ASSESSMENT OF SUBSURFACE VAPOUR TRANSPORT THROUGH TRIASSIC SANDSTONE AND QUARRY FILL INTO INDOOR AIR IN WESTON VILLAGE, RUNCORN, UK

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ABSTRACT
Subsurface vapour intrusion into indoor air by volatile organic compounds (VOCs) associated with contaminated land is a potential exposure pathway of increasing interest. This paper describes a comprehensive case study of this pathway, including: indoor air quality (IAQ) monitoring at 0.003 parts-per-billion (ppb) quantitation limit (QL), a detailed geologic characterization, extensive subsurface vapour sampling and analysis, pneumatic testing at the laboratory and field scales, building pressure and ventilation studies, a comprehensive statistical analysis of the vapour attenuation coefficient ("alpha factor"), and a comparison to the USEPA spreadsheet version Johnson and Ettinger (1991) model. The results show that the vapour concentrations in indoor air are dramatically influenced by the gas permeability and structure of the subsurface geologic materials. Properties built on the sandstone bedrock had IAQ that was barely distinguishable from outdoor air quality (OAQ); whereas, properties built on poorly consolidated quarry spoil backfill typically had IAQ 2 to 3 orders of magnitude more concentrated than OAQ.

INDEX TERMS
Subsurface vapour intrusion, Indoor air quality, Pressure/ventilation testing, Pneumatic testing, Alpha factor

INTRODUCTION
Management of contaminated land must be guided by scientific information that allows an understanding of the processes affecting chemical fate and transport; otherwise, there can be no predictive capability for assessing conditions between and beyond sample locations, or conditions over future time periods during which the contamination will persist. This paper provides an overview of a comprehensive study of site conditions and transport processes at a former waste disposal site operated by ICI in northwest England.

About 6,000 tonnes of volatile organic compounds (VOCs) were disposed of in two abandoned sandstone quarries (North and South Quarry). About 100 residential properties are located adjacent to the former quarries. A preliminary hazard review identified the potential for subsurface vapour migration to cause inhalation exposures via intrusion into indoor air at these properties. A comprehensive site characterization has been performed over the past three years. ICI assembled a team of specialists to evaluate the vapour distributions and vapour transport mechanisms in order to understand the root cause of the IAQ issues. A conceptual model of North Quarry is shown in Figure 1.

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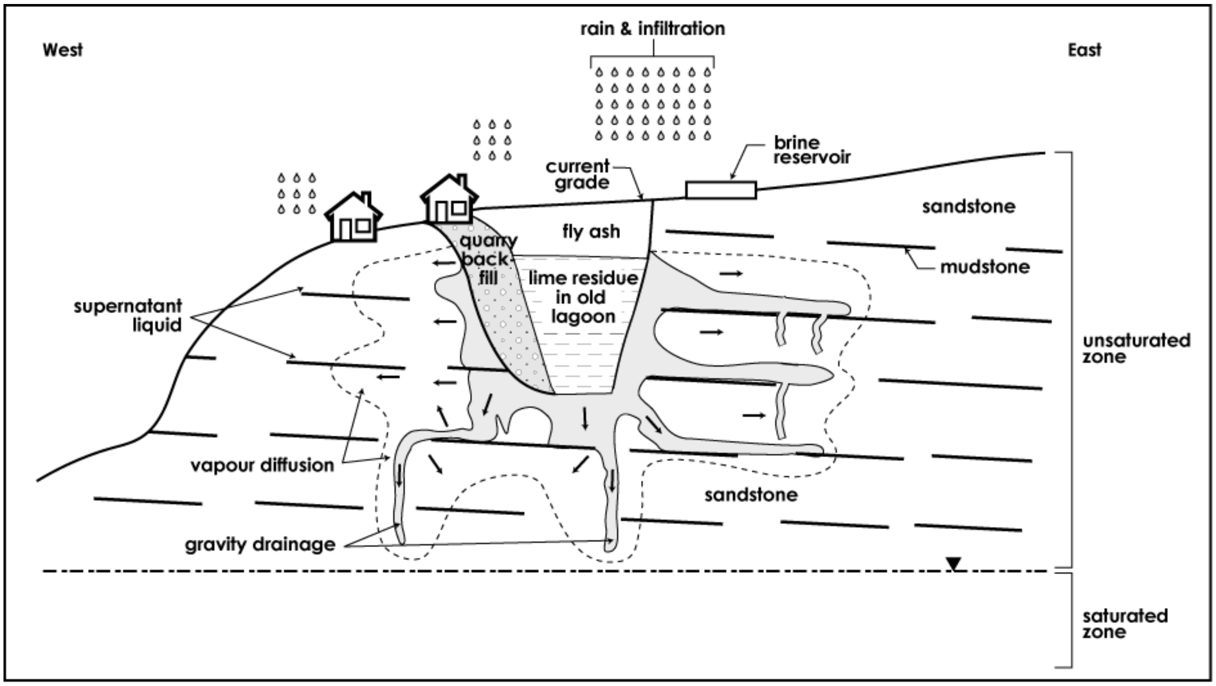

