Vapor Intrusion (VI), defined as the migration of volatile contaminants from the subsurface into the indoor air of overlying buildings, is a major and challenging environmental issue for both regulators and the regulated community—one that continues to elicit heated debate among stakeholders. Eight factors associated with the VI pathway that contribute to its challenging nature are discussed below.

**WHAT IS THE MAGNITUDE OF THE PROBLEM?**

The number of contaminated sites in the United States is not known with certainty, but it’s undoubtedly large. The U.S. Environmental Protection Agency’s (EPA) 2002 VI guidance document references a total of 374,000 contaminated sites, the National Research Council reports that the number may be as high as 439,000, and an often cited total in brownfields redevelopment literature is 500,000 sites. The fraction of these contaminated sites with conditions favorable for VI also is not known with certainty, but will depend, in part, on the number of sites that contain volatile organic compounds (VOCs). Volatile contaminants have been reported at approximately one-half of all Superfund and similar cleanup sites. Preliminary estimates suggest that approximately one-half of volatile-contaminated sites have conditions that could be favorable for VI. This suggests, therefore, that VI may be an issue at one-quarter of the total number of contaminated sites in the United States.

VI analysis and control has not been approached in a systematic way at the universe of potential sites. Instead, assessments have likely been biased toward those sites with a higher potential for VI problems (e.g., sites with off-property groundwater plumes). If this is the case, the results to date may overestimate the extent of the problem. Nonetheless, these assessments indicate that a disturbing proportion of individual sites have a “complete” exposure pathway (i.e., VI is occurring). Frequently, the resulting exposures exceed risk-based targets and are therefore classified as being “unacceptable.”

Conversely, existing VI assessments may underestimate the magnitude of the problem. The assessments to date have focused on sites with groundwater ingestion threats. VI, however, can be a threat from other types of contamination, such as sites with nonpotable aquifers, perched (nonaquifer) waters, and/or soil contamination. Furthermore, these conditions may be most common in urban areas where there are more buildings and larger populations. In addition, existing estimates of VI potential may underestimate impacts to nearby and adjacent properties if the groundwater plumes continue to spread or actually extend beyond the assumed boundaries. In some cases, VI risks may exist a mile beyond the supposed plume boundary.

**INHALATION AND OTHER ROUTES OF EXPOSURE**

The three most commonly considered routes for environmental contaminants to enter the human body are ingestion, dermal contact, and inhalation. Risk assessment calculations typically are based on a reasonably worst-case set of assumptions for each route and the estimated exposures may be theoretical in nature and far exceed any realistic or actual exposures. This is less true for the VI pathway because of the unique characteristics of inhalation exposures.

The estimated exposures often are real exposures. VI exposures occur indoors and people in the United States spend more than 90% of their lives indoors. People who are unhealthy or who are relatively more susceptible to the effects of toxicants—for example, people who are elderly, ill, or immobile; pregnant women and their developing fetuses; newborns, infants, and toddlers—are very likely to spend 90% or more of their time indoors. In many cases, this time is largely spent in a single building, the home.

Children are at a higher risk than adults for both physiological and logistical reasons. Physiology-based studies indicate that there is a twofold greater inhalation dose in children than adults. Also, very young children spend substantial amounts of time at floor level, potentially closer to the location of intruding vapors and presumably could be exposed to higher concentrations than adults.

Inhalation is not voluntary. The typical adult is assumed to inhale 20,000 L/day of air and consume 2 L/day of drinking water. People may forego drinking tap water and use alternative sources, but they cannot forego inhaling the air.
in their immediate environment. Obviously, the concentration of contaminants in breathing air is very important, and measuring or predicting this concentration is a major focus of VI studies.

The inhalation route of exposure has been observed to lead to higher toxicities than exposures via the oral route of entry, though there can be route-specific and more complex toxicology for some chemicals. The higher toxicities for inhalation may reflect the fact that the barrier between contaminated air and the human blood system is as small as a single cell and that these cells are membranes whose purpose is the efficient exchange of inhaled gases with the blood.

