A Stakeholder's Guide to Vapor Intrusion: Update

By Lenny Siegel
November, 2015

The specter of unseen toxic vapors—capable of causing cancer, birth defects, or neurological disease—intruding into our homes, schools, and workplaces is enough to scare anyone. The vapor intrusion pathway, a national concern for at least a dozen years, poses a threat to the health of building occupants; it may undermine property values; and it can throw a wrench into plans for new construction. However, the health and economic risks of vapor intrusion can be managed. To ensure they are addressed properly, the people whose lives may be impacted need to understand how vapor intrusion is investigated and mitigated.

Vapor intrusion refers to the migration of toxic vapors from the subsurface—that is, soil or groundwater—into overlying buildings. Though many substances, such as petroleum hydrocarbons and even elemental mercury, can intrude into buildings, sites that require a response usually contain chlorinated solvents—that is, chlorine-containing volatile organic compounds (VOCs) such as trichloroethylene (TCE) and tetracholoroethylene (also known as perchloroethylene or PCE). TCE was widely used as a solvent in industries such as aerospace and electronics, but in recent years a relatively small number of businesses, primarily in metals processing, have continued to use it. It is still found in consumer products such as gun cleaner and plastic cement. PCE is still widely used in dry-cleaning and automotive servicing in much of the country. Toxic compounds found in petroleum products, such as benzene, toluene, ethylbenzene, and xylene (BTEX), and trimethylbenzene may also pose a vapor intrusion risk, but petroleum vapor intrusion is uncommon because at many sites these compounds degrade near the ground surface as they come into contact with atmospheric oxygen.

For more information on how **Gasoline Leaks and Spills** are different from other release with a potential for vapor intrusion, go to http://www.cpeo.org/pubs/SGVI/Gasoline.pdf .

While individual scientists and some states, such as Massachusetts and Colorado, have been addressing vapor intrusion since the 1990s, vapor intrusion started to become a standard part of contaminated-site response in 2001, when U.S. EPA's Resource Conservation and Recovery Act program stipulated such an assessment for all Environmental Indicator human health decisions. In early 2002, the *Denver Post* brought national attention to the problem with a landmark series on vapor intrusion. Since then many environmental regulatory agencies across the country have developed technical and policy guidance for investigating and mitigating toxic gas vapors. As researchers and regulators learn more about how vapor intrusion manifests in the real world of homes, businesses, schools, and other buildings, new strategies for vapor response are continuously rising to the surface. U.S. EPA promulgated its long-awaited vapor intrusion Technical Guides in June of this year, reflecting the latest in vapor intrusion science and policy. You can download the *OSWER Technical Guide for Assessing and Mitigating the Vapor Intrusion Pathway from Subsurface Vapor Sources to Indoor Air* from http://www.epa.gov/oswer/vaporintrusion/guidance.html#EO12866OSWERVI.

Vapor intrusion responses are often major local news stories. But many Americans who are potentially exposed via the vapor intrusion pathway do not know about it, and many who know about it do not understand the many complexities involved in assessing and responding to vapor intrusion. Indeed, many people leave public meetings on local vapor intrusion investigations confused. But the average person is capable of understanding the basics of vapor intrusion, and this guide is designed to give people enough information to engage constructively in decisions that affect their health, their families, and their property.

At the Center for Public Environmental Oversight, we believe that such engagement is the number one factor in determining whether people get the protection they need. The polluters responsible for cleanup as well as the government agencies whose jobs it is to defend the environment are more likely to address public concerns if community members learn about technologies and policies and come to the table collectively to provide advice and insist upon results. Furthermore, vapor intrusion responses usually require the cooperation and even the permission of building owners and occupants. This guide is intended to serve as an introduction —Vapor Intrusion 101—to community stakeholders, including residents and other property owners, other building occupants, local officials, and developers.

Click on **Who Is Responsible** http://www.cpeo.org/pubs/SGVI/Responsible.pdf for a description of who normally conducts and pays for vapor intrusion response. Click on **Regulatory Programs** http://www.cpeo.org/pubs/SGVI/Regulatory.pdf for a discussion of government oversight of vapor intrusion response.

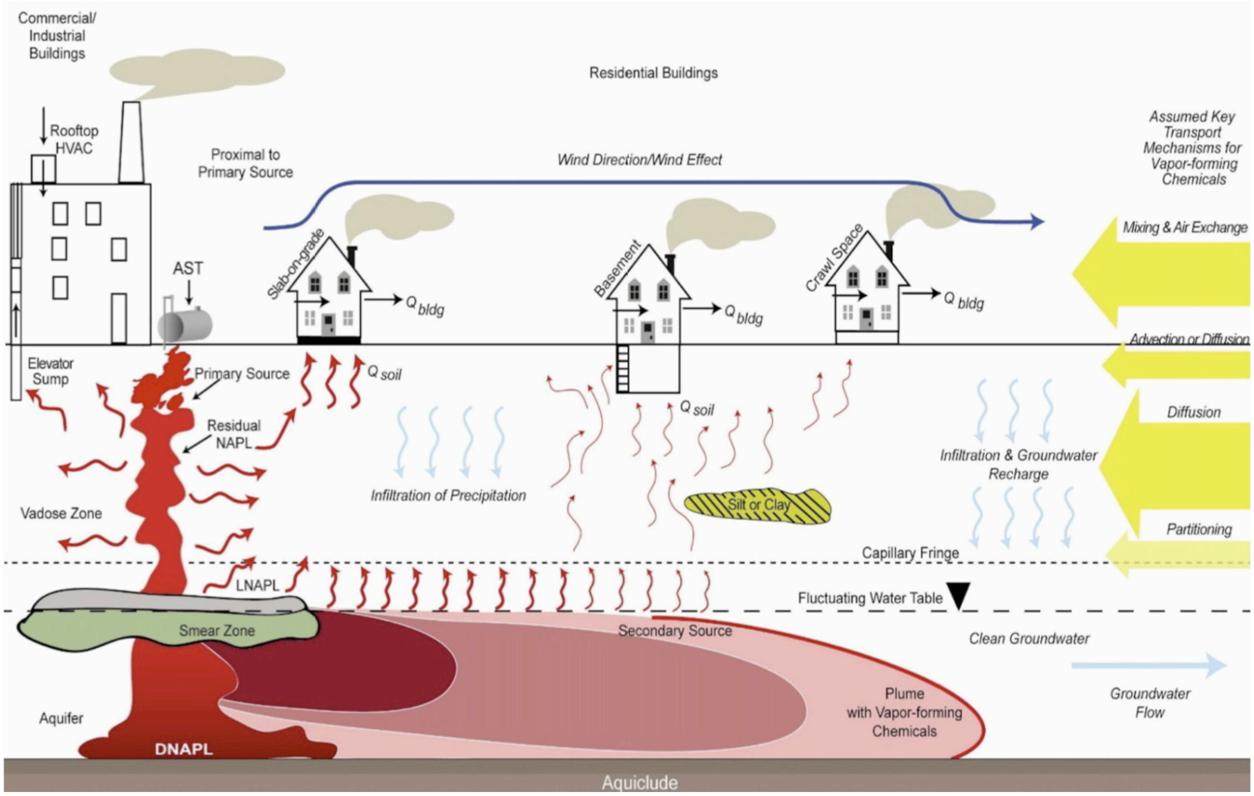
Conceptual Site Model

When consultants or regulators begin a vapor intrusion investigation, they create a **conceptual site model** to guide the collection of data. In simplest terms, this is a site-specific description or diagram that defines the likely sources of contamination, the receptors (building occupants), the pathways through which contamination may enter the building, and the forces that bring the toxic substances into the building. It is essential that stakeholders understand the basic conceptual site model for their site if they are to understand the investigation.

The illustration below, Figure 2-1 from EPA's *Technical Guide,* is designed to show the key elements of a conceptual site model, for four types of buildings.

To understand the typical conceptual site model, one needs to know a little bit about hydrogeology: how water acts on or under the surface of the Earth. **Groundwater** is the water that one finds when one digs or drills a hole in the ground. It can be found at several depths beneath the surface. In general it fills in the pore spaces that surround the sand, clay, and rocks that make up the soil. It is sometimes referred to as the **saturated zone.** With exceptions such as swamps, seeps, and springs, groundwater is not present at the surface.

