

Understanding and Managing Indoor Air Exposure Assessments at RCRA Sites

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The 2000 RCRA National Conference was conducted August 15–17, 2000, in Washington, D.C., to allow state and federal authorities to review regulatory issues associated with the Resource Conservation and Recovery Act (RCRA) program. One of the RCRA reform issues discussed at the conference included the Government Performance and Results Act (GPRA) Environmental Indicators (EI). EIs have been designed to provide clarity in cleanup objectives and spur progress towards meeting the U.S. Environmental Protection Agency's (USEPA's) national RCRA cleanup goals. This article focuses on the human exposure indicator and, more specifically, on indoor air exposures and how to assess whether such exposure is actually occurring. While indoor air exposure can be a critical component of the human exposure scenarios, realistic predictions of the exposures are difficult to produce. This article provides an overview of the regulatory issues related to the indoor air exposure pathway. It also discusses the use of modeling in criteria development and risk evaluation and presents a case study of how the USEPA wants the modeling to occur, and an opinion of where this RCRA reform issue is heading and how to evaluate indoor air exposures. © 2000 John Wiley & Sons, Inc.

REGULATORY ISSUES RELATED TO THE INDOOR AIR EXPOSURE PATHWAY

Volatilization of organic vapors located in subsurface soils or groundwater and the subsequent mass transport of these vapors into indoor spaces constitutes a potential inhalation exposure pathway that may need to be evaluated when preparing risk assessments under the Resource Conservation and Recovery Act (RCRA) Corrective Action Program. Recent increased regulatory attention to the indoor air exposure pathway can be partially attributed to the Government Performance and Results Act (GPRA). Under pressure by Congress to show more progress in the RCRA Corrective Action Program, the U.S. Environmental Protection Agency (USEPA) in July 1999 proceeded with RCRA Cleanup Reforms. One of the more visible manifestations of the reforms to owners and operators of RCRA corrective action facilities are the Environmental Indicators (EIs). EIs

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The USEPA developed two EIs—the Current Human Exposures Under Control and the Migration of Contaminated Groundwater Under Control. When current human health exposure pathways are demonstrated to be controlled at a site, the Human Exposures EI is coded as a “YES” in the USEPA's EI documentation for the site. Similarly, when the off-site Migration of Contaminated Groundwater is shown to be stabilized at a site, the Groundwater EI is coded as a “YES.”

Out of the entire universe of RCRA corrective action sites, the USEPA chose 1,714 sites as a baseline for their target. As a quantitative measure of progress in hazardous waste site evaluation and remediation, the USEPA has established the goal of achieving the following measures by the year 2005:

- A code of Yes on 70 percent of the Migration of Contaminated Groundwater EIs; and
- A code of Yes on 95 percent of the Human Exposures EIs.

In the year following the introduction of the EIs, the USEPA provided considerable training to state regulators and regional USEPA staff on consistent EI implementation, and industry representatives were allowed to participate in some of the training sessions. One major issue that emerged from the training sessions was the need for detailed guidance for characterizing the indoor air exposure pathway.

The 2000 RCRA National Meeting was conducted August 15–17, 2000, in Washington, D.C., to allow state and federal authorities to review regulatory issues associated with the RCRA program. During the meeting, the USEPA held a concurrent EI Forum for which industry representatives were encouraged to attend and participate. About one-third of the EI Forum was devoted to the indoor air exposure pathway, which has a profound affect on the Human Exposures EI.

A wide range of indoor air case studies was presented, ranging from specific state regulatory programs to various methods of determining chemical concentrations in indoor air. Case studies of two sites in Colorado were presented as examples of human receptors exposed via the indoor air pathway.

The regulatory agency and industry representatives left the EI Forum without reaching a consensus on how to characterize the indoor air exposure pathway for the Human Exposures EI. As a result, the USEPA is contemplating forming an “Expert Workgroup” to develop detailed guidance on the indoor air exposure pathway issue. Until such guidance is issued, facilities that have a groundwater plume of volatile organic compounds (VOCs) located near or beneath a building occupied by humans (i.e., candidates for potential indoor air exposure issues) must proceed using the currently available methods presented below.