Figure 1: Conceptual Model of North Quarry

METHODS

The study began with an historical review of quarry waste disposal practices. Lime slurry, consisting mostly of water with fine particles and low percentage concentrations of VOCs and still heavies (chlorinated butadienes) was disposed of in lagoons at the south end of North Quarry. Supernatant liquids exfiltrated into the surrounding geologic material until the settled solids had a consistency like margarine. Settled solids were dredged and relocated to the northern part of North Quarry. South Quarry was filled with mixed wastes, but not lime slurry. Both quarries have been inactive and capped for the past few decades.

The geology has been characterised by four deep (>70m) continuously-cored boreholes, and 48 vapour monitoring well boreholes, seven of which extend to depths in the range of about 30 to 40 m. Outcrop mapping, ground-level reconnaissance, cross-hole resistivity and surface RESCAN surveys have also been employed to assess the distribution of native bedrock and quarry backfill, as well as the permeation of geologic media with supernatant liquids from the former lagoons. Over 1,000 sandstone core samples were tested to measure the gas permeability (which ranged from about 10^{-11} to 10^{-16} m^2) and total porosity (which ranged from about 15 to 30%) (BGS, 1998). The bedrock consists of Triassic sandstone with interbeds of varying texture, and occasional mudstone layers. Perched water was observed above the mudstone layers in some locations. The bedding dips at 3 to 5 degrees to the southeast. Steeply dipping fractures are present, although they are filled with sand and silt where exposed. The quarry backfill consists of a matrix of granular sand with rock fragments that range in size from gravel to blocks, which is poorly consolidated and well-drained.

IAQ and OAQ were characterised by about 3,000 samples collected during four rounds of monitoring using automatic thermal desorption (ATD) tubes, and analysed by GC/MS with a QL of 0.003 ppb by volume. The analytical method was developed specifically for this study by BRE and QinetiQ (formerly DERA), and accredited by the United Kingdom Accreditation Service (UKAS), as described in other papers in these proceedings (Crump, et. al., 2002; Hafkenscheid & Wilkinson, 2002; Wilkinson et. al., 2002). Each of the 145 properties were sampled with four rounds of samples, each in duplicate. Several properties were studied in more detail to assess spatial and temporal variability in detail, which showed average variability of a factor of 5.

Vapour monitoring wells (VMWs) were drilled under BGS supervision using air-rotary methods, with helium added to the air stream at a concentration of about 1%. The wells were constructed of nominal 2-inch (~5cm) diameter PVC, with slotted screens and solid casing. The screens were surrounded with a gravel pack and the casings were sealed against the borehole wall using a cement-bentonite slurry. After the seals set, the VMWs were purged until helium concentrations were below 0.01%, indicating the remaining subsurface gas was more than 99% free of drill air. Eight rounds of VMW sampling were conducted. The VMWs were purged of at least 3 times the standing volume of air in the well and the CO_2, O_2 and photoionization detector readings were stable prior to sample collection onto ATD tubes.

Pneumatic tests were performed by GeoSyntec to assess the large-scale gas permeability in the geologic materials surrounding two VMWs, one in the native sandstone bedrock and one in the quarry backfill. These tests were simulated using a vapour flow model with a specified gas extraction rate matching the measured field values. The horizontal and vertical gas permeabilities in the model were adjusted iteratively until the vacuum simulated by the model matched the vacuum measured at nearby VMWs. These tests indicated a vertical gas permeability in the sandstone on the order of 10^{-11} m^2, which is consistent with the upper range of values measured on small core samples by BGS. The vertical gas permeability of the quarry backfill was more than 20 times greater than that of the sandstone. No measurable vacuum was propagated past a mudstone layer in the bedrock test, indicating the mudstone layer (upon which perched groundwater was observed during drilling) provides considerable resistance to vertical flow of subsurface vapours.

