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An Evaluation of Vapor Intrusion Into Buildings Through a Study of Field Data

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Abstract

A systematic examination of cases on file with the Massachusetts Department of Environmental Protection was undertaken to identify a universe of VOC contaminated sites in close proximity to buildings. Such locations were grouped according to site variables, such as contaminants of concern and concentrations in various media; soil type; depth to groundwater; distance to building; and building construction. Indoor air, soil gas, and/or groundwater field data collected from these sites was then assembled and used to: (1) evaluate available transport models which describe the intrusion of vapors into buildings and predict indoor air contaminant concentrations resulting from the volatilization of VOCs in the subsurface; (2) examine the validity of established regulatory criteria; (3) identify specific trends and field conditions which appear to most influence vapor phase contaminant migration and intrusion processes; and (4) evaluate the possibility of vapor migration being inhibited by a "fresh water lens".

INTRODUCTION

Soil and groundwater contamination by volatile organic compounds (VOCs) is a well documented problem throughout the United States. In Massachusetts alone, there are thousands of sites where releases of petroleum products, dry cleaning fluids, and industrial solvents have significantly impacted subsurface soils and groundwater[1]. When these releases occur near buildings, volatilization of contaminants from the dissolved or pure phases in the subsurface can result in the intrusion of vapor-phase contaminants into indoor air. Accordingly, both researchers and regulatory agencies are attempting to address the increasing concerns over indoor air contamination via this pathway[2].

In 1993, the Massachusetts Department of Environmental Protection (MADEP) established generic soil and groundwater cleanup standards for use at sites contaminated by releases of oil and/or hazardous materials[3]. These standards were calculated based upon a consideration of a variety of human and ecological exposure and contaminant fate and transport scenarios[4].

Groundwater concentrations of VOCs protective of indoor-air exposure concerns, codified by MADEP as "GW-2 Standards", were calculated by the agency using the Heuristic Model developed by Johnson and Ettinger[5]. These calculations involved two key assumptions:

- Soil gas concentrations of dissolved VOCs are present beneath a structure at 10% of the equilibrium condition predicted using Henry's Law; and

- Building and site conditions are consistent with the assumptions used by Johnson and Ettinger in developing Figure 3 of their paper, with soil permeability assumed to be 10^{-7} cm^2, resulting in an indoor air/vadose zone "Attenuation Coefficient" (AC) of 5 x 10^{-4}.

MADEP GW-2 groundwater standards were back-calculated from "acceptable" indoor-air VOC concentrations using the selected Attenuation Coefficient. The "acceptable" indoor air concentration designated for each VOC was the lowest of: (1) the one in one million Excess Lifetime Cancer Risk (ELCR) concentration; (2) 20% of the Reference Concentration (RfC); and (3) the 50% odor recognition threshold. In cases where such a value would be less than expected indoor air "background" concentrations (e.g., benzene), the acceptable indoor air concentration defaulted to the background condition.

In 1996, MADEP began a systematic effort to determine the reasonableness of the above assumptions, and protectiveness of its regulatory (GW-2) standards. The focus of initial efforts in this regard was a review and evaluation of site information and data contained in agency files. The preliminary results and findings of this effort are the subject of this paper.

Scope and Objectives

Under Massachusetts law and regulations, parties deemed responsible for contaminated sites are required to engage the services of private environmental/engineering firms to investigate and evaluate site conditions, using accepted and appropriate practices. Reports detailing methods and findings are then submitted to MADEP for possible review, audit, and/or archiving. As a repository for thousands of such reports, agency files provide a large and unique collection of site investigative studies. Using available databases, and the recommendations and institutional memory of agency staff, a study was undertaken to identify and review reports of this nature concerned with VOC partitioning and indoor air impacts.

The objective of this effort was to try to discern o*rder of magnitude* findings, factors, and trends in VOC partitioning and vapor-phase infiltration to impacted structures, based upon "real world" data. It was hoped that information and data obtained from this study would enable the agency to: (1) better evaluate available vapor-phase transport/infiltration models; (2) examine the validity of established regulatory criteria; and (3) identify specific field conditions and factors which appear to most influence vapor phase contaminant migration and intrusion processes.

Limitations and Biases

While the benefits of using actual site data are self-evident, there are important drawbacks to using such an approach, which need to be understood and accepted. Listed below are the most significant limitations in this regard, relative to this effort:

- Unlike a laboratory or pilot study, all variables at "real world" sites cannot be reasonably known or controlled. Moreover, the degree of characterization of sites examined during this effort ranged from moderately complete to extremely limited; almost all sites examined had limited spatial and temporal data, in some cases revealing significant gaps or anomalies in site investigative efforts. To compensate for data gaps and unknowns, a significant degree of professional judgement was used to enhance the qualitative and semi-quantitative interpretation of available data.

