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Emergency Standard Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites[1]

This Emergency Standard is issued by ASTM in accordance with a special procedure to meet the demand for rapid issuance of specific documents.[2]

1. Scope

1.1 This guide covers risk-based corrective action (RBCA), that is a consistent decision-making process for the assessment and response to subsurface contamination, based on the protection of human health and environmental resources. Sites with subsurface contamination vary greatly in terms of complexity, physical and chemical characteristics, and in the risk that they may pose to human health and environmental resources. The RBCA process recognizes this diversity, and utilizes a tiered approach where assessment and remediation activities are appropriately tailored to site-specific conditions and risks. This flexibility allows RBCA to be more cost-effective than traditional approaches under which all sites conform to uniform standards and procedures. While the RBCA process is not limited to a particular class of compounds, this guide emphasizes the application of RBCA to petroleum fuel releases.

1.2 The decision process described in this guide integrates risk and exposure assessment practices, as suggested by the United States Environmental Protection Agency (USEPA), with site assessment activities and remedial measure selection to ensure that the chosen action is protective of human health and environmental resources. The following general sequence of events is prescribed in RBCA, once the process is triggered by the suspicion or confirmation of hazardous hydrocarbon levels:

1.2.1 A Tier 1, or preliminary site assessment,

1.2.2 Classification of the site by the urgency of initial response,

1.2.3 Implementation of an initial response action appropriate for the selected site classification,

1.2.4 Comparison of site conditions with Tier 1 screening levels given in an evergreen "look-up" table containing conservative risk-based screening levels and other relevant criteria (drinking water standards, aesthetic criteria, ecological criteria, etc.),

1.2.5 Deciding if Tier 1 screening target levels are appropriate, and if not,

1.2.5.1 Collect additional site-specific information as required, and

1.2.5.2 Develop site-specific target levels and points of compliance (Tiers 2 and 3).

1.2.6 Comparison of the negotiated target levels with site conditions at the appropriate points of compliance, and if any exceedences are noted,

1.2.6.1 Develop a corrective action plan to achieve the negotiated target levels in an appropriate time period (based on risks posed by the site). Alternatives to be considered include combinations of traditional remedial methods (for example, excavation, pump and treat, and soil vapor extraction) with institutional controls and natural attenuation.

1.3 This guide describes the previously outlined process in more detail. For those interested only in becoming familiar with RBCA, the short main body of text provides a brief overview of the RBCA process (see Section 4), and then presents RBCA procedures in a step-by-step fashion (see Section 5) followed by a discussion of ways in which the process can be misapplied (see Section 6). For those interested in additional background information, appendixes have been included. These are focused on the following:

1.3.1 Characteristics of petroleum fuels (see Appendix X1),

1.3.2 Derivation of the example Tier 1 RBSL Look-Up Table (see Appendix X2),

1.3.3 Uses of predictive modeling relative to the RBCA process (see Appendix X3),

1.3.4 Considerations for institutional controls (see Appendix X4), and

1.3.5 RBCA examples (Appendix X5).

1.4 The values stated in inch-pound units are to be regarded as the standard. The SI units given in parentheses are for information only.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Significance and Use

2.1 The allocation of limited resources (for example, time, money, regulatory oversight, qualified professionals) to any one petroleum release site necessarily influences corrective action decisions at other sites. This has spurred the search for innovative and cost-effective approaches to corrective action decision making, that still ensures that human health and environmental resources are protected.

2.2 The RBCA process presented in this guide is a rational and consistent, streamlined decision process for selecting appropriate corrective actions at petroleum release sites. Advantages of the RBCA approach are as follows:

2.2.1 Decisions are based on reducing the risk of adverse human or environmental impacts to appropriate levels,

2.2.2 Ensurance that site assessment activities are focussed on collecting only that information that is necessary to making risk-based corrective action decisions,

2.2.3 Ensurance that limited resources are focussed towards those sites that pose the greatest risk to human health

[1] This emergency standard is under the jurisdiction of ASTM Committee E-50 on Environmental Assessment and is the direct responsibility of Subcommittee E50.01 on Storage Tanks.

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[2] See paragraph 13.2 of the Regulations Governing ASTM Technical Committees.

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and environmental resources at any time,

2.2.4 Ensurance that the preferred remedial option is the most economically favorable one that has a high probability of achieving the negotiated degree of exposure and risk reduction, and

2.2.5 Compliance can be evaluated relative to site-specific standards applied at site-specific points of compliance.

2.3 This guide is intended to be consistent with USEPA guidance for risk and exposure assessment (**1–8**).[3]

3. Tiered Approach to RBCA at Petroleum-Release Sites

3.1 In risk-based corrective action, traditional components of corrective action programs (site assessment, remedial action selection, and compliance monitoring) are integrated with USEPA-recommended risk and exposure assessment practices to create a process by which corrective action decisions are made in a consistent and cost-effective manner that is protective of human health and environmental resources.

3.2 In order to streamline the RBCA process, it is implemented in a tiered approach, involving increasingly sophisticated levels of data collection and analysis. The conservative assumptions of earlier tiers are replaced with site-specific assumptions. Upon completion of each tier, the user reviews the results and recommendations, and decides if more site-specific analysis is required. The following forms the basis for a three-tiered RBCA planning process:

3.2.1 *Tier 1: Site Classification and Non-Site-Specific Screening-Level Corrective Action Goals*—In Tier 1, sites are classified by the urgency of need for initial corrective action, based on information collected from historical records, a visual inspection, and minimal site assessment data. The user is required to identify contaminant sources, obvious environmental impacts, if any, the presence of potentially impacted humans and environmental resources (for example, workers, residents, water bodies, etc.), and potential significant transport pathways (for example, ground water flow, atmospheric dispersion, etc.). Associated with site classifications are prescribed initial response actions that are to be implemented prior to proceeding further with the RBCA process.

3.2.1.1 In addition, as part of Tier 1, conservative corrective action goals are based on an evergreen list of non-site-specific, risk-based screening levels (RBSLs), aesthetic criteria, and other appropriate standards such as Maximum Contaminant Levels (MCLs) for potable ground water use. Tier 1 RBSLs are typically derived for standard exposure scenarios using current reasonable maximum exposure (RME) and toxicological parameters as recommended by the USEPA, and conservative contaminant migration models. These values are "evergreen" and will change as new methodologies and parameters are developed. Tier 1 RBSLs may be presented as a range of values, corresponding to a range of risks, and a risk management decision is made to select the screening levels to be used. This evaluation may include a cost-benefit analysis, where the user considers the costs associated with achieving various levels of risk reduction.

3.2.2 *Tier 2: Site-Specific Corrective Action Goals*—Tier 2 provides the user with an option for determining site-specific target levels (SSTLs) and appropriate points of compliance when it is judged that Tier 1 corrective action goals are not appropriate. This decision is typically based on comparing the cost of achieving Tier 1 corrective action goals with the cost for Tier 2 analyses, considering the probability that the Tier 2 site-specific goals will be significantly less costly to achieve than Tier 1 goals. It is important to note that both Tier 1 and Tier 2 screening levels are based on achieving similar levels of human health and environmental resource protection (for example, 10^{-4} to 10^{-6} risk levels); however, in moving to higher tiers the user is able to develop more cost-effective corrective action plans because the conservative assumptions of earlier tiers are replaced with more realistic site-specific assumptions. Additional site assessment data may be required, but minimal incremental effort is usually required relative to Tier 1. In some cases the Tier 2 SSTLs are derived from the same equations used to calculate Tier 1 RBSLs, except that site-specific parameters are used in the calculations. At other sites, the Tier 2 analysis may involve applying Tier 1 RBSLs at more probable points of exposure, such as property boundaries and negotiated points of compliance, and then deriving Tier 2 corrective action goals for the petroleum source areas based on demonstrated and predicted attenuation of hydrocarbon compounds with distance (see 5.6.3). Again, Tier 2 corrective action goals are considered conservative and are consistent with USEPA-recommended practices.

3.2.3 *Tier 3: Site-Specific Corrective Action Goals*—Tier 3 provides the user with an option for determining SSTLs and appropriate points of compliance when it is judged that Tier 2 corrective action goals are not appropriate. As stated in 3.2.3, this decision is typically based on comparing the cost of achieving Tier 2 corrective action goals with the cost for Tier 3 analyses, considering the probability that the Tier 3 site-specific goals will be significantly less costly to achieve than Tier 2 goals. The major distinction between Tier 2 and Tier 3 analyses is that a Tier 3 analysis is generally a substantial incremental effort relative to Tiers 1 and 2, as the analysis is much more complex and may include detailed site assessment, probabilistic evaluations, and sophisticated chemical fate/transport models.

3.3 If the selected target levels are exceeded and corrective action is necessary, the user develops a corrective action plan in order to reduce the potential for adverse impacts. One option is to utilize traditional remediation processes to reduce contaminant concentrations below the target levels. Another equally viable option is to achieve exposure reduction (or elimination) through the institutional controls discussed in Appendix X4, or through the use of containment measures, such as capping and hydraulic control.

4. Risk-Based Corrective Action (RBCA) Procedures

4.1 The sequence of principal tasks and decisions associated with the RBCA process are outlined on the flowchart shown in Fig. 1. Each of these tasks and decisions is discussed as follows:

4.2 *Step 1: Initial Site Assessment*—Collect and assemble the data necessary to complete the Tier 1 analyses. In the interest of minimizing costs and expediting the RBCA

[3] The boldface numbers in parentheses refer to the list of references at the end of this standard.

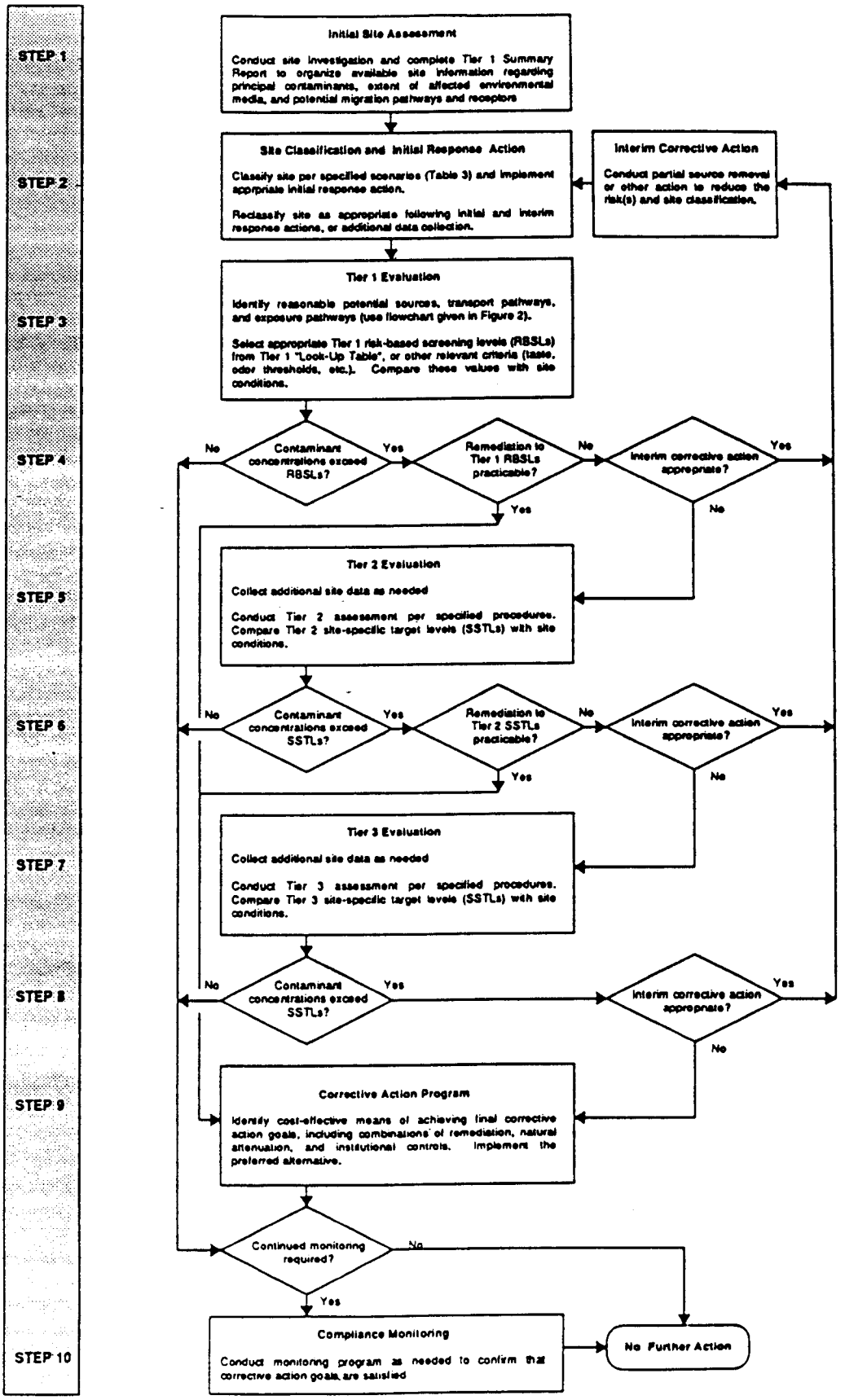

FIG. 1 Risk-Based Corrective Action Process Flowchart

process, it is important to focus initial site assessment activities on gathering that information which is necessary for the Tier 1 evaluation. As needed for Tier 2 or Tier 3 analyses, additional information (aquifer hydraulic properties, site-specific contaminant attenuation parameters, etc.), can be collected as the RBCA program proceeds. Tier 1 requirements and activities include the following:

4.2.1 *Source Characterization*—Historical records of site activities and past releases, and chemical analyses results are used to identify contaminants of concern and to locate major sources of these compounds. The field sampling program is then focussed toward identifying maximum concentrations of those most prevalent, toxic, and mobile compounds, and towards identifying if both soil and ground water have been impacted (see Appendix X1 for a discussion of the properties of common petroleum fuel products, as well as a summary of the relevant chemical and toxicological properties of key constituents). Initially, chemical analyses may include a wide range of suspected contaminants; however, as the investigation proceeds, the list of analytes can be narrowed to those compounds that consistently exceed the values given in a Tier 1 Look-Up Table (see 4.4). Most investigations will encompass the sampling of all media (soil, ground water, soil gas) to some degree; although, the analyses conducted on each may be very different. For example, soil samples may be sent to a laboratory for detailed gas chromatography (GC) analyses, while soil gas samples from a utility conduit may be analyzed by a portable explosimeter when the goal is to verify if immediately hazardous levels exist. The amount of information necessary for the Tier 1 assessment is generally less than that collected for Tier 2 and Tier 3 analyses.

4.2.2 *Potential for Exposure and Degradation of Beneficial Uses*—The locations of humans and environmental resources that could reasonably be impacted "receptors," identification of potential significant transport and exposure pathways (ground water transport, vapor migration through soils and utilities, etc.), and current and potential future uses of the surrounding land, ground water, surface water, and sensitive habitats is recorded. This information can be obtained from visual inspections, well inventory records, engineering drawings, and hydrogeological assessment data, and is used to determine the potential for continued near-term and future impacts to human and environmental receptors.

4.2.3 *Extent of Migration*—In addition to the sampling of source areas, concentrations are measured at potential points of exposure or concern (for example, dissolved concentrations in nearby drinking water wells, or vapor concentrations in nearby conduits or sewers). If it is already known that maximum source area concentrations exceed the Tier 1 non-site-specific RBSLs, aesthetic criteria, or other relevant criteria (for example, explosive limits), then it is useful at this point to also define the boundaries where these criteria are exceeded. The investigation should assess any potential preferential migration pathway, such as sewers, electrical conduits, etc.

4.2.4 *Summary of Site Characterization Results*—The site characterization data should be summarized in a clear and concise format. This can be accomplished through the use of preformatted tables and figures. This has the added advantage that the consistent presentation of results for many sites often speeds the review process. Tables 1 and 2 present outlines for tables and figures, respectively, that can be used to effectively present the site characterization results.

4.3 *Step 2: Site Classification and Initial Response Action*—As the user gathers data, site conditions should be compared with the scenarios listed in Table 3, and the scenario/classification most representative of actual site conditions should be selected, beginning with Classification 1 scenarios. Then an appropriate initial response action should be implemented, consistent with site conditions. This process is repeated every time additional data is collected at a site.

4.3.1 The classification scheme given in Table 3 is based on the current and projected degree of hazards to human health and environmental resources. "Classification 1" sites are associated with immediate threats to human health and environmental resources, while "Classification 4" sites are associated with no reasonable potential threat to human health or to environmental resources. Classification levels falling between the two extremes are representative of varying degrees of potential impacts.

4.3.2 Associated with each classification in Table 3 is a potential initial response action; the initial response actions are implemented in order to eliminate any potential immediate impacts to human health and environmental resources as well as to minimize the potential for future impacts that may occur as one proceeds with the RBCA process, or while limited resources are focussed on higher priority sites. Note that initial response actions do not always require active remediation; in many cases the initial response action is to monitor or further assess site conditions to ensure that risks posed by the site do not increase above acceptable levels with time. The initial response actions given in Table 3 should be regarded as recommendations, and the user is free to negotiate other appropriate alternatives.

4.3.3 The site classification should be reevaluated whenever additional site information is collected or whenever implementation of an interim corrective action causes a significant change in site conditions.

4.4 *Step 3: Comparison of Site Conditions with Tier 1 RBSLs and Tier 1 Corrective Action Selection*—Select the reasonable potential exposure scenario(s), if any, most appropriate for the site from a list of predefined exposure scenarios. At a minimum the list of predefined exposure scenarios includes residential and commercial/industrial scenarios; however, in some cases it may also be desirable to supplement these with an infrequent construction worker scenario.

4.4.1 The risk evaluation flowchart presented in Fig. 2 is a tool that can be used to guide the user in selecting appropriate exposure scenarios based on site characterization information. This worksheet is also used in the evaluation of corrective action alternatives. To complete this flowchart, a step-wise process is followed:

4.4.1.1 *Exposure Pathway Characterization*—Identify primary sources, secondary sources, transport mechanisms, and exposure pathways.

4.4.1.2 Using the data summarized from Tier 1, customize the risk evaluation flowchart for the site by checking the small checkbox for every relevant source, transport mechanism, and exposure pathway.

4.4.1.3 *Exposure Scenario Characterization*—Select ap-

TABLE 1 RBCA Tier 1 Example of Table Summary

Table Number	Title	Contents
1	Executive Summary	Summary of visual & historic assessments Summary of receptor characterization Summary of tasks completed to date Results of classification exercise and selected interim response action Corrective action criteria exceeded Proposed/implemented corrective action
2	Site Description	Site address Site owner/contact Agency contacts Local land use Topography Surface water characterization Climatic information
3	Site Ownership and Activity Record	Describe past production and materials handling activities, waste disposal practices, chemicals used, and site ownership
4	Past Releases or Source Areas	Describe potential sources and spill events including: location, type and volume of materials released, time and duration of release, and affected media (soil, ground water, surface water, etc.) Discuss past remediation efforts as appropriate List any potential off-site sources
5	Summary of Current and Completed Site Activities	Describe all relevant ongoing and completed corrective-action activities at the site (site investigation, emergency response, etc.)
6	Regional Hydrogeologic Conditions	Describe regional geologic framework through depth of principal aquifer and any other potentially impacted units
7	Site Hydrogeologic Conditions	Describe site geologic framework through depth of principal aquifer and any other potentially impacted units Vadose zone thickness and geology Depth to ground water Thickness of aquifer Maximum well yield Flow direction and gradient Description of any confining units Current ground water quality (TDS) Off-site water quality
8	Beneficial Use Summary	Identify existing and reasonable potential beneficial uses for land, ground water, and surface water
9	Receptor Survey (wells, utilities, basements, surface water, environmental resources, etc.)	Summarize relevant results (that is, for well survey: well designation, distance from site, depth, construction details, age, etc. of wells for 0.5-mile (0.8-km) radius around site) Identify those receptors most likely to be impacted
10	Analytical Summary Sheets (these are intended for use as a tool to summarize analytical data and provide a tool for comparing site data with Tier 1 screening levels)	Compounds detected Analytical method(s) used Practical quantification limit Number of samples analyzed Compound detection frequency Maximum concentration detected Location of maximum concentration Sampling date Background concentrations Trend (stable, increasing, decreasing) Appropriate Tier 1 target levels (RBSLs, MCLs, etc.)
11	Ecological Assessment Summary Sheet	Observed impacts associated with site to vegetation, birds, fish, mammals, etc. Presence and description of any impacted sensitive habitats Ecological receptors (threatened or endangered species, economically or sport-important species, etc.)

propriate receptors (if any) and exposure scenarios based on current and projected reasonable use scenarios.

4.4.1.4 For each exposure pathway selected, check the most appropriate exposure scenario description (residential, commercial, etc.). Consider land use restrictions and surrounding land use when making this selection. Residential exposure scenarios (the most conservative) are appropriate for residential, or unrestricted future land use. Commercial exposure scenarios are used to characterize current and projected future commercial and light industrial land use. Do not check any boxes if there are no receptors present, or likely to be present, or if institutional controls prevent exposure from occurring, and are likely to stay in place.

4.4.2 For each compound and selected exposure scenario, use Tier 1 RBSL "Look-Up Tables" to identify the corresponding RBSLs for a range of carcinogenic risk levels (from 10^{-6} to 10^{-4} are often evaluated) and hazard quotients (HQ) equal to unity. After considering aesthetic, ecological, other relevant criteria, and background levels, select appropriate Tier 1 screening level(s). Then compare these values with site conditions and identify any exceedences. If there is sufficient site characterization data, the user may opt to compare screening level values with statistical limits (for example, upper confidence levels) rather than maximum values detected.