Groundwater reservoirs are known as **aquifers**. Most areas have multiple aquifers or zones, vertically, separated by low-permeability layers such as clay. Groundwater tends to move laterally through the subsurface, slowly, following the slope of the low-permeability layer, but it also can move downward between aquifer layers if the strata are more permeable, or upward between layers if a high enough pressure exists. The **water table** marks the upper reach of the uppermost aquifer at any given time. The soil above the water table is known as the **vadose zone** or the **unsaturated zone.**



The source of contamination is normally a toxic liquid release—from a leaking tank or pipe, spill, or even deliberate dumping. In most cases the toxic substance first impacts the vadose zone, either remaining there or descending into aquifers below. If the liquid contains chlorinated solvents, they eventually sink to the bottom of each aquifer because they are heavier than water. Lighter than water contaminants such as petroleum stay near the top of the aquifer. Both of these types of contaminants slowly dissolve in the water due to a variety of forces. For the most part, the main driver is known as **advection**, which is the mechanical mixing of the groundwater as it moves through a given location. In most cases contaminants move laterally or vertically with the groundwater. The oval or feather-like shapes that contamination forms in groundwater are known as **plumes**.

Vapor intrusion can occur when **volatile** (vapor-forming) liquids are found in either the uppermost aquifer or in the vadose zone. Like the carbon dioxide in soda drinks, a portion of the substance rises as a gas, or **volatilizes** into the vadose zone, where it can be measured in **soil gas** (the gas between grains of soil). The fraction of the liquid contamination that volatilizes into the gas phase, as well as the rate of volatilization, varies by chemical.

Contaminants in soil gas tend to **diffuse**, or spread out to equalize the gaseous concentration, but the principal reason that soil gas enters buildings is that buildings tend to have a lower pressure (*i.e.,* negative pressure) than the subsurface. That is, like a weak vacuum cleaner a building sucks up gaseous contaminants, not just from the soil directly beneath, but also from the area around the building. This occurs whether the building has a poured (concrete) slab foundation at-grade, a crawlspace over dirt, or a basement with or without a slab floor. Where fireplaces or furnaces are used to heat homes, this pressure differential is even more pronounced during winter months, as indoor air is consumed for combustion and exhausts up the chimney.

Like air escaping through a tiny puncture in a tire, the soil gas "finds" holes or cracks in the slab or floor above. It can even flow through some forms of concrete. As the vapor contaminant enters the overlying building, it spreads out, so contaminant gas concentrations inside are generally much lower than those found in soil gas. If the building or crawlspace is well ventilated, indoor concentrations tend to be reduced further. The ratio of the indoor concentration of a chemical of concern to the soil gas concentration is called the **attenuation factor.** U.S. EPA has collected an extensive database of attenuation factors from chlorinated-solvent vapor intrusion investigations. The real-world factors vary by orders of magnitude.

Go to http://www.cpeo.org/pubs/SGVI/Attenuation.pdf for background on **the attenuation factor**.

The attenuation factor and thus magnitude of vapor intrusion—indeed, whether vapors from the subsurface are found inside buildings—is a function of the **source**, the **structure**, and **atmospheric conditions.** The source refers to the contamination in the subsurface, under or near the building. It can be in groundwater or the vadose zone. In either case, it causes contaminant vapors to collect underneath the building. The source can increase over time if a groundwater plume is migrating toward the building's footprint, and it can decrease if the contamination is degrading in the subsurface. Under large buildings as well as small buildings on slopes, the source may be present in different concentrations under different parts of the building. Where groundwater is the source of soil gas, soil gas concentrations tend to decline as the contamination rises toward the surface. But in areas where the original release occurred, concentrations tend to be greater near the surface.

The integrity of the structure—that is, how easily vapors flow through the floor or slab—determines how much toxic vapor ends up inside, and how much stays inside depends upon the ventilation rate of the interior as well as the crawlspace. In fact, it's common for different rooms (**airspaces**) in the same building to have different levels of indoor air contamination. Heating, ventilation, and air conditioning systems influence indoor concentrations both by reducing or increasing indoor air pressure as well as by establishing the air exchange rate for the structure.

However, the level of intrusion is not constant, even if source and building conditions do not change. Multi-year continuous measurements at fully instrumented, unoccupied residences in Indiana and Utah have demonstrated conclusively that the indoor air concentrations of intruding vapors vary significantly over time—daily, seasonally, and by the weather. This is particularly important where **short-term** peak exposures are a health concern, as opposed to **chronic** (long-term) exposures, where average levels provide a reliable indication of risk. In those parts of the U.S. that experience cold winters, vapor intrusion is generally most potent in those months.

For more information on **temporal variability,** the variation in toxic substance concentrations over time, go to http://www.cpeo.pubs/SGVI/Time.pdf .

Health Risk

The regulatory goal of vapor intrusion response is to reduce exposures due to vapor intrusion below thresholds that regulatory agency scientists associate with acceptable risk. Many members of impacted communities, particularly homeowners, however, consider vapor intrusion a **trespass**. That is, without their knowledge or permission, a polluter has caused toxic vapors to enter their homes. They argue that no level is acceptable. Fortunately, standard mitigation techniques usually drive indoor air concentrations of vapor contaminants down to the levels found in **ambient**—that is, nearby outdoor—air. Because outdoor air readily mixes with indoor air, it is generally not practical to reduce levels below those found outside.

Indoor air concentrations of compounds such as TCE and PCE from vapor intrusion are usually very low, but most toxicologists believe that chronic exposure, even at low concentrations, increases the chance of contracting cancer or other serious diseases. It's unusual but possible for vapor intrusion to cause exposures at levels high enough to cause **acute**—that is, more immediate—health concerns. Actual risk from a substance, of course, is a function of all exposures, including contaminated drinking water and vapors from showers.

In a 2011 peer-reviewed Toxicity Assessment, U.S. EPA found that pregnant women continuously exposed to TCE at a low level, through inhalation, face an unacceptable increased risk of having babies with heart defects. Clearly the exposure has to occur during the nine months or so of the typical pregnancy—as opposed to the decades usually associated with chronic risk—and EPA and state toxicologists suggest that the critical exposure period is anywhere from one day to three weeks during the first trimester (three months) of pregnancy. Because most women do not know that they are pregnant at the critical time, risk management is designed to protect all women capable of bearing children.

Regulatory acknowledgement of this short-term risk—under vigorous challenge by the producers, users, and releasers of TCE—has changed the way TCE exposure is viewed. Because vapor intrusion levels vary over time, repeated sampling is necessary to ensure that women are not exposed to peak concentrations that would have been missed during an annual or semi-annual sampling event. Second, it's important to notify immediately women of child-bearing age of this risk so they can take personal **risk management** decisions—that is, decide to spend less or no time in buildings likely to contain TCE vapors—even if regulators do not believe evacuation is necessary. Also, with such knowledge, after their babies are born, mothers (and their spouses) can ask their pediatricians to more carefully evaluate the infants for cardiac malformations. And third, regulators and others responsible for the response should act immediately to mitigate vapor intrusion once it is identified above regulatory thresholds. Some regulators will argue that all buildings should meet the concentration limit established to protect pregnant women, to avoid gender discrimination, while others may impose weaker standards if it's known that no women of child-bearing age are regularly in a building.

Some pregnant employees in this office building spent more time working at home until TCE levels were reduced below detection limits.

Beginning the Investigation

While occasionally a vapor intrusion site is discovered through direct measurements of indoor air, most are identified from areas of known groundwater contamination. In some cases groundwater contamination is mapped after a hazardous substance release is reported from a factory, dry cleaner, or other source; in others elevated levels of contamination are first found in drinking water supplies—particularly shallow private wells.

In areas where groundwater is not used as a drinking water supply, such as New York City, there may be unknown or unreported plumes of groundwater contaminated with volatiles such as TCE and PCE. In such cases, it is important to evaluate the potential for vapor intrusion in the environmental site assessments that are normally conducted for a change of land ownership or use. Properties containing or near present or former dry cleaners, metals manufacturers, or automobile service centers should be carefully examined for possible volatile contamination.