REGULATORY CRITERIA FOR INDOOR AIR

State jurisdictions have developed multiple sets of groundwater standards and criteria addressing a different human health exposure

pathway or environmental risks. Such standards are designed to be protective not only for ingestion of groundwater as drinking water, but for other pathways such as migration of VOCs from the groundwater to indoor air and discharge of contaminated groundwater into surface water bodies. The USEPA has not developed groundwater criteria for multiple exposure pathways, and has typically used drinking water maximum contaminant levels developed under the Safe Drinking Act as an initial point of departure for screening human health risks presented by VOC-containing groundwater.

For example, the Massachusetts Department of Environmental Protection has three sets of groundwater standards, all of which could potentially apply to a given location. GW-1 standards apply to groundwater that is a current or potential drinking water supply and serve a function similar to federal maximum contaminant levels. GW-2 standards are designed to address migration of VOCs from groundwater to indoor air. The GW-2 criteria apply only to locations within 30 feet of a current or planned building and where groundwater is less than 15 feet deep, conditions thought to increase the probability of a migration pathway for volatiles to enter indoor air. Finally, GW-3 standards address potential effects on surface water and apply to all groundwater, on the assumption that most locations in Massachusetts can eventually discharge to a stream.

Connecticut similarly has groundwater protection, volatilization, and surface water protection criteria analogous to the Massachusetts GW-1, GW-2, and GW-3 standards. The Connecticut volatilization criteria are also applicable only to groundwater less than 15 feet deep. Other jurisdictions with multiple groundwater standards or guidelines for indoor air and other noningestion pathways include Michigan and Ontario. Additional states, such as Ohio, do not have numerical volatilization criteria, but require site-specific consideration of the indoor air pathway.

Groundwater criteria for the indoor air pathway are typically less stringent than drinking water standards.

Groundwater criteria for the indoor air pathway are typically less stringent than drinking water standards. For example, the Massachusetts GW-1 standard (i.e., ingestion) for trichloroethene (TCE) is 5 µg/l, while the GW-2 standard (i.e., indoor air) for the same chemical is 300 µg/l. In a location where both standards apply, the GW-2 standard is superceded by the lower GW-1 standard. On the other hand, the GW-2 standard could be critical where groundwater is not a potential drinking water source. In addition, there are exceptions where chemicals have a GW-2 standard that is more stringent than the GW-1 standard. The compound 1,1-dichloroethene (1,1-DCE) is one of several with a GW-2 standard (1 µg/l) that is lower than the GW-1 standard (7 µg/l). This situation occurs when a chemical readily volatilizes from the dissolved to the vapor phase, as indicated by a high Henry's Law constant, which increases the probability of a hazard through the indoor air pathway.

USE OF MODELING IN CRITERIA DEVELOPMENT AND RISK EVALUATION

State agencies have developed criteria addressing indoor air pathways primarily through the use of mathematical modeling. The model

Fate and transport modeling can be applied more generally to the task of evaluating risks on sites in conjunction with environmental investigations or remedies.

most commonly used for this purpose was developed by Johnson and Ettinger (1991). The Johnson and Ettinger (J&E) model is based on analytical screening (in contrast to a numerical model), which means that with a straightforward application of a set of equations, the concentration of a chemical in indoor air can be predicted. The predictions depend on a variety of input parameters representing the characteristics of the chemical of concern, the soil, and the building (actual or hypothetical). Criteria such as the Massachusetts GW-2 standards have been calculated by applying the J&E model with conservative assumptions such as permeable soil and a shallow groundwater table. The groundwater standard is that concentration in groundwater predicted to produce indoor air concentrations equal to a risk-based target air concentration.

Fate and transport modeling can be applied more generally to the task of evaluating risks on sites in conjunction with environmental investigations or remedies. The J&E model simulates two major processes responsible for migration of VOC vapors through the subsurface, diffusion and advection. Diffusion is the random movement of gas molecules through the air in the soil pores, resulting in a net migration from higher to lower concentration locations. Convection is actual movement of air along with any chemical vapors contained within the air.

The J&E model assumes that the vapors diffuse (with negligible convection) through the soil pores from the high-concentration source area (e.g., the region just above the impacted groundwater) to the immediate vicinity of the building foundation where lower concentrations are prevalent. Once near the building, the air and associated vapors are drawn into the building through cracks or seams in the foundation, because of the pressure difference that typically exists between the inside and outside of a building. Thus, both convection and diffusion are assumed to occur near the building. The effect of these processes on air quality inside the building depends in a complex manner on the assumed soil and building characteristics.