4.4.3 Note that when the potential for carcinogenic human health effects is of concern, an acceptable risk level is selected to complete this step, and this value must be negotiated between all parties involved, and may involve using results from a cost-benefit analysis. One approach is to

TABLE 2 RBCA Tier 1 Example of Figure Summary

Figure Number	Title	Contents
1	Site Location Map	Show general vicinity Identify surface water bodies Show ground water supply wells and designation (for example, drinking water, irrigation, etc.) Identify other potential receptors Show topography (use USGS quad maps, if available)
2	Extended Site Map	Show local use including schools, hospitals, retirement homes, residential areas, commercial areas, and any ground water supply wells
3	Site Plan View (This map should be developed from historical maps, plans, and aerial photos, and should encompass potentially impacted areas.)	Location of all structures Location of buried tanks Location of buried conduits Location of suspected/confirmed sources Areas of ecological interest Areas of soil contamination
4	Site Photos	Provide photos of site, potentially contaminated areas, tank excavations, and surrounding property (show in chronological order)
5	Ground water Elevation Map	Potentiometric surface contour map for any potentially impacted water-bearing units Date
6	Geologic Cross Section(s)	Show site stratigraphy through full depth of potentially impacted water-bearing units, including underlying confining layer Prepare two cross sections for each site (parallel and perpendicular to ground water flow) Indicate contaminant concentrations Indicate subsurface piping, conduits, tanks, etc.
7	Dissolved Contaminant Plume Map(s)	Show lateral extent of impacted ground water Indicate sampling locations and concentrations Show location of any free product Show time series data (if possible)

select target risk levels that reflect the probability of exposure; more conservative risk levels are selected for actual exposures and less conservative risk levels are chosen for potential exposure scenarios. For reference, risks in the 10^{-6} to 10^{-4} risk range are generally considered acceptable at this time. When selecting a target risk level it is important to be aware of background concentrations; for example, as shown in Table 4, national ambient background benzene vapor concentrations exceed concentrations corresponding to the 10^{-6} risk level (as calculated using USEPA reasonable maximum exposure (RME) parameter values). Note that additivity of risks is not explicitly considered in the Tier 1 analysis, as it is expected that the screening levels are very conservative, and typically a limited number of chemicals is considered to be of concern at most sites. Additivity is addressed in Tier 2 and Tier 3 analyses.

4.4.4 Tier 1 "Look-Up Tables" contain conservative, non-site-specific RBSLs for a range of prescribed scenarios, and may also include aesthetic criteria, and other appropriate standards. The RBSLs are calculated in accordance with methodology suggested by the USEPA. For each exposure scenario the RBSLs are based on current USEPA RME parameters, and current toxicological information given in the USEPA integrated risk information system (IRIS) database, health effects assessment summary tables (HEAST), or peer-reviewed source(s). Consequently, the RBSL look-up table is an "evergreen" set of values that is continually updated whenever new methodologies and parameters are developed. Where required, hydrocarbon fate and transport estimations are based on conservative fate and transport models.

4.4.5 Table 4 is an example of an abbreviated Tier 1 RBSL Look-Up Table for compounds of concern associated with petroleum fuel releases. The exposure scenarios selected in this case are for residential and industrial/commercial scenarios characterized by USEPA RME parameters for adult males. The assumptions and methodology used in deriving Table 4 are discussed in Appendix X2. Note that not all possible exposure pathways are considered in the derivation of Table 4, that is presented here only as an example. The user should always review the assumptions and methodology used to derive values in a look-up table to make sure that they are consistent with reasonable exposure scenarios for the site being considered as well as currently accepted methodologies. The value of creating a standard look-up table is that users do not have to repeat the conservative exposure calculations for each site encountered, except when RME parameters, toxicological information, or recommended methodologies are updated. Many states have compiled such tables for direct exposure pathways, and for the most part many of these tables contain identical values (as they are based on the same assumptions). Values for the cross-media pathways (for example, volatilization and leaching), when available, often differ; because these involve coupling exposure calculations with predictive equations for the fate and transport of chemicals in the environment. As yet, there is little agreement in the technical community as to conservative non-site-specific values for the transport and fate model parameters, or as to the choice of the models themselves. Again, note that Table 4 is presented here only as an abbreviated example of a Tier 1 RBSL Look-Up Table for typical compounds of concern associated with petroleum fuels. It should not be interpreted as a list of proposed standards.

4.4.6 *Use of Total Petroleum Hydrocarbons (TPH) Measurements*—Various chemical analysis methods commonly referred to as TPH are often used in site assessments. These methods usually determine the total amount of hydrocarbons present as a single number, and give no information on the types of hydrocarbon present. Such TPH methods are useful for identifying the boundaries of contamination and for locating "hot spots", and may be useful for risk assessments where the whole product toxicity approach is appropriate. However in general, TPH should not be used for

TABLE 3 Site Classification Scenarios and Potential Initial Response Actions[A]

NOTE—For the purpose of this site classification process, an aquifer is considered to be a potential potable water supply if it has the potential to yield > 200 gal/day (756 L/day), and meets local water quality criteria (that is total dissolved solids (TDS) < 10 000 mg/L).

Classification	Criteria and Prescribed Scenarios	Possible Initial Response Actions[B]
1	*Immediate Threat to Human Health, Safety, or Sensitive Environmental Receptors:*	*Notify Appropriate Authorities, Property Owners, and Potentially Affected Parties, and Evaluate the Need to:*
1.1	Explosive levels, or concentrations of vapors that could cause acute health effects, are present in a residence or other building.	Evacuate occupants, begin abatement measures such as subsurface ventilation, or building pressurization.
1.2	Explosive levels of vapors are present in subsurface utility system(s), but no building or residences are impacted.	Evacuate immediate vicinity, begin abatement measures such as ventilation
1.3	Free-product is present in significant quantities at ground surface, on surface water bodies, in utilities other than water supply lines, or in surface water runoff.	Prevent further free-product migration by appropriate containment measures, institute free-product recovery, restrict area access.
1.4	An active public water supply well, public water supply line, or public surface water intake is impacted or immediately threatened.	Notify user(s), provide alternate water supply, hydraulically control contaminated water, and treat water at point-of-use.
1.5	Ambient vapor/particulate concentrations exceed concentrations of concern from an acute exposure, or safety viewpoint.	Install vapor barrier (capping, foams, etc.), remove source, or restrict access to affected area.
1.6	A sensitive habitat or sensitive resources (sport fish, economically important species, threatened and endangered species, etc.) are impacted and affected.	Minimize extent of impact by containment measures and implement habitat management to minimize exposure.
2	*Short-Term (0 to 2 years) Threat to Human Health, Safety, or Sensitive Environmental Receptors:*	*Notify Appropriate Authorities, Property Owners, and Potentially Affected Parties, and Evaluate the Need to:*
2.1	There is potential for explosive levels, or concentrations of vapors that could cause acute effects, to accumulate in a residence or other building.	Assess the potential for vapor migration (through monitoring/modeling) and remove source (if necessary), or install vapor migration barrier.
2.2	Shallow contaminated surface soils are open to public access, and dwellings, parks, playgrounds, day-care centers, schools, or similar use facilities are within 500 ft (152.4 m) of those soils.	Remove soils, cover soils, or restrict access.
2.3	A non-potable water supply well is impacted or immediately threatened.	Notify owner/user, evaluate the need to install point-of-use water treatment, hydraulic control, or alternate water supply.
2.4	Ground water is impacted and a public or domestic water supply well producing from the impacted aquifer is located within two years projected ground water travel distance downgradient of the known extent of contamination.	Institute monitoring, then evaluate if natural attenuation is sufficient, or if hydraulic control is required.
2.5	Ground water is impacted and a public or domestic water supply well producing from a different interval is located within the known extent of contamination.	Monitor ground water well quality and evaluate if control is necessary to prevent vertical migration to the supply well.
2.6	Impacted surface water, storm water, or ground water discharges within 500 ft (152.4 m) of a sensitive habitat, or surface water body used for human drinking water or contact recreation.	Institute containment measures, restrict access to areas near discharge, and evaluate the magnitude and impact of the discharge.
3	*Long-Term (>2 Years) Threat to Human Health, Safety, or Sensitive Environmental Receptors:*	*Notify Appropriate Authorities, Property Owners, and Potentially Affected Parties, and Evaluate the Need to:*
3.1	Subsurface soils (>3 ft (0.9 m) BGS) are impacted and depth between impacted soils and the first potable aquifer is less than 50 ft (15.2 m).	Monitor ground water and determine the potential for future contaminant migration to the aquifer.
3.2	Ground water is impacted and potable water supply wells producing from the impacted interval are located >2 years ground water travel time from the dissolved plume.	Monitor the dissolved plume and evaluate the potential for natural attenuation and the need for hydraulic control.
3.3	Ground water is impacted and non-potable water supply wells producing from the impacted interval are located >2 years ground water travel time from the dissolved plume.	Identify water usage of well, assess the effect of potential impact, monitor the dissolved plume, and evaluate whether natural attenuation or hydraulic control are appropriate control measures.
3.4	Ground water is impacted and non-potable water supply wells that do not produce from the impacted interval are located within the known extent of contamination.	Monitor the dissolved plume, determine the potential for vertical migration, notify the user, and determine if any impact is likely.
3.5	Impacted surface water, storm water, or ground water discharges within 1500 ft (457.2 m) of a sensitive habitat, or surface water body used for human drinking water or contact recreation.	Investigate current impact on sensitive habitat or surface water body, restrict access to area of discharge (if necessary), and evaluate the need for containment/control measures.
3.6	Shallow contaminated surface soils are open to public access, and dwellings, parks, playgrounds, day-care centers, schools, or similar use facilities are more than 500 ft (152.4 m) of those soils.	Restrict access to impact soils.
4	*No Demonstrable Long-Term Threat to Human Health, Safety, or Sensitive Environmental Receptors:* Priority 4 scenarios encompass all other conditions not described in Priorities 1, 2, and 3, and that are consistent with the priority description previously given. Some examples are:	*Notify Appropriate Authorities, Property Owners, and Potentially Affected Parties, and Evaluate the Need to:*
4.1	Non-potable aquifer with no existing local use impacted.	Monitor ground water and evaluate effect of natural attenuation on dissolved plume migration.
4.2	Impacted soils located more than 3 ft (0.9 m) BGS and greater than 50 ft (15.2 m) above nearest aquifer.	Monitor ground water and evaluate effect of natural attenuation on leachate migration.
4.3	Ground water is impacted and non-potable wells are located down-gradient outside the known extent of contamination, and they produce from a nonimpacted zone.	Monitor ground water and evaluate effect of natural attenuation on dissolved plume migration.

[A] Johnson, D. C., DeVaull, G. E., Ettinger, R. A., MacDonald, R. L. M., Stanley, C. C., Westby, T. S., and Conner, J., "Risk-Based Corrective Action: Tier 1 Guidance Manual," Shell Oil Co., July 1993.

[B] Note that these are potential initial response actions that may not be appropriate for all sites. The user is encouraged to select options that best address the short-term health and safety concerns of the site, while the RBCA process progresses.

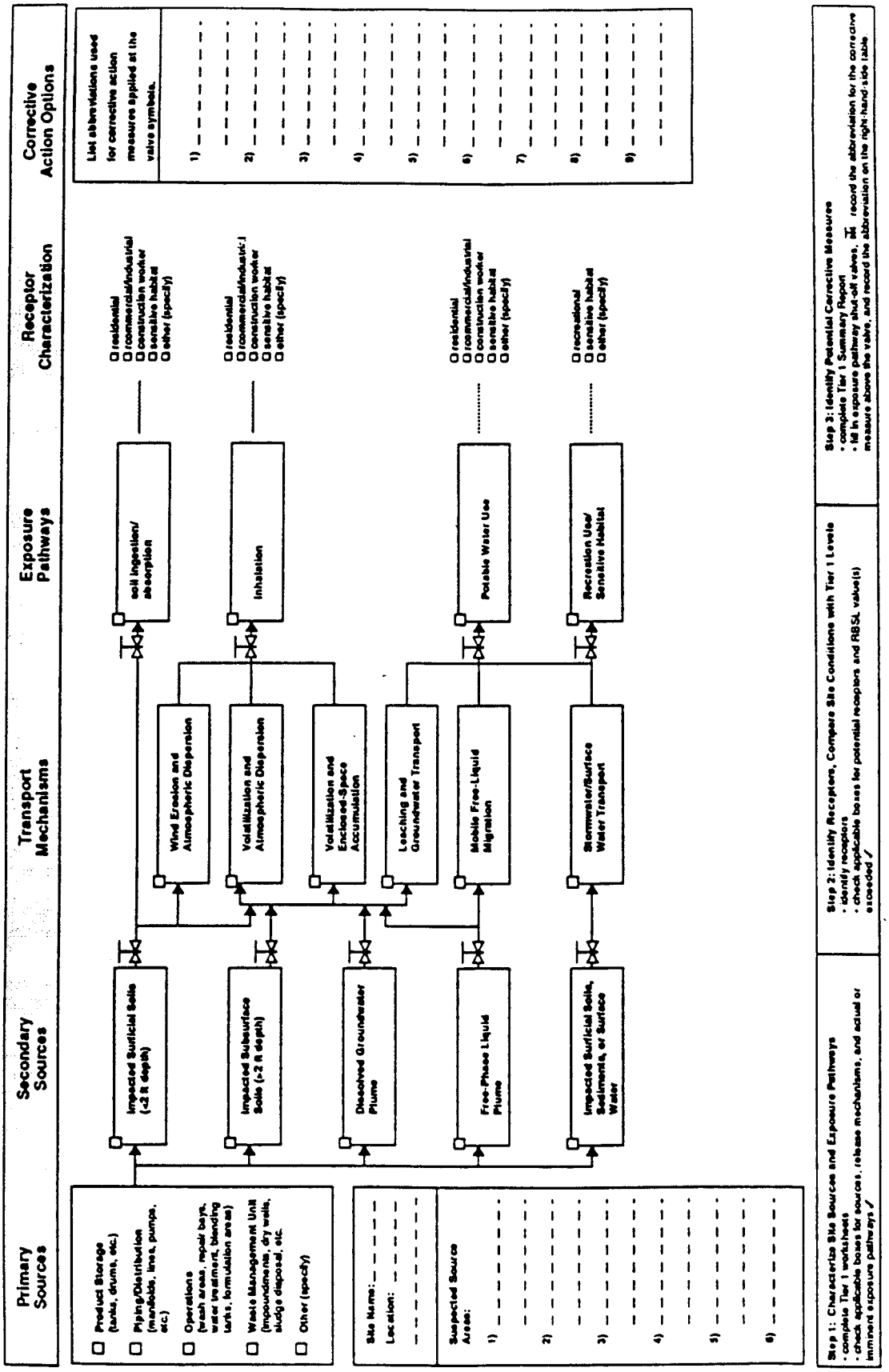

FIG. 2 Exposure Scenario Evaluation Flowchart

TABLE 4 Example Tier 1 Risk-Based Screening Level (RBSL) Look-Up Table

NOTE—This table is presented here only as an example set of Tier 1 RBSLs. It is not a list of proposed standards. The user should review all assumptions prior to using any of the values. Appendix [illegible] describes the basis of these values.

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Toluene	Xylenes (mixed)	Naphthalene	Benzo(a)pyrene
AIR	Indoor Air Screening Levels for Inhalation Exposure (µg/m^3)	Residential	Cancer Risk = 1E-06	[illegible]					1.86E-03
			Cancer Risk = 1E-04	[illegible]					1.86E-01
			Chronic HQ = 1		[illegible]	5.56E+02	9.73E+03	1.95E+01	
		Commercial/ Industrial	Cancer Risk = 1E-06	[illegible]					2.35E-03
			Cancer Risk = 1E-04	[illegible]					2.35E-01
			Chronic HQ = 1		[illegible]	5.84E+02	1.02E+04	2.04E+01	
	Outdoor Air Screening Levels for Inhalation Exposure (µg/m^3)	Residential	Cancer Risk = 1E-06	[illegible]					1.40E-03
			Cancer Risk = 1E-04	[illegible]					1.40E-01
			Chronic HQ = 1		[illegible]	4.17E+02	7.30E+03	1.46E+01	
		Commercial/ Industrial	Cancer Risk = 1E-06	[illegible]					2.35E-03
			Cancer Risk = 1E-04	[illegible]					2.35E-01
			Chronic HQ = 1		1.46E+03	5.84E+02	1.02E+04	2.04E+01	
	OSHA TWA PEL (µg/m^3)			3.20E+00	4.35E+05	7.53E+05	4.35E+05	5.00E+04	2.00E+02 [1]
	Mean Odor Detection Threshold (µg/m^3) [2]			1.98E+05		6.00E+03	8.70E+04	2.00E+02	
	National Indoor Background Concentration Range (µg/m^3) [3]			3.25E+00 - 2.15E+01	2.20E+00 - 9.70E+00	9.60E-01 - 2.91E+01	4.85E+00 - 4.76E+01		
SOIL	Soil - Volatilization to Outdoor Air (mg/kg)	Residential	Cancer Risk = 1E-06	2.72E-01					RES
			Cancer Risk = 1E-04	2.72E+01					RES
			Chronic HQ = 1		RES	RES	RES	RES	
		Commercial/ Industrial	Cancer Risk = 1E-06	4.57E-01					RES
			Cancer Risk = 1E-04	4.57E+01					RES
			Chronic HQ = 1		RES	RES	RES	RES	
	Soil - Vapor Intrusion from Soil to Buildings (mg/kg)	Residential	Cancer Risk = 1E-06	5.37E-03					RES
			Cancer Risk = 1E-04	5.37E-01					RES
			Chronic HQ = 1		3.46E+01	2.08E+01	RES	4.07E+01	
		Commercial/ Industrial	Cancer Risk = 1E-06	1.69E-02					RES
			Cancer Risk = 1E-04	1.69E+00					RES
			Chronic HQ = 1		9.08E+01	5.45E+01	RES	1.07E+02	
	Surficial Soil (0-3 ft.) Ingestion/ Dermal/ Inhalation (mg/kg)	Residential	Cancer Risk = 1E-06	5.82E+00					1.30E-01
			Cancer Risk = 1E-04	5.82E+02					1.30E+01
			Chronic HQ = 1		7.83E+03	1.33E+04	1.45E+05	9.77E+02	
		Commercial/ Industrial	Cancer Risk = 1E-06	1.00E+01					3.04E-01
			Cancer Risk = 1E-04	1.00E+03					3.04E+01
			Chronic HQ = 1		1.15E+04	1.87E+04	2.08E+05	1.50E+03	
	Soil - Leachate to Protect Groundwater Ingestion Target Level (mg/kg)	MCL's		2.93E-02	9.11E+00	1.77E+01	3.05E+02	N/A	9.42E+00
		Residential	Cancer Risk = 1E-06	1.72E-02					5.50E-01
			Cancer Risk = 1E-04	1.72E+00					RES
			Chronic HQ = 1		4.75E+01	1.29E+02	RES	2.29E+01	
		Commercial/ Industrial	Cancer Risk = 1E-06	5.78E-02					1.85E+00
			Cancer Risk = 1E-04	5.78E+00					RES
			Chronic HQ = 1		1.33E+02	3.61E+02	RES	6.42E+01	
GROUND WATER	Groundwater - Volatilization to Outdoor Air (mg/L)	Residential	Cancer Risk = 1E-06	1.10E+01					> S
			Cancer Risk = 1E-04	1.10E+03					> S
			Chronic HQ = 1		> S	> S	> S	> S	
		Commercial/ Industrial	Cancer Risk = 1E-06	1.84E+01					> S
			Cancer Risk = 1E-04	> S					> S
			Chronic HQ = 1		> S	> S	> S	> S	
	Groundwater Ingestion (mg/L)	MCL's		5.00E-03	7.00E-01	1.00E+00	1.00E+01	N/A	2.00E-04
		Residential	Cancer Risk = 1E-06	2.94E-03					1.17E-05
			Cancer Risk = 1E-04	2.94E-01					1.17E-03
			Chronic HQ = 1		3.65E+00	7.30E+00	7.30E+01	1.46E-01	
		Commercial/ Industrial	Cancer Risk = 1E-06	9.87E-03					3.92E-05
			Cancer Risk = 1E-04	9.87E-01					> S
			Chronic HQ = 1		1.02E+01	2.04E+01	> S	4.09E-01	
	Groundwater - Vapor Intrusion from Groundwater to Buildings (mg/L)	Residential	Cancer Risk = 1E-06	8.12E-02					> S
			Cancer Risk = 1E-04	8.12E+00					> S
			Chronic HQ = 1		> S	1.14E+02	> S	1.06E+01	
		Commercial/ Industrial	Cancer Risk = 1E-06	2.56E-01					> S
			Cancer Risk = 1E-04	2.56E+01					> S
			Chronic HQ = 1		> S	3.00E+02	> S	2.78E+01	

[A] As benzene soluble coal tar pitch volatiles.

[B] American Industrial Hygiene Association, *Odor Thresholds for Chemicals with Established Occupational Health Standards*, 1989.

[C] From: Shah and Singh, *Environmental Science Technolology* Vol 22, No. 12; ATSDR, 1988, Toxilogical Profiles, U.S. Public Health Services, 1988, and Wallace, L. A., *Journal of Occupational Medicine*, Vol 28, No. 5, 1986.

[D] "RES"—selected risk level is not exceeded for pure compound present at any concentration.

[E] ">S"—selected risk level is not exceeded for all possible dissolved levels (≤ pure component solubility).