Bronx, New York school built inside former factory with TCE in the subsurface

Since known shallow groundwater contamination is often the trigger that starts a vapor intrusion investigation, some groundwater data is usually already available. However, sampling points may not be broad enough or dense enough to support a vapor intrusion investigation. While variations in groundwater concentrations may have little bearing on strategies to protect public drinking water supplies (because they are designed to protect large areas), small variations in groundwater concentrations may influence decisions on where to sample soil gas and indoor air to investigate vapor intrusion at individual buildings. So in many cases additional groundwater sampling is conducted to support the vapor investigation.

There are formulas for predicting soil gas levels from shallow groundwater concentrations, and indoor air concentrations from soil gas concentrations. Some state regulatory agencies adjust those formulas based upon climate, since cold weather tends to reduce volatilization. (On the other hand, lower outdoor temperatures also increase the pressure differentials and increase the flow of soil-gas into indoor air.) However, groundwater concentrations are only a rough indicator of soil gas levels due to soil types at the water table, fluctuating water table levels, rainfall, etc. For these reasons, groundwater data is generally used only to establish rough boundaries for vapor intrusion studies.

Regulatory agencies generally use the Maximum Contaminant Level (MCL), or drinking water standard, to delineate the boundary of vapor intrusion investigations—with an additional 100 feet added laterally to account for uncertainty and/or gas migration. At most locations this is currently 5 parts per billion (ppb) for TCE and PCE, but at some sites 1 ppb is used as the investigative boundary. Using the drinking water standard to map plumes is convenient because, in a majority of cases, the maps already exist.

However, EPA stresses that the 100-foot buffer may need to be adjusted up or down. In CPEO’s experience, it’s more likely that the buffer needs to be larger. Preferential pathways such as utilities and the loose soil around them, sewer lines, and steam tunnels can allow vapors to move greater distances, and the frequently sparse geometry of monitoring wells means that the plume contour lines, as drawn, do not always fully capture the breadth of contamination.

The likelihood of significant vapor intrusion decreases with increased depth to groundwater, but vapor intrusion problems have been reported at locations where the top of the contaminated aquifer is more than 100 feet below the surface. More important, concentrations in the shallowest (uppermost) aquifer are all that matters in the near term. Contamination from deeper aquifers cannot release gases to the surface without impacting shallower groundwater. Of course, low levels in shallow aquifers needs to be confirmed periodically, especially if deep concentrations are particularly high.

Scientists who study the causes of vapor intrusion suggest that fluctuations in the water table are a key factor determining soil gas concentrations. That is, as the top of the groundwater moves up and down, vapors are released into the vadose zone. However, thus far no one has proposed a method to predict changes in vapor intrusion based upon measurements of the changing depth to water.

Historically, those conducting vapor intrusion investigations have measured exterior soil gas—volatile-substance vapors outside a building’s footprint, to predict whether vapor intrusion is likely to exceed regulatory thresholds. However, research has found that exterior soil gas concentrations “may be substantially different from the concentration underneath the building (*e.g.,* the sub-slab concentration), depending on site-specific conditions and the location and depth of the exterior soil gas sample.”

Notifying the Public

While in some cases property owners and developers may conduct a vapor intrusion response independent of environmental regulatory agencies, in most cases investigations, mitigation, and subsurface remediation are conducted or overseen by environmental agencies. While it’s important to inform the public at large through the news media, organizational newsletters, and on-line social networks, most agencies recognize that the best way to build trust among people whose homes, businesses, schools, and other buildings are subject to investigation is to approach them privately, knocking on doors and explaining vapor intrusion at the kitchen table or other informal settings. It’s impossible to reach everyone in this way, but most people would prefer not to learn that their homes are sitting on a puddle of cancer-causing substances from the eleven o’clock news.

Once sampling results are reported to the agencies or consultants, most agencies have a policy of anonymity, to protect the privacy of the people whose homes are at risk. They directly pass along the data to residents, but when they present results at public meetings, they identify them by labels such as "house #1," etc. not specific street addresses. But some residents—such as the people living in the South Hill neighborhood in Ithaca, New York—want to share their data, and the regulators should make that possible, too.

Assessing the Potential for Vapor Intrusion with Multiple Lines of Evidence

Vapor intrusion can involve liquid, solid (soil), and gaseous materials, so vapor intrusion investigations typically require sampling in multiple media, particularly the groundwater, soil gas, indoor air, and outdoor air. Because the physical phenomenon of vapor intrusion is very complex and remains incompletely understood, single lines of evidence (*e.g.,* similar samples from a single medium) are often insufficient to identify the source of indoor contamination or the potential for future vapor intrusion. That is, **multiple lines of** (independent) **evidence** often must be evaluated to develop a defensible conclusion on whether vapor intrusion is occurring or likely to occur. As consultants and researchers learn from more sites, new lines of evidence are increasingly being utilized.

For example, measuring the indoor air concentrations of toxic substances is the best measure of building-occupant exposure, but conventional sampling techniques cannot by themselves determine if the vapors are emanating from indoor **background** sources. Such sources can be as varied as cans of TCE-containing gun cleaner or pepper spray, garments recently dry-cleaned with PCE, or Christmas ornaments that off-gas dichloroethane. At school sites and commercial buildings, TCE may still be in use to clean centralized boilers.

At most vapor intrusion investigations, building occupants are asked to remove potential indoor sources before sampling begins, because they may show up as **false positives,** data that seem to indicate vapor intrusion when it is not really occurring. But often background sources are missed. Sometimes one can determine that contamination is coming from below by comparing sub-slab soil gas readings and indoor air levels, but increasingly consultants are employing emerging sampling strategies to determine how much of the indoor air contamination is coming from inside and how much is rising from the subsurface. If indoor sources are found, those conducting vapor intrusion investigations should notify building occupants of the presence of such chemicals in the expectation that they will take steps to remove them.

Go to http://www.cpeo.org/pubs/SGVI/EmergingStrategies.pdf to learn more about **Emerging Sampling Strategies**.

Similarly, at a small number of potential vapor intrusion sites outdoor concentrations of volatile compounds are elevated above regulatory standards. At some locations, ambient air contamination derives from the same groundwater plume, with vapors rising from springs or being released from air treatment systems, while at other sites nearby factories and dry cleaners may be responsible for the releases. Petroleum hydrocarbons are frequently found in outdoor air anywhere gasoline is stored or cars are driven. At buildings near busy roadways, therefore, it is difficult to attribute the presence of chemicals found in gasoline and exhaust to subsurface sources.

Still, it’s important to rely upon ambient air sampling conducted near the buildings being investigated at the same time as indoor air sampling. Generic—that is, for a region or the country as a whole—historical background data are usually out of date and generally unreliable.

Soil gas concentrations, particularly when measured directly underneath buildings, represent the potential for vapor intrusion. Holes or cracks in the slab or floor are necessary for vapors to make it indoors, but sometimes seemingly solid concrete slabs are permeable to toxic vapors. Thus, risk management strategies must consider the likelihood of future intrusion at sites with low indoor contaminant levels but significant soil gas concentrations. Furthermore, soil gas easily rises through dirt basements while wet basements within shallow groundwater plumes directly release vapors into overlying buildings.

There are basically two strategies for collecting multiple lines of evidence when investigating vapor intrusion: Some regulatory agencies start an assessment of potential vapor intrusion by measuring exterior or possibly sub-slab soil gas, using those results to decide whether to sample indoor air. This approach sometimes avoids intense interaction with residents.

Others believe that soil gas and indoor air sampling should be conducted simultaneously. They consider exterior-soil-gas sampling too uncertain, since there is evidence that it often underestimates soil gas levels under buildings. In buildings above known plumes, they require simultaneous indoor *and* sub-slab or crawlspace samples.

Many community members—residents, school parents, etc.—prefer the latter approach. That is, they don’t trust an “all clear” finding based only upon a mathematical calculation estimating indoor air concentrations. Furthermore, scientists increasingly prefer to include indoor air sampling in initial investigations. Emerging sampling strategies, they say, can be used to distinguish indoor sources from subsurface intrusion.

