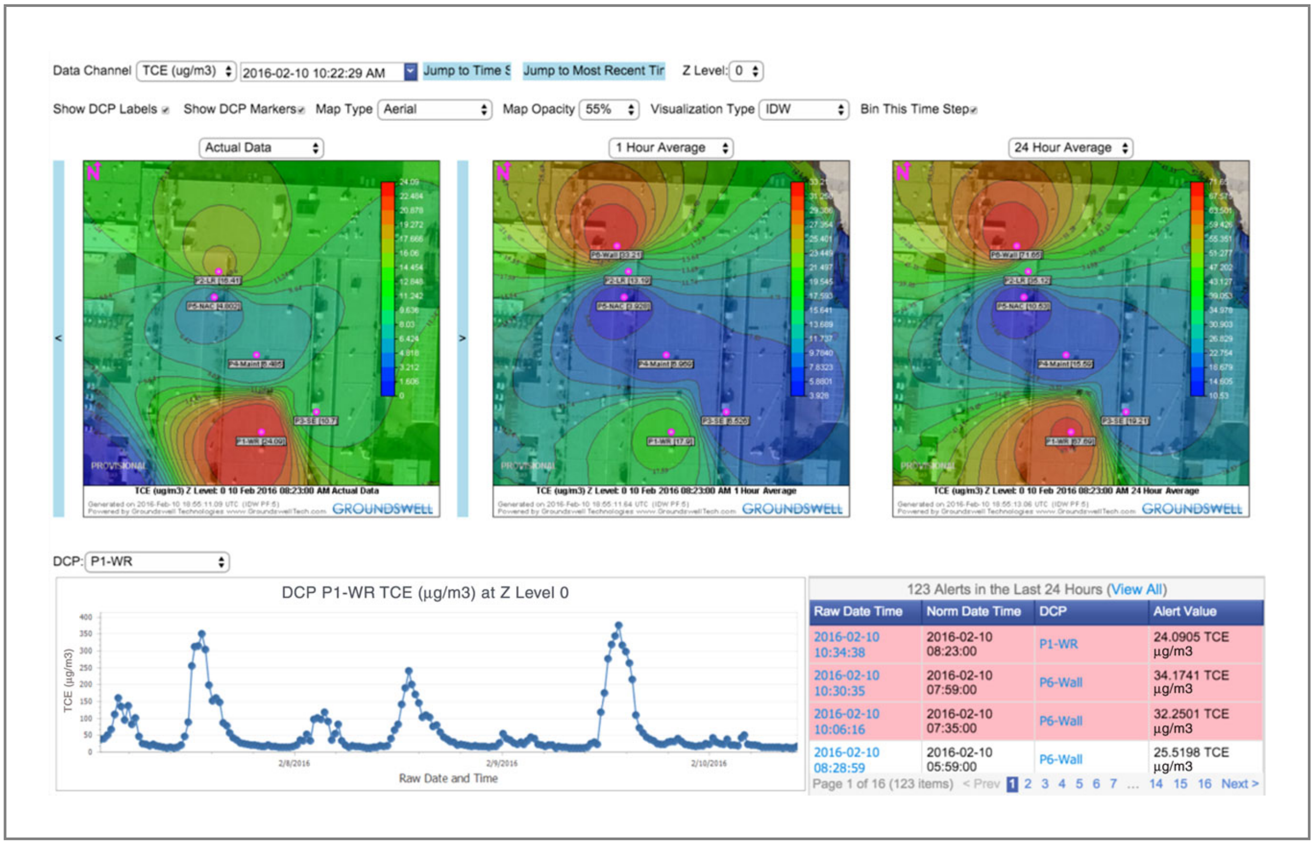

Exhibit 1. Near real-time reporting dashboard displaying temporal and spatial relationships and alerts

two user-selected increments. For this project, a complete contour image (including all six data collection points) was generated approximately every 30 min. When an exceedance was recorded, an email alert was automatically delivered within one minute of the analysis, regardless of the status of the generation of a complete contour image.