Building pressure/ventilation studies were conducted on selected properties by BRE to assess the ambient ventilation rate and changes under positive and negative pressure, with sealed and unsealed floors. Both pneumatic and tracer (SF_6) data were collected. These studies showed the ambient ventilation rates are one air exchange about every hour or two. The properties in the study area are typically built with suspended timber floors. Pressure tests with sealed and unsealed floors confirmed that the timber floors yielded up to half of the air flow into the property. Recent additions and renovations occasionally had concrete slab-on-grade floors, which supplied only a very small fraction of the total air flow during pressure tests. Air circulation within the properties studied was sufficient to maintain similar IAQ (typically less than a factor of 2 range in IAQ) throughout different rooms and floors.

The vapour attenuation coefficient (or “alpha factor”, defined as the concentration of a vapour in indoor air divided by the concentration at a specified depth in the subsurface) was calculated based on the field data and simulated using the Johnson and Ettinger (1991) model. The average OAQ was subtracted from the average IAQ to estimate the indoor air vapour concentrations attributable to subsurface vapour intrusion, referred to as the “corrected indoor air concentrations” or CIAQ. Analysis of variance (ANOVA) testing showed that the OAQ data had no statistically significant spatial variability at a 95% confidence interval. Alpha factors were calculated for individual properties by dividing the CIAQ by the subsurface vapour concentration. The subsurface vapour concentration was estimated either: a) from the nearest VMW (if within 30 m and screened in the same subsurface material that underlies the property), or; b) from the average of typically several VMWs assigned to localised neighbourhoods of properties with similar IAQ and subsurface materials. Analytical results below the QL were assigned a value of ½ the QL. Reliability was ensured by excluding properties where the IAQ was not statistically different than the OAQ using a Student's T-test at a 95% confidence interval. Data sets with low detection frequencies (<50% for small data sets, and <25% for larger data sets) were excluded because they may provide a biased estimate of central tendency. Negative CIAQ values were also excluded, which may impose a positive bias in the retained alpha factors.

RESULTS

Figure 2 shows the IAQ data (average of the first three rounds of sampling) for each of the 145 properties monitored. Hexachlorobutadiene (HCBD) was detected at concentrations that were consistently two to three orders of magnitude above the QL of 3 ppt in properties built on quarry backfill. Properties on bedrock had noticeably lower IAQ for HCBD, with the vast majority (about 80%) having average concentrations within a factor of 2 of the average OAQ.