Of course, where there is no building, or existing buildings are slated for removal, soil gas sampling may be the best way to predict the potential for vapor intrusion in new structures planned for a site.

Any time sampling is required in residential settings, one of the biggest challenges facing vapor intrusion investigations in residential neighborhoods is enlisting the cooperation of homeowners and, in some cases, renters to gain access for sampling. Investigators usually must collect samples in homes or yards. They may need to drill holes in floors, and they may restrict the opening of doors and windows. If samples are taken from indoor air, they will require the removal of VOC-containing commercial products from cupboards and perhaps attached garages.

While some residents welcome the opportunity to be tested, others are mistrustful of government agencies and/or corporate polluters. In some cases the mistrust results from denials of the existence of, or responsibility for, contamination or the slow pace of response, but in others people are mistrustful because of experiences which may have occurred decades before or in far away locations. Regulatory agencies often must devote extensive time and resources to winning public confidence, but there are models of public involvement—such as the establishment of community advisory groups or partnering with existing community organizations—that usually help increase cooperation.

Plugged sampling hole in Ithaca, New York basement

In general, environmental regulators are reluctant to force owner-occupants of residential property to cooperate with a vapor intrusion response, be it sampling or mitigation. If that's the case, it's incumbent upon them to establish a mechanism to track changes in ownership or new rentals. New residents may wish to cooperate, but in many states laws requiring sellers or landlords to notify new owners or tenants about environmental conditions are weak or ignored. Regulators can work with other government agencies and private data base companies to identify property transactions and changes of tenancy.

There have also been situations where the owners of both commercial and residential rental property have failed to inform their tenants about vapor intrusion risks, and in other cases landlords have initially refused permission for sampling, even though tenants wanted it. In response, New York State passed a tenant notification law and in Mountain View, California, an apartment owner became more cooperative after negative press coverage and the threat of EPA legal action. Regulators have the authority to insist on access, but they rarely use it. It is often up to the activist public or local governments to ensure that all people at risk get equal protection.

Soil Gas Screening.

Soil gas measurements have generally been regarded as the best external predictors of vapor intrusion, particularly if the measurements are made immediately under the building of concern (*i.e.,* sub-slab samples). If the measured values exceed the regulatory soil gas screening level, derived from the health-based indoor air goal and a default attenuation factor, then a plan is developed to sample indoor air. Agencies with strong programs set the default attenuation factor with the goal of addressing all vapor intrusion problems, so the number is conservative (larger than the factor representing the mean or median case).

Here are U.S. EPA's generic attenuation factors for the three most commonly measured media. Some state guidances use much lower factors—that is, they predict much lower concentrations of intruding contaminants. The .03 value means, for example, that a soil gas level of 1000 $\mu g/m^3$ for a chemical of concern could generate an indoor air concentration of 30 $\mu g/m^3$ for the same contaminant. The factor of 1.0 for crawlspace air says that contaminants in a crawl space may be found in the overlying room at the same concentration.

Indoor air to Sub-slab soil gas, generic value	0.03
Indoor air to "Near-source" exterior soil gas, generic value except for sources in the vadose zone (less than five feet below foundation) or presence of routes for preferential vapor migration in vadose zone soils	0.03
Indoor air to Crawlspace air, generic value	1.0

Some regulators, such as those in New York State, require vapor intrusion mitigation based upon high levels in soil gas even if indoor air concentrations are low or unknown. This is because ground movement or occupant activity could open up future pathways from the subsurface to the indoors.

Exterior soil gas measurements are collected above the water table but in most cases more than five feet from the ground surface, while sub-slab samples are taken just below the foundation slab. There are three principal scenarios:

1) Exterior samples near structures are rough indicators of the potential for vapor intrusion, but they often do not provide accurate predictions of indoor air levels. Even near-slab soil gas measurements are often much lower than results from samples taken directly beneath the slab.

2) Sub-slab or crawlspace samples, from directly beneath structures, better represent the conditions influencing the buildings above. However, sub-slab results have been found to vary significantly under the same structure, even beneath small individual residences. At large buildings (apartments, townhomes, schools, offices, etc.) soil gas variations are more likely. Where a building sits almost directly on fractured bedrock, variability in sub-slab soil gas can be even more pronounced. In most cases, sub-slab sampling—where it requires the drilling of holes through floors (to be plugged airtight once the sample is taken)—requires coordination with building occupants. While residents are often uncomfortable about holes being drilled in their living-space floors (as opposed to basements), the physical intrusion can be minimized by placing the holes in closets or under carpets.

3) On vacant property planned for development, soil gas and groundwater measurements are the best ways to roughly predict future indoor air levels, but construction—when it occurs—should be expected to alter the flow of soil gas and actual or air concentrations that result.

Indoor Air Sampling

Indoor air sampling is the most direct way to measure what is in the indoor air (*i.e.,* the concentration to which building occupants are exposed). Typically, indoor air sampling is conducted in consort with soil gas and outdoor air testing. Most regulatory agencies specify that sampling devices be placed at "breathing height," but some also place instruments near potential vapor entry points. Buildings should be tested with windows and doors closed—or the samples will simply reflect concentrations in outdoor air. School buildings are usually sampled during week-ends or holiday breaks. In most parts of the country, winter is the time of year during which vapor intrusion is most likely to be detected, because windows are closed and heaters lower indoor air pressure.

Go to http://www.cpeo.org/pubs/SGVI/Samplers.pdf for basic information about common sampling devices.

EPA recommends the increasingly common practice of sampling non-residential buildings when the heating, ventilation, and air-conditioning (HVAC) systems are not operating. This can be done in addition to indoor air sampling in the same season with the HVAC system on.

> Reasonably expected future risks posed by subsurface contamination warrant consideration, in addition to risks posed under current conditions…. For example, current building use and HVAC systems might not be sustained perpetually. Therefore, when the subsurface vapor source(s) underneath or near a building with an over-pressurizing HVAC system has (have) significant potential to pose a vapor intrusion threat, it may be useful to assess susceptibility to soil gas entry and diagnose vapor … in such buildings under conditions when the HVAC system is not operating. (In addition, indoor air testing could be conducted during periods when the HVAC system operates with diminished flows, such as weekends or evenings.)

Even if elevated levels of the target contaminants are found, sources other than vapor intrusion need to be considered. Building occupants and owners are routinely asked to identify and remove chemical sources that might contribute to false positives, but vapor intrusion folklore is rife with stories of TCE-laden gun cleaner buried in the depths of household closets or teachers wearing PCE-cleaned suits to schools. One solution is to insist on more thorough inventories of indoor chemical containers, but that usually won't help find solvent-emitting clothes or Christmas ornaments that off-gas dichloroethane.

If a compound is measured in indoor air but not in soil gas, or even in soil gas at comparable concentrations to indoor air levels, that suggests that the subsurface is not the primary source of indoor contamination. If there are multiple compounds found both in soil gas and indoor air, their ratios (attenuation factors) should be roughly the same. If a compound attenuates less than its co-contaminants, that suggests that there is a supplementary indoor source.

Naturally occurring radon attenuates between the subsurface and indoors at roughly the same ratio as VOCs, so inexpensive radon detectors may be used to indicate whether soil gas intrusion is occurring. If the ratio of a VOC indoors to its subsurface level is much higher than the ratio of indoor radon to soil gas radon, that again suggests an indoor VOC source. Because subsurface radon concentration patterns do not necessarily match those of VOCs in soil gas, there may be quantitative differences in the apparent attenuation factors. (Radon is typically spread more evenly in soil than VOCs are, so variations in subsurface VOC measurements may lead to differences in measured attenuation.)

In some cases, investigators are using more sophisticated, emerging sampling strategies to distinguish buildings with indoor sources from those with genuine vapor intrusion. These include Building Pressure Control, Real/Near-Real-Time Sampling, Isotope Analysis, and Mass Flux monitoring. In general these methods are permitted, but not specifically mentioned in regulatory guidance.