Application of the J&E model requires the following types of input parameters:

- Chemical properties, such as Henry's Law constant, diffusion coefficient in air, and organic carbon partition coefficient;
- Soil characteristics, such as permeability to vapor flow, bulk density, total porosity, water-filled porosity, and depth of the water table;
- Depth, thickness, and area of the building foundation;
- The total area of cracks in the foundation;
- Pressure difference between outside and inside the building, and the building ventilation rate; and
- Concentration of the chemical in soil or groundwater.

If a volatile chemical is present in the groundwater at a given concentration, the concentration in the soil pore air immediately above the

groundwater can be predicted (assuming equilibrium between the dissolved and vapor phases) as follows:

$$C_v = HC_{gw}$$

where H is the Henry's Law constant, C_v is the concentration in soil vapor, and C_{gw} is the concentration in groundwater. H is a temperature-dependent characteristic of each chemical, with higher H corresponding to more volatile chemicals. The J&E model then accounts for the effects of diffusion through the air-filled portion of the soil pores to the region near the foundation (diffusion through water is negligible by comparison). Finally, the model calculates the rates of convection and diffusion through the foundation cracks, the dilution inside the air space of the building, and the resulting concentration in the indoor air.

The effect and relative importance of the various input parameters do not necessarily conform to intuition. For example, it is commonly believed that an increase in soil permeability always implies an increased rate of vapor intrusion. It is true that vapors will migrate more rapidly through permeable formations such as sand and gravel than through clay. However, the predicted indoor air concentration is proportional to the soil permeability only within a certain permeability range. At permeability values below 10^{-8} cm² (corresponding to a hydraulic conductivity below 10^{-3} cm/sec), diffusion dominates convection, and diffusion depends on the air-filled soil porosity rather than the permeability. At high permeability values, the rate of contaminant transport becomes limited by the rate of diffusion from the source area vertically to the foundation vicinity; so increased permeability will no longer result in an increased rate of VOC entry into the building. As a result, if the soil permeability does not lie within the intermediate range in which vapor intrusion is proportional to permeability, precise estimation of the permeability might not be critical. On the other hand, in such "diffusion-limited" conditions, the assumed water- and air-filled soil porosity values become critical input parameters, because diffusion occurs mainly through the air-filled pores.

As a result, if the soil permeability does not lie within the intermediate range in which vapor intrusion is proportional to permeability, precise estimation of the permeability might not be critical.

A similarly counterintuitive result is that the extent of foundation cracking is important with low- to medium-permeability soils but not with highly permeable soils. Under the permeable soil scenario, convection-dominated conditions, the critical factor is the rate of airflow through the cracks, which is not strongly dependent on the size of the cracks. With low-permeability diffusion-dominated conditions, the rate of diffusion through the cracks and, thus, the rate of entry of vapors into the building are proportional to the crack size. These complexities illustrate the importance of applying the model over a range of input parameter values, particularly for parameters that are uncertain or vary because of site heterogeneity.

Its authors intended the J&E model as a screening tool, to identify situations where migration of contaminant vapors from groundwater to indoor air could be a potential concern. The USEPA and some state environmental agencies have suggested using the J&E model as a default screening assessment of the indoor air exposure pathway. The EPA has

One disadvantage of the J&E model is that it does not account for the spatial variability in concentrations of chemicals of concern.

prepared a spreadsheet that incorporates the mathematical formulas in the J&E model. The spreadsheet can be downloaded from the EPA Superfund website (www.epa.gov/oerrpage/superfund/programs/risk/airmodel/johnson_ettinger.htm). The model can be run in a screening mode in which the user specifies a small number of parameters, and the remaining parameters are assigned default values. In a "Tier 2" portion of the spreadsheet, the user can input all parameters to perform a site-specific analysis. The EPA spreadsheet combines the J&E model with standard risk assumptions and chemical-specific toxicological data to calculate a soil or groundwater cleanup level for the chemical for a specified target risk level.