Pressure differentials were measured from a location near the women's restroom using a digital micromanometer (DG-700) from The Energy Conservatory (Minneapolis, MN). One port was connected to a tube extending to approximately 1 inch below the base of the slab, whereas the other port was open to air inside the building. Data were recorded every 15 seconds, and were manually retrieved on a periodic basis. The DG-700 has a resolution of 0.2 Pa and has an "auto-zeroing" feature, which adjusts for sensitivity in response to position and operating temperature.

Results and Discussion

Exhibit 1 includes time series for TCE concentration collected in near real time from one of the monitoring locations, a contour image for near real-time geospatial distribution of TCE, contour images for time-weighted TCE averages (1 and 24 hr, respectively), and an alert log documenting actions automatically engaged when concentration threshold exceedances were recorded, when and where they were recorded, and the observed TCE concentrations for those time steps. Every time concentrations exceeded 24 $\mu g/m^3$,

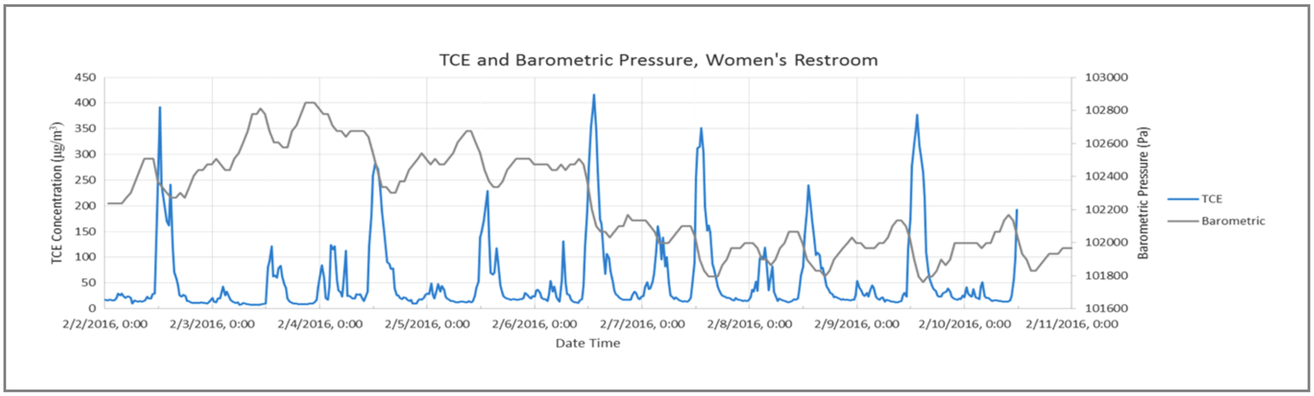

Exhibit 2. Indoor TCE concentration versus barometric pressure

alerts were automatically delivered to designated project personnel. Exceedances recorded within the past hour were automatically highlighted. Note that the geospatial renderings are considered provisional, as deterministic interpolations were employed. The raw data were available for downloading and geostatistical rendering, modeling, and model calibration. As can be seen in the contour images, some of the locations selected consistently display elevated TCE concentrations during the episodic increases observed. Several of these locations have been considered candidate intrusion points, whereas others are considered possible inhabitant exposure locations based on consistent TCE concentrations that exceed regulatory action thresholds.