School in Queens, New York, where elevated PCE levels were coming from outdoor air

Outdoor Air

Since most of the air inside a building is from outdoor air, an "ambient" outdoor air sample is routinely taken near the buildings where indoor air samples are collected. This is for two reasons: First, elevated outdoor concentrations may account for elevated indoor concentrations in the same range. Second, the standard methods for reducing indoor air contamination will not work if contamination from outdoor air can simply enter the building through windows, doors, or HVAC systems.

Though they do not naturally occur, chlorinated solvents such as TCE and PCE are found at low levels in outdoor air in metropolitan areas throughout the U.S. This must be caused by continuing releases, because TCE has a half-life of three to seven days in outdoor air. That is, every three to seven days, TCE mixed into the atmosphere degrades to half the concentration. (A rule of thumb is that it takes ten half-lives to degrade to a non-detectible amount. Thus TCE would not be present in 30 to 70 days if there were no ongoing release.) TCE is in some consumer products, and a small number of industrial operations still use the chemical, but contaminated groundwater appears to be the primary source, through pathways such as treatment systems, vapor intrusion, and fugitive releases (through soil to the surface). PCE is still widely used in dry-cleaning, so ongoing operations are a major source of PCE in outdoor air, particularly in urban areas such as New York City, where dry cleaners are mixed with other land uses. California is gradually eliminating PCE from dry-cleaning uses, and New York is restricting its use in cleaning establishments collocated with residences.

These ambient sources represent a health risk similar to vapor intrusion. More people are exposed, but at lower concentrations. In fact, where TCE and PCE are consistently found at comparable levels in outdoor air, there may be a greater overall risk, because vast numbers of people may be exposed continuously throughout the air shed. Still, the officials responsible for groundwater cleanup and vapor intrusion response do not have the authority to address TCE, PCE, and other chemicals released from current business operations. At best, they will report their findings to the agencies (or branches of the same agencies) responsible for monitoring and cleaning air toxics.

However, environmental regulators do have the authority to address releases from groundwater treatment systems, such as air strippers, and surface waters contaminated by the same groundwater sources suspected of originating vapor intrusion. There is a relatively easy fix for air strippers, but groundwater entering surface water systems is more difficult to control. Near Asheville, North Carolina, homes on a property downhill from the CTS Superfund site were evacuated because of high levels of TCE vapors emanating from a private spring, the source of which was contaminated groundwater on the CTS site.

Action Levels

Reviewing groundwater, soil gas, indoor air, outdoor air and other data, environmental regulators and the entities that they regulate determine whether they believe vapor intrusion is occurring, and *whether the contamination level in the soil gas and/or indoor air is high enough to require a response.* If it is, they will order or implement vapor intrusion mitigation. That is, if the indoor concentration of a chemical of concerns if found to exceed the action level, a mitigation system will be installed and operated. If contamination is found, but at a level not far below the action level, either regulators or responsible parties may conduct more sampling. However, they may also decide, based for example on groundwater trends or sampling at neighboring buildings, to go straight to mitigation.

Spring at CTS Asheville contaminated by TCE from groundwater plume

Determining whether contamination levels in the soil gas and/or indoor air are high enough to require a response is no simple question. Many regulatory agencies set **cancer action levels** for chemicals believed to cause cancer, such as TCE and PCE, equal to the concentration believed to cause an excess lifetime cancer risk of one in a million, or ten-to-the minus-six (10^{-6}). This means that if a million people are exposed to the specified concentration round-the-clock for thirty years (or longer with some agencies), then one additional person is expected to contract cancer as a result of that exposure. Round-the-clock exposure is known as the **residential scenario**, because it's possible that people will be in their homes 24-7.

Based on U.S. EPA's September, 2011 Toxicological Review of TCE, the one-in-a-million residential indoor air action level is .48 micrograms per cubic meter ($\mu g/m^3$), equivalent to .09 parts per billion by volume (ppbv). In jurisdictions that use a cancer risk goal of one in 100,000, the action level is 4.8 $\mu g/m^3$. Where the goal is one in 10,000, the action level is 48.0 $\mu g/m^3$, a level unlikely to be found at any but the worst vapor intrusion sites. (Depending on the jurisdiction, there may be slightly different numbers.)

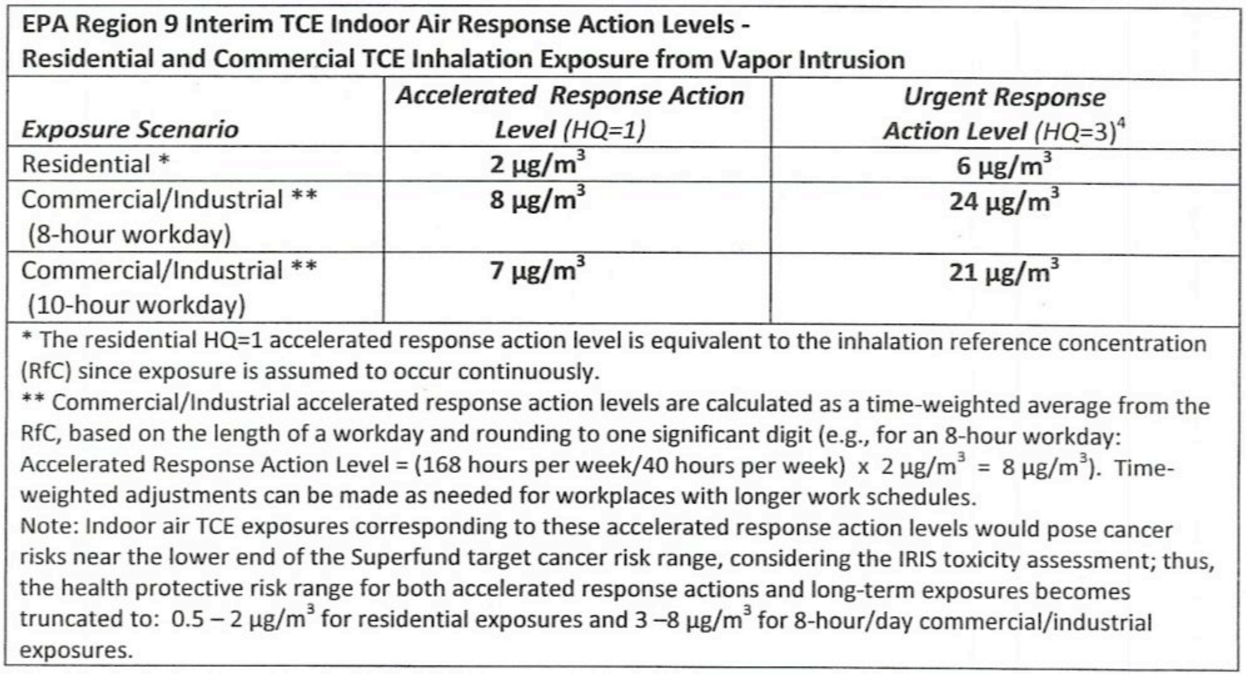
U.S. EPA applies a flexible risk range, with a preference for one in a million. The *Technical Guide* explains, in carefully worded language:

> EPA generally uses a cancer risk range of 10^{-6} to 10^{-4} as a "target range" within which to manage human health risk as part of site cleanup.… Once a decision has been made to undertake a response action, *EPA has expressed a preference for cleanups that are at the more protective end of the cancer risk range.* Thus, EPA recommends using an individual lifetime cancer risk of 10^{-6} as a point of departure for establishing cleanup levels based upon potential cancer effects. [Emphasis added]

Based upon EPA's February 2012 findings for PCE, the one-in-a-million cancer risk action level is 11.0 $\mu g/m^3$. The levels associated with less protective cancer-risk goals, 110 $\mu g/m^3$ and 1,100 $\mu g/m^3$, are very rarely reached. In California, where the state does its own independent assessments, the one-in-a-million level remains .41 $\mu g/m^3$. A few other states may also retain their more protective standards.

Go to http://www.cpeo.org/pubs/SGVI/Regulatory.pdf for a brief discussion of how different **regulatory programs** end up with different action levels and screening levels.