- Certain regional and methodological biases are present. Specifically, sites evaluated during this study were located within the Metropolitan Boston area, in which the depth to groundwater was generally within 1 to 5 meters from the ground surface. Moreover, the evaluation of indoor air impacts focused on investigations conducted during the winter months, when "worst case" vapor infiltration conditions may be expected.

- Virtually all data evaluated during this study was produced by others. If accepted procedures were followed, and adequate documentation was provided, groundwater and soil gas monitoring wells were assumed to be properly constructed and developed; groundwater, soil gas, and indoor air sampling and analysis were assumed to be properly performed; and presented information and data was assumed to be accurate and reliable.

- Finally, in attempting to discern an impact to indoor air, it was necessary to designate "background" concentrations of common VOCs, based upon national and state databases.[4] This may result in a finding of "no impact" at a site were infiltration is in fact occurring, or an incorrect "impact" finding at a site with high VOC background levels.

Despite these limitations, the observations and data obtained from this effort are believed to provide useful *order of magnitude* findings and context, in an area of study and regulation deficient in such a grounding.

IMPLEMENTATION

Site Identification

Phase I of the project focused upon the identification of sites to include in the study. A broad-based approach was initially employed to identify those sites where a release of volatile organic compounds (VOCs) had impacted groundwater and/or indoor air. To accomplish this task, a database search was conducted on over 6,000 files maintained by MADEP in its Northeast Regional Office. The Northeast Region is comprised of 95 cities and towns within the greater-Boston Metropolitan Area, representing a population of approximately three million people, or roughly half the population of the State of Massachusetts. Agency staff familiar with specific sites also provided information to assist in the identification of appropriate candidates for incorporation into the study.

As a result of the initial database and staff searches, the list of potential candidates was narrowed to 165 sites where elevated concentrations of VOCs present in groundwater were potentially impacting indoor air within a building. File reviews were then conducted on each of the 165 sites to determine if relevant and reliable groundwater, soil gas, and/or indoor air data was available, and whether MADEP GW-2 standards would be applicable. Under state regulations, GW-2 groundwater standards are applicable at sites where: (a) the annual average depth to the water table is less than or equal to five (5) meters below surface grade; and (b) groundwater contamination exists within 10 meters of an occupied building.

Of the 165 sites evaluated, 68 had some relevant combination of groundwater, soil gas, and or indoor air data. The field of sites was then narrowed once again to single out those sites most suitable for the study by applying the following site selection criteria:

- presence of high levels of VOCs in groundwater;
- sufficient downgradient distance from release area;
- water table monitoring wells located in building or within 10 meters of the on-site building;
- indoor air monitoring conducted between the months of December through March;
- soil gas points at depths beneath the building;
- soil gas points <3 meters above the water table;
- synoptic groundwater, soil gas, and/or indoor air data.

Using the above criteria, forty-seven (47) sites and sub-sites were determined to represent the best candidates for incorporation into the study. For the purpose of the study, "sub-sites" were defined as discrete locations within a larger site for which groundwater, soil gas, and/or indoor air data was available. For example, different residential neighborhoods impacted by the same trichloroethene (TCE) plume would each constitute a "sub-site". The term "sites" as used throughout the remainder of this paper represents both "sites" and "sub-sites".

Of the 47 sites identified, 26 (55%) had been impacted by releases of chlorinated VOCs, while 21 (45%) were associated with gasoline releases (i.e. benzene, toluene, ethylbenzene, and xylenes (BTEX)). Of the buildings involved, 24 (52%) were residential homes (single family, condominium apartments, and townhouses), 1 (2%) was a school, and 21 (46%) were commercial buildings (restaurants, fitness centers, retail stores).

Data Evaluation

Phase II of the project focused upon the evaluation of the groundwater, soil gas, and indoor air data available for the subject sites. Confidence criteria were developed to characterize and score the relevance and quality of respective field data. All data were assigned an initial baseline value of "+5" and points were then added or subtracted, based upon these criteria. A higher score reflected a relative abundance of high-quality spatial and/or temporal data, whereas a lower score indicated a condition of limited or suspect data. The specific "positive" and "negative" criteria applied to each media are provided below. Miscellaneous considerations for each data set were also evaluated during the scoring procedure on an case-by-case basis.