The time series chart in Exhibit 2 displays TCE concentration dynamics for a monitoring point located in the women's restroom. The women's restroom data were selected for additional analyses below because this location represents an area of concern from an acute TCE risk perspective, and because the highest observed concentrations were recorded at this monitoring point. Concentrations reached 416 $\mu g/m^3$ at 1:21 pm PST on February 6, 2016. Over the duration of the continuous monitoring survey, concentrations tended to rise most during the mid-late morning, with another modest rise in the middle of the night often through the early morning. This pattern raised questions about what might be causing the mid-morning concentration rise. As such, barometric pressure readings were obtained from instrumentation deployed at the local airport and it was decided that pressure differential should be evaluated. Exhibit 2 also displays TCE concentration versus barometric pressure for a monitoring location in the women's restroom. The pattern observed reveals an inverse temporal correlation between barometric pressure trend and concentration. For instance, at the beginning of a documented drop in barometric pressure, a rise in indoor TCE concentration can be observed. Conversely, at the beginning of a rise in barometric pressure, indoor TCE concentrations decrease and remain relatively low until the next drop in barometric pressure. Exhibit 3 displays TCE versus pressure differential for the same monitoring location. An increase in pressure differential (where a positive number reflects a relatively higher pressure in the subsurface relative to indoors) correlates temporally and visually with an increase in TCE concentration. Similar temporal correlations were observed for the other monitoring locations in the building.

Exhibit 4 presents a scatter plot of indoor TCE concentration in the women's restroom and contemporaneously measured pressure differential. The pattern reflects a

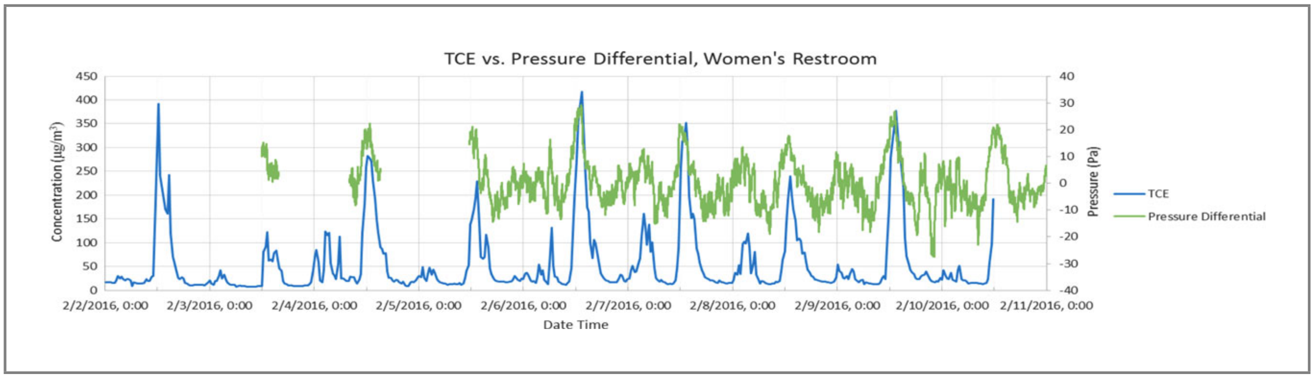

Exhibit 3. Indoor TCE concentration versus pressure differential – temporal relationship