**MAGNITUDE OF EXPOSURES MAY BE HIGH**

Pollutant concentrations of 100 µg/m³ or greater have been observed in indoor air due to VI. Assuming a 24-hr exposure and 20 m³/day of respiration, the expected adult applied dose of 2000 µg/day (2 mg/day) of these toxicants could be significant to the health of some individuals. Even higher levels of exposure are possible. Concentrations for a single VOC of 790 µg/m³ or even 1700 µg/m³ have been observed in indoor air due to VI.⁹,¹⁰

**FATE AND TRANSPORT OF SUBSURFACE VAPORS**

The study of the fate and transport of contaminant vapors both in the subsurface and within buildings is a relatively new field and is progressing rapidly. By comparison, over 25 years have been spent studying the fate and transport of contaminants in groundwater for potential ingestion exposures. Over this time, a consensus has developed regarding assessment methods, regulatory policies, and risk management. It is likely that it will be some years before we arrive at a similar understanding and consensus for the issues associated with the fate and transport of contaminant vapors in the subsurface and their intrusion into overlaying buildings.

The intrusion of VOCs can be quite similar to that of radon gas and some lessons can be drawn from EPA’s experience with radon. When radon first became an issue in the mid-1980s, there were hopes that the presence of radon in buildings could be predicted from measurements of radon in the soil. In 1991, however, EPA’s Office of Research and Development addressed this issue: “Several studies¹¹,¹² have attempted to make simple correlations between radon or radium concentrations in the soil and indoor radon concentrations. No significant correlations were made between these variables and indoor radon concentrations cannot yet be predicted from soil radon values. The possibilities are not promising for designing a device and/or technique that builders can rely on to exclude building sites as potential indoor radon problems. As shown by the Florida and New Jersey data, multiple measurements would be required at each building site, and even those vary by orders of magnitude.”¹³

Today, after more than 20 years of study and the collection of approximately 18 million measurements of indoor radon, EPA’s Radon Web site (www.epa.gov/radon) continues to recommend that homes be tested for radon over modeling because reliable predictive methods have not yet been developed. Nevertheless, studies of radon gas intrusion continue and may be of interest to the VI community.¹⁴,¹⁵ Font et al., for example, modeled the time to reach a new steady-state radon concentration in indoor air after a change in the soil water saturation due to precipitation. While, Groves-Kirkby et al.¹⁶ noted that natural radon variability cause many one-week results to be equivocal (as opposed to three-month tests), necessitating repetition of the measurement. This suggests that the typical 8-hr or 24-hr indoor air measurements for VOCs may be less than ideal.

The experience with radon suggests that we still have a significant challenge ahead of us when assessing the vapor intrusion of toxics, especially for sites where the measured values fall within an order of magnitude or so of screening or action levels.

**A LARGE NUMBER OF VARIABLES**

The list of factors believed to influence VI—whether subsurface, near-surface, above-ground, or in-building—is long and still growing as new research becomes available. For example, the effect of surface winds on building pressures, which, in turn, influence vapor migration, was identified as a key variable in recent studies in Santa Maria, CA, and Casper, WY. A similar effect was observed in a radon study, which found that the variability in indoor radon was primarily dependent on barometric pressure and wind variation acting “in a complex way” on the subsurface, and that weather/temperature-controlled water vapor pressures were a principal determinant of short-term variability.¹⁶ In another example, falling water tables have been observed to cause the rapid evolution of volatiles in sand tank experiments,¹⁷ although this has yet to be studied in the field.

**HOW TO MEASURE SUCCESS?**

The ultimate challenge for regulators in the development of VI screening criteria is to select criteria that are adequately protective for all recognized uncertainties, but do not screen in every site for more investigation. The criteria need to have some specificity and utility for real-world scenarios. The development of such screening criteria has been a tremendous challenge for regulators.