Groundwater

<u>Positive Attributes</u>

- Monitoring wells located inside building
- More than one well within 10 meters of building
- Multiple groundwater monitoring events
- Data collected between the months of December through February
- Monitoring events synoptic with soil gas and/or indoor air monitoring events

<u>Negative Attributes</u>

- Nearest well > 10 meters from building
- Downgradient wells only
- Gas chromatograph screening data only
- Unknown well screen interval

Soil Gas

Positive Attributes

- o Sampling point(s) installed in building, directly beneath foundation
- o More than one sampling point within 10 meters of building
- o Multiple soil gas monitoring events
- o Data collected between the months of December through February
- o Monitoring events synoptic with groundwater and/or indoor air monitoring events

Negative Attributes

- o Nearest sampling point >10 meters from building
- o Data collected >1 year from groundwater data
- o Extraction point >2 meters below building foundation
- o Extraction point >3 meters above water table

Indoor Air

Positive Attributes

- o Data collected between the months of December through February
- o Multiple indoor air monitoring events
- o Analysis by EPA Method TO-1, TO-2, or TO-14
- o Monitoring events synoptic with groundwater and/or soil gas monitoring events

Negative Attributes

- o Data collected between the months of April through September
- o Data collected >1 year from groundwater and/or soil gas data

Data Collection and Manipulations

A master spreadsheet was created to record on-site VOC contaminant concentrations in all media; sampling dates and locations; calculated Attenuation Coefficients (ACs); calculated % Henry's Constant partitioning conditions (%Hc); environmental site conditions; and building characteristics.

Using the groundwater, soil gas, and indoor air data available for each site, "low", "high", and "likely/average" VOC concentrations were determined for each media at the respective site building location. Factors such as the date of sample collection, the proximity of the sampling point to the building, and the type of surface between the sampling point and the building (e.g. grass versus pavement) were taken into consideration to arrive at the high, low, and likely concentration values. In most cases, these values corresponded to actual site data; in a few cases, professional judgement was used to average data or reconcile anomalies or data gaps. Site-specific AC and %Hc values were then calculated for each VOC using the appropriate combination of groundwater, soil gas, and/or indoor air data as described below.

- **Attenuation Coefficients (ACs)**

  ACs were calculated for 22 sites with available indoor air and soil gas data. The AC was derived from the ratio of "likely/average" VOC concentrations measured in indoor air to those measured in soil gas.

- **% Henry's Constant Partitioning (%Hc)**

  The %Hc was determined for 24 sites with groundwater and soil gas data. The %Hc was calculated by taking the ratio of "likely/average" concentrations of individual VOCs in soil gas to the concentrations predicted by their theoretical Henry's Constants and the "likely/average" groundwater concentrations measured at the sites.

In order to aid in the evaluation of data, available information on relevant site conditions and features were recorded, including:

- depth to the water table
- vadose zone soil type
- monitoring well and soil gas point locations
- depth of monitoring wells and soil gas points
- surface conditions between sampling points and buildings
- location of indoor air sampling within building

Building characteristics which were recorded include the following:

- type of building (residential, school, commercial)
- presence of basement
- type of foundation (concrete, slab-on-grade, earthen)
- integrity of foundation (few cracks, many cracks)
- wall construction (poured concrete, block, fieldstone)
- presence of sumps
- presence of products containing VOCs (gasoline, cleaners)

RESULTS

Table 1 presents the range, mean, and standard deviation values for the Attenuation Coefficients (ACs) calculated for:

* all VOCs at all of the sites which had both indoor air and soil gas data available;

* all VOCs at sites with a high confidence ranking which had both indoor air and soil gas data available; and

* the individual VOCs TCE, PCE, 1,1-DCE, and benzene at relevant sites which had both indoor air and soil gas data available.

As shown in Table 1, the ACs for the 22 sites with relevant soil gas and indoor air data, as well as for the 13 high confidence sites in this category, ranged from 2E-6 to 1.4E-1, with mean values of 5.4E-2 and 4.3E-2, respectively. The subset of 13 high confidence sites varied little from the collective grouping.

TABLE 1: ATTENUATION COEFFICIENTS (ACs)

SITE TYPE	# SITES	AC RANGE	MEAN	STD DEV
All	22	2E-6 - 1.4E-1	5.4E-2	5.8E-2
High Confidence	13	2E-6 - 1.4E-1	4.3E-2	7.5E-2
PCE	6	1.3E-4 - 1E-1	2.8E-2	3.9E-2
TCE	11	9E-5 - 9.7E-2	2E-2	2.4E-1
DCE	2	2E-3 - 1.4E-1	4E-2	6.7E-2
Benzene	3	1.5E-5 - 4E-5	2.8E-5	1.3E-5

Note: Since the AC is the ratio of the contaminant concentration measured in the indoor air to that measured in the soil gas, "larger" ACs imply that greater levels of contaminants are migrating into the building. For the purpose of this paper, "larger" refers to a relative location on a number line which runs from negative infinity to "+1", with "+1" being the largest attainable value. In simpler terms, the smaller the AC value, the more attention that is expected as VOC vapors migrate into a building.