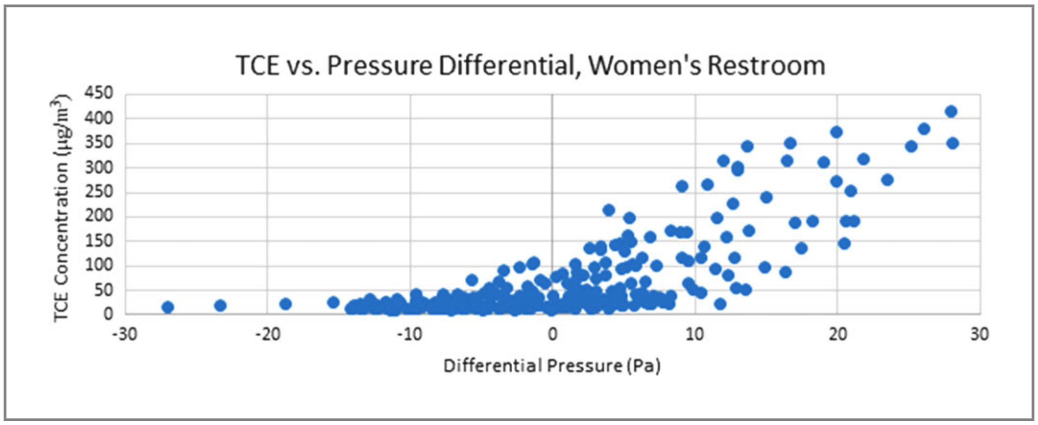

Exhibit 4. Indoor TCE concentration versus pressure differential

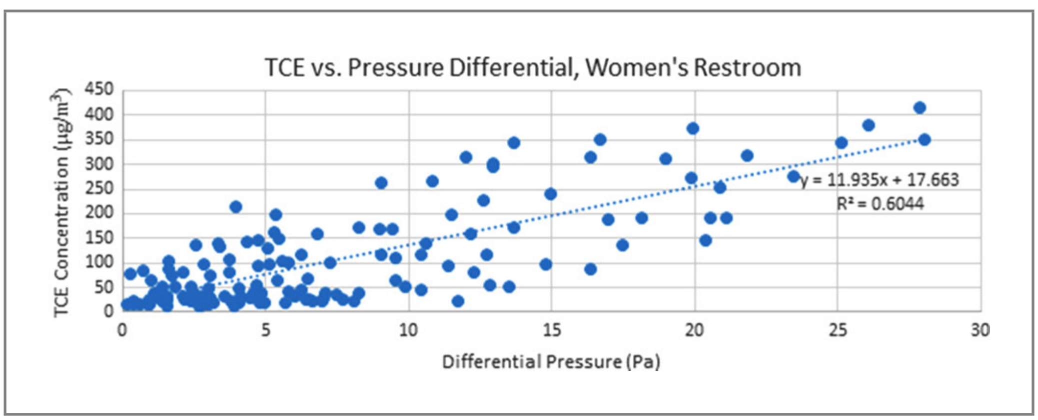

Exhibit 5. Indoor TCE concentration versus pressure differential values greater than zero

correlation that suggests an increase in TCE concentration as pressure differential increases. Elevated TCE concentrations observed during modestly negative and modestly positive pressure differential values may be due to a lag effect or potentially preferential vapor migration pathways. Exhibit 5 displays TCE concentration in the women's restroom versus contemporaneously measured pressure differential for pressure differential values

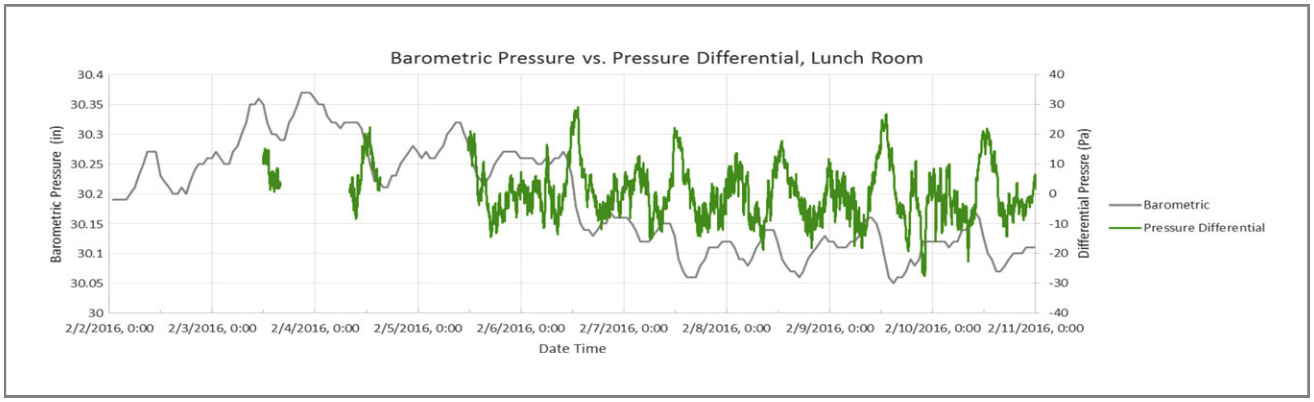

Exhibit 6. Barometric pressure versus pressure differential

above zero. While there is scatter in these data, a positive correlation (r^2 of 0.6) suggests that pressure differential is a driver for advective intrusion of TCE vapor at this site.