Agencies also set non-cancer exposure standards for both cancer-causing substances and chemicals that they do not believe cause cancer. Typically, it's the lowest concentration believed to cause any disease, condition, birth defect, etc. While cancer risk goals vary from jurisdiction to jurisdiction, non-cancer limits, called **reference concentrations** for vapors, are more uniform. Since the cancer action level (obviously calculated only for carcinogens) and reference concentration are rarely the same, each agency uses the lower (more protective) standard of the two as the action threshold.



EPA Region 9 Interim TCE Indoor Air Response Action Levels - Residential and Commercial TCE Inhalation Exposure from Vapor Intrusion

Exposure Scenario	*Accelerated Response Action Level (HQ=1)*	*Urgent Response Action Level (HQ=3)*[4]
Residential *	**2 $\mu g/m^3$**	**6 $\mu g/m^3$**
Commercial/Industrial ** (8-hour workday)	**8 $\mu g/m^3$**	**24 $\mu g/m^3$**
Commercial/Industrial ** (10-hour workday)	**7 $\mu g/m^3$**	**21 $\mu g/m^3$**

* The residential HQ=1 accelerated response action level is equivalent to the inhalation reference concentration (RfC) since exposure is assumed to occur continuously.

** Commercial/Industrial accelerated response action levels are calculated as a time-weighted average from the RfC, based on the length of a workday and rounding to one significant digit (e.g., for an 8-hour workday: Accelerated Response Action Level = (168 hours per week/40 hours per week) x 2 $\mu g/m^3$ = 8 $\mu g/m^3$). Time-weighted adjustments can be made as needed for workplaces with longer work schedules.

Note: Indoor air TCE exposures corresponding to these accelerated response action levels would pose cancer risks near the lower end of the Superfund target cancer risk range, considering the IRIS toxicity assessment; thus, the health protective risk range for both accelerated response actions and long-term exposures becomes truncated to: 0.5 – 2 $\mu g/m^3$ for residential exposures and 3 –8 $\mu g/m^3$ for 8-hour/day commercial/industrial exposures.

For TCE, the prevailing non-cancer risk standard is 2 $\mu g/m^3$ in a residential scenario. So for jurisdictions where 10^{-6} is the target cancer risk, .48 $\mu g/m^3$ (or a slight variation) is the current action level. In jurisdictions where the cancer risk target is less protective, the action level becomes the non-cancer 2 $\mu g/m^3$ because the cancer action level would be 4.8 $\mu g/m^3$ or higher.[1]

EPA's September 2011 conclusion that pregnant women who breathe TCE face an increased risk of bearing children with cardiac birth defects threw a new wrinkle into the establishment of exposure limits. First, since non-cancer risk goals do **not** vary from state to state, the non-cancer residential action level is now 2 $\mu g/m^3$ across the country. Because toxicologists believe that birth defects are caused during the first trimester of pregnancy, when most women do not even know that they are pregnant, the concern is for all women of child-bearing age. Because there are few settings where women of child-bearing age can legally be excluded from buildings, this standard is close to universal. Furthermore, in the case of pregnant women's exposure to TCE, EPA regions and some other agencies have defined an **urgent action level**, equal to about three times the non-cancer action level. Because of the short-term risk, exceedances trigger immediate action.

Moreover, because the period of exposure likely to trigger a birth defect is anywhere from one day to three weeks, sampling strategies must be designed to detect short-term peaks in indoor TCE concentrations. Implementation of this new standard is driving the development of new sampling strategies and tools that are continuous or near-continuous. However, unless health studies show a similar link between PCE and birth defects at comparable concentrations, PCE sampling will remain targeted at chronic, or long-term exposures.

Action levels for both cancer and non-cancer risk are typically defined for residential scenarios, but most agencies use multipliers for the **occupational scenario**. For people who are expected to work eight hours a day, five days a week in a building threatened by vapor intrusion, the exposure standard is usually about four times as much as (less protective than) the residential standard. Thus, based on the shorter periods of exposure, EPA regions set a non-cancer occupational vapor standard of 8 $\mu g/m^3$ for TCE.

Some industrial interests have suggested that the much less protective (by orders of magnitude) Permissible Action Levels (PELs) of the U.S. Occupational Safety and Health Administration (OSHA) should apply, even to office workers or teachers in buildings with vapor intrusion. So far, regulatory agencies, including OSHA, have rejected that argument. OSHA standards were developed on the assumption that workers are prepared to handle toxic chemicals, and OSHA now considers its PELs outdated and unprotective for that purpose.

Though a great deal of scientific research has gone into the development of these action levels, they are arguable and uncertain. The various studies give conflicting answers. There are disagreements over how to protect more vulnerable populations, such as children or people with diseases, such as diabetes, or who take some medications that interact with the contaminants, making them more susceptible to typical vapor intrusion releases. There are also disagreements

---

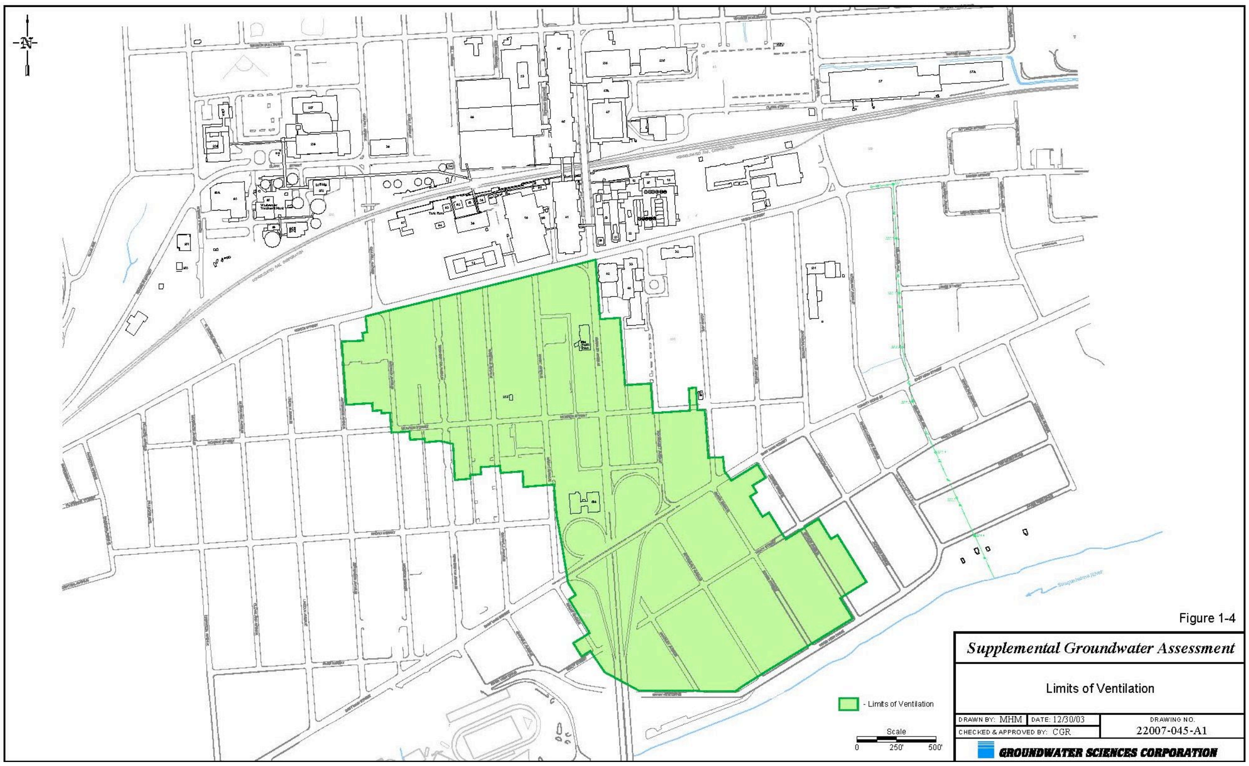
[1] EPA does not change action levels every time the toxicologists come up with new numbers. At the Moffett-MEW site in Mountain View, California, it stuck with old action level of 1 $\mu g/m^3$ even after EPA's national 2011 toxicity assessment because it was still within EPA's cancer risk range.

over how to handle cumulative exposures, including exposure to multiple chemicals through multiple pathways.