"individual constituent" risk assessments because the general measure of TPH provides insufficient information about the amounts of individual compounds present.

4.4.7 *Corrective Action Assessment*—Identify potential Tier 1 corrective measures that will remove sources, limit release mechanisms, block exposure pathways that are responsible for the screening level concentration exceedences. Record these on the Tier 1 analysis summary sheet.

4.4.8 The exposure scenario evaluation flowchart (see Fig. 2) can be used to graphically portray the effect of the Tier 1 corrective action. Select the Tier 1 corrective measure or measures (shown as valve symbols) that will break the lines linking sources, transport mechanisms, and pathways causing the screening level concentration to be exceeded. Adjust the mix of corrective measures until no affected receptors exceed the screening levels with the corrective measures in place. Show the most likely Tier 1 corrective measure(s) selected for this site by marking the appropriate valve symbols on the flowchart and recording a corrective measure abbreviation (defined by the user on the right-hand-side of Fig. 2).

4.5 *Step 4: Evaluation of Tier 1 Results*—At this point, results of the Tier 1 assessment are reviewed and one of the following four options is selected:

4.5.1 *No Action*—If source concentrations do not exceed applicable screening level concentrations, no further action may be required. Compliance monitoring may be implemented, as appropriate, to confirm that current conditions persist or improve with time.

4.5.2 *Final Corrective Action*—If source concentrations exceed applicable screening level concentrations, a corrective action program may be designed and implemented to achieve the Tier 1 corrective action goals. This program may include some combination of source removal and containment technologies, as well as institutional controls.

4.5.3 *Interim Corrective Action*—If achieving the necessary risk reduction is impracticable due to technology or resource limitations, an interim corrective action, such as removal or treatment of "hot spots", may be conducted to address the most significant concerns, change the site classification and initial response, and facilitate reassessment of the corrective action plan.

4.5.4 *Tier Upgrade—Further Analysis*—If remediation, containment measures, and institutional controls are judged to be impracticable or inappropriate, additional site information can be collected as needed for reassessment of corrective action goals in accordance with Tier 2 of the RBCA process. This decision is typically based on comparing the cost of achieving Tier 1 corrective action goals with the cost for Tier 2 analyses, considering the probability that the Tier 2 site-specific goals will be significantly less costly to achieve than Tier 1 goals. It is important to note that both Tier 1 and Tier 2 screening levels are based on achieving similar levels of human health and environmental resource protection (for example, 10^{-4} to 10^{-6} risk levels); however, in moving to higher tiers the user is able to develop more cost-effective corrective action plans because the conservative assumptions of earlier tiers are replaced with more realistic site-specific assumptions.

4.5.5 This decision and the scope of any proposed RBCA activities are now recorded and the Tier 1 analysis is complete.

4.6 *Step 5: Tier 2—Expanded Site Assessment, Reclassification, and Site-Specific Corrective Action Goals (Optional)*—Tier 2 provides the user with an option for negotiating site-specific risk-based corrective action goals and points of compliance when there is an economic incentive to do so (see 4.5.4). Additional site assessment data may be required; however, the incremental effort is typically minimal relative to Tier 1. In most cases, only a limited number of pathways, exposure scenarios, and chemicals are considered in the Tier 2 analysis since many are eliminated from consideration during the Tier 1 evaluation. In Tier 2 the user negotiates compliance points and target concentrations at these points, and uses a combination of assessment data and predictive modeling results to determine target source area concentrations that correspond to compliance with the negotiated compliance point target levels. Examples of Tier 2 analyses include:

4.6.1 Application of Tier 1 RBSLs Look-Up Table values at reasonable points of compliance (as opposed to anywhere in an aquifer, geologic formation, or atmosphere as is done in Tier 1), such as property boundaries or negotiated compliance points located somewhere between source areas and reasonable potential receptors. Corrective action goals (site-specific target levels, time to achieve these values, etc.) for source areas are then based on the demonstrated and predicted attenuation (reduction in concentration with distance) of compounds that migrate away from the source area.

4.6.2 Applying the methodology for deriving values in the Tier 1 RBSL Look-Up Table, with the exception that site-specific parameters may replace the Tier 1 conservative assumptions. An example might be in the modeling of hydrocarbons leaching from soils to ground water, where assumed infiltration rates, source sizes, and aquifer parameters are replaced with the actual values for a given site.

4.6.3 An example of a Tier 2 application is illustrated in Fig. 3. Here, fuel has been released from a leaking product line and ground water is impacted. The responsible party wishes to establish target concentrations for ground water in the source areas based on assessment data that demonstrates the attenuation of contaminants down-gradient of the source area. A negotiated compliance point is selected down-gradient of the source area and up-gradient of any actual potential receptors. Data from the site indicates that contaminant concentrations are observed, and predicted, to decline by a factor of 100 between the source area and the compliance point, therefore the target source area ground water concentration is established at 100 times the compliance point concentration.

4.6.4 Tiers 2 and 3 of the RBCA process involve the development of SSTLs based on the measured and predicted attenuation of contaminants away from the source area(s). Tier 2 is based on the practical realization that our ability to characterize sites is limited; and, therefore, expectations for compound attenuation with distance from source area(s) are based on interpolating and extrapolating site-specific data through the use of relatively simplistic "screening" mathematical models. These predictive equations are characterized by the following:

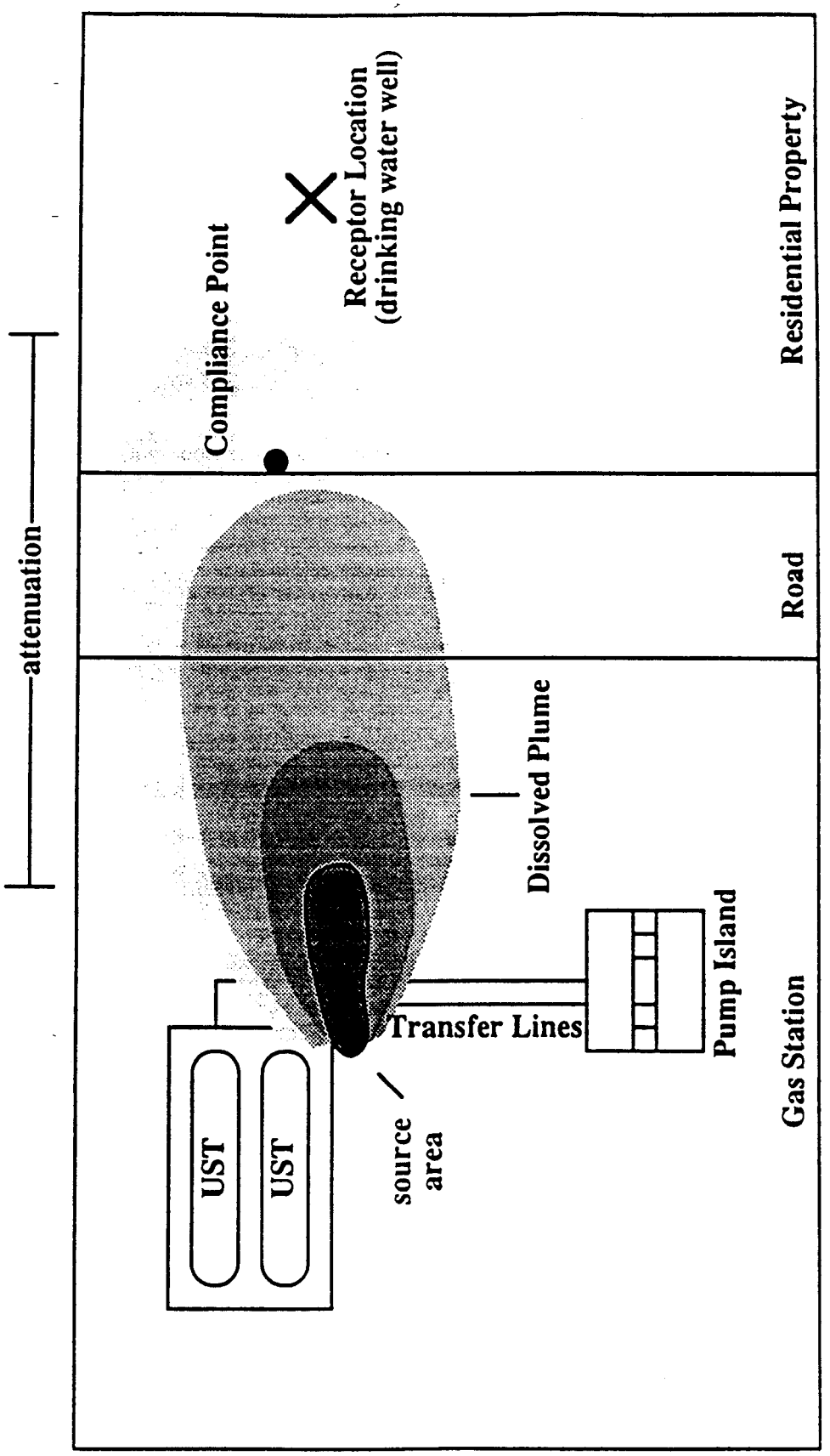

FIG. 3 Attenuation of Contaminants Dissolved in Ground water With Distance Down-Gradient of Source Area

4.6.4.1 The models are relatively simplistic, and are often algebraic or semi-analytical expressions,

4.6.4.2 Model input is limited to practicably attainable site-specific data, or easily estimated quantities (for example, total porosity, soil bulk density), and

4.6.4.3 The models are based on descriptions of relevant physical/chemical phenomena. Any mechanisms that are neglected result in predictions that are conservative relative to those likely to occur (for example, assuming constant concentrations in petroleum source areas, or neglecting attenuation due to natural biodegradation). In other words, these models are biased towards predicting exposure concentrations in excess of those likely to occur. Appendix X3 discusses the use of predictive models and presents example screening level models that might be considered for Tier 2 analyses.

4.7 *Step 6: Evaluation of Tier 2 Results*—At this point, results of the Tier 2 analyses are reviewed and one of the following four options is selected:

4.7.1 *No Action*—If source concentrations do not exceed Tier 2 SSTLs, no further action may be required. Compliance monitoring may be implemented, as appropriate, to confirm that current conditions persist or improve with time.

4.7.2 *Final Corrective Action*—If source concentrations exceed Tier 2 SSTLs, a corrective action program may be designed and implemented. This program may include some combination of source removal, treatment, and containment technologies, as well as institutional controls.

4.7.3 *Interim Corrective Action*—If achieving the desired risk reduction is impracticable due to technology or resource limitations, an interim corrective action, such as removal or treatment of "hot spots," may be conducted to address the most significant concerns, change the site classification, and facilitate reassessment of the corrective action plan.

4.7.4 *Tier Upgrade—Further Analysis*—If remediation, containment measures, and institutional controls are judged to be impracticable, additional site information can be collected as needed for reassessment of corrective action goals in accordance with Tier 3 of the RBCA process. This decision is typically based on comparing the cost of achieving Tier 2 corrective action goals with the cost for Tier 3 analyses, considering the probability that the Tier 3 site-specific goals will be significantly less costly to achieve than Tier 2 goals. It is important to note that both Tier 2 and Tier 3 screening levels are based on achieving similar levels of human health and environmental resource protection (for example, 10^{-4} to 10^{-6} risk levels); however, in moving no higher tiers the user is able to develop more cost-effective corrective action plans because the conservative assumptions of earlier tiers are replaced with more realistic site-specific assumptions.

4.7.5 This decision and the scope of any proposed RBCA activities are now recorded and Tier 2 is complete.

4.8 *Step 7: Tier 3—Expanded Site Assessment, Reclassification, and Site-Specific Corrective Action Goals (Optional)*—In a Tier 3 assessment, SSTLs are developed on the basis of more sophisticated statistical and contaminant fate and transport analyses, using site-specific input parameters (for example, Monte Carlo simulations). Tier 3 corrective action assessments commonly involve collection of significant additional site information and completion of more costly modeling efforts than required for either a Tier 1 or Tier 2 planning effort. Examples of Tier 3 analyses include the following:

4.8.1 The use of numerical ground water codes that predict time-dependent dissolved contaminant transport under conditions of spatially varying permeability fields to predict exposure point concentrations,

4.8.2 The use of site-specific data, screening level models, and Monte Carlo analyses to predict a statistical distribution of exposures and risks for a given site, and

4.8.3 The gathering of sufficient data to refine site-specific parameter estimates (for example, biodegradation rates) and improve model accuracy in order to minimize future monitoring requirements.

4.9 *Step 8: Evaluation of Tier 3 Results*—At this point, results of the Tier 3 analyses are reviewed and one of the following four options is selected:

4.9.1 *No Action*—If source concentrations do not exceed Tier 3 SSTLs, no further action may be required. Compliance monitoring may be implemented, as appropriate, to confirm that current conditions persist or improve with time.

4.9.2 *Final Corrective Action*—If source concentrations exceed Tier 3 SSTLs, a corrective action program may be designed and implemented. This program may include some combination of source removal, treatment, and containment technologies, as well as institutional controls.

4.9.3 *Interim Corrective Action*—If achieving the desired risk reduction is impracticable due to technology or resource limitations, an interim corrective action, such as removal or treatment of "hot spots," may be conducted to address the most significant concerns, change the site classification, and facilitate reassessment of the corrective action plan.

4.9.4 This decision and the scope of any proposed RBCA activities are now recorded and Tier 3 is complete.

4.10 *Step 9: Implementing the Selected Corrective Action Program*—When it is judged that no further assessment is necessary, or practicable, an engineering feasibility study should be conducted to confirm the most cost-effective option for achieving the final corrective action levels. Detailed design specifications may then be developed for installation and operation of the selected measure. The corrective action must continue until such time as compliance monitoring indicates that contaminant concentrations no longer exceed the negotiated compliance levels. Corrective action options include mass removal (treatment, excavation, etc.) methods as well as containment and institutional controls (for example, deed restrictions).

4.11 *Step 10: Compliance Monitoring and Site Maintenance*—In many cases, compliance monitoring for a limited time period is required to demonstrate the effectiveness of implemented corrective action measures. Upon completion of this monitoring effort (if required), no further action is required. In addition, some measures (for example, physical barriers—capping, hydraulic control, etc.) require maintenance to ensure integrity and continued performance.

4.12 *No Further Action and Site Closure*—When RBCA goals have been demonstrated to be achieved, and compliance monitoring and site maintenance are no longer required to ensure that this condition persists, then no further action is necessary—except to ensure that institutional controls (if any) remain in place.

5. Potential Problems

5.1 As with any process, the potential exists for misapplication of the RBCA process. In most cases the root cause will be a lack of understanding of the process and improper use of process components. In order to prevent misuse of the process, the following should be avoided:

5.1.1 Use of Tier 1 risk-based screening levels as default remediation standards rather than conservative screening levels,

5.1.2 Placing arbitrary time constraints on the process; for example, requiring that Tiers 1, 2, and 3 be completed within 30-day time periods rather than letting the time frame be based on risks posed by the site,

5.1.3 Use of the process as a closure tool only, rather than a process that is applicable during all phases of corrective action,

5.1.4 Requiring responsible parties to achieve technology-based remedial limits prior to requesting the approval for site-specific goals,

5.1.5 Inappropriate use of predictive modelling,

5.1.6 Dictating that corrective action goals can only be achieved through source removal and treatment actions, thereby restricting the use of exposure reduction options, such as containment and institutional controls,

5.1.7 Use of inappropriate or unfounded exposure factors,

5.1.8 Use of antiquated toxicity parameters,

5.1.9 Neglecting aesthetic and other criteria when negotiating target concentrations,

5.1.10 Not considering the effects of additivity when screening multiple chemicals,

5.1.11 Not negotiating institutional controls, compliance points, and target risk ranges before submitting corrective action plans, and

5.1.12 Not honoring institutional controls.

APPENDIXES

(Nonmandatory Information)

X1. PETROLEUM FUEL CHARACTERISTICS: COMPOSITION, PHYSICAL CHEMICAL PROPERTIES, AND TOXICOLOGICAL ASSESSMENT SUMMARY

X1.1 *Introduction:*

X1.1.1 Petroleum fuels originating from crude oil are complex mixtures of hundreds to thousands of chemicals; however, practical limitations allow us to focus only on a limited subset of key components when assessing the impact of petroleum fuel releases to the environment. Thus, it is important to have a basic understanding of petroleum fuel properties, compositions, and the physical, chemical, and toxicological properties of some compounds most often identified as the key, or "indicator," chemicals.

X1.1.2 This appendix provides a basic introduction to the physical, chemical, and toxicological characteristics of petroleum fuels (gasoline, diesel fuel, jet fuel, etc.)[4] focussed primarily towards that information which is most relevant to assessing potential impacts due to releases of these fuels into the subsurface. Much of the information presented is summarized from the references listed at the end of this guide. For specific topics, the reader is referred to the following sections of this appendix:

X1.1.2.1 *Composition of Petroleum Fuels*—See X1.2.

X1.1.2.2 *Physical, Chemical, and Toxicological Properties of Petroleum Fuels*—See X1.3.

X1.1.2.3 *Indicator Compounds*—See X1.4.

X1.1.2.4 *Toxicity of Petroleum Hydrocarbons*—See X1.5.

X1.1.2.5 *Profiles of Select Compounds*—See X1.6.

X1.2 *Composition of Petroleum Fuels:*

X1.2.1 Most petroleum fuels are derived from crude oil by distillation, which is a process that separates compounds by volatility. Crude oils are variable mixtures of thousands of chemical compounds, primarily hydrocarbons; consequently, the petroleum fuels themselves are also variable mixtures of large numbers of components. The biggest variations in composition are from one type of product to another (for example, gasoline to motor oil); however, there are even significant variations within different samples of the same product type. For example, samples of gasoline taken from the same fuel dispenser on different days, or samples taken from different service stations will have different compositions. These variations are the natural result of differing crude oil sources, refining processes and conditions, and kinds and amount of additives used.

X1.2.2 *Components of Petroleum Fuels*—The components of petroleum fuels can be generally classified as either hydrocarbons (organic compounds composed of hydrogen and carbon only) or as non-hydrocarbons (compounds containing other elements, such as oxygen, sulfur, or nitrogen). Hydrocarbons make up the vast majority of the composition of petroleum fuels. The non-hydrocarbon compounds in petroleum products are mostly hydrocarbon-like compounds containing minor amounts of oxygen, sulfur, or nitrogen. Most of the trace levels of metals found in crude oil are removed by refining processes for the lighter petroleum products.

X1.2.3 *Descriptions and Physical Properties of Petroleum Fuels*—In order to simplify the description of various petroleum products, boiling point ranges and carbon number (number of carbon atoms per molecule) ranges are commonly used to describe and compare the compositions of various petroleum products. Table X1.1 summarizes these characteristics for a range of petroleum products. Moving down the list from gasoline, increases in carbon number range and boiling range and decreases in volatility (denoted

[4] "Alternative Fuels," or those fuels not based on petroleum hydrocarbons (or containing them in small amounts), such as methanol or M85 are beyond the scope of the discussion in this appendix.

by increasing flash point) indicate the transition to "heavier products." Additional descriptions of each of these petroleum fuels are provided below.

X1.2.4 *Gasoline*—Gasoline is composed of hydrocarbons and "additives" that are blended with the fuel to improve fuel performance and engine longevity. The hydrocarbons fall primarily in the C4 to C12 range. The lightest of these are highly volatile and rapidly evaporate from spilled gasoline. C4 and C5 aliphatic hydrocarbons rapidly evaporate from spilled gasoline (hours to months, depending primarily on the temperature and degree of contact with air). Substantial portions of the C6 and heavier hydrocarbons also evaporate, but at lower rates than for the lighter hydrocarbons.

X1.2.4.1 Figure X1.1 shows gas chromatograms of a fresh gasoline and the same gasoline after simulated weathering; air was bubbled through the gasoline until 60 % of its initial volume was evaporated. In gas chromatography, the mixture is separated into its components, with each peak representing different compounds. Higher molecular weight components appear further to the right along the *x*-axis. For reference, positions of the *n*-aliphatic hydrocarbons are indicated in Fig. X1.1. The height of, and area under, each peak are measures of how much of that component is present in the mixture. As would be expected by their higher volatilities, the lighter hydrocarbons (up to about C7) evaporate first and are greatly reduced in the weathered gasoline. The gas chromatogram of a fuel oil is also shown for comparison.

X1.2.4.2 The aromatic hydrocarbons in gasoline are primarily: benzene (C_6H_6), toluene (C_7H_8), ethylbenzene (C_8H_{10}), and xylenes (C_8H_{10}); these are collectively referred to as "BTEX." Some heavier aromatics are present also, including low amounts of polyaromatic hydrocarbons (PAHs). Aromatics typically comprise about 10 to 40 % of gasoline.

X1.2.4.3 Oxygenated compounds ("oxygenates") such as alcohols (for example, methanol or ethanol) and ethers (for example, methyl tertiarybutyl ether—MTBE) are sometimes added to gasoline as octane boosters and to reduce carbon monoxide exhaust emissions. MTBE has been a common additive only since about 1980.

X1.2.4.4 Leaded gasoline, that was more common in the past, contained lead compounds added as octane boosters. Tetraethyl lead (TEL) is one lead compound that was commonly used as a gasoline additive. Other similar compounds were also used. Sometimes mixtures of several such compounds were added. Because of concerns over atmospheric emissions of lead from vehicle exhaust, the EPA has reduced the use of leaded gasolines. Leaded gasolines were phased out of most markets by 1989.

X1.2.4.5 In order to reduce atmospheric emissions of lead, lead "scavengers" were sometimes added to leaded gasolines. Ethylene dibromide (EDB) and ethylene dichloride (EDC) were commonly used for this purpose.