MASS LIMIT CALCULATIONS

One disadvantage of the J&E model is that it does not account for the spatial variability in concentrations of chemicals of concern. The extent of a groundwater plume or zone of affected soil is frequently much smaller than the size of a building, particularly for large commercial or industrial facilities. Although the EPA modeling spreadsheet considers the total mass of the chemical of concern based on the concentration and vertical extent, the specified chemical concentration is still assumed to be present under the entire building, resulting in an overestimate of the risk. As an alternative to the J&E model, a mass limit calculation can be performed.

If a site has been extensively investigated, it is often feasible to estimate the total mass (M) of each chemical present in the soil and groundwater. The mass can be estimated from an analysis of the chemical concentrations (e.g., by measuring the areas between contour lines on an isopleth map depicting chemical concentrations). This information can be used to conduct a worst-case calculation of the average concentration to which a building occupant would be exposed, on the assumption that the entire chemical mass enters the building over a given period of time:

$$C_{\text{bdlg}} = M / (Q_{\text{bdlg}} T)$$

Where:

C_{bdlg} = average concentration in the building (mg/m^3)

M = total mass of the chemical (mg)

Q_{bdlg} = building ventilation rate (m^3/hr) = number of air exchanges/hr \times building volume in m^3

T = averaging time (hr) (or years \times 8,760 hr/yr)

A typical default averaging time "T" would be the exposure duration used in risk calculations (e.g., screening level exposure duration of 6 years for a resident child or 30 years for an adult).

The mass limit approach avoids the assumption inherent in the J&E calculations that the source extends under the entire building and is not depleted over time as volatilization occurs. The calculated value of C_{bdlg} should be compared to an appropriate target air concentration, such as the EPA Region 9 preliminary remediation goals (PRGs) for ambient air.

permissible exposure levels (PELs) for occupational exposures (in an industrial setting), or site-specific cleanup goals.

Alternatively, the mass limit calculation can be used to determine the averaging time (T) required for the predicted chemical concentration in air in the building (C_{bldg}) to exceed the target concentration. If T is low (e.g., 1 year or less), then the data indicate that the entire mass of the chemical would not actually enter the building in such a short time, and that adverse health effects from volatilization into the building are therefore unlikely.

VAPOR MONITORING

If the results of both the J&E screening model and the mass limit calculation indicate that vapor intrusion into a building could pose a potential concern, vapor monitoring would typically be warranted to explore the issue further. There are at least two distinct monitoring strategies that could be pursued: soil vapor monitoring or direct sampling of the indoor air.

Collection and analysis of soil vapor samples would provide data on concentrations of VOCs in soil immediately under the slab. Data should ideally be obtained at several different locations under the building and at several different times to obtain an estimate of the long-term average concentration. The J&E model can then be used to predict the indoor air concentration and associated risk that would result from the measured soil vapor levels. The J&E model typically predicts an attenuation factor of several orders of magnitude between the soil vapor and the indoor air. Although modeling is still used to simulate migration through the foundation, the uncertainty associated with modeling chemical transport from the source area (e.g., water table) to the foundation is eliminated and is replaced by direct measurement of the soil vapor concentrations. Therefore, if processes not accounted for by the J&E model are important at the site (e.g., a layer of clean groundwater at the water table that would inhibit volatilization from deeper groundwater, or macrostructures in soil that would enhance migration), the predicted concentration in the building will be more realistic.

The risk or hazard quotient resulting from a measured concentration in soil vapor under the slab can be determined by applying the J&E spreadsheet with an assumed shallow water table. The depth to the water table should be assumed to be the depth of the foundation plus the thickness of the capillary zone, which is calculated by the model based on the soil type and provided in a table of intermediate calculations. The intermediate calculations worksheet of the EPA spreadsheet provides the predicted attenuation coefficient, which can be multiplied by the measured soil vapor concentration to yield the predicted indoor air concentration.

Indoor air monitoring provides the most direct indication of the groundwater-to-indoor-air pathway. However, if the chemical of concern in groundwater is also used in facility operations, detection of the chemical in air could be associated with operations rather than volatilization from groundwater. Another uncertainty associated with indoor air monitoring is that the results can be variable due to fluctuations in weather and building

The risk or hazard quotient resulting from a measured concentration in soil vapor under the slab can be determined by applying the J&E spreadsheet with an assumed shallow water table.

ventilation patterns. Therefore, multiple indoor air samples should be collected over time to minimize uncertainties associated with estimating long-term average concentrations of chemicals in air.