The compound-specific breakdown indicates that the ACs associated with the chlorinated VOCs are several orders of magnitude larger than those exhibited by the non-chlorinated VOCs, represented by benzene (i.e., mean values of E-2 vs E-5). ACs calculated for toluene, ethylbenzene, and xylenes fell within similar, if not lower, ranges than those observed for benzene. 1,1-Dichloroethene (DCE) exhibited the largest mean AC (4E-2) and the largest individual AC (1.4E-1).

Table 2 presents the range, mean, and standard deviation for calculated %Hc values. Based upon groundwater and soil gas data available for all 24 relevant sites, the %Hc ranged from 7E-3 to 10, with a mean value of 0.66%. As with the AC values, the subset of 16 high confidence sites varied little from the collective grouping, ranging from 2E-3 to 10 with a mean value of 0.72%.

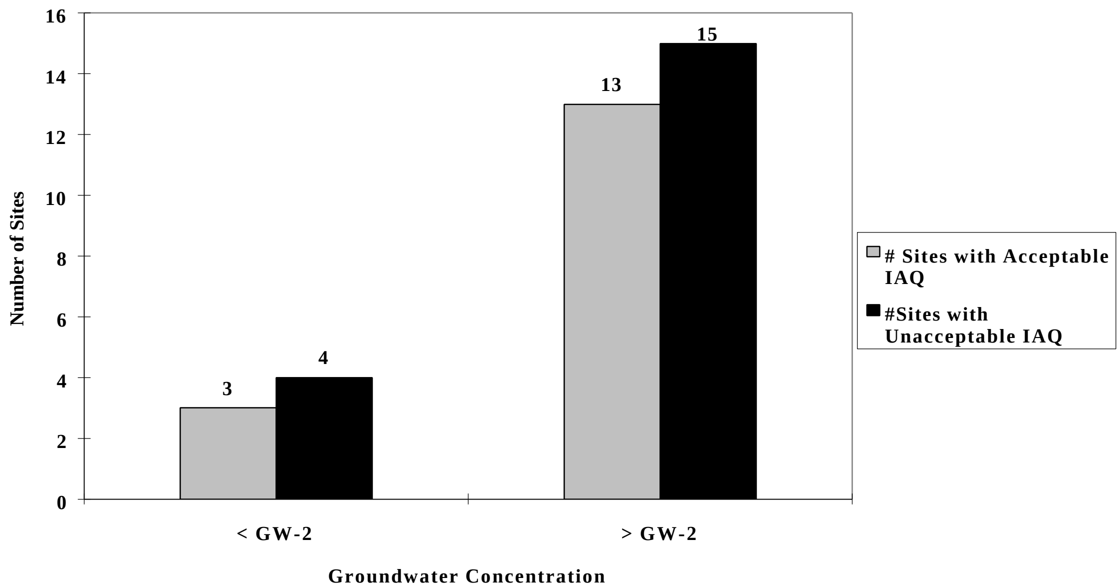
TABLE 2: % HENRY'S CONSTANT PARTITIONING (%Hc)

SITE TYPE	# SITES	%Hc RANGE	MEAN	STD.DEV.
All	24	7E-3 - 10	0.661%	1.73
High Confidence	16	2E-3 - 10	0.721%	1.66
PCE	6	2.5E-2 - 1	0.48%	0.56
TCE	14	2E-3 - 10	1.15%	2.4
DCE	3	3E-2 - 1.4	0.671%	0.73
Benzene	5	9E-3 - 1.4E-1	0.05%	0.05

Comparison of the mean %Hc values for the specific compounds shows that while all of the chlorinated VOCs are well within an order of magnitude of each other, the mean value of 0.05% for the non-chlorinated VOCs, again represented by benzene, is lower than those values exhibited by the chlorinated VOCs by at least an order of magnitude. Both the highest mean and individual %Hc values (1.15% and 10%, respectively,) were exhibited by TCE. Benzene demonstrated the lowest standard deviation among individual compounds.

Figure 1 provides a breakdown of the study sites with available groundwater and Indoor Air Quality (IAQ) data and indicates whether: (a) concentrations of VOCs measured in groundwater exceeded their respective MADEP regulatory standards (i.e., < or > GW-2); and (b) whether concentrations of VOCs measured in indoor air were found to be "acceptable" or "unacceptable" based upon comparison with the indoor air target concentrations used to develop GW-2 standards protective of indoor air exposures.