X1.2.5 *Kerosene and Jet Fuel*—The hydrocarbons in kerosene commonly fall into the C11 to C13 range, and distill at approximately 150 to 250°C. Special wide-cut (that is, having broader boiling range) kerosenes and low-flash kerosenes are also marketed. Both aliphatic and aromatic hydrocarbons are present, including more multi-ring compounds than gasoline.

X1.2.5.1 Commercial jet fuels JP-8 and Jet A have similar compositions to kerosene. JP-4 and JP-5 are wider cuts used by the military. They contain lighter distillates and have some characteristics of both gasoline and kerosene.

X1.2.5.2 Aromatic hydrocarbons comprise about 10 to 20 % of kerosene and jet fuels.

X1.2.6 *Diesel Fuel and Light Fuel Oils*—Light fuel oils include No. 1 and No. 2 fuel oils, and boil in the range from 160 to 400°C. Hydrocarbons in light fuel oils and diesel fuel typically fall in the C10 to C20 range. Because of their higher molecular weights, constituents in these fuels are less volatile, less water soluble, and less mobile than gasoline or kerosene range hydrocarbons.

X1.2.6.1 About 25 to 35 % of No. 2 fuel oil is composed of aromatic hydrocarbons, primarily alkylated benzenes and naphthalenes. BTEX concentrations are generally low.

X1.2.6.2 Number 1 fuel oil is typically a straight run distillate.

X1.2.6.3 Number 2 fuel oil can be either a straight run distillate, or else is produced by catalytic cracking (a process in which larger molecules are broken down into smaller ones). Straight run distillate No. 2 is commonly used for home heating fuel, while the cracked product is often used for industrial furnaces and boilers. Both No. 1 and No. 2 fuel oils are sometimes used as blending components for jet fuel or diesel fuel formulations.

X1.2.7 *Heavy Fuel Oils*—The heavy fuel oils include Nos. 4, 5, and 6 fuel oils. They are sometimes referred to as "gas oils" or "residual fuel oils." These are composed of hydrocarbons ranging from about C19 to C25 and have a boiling range from about 315 to 540°C. They are dark in color and considerably more viscous than water. They typically contain 15 to 40 % aromatic hydrocarbons, dominated by alkylated phenanthrenes and naphthalenes. Polar compounds containing nitrogen, sulfur, or oxygen may comprise 15 to 30 % of the oil.

X1.2.7.1 Number 6 fuel oil, also called "Bunker Fuel" or "Bunker C," is a gummy black product used in heavy industrial applications where high temperatures are available to fluidize the oil. Its density is greater than that of water.

X1.2.7.2 Numbers 4 and 5 fuel oils are commonly produced by blending No. 6 fuel oil with lighter distillates.

X1.3 *Physical, Chemical, and Toxicological Characteristics of Petroleum Fuels:*

X1.3.1 *Trends in Physical/Chemical Properties of Hydrocarbons*—In order to better understand the subsurface behavior of hydrocarbons it is helpful to be able to recognize trends in important physical properties with increasing

TABLE X1.1 Generalized Chemical and Physical Characterization of Petroleum Fuels

	Predominant Carbon No. Range	Boiling Range, (°C)	Flash Point,[A] (°C)
Gasoline	C4 to C12	25 to 215	−40
Kerosene and Jet Fuels	C11 to C13	150 to 250	<21,[B] 21 to 55,[C] >55[D]
Diesel Fuel and Light Fuel Oils	C10 to C20	160 to 400	>35
Heavy Fuel Oils	C19 to C25	315 to 540	>50

[A] Typical values.
[B] Jet-B, AVTAG and JP-4.
[C] Kerosene, Jet A, Jet A-1, JP-8 and AVTUR.
[D] AVCAT and JP-5.

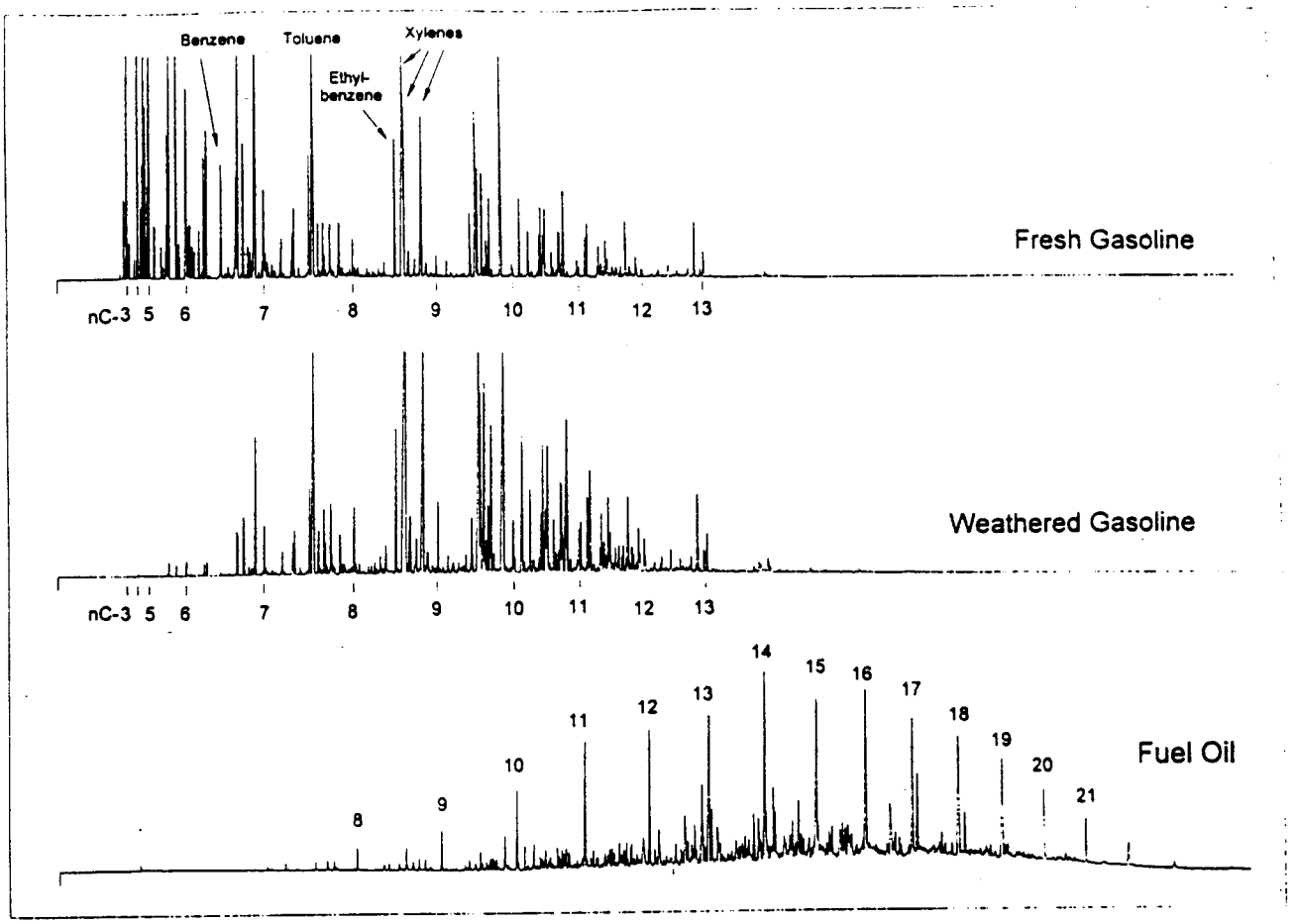

FIG. X1.1 Gas Chromatograms of Some Petroleum Fuels

number of carbon atoms. These trends are most closely followed by compounds with similar molecular structures, such as the straight-chained, single-bonded aliphatic hydrocarbons. In general, as the carbon number (or molecule size) increases, the following trends are observed.

X1.3.1.1 Higher boiling points (and melting points),

X1.3.1.2 Lower vapor pressure (volatility),

X1.3.1.3 Greater density,

X1.3.1.4 Lower water solubility, and

X1.3.1.5 Stronger adhesion to soils and less mobility in the subsurface.

X1.3.2 Table X1.2 lists physical, chemical, and toxicological properties for a number of hydrocarbons found in petroleum fuels. In general:

X1.3.2.1 Aliphatic petroleum hydrocarbons with more than ten carbon atoms are expected to be immobile in the subsurface, except when dissolved in non-aqueous phase liquids (NAPLs), due to their low water solubilities, low vapor pressures, and strong tendency to adsorb to soil surfaces.

X1.3.2.2 Aromatic hydrocarbons are more water soluble and mobile in water than aliphatic hydrocarbons of similar molecular weight.

X1.3.2.3 Oxygenates generally have much greater water solubilities than hydrocarbons of similar molecular weight, and hence are likely to be the most mobile of petroleum fuel constituents in leachate and ground water. The light alcohols, including methanol and ethanol, are completely miscible with water in all proportions.

X1.3.3 *Properties of Mixtures*—It is important to note that the partitioning behavior of individual compounds is affected by the presence of other hydrocarbons in the subsurface. The maximum dissolved and vapor concentrations achieved in the subsurface are always less than that of any pure compound, when it is present as one of many constituents of a petroleum fuel. For example, dissolved benzene concentrations in ground water contacting gasoline-impacted soils rarely exceed 1 to 3 % of the ≈1800 mg/L pure component solubility of benzene.

X1.3.4 *Trends in Toxicological Properties of Hydrocarbons*—A more detailed discussion of toxicological assessment is given in X1.5 (see also Appendix X3), followed by profiles for select chemicals found in petroleum fuels given in X1.6. Of the large number of compounds present in petroleum fuels, aromatic hydrocarbons (BTEX, PAH's, etc.) are the constituents that human and aquatic organisms tend to be most sensitive to (relative to producing adverse health impacts).

X1.4 *Indicator Compounds for Risk Assessments:*

X1.4.1 It is not practicable to evaluate every compound

TABLE X1.2 Chemical and Toxicological Properties of Selected Hydrocarbons

Compounds	Weight of Evidence Class[A]	Oral RfD [mg/kg-day]	Inhalation RfC [mg/m³]	Oral Slope Factor[A] [mg/kg-day]⁻¹	Drinking Water MCL[A] [mg/L]	Solubility[B] [mg/L]	Octanol/Water Partition Coefficient[B] [log K_{ow}]	Organic Carbon Adsorption Coefficient[B] [log K_{oc}]
Benzene	A	...	...	0.029[G]	0.005	1750	2.12	1.92
Toluene	D	0.2[A]	0.4[A]	...	1	535	2.73	2.48
Ethylbenzene	D	0.1[A]	1[A]	...	0.7	152	3.15	3.04
Xylenes	D	2[A]	0.3[C,E]	...	10.0	198	3.26	2.38
n-Hexane	[E]	0.06[C], 0.6[D]	0.2[D]	...	...	13[L]	...	...
MTBE	...	[E]	3[A]	...	...	48 000[M]	1.06–1.30[N]	1.08[O]
MEK	D	0.6[A]	1[A]	...	[I]	268 000	0.26	0.65
MIBK	...	[F]	0.08[C,E], 0.8[D]	...	...	...	...	...
Methanol	...	0.5[A]	[E]	...	...	...	...	...
Ethanol	...	...	...	...	...	1 000 000	−0.32	0.34
TBA	...	...	...	...	...	...	...	...
Lead	B2	...	...	...	0.015[J]	...	...	...
EDC	B2	...	...	0.091	0.005	8 520	1.48	1.15
EDB	B2	...	...	85	0.00005	4 300	1.76	1.64
PAHs:								
Pyrene	D	0.03[A]	...	...	...	0.132	4.88	4.58
Benzo(a)pyrene	B2	...	...	7.3	0.0002	0.00120	6.06	6.74
Anthracene	D	0.3[A]	...	...	...	0.0450	4.45	4.15
Phenanthrene	D	...	...	...	...	1.00	4.46	4.15
Naphthalene	D[E]	0.004[C], 0.04[D]	...	...	...	31.0[L]	3.01[L]	3.11[P]
Chrysene	B2	...	...	1.15[H]	0.0002	0.00180	5.61	5.30
Benzo(k)fluoranthene	B2	...	...	...	0.0002[K]	0.00430	6.06	5.74
Fluorene	D	0.04[A]	...	...	...	1.69	4.20	3.86
Fluoranthene	D	0.04[A]	...	...	...	0.206	4.90	4.58
Benzo(g,h,i)perylene	D	...	...	...	...	0.000700	6.51	6.2
Benzo(b)fluoranthene	B2	...	...	...	0.0002[K]	0.0140	6.06	5.74
Benz(a)anthracene	B2	...	...	...	0.0002[K]	0.00570	5.60	6.14

[A] See Ref (6).
[B] See Ref (4).
[C] See Ref (7).
[D] See Ref (7).
[E] The data is pending in the EPA-IRIS database.
[F] The data has been withdrawn in the EPA-IRIS database.
[G] The inhalation unit risk for benzene is 8.3×10^{-3} (mg/m³)⁻¹. The drinking water unit risk for benzene is 8.3×10^{-4} (mg/L)⁻¹.
[H] See Ref (10). Health-based criteria for carcinogenic polycyclic aromatic compounds (PAHs) with the exception of dibenzo(a,h)anthracene are set at one tenth of the level of benzo(a)pyrene due to their recognized lesser potency. .
[I] Listed in the January 1991 Drinking Water Priority List and may be subject to future regulation (56 FR 1470, 01/14/91).
[J] USEPA. May 1993. Office of Drinking Water. 15 µg/L is an action level; standard for tap water.
[K] Proposed standard.
[L] See Ref (11).
[M] See Ref (12).
[N] See Ref (13).
[O] Estimation Equation (from (14)):
(1) $\log K_{oc} = -0.55 \log S + 3.64$, where S = water solubility (mg/L)
(2) $\log K_{oc} = 0.544 \log P + 1.377$
[P] See Ref (9).

present in a petroleum product to assess the human health or environmental risk from a spill of that product. For this reason, risk management decisions are generally based on assessing the potential impacts from a select group of "indicator" compounds. It is inherently assumed in this approach that a significant fraction of the total potential impact from all chemicals is due to the indicator compounds. The selection of indicator compounds is based on the consideration of exposure routes, concentrations, mobilities, toxicological properties and aesthetic characteristics (taste, odor, etc.). Historically, the relatively low toxicities and dissolved-phase mobilities of aliphatic hydrocarbons have made these compounds of less concern relative to aromatic hydrocarbons. When additives are present in significant quantities, consideration should also be given to including these as indicator compounds.

X1.4.2 Table X1.3 identifies indicator compounds most often considered when assessing impacts of petroleum fuels, based on knowledge of their concentration in the specific fuel, as well as their toxicity, water solubility, subsurface

TABLE X1.3 Commonly Selected Indicator Compounds for Petroleum Fuels

	Unleaded Gasoline	Leaded Gasoline	Kerosene/ Jet Fuels	Diesel/ Light Fuel Oils	Heavy Fuel Oils
Benzene	X	X	X	...	...
Toluene	X	X	X	...	...
Ethylbenzene	X	X	X	...	...
Xylene	X	X	X	...	...
MTBE, TBA, MEK, MIBK, methanol, ethanol	When suspected[A]	When suspected[A]	...	...	...
Lead, EDC, EDB	...	X	...	...	...
PNAs[B]	...	...	X	X	X

[A] For example, when these compounds may have been present in the spilled gasoline. These additives are not present in all gasolines.
[B] A list of selected PNAs for consideration is presented in Table X1.2

mobility, aesthetic characteristics, and the availability of sufficient information to conduct risk assessments. The indicator compounds are identified by an "X" in the appropriate column.

X1.5 *Toxicity of Petroleum Hydrocarbons:*

X1.5.1 The following discussion gives a brief overview of origin of the toxicity parameters (reference doses (RfDs), and slope factors (SFs), a justification for common choices of indicator compounds and then, in X1.6, a brief summary of the toxicological, physical, and chemical parameters associated with common indicator compounds.

X1.5.2 *How Toxicity Is Assessed: Individual Chemicals Versus Mixtures*—The toxicity of an individual chemical is typically established based on dose-response studies that estimate the relationship between different dose levels and the magnitude of their adverse effects (that is, toxicity). The dose-response data is used to identify a "safe dose" or a toxic level for a particular adverse effect. For a complex mixture of chemicals, the same approach can be used. For example, to evaluate the toxicity of gasoline, a "pure" reference gasoline would be evaluated instead of the individual chemical. This "whole-product" approach to toxicity assessment is strictly applicable only to mixtures identical to the evaluated mixture; gasolines with compositions different from the reference gasoline might have toxicities similar to the reference, but some differences would be expected. In addition, as the composition of gasoline released to the environment changes through natural processes (volatilization, leaching, biodegradation), the toxicity of the remaining portion may change also.

X1.5.3 An alternative to the "whole-product" approach for assessing the toxicity of mixtures is the "individual-constituent" approach. In this approach, the toxicity of each individual constituent (or a selected subset of the few most toxic constituents, so-called "indicator compounds") is separately assessed and the toxicity of the mixture is assumed to be the sum of the individual toxicities using a hazard index approach. This approach is often used by the USEPA; however, it is inappropriate to sum hazard indices unless the toxicological endpoints and mechanisms of action are the same for the individual compounds. In addition, the compounds to be assessed must be carefully selected based on their concentrations in the mixture, their toxicities, how well their toxicities are known, and how mobile they are in the subsurface. Lack of sufficient toxicological information is often an impediment to this procedure.

X1.5.4 *Use of TPH Measurements in Risk Assessments*—Various chemical analysis methods commonly referred to as "total petroleum hydrocarbons" (TPH) are often used in site assessments. These methods usually determine the total amount of hydrocarbons present as a single number, and give no information on the types of hydrocarbon present. Such TPH methods are useful for identifying the boundaries of contamination and for locating "hot spots," and may be useful for risk assessments where the whole product toxicity approach is appropriate. However in general, TPH should not be used for "individual constituent" risk assessments because the general measure of TPH provides insufficient information about the amounts of individual compounds present.

X1.5.5 *Toxicity Assessment Process*—Dose-response data are used to identify a "safe dose" or toxic level for a particular observed adverse effect. Observed adverse effects can include whole body effects (for example, weight loss, neurological observations), effects on specific body organs, including the central nervous system, teratogenic effects (defined by the ability to produce birth defects), mutagenic effects (defined by the ability to alter the genes of a cell) and carcinogenic effects (defined by the ability to produce malignant tumors in living tissues). Because of the great concern over risk agents which may produce carcinogenic effects, the U.S. Environmental Protection Agency has developed weight-of-evidence criteria for determining whether a risk agent should be considered carcinogenic (see Table X1.2).

X1.5.6 Most estimates of a "safe dose" or toxic level are based on animal studies. In rare instances, human epidemiological information is available on a chemical. Toxicity studies can generally be broken into three categories based on the number of exposures to the risk agent and the length of time the study group was exposed to the risk agent. These studies can be described as follows:

X1.5.6.1 *Acute Studies*—Acute studies, typically use one dose or multiple doses over a short time frame (24 h). Symptoms are usually observed within a short time frame and can vary from weight loss to death.

X1.5.6.2 *Chronic Studies*—Chronic studies, use multiple exposures over an extended period of time, or a significant fraction of the animal's (typically two years) or the individual's lifetime. The chronic effects of major concern are carcinogenic, mutagenic, and teratogenic effects. Other chronic health effects such as liver and kidney damage are also important.

X1.5.6.3 *Subchronic Studies*—Subchronic studies, use multiple or continuous exposures over an extended period (three months is the usual time frame in animal studies). Observed effects include those given for acute and chronic studies.

1.5.6.4 Ideally, safe or acceptable doses are calculated from chronic studies, although, due to the frequent paucity of chronic data, subchronic studies are used.

X1.5.7 Data from the above studies are used to generate reference doses (RfDs), reference concentrations (RfCs), and are also used in generating drinking water maximum concentration levels (MCLs) and goals (MCLGs), health advisories (HAs) and water quality criteria. These terms are defined in Table X1.4.

X1.5.8 *Selection of Indicator Compounds*—The impact on human health and the environment in cases of gasoline and middle distillate contamination of soils and ground water can be assessed based on potential receptor (that is, aquatic organisms, human) exposure to three groups of materials; light aromatic hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), and in older spills, lead. Although not one of the primary contaminants previously described, ethylene dibromide (EDB) and ethylene dichloride (EDC) were used as lead scavengers in some leaded gasolines and may be considered compounds of concern, when present.

X1.5.9 The light aromatics, benzene, toluene, xylenes, and ethylbenzene have relatively high water solubility and sorb poorly to soils. Thus, they have high mobility in the environment, moving readily through the subsurface. When

TABLE X1.4 Weight of Evidence Criteria for Carcinogens

Category	Criterion
A	Human carcinogen, with sufficient evidence from epidemiological studies
B1	Probable human carcinogen, with limited evidence from epidemiological studies
B2	Probable human carcinogen, with sufficient evidence from animal studies and inadequate evidence or no data from epidemiological studies
C	Possible human carcinogen, with limited evidence from animal studies in the absence of human data
D	Not classifiable as to human carcinogenicity, owing to inadequate human and animal evidence
E	Evidence of noncarcinogenicity for humans, with no evidence of carcinogenicity in at least two adequate animal tests in different species, or in both adequate animal and epidemiological studies

released into surface bodies of water, these materials exhibit moderate to high acute toxicity to aquatic organisms. Although environmental media are rarely contaminated to the extent that acute human toxicity is an issue, benzene is listed by the USEPA as a Group A Carcinogen (known human carcinogen) and, thus, exposure to even trace levels of this material is considered significant.