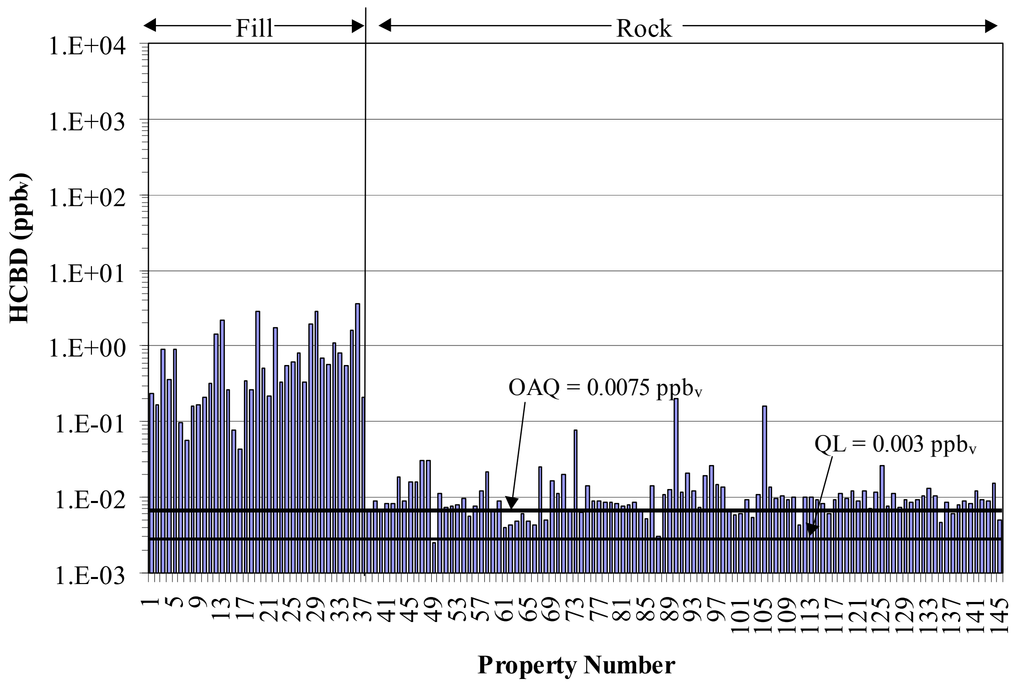

Figure 2: IAQ data for HCBD in 145 properties monitored during Rounds 1,2 and 3.

Figure 3 shows the VMW data for the 30 shallow (about 5 m depth) VMWs used in the alpha factor calculations. The average concentrations of HCBD are generally all above the QL (500 ppt), in some cases by up to about 3 orders of magnitude. HCBD concentrations for VMWs screened in rock are similar to the VMWs screened in fill, for a given distance from the quarries.

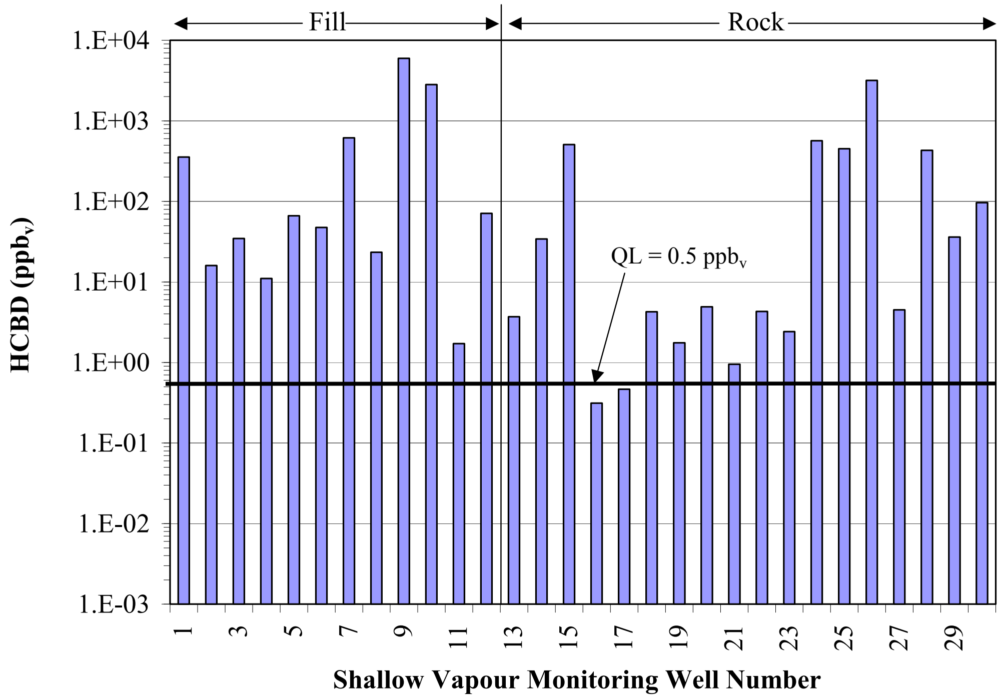

Figure 3: Average concentrations of HCBD in VMW samples

Figure 4 shows the alpha factors calculated from the CIAQ and VMW data for HCBD. The average alpha factor for properties on quarry backfill was about $2x10^{-2}$ and for properties built on bedrock was about $4x10^{-4}$, which demonstrates that the bedrock is on average about 50 times more protective of subsurface vapour intrusion. This factor is similar to the difference in the vertical gas permeability between native bedrock and quarry backfill.