Figure 1 - Protectiveness of MADEP GW-2 Standards



Three sites with VOC levels in groundwater below the applicable GW-2 standards had acceptable VOC concentrations in indoor air. Unacceptable concentrations of VOCs were measured in indoor air at 15 sites which exceeded the GW-2 standards. Both site scenarios were predictable and expected, considering that the GW-2 standards were developed to be protective of indoor air exposures. It is noted that of the 15 sites with unacceptable concentrations in both indoor air and groundwater, 14 were associated with chlorinated VOCs while only 1 related to a gasoline release.

Conversely, 13 sites with VOC concentrations above the GW-2 standards exhibited acceptable levels of the same VOCs in indoor air. Of these sites, 10 were related to gasoline releases, while the remaining 3 concerned residential homes in a downgradient portion of a large TCE plume. Lastly, and perhaps the most striking of the findings, was that unacceptable indoor air concentrations were measured at 4 sites where VOC concentrations in groundwater did not exceed the applicable GW-2 standards. This suggests that either the GW-2 standards may not be protective enough, or that other site-specific factors which do not fit the model assumptions used to derive the GW-2 standards may be influencing the migration of VOCs into the buildings.

These sites included:

(1) a commercial fitness facility with an indoor air concentration of 5.1 ug/m^3 TCE;

(2) a tavern (converted residence) with an indoor air concentration of 30 ug/m^3 PCE;

(3) a private club with an indoor air concentration of 38 ug/m^3 PCE; and

(4) an office building with an indoor air concentration of 33 ug/m^3 benzene.

DISCUSSION

Attenuation Coefficients (ACs)

Based upon a review of the presented data, two important findings are noted:

- AC values for chlorinated VOCs appear to be about 2 orders of magnitude higher than the 5E-4 value used in the development of MADEP GW-2 standards; and

- AC values for chlorinated VOCs appear to be significantly higher than values associated with non-chlorinated VOCs.

In general, the AC ranges and the mean AC values of 2E-2 to 4E-2 exhibited by the chlorinated VOCs suggest that the 5E-4 value chosen by MADEP during the development of the GW-2 standards may not be protective of indoor air exposures at such sites. With respect to the non-chlorinated VOCs, despite the limited soil gas and indoor air data set available for the BTEX constituents, their observed AC values appear to consistently fall near or below the selected 5E-4 value. This implies that the GW-2 standards derived for the non-chlorinated VOCs are adequate, provided that certain site-specific conditions and/or building parameters do not compromise the parameter assumptions of the Johnson & Ettinger Heuristic Model.

<u>Higher AC values</u>

The AC value of 5E-4 used by MADEP in the calculation of the GW-2 standards was based upon the generic conditions and assumptions used by Johnson and Ettinger in the preparation of Figure 3 of their Heuristic Model. There are a number of reasons why site AC values could be several orders of magnitude higher:

o Johnson and Ettinger assumed a basement depressurization (ΔP) value of only 1 Pascal in estimating soil gas infiltration to an impacted structure. Conversely, significantly higher ΔP values would be expected for the "worst case" winter data evaluated during this study, due to the operation of combustion furnaces and attendant chimney stack effects. This could significantly change AC values at sites where convective transport is dominant.

o The soil gas data recorded for evaluated sites and used to calculate ACs should be viewed as "minimum" values. Spatial limitations in a soil gas sampling network could miss higher or "hot spot" concentration levels; temporal limitations in data collection might have resulted in the recording of lower than average values following a precipitation event. Since the Attenuation Coefficient is defined as the concentration of VOCs in indoor air over the concentrations in the soil gas, higher concentrations of soil gas would result in lower AC values.

o At sites with permeable soils and convective soil gas transport, the Johnson and Ettinger model is quite sensitive to changes in soil permeabilities. In calculating GW-2 values, MADEP chose a soil permeability value of 10^{-7} cm^2, consistent with a fine sand. If a coarser sand condition was assumed, the resultant permeability value of 10^{-6} cm^2 would raise the AC from 5E-4 to about 1E-2, which is consistent with the mean AC values observed during this study.

Compounding all of the above is the overall "order of magnitude" limitations involved in this study effort. Nevertheless, on the basis of these findings, it would appear that selection of a 5E-4 AC value cannot be described as a "reasonable worst case" consideration in the calculation of generic cleanup standards.