X1.5.10 Polycyclic aromatics can be broken into two categories: naphthalenes and methylnaphthalenes (diaromatics) have moderate water solubility and soil sorption potential and, thus, their movement through the subsurface tends to be less than monoaromatics, but substantial movement can still occur. When released into surface bodies of water, these materials have moderate to high toxicity to aquatic organisms. PAHs with three or more condensed rings have very low solubility (typically less than 1 μg/L) and sorb strongly to soils. Thus, their movement in the subsurface is minimal. Several members in the group of three to six ring PAHs are known or suspected carcinogens and, thus, exposure to low concentrations in drinking water or through the consumption of contaminated soil by children is significant. In addition, materials containing four to six ring PAHs are poorly biodegradable and, coupled with the potential to bioaccumulate in tissues of aquatic organisms, these materials have the potential to bioconcentrate (be found at levels in living tissue far higher than present in the general surroundings) in the environment.

X1.5.11 Although almost totally eliminated from use in gasolines in the United States, lead is found associated with older spills. Lead was typically added to gasoline either as tetraethyl or tetramethyl lead and may still be found in its original form in areas containing free product. Typically outside the free product zones, these materials have decomposed into inorganic forms of lead. Lead is a neurotoxin and lead in the blood of children has been associated with reduced intellectual development. The ingestion by children of lead-contaminated soils is an exposure route of great concern, as is the consumption of lead-contaminated drinking water. EDC and EDB, used as lead scavengers in gasolines, are of concern because of their high toxicity (potential carcinogens) and their high mobility in the environment.

X1.5.12 In summary, benzene and benzo(a)pyrene (and in some cases EDB and EDC) are indicator compounds because of their carcinogenicity. Other PAHs may also be grouped with B(a)P because of uncertainties in their carcinogenicity and because they may accumulate (bioconcentrate) in living tissue.

X1.5.13 *Toxicity and Physical/Chemical Properties for Indicator Compounds*—A summary of health effects and physical/chemical properties for a number of indicator compounds are provided in Table X1.2. This table provides toxicological data from a variety of sources, regardless of data quality. A refined discussion for selected indicator compounds are given below. The reader is cautioned that this information is only current as of the dates quoted below, and the sources quoted below may have been updated, or more recent information may be available in the peer-reviewed literature.

X1.5.13.1 The RfD or SF values are generally obtained from a standard set of reference tables (for example, Integrated Risk Information System, IRIS (6) or the Health Effects Summary Assessment Tables, HEAST (7)). Except as noted, the toxicity evaluations that follow were taken from IRIS (6) because these are EPA-sanctioned evaluations. The information in IRIS (6), however, has typically only been peer-reviewed within the EPA and may not always have support from the external scientific community. The information in IRIS may also be subject to error (as exampled by recent revisions in the slope factor for B(a)P and RfC for MTBE).

X1.5.13.2 HEAST (7) is a larger database than IRIS (6) and is often used as a source of health effects information. Whereas the information in IRIS (6) has been subject to data quality review, however, the information in the HEAST (7) tables has not. The user is expected to consult the original assessment documents to appreciate the strengths and limitations of the data in HEAST (7). Thus, care should be exercised in using the values in HEAST (7).

TABLE X1.5 Definitions of Important Toxicological Characteristics

Reference Dose—A reference dose is an estimate (with an uncertainty typically spanning an order of magnitude) of a daily exposure (mg/kg/day) to the general human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime of exposure.

Reference Concentration—A reference concentration is an estimate (with an uncertainty spanning perhaps an order of magnitude) of a continuous inhalation exposure to the human population (including sensitive subgroups) that is likely to be without appreciable deleterious effects during a lifetime.

Slope Factor—The slope of the dose-response curve in the low-dose region. When low-dose linearity cannot be assumed, the slope factor is the slope of the straight line from zero dose to the dose at 1 % excess risk. An upper bound on this slope is usually used instead of the slope itself. The units of the slope factor are usually expressed as $(mg/kg/day)^{-1}$.

Drinking Water MCLs and MCLGs—Maximum Contaminant Levels (MCLs) are drinking water standards established by the EPA that are protective of human health. However, these standards take into account the technological capability of attaining these standards. The EPA has, therefore, also established MCL goals (MCLGs) which are based only on the protection of human health. The MCL standards are often used as clean-up criteria.

Drinking Water Health Advisories—The Office of Drinking Water provides health advisories (HAs) as technical guidance for the protection of human health. They are not enforceable federal standards. HAs are the concentration of a substance in drinking water estimated to have negligible deleterious effects in humans, when ingested for specified time periods.

Water Quality Criteria—These criteria are not rules and they do not have regulatory impact. Rather, these criteria present scientific data and guidance of the environmental effects of pollutants which can be useful to derive regulatory requirements based on considerations of water quality impacts.

X1.5.13.3 References for the physical/chemical properties are provided in Table X1.2. All Henry's law constants quoted in text are from Ref (9) except MTBE that is from estimation: $H = (P_{[illegible]})/760(S)$, where MW is the molecular weight, $P_{[illegible]}$ is at 100°F, and $S = 48\,000$ mg/L.

X1.6 *Profiles of [illegible]*

X1.6.1 *Benzene:*

X1.6.1.1 *Toxicity Summary*—Based on human epidemiological studies, benzene has been found to be a human carcinogen (classified as a Group A carcinogen, known human carcinogen by the USEPA). An oral slope factor of 2.9×10^{-2} (mg/kg/day)$^{-1}$ has been derived for benzene based on the observance of leukemia from occupational exposure by inhalation. USEPA has set a drinking water maximum contaminant level (MCL) of 5 µg/L (based on the analytical detection limits). The maximum contaminant level goal (MCLG) for benzene is set at zero.

X1.6.1.2 Although EPA does not usually set long-term drinking water advisories for carcinogenic materials (no exposure to carcinogens is considered acceptable), a ten-day drinking water health advisory for a child has been set at 0.235 mg/L based on hematological impairment in animals. The EPA is in the process of evaluating noncancer effects and an oral RfD for benzene is pending.

X1.6.1.3 In situations in which both aquatic life and water are consumed from a particular body of water, a recommended EPA water-quality criterion is set at 0.66 µg/L. When only aquatic organisms are consumed, the criterion is 40 µg/L. These criteria were established at the one-in-one-million risk level (that is, the criteria represent a one-in-one-million estimated incremental increase in cancer risk over a lifetime).

X1.6.1.4 *Physical/Chemical Parameter Summary*—Benzene is subject to rapid volatilization (Henry's law constant $= 5.5 \times 10^{-3}$ m^3-atm/mol) under common above-ground environmental conditions. Benzene will be mobile in soils due to its high water solubility (1.75×10^6 µg/L) and relatively low sorption to soil particles (log $K_{oc} = 1.92$) and, thus, has the potential to leach into ground water. Benzene has a relatively low log K_{ow} value (2.12) and is biodegradable. Therefore, it is not expected to bioaccumulate. In laboratory tests, when a free gasoline phase was in equilibrium with water, typical benzene concentrations in water ranged from 2.42×10^4 to 1.11×10^5 µg/L.

X1.6.2 *Toluene:*

X1.6.2.1 *Toxicity Summary*—Using data from animal studies, the USEPA has set an oral RfD for toluene at 0.2 mg/kg/day. In converting a no-observed adverse effect level (NOAEL) from the animal study, in which the critical effect observed was changes in liver and kidney weights, an uncertainty factor of 1000 and a modifying factor of 1 were used. The EPA has assigned an overall medium level of confidence in the RfD because although the principal study was well performed, the length of the study corresponded to only subchronic rather than a chronic evaluation and reproductive aspects were lacking. Based on the RfD and assuming 20 % exposure from drinking water, the EPA has set both drinking water MCL and MCLG of 1000 µg/L. Drinking water health advisories range from 1 mg/L (lifetime equivalent to the RfD) to 20 mg/L (one-day advisory for a child).

X1.6.2.2 In situations in which both aquatic life and water are consumed from a particular body of water, the recommended water quality criterion is set at 1.43×10^4 µg/L. When only aquatic organisms are consumed, the criterion is 4.24×10^5 µg/L.

X1.6.2.3 An inhalation RfC of 0.4 mg/m^3 was derived based on neurological effects observed in a small worker population. An uncertainty factor of 300 and a modifying factor of 1 were used to convert the lowest observed adverse effect level (LOAEL) to the RfC. The overall confidence in the RfC was established as medium because of the use of a LOAEL and because of the paucity of exposure information.

X1.6.2.4 *Physical/Chemical Parameter Summary*—Toluene is expected to volatilize rapidly, under common above-ground environmental conditions, due to its relatively high Henry's law constant (6.6×10^{-3} m^3-atm/mol). It will be mobile in soils based on an aqueous solubility of 5.35×10^5 µg/L and relatively poor sorption to soils (estimated log $K_{oc} = 2.48$) and, hence, has a potential to leach into ground water. Toluene has a relatively low log K_{ow} (2.73) and is biodegradable. Bioaccumulation of toluene is, therefore, expected to be negligible. In laboratory tests, when a free gasoline phase was in equilibrium with water, typical toluene concentrations in water ranged from 3.48×10^4 to 8.30×10^4 µg/L.

X1.6.3 *Xylenes:*

X1.6.3.1 *Toxicity Summary*—Using data from animal studies, the USEPA has set an oral RfD for xylenes at 2.0 mg/kg/day. In converting a no-observed adverse effect level (NOAEL) from the animal study, in which the critical effects observed were hyperactivity, decreased body weight, and increased mortality (among male rats), an uncertainty factor of 100 and a modifying factor of 1 were used. The EPA has assigned an overall medium level of confidence in the RfD because although the principal study was well designed and performed, supporting chemistry was not performed. A medium level of confidence was also assigned to the database. Based on the RfD and assuming 20 % exposure from drinking water, the EPA has set both drinking water MCL and MCLG of 10 000 g/L. Drinking water health advisories of 10 mg/L (lifetime, adult) and 40 mg/L (one-day, ten-day, and long-term child) are quoted by the EPA's Office of Drinking Water. No USEPA ambient water criteria are available for xylenes at this time. Evaluation of an inhalation RfC is pending.

X1.6.3.2 *Physical/Chemical Parameter Summary*—Xylenes are expected to rapidly volatilize under common above-ground environmental conditions based on their Henry's law constants (for *o*-xylene, $H = 5.1 \times 10^{-3}$ m^3-atm/mol). Xylenes have a moderate water solubility (1.46–1.98×10^5 µg/L) (pure compound) as well as moderate capacities to sorb to soils (estimated log K_{oc} 2.38–2.79) and, therefore, they will be mobile in soils and may leach into ground water. Xylenes are biodegradable, and with log K_{ow} values in the range from 2.8 to 3.3, they are not expected to bioaccumulate. In laboratory tests, when a free gasoline phase was in equilibrium with water, typical combined ethylbenzene and xylenes concentrations in water ranged from 1.08×10^4 to 2.39×10^4 µg/L.

X1.6.4 *Ethylbenzene:*

X1.6.4.1 *Toxicity Summary*—Using data from animal studies, the USEPA has set an oral RfD for ethylbenzene at 0.1 mg/kg/day. In [illegible] a no-observed adverse effect level (NO[illegible]) [illegible] study, in which the critical effects observed [illegible] toxicity, an uncertainty factor of [illegible] modifying factor of 1 were used. The EPA has [illegible] level of confidence in the RfD because the study was poorly designed and confidence in the supporting database is also low. Based on the RfD and assuming 20 % exposure from drinking water, the EPA has set both drinking water MCL and MCLG at 700 µg/L. Drinking water health advisories ranged from 700 µg/L (lifetime equivalent to the RfD) to 33 mg/L (one-day advisory for a child). In situations in which both aquatic life and water are consumed from a particular body of water, a recommended ambient water criterion is set at 1400 µg/L. When only aquatic organisms are consumed, the criterion is 3280 µg/L. An inhalation RfC of 1 mg/m^3 was derived based on developmental toxicity effects observed in rats and rabbits. An uncertainty factor of 300 and a modifying factor of 1 were used to convert the NOAEL to the RfC. Both the study design and database were rated low and, thus, the overall confidence in the RfC was established as low.

X1.6.4.2 *Physical/Chemical Parameter Summary*—Ethylbenzene has a relatively high Henry's law constant (8.7 × 10^{-3} m^3-atm/mol) and, therefore, can rapidly volatilize under common above-ground environmental conditions. Based on its moderate water solubility (1.52 × 10^5 µg/L) and moderate capacity to sorb to soils (Estimated log K_{oc} = 3.04), it will have moderate mobility in soil and may leach into ground water. In laboratory tests, when a free gasoline phase was in equilibrium with water, typical combined ethylbenzene and xylenes concentrations in water ranged from 1.08 × 10^4 to 2.39 × 10^4 µg/L, due to partitioning effects. Ethylbenzene has a moderate low K_{ow} value (3.15), and is biodegradable. Therefore, it is not expected to bioaccumulate. In laboratory tests, when a free gasoline phase was in equilibrium with water, typical combined ethylbenzene and xylenes concentrations in water ranged from 1.08 × 10^4 to 2.39 × 10^4 µg/L.

X1.6.5 *Naphthalenes:*

X1.6.5.1 *Toxicity Summary*—In general, poisoning may occur by ingestion of large doses, inhalation, or skin adsorption of naphthalene. It can cause nausea, headache, diaphoresis, hematuria, fever, anemia, liver damage, vomiting, convulsions, and coma. Methylnaphthalenes are presumably less acutely toxic than naphthalene. Skin irritation and skin photosensitization are the only effects reported in man. Inhalation of the vapor may cause headache, confusion, nausea, and sometimes vomiting. The environmental concerns with naphthalenes are primarily attributed to effects on aquatic organisms. As a consequence, the EPA has not set any human health criteria for these materials (that is, there is no RfD or RfC, no drinking water MCL or MCLG or ambient water quality criteria). A risk assessment to define a RfD for these materials is presently under review by the EPA. Drinking water health advisories range from 20 µg/L (lifetime, adult) to 500 µg/L (one-day advisory for a child).[5]

X1.6.5.2 *Physical/Chemical Parameter Summary: Naphthalene*—Naphthalene has a relatively high Henry's Law constant (1.15 × 10^{-3} m^3-atm/mol) and, thus, has the capacity to volatilize rapidly under common above-ground environmental conditions. It has a moderate water solubility (3.10 × 10^4 µg/L) and log K_{oc} (3.11) and has the potential to leach to ground water. A moderate log K_{ow} value of 3.01 has been reported, but because naphthalene is very biodegradable, it is unlikely to bioconcentrate to a significant degree.

X1.6.5.3 *Methylnaphthalenes*—Henry's law constants (2.60 × 10^{-4} m^3-atm/mol and 5.18 × 10^{-4} m^3-atm/mol for 1- and 2-methylnaphthalene, respectively) suggest that these materials have the potential to volatilize under common above-ground environmental conditions. 1-Methylnaphthalene exhibits a water solubility similar to naphthalene (2.60 × 10^4 µg/L to 2.8 × 10^4 µg/L). However, solubility decreases with increasing alkylation (dimethylnaphthalenes: 2.0 × 10^3 µg/L to 1.1 × 10^4 µg/L, 1,4,5-trimethylnaphthalene: 2.0 × 10^3 µg/L). These materials are, therefore, expected to be slightly mobile to relatively immobile in soil (for example, log K_{oc} is in the range from 2.86 to 3.93 for 1- and 2-methylnaphthalenes). In aquatic systems, methylnaphthalenes may partition from the water column to organic matter contained in sediments and suspended solids. Methylnaphthalenes have high log K_{ow} values (greater than 3.5) and have the potential to bioaccumulate. They do, however, exhibit a moderate degree of biodegradation, which typically decreases with increased alkylation.

X1.6.6 *Three to Six-Ringed PAHs*—The most significant health effect for this class of compounds is their carcinogenicity, which is structure-dependent. Anthracene and phenanthrene have not been shown to cause cancer in laboratory animals. The available data does not prove pyrene to be carcinogenic to experimental animals. On the other hand, benz[a]anthracene, benzo[a]pyrene, dibenz[a,h]anthracene, and 7,12-dimethylbenz[a]anthracene have been shown to be carcinogenic in laboratory animals. B(a)P and pyrene are discussed in X1.6.7 and X1.6.8 as representatives of carcinogenic and noncarcinogenic effects of this class.

X1.6.7 *Benzo(a)pyrene (BaP):*

X1.6.7.1 *Toxicity Summary*—Based on animal data, B(a)P has been classified as a probable human carcinogen (B2 carcinogen) by the USEPA. A range of oral slope factors from 4.5 to 11.7 (mg/kg/day)$^{-1}$ with a geometric mean of 7.3 (mg/kg/day)$^{-1}$ has been derived for B(a)P based on the observance of tumors of the forestomach and squamous cell carcinomas in mice. The data was considered less than optimal but acceptable (note that the carcinogenicity assessment for B(a)P may change in the near future pending the outcome of an on-going EPA review). The EPA has proposed a drinking water maximum contaminant level (MCL) at 0.2 µg/L (based on the analytical detection limits). The maximum contaminant level goal (MCLG) for B(a)P is set at zero. In situations in which both aquatic life and water are consumed from a particular body of water, a recommended EPA water quality criterion is set at 2.8 × 10^{-3} µg/L. When only aquatic organisms are consumed, the criterion is 3.11 × 10^{-2} µg/L.

[5] Office of Water, USEPA, Washington, DC.

X1.6.7.2 *Physical/Chemical Parameter Summary*—When released to water, PAHs are not subject to rapid volatilization (Henry's law constants are on the order of 1.0 × 10^{-4} m^3-atm/mol or less) under common environmental conditions. They have low aqueous solubility values and tend to sorb to soils and sediments and remain fixed in the environment. Three ring members of this group such as anthracene and phenanthrene have water solubilities on the order of 1000 μg/L. The water solubilities decrease substantially for larger molecules in the group, for example, benzo[a]pyrene has a water solubility of 1.2 μg/L. The log K_{oc} values for PAHs are on the order of 4.3 and greater, which suggests that PAHs will be expected to adsorb very strongly to soil. PAHs with more than three rings generally have high log K_{ow} values (6.06 for benzo[a]pyrene), have poor biodegradability characteristics and tend to bioaccumulate.

X1.6.8 *Pyrene:*

X1.6.8.1 *Toxicity Summary*—Using data from animal studies, the USEPA has set an oral RfD for pyrene at 3 × 10^{-2} mg/kg/day. In converting a no-observed adverse effect level (NOAEL) from the animal study, in which the critical effects observed were kidney toxicity, an uncertainty factor of 3000 and a modifying factor of 1 were used. The EPA has assigned an overall low level of confidence in the RfD because although the study was well-designed, confidence in the supporting database is low. No drinking water MCLs or health advisories have been set. In situations in which both aquatic life and water are consumed from a particular body of water, a recommended EPA water quality criterion is set at 2.8 × 10^{-3} μg/L. When only aquatic organisms are consumed, the criterion is 3.11 × 10^{-2} μg/L.

X1.6.8.2 *Physical/Chemical Parameter Summary*—Refer to X1.6.7.2 for BaP. Also see Table X1.2.

X1.6.9 *MTBE:*

X1.6.9.1 *Toxicity Summary*—Using data from animal studies, the USEPA has set an inhalation RfC for MTBE at 3 mg/m^3. In converting a no-observed adverse effect level (NOAEL) from the animal study, in which the critical effects observed included increased liver and kidney weight and increased severity of spontaneous renal lesions (females), increased prostration (females) and swollen pericolar tissue, an uncertainty factor of 100 and a modifying factor of 1 were used. The EPA has assigned an overall medium level of confidence in the RfC because although the study was well-designed, some information on the chemistry was lacking. The confidence in the supporting database is medium to high. No drinking water MCLs or ambient water quality criteria have been set. However, a risk assessment, that may define a RfD for this material, is presently under review by EPA. Drinking water health advisories range from 40 μg/L (lifetime, adult) to 3000 μg/L (one-day advisory for a child).[5]

X1.6.9.2 *Physical/Chemical Parameter Summary*—The Henry's law constant for MTBE is estimated to be approximately 1.0 × 10^{-3} m^3-atm/mol. It is, therefore, expected to have the potential to rapidly volatilize under common above-ground environmental conditions. It is very water soluble (water solubility is 4.8 × 10^7 μg/L), and with a relatively low capacity to sorb to soils (estimated log K_{oc} = 1.08), MTBE will migrate at the same velocity as the water in which it is dissolved in the subsurface. The log K_{ow} value has been estimated to be between 1.06 and 1.30, indicating MTBE's low bioaccumulative potential. It is expected to have a low potential to biodegrade, but no definitive studies are available.

X1.6.10 *Lead:*

X1.6.10.1 *Toxicity Summary—(The following discussion is for inorganic lead—not the organic forms of lead (tetraethyllead, tetramethyllead) that were present in petroleum products.)* A significant amount of toxicological information is available on the health effects of lead. Lead produces neurotoxic and behavioral effects particularly in children. However, EPA believes that it is inappropriate to set an RfD for lead and its inorganic compounds because the agency believes that some of the effects may occur at such low concentrations as to suggest no threshold. The EPA has also determined that lead is a probable human carcinogen (classified as B2). The agency has chosen not to set a numeric slope factor at this time, however, because it is believed that standard procedures for doing so may not be appropriate for lead. At present, the EPA has set an MCLG of zero but has set no drinking water (MCL) or health advisories because of the observance of low level effects, the overall Agency goal of reducing total lead exposure and because of its classification as a B2 carcinogen. An action of level of 15 μg/L has been set for water distribution systems (standard at the tap). The recommended EPA water quality criterion for consumption of both aquatic life and water is set at 50 μg/L.