The Decision to Mitigate

New York State, one of the most active jurisdictions in addressing vapor intrusion, uses matrices (tables), where the requirement for action is based upon two numbers, the sub-slab soil gas level and the indoor air level. The matrix approach has two advantages: 1) If soil gas levels represent a threat of vapor intrusion that has not yet materialized in indoor air, action may be required, if the concentrations are high enough; and 2) If soil gas levels are low enough to suggest other sources of indoor air contamination, action may be put off. However, New York's default indoor air action level for PCE is 30 $\mu g/m^3$, high enough to make PCE mitigation a rarity unless regulators make a site-specific adjustment.

Complicating the situation, soil gas and indoor air measurements vary significantly over time and space. In some situation, this triggers more intense or repeated sampling. In other cases, however, those conducting the investigation may decide that it is cheaper and more protective to start mitigation right away, rather than delay the decision and collect more data. This is known as **pre-emptive mitigation (PEM)** or **early action**. In its *Technical Guide,* EPA suggests that early action decisions consider operation and maintenance requirements, as well as monitoring obligations and costs.



Depiction of "blanket" mitigation zone in Endicott, New York

In some locations, they will draw a line around the apparently impacted area and require or implement mitigation for all the buildings within the area, rather than rely on sampling for each structure. Known as the **blanket approach**, this is similar to what has often been done for contaminated private drinking water wells.

Community members at vapor intrusion sites tend to support early action or the blanket approach. They don't understand why one home might have a mitigation system, but its neighbors do not. Furthermore, if the action levels for their site are not as protective as those in other communities, with similar circumstances, they want comparable thresholds. In fact, many want a response wherever and whenever indoor air contamination, documented to be from the subsurface, exceeds the level in the outdoor air. They are mistrustful that the standards are based upon calculations that "risk away" the problem.

On the other hand, other community members may prefer not to have mitigation systems. Some property owners fear that the presence of mitigation systems will depress their property values. Others are simply uncomfortable letting government agencies and unfamiliar business entities into their homes.

Go to http://www.cpeo.org/pubs/SGVI/Property.pdf for a brief discussion of vapor intrusion and **property values**.

CPEO supports an approach, suggested by some EPA officials and others, that could satisfy community members who want faster, stronger responses to the threat of vapor intrusion and those who fear the stigma of even the most tentative vapor intrusion investigation. Polluters, regulators, residents, and local governments could set a goal for making city blocks or even neighborhoods **soil gas safe**. Every home within the soil-gas-safe boundary would be equipped with a soil gas mitigation system, just as every home in many communities is now required to have a smoke detector. There is no stigma associated with a smoke detector because everyone has one. The risks of soil gas exposure go well beyond sites where contaminants such as TCE and PCE are found in groundwater plumes, so the situations are somewhat analogous. However, since installing smoke detectors is less expensive and the responsibility of property owners or builders, arrangements would have to be made to fund mitigation for those homes where there is no polluter with a financial responsibility.

Mitigation Systems

Compared to remediating groundwater at the source, it is relatively easy and inexpensive to prevent vapor intrusion. Sub-slab and sub-membrane depressurization systems, developed through decades of response to radon intrusion, can prevent the flow of contaminants from the subsurface into buildings.

Sub-slab depressurization systems (SSD)

In existing structures, SSD systems are installed by cutting one or more holes in the slab, removing a small quantity of soil from beneath the slab to create an open hole or "suction pit" (with a 6- to 18-inch radius), and placing into the holes vertical suction pipes, which are in turn vented outdoors. One or two suction pits are adequate to depressurize typical residential homes.

In new buildings perforated pipes are usually placed horizontally before laying the foundation directly above. Larger buildings may require multiple pipes, connected by manifolds. The pipe or manifold is connected to an exhaust pipe that rises through the building or alongside an exterior wall, where it ventilates above the roofline. **Active** depressurization systems have blower fans that suck vapors from beneath the building. While fan size and system design are usually based on the tried-and-true radon mitigation experience, some consultants are now sizing them based upon site-specific analysis while others are installing systems that turn on and off automatically, as needed.

Mitigation vent pipe and fan on commercial building in Endicott, New York

In some cases, **passive** systems are installed, relying upon atmospheric conditions to create a pressure differential that draws gases from the subsurface out through a stack pipe. Passive systems are generally not as reliable as active systems, but if installed during the construction of new buildings they may be activated later, with the additions of fans, if testing shows that indoor air contamination is a problem. It is much easier—cheaper, less disruptive, aesthetically acceptable—to insert pipe into the subsurface before, rather than after, construction.

Indeed, the low cost of passive venting in new construction suggests that it should perhaps be required anywhere in the vicinity of known subsurface contamination with chlorinated VOCs such as TCE or PCE. In many cases, the costs of mitigation are lower than the cost of sampling required to show that mitigation is unnecessary, but the comparison depends upon how much monitoring is needed after the building is constructed to determine if the passive system should be made active or to ensure that the active system is functioning properly. EPA notes, "Passive systems are generally less predictable and less efficient at preventing vapor intrusion than active systems and, therefore, typically warrant more intensive monitoring, all else being equal."

In Mountain View, California, the city required a new residential complex near a major Superfund TCE plume to be constructed with passive mitigation. When new TCE contamination was found adjacent to the project—due to past leaks in the sewer line running under the street—the mitigation turned out to be a good investment.

While depressurization systems may remove toxic fumes from the soil gas, that's not exactly what makes them protective for building occupants. *They are protective because they lower the pressure beneath the building so that pressure inside the building is higher than below the building.* Thus, even if there are holes, cracks, gaps (between walls and the foundation), or other pathways between the building and the subsurface, vapors flow downward, not upward. Thus, a well-designed depressurization system prevents toxic vapors from intruding above.

These Mountain View, California homes were built to be soil gas safe, and they remained so even when TCE groundwater hotspots were discovered along their street.

Go to http://www.cpeo.org/pubs/SGVI/Construction.pdf to learn more about the advantages of incorporating mitigation into **New Construction**.

The installation of vapor mitigation systems must follow building codes. Exhaust pipes should extend beyond the roof and away from windows, and they must also not impact adjacent buildings. In colder climates drip-legs are often installed in vent pipes to keep condensation from freezing and blocking the exhaust.

In locations that use furnaces or other types of combustion heating, **backdrafting** should be considered prior to installation of the SSD system. While rare, backdrafting is of concern if negative pressures (created by the SSD) within the building are stronger than the pressures that would drive the combustion gases up a chimney or stack. In such rare cases, potentially deadly combustion gases (*e.g.,* carbon monoxide) could be concentrated within the building. An HVAC or vapor mitigation contractor should be able to diagnose the potential for this problem.

Sub-membrane depressurization systems

These systems are similar to sub-slab systems, but they are applied to buildings with crawlspaces. Plastic or rubber membranes that are impermeable to gases are placed directly on the soil, and one or more perforated pipes are placed beneath to create a downward air flow. Alternatively, membranes are placed under the floor and fans are used to depressurize the crawlspace. This is less reliable because the lower pressure from the crawlspace can pull vapors up from the soil below.

Sub-slab or sub-membrane depressurization has additional benefits. In fact, these technologies were originally developed to reduce the risk from exposure to naturally occurring radon gas. Radon, which occurs at some level in soil gas throughout the U.S., enters overlying buildings via mechanisms almost identical to those of chemical vapor intrusion. Studies of human health and residential indoor air radon levels from across the U.S. and Europe have shown significantly elevated rates of lung cancer for residents in homes with higher radon levels. Furthermore, depressurization systems also reduce the risks from moisture-induced problems such as mold.

Simple in theory, installing these systems properly takes some expertise. It may be necessary to conduct pilot studies beforehand to determine the zone of influence from each pipe or suction field. That zone depends upon soil conditions. The primary performance standard used to confirm effective depressurization system operation is the demonstration of a negative pressure field extending under the entire building, using pressure testing at "worst case" test holes after system startup. In addition, smoke tests or equivalent methods are used to test connections, holes, and membranes for leaks.