Differences between Chlorinated and Non Chlorinated VOCs

Although not directly investigated during this study, the orders of magnitude differences between AC values observed for chlorinated vs non-chlorinated VOCs are likely attributable to a long-known but poorly understood phenomenon: biodegradation. Specifically, it would appear that significant biodegradation of petroleum hydrocarbons is occurring in the vadose zone at many sites, between the point and time that BTEX compounds were measured in the soil gas, and the point and time they were measured in indoor air. Such an assumption is consistent with the findings and conclusions reached by Fischer et.al. in their investigation and evaluation of indoor-air impacts at a gasoline contaminated site in California.[6] Additional lines of evidence of this mechanism observed during the course of this study are presented and discussed below.

% Henry's Constant Partitioning Condition (%Hc)

Based upon an evaluation of the presented data, two of the most significant findings are noted:

- The 10%Hc value used as the presumed "reasonable worst case" partitioning condition in the development of the MADEP GW-2 standards appears to adequately represent the upper limit for %Hc values; and

- Substantially lower %Hc values were consistently exhibited for non-chlorinated VOCs.

As a class, the chlorinated VOCs exhibited %Hc values ranging from 2E-3% to 10%, with mean values of 4.8E-1% to 1.15%. TCE exhibited the greatest range of values, as well as the highest mean (1.15%) and individual value (10%).

The "worst case" 10% partitioning condition was observed at a site where TCE concentrations of 5,900 ug/l and 200,000 ug/m^3 were measured in groundwater and soil gas, respectively; the depth to the water table was approximately one meter below grade; and the vadose zone consisted of fine to medium sand. Six other chlorinated sites which exhibited %Hc ranging from 1% - 5% had some combination of shallow water tables, fine to medium sands, proximity to the source area, and basements with earthen floors, sumps, fieldstone foundations, and/or numerous cracks.

However, substantially lower %Hc values were exhibited by non-chlorinated VOCs. The %Hc values for benzene, for example, ranged from 9E-3% to 1.4E-1% with a mean value of 5E-2%, at least an order of magnitude below those calculated for the chlorinated VOCs.

The following factors provide some explanations for the diminished %Hc values. Speculations regarding the significance of each factor, relative to chlorinated VOCs and non-chlorinated VOCs, are also presented.

o The theoretical Henry's Constant (Hc) partitioning conditions predicted for both chlorinated and non-chlorinated VOCs are not expected in environmental groundwater-soil gas systems for a variety of reasons including, but not limited to, the presence of mixtures of contaminants in groundwater and temperature variations (i.e., the typical temperature of groundwater is 15^{o}C, whereas Hc values are generally based upon temperatures of 20^{o}C and 25^{o}C).

- o Raoult's Law of Partial Pressures states that the vapor pressure exhibited by an individual component of a mixture is a function of the component's mole fraction within the mixture. More simply stated, a component in a mixture does not exhibit as high a vapor pressure as it does in its pure state.

  The occurrence of contaminant mixtures in groundwater appears to be particularly significant for the BTEX compounds since their presence in an aquifer is generally the result of a gasoline release (as opposed to a release of a single chlorinated VOC which may/may not degrade over time to its daughter constituents). If one assumes benzene to comprise 10% - 25% of a dissolved gasoline mixture, its diminished vapor pressure may provide an explanation for up to a one order of magnitude decrease in its observed %Hc.

- o Concentrations of both chlorinated and non-chlorinated VOCs are expected to decrease with distance from the water table due to diffusion through the vadose zone. Based upon a simple Fickian Diffusion evaluation of soil gas transport through a porous media, concentrations may decrease by up to a factor of four with increasing distance from the water table.

  However, a comparison of the observed gradients in soil gas concentrations for both classes of VOCs indicates that diffusion of VOCs from the water table to the sampling point is neither the sole, nor the most important mechanism contributing to the decreased soil gas concentration observed for non-chlorinated VOCs. Rather, it is likely that intrinsic biodegradation plays the more critical role in diminishing the concentrations of non-chlorinated VOCs in soil gas as diffusion occurs upward through the vadose zone.

  To illustrate, order of magnitude decreases in the %Hc values for toluene (i.e., 0.3%Hc and 0.006%Hc) correlated with increasing distance from the water table at two sites with fine to medium sands present in the vadose zone and water tables located at depths of 2 and 4 meters, respectively. Soil gas concentrations of benzene measured at another site also decreased by two orders of magnitude with distance from the source. Conversely, sites impacted by the chlorinated VOCs TCE, PCE, and 1,1-DCE exhibited %Hc values of 1E-1 to 1E-2 in magnitude which varied little with distance from the water table (water table depths ranged from 2 - 4 meters below grade at the selected sites). The exceptions to this finding included the sites previously discussed with elevated %Hc values.