X1.6.10.2 *Physical/Chemical Parameter Summary*—Organic lead additive compounds are volatile (estimated Henry's law constant for tetraethyl lead = 7.98 × 10^{-2} m^3-atm/mol) and may also sorb to particulate matter in the air. Tetraethyl lead has an aqueous solubility of 800 μg/L and an estimated log K_{oc} of 3.69 and, therefore, should not be very mobile in the soil. It decomposes to inorganic lead in dilute aqueous solutions and in contact with other environmental media. In free product (gasoline) plumes, however, it may remain unchanged. Inorganic lead compounds tightly bind to most soils with minimal leaching under natural conditions. Aqueous solubility varies depending on the species involved. The soil's capacity to sorb lead is correlated with soil pH, cation exchange capacity and organic matter. Lead does not appear to bioconcentrate significantly in fish but does in some shellfish, such as mussels. Lead is not biodegradable.

X2. DEVELOPMENT OF RISK-BASED SCREENING LEVELS (RBSLs) APPEARING IN SAMPLE LOOK-UP TABLE X2.1

X2.1 *Introduction:*

X2.1.1 This appendix contains the equations and parameters used to construct the example "Look-Up" (see Table X2.1). This table was prepared solely for the purpose of presenting an example Tier 1 matrix of risk-based screening levels (RBSLs), and these values should not be viewed, or

misused, as proposed remediation "standards." The reader should note that not all possible pathways have been considered and a number of assumptions concerning exposure scenarios and parameter values have been made. These should be reviewed for appropriateness before using the listed RBSLs as Tier 1 screening values.

X2.1.2 The approaches used to calculate RBSLs appearing in Table X2.1 are briefly discussed for exposure to vapors, ground water, surficial soils, and subsurface soils by means of the following pathways:

X2.1.2.1 Inhalation of vapors,

X2.1.2.2 Ingestion of ground water,

X2.1.2.3 Inhalation of outdoor vapors originating from dissolved hydrocarbons in ground water,

X2.1.2.4 Inhalation of indoor vapors originating from dissolved hydrocarbons in ground water,

TABLE X2.1 Volatilization Factors (VF_i), Leaching Factor (LF_{sw}), and Effective Diffusion Coefficients (D_i^{eff})

Symbol	Cross-Media Route (or Definition)	Equation
CM-6 VF_{wesp}	Ground water → enclosed-space vapors	$VF_{wesp}\left[\frac{(mg/m^3\text{-}air)}{(mg/L\text{-}H_2O)}\right] = \frac{H\left[\frac{D_{ws}^{eff}/L_{gw}}{ER\,L_B}\right]}{1+\left[\frac{D_{ws}^{eff}/L_{gw}}{ER\,L_B}\right]+\left[\frac{D_{ws}^{eff}/L_{gw}}{(D_{crack}^{eff}/L_{crack})\eta}\right]} \times 10^{-3}\,\frac{L}{m^3}$ [A]
CM-5 VF_{wamb}	Ground water → ambient (outdoor) vapors	$VF_{amb}\left[\frac{(mg/m^3\text{-}air)}{(mg/L\text{-}H_2O)}\right] = \frac{H}{1+\left[\frac{U_{air}\delta_{air}L_{gw}}{WD_{ws}^{eff}}\right]} \times 10^{-3}\,\frac{L}{m^3}$ [B]
VF_{ss}	Surficial soils → ambient air (vapors)	$VF_{ss}\left[\frac{(mg/m^3\text{-}air)}{(mg/kg\text{-}soil)}\right] = \frac{2W\rho_s}{U_{air}\delta_{air}}\sqrt{\frac{D_s^{eff}H}{\pi[\theta_{ws}+k_s\rho_s+H\theta_{as}]T}} \times 10^3\,\frac{cm^3\text{-}kg}{m^3\text{-}g}$ [C] or: $VF_{ss}\left[\frac{(mg/m^3\text{-}air)}{(mg/kg\text{-}soil)}\right] = \frac{W\rho_s d}{U_{air}\delta_{air}T} \times 10^3\,\frac{cm^3\text{-}kg}{m^3\text{-}g}$; whichever is less [D]
CM-2 VF_p	Surficial soils → ambient air (particulates)	$VF_p\left[\frac{(mg/m^3\text{-}air)}{(mg/kg\text{-}soil)}\right] = \frac{P_e W}{U_{air}\delta_{air}} \times 10^3\,\frac{cm^3\text{-}kg}{m^3\text{-}g}$ [E]
CM-3 VF_{samb}	Subsurface soils → ambient air	$VF_{samb}\left[\frac{(mg/m^3\text{-}air)}{(mg/kg\text{-}soil)}\right] = \frac{H\rho_s}{[\theta_{ws}+k_s\rho_s+H\theta_{as}]\left(1+\frac{U_{air}\delta_{air}L_s}{D_s^{eff}W}\right)} \times 10^3\,\frac{cm^3\text{-}kg}{m^3\text{-}g}$ [E]
CM-4 VF_{sesp}	Subsurface soil → enclosed-space vapors	$VF_{sesp}\left[\frac{(mg/m^3\text{-}air)}{(mg/kg\text{-}soil)}\right] = \frac{\frac{H\rho_s}{[\theta_{ws}+k_s\rho_s+H\theta_{as}]}\left[\frac{D_s^{eff}/L_s}{ER\,L_B}\right]}{1+\left[\frac{D_s^{eff}/L_s}{ER\,L_B}\right]+\left[\frac{D_s^{eff}/L_s}{(D_{crack}^{eff}/L_{crack})\eta}\right]} \times 10^3\,\frac{cm^3\text{-}kg}{m^3\text{-}g}$ [A]
CM-7 LF_{sw}	Subsurface soils → ground water	$LF_{sw}\left[\frac{(mg/1\text{-}H_2O)}{(mg/kg\text{-}soil)}\right] = \frac{\rho_s}{[\theta_{ws}+k_s\rho_s+H\theta_{as}]\left(1+\frac{U_{gw}\delta_{gw}}{IW}\right)} \times 10^0\,\frac{cm^3\text{-}kg}{L\text{-}g}$ [B]
D_s^{eff}	Effective diffusion coefficient in soil based on vapor-phase concentration	$D_s^{eff}\left[\frac{cm^2}{s}\right] = D^{air}\frac{\theta_{as}^{3.33}}{\theta_T^{3.33}} + D^{wat}\frac{1}{H}\frac{\theta_{ws}^{3.33}}{\theta_T^{3.33}}$ [A]
D_{crack}^{eff}	Effective diffusion coefficient through foundation cracks	$D_{crack}^{eff}\left[\frac{cm^2}{s}\right] = D^{air}\frac{\theta_{acrack}^{3.33}}{\theta_T^{3.33}} + D^{wat}\frac{1}{H}\frac{\theta_{wcrack}^{3.33}}{\theta_T^{3.33}}$ [A]
D_{cap}^{eff}	Effective diffusion coefficient through capillary fringe	$D_{cap}^{eff}\left[\frac{cm^2}{s}\right] = D^{air}\frac{\theta_{acap}^{3.33}}{\theta_T^{3.33}} + D^{wat}\frac{1}{H}\frac{\theta_{wcap}^{3.33}}{\theta_T^{3.33}}$ [A]
D_{ws}^{eff}	Effective diffusion coefficient between ground water and soil surface	$D_{ws}^{eff}\left[\frac{cm^2}{s}\right] = (h_{cap}+h_v)\left[\frac{h_{cap}}{D_{cap}^{eff}}+\frac{h_v}{D_s^{eff}}\right]^{-1}$ [A]
C_s^{sat}	Soil concentration at which dissolved pore-water and vapor phases become saturated	$C_s^{sat}\left[\frac{mg}{kg\text{-}soil}\right] = \frac{S}{\rho_s} \times [H\theta_{as}+\theta_{ws}+k_s\rho_s] \times 10^0\,\frac{L\text{-}g}{cm^3\text{-}kg}$ [E]

[A] See Ref (18).
[B] See Ref (16).
[C] See Ref (19).
[D] Based on mass balance.
[E] See Ref (20).

X2.1.2.5 Ingestion of surficial soil, inhalation of outdoor vapors and particulates emanating from surficial soils, and dermal absorption resulting from surficial soil contact with skin,

X2.1.2.6 Inhalation of outdoor vapors originating from hydrocarbons in subsurface soils,

X2.1.2.7 Inhalation of indoor vapors originating from subsurface hydrocarbons, and

X2.1.2.8 Ingestion of ground water impacted by leaching of dissolved hydrocarbons from subsurface soils.

X2.1.3 For the pathways considered, approaches used in this appendix are consistent with guidelines contained in Ref (1).

X2.1.4 The following development presented focuses only on human-health RBSLs for chronic (long-term) exposures.

X2.1.4.1 In the case of compounds that have been classified as carcinogens, the RBSLs are based on the general equation:

$$\textit{risk} = \textit{average lifetime intake}\ [\text{mg/kg-day}] \times \textit{potency factor}\ [\text{mg/kg-day}]^{-1}$$

where the intake depends on exposure parameters (ingestion rate, exposure duration, etc.), the source concentration, and transport rates between the source and receptor. The potency factor is selected after reviewing a number of sources, including the USEPA Integrated Risk Information System (IRIS) (6) database, USEPA Health Effects Assessment Summary Tables (HEAST), (7), and peer-reviewed sources.

TABLE X2.2 Equations Used to Develop Example Tier 1 Risk-Based Screening Level (RBSLs) Appearing in "Look-Up" Table X2.1—Carcinagenic Effects[A]

NOTE—See Tables X2.3 through X2.6 for definition of parameters.

Medium	Exposure Route	Risk-Based Screening Level (RBSL)
Air	Inhalation[B]	$RBSL_{air}\left[\frac{\mu g}{m^3\text{-}air}\right] = \frac{TR \times BW \times AT_c \times 365\ \frac{days}{years} \times 10^3\ \frac{\mu g}{mg}}{SF_i \times IR_{air} \times EF \times ED}$
Ground water	Ingestion (potable ground water supply only)[B]	$RBSL_w\left[\frac{mg}{L\text{-}H_2O}\right] = \frac{TR \times BW \times AT_c \times 365\ \frac{days}{years}}{SF_o \times IR_w \times EF \times ED}$
Ground water[C]	Enclosed-space (indoor) vapor inhalation[D]	$RBSL_w\left[\frac{mg}{L\text{-}H_2O}\right] = \frac{RBSL_{air}\left[\frac{\mu g}{m^3\text{-}air}\right]}{VF_{wesp}} \times 10^{-3}\ \frac{mg}{\mu g}$
Ground water[C]	Ambient (outdoor) vapor inhalation[D]	$RBSL_w\left[\frac{mg}{L\text{-}H_2O}\right] = \frac{RBSL_{air}\left[\frac{\mu g}{m^3\text{-}air}\right]}{VF_{wamb}} \times 10^{-3}\ \frac{mg}{\mu g}$
Surficial soil	Ingestion of soil, inhalation of vapors and particulates, and dermal contact[B]	$RBSL_s\left[\frac{\mu g}{kg\text{-}soil}\right] = \frac{TR \times BW \times AT_c \times 365\ \frac{days}{years}}{EF \times ED\left[\left(SF_o \times 10^{-6}\ \frac{kg}{mg} \times (IR_{soil} \times RAF_o + SA \times M \times RAF_d)\right) + (SF_i \times IR_{air} \times (VF_{ss} + VF_p))\right]}$ For surficial and excavated soils (0 to 1 m)
Subsurface soil[C]	Ambient (outdoor) vapor inhalation[D]	$RBSL_s\left[\frac{mg}{kg\text{-}soil}\right] = \frac{RBSL_{air}\left[\frac{\mu g}{m^3\text{-}air}\right]}{VF_{samb}} \times 10^{-3}\ \frac{mg}{\mu g}$
Subsurface soil[C]	Enclosed space (indoor) vapor inhalation[D]	$RBSL_s\left[\frac{mg}{kg\text{-}soil}\right] = \frac{RBSL_{air}\left[\frac{\mu g}{m^3\text{-}air}\right]}{VF_{sesp}} \times 10^{-3}\ \frac{mg}{\mu g}$
Subsurface soil[C]	Leaching to ground water[D]	$RBSL_s\left[\frac{mg}{kg\text{-}soil}\right] = \frac{RBSL_{wt}\left[\frac{mg}{L\text{-}H_2O}\right]}{LF_{sw}}$

[A] Note that all RBSL values should be compared with thermodynamic partitioning limits, such as solubility levels, maximum vapor concentrations, etc. If a RBSL exceeds the relevant partitioning limit, this is an indication that the selected risk or hazard level will never be reached or exceeded for that chemical and the selected exposure scenario.

[B] Screening levels for these media based on other considerations (for example, aesthetic, background levels, environmental resource protection, etc.) can be derived with these equations by substituting the selected target level for $RBSL_{air}$ or $RBSL_w$ appearing in these equations.

[C] These equations are based on Ref (1).

[D] These equations simply define the "cross-media partitioning factors," VF_i and LF_{sw}.

TABLE X2.3 Equations Used to Develop Example Tier 1 Risk-Based Screening Level (RBSLs) Appearing in "Look-Up" Table X2.1—Noncarcinogenic Effects[A]

Medium	Exposure Route	Risk-Based Screening Level (RBSL)
Air	Inhalation[B]	$RBSL_{air}\left[\frac{\mu g}{m^3\text{-}air}\right] = \frac{THQ \times RfD_i \times BW \times AT_n \times 365 \frac{days}{years} \times 10^3 \frac{\mu g}{mg}}{IR_{air} \times EF \times ED}$
Ground water	Ingestion (potable ground water supply only)[B]	$RBSL_w\left[\frac{mg}{L\text{-}H_2O}\right] = \frac{THQ \times RfD_o \times BW \times AT_n \times 365 \frac{days}{years}}{IR_w \times EF \times ED}$
Ground water[C]	Enclosed-space (indoor) vapor inhalation[D]	$RBSL_w\left[\frac{mg}{L\text{-}H_2O}\right] = \frac{RBSL_{air}\left[\frac{\mu g}{m^3\text{-}air}\right]}{VF_{wesp}} \times 10^{-3} \frac{mg}{\mu g}$
Ground water[C]	Ambient (outdoor) vapor inhalation[D]	$RBSL_w\left[\frac{mg}{L\text{-}H_2O}\right] = \frac{RBSL_{air}\left[\frac{\mu g}{m^3\text{-}air}\right]}{VF_{wamb}} \times 10^{-3} \frac{mg}{\mu g}$
Surficial soil	Ingestion of soil, inhalation of vapors and particulates, and dermal contact[B]	$RBSL_s\left[\frac{\mu g}{kg\text{-}soil}\right] = \frac{THQ \times BW \times AT_n \times 365 \frac{days}{years}}{EF \times ED \frac{\left(10^{-6} \frac{kg}{mg} \times (IR_{soil} \times RAF_o + SA \times M \times RAF_d)\right)}{RfD_o} + \frac{(IR_{air} \times (VF_{se} + VF_{pl}))}{RfD_i}}$ For surficial and excavated soils (0 to 1 m)
Subsurface soil[C]	Ambient (outdoor) vapor inhalation[D]	$RBSL_s\left[\frac{mg}{kg\text{-}soil}\right] = \frac{RBSL_{air}\left[\frac{\mu g}{m^3\text{-}air}\right]}{VF_{samb}} \times 10^{-3} \frac{mg}{\mu g}$
Subsurface soil[C]	Enclosed space (indoor) vapor inhalation[D]	$RBSL_s\left[\frac{mg}{kg\text{-}soil}\right] = \frac{RBSL_{air}\left[\frac{\mu g}{m^3\text{-}air}\right]}{VF_{sesp}} \times 10^{-3} \frac{mg}{\mu g}$
Subsurface soil[C]	Leaching to ground water[D]	$RBSL_s\left[\frac{mg}{kg\text{-}soil}\right] = \frac{RBSL_{wt}\left[\frac{mg}{L\text{-}H_2O}\right]}{LF_{sw}}$

[A] Note that all RBSL values should be compared with thermodynamic partitioning limits, such as solubility levels, maximum vapor concentrations, etc. If a RBSL exceeds the relevant partitioning limit, this is an indication that the selected risk or hazard level will never be reached or exceeded for that chemical and the selected exposure scenario.

[B] Screening levels for these media based on other considerations (for example, aesthetic, background levels, environmental resource protection, etc.) can be derived with these equations by substituting the selected target level for $RBSL_{air}$ or $RBSL_w$ appearing in these equations.

[C] These equations are based on Ref (1).

[D] These equations simply define the "cross-media partitioning factors," VF_{ij} and LF_{sw}.

The RBSL values appearing in Table X2.1 correspond to probabilities of adverse health effects ("risks") in the range from 10^{-6} to 10^{-4} resulting from the specified exposure. Note that this risk value does not reflect the probability for the specified exposure scenario to occur. Therefore, the actual potential risk to a population for these RBSLs is lower than the 10^{-6} to 10^{-4} range.

X2.1.4.2 In the case of compounds that have not been classified as carcinogens, the RBSLs are based on the general equation:

hazard quotient = *average intake* [mg/kg-day]/ *reference dose* [mg/kg-day]

where the intake depends on exposure parameters (ingestion rate, exposure duration, etc.), the source concentration, and transport rates between the source and receptor. The reference dose is selected after reviewing a number of sources, including the USEPA Integrated Risk Information System (IRIS) (6) database, USEPA Health Effects Assessment Summary Tables (HEAST) (7), and peer-reviewed sources. RBSL values appearing in Table X2.1 correspond to hazard quotients of unity resulting from the specified exposure. Note that this hazard quotient value does not reflect the probability for the specified exposure scenario to occur. Therefore, the actual potential impact to a population for

TABLE X2.4 Exposure Parameters Appearing in Tables X2.2 and X2.3

Parameters	Definitions (Units)	Residential	Commercial/Industrial
AT_c	Averaging time for carcinogens (years)	70 years	70 years[A]
AT_n	Averaging time for non-carcinogens (years)	30 years	25 years[A]
BW	Adult body weight (kg)	70 kg	70 kg[A]
ED	Exposure duration (years)	30 years	25 years[A]
EF	Exposure frequency (days/years)	350 days/years	250 days/years[A]
IR_{soil}	Soil ingestion rate (mg/day)	100 mg/day	50 mg/day[A]
IR_{air}-Indoor	Daily indoor inhalation rate (m^3/day)	15 m^3/day	20 m^3/day[A]
IR_{air}-outdoor	Daily outdoor inhalation rate (m^3/day)	20 m^3/day	20 m^3/day[A]
IR_w	Daily water ingestion rate (L/day)	2 L/day	1 L/day[A]
LF_{gw}	Leaching factor (mg/L-H_2O)/(mg/kg-soil)—see Table X2.5	Chemical-specific	Chemical-specific
M	Soil to skin adherence factor (mg/cm^2)	0.5	0.5[B]
RAF_d	Dermal relative absorption factor (volatiles/PAHs)	0.5/0.05	0.5/0.05[B]
RAF_o	Oral relative absorption factor	1.0	1.0
$RBSL_i$	Risk-based screening level for media i (mg/kg-soil, mg/L-H_2O, or µg/m^3-air)	Chemical-, media-, and exposure route-specific	Chemical-, media-, and exposure route-specific
RfD_i	Inhalation chronic reference dose (mg/kg-day)	Chemical-specific	Chemical-specific
RfD_o	Oral chronic reference dose (mg/kg-day)	Chemical-specific	Chemical-specific
SA	Skin surface area (cm^2/day)	3160	3160[A]
SF_i	Inhalation cancer slope factor ((mg/kg-day)$^{-1}$)	Chemical-specific	Chemical-specific
SF_o	Oral cancer slope factor ((mg/kg-day)$^{-1}$)	Chemical-specific	Chemical-specific
THQ	Target hazard quotient for individual constituents (unitless)	1.0	1.0
TR	Target excess individual lifetime cancer risk (unitless)	for example, 10^{-6} or 10^{-4}	for example, 10^{-6} or 10^{-4}
VF_i	Volatilization factor (mg/m^3-air)/(mg/kg-soil) or (mg/m^3-air)/(mg/L-H_2O)—see Table X2.1	Chemical- and media-specific	Chemical- and media-specific

[A] See Ref (8).
[B] See Ref (15).

TABLE X2.5 Soil, Building, Surface, and Subsurface Parameters Used in Generating Example Tier 1 RBSLs

NOTE—See X2.10 for justification of parameter selection.