Exhibit 6 displays barometric pressure versus pressure differential observed. There is a close temporal correlation between the drop in barometric pressure and the corresponding increase in pressure differential, where the positive differential value reflects a relatively higher pressure in the subsurface than at the ground surface. This relationship suggests that barometric pressure change can be a driver for VI, as the resulting pressure differential can induce advective flow from the subsurface soil pores to the surface. The resulting pressure differential can also result in vapor transport from the vadose zone toward the surface (and potentially into overlying structures).

One possible interpretation of the observations in Exhibits 2 through 6 is that pressure conditions in the shallow subsurface tend toward equilibrium with the surface environment, and that a temporal lag can develop at various times within this dynamic barometric pumping pattern. As such, during a drop in barometric pressure at the land surface either caused by temperature-driven diurnal fluctuations or an approaching storm, the net pressure in the subsurface environment initially reflects the relatively higher pressure value achieved during the previous equilibrium condition that preceded the drop in barometric pressure. The resulting pressure differential represents an advective gradient capable of transporting soil pore vapors toward the surface and into overlying buildings until a new pressure equilibrium is established or land surface pressure increases relative to the net subsurface pressure. Therefore, at the beginning of a barometric pressure reducing trend, one can observe a pressure differential which can cause advective flow of TCE-entrained soil vapors into overlying structures. A key observation includes the documentation that the diurnal differential pressures (e.g., 30 Pa maximum) associated with VI at this site can mobilize significant amounts of subsurface vapor phase mass. In comparison, ASTM maintains that even with elevated subsurface methane concentrations, no further action is recommended unless pressure differential exceeds 500 Pa (ASTM International, 2016). This position is based on the assumption that an elevated (and relatively less common) pressure differential of 500 Pa is required to mobilize sufficient mass (e.g., explosive levels) of methane indoors. For the Building 379 site investigated, much lower pressure differentials observed were associated with modest changes in barometric pressure (e.g., 100 Pa or less) and indoor TCE concentration dynamics and risk exceedances that occur with high frequency (e.g., daily). Some of the differences

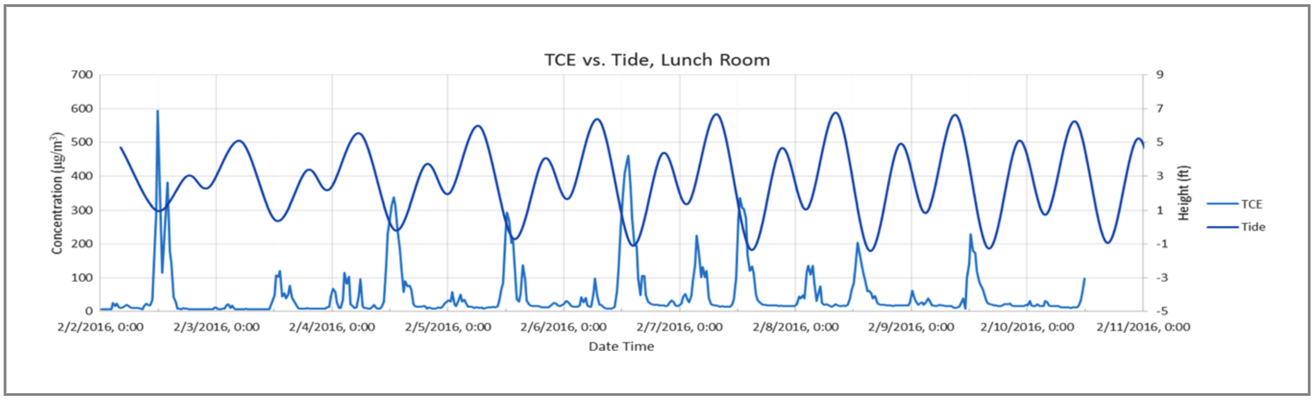

Exhibit 7. Indoor TCE concentration versus tide (MSL)

between risks posed by methane and TCE soil vapor migration can be attributed to the fact that very low concentrations of TCE can represent a short-term risk.