- o The length of the effective diffusion pathway to the monitoring point (i.e., the distance from the water table) appears to be a significant factor contributing to the intrinsic biodegradation of non-chlorinated VOCs as they migrate through the vadose zone. Chlorinated VOCs, which demonstrate greater persistence in the vadose zone, do not appear to degrade as readily and therefore appear to be less sensitive to this parameter.

- o Liquid phase diffusion of VOCs through the capillary fringe is expected to limit the rate of VOC partitioning from groundwater into the air-filled pore spaces of the vadose zone. Since diffusion is driven by a concentration gradient, aqueous concentrations of VOCs within the capillary fringe will decrease with distance from the water table. Therefore, depending on the thickness of the capillary fringe exhibited by the soil (e.g., typical values of 4 cm in coarse sand, 15 cm in medium sand), VOC concentrations exhibited in soil gas may be 2 - 3 orders of magnitude below those predicted by Henry's Law.

GW-2 Standards

Based upon a review of the presented data, three important findings are noted:

- Overall, 15 of 28 sites with groundwater VOC concentrations above applicable GW-2 standards were found to have unacceptable indoor air impacts, suggesting that such standards cannot be considered overly-conservative;

- Based upon a limited database, 4 of 7 sites with groundwater VOC concentrations below applicable GW-2 standards were found to have unacceptable indoor air impacts, suggesting that such standards are not protective under certain site conditions; and

- Unacceptable indoor air impacts are more likely to occur at sites contaminated by chlorinated VOCs, as compared to non-chlorinated VOCs.

<u>Biases</u>

Despite the findings presented above, it is likely that less than 50% of sites exceeding GW-2 standards will experience unacceptable indoor air concentrations, and less than 50% of sites below the GW-2 standards will experience unacceptable indoor air concentrations. This is due to biases present in the investigation methodology, which relied upon available reports prepared by private engineering firms.

Specifically, sites that had experienced indoor air odor complaints are more likely to have undertaken indoor air sampling efforts than sites that did not experience such problems. This is particularly true for sites with groundwater concentrations of VOCs less than GW-2 standards. A more representative sample within either category would likely yield less positive findings. Nonetheless, concern does exist on the degree of conservatism incorporated into the GW-2 standards.

<u>Chlorinated vs Non-Chlorinated VOCs</u>

The findings of the groundwater and indoor air evaluation indicate that an exceedance of the GW-2 standard for a chlorinated VOC in groundwater generally resulted in unacceptable levels of the same VOC in indoor air within the on-site building. Three sites where such a condition was not observed were homes in a residential neighborhood in a downgradient portion of a 1/2 mile long TCE plume.

Conversely, of the 11 sites with concentrations of BTEX above their respective groundwater standards, only one exhibited unacceptable levels of benzene in indoor air. As suggested in the previous section, this finding supports the speculation that non-chlorinated VOCs such as the BTEX compounds are more likely to naturally attenuate through intrinsic biodegradation processes as they diffuse upward from the water table through the vapor-filled pore spaces. In the case of the one problematic site in this category, the occurrence of unacceptable levels of benzene in indoor air may be attributable to an insufficient distance between the water table and the building foundation to allow natural degradation to occur within the vadose zone.

Non-Protective Sites

The 4 sites which exhibited unacceptable levels of VOCs in indoor air despite the achievement of the groundwater standards were re-evaluated to determine if unique or unusual site conditions or building characteristics may have contributed to the indoor air problem. The review yielded the following information:

- The level of 5.1 ug/m^3 TCE measured at the commercial fitness facility slightly exceeded 5 ug/m^3, the level generally accepted by MADEP as background for TCE in indoor air. Therefore, it is possible that the TCE concentration measured at this site is attributable to background conditions.

- The basement of the tavern (converted residence) consists of an earthen floor and fieldstone foundation. The building is heated by a forced hot air furnace located in the basement and an exhaust fan reportedly operates in the building. The Johnson & Ettinger Heuristic Model is based upon diffusive and advective vapor flow of contaminants in soil gas through a foundation crack of a given length, width, and areal ratio within the building, rather than through an earthen floor. In this case, the indoor air concentration of 30 ug/m^3 PCE is likely the result of the combined presence of an earthen floor basement, multiple cracks in the fieldstone walls, and an enhanced negative pressure gradient created by the hot air furnace and the exhaust fan.

- The basement of the private club consists of a concrete/concrete block floor with many cracks and concrete block walls. The building is reportedly located within approximately 20 - 25 meters of the source of a PCE release. The area between the source and the building is entirely paved. Based upon this information, the elevated indoor air concentration of 38 ug/m^3 may be attributable to a combination of the multiple cracks in the building foundation and the presence of pavement which prevents both the flux of soil gas to the atmosphere and the infiltration of uncontaminated recharge, thus increasing the tendency of vapors in the soil gas to flow into a basement under negative pressure.