Parameters	Definitions (Units)	Residential	Commercial/Industrial
d	Lower depth of surficial soil zone (cm)	100 cm	100 cm
D^{air}	Diffusion coefficient in air (cm^2/s)	Chemical-specific	Chemical-specific
D^{wat}	Diffusion coefficient in water (cm^2/s)	Chemical-specific	Chemical-specific
ER	Enclosed-space air exchange rate (L/s)	0.00014 s^{-1}	0.00023 s^{-1}
f_{oc}	Fraction of organic carbon in soil (g-C/g-soil)	0.01	0.01
H	Henry's law constant (cm^3-H_2O)/(cm^3-air)	Chemical-specific	Chemical-specific
h_{cap}	Thickness of capillary fringe (cm)	5 cm	5 cm
h_v	Thickness of vadose zone (cm)	295 cm	295 cm
I	Infiltration rate of water through soil (cm/years)	30 cm/years	30 cm/years
k_{oc}	Carbon-water sorption coefficient (g-H_2O/g-C)	Chemical-specific	Chemical-specific
k_s	Soil-water sorption coefficient (g-H_2O/g-soil)	$f_{oc} \times k_{oc}$	$f_{oc} \times k_{oc}$
L_B	Enclosed-space volume/infiltration area ratio (cm)	200 cm	300 cm
L_{crack}	Enclosed-space foundation or wall thickness (cm)	15 cm	15 cm
L_{GW}	Depth to ground water = $h_{cap} + h_v$ (cm)	300 cm	300 cm
L_S	Depth to subsurface soil sources (cm)	100 cm	100 cm
P_e	Particulate emission rate (g/cm^2-s)	6.9×10^{-14}	6.9×10^{-14}
S	Pure component solubility in water (mg/L-H_2O)	Chemical-specific	Chemical-specific
U_{air}	Wind speed above ground surface in ambient mixing zone (cm/s)	225 cm/s	225 cm/s
U_{gw}	Ground water Darcy velocity (cm/s)	2500 cm/years	2500 cm/years
W	Width of source area parallel to wind, or ground water flow direction (cm)	1500 cm	1500 cm
δ_{air}	Ambient air mixing zone height (cm)	200 cm	200 cm
δ_{gw}	Ground water mixing zone thickness (cm)	200 cm	200 cm
η	Areal fraction of cracks in foundations/walls (cm^2-cracks/cm^2-total area)	0.01 cm^2-cracks/cm^2-total area	0.01 cm^2-cracks/cm^2-total area
θ_{acap}	Volumetric air content in capillary fringe soils (cm^3-air/cm^3-soil)	0.038 cm^3-air/cm^3-soil	0.38 cm^3-air/cm^3-soil
θ_{acrack}	Volumetric air content in foundation/wall cracks (cm^3-air/cm^3 total volume)	0.26 cm^3-air/cm^3 total volume	0.26 cm^3-air/cm^3 total volume
θ_{av}	Volumetric air content in vadose zone soils (cm^3-air/cm^3-soil)	0.26 cm^3-air/cm^3-soil	0.26 cm^3-air/cm^3-soil
θ_T	Total soil porosity (cm^3/cm^3-soil)	0.38 cm^3/cm^3-soil	0.38 cm^3/cm^3-soil
θ_{wcap}	Volumetric water content in capillary fringe soils (cm^3-H_2O/cm^3-soil)	0.342 cm^3-H_2O/cm^3-soil	0.342 cm^3-H_2O/cm^3-soil
θ_{wcrack}	Volumetric water content in foundation/wall cracks (cm^3-H_2O/cm^3 total volume)	0.12 cm^3-H_2O/cm^3 total volume	0.12 cm^3-H_2O/cm^3 total volume
θ_{wv}	Volumetric water content in vadose zone soils (cm^3-H_2O/cm^3-soil)	0.12 cm^3-H_2O/cm^3-soil	0.12 cm^3-H_2O/cm^3-soil
ρ_b	Soil bulk density (g-soil/cm^3-soil)	1.7 g/cm^3	1.7 g/cm^3
τ	Averaging time for vapor flux (s)	9.46×10^8 s	9.46×10^8 s

these RBSLs is lower than a hazard quotient of unity.

X2.1.5 Tables X2.2 through X2.6 summarize the equations and parameters used to prepare the example look-up Table X2.1 appearing in the main body of this guide. The basis for each of these equations is discussed in X2.2 through X2.10.

X2.2 *Air—Inhalation of Vapors (Outdoors/Indoors):*

X2.2.1 In this case chemical intake results from the inhalation of vapors. It is assumed that vapor concentrations remain constant over the duration of exposure, and all inhaled chemicals are absorbed. Equations appearing in Tables X2.2 and X2.3 for estimating RBSLs for vapor concentrations in the breathing zone follow guidance given in Ref (1). Should the calculated RBSL exceed the saturated

TABLE X2.6 Chemical-Specific Properties Used in the Derivation Example Tier 1 RBSLs[A]

Chemical	CAS Number	M_w, g/mol	H, L-H_2O/L-air	D^{air}, cm²/s	D^{w}, cm²/s	log(K_{oc}), L/kg	log(K_{ow}), L/kg
Benzene	71-43-2	78[A]	0.22[A]	0.093[A]	1.1×10^{-5}[A]	1.58[A]	2.13[A]
Toluene	108-88-3	92[A]	0.26[A]	0.085[A]	9.4×10^{-6}[D]	2.13[A]	2.65[A]
Ethyl benzene	100-41-4	106[A]	0.32[A]	0.076[A]	8.5×10^{-6}[D]	1.98[A]	3.13[A]
Mixed xylenes	1330-20-7	106[A]	0.29[A]	0.072[D]	8.5×10^{-6}[D]	2.38[A]	3.26[A]
Naphthalene	91-20-3	128[A]	0.049[A]	0.072[D]	9.4×10^{-6}[A]	3.11[A]	3.28[A]
Benzo(a)pyrene	50-32-8	252[C]	1.4×10^{-9}[B]	0.050[D]	5.8×10^{-6}	5.59[E]	5.98[B]

Chemical	CAS Number	SF_o, kg-day/mg	SF_i, kg-day/mg	RfD_o, mg/kg-day	RfD_i, mg/kg-day
Benzene	71-43-2	0.029[F]	0.029[F]	...	..
Toluene	108-88-3	...	...	0.2[F]	0.11[F]
Ethyl benzene	100-41-4	...	...	0.1[F]	0.29[F]
Mixed xylenes	1330-20-7	...	...	2.0[F]	2.0[F]
Naphthalene	91-20-3	...	...	0.004[G]	0.004[G]
Benzo(a)pyrene	50-32-8	7.3[F]	6.1[F]	...	...

[A] See Ref (21).
[B] See Ref (22).
[C] See Ref (11).
[D] Diffusion coefficient calculated using the method of Fuller, Schettler, and Giddings, from Ref (9).
[E] Calculated from K_{ow}/K_{oc} correlation: $\log(K_{oc}) = 0.937 \log(K_{oc}) - 0.006$, from Ref (9).
[F] See Ref (6).
[G] See Ref (7).

vapor concentration for any individual component, "$>P_{vap}$" is entered in the table to indicate that the selected risk level or hazard quotient cannot be reached or exceeded for that compound and the specified exposure scenario.

X2.3 *Ground water—Ingestion of Ground water*—In this case chemical intake results from ingestion of ground water. It is assumed that the dissolved hydrocarbon concentrations remain constant over the duration of exposure. Equations appearing in Tables X2.2 and X2.3 for estimating RBSLs for drinking water concentrations follow guidance given in Ref (1) for ingestion of chemicals in drinking water. Should the calculated RBSL exceed the pure component solubility for any individual component, ">S" is entered in the table to indicate that the selected risk level or hazard quotient cannot be reached or exceeded for that compound and the specified exposure scenario (unless free-phase product is mixed with the ingested water).

X2.4 *Ground water—Inhalation of Outdoor Vapors:*

X2.4.1 In this case chemical intake is a result of inhalation of outdoor vapors which originate from dissolved hydrocarbons in ground water located some distance below ground surface. Here the goal is to determine the dissolved hydrocarbon RBSL that corresponds to the target RBSL for outdoor vapors in the breathing zone, as given in X2.2. If the selected target vapor concentration is some value other than the RBSL for inhalation (that is, odor threshold or ecological criterion), this value can be substituted for the $RBSL_{air}$ parameter appearing in the equations given in Tables X2.2 and X2.3.

X2.4.2 A conceptual model for the transport of chemicals from ground water to ambient air is depicted in Fig. X2.1. For simplicity, the relationship between outdoor air and dissolved ground water concentrations is represented in Tables X2.2 and X2.3 by the "volatilization factor," VF_{wamb} [(mg/m³-air)/(mg/L-H_2O)], defined in Table X2.1. It is based on the following assumptions:

X2.4.2.1 A constant dissolved chemical concentration in ground water,

X2.4.2.2 Linear equilibrium partitioning between dissolved chemicals in ground water and chemical vapors at the ground water table,

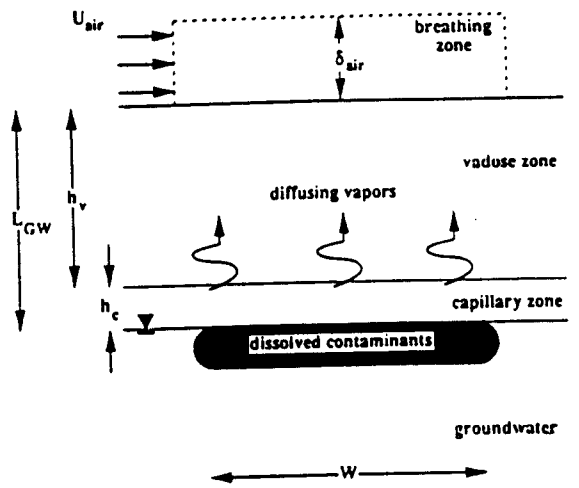

FIG. X2.1 Volatilization from Ground Water to Ambient Air

X2.4.2.3 Steady-state vapor- and liquid-phase diffusion through the capillary fringe and vadose zones to ground surface,

X2.4.2.4 No loss of chemical as it diffuses towards ground surface (that is, no biodegradation), and

X2.4.2.5 Steady well-mixed atmospheric dispersion of the emanating vapors within the breathing zone as modeled by a "box model" for air dispersion.

X2.4.3 Should the calculated $RBSL_w$ exceed the pure component solubility for any individual component, ">S" is entered in the table to indicate that the selected risk level or hazard quotient cannot be reached or exceeded for that compound and the specified exposure scenario.

X2.5 *Ground water—Inhalation of Enclosed-Space (Indoor) Vapors:*

X2.5.1 In this case chemical intake results from the inhalation of vapors in enclosed spaces. The chemical vapors originate from dissolved hydrocarbons in ground water located some distance below ground surface. Here the goal is to determine the dissolved hydrocarbon RBSL that corresponds to the target RBSL for vapors in the breathing zone,

as given in X2.2. If the selected target vapor concentration is some value other than the RBSL for inhalation (that is, odor threshold or ecological criterion), this value can be substituted for the $RBSL_{air}$ parameter appearing in the equations given in Tables X2.2 and X2.3.

X2.5.2 A conceptual model for the transport of chemicals from ground water to indoor air is depicted in Fig. X2.2. For simplicity, the relationship between enclosed-space air and dissolved ground water concentrations is represented in Tables X2.2 and X2.3 by the "volatilization factor" VF_{wesp} [(mg/m^3-air)/(mg/L-H_2O)] defined in Table X2.1. It is based on the following assumptions:

X2.5.2.1 A constant dissolved chemical concentration in ground water,

X2.5.2.2 Equilibrium partitioning between dissolved chemicals in ground water and chemical vapors at the ground water table,

X2.5.2.3 Steady-state vapor- and liquid-phase diffusion through the capillary fringe, vadose zone, and foundation cracks,

X2.5.2.4 No loss of chemical as it diffuses towards ground surface (that is, no biodegradation), and

X2.5.2.5 Steady, well-mixed atmospheric dispersion of the emanating vapors within the enclosed space, where the convective transport into the building through foundation cracks or openings is negligible in comparison with diffusive transport.

X2.5.3 Should the calculated $RBSL_w$ exceed the pure component solubility for any individual component, ">S" is entered in the table to indicate that the selected risk level or hazard quotient cannot be reached or exceeded for that compound and the specified exposure scenario.

X2.6 *Surficial Soils—Ingestion, Dermal Contact, and Vapor and Particulate Inhalation:*

X2.6.1 In this case it is assumed that chemical intake results from a combination of intake routes, including: ingestion, dermal absorption, and inhalation of both particulates and vapors emanating from surficial soil.

X2.6.2 Equations used to estimate intake resulting from ingestion follow guidance given in Ref (1) for ingestion of chemicals in soil. For this route, it has been assumed that surficial soil chemical concentrations and intake rates remain constant over the exposure duration.

X2.6.3 Equations used to estimate intake resulting from dermal absorption follow guidance given in Ref (1) for dermal contact with chemicals in soil. For this route, it has been assumed that surficial soil chemical concentrations and absorption rates remain constant over the exposure duration.

X2.6.4 Equations used to estimate intake resulting from the inhalation of particulates follow guidance given in Ref (1) for inhalation of airborne chemicals. For this route, it has been assumed that surficial soil chemical concentrations, intake rates, and atmospheric particulate concentrations remain constant over the exposure duration.

X2.6.5 Equations used to estimate intake resulting from the inhalation of airborne chemicals resulting from the volatilization of chemicals from surficial soils follow guidance given in Ref (1) for inhalation of airborne chemicals.

X2.6.6 A conceptual model for the volatilization of chemicals from ground water to outdoor air is depicted in Fig. X2.3. For simplicity, the relationship between outdoor air and surficial soil concentrations is represented in Tables X2.2 and X2.3 by the "volatilization factor" VF_{ss} [(mg/m^3-air)/(mg/kg-soil)] defined in Table X2.1. It is based on the following assumptions:

X2.6.6.1 Uniformly distributed chemical throughout the depth 0—*d* (cm) below ground surface,

X2.6.6.2 Linear equilibrium partitioning within the soil matrix between sorbed, dissolved, and vapor phases, where the partitioning is a function of constant chemical- and soil-specific parameters.

X2.6.6.3 Diffusion through the vadose zone,

X2.6.6.4 No loss of chemical as it diffuses towards ground surface (that is, no biodegradation), and

X2.6.6.5 Steady well-mixed atmospheric dispersion of the emanating vapors within the breathing zone as modeled by a "box model" for air dispersion.

X2.6.7 In the event that the time-averaged flux exceeds that which would occur if all chemical initially present in the surficial soil zone volatilized during the exposure period, then the volatilization factor is determined from a mass balance assuming that all chemical initially present in the surficial soil zone volatilizes during the exposure period.

X2.7 *Subsurface Soils—Inhalation of Outdoor Vapors:*

X2.7.1 In this case chemical intake is a result of inhalation of outdoor vapors which originate from hydrocarbons contained in subsurface soils located some distance below ground surface. Here the goal is to determine the RBSL for

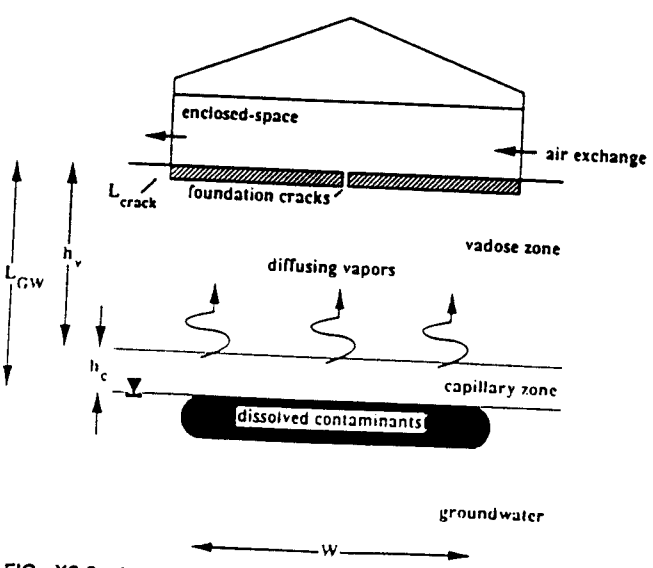

FIG. X2.2 Volatilization from Ground Water to Enclosed-Space Air

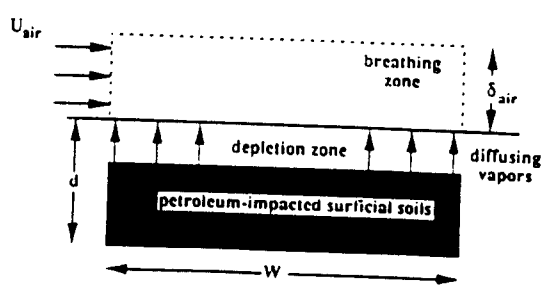

FIG. X2.3 Volatilization from Surficial Soils

subsurface soils that corresponds to the target RBSL for outdoor vapors in the breathing zone, as given in X2.2. If the selected target vapor concentration is some value other than the RBSL for inhalation (that is, odor threshold or ecological criterion), this value can be substituted for the $RBSL_{air}$ parameter appearing in the equations given in Tables X2.2 and X2.3.

X2.7.2 A conceptual model for the transport of chemicals from subsurface soils to ambient air is depicted in Fig. X2.4. For simplicity, the relationship between outdoor air and soil concentrations is represented in Tables X2.2 and X2.3 by the "volatilization factor," VF_{samb} [(mg/m^3-air)/(kg-soil)], defined in Table X2.1. It is based on the following assumptions:

X2.7.2.1 A constant chemical concentration in subsurface soils,

X2.7.2.2 Linear equilibrium partitioning within the soil matrix between sorbed, dissolved, and vapor phases, where the partitioning is a function of constant chemical- and soil-specific parameters,

X2.7.2.3 Steady-state vapor- and liquid-phase diffusion through the vadose zone to ground surface,

X2.7.2.4 No loss of chemical as it diffuses towards ground surface (that is, no biodegradation), and

X2.7.2.5 Steady well-mixed atmospheric dispersion of the emanating vapors within the breathing zone as modeled by a "box model" for air dispersion.

X2.7.3 Should the calculated $RBSL_s$ exceed the value for which the equilibrated vapor and dissolved pore-water phases become saturated, C_s^{sat} [mg/kg-soil] (see Table X2.1 for calculation of this value), "RES" is entered in the table to indicate that the selected risk level or hazard quotient cannot be reached or exceeded for that compound and the specified exposure scenario (even if free-phase product or precipitate is present in the soil).

X2.8 *Subsurface Soils—Inhalation of Enclosed-Space (Indoor) Vapors:*

X2.8.1 In this case chemical intake is a result of inhalation of enclosed-space vapors which originate from hydrocarbons contained in subsurface soils located some distance below ground surface. Here the goal is to determine the RBSL for subsurface soils that corresponds to the target RBSL for indoor vapors, as given in X2.2. If the selected target vapor concentration is some value other than the RBSL for inhalation (that is, odor threshold or ecological criterion), this value can be substituted for the $RBSL_{air}$ parameter appearing in the equations given in Tables X2.2 and X2.3.

X2.8.2 A conceptual model for the transport of chemicals from subsurface soils to enclosed spaces is depicted in Fig. X2.5. For simplicity, the relationship between indoor air and soil concentrations is represented in Tables X2.2 and X2.3 by the "volatilization factor," VF_{sesp} [(mg/m^3-air)/(kg-soil)], defined in Table X2.1. It is based on the following assumptions:

X2.8.2.1 A constant chemical concentration in subsurface soils,

X2.8.2.2 Linear equilibrium partitioning within the soil matrix between sorbed, dissolved, and vapor phases, where the partitioning is a function of constant chemical- and soil-specific parameters,

X2.8.2.3 Steady-state vapor- and liquid-phase diffusion through the vadose zone and foundation cracks,

X2.8.2.4 No loss of chemical as it diffuses towards ground surface (that is, no biodegradation), and

X2.8.2.5 Well-mixed atmospheric dispersion of the emanating vapors within the enclosed space.

X2.8.3 Should the calculated $RBSL_s$ exceed the value C_s^{sat} [mg/kg-soil] for which the equilibrated vapor and dissolved pore-water phases become saturated (see Table X2.1 for calculation of this value), "RES" is entered in the table to indicate that the selected risk level or hazard quotient cannot be reached or exceeded for that compound and the specified exposure scenario (even if free-phase product or precipitate is present in the soil).

X2.9 *Subsurface Soils—Leaching to Ground Water:*

X2.9.1 In this case chemical intake is a result of chemicals leaching from subsurface soils, followed by inhalation of enclosed-space vapors, inhalation of outdoor vapors, or ingestion of ground water as discussed in X2.2 through X2.4. Here the goal is to determine the RBSL for subsurface soils that corresponds to the target RBSLs for the inhalation or ingestion routes. If the selected target ground water concentration is some value other than an RBSL for ground water (that is, odor threshold or ecological criterion), this value can be substituted for the $RBSL_w$ parameter appearing in the equations given in Tables X2.2 and X2.3.