Exhibit 7 displays TCE concentration versus tidal fluctuations. While tidal fluctuation beneath the facility is minimal, a temporal evaluation of concentration versus tide was performed to better understand observations regarding pressure dynamics by process of elimination. It appears that for at least part of the monitoring campaign there was a temporal correlation between a drop in tide and an increase in TCE concentration. However, this was not always in phase and the rise in TCE did not always correspond to the beginning of the drop in tide. Furthermore, the relationship between tide and indoor TCE concentration was expected to be direct (e.g., tidal rise corresponding to an increase in TCE indoor concentration) due to a piston type of the vapor displacement mechanism in the shallow subsurface. The opposite was observed (at least for selected time ranges). Since tidal fluctuations directly beneath the building are believed to be minimal, any correlations made with regional tidal changes may be spurious. To more confidently conclude whether tidal fluctuations have a consistent impact on VI at this facility, it will be important to deliberately monitor TCE concentrations during times when tidal fluctuations are not in phase with barometric fluctuations. Additional data (e.g., continuous potentiometric surface monitoring along with concentration) will also need to be collected to more thoroughly understand whether there is an additive or subtractive response associated with potential tidal influence on VI.

Exhibit 8 displays TCE concentration versus wind speed. The rise, peak, and fall of wind speed tend to occur during the middle of the day and at key times correlate temporally with observed TCE concentration dynamics. The wind speeds recorded are relatively modest and, as such, are thought to only contribute slightly or not at all to VI (at least for this site). In addition, there are times when wind occurs, yet indoor TCE concentration is minimal. However, these tend to occur when wind speeds are less than 5 miles per hour (mph). The highest TCE concentrations tend to occur at the same time relatively higher winds (e.g., greater than 5 mph) occur. As such, this suggests that wind is not the cause of TCE intrusion, but could be an artifact related to barometric pressure dynamics that result in both VI as well as a sea breeze. Exhibit 9 displays wind speed relative to barometric pressure. Not surprisingly, wind speed tends to increase during a drop in barometric pressure for this climatic regime. This can be attributed to a regional above-ground