- The basement foundation of the office building which exhibited an indoor air concentration of 33 ug/m^3 benzene consists of a poured concrete floor (few cracks) and concrete block walls. The water table lies approximately 2 meters below surface grade. A sump is present in the basement, and building occupants have complained of odors. These conditions suggest that the elevated concentration of benzene measured within the building could be the result of direct off-gassing of gasoline vapors from the sump water into the building.

Other Considerations

Building Characteristics

A number of building and foundation characteristics believed to contribute to and even promote the migration of VOCs into a building have been identified throughout this paper. Many of these conditions, such as the presence of earthen floors, fieldstone foundations, sumps, or other preferential migration pathways, were not incorporated into the assumptions of the Johnson and Ettinger Heuristic Model used by MADEP to derive an AC value of 5E-4 and subsequently, the GW-2 standards. Other parameters, including the pressure differential existing between the building and the outside environment and/or the volumetric flow rate of air through the building, may vary widely depending upon seasonal considerations, the presence of combustion furnaces, and variances among heating and ventilation systems.

Soil as VOC Source

At present, MADEP cleanup standards address VOC impacts to subsurface structures solely through a consideration of groundwater-to-vadose-zone transport mechanisms. Nevertheless, direct partitioning of VOCs from contaminated soil is also a concern, at sites where such source areas are present. For this reason, sites included in this study were limited to locations believed to be sufficiently distanced from such vadose zone source areas.

Fresh Water Lens

The occurrence and transport of VOCs within the vadose zone is a dynamic process, especially in areas like Massachusetts where a significant amount of precipitation and groundwater recharge can be expected. Infiltrating precipitation can result in the physical displacement and movement of soil gases, and re-dissolution of VOCs contained in air-filled pore spaces.

Beyond such localized effects, one can surmise that plume movement in the shallow groundwater away from a source area will be influenced by the degree of infiltrative recharge occurring. Specifically, at some distance downgradient from the source area, sufficient infiltration of (uncontaminated) fresh water will occur to result in the "sinking" of the water table plume, and establishment of a fresh water lens at the water table/capillary fringe interface. Because of the slow rate of liquid/liquid diffusion processes, a sufficiently thick fresh water lens can create an effective barrier to VOC partitioning into the vadose zone, and effectively "protect" overlying structures from adverse indoor air impacts.

Evidence of the occurrence of such a freshwater lens has been collected from a limited number of sites. At a site which abuts a large wetland, several thousand feet from the point of TCE discharge, a groundwater sample collected from the uppermost portion of the water table showed "non detect" concentrations of TCE upon analysis. Samples collected from the same well point at slightly greater depths exhibited TCE concentrations orders of magnitude higher. TCE concentrations measured in indoor air in residential homes at the site were found to be less than the accepted background level of 5 ug/m^3.

While additional investigation is needed to more fully evaluate the parameters and dynamics of such a phenomenon, it would appear to be a potentially significant element in the evaluation of vapor phase transport and infiltration.

CONCLUSIONS

On the basis of the information and data presented in this paper, and subject to the limitations and biases of investigative methods, the following conclusions are offered:

(1) Significant differences appear to exist between the fate/transport and impacts of chlorinated and non-chlorinated VOCs partitioning from a contaminated groundwater plume.

(2) Indoor-air/soil-gas Attenuation Coefficients for chlorinated VOCs at a number of sites evaluated in eastern Massachusetts appear to be in the range of 1E-1 to 1E-3, significantly higher than the 5E-4 value assumed by MADEP in its calculation of regulatory (GW-2) standards.

(3) Indoor-air/soil-gas Attenuation Coefficients for non-chlorinated VOCs at a limited number of sites evaluated in eastern Massachusetts appear to be in the range of 1E-4 to 1E-5, consistent with the value of 5E-4 assumed by MADEP in its calculation of regulatory (GW-2) standards.

(4) The mean degree of partitioning of chlorinated VOCs observed in the vadose zone was around 1% of theoretical equilibrium conditions predicted using Henry's Law. Although similar levels of partitioning of non-chlorinated VOCs may be occurring, levels detected in the vadose zone are typically 1 to 2 orders of magnitude lower, due apparently to biodegradation of these non-chlorinated (BTEX) VOCs above the water table.

(5) MADEP groundwater standards protective of indoor-air impacts (GW-2) are not overly conservative, and may not be protective enough under certain site conditions not uncommon to Massachusetts.

DISCLAIMER

The findings and opinions expressed in this paper are the personal views of the authors, and do not necessarily reflect the position, recommendation, or policy of the Massachusetts Department of Environmental Protection.

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