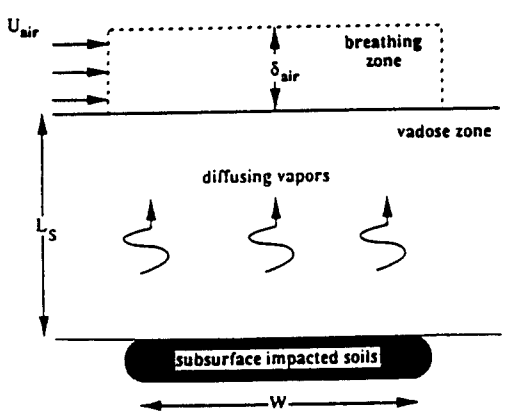

FIG. X2.4 Volatilization From Subsurface Soils to Ambient Air

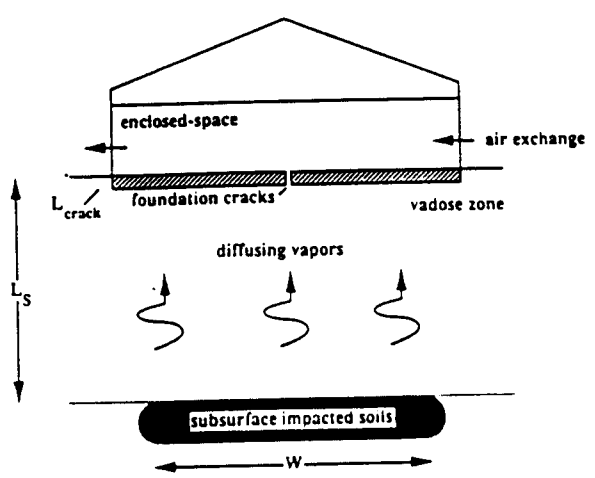

FIG. X2.5 Volatilization From Subsurface Soils to Enclosed-Space Air

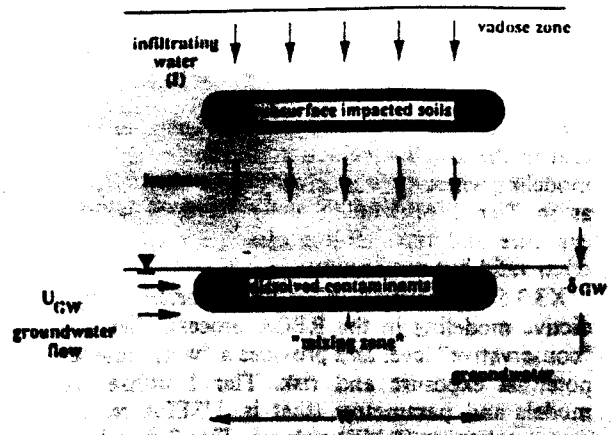

FIG. X2.6 Leaching from Subsurface Soils to Ground Water

X2.9.2 A conceptual model for the leaching of chemicals from subsurface soils to ground water is depicted in Fig. X2.6. For simplicity, the relationship between ground water and soil concentrations is represented in Tables X2.2 and X2.3 by the "leaching factor," LF_{sw} [(mg/L-H_2O)/ (mg/kg-soil)], defined in Table X2.1. It is based on the following assumptions:

X2.9.2.1 A constant chemical concentration in subsurface soils,

X2.9.2.2 Linear equilibrium partitioning within the soil matrix between sorbed, dissolved, and vapor phases, where the partitioning is a function of constant chemical- and soil-specific parameters,

X2.9.2.3 Steady-state leaching from the vadose zone to ground water resulting from the constant leaching rate I [cm/s],

X2.9.2.4 No loss of chemical as it leaches towards ground water (that is, no biodegradation), and

X2.9.2.5 Steady well-mixed dispersion of the leachate within a ground water "mixing zone."

X2.9.3 Should the calculated $RBSL_s$ exceed the value for which the equilibrated vapor and dissolved pore-water phases become saturated (see Table X2.1 for calculation of this value), "RES" is entered in the table to indicate that the selected risk level or hazard quotient cannot be reached or exceeded for that compound and the specified exposure scenario (even if free-phase product or precipitate is present in the soil).

X2.9.4 In some regulatory programs, "dilution attenuation factors" (DAFs) are currently being proposed based on fate and transport modeling results. A DAF is typically defined as the ratio of a target ground water concentration divided by the source leachate concentration, and is inherently very similar to the leachate factor, LF_{sw}, discussed here. The difference between these two terms is that LF_{sw} represents the ratio of the target ground water concentration divided by the source area soil concentration. Should a regulatory program already have a technically defensible DAF value, it can be equated to a leachate factor by the following expression:

$$LF_{sw} = \frac{DAF \times \rho_s}{[\theta_{ws} + k_s\rho_s + H\theta_{as}]} \times 10^0 \frac{\text{cm}^3\text{-kg}}{L\text{-g}}.$$

where the parameters are defined in Table X2.6.

X2.10 *Parameter Values:*

X2.10.1 Table X2.4 lists exposure parameters used to calculate the RBSLs appearing in sample Look-Up Table X2.1. All values given are based on adult exposures only. With the exception of the dermal exposure parameters (SA, M, and RAF_d), the values given are reasonable maximum exposure (RME) values presented in Ref (8) and are regarded as upper bound estimates for each individual exposure parameter.

X2.10.2 The skin surface area, SA = 3160 cm^2/day, is based on the average surface area of the head, hands, and forearms for adult males given in Ref (8). The soil-to-skin adherence factor, M [mg/cm^2], and dermal relative absorption factor, RAF_d [mg-absorbed/mg-applied], are based on guidance issued by Ref (15).

X2.10.3 Soil properties are based on typical values for sandy soils and are consistent with values given in Ref (16).

X2.10.4 Physical dimensions are consistent with the scale of typical underground fuel tank releases.

X2.10.5 Particulate emission rates were estimated by the approach presented by Cowherd et al (17). It was assumed that the mode of the surficial soil size distribution was 2 mm, the erosion potential was unlimited, there was no vegetative cover, and the mean average annual wind speed was 4 m/s.

X2.10.6 The chemical-specific parameters used are defined in Table X2.6.

X2.10.7 In this development, surficial soils are defined as those soils present within 1 m of ground surface. Subsurface soil RBSLs are based on assumed source depths of 1 m. Ground water is assumed to be located 3 m below ground surface.

X2.10.8 Once again, the reader is reminded that the parameter (and corresponding RBSL) values are presented as examples only, and are not intended to be used as standards. At best, the parameters presented are reasonable values based on current information and professional judgment. The reader should review and verify all assumptions prior to using any of the example RBSLs as screening level values.

X3. INTEGRATION OF PREDICTIVE MODELING WITH RISK-BASED CORRECTIVE ACTION PROCESS

X3.1 *Introduction:*

X3.1.1 In the context of risk-based corrective action (RBCA), predictive modeling is not only used to predict the future migration of chemicals, but is also used to interpret, or extrapolate, site characterization data, historical monitoring data, and toxicological information. Still another use is in the design of remedial systems and compliance monitoring plans. Predictive modeling is therefore another valuable tool that can provide information to the risk management process. This appendix discusses:

X3.1.1.1 Appropriate uses for predictive modeling,

X3.1.1.2 Defining the scope and inputs of a predictive

modeling exercise,

X3.1.1.3 Migration models, and

X3.1.1.4 Risk and exposure assessment models.

X3.2 *Uses of Predictive Modeling:*

X3.2.1 Predictive modeling results play a key role in many phases of RBCA including:

X3.2.1.1 Determining the potential urgency of response based on estimated migration and attenuation rates of compounds of concern,

X3.2.1.2 Determining the extent of corrective action based on estimated migration and attenuation rates of compounds of concern,

X3.2.1.3 Establishing relationships between administered doses and adverse impacts to humans and sensitive environmental receptors, and

X3.2.1.4 Determining risk-based screening level (RBSLs) concentrations at points of exposure.

X3.2.2 Examples of predictive modeling uses in the RBCA process include:

X3.2.2.1 The interpolation of site-specific data, as in the case of drawing contour maps for ground water concentrations and ground water elevations,

X3.2.2.2 The prediction of contaminant concentration distributions for future times based on historical trend data, as in the case of ground water transport modeling,

X3.2.2.3 The recommendation of sampling locations and sampling frequency based on current interpretation and future expectations of contaminant distributions, as in the design of ground water monitoring networks,

X3.2.2.4 The design of corrective action measures, as in the case of hydraulic control systems, and

X3.2.2.5 The calculation of site-specific exposure point concentrations based on assumed exposure scenarios, as in the case of direct exposure to surficial soils.

X3.2.3 Predictive modeling is not used in the RBCA process as a substitute for site-specific verification data.

X3.3 *Interpretation of Predictive Modeling Results:*

X3.3.1 Predictive models are mathematical approximations of real processes, such as the movement of chemicals in the subsurface, the ingestion of chemicals contained in drinking water, and adverse impacts to human health and environmental resources resulting from significant exposures. One key step towards evaluating model results is first to determine the accuracy, uncertainty, and validity of the model used.

X3.3.2 The "accuracy" of modeling predictions is judged based on how well the model predicts observed behavior, and is dependent upon a number of factors including:

X3.3.2.1 The approximations used when describing the real system by mathematical expressions,

X3.3.2.2 The input parameters used to generate the results, and

X3.3.2.3 The mathematical methods used to solve the governing equations (for example, numerical solution methods, expansion approximations, etc.).

X3.3.3 Predictive modeling results are always subject to some degree of uncertainty. It is important to quantify this uncertainty in order to properly interpret the results. Many times this is done with a "sensitivity" analysis in which the user quantifies the influence of changes in input parameters on the predictive model results, and then identifies those parameters that most significantly influence the results.

X3.3.4 The "validation" of model results is dependent upon the predictive model meeting preestablished modeling objectives. Predictive modeling results may therefore be "validated," without being accurate. This is especially important in the area of predictive risk and exposure assessment modeling where the modeling objective in many cases (such as in Tier 1 of RBCA) is to overestimate the potential exposure and risk. In this case the predictive models are often valid but not accurate.

X3.3.5 "Conservatism" is an important criterion of predictive modeling in the RBCA process. Tier 1 is the most "conservative" level and provides a "worst case scenario" for potential exposure and risk. Tier 1 utilizes conservative models and parameters (that is, USEPA reasonable maximum exposure (RME) values). Tier 2 is still conservative but provides flexibility for a more "reasonable case scenario." This level requires more specific information about the release site and may involve the use of either simple or moderately complex, but conservative, mathematical models. It may involve the use of most-likely exposure scenarios (that is, USEPA MLE values). This information is used to set "conservative" corrective action objectives that are still regarded as overly protective. Tier 3 site-specific target levels (SSTLs) are determined using site-specific transport and exposure models, and in some cases, parameter distributions. Tier 3 provides the most realistic evaluation of potential exposure and risk.

X3.4 *Types of Predictive Migration and Risk Assessment Models:*

X3.4.1 Predictive models typically used in the RBCA process can be grouped into two broad categories:

X3.4.1.1 Migration models, and

X3.4.1.2 Exposure, risk, and dose-response assessment models.

X3.4.2 The determination of Tier 1 risk-based screening levels, or Tiers 2 and 3 site-specific target levels generally involves the use of combinations of both types of models. A more detailed description of each group of models is given in X3.5 and X3.6.

X3.5 *Migration Models:*

X3.5.1 Migration (fate and transport) models predict the movement of a petroleum release through soil, ground water, or air, or combination thereof, over time. Most models focus on specific phenomena (for example, ground water transport) and vary in complexity, depending on assumptions made during model development. In RBCA, simplistic screening-level migration models are utilized in Tiers 1 and 2, while more complex models are utilized in Tier 3.

X3.5.2 Examples of screening-level models for a number of pathways relevant to petroleum releases are listed in Table X3.1. Most of the screening level migration models have a simple mathematical form and are based on rough conceptual approximations of actual phenomena. For example, the travel time between the leading edge of a dissolve hydrocarbon plume and a ground water well can be approximated by:

$$\frac{\textit{distance to well}\ (\text{ft})}{\textit{retarded flow velocity}\ (\text{ft/year})} = \frac{1000\ \text{ft}\ (304.8\ \text{m})}{100\ \text{ft/year}\ (30.4\ \text{m})} = 10\ \text{years}$$

X3.5.3 The use of more complex models is not precluded

in the RBCA process; however, given limited data and assumptions that must be made, many complex numerical models reduce to the analytical expressions given in Table X3.1.

X3.5.4 *Migration Model Data Requirements*—Predictive migration models require input of site-specific characteristics; a review of the parameters listed in Table X3.1 indicates

TABLE X3.1 Example Screening Level Transport Models

Description	Mathematical Approximation	Parameters
Dissolved Phase Transport:		
Maximum transport rate $u_{d,max}$ [cm/d] of dissolved plume[A]	$u_{d,max} = \frac{K_s i}{\theta_s R_s}$	$C(x)$ = dissolved hydrocarbon concentration along centerline (x, y = 0, z = 0) of dissolved plume [g/cm³-H_2O] C_{source} = dissolved hydrocarbon concentration in dissolved plume source area [g/cm³-H_2O] i = ground water gradient [cm/cm] K_s = saturated hydraulic conductivity [cm/d]
Minimum time $\tau_{d,min}$ [d] for leading edge of dissolved plume to travel distance, L [cm][A]	$\tau_{d,min} = \frac{L}{u_{d,max}}$	k_s = sorption coefficient [(g/g-soil)/(g/cm³-H_2O)] L = distance downgradient [cm] R_s = retardation factor = $[1 + k_s\rho_s/\theta_s]$ S_w = source width (perpendicular to flow in the horizontal plane) [cm] S_d = source width (perpendicular to flow in the vertical plane) [cm]
Steady-state attenuation [(g/cm³-H_2O)/(g/cm³-H_2O)] along the centerline (x, y = 0, z = 0) of a dissolved plume[A]	$\frac{C(x)}{C_{source}} = \exp\left\{\frac{x}{2\alpha_x}\left[1 - \left(1 + \frac{4\lambda\alpha_x}{u}\right)\right]\right\} \cdot \left(erf\left[\frac{S_w}{4\sqrt{\alpha_y x}}\right]\right)\left(erf\left[\frac{S_d}{4\sqrt{\alpha_z x}}\right]\right)$ where: $u = K_s i/\theta_s$	u = specific discharge [cm/d] $u_{d,max}$ = maximum transport rate of dissolved plume [cm/d][A] x = distance along centerline from downgradient edge of dissolved plume source zone [cm] y = depth below water table [cm] z = lateral distance away from dissolved plume centerline [cm] α_x = longitudinal dispersivity [cm] ≈ 0.10 x α_y = transverse dispersivity [cm] ≈ $\alpha_x/3$ α_z = vertical dispersivity [cm] ≈ $\alpha_x/20$ λ = first-order degradation constant [d^{-1}] θ_s = volumetric water content of saturated zone [cm³-H_2O/cm³-soil] ρ_s = soil bulk density [g-soil/cm³-soil] $\tau_{d,min}$ = minimum convective travel time of dissolved hydrocarbons to distance L [d][A] $erf(\eta)$ = error function evaluated for value η
Immiscible Phase Transport:		
Maximum depth D_{max} [cm] of immiscible phase penetration[A]	$D_{max} = \frac{V_{spill}}{\theta_R \pi R_{spill}^2}$	C_{soil} = total soil hydrocarbon concentration [g/g-soil] $C_{v,eq}$ = equilibrium vapor concentration [g/cm³-vapor][A] $C_{w,eq}$ = equilibrium dissolved concentration [g/cm³-H_2O][A] D_{max} = maximum depth of immiscible phase penetration [cm][A] H = Henry's Law Constant [(g/cm³-vapor)/(g/cm³-H_2O)]
Equilibrium Partitioning:		
Vapor Concentration:		
$C_{v,eq}$ [g/cm³-vapor]		
Maximum vapor concentration above dissolved hydrocarbons[A]	$C_{v,eq} = HC_{w,eq}$	k_s = sorption coefficient [(g/g-soil)/(g/cm³-H_2O)] M_w = molecular weight [g/mol] P_v^i = vapor pressure of compound i [atm]
Maximum vapor concentration when immiscible hydrocarbon is present[A]	$C_{v,eq} = \frac{x_i P_v^i M_w}{RT}$	R = gas constant = 82 cm³-atm/mol-K R_{spill} = radial extent of hydrocarbon impact [m] S_i = pure component solubility [g/cm³-H_2O] T = absolute temperature [K]
Maximum vapor concentrations in soil pores (no immiscible phase present)[A]	$C_{v,eq} = \frac{HC_{soil}\rho_s}{[\theta_w + k_s\rho_s + H\theta_v]}$	V_{spill} = volume of hydrocarbon released [cm³] x_i = mol fraction of component i θ_R = volumetric residual content of hydrocarbon under drainage conditions [cm³-hydrocarbon/cm³-soil]
Dissolved Concentration:		
$C_{w,eq}$ [g/cm³-H_2O]		θ_w = volumetric content of soil pore water [cm³-H_2O/cm³-soil] θ_v = volumetric content of soil vapor [cm³-vapor/cm³-soil]
Maximum dissolved concentration when immiscible hydrocarbon is present[A]	$C_{w,eq} = x_i S_i$	π = 3.1416 ρ_s = soil bulk density [g-soil/cm³-soil]
Maximum dissolved concentration in soil pores (no immiscible phase present)[A]	$C_{w,eq} = \frac{C_{soil}\rho_s}{[\theta_w + k_s\rho_s + H\theta_v]}$	(C_{soil}) = concentration at which immiscible phase forms in soil [g/g-soil][A]
Equilibrium Partioning:		
Soil Concentrations [g/g-soil]:		D^{air} = pure component diffusion coefficient in air [cm²/d]
Soil concentration [C_{soil}] [g/g-soil] at which immiscible hydrocarbon phase forms in soil matrix[A]	$(C_{soil}) = \frac{S_i}{\rho_s}[\theta_w + k_s\rho_s + H\theta_v]$	D_{eff} = effective diffusion coefficient for combined vapor and solute transport, expressed as a vapor phase diffusion coefficient (no immiscible hydrocarbon present outside of source area) [cm²/d][A]
Vapor Phase Transport:		D^w = pure component diffusion coefficient in water [cm²/d]
Effective porous media diffusion coefficient D^{eff} [cm²/d] for combined vapor and solute transport, expressed as a vapor phase diffusion coefficient (no immiscible hydrocarbon present outside of source area)[A]	$D^{eff} = \frac{\theta_v^{3.33}}{\theta_T^{3.33}} D^{air} + \frac{1}{H}\frac{\theta_w^{3.33}}{\theta_T^{3.33}} D^w$	H = Henry's Law Constant [(g/cm³-vapor)/(g/cm³-H_2O)] k_s = sorption coefficient [(g/g-soil)/(g/cm³-H_2O)] k_v = permeability to vapor flow [cm²] L = distance [cm]
Porous media "retardation" factor R_v (no immiscible hydrocarbon present outside of source area)[A]	$R_v = \left[\frac{\theta_w}{H} + \frac{k_s\rho_s}{H} + \theta_v\right]$	R_v = porous media "retardation" factor (no immiscible hydrocarbon present outside of source area) S_i = pure component solubility [g/cm³-H_2O] $u_{v,max}$ = maximum convective transport rate of vapors [cm/d][A] ∇P = vapor phase pressure gradient [g/cm²-s²] θ_w = volumetric content of soil pore water [cm³-H_2O/cm³-soil]

TABLE X3.1 *Continued*

Description	Mathematical Approximation	Parameters
Maximum convective transport rate $u_{v,max}$ [cm/d] of vapors[A]	$u_{v,max} = \frac{1}{R_v}\frac{k_v}{\mu_v}\nabla P$	θ_v = volumetric content of soil vapor [cm³-vapor/cm³-soil] θ_T = total volumetric content of pore space in soil matrix [cm³/cm³-soil] μ_v = vapor viscosity [g/cm-s] ρ_s = soil bulk density [g-soil/cm³-soil] $\tau_{c,min}$ = minimum time for vapors to travel a distance L [cm] by convection [day][A] $\tau_{d,min}$ = minimum time for vapors to travel a distance L [cm] by diffusion [day][A] C_{soil} = total soil hydrocarbon concentration [g/g-soil] $C_{v,eq}$ = equilibrium vapor concentration [g/cm³-vapor][A] d = distance below ground surface to top of hydrocarbon vapor source [cm] D^{eff} = effective diffusion coefficient for combined vapor and solute transport, expressed as a vapor phase diffusion coefficient (no immiscible hydrocarbon present outside of source area) [cm²/d][A] R_v = porous media "retardation" factor (no immiscible hydrocarbon present outside of source area)[A] $u_{v,max}$ = maximum convective transport rate $u_{v,max}$ of vapors [cm/d][A] ρ_s = soil bulk density [g-soil/cm³-soil] τ = averaging time [s] A_B = total area of enclosed space exposed to vapor intrusion (area of foundation) [cm²] A_{crack} = area of foundation through which vapors are transported (area of cracks, open seams, etc.) [cm²] C_{soil} = total soil hydrocarbon concentration [g/g-soil] $C_{v,eq}$ = equilibrium vapor concentration [g/cm³-vapor][A] d = distance between foundation/walls and hydrocarbon vapor source [cm] D^{eff} = effective diffusion coefficient through soil for combined vapor and solute transport, expressed as a vapor phase diffusion coefficient (no immiscible hydrocarbon present outside of source area) [cm²/d][A] D^{crack} = effective diffusion coefficient through foundation cracks [cm²/d][A] L_{crack} = thickness of foundation/wall [cm] $M_{w,i}$ = molecular weight of i [g/mol] $M_{w,T}$ = average molecular weight of the hydrocarbon mixture [g/mol] P_i^v = vapor pressure of pure component i [atm] Q_B = volumetric flow rate of air within enclosed space [cm³/s] Q_{soil} = volumetric infiltration flow rate of soil gas into enclosed space [cm³/s] R = gas constant = 82 atm-cm³/mol-K R_v = porous media "retardation" factor[A] T = absolute temperature [K] x_i = mol fraction of component i θ_v = volumetric content of soil vapor [cm³-vapor/cm³-soil] ρ_s = soil bulk density [g-soil/cm³-soil] π = 3.1416 τ = averaging time [s] $C_{w,eq}$ = equilibrium dissolved concentration in leachate source area [g/cm³-H_2O][A] E_B = enclosed space air exchange rate [l/d] E_{max} = vapor emission rate intd enclosed space [g/d][A] F = vapor flux [g/cm²-d][A] i = ground water gradient [cm/cm] K_s = saturated hydraulic conductivity [cm/d] L = downwind length of vapor emissions source area [cm] M = ground water mixing zone thickness [cm] q_i = water infiltration rate [cm/d]
Minimum time $\tau_{v,min}$ [d] for vapors to travel a distance L [cm] from source area by convection[A]	$\tau_{c,min} = \frac{L}{u_{v,max}}$	
Minimum time $\tau_{v,min}$ [d] for vapors to travel a distance L [cm] from source area by diffusion[A]	$\tau_{d,min} = \frac{L^2}{(D^{eff}/R_v)}$	
Vapor Emissions from Subsurface Vapor Sources to Open Surfaces:		
Maximum diffusive vapor flux F_{