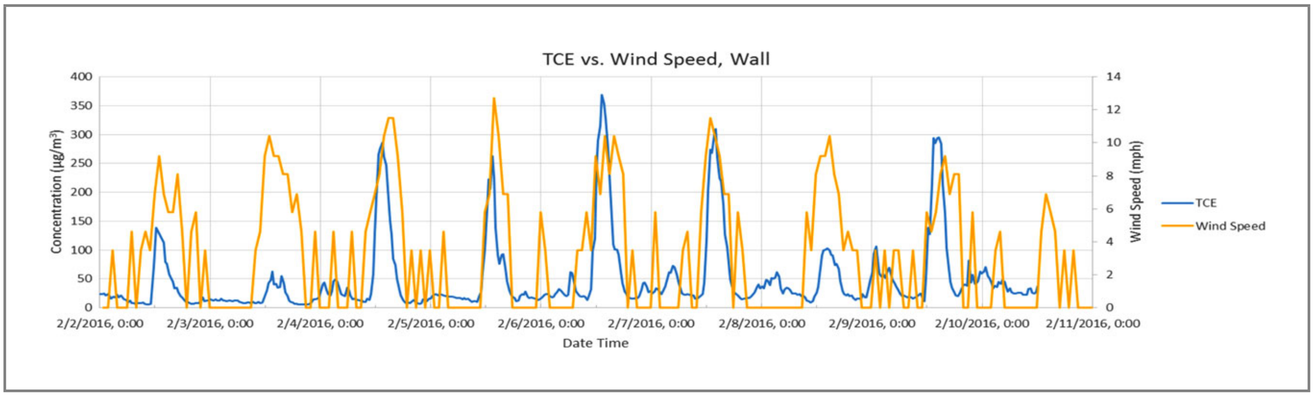

Exhibit 8. Indoor TCE concentration versus wind speed

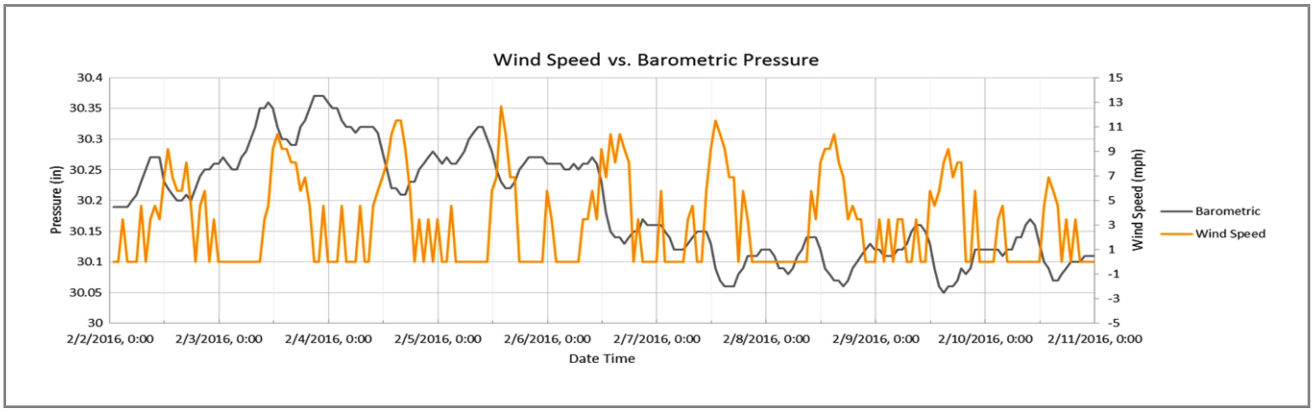

Exhibit 9. Wind speed versus barometric pressure

pressure differential induced by the relatively lower heat capacity on land versus the ocean, which results in the common onshore breeze observed in coastal regions worldwide.

To summarize, a temporal correlation between indoor TCE concentration and a slight drop in barometric pressure has been documented (Exhibit 2). One interpretation is that the regional drop in barometric pressure caused by the heating of the land in the mid-late morning also creates a localized pressure differential between the subsurface soils and land surface that results in advective TCE transport into the building (Exhibits 3–6). As stated above, this daily drop in barometric pressure can also result in an onshore breeze in coastal zones. Similarly, this diurnal pattern can potentially also induce VI in coastal zones. As stated, the pressure range during this diurnal barometric cycling is typically not very large. Similarly, the barometrically induced pressure differential required to move TCE vapors from the subsurface through a building slab at concentrations of concern does not appear to be significant (e.g., typically 20 Pa or less) for this facility.

A relatively larger increase in TCE is observed during the mid-day hours, which could potentially be due to the fact that the pressure differential between the ocean and land during the evening and early morning tend to be less than during the middle of the day. It is also possible that these factors can be additive in some cases and could potentially offset each other in select situations. Furthermore, the naturally occurring barometric pressure

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dynamics and frequency observed are considered typical for much of the year in coastal regions. However, there are many situations that can occur, albeit less frequently, that have a potentially greater impact on TCE VI. For instance, a quickly approaching storm could result in a larger pressure differential and subsequently a greater amount of advective TCE mass flux.