Many officials consider pressure monitoring an adequate indicator of satisfactory system operation. Others, however, including many from the impacted public, also insist upon at least initial post-mitigation or periodic indoor air sampling to confirm that contaminant concentrations in indoor air are reduced to acceptable levels. Even those officials eschewing periodic indoor air testing may agree to at least one additional indoor-air sampling event during the worst-case months.

Beyond their performance, depressurization systems should be designed to be non-obtrusive. Noise and power consumption should be minimized, and residents should not be stuck with the operating costs. Installation disruption should be minimized, and disturbed flooring should be restored. These may seem like small concerns, but they may be key to maintaining cooperative relationships with building owners and occupants.

In commercial structures and schools, centralized **heating, ventilation, and air conditioning** systems may also discourage vapor intrusion. HVAC systems may remove toxic vapors due to high ventilation rates or prevent intrusion by creating a positive air pressure (compared to the subsurface) inside. Because operating HVAC systems for long enough periods to prevent intrusion may add significantly to energy bills, they are generally considered helpful but not generally accepted as stand-alone remedies.

Others technologies, such as **air filtration** or **sub-slab pressurization/venting**, may be introduced in unusual situations, but depressurization systems are the proven, reliable, inexpensive choice in the vast majority of situations. In dirt basements, which are particularly susceptible to intrusion, **intake and exhaust fans** may be used—without piping—to reduce toxic vapor levels, although the effectiveness of these needs to be demonstrated at each location.

Long-Term Management

Depressurization systems are an effective form of vapor intrusion mitigation, and other technologies may be applicable as well. *However, they only work as long as they work.* To ensure that building occupants are protected, mitigation should be anchored in long-term management, which includes operation and maintenance, monitoring and inspection, contingency planning, notification, institutional controls, and periodic review.

```
X790_D_DHW_T1_SUPPLY_TE...  UNACK  Lo    X790_BUILDING_D...  NaN     83.0
X790_FPB_3_52.ROOM_TEMP...  UNACK  Lo    X790_ROOM_357       NaN     50.0
X790_AHU_04.SF_ALARM        UNACK  DSC   X790_BUILDING_D...  ALARM   ALARM
X790_RTU_03_RETURN_AIR...   UNACK  DSC   X790_BUILDING_C...  NORMAL  ALARM
```

Building Management System for monitoring mitigation fan at a Bronx, New York school

Operation and Maintenance

While all elements of mitigation systems should function as long as intrusion remains a threat, the element requiring the most attention is usually the fan. Either a maintenance person or building occupant should check frequently to ensure that fans are operating properly, for example, by performing a visual check of the system's pressure gauge showing proper operational status, or there should be an alarm system that notifies responsible persons of breakdown. This can be an audio alarm, an autodial phone line, or ideally, a continuous Internet signal that stops when the fan fails. Broken fans should be fixed or replaced as soon as possible. Millions of radon removal systems are in place across the country, and U.S. EPA's Office of Air and Radiation has found that the average fan remains operable approximately ten years. Furthermore, it should be clear up front how much of the time active systems—depressurization, HVAC, basements fans—need to remain on. Some consultants even rely on real-time pressure measurements to turn fans on and off.

Contingency Planning.

At the time mitigation systems are installed, there should be clear plans with site-specific triggers for doing something more should they fail, whether that failure is due to equipment malfunction, changes in the extent and concentration of the contamination, building remodeling, natural disasters, or other catastrophes. For example, one might specify that additional depressurization pipes shall be installed if indoor air testing indicates unacceptable contaminant levels after system installation.

Notification.

Regular building occupants, present and future, should be made aware of the potential for vapor intrusion and the need for continuing mitigation. Owners should notify renters and workers. School buildings should contain entrance plaques or signs notifying people that structures are subject to a vapor intrusion site management plan. States have varying requirements for notifying potential homebuyers, but at a minimum they should be informed about the vapor intrusion problem *before* the paper-signing session that closes the home-purchase deal.

Failure to inform building buyers, renters, and other occupants invariably creates mistrust once people learn about vapor intrusion, or even the potential for it to occur. Mistrust breeds non-cooperation. In early 2015 in Winston-Salem, North Carolina, angry parents successfully demanded that a middle-school campus be closed, with students moved in the middle of the school year, because they had not been not aware of underlying PCE and TCE contamination. This happened despite officially acceptable contamination levels and the likelihood that the school district would quickly have installed pre-emptive mitigation.

Institutional Controls.

Most simply, there should be proprietary controls (deed restrictions) or zoning overlays to prevent a change in use or access without considering the potential for additional vapor intrusion exposures. But more important, the responsible party, property owner, or other entity must be given legally binding responsibility for all of the other aspects of long-term management. This party should demonstrate up front that it has the capacity to take responsibility for protecting building occupants for the life of the contamination.

Periodic Review

In CPEO’s view, the entire vapor intrusion response should be reviewed for protectiveness every five years or less. This requirement already applies to Superfund sites. For occupants of buildings requiring mitigation, the risk from a small site or a different regulatory program may be just as serious. In particular, mitigation voluntarily installed by developers with no regulatory oversight needs some type of regular evaluation.

If, in that review, mitigation is found not to be sufficiently effective, more should be done. On the other hand, if the contaminant source no longer poses a vapor intrusion threat, then mitigation may be suspended. (However, there is a benefit to continuing the operation of depressurization systems, because these systems provide significant health benefits by reducing radon concentrations in indoor air as well as by reducing indoor moisture and molds.) All aspects of the long-term management plan should be checked, and the affected public should be given the opportunity to comment.

Carbon adsorption system for groundwater treatment

Remediation

In the long run, the best way to prevent vapor intrusion is to remove the contaminant source. Unfortunately, contaminants such as PCE and TCE are denser than water. In liquid form, they tend to descend to the bottom of aquifers. They also may sorb to the soil matrix. It is difficult and time-consuming—normally taking decades—to achieve groundwater cleanup objectives using conventional cleanup technologies such as pump-and-treat and soil vapor extraction. Furthermore, while some states, such as arid California, require the cleanup of all *potential* drinking water supplies, others lack such a requirement. That's why the state of New York doesn't even track solvent plumes in most of New York City. The City gets its water from upstate. Yet those plumes may be releasing toxic fumes into a large number of buildings.

The first imperative, therefore, is to make sure contaminant plumes are identified and regulated anywhere they pose a threat of vapor intrusion. Once that is done, they should be folded into official cleanup programs. (See http://www.cpeo.org/pubs/SGVI/Regulatory.pdf.) Even if mitigation is successful in the short run, that should not exempt such sites from remedial action. Not only may mitigation efforts break down or even be forgotten, but there is also evidence that persistent shallow plumes release contaminants to the outdoor air, contributing to the omnipresent background levels of these chemicals in the atmosphere.

Thus, decreasing the time to reach current groundwater concentration remedial objectives—usually five parts per billion for TCE and PCE—should itself become a remedial objective. That is, decision-makers should select remedial alternatives that speed up the cleanup process, at least for the shallow aquifer, because vapor intrusion represents a continuing risk. In fact, at sites where pump-and-treat remedies were chosen years ago, newer, alternative remedial technologies should be considered. Though it may seem difficult to re-open operating cleanup projects, responsible parties and regulators may actually go along because in most cases the financial, energy, and carbon footprint costs of conventional extraction systems just continue and grow.

Few people were aware of the threat of vapor intrusion when many cleanup projects were initiated in the 1980s or 1990s. Now the vapor intrusion pathway is known to be widespread enough that it should cause us to re-think our entire groundwater protection strategy.

Ideally, the response to VOC vapor intrusion, radon intrusion, and the migration of other subsurface hazards will move from a reactive to a pro-active strategy. New buildings will be designed to prevent intrusion, and older structures will be modified to resist it. We can imagine a situation in which not just buildings, but entire neighborhoods or communities take steps tp address the intrusion of any hazard from the subsurface. Instead of facing the stigma of being located on or near a contamination site, owners and occupants will rest easy knowing that their buildings are **soil gas safe**.

Go to http://www.cpeo.org/pubs/SGVI/References.pdf for **Selected References**.