For the regulated community, no matter what their opinion of the screening criteria, current compliance with federal or state guidance increasingly is only part of the story. First, the best-case scenario for a given site is a “no further action” (NFA) decision, but it is becoming increasingly apparent that not all NFA decisions provide the same level of confidence over time. Some NFA decisions will likely need to be revisited, as conditions or knowledge change. Second, VI assessments
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are no longer only for and between regulators and the responsible parties. Innocent third-party purchasers and landowners interested in protecting themselves are gaining a greater role, as are environmental insurance companies.

There is a need for the protection of innocent purchasers of properties that were not the source of contamination, but are only situated near contaminated industrial or brownfield properties. This need is now being addressed by the American Society for Testing and Materials’ (ASTM) recently formed VI Task Group (E50.02.06). In business settings, there is a strong desire to have a clear yes-or-no answer. Unfortunately, that can be difficult given the complexity of the natural phenomenon involved and with the current state of understanding of VI science. A practical means of making business decisions for VI threats is needed.

EVIDENCE FOR HEALTH OUTCOMES IS LIMITED

There are some observations of statistically significantly elevated disease rates in one of the early health studies of a VI-exposed population. Elevated rates of kidney and testicular cancers in adults and low birth weight and cardiac birth defects in children were found. Although the results were adjusted for a number of risk factors, the causes of the specific individual cases at this site may still be due to risk factors other than VI, and case-specific assessments are being contemplated. Nevertheless, the pattern of multiple disease types in adults and children that appears consistent with the known animal and suspected human effects for the primary contaminant at this site raises some concern. Additionally, some earlier non-VI health studies found elevated rates of disease in populations whose exposure assessments were based simply on the proximity to hazardous waste sites. It is possible that VI may have played some contributory role in the exposures and possibly to the observed health effects associated with simple proximity to hazardous waste sites in earlier studies.

HEALTH IMPROVEMENTS BEGIN WITH EXPOSURE CONTROLS

For groundwater contamination in general, public health protective and cost-effective exposure controls (e.g., providing permanent alternate water supplies) have been used to successfully avoid a great deal of toxic exposure—and an unknown number of cases of disease—over the years. It is possible that similar measures for VI-related exposures would have a similar positive outcome.

Various interim response exposure-man...
Management technologies, such as subslab depressurization systems, have been used for years to control the intrusion of naturally occurring radon gas and have been demonstrated to effectively reduce toxic VI exposures to acceptable levels. Even concentrations up to 790 µg/m³ in indoor air have been reduced to below 1 µg/m³ using such active vapor control technologies. While the effective use of these technologies can be more complicated than it first appears, the use of such vapor control systems appears roughly comparable, in cost and difficulty of implementation, to similar exposure control techniques for groundwater contamination (e.g., providing permanent alternate drinking water supplies).

Providing alternate water supplies is a recognized technology “standard” for preventing inappropriate tap-water exposures from contaminated groundwater. Formal technology-based standards, which have typically been used for the control of point-source emissions to air, are recognized as providing some of the most effective and cost-effective improvements in environmental quality in this country. Technology-based standards have many clear advantages and perhaps they should play a larger role in the VI challenge. For example, in one way, vapor control technologies could be considered Maximum Achievable (Exposure) Control Technology (MACT) and be an easily recognized standard of protection in areas where the evidence for VI is arguable (as it often is). The preventive application of such exposure control technologies could be one way to help manage the very large uncertainties that exist in our understanding of the VI exposure pathway. A preventive approach might also include appropriate limits to ongoing liabilities where the impacts of VI are arguable. Such a preventive approach could help provide environmental managers, property developers, and decision-makers with a more defensible, and likely more cost-effective, yes-or-no answer to the VI problem.

SUMMARY
In many ways, VI presents a major environmental challenge, but it also provides a tremendous opportunity for regulators and responsible parties to work together toward a better future by helping implement the cost-effective protection of public health by preventing further unnecessary VI exposures today.

ACKNOWLEDGMENTS
Many thanks to a long list of bright people who have helped accelerate the assessment of VI, increase the recognition of the impact of subsurface contamination on the indoor environment, and reduced the toxic exposures to thousands of families.