CONCLUSIONS

Daily episodic increases in indoor TCE concentrations were documented for a building located in the Southern California coastal region. Dynamic vapor concentrations were automatically monitored continuously from six indoor locations for approximately one week. During this time, dramatic concentration increases exceeding 100 $\mu g/m^3$ coincided with slight drops in regional diurnal barometric pressure and increases in localized pressure differential between the shallow subsurface and indoor environments. Highest episodic concentration increases consistently occurred midday. This is an important observation for many reasons. For instance, if a VI monitoring campaign is to include a discrete "grab" sample collected in the early morning or after work hours at this facility, this would exhibit a much lower indoor concentration than if collected at specific times in the middle of the day when barometric pumping has resulted in advective vapor transport into the building. In addition, time-integrated sample results would depend upon the timing of the beginning and end of the sampling duration relative to the barometric cycling. For instance, an eight-hour passive sample collected after normal working hours would most likely underestimate exposure risks at this facility. A 24-hr passive sample could also yield results that are potentially biased low, as occupants tend to inhabit buildings during the middle of the day when relatively higher concentrations are expected to occur. Based on the temporal correlation between pressure differential and indoor concentration, it is anticipated that the highest time-integrated and grab sample concentration values would occur when the sampling campaign duration overlaps an approaching storm event. This would be consistent with CIRIA (2007) guidance.

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Traditional VI characterization approaches that include time-integrated methodologies do not allow for temporal resolution afforded by the type of continuous monitoring implemented for this project, as traditional laboratory results are presented as a single aggregated time-weighted estimate. As such, the patterns documented by implementing high-frequency continuous concentration monitoring remained undetected at this facility for years and resulted in uncertainties regarding potential exposure risks, the potential for indoor TCE sources, and identification of vapor entry locations. Within a few days of automated high-frequency continuous monitoring, new insights regarding cause-and-effect relationships and targeted mitigation strategies became available to the project personnel. By implementing high-frequency continuous concentration monitoring, not only was it possible to gain a superior understanding of naturally occurring processes and their impact on exposure concentrations, but the approach allowed practitioners to respond to and prevent acute exposure risks while meeting the most stringent time-sensitive response criteria in the United States (e.g., USEPA, 2016a). Furthermore, it now becomes possible to derive building-specific chronic risk screening levels. For instance, concentration time series data can be used to derive time-weighted averages, accrued dosage based on exposure mass over specific windows of susceptibility, and can be used to estimate the percentage of time conditions exceed risk threshold levels while buildings are inhabited. As such, if chronic cancer risks are observed to slightly exceed generic screening thresholds only 10 percent of the time, and a 30-year window is considered an appropriate chronic exposure duration for developing cancer, then the true exposure exceedance duration for that particular site is not 30 years, but 10 percent of 30 years (e.g., three years). Since risk concerns are based on a combination of exposure duration and concentration, it could be argued that the allowable building-specific screening level should be set at ten times the currently prescribed 30-year screening level for the example provided. In the context of barometric pressure-driven exposures, limiting building inhabitant exposures during key hours of the day based on climate forecasting also becomes a potentially viable option. Furthermore, as with the implementation of passive vapor extraction techniques (Riha, 2005), exploitation of anticipated barometric pressure changes can be incorporated into mitigation and system performance evaluation strategies.

When extreme indoor concentration dynamics occurs, as has been demonstrated in the case described above, continuous monitoring enables improved risk evaluations, understanding of temporally and spatially resolved cause-and-effect relationships, and improvements associated with remediation design, risk mitigation, and mitigation system performance verification. Furthermore, risks can be managed, as the detection system and associated software can be integrated with customized mitigation and existing climate control systems that automatically reduce indoor and subsurface concentrations.

While these findings suggest that the relationship observed between a slight drop in barometric pressure and corresponding increase in VI could occur in other regions throughout the world, additional effort will be required using similar types of high-frequency monitoring before drawing such conclusions. As such, it will be critical to perform similar investigations at other TCE release sites located in coastal and other regions subject to diurnal and extreme barometric pressure dynamics and to evaluate impacts based on soil type, soil moisture, site specific plume considerations, indoor TCE concentrations during SSD system operations, and other factors that could potentially impact VI associated with barometric pumping. More specifically, it is recommended that dynamic oxygen profiles, pressure profiles, and variable soil moisture impacts also be investigated to more thoroughly understand factors controlling TCE vapor transport, and at least for this facility, that these future investigations be performed when the tide is out of synch with the anticipated peak pressure differential.

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