Because regulatory concern over the indoor air pathway has emerged only recently, data comparing model predictions to actual monitoring results have not been routinely published.

CASE STUDY

Because regulatory concern over the indoor air pathway has emerged only recently, data comparing model predictions to actual monitoring results have not been routinely published. In one investigation conducted by Environmental Strategies Corporation, fate and transport modeling and indoor air monitoring were conducted at the same site, allowing such a comparison.

The facility consists of a 210,000-square-foot plant building (700 feet long and 300 feet wide) with slab on grade construction. The plant previously cleaned metal parts with TCE, and the degreaser rested in a 15-foot-deep concrete sump. Several years ago, the degreaser and the sump were removed, and the excavation was filled with sand. The native soil consists of silty clay, and groundwater occurs at a depth of approximately 20 feet below the ground surface (bgs).

Soil samples collected from locations surrounding the sump were found to contain up to 2,500 mg/kg of TCE, with an average concentration of approximately 500 mg/kg. The TCE was detected at a depth of approximately 15 feet bgs, just below the bottom of the sump. In addition, groundwater in this area contained up to 20 mg/l of TCE, with a long-term average value of 7 mg/l.

The J&E model was applied with the assistance of the USEPA spreadsheets for soil and groundwater. The spreadsheets for data entry, intermediate calculations, and results are displayed in **Exhibits 1, 2, and 3**, respectively. Given the relative concentrations detected in soil and groundwater, soil was found to be a much greater potential contributor to vapor intrusion. Therefore, this example will focus on the soil.

The data entry sheet from the USEPA spreadsheet (Exhibit 1) shows the input parameters used in the screening calculation. The parameters are consistent with a 6-inch-thick slab on grade building, the presence of 500 mg/kg of TCE at a depth of 15 feet bgs, and sandy soil (representing the fill material for the degreaser sump). The spreadsheet assigns the soil permeability based on the specified soil type; the user also has the option of specifying a numerical permeability value. Soil properties are based on site-specific data where available. The building is assumed to have a 0.1-cm crack extending along the entire floor-wall seam. The indoor air exchange rate is conservatively assumed to be the USEPA's default value of 0.45 air changes per hour. We have found little published information on typical air exchange rates for commercial buildings, and the results of the J&E model are sensitive to the specified air exchange value.

As indicated in the intermediate calculations worksheet (Exhibit 2), the TCE vapor concentration in the source area (within the contaminated soil) is estimated to be $9.09 \times 10^7 \mu\text{g}/\text{m}^3$. The concentration inside the building is predicted to be $1,950 \mu\text{g}/\text{m}^3$. The results worksheet (Exhibit 3) indicates

Exhibit 1. Data Entry Sheet: Ohio Industrial Site

CALCULATE RISK-BASED SOIL CONCENTRATION (enter "X" in "YES" box)

YES OR

OR

CALCULATE INCREMENTAL RISKS FROM ACTUAL SOIL CONCENTRATION (enter "X" in "YES" box and initial soil conc. below)

YES X

VERSION 1.2
September, 1998

ENTER Initial soil conc., C_s (numbers only, no dashes) (pg/kg)

78016 50000

Chemical

Trichloroethylene

| ENTER Average soil temperature, T_s (°C) | ENTER Depth below grade to bottom of enclosed space floor, L_f (cm) | ENTER Depth below grade to top of contamination, L_1 (cm) | ENTER Depth below grade to bottom of contamination, if value is unknown (enter value of 0) L_b (cm) | ENTER Thickness of soil stratum A, h_a (cm) | ENTER Thickness of soil stratum B, h_b (cm) | ENTER Thickness of soil stratum C, h_c (cm) | ENTER Soil stratum A SCS soil type (used to estimate soil vapor permeability) S |
|--|---|---|---|---|---|---|---|
| 10 | 15 | 450 | 600 | 450 | 0 | 0 | |