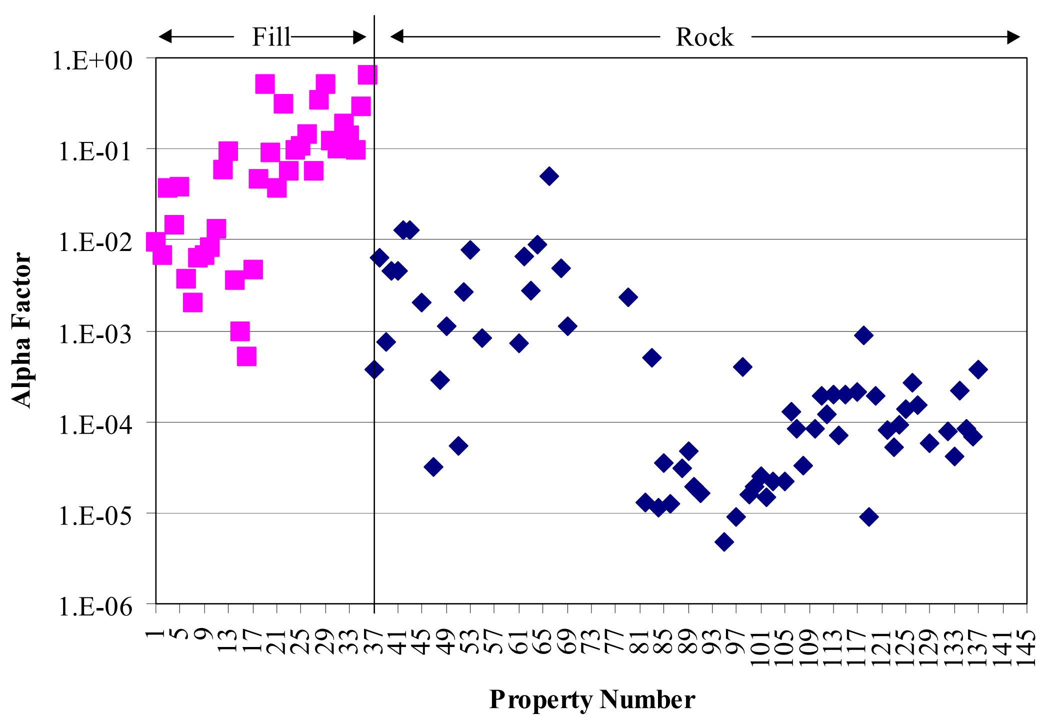

Figure 4: Alpha factors calculated using the site data

The alpha factors calculated using the Johnson and Ettinger (1991) model were $2x10^{-4}$ for fill and $5x10^{-5}$ for rock using site-specific input data. These values underpredict the measured alpha factors by about 2 orders of magnitude, which would tend to underpredict the indoor air concentrations, which is not cautious. The model is formulated to simulate steady-state, 1-dimensional diffusive transport from a source underlying the building. This requires a linear concentration gradient, with concentrations decreasing from the subsurface source toward the building floor. This formulation may not be strictly applicable at this site, since the quarries are located beside, and not beneath the properties, in which case, the concentration gradient would be oriented horizontally, not vertically. This scenario can still be approximated by the model, simply by changing the assigned source depth to a shallower depth. When the source depth was assigned to be just beneath the building floor, the alpha factors were $2x10^{-2}$ for fill and $2x10^{-3}$ for rock, which are much closer to the measured alpha factors, and would tend to overpredict indoor air concentrations, which is cautious.

CONCLUSIONS AND IMPLICATIONS

Subsurface vapour intrusion into indoor air has been demonstrated to occur for properties on quarry backfill adjacent to North Quarry. The IAQ data are dramatically lower for properties on bedrock, which is less permeable and contains mudstone interbeds that are relatively impermeable to vertical gas flow. The protection provided by the bedrock is largely attributable to the finer-grained sandstone and mudstone layers that are less gas permeable, which is amplified by higher moisture contents caused by capillary tension. The protection provided by the bedrock is unlikely to change significantly with time. The characterisation of IAQ, as well as the transport processes and associated material properties is sufficient to proceed with management decisions for prevention of unacceptable inhalation exposures, now and in the future.

ACKNOWLEDGEMENTS

ICI recognised the importance of this study at an early stage, assembled an international team of specialists and managed a comprehensive, technically robust and ground-breaking study with rigorous quality assurance, quality control and extensive peer technical review. ICI's team performed at the highest technical level amidst public involvement, regulatory scrutiny, press attention and very challenging time constraints and provided adequate funding for systematic study of all facets, many of which were developed or advanced specifically for this study. The ICI Project Manager was Richard Moss. Adrian Lawrence and Colin Cheney of the British Geological Survey were also key members of the project team.

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