| ENTER Stratum A soil dry bulk density, ρ_s (g/cm ³) | ENTER Stratum A soil total porosity, n^* (unitless) | ENTER Stratum A soil organic carbon fraction, f_{oc} (unitless) | ENTER Stratum B soil dry bulk density, ρ_b (g/cm ³) | ENTER Stratum B soil total porosity, n^* (unitless) | ENTER Stratum B soil water-filled porosity, θ_w (cm ³ /cm ³) | ENTER Stratum C soil total porosity, n^* (unitless) | ENTER Stratum C soil organic carbon fraction, f_{oc} (unitless) | ENTER Stratum C soil water-filled porosity, θ_w (cm ³ /cm ³) | ENTER User-defined soil vapor permeability, k_v (cm ²) |
|--|---|---|--|---|--|---|---|--|--|
| 1.5 | 0.43 | 0.006 | 1.5 | 0.43 | 0.15 | 0.43 | 0.008 | 1.5 | 0.43 |

| ENTER Enclosed space floor thickness, L_{max} (cm) | ENTER Soil-bldg. pressure differential, ΔP (g/cm ²) | ENTER Enclosed space floor length, L_0 (cm) | ENTER Enclosed space floor width, W_0 (cm) | ENTER Enclosed space height, H_0 (cm) | ENTER Floor-wall seam crack width, w (cm) | ENTER Indoor air exchange rate, ER (1/h) |
|--|---|---|--|---|---|--|
| 15 | 4.0 | 21360 | 9150 | 488 | 0.1 | 0.45 |

| ENTER Averaging time for carcinogens, AT_c (hrs) | ENTER Averaging time for noncarcinogens, AT_{nc} (hrs) | ENTER Exposure duration, ED (hrs) | ENTER Exposure frequency, EF (days/yr) | ENTER Target risk for carcinogens, TR (unitless) | ENTER Target hazard quotient for noncarcinogens, THQ (unitless) |
|--|--|-----------------------------------|--|--|---|
| 70 | 30 | 30 | 350 | 1.0E-06 | 1 |

Used to calculate risk-based soil concentration.



CONCLUSIONS

The case study illustrates some of the challenges that are being addressed by regulatory agencies attempting to characterize the significance of the indoor air exposure pathways. The complexities of heterogeneous subsurface conditions can never be adequately characterized in a default-screening model. By convention, regulators typically address uncertainty in risk assessment through the use of conservative assumptions. The required simplifications can result in overestimates of chemical transport and risk to human receptors.

The fundamentally uncertain nature of exposure and risk assessment is the root of most debates about the extent of corrective action that is required at RCRA corrective action facilities. When the uncertainties and conservatism associated with default risk assessments contribute to a perceived mischaracterization of actual risks to health, owners and operators of RCRA corrective action facilities have financial inducements to generate competing technical analyses. The essential problem with the dueling scientists approach is that the adversaries recognize that each group can manipulate or distort its analysis to support their particular positions. The resulting suspicions make it difficult for parties to generate technical information that is credible to opposing parties.

The authors' experiences characterizing the indoor air exposure pathway for purposes of evaluating corrective action alternatives have identified numerous scientific shortcomings. Of critical importance to the RCRA program is that most affected soil and groundwater at corrective action facilities involves potential exposure to workers in commercial and industrial buildings. Actual exposure of residential receptors is less common. However, the EPA's default screening models for the indoor air exposure pathway have been developed using defaults for residential buildings. Our research has found little published information that can be used to characterize the conditions in commercial and industrial buildings.

As a result of competing political agendas and red tape, USEPA cannot always quickly promulgate common-sense guidance on default situations where, in this case, the indoor air pathway can be considered significant. For example, the Massachusetts and Connecticut criteria are applicable only to groundwater conditions less than 15 feet deep. The RCRA Corrective Action program has not provided similar guidance, and the authors have been involved in RCRA sites where regulators have insisted that VOCs in deep aquifers more than 60 feet bgs present immediate risks to human health.

In the absence of clear guidance and appropriate modeling parameters, owners and operators of RCRA corrective action facilities may want to consider air or soil vapor monitoring up front to alleviate many of the issues and uncertainties raised in this article. Air monitoring is not a standard component of RCRA Facility Investigation (RFI) reports, and a supplemental investigation of indoor air quality is often required after soil and groundwater has already been characterized. The USEPA's default parameters for the J&E model are not directly applicable to industrial facilities, and the results are often not duplicated by actual monitoring data.

The authors' experiences characterizing the indoor air exposure pathway for purposes of evaluating corrective action alternatives have identified numerous scientific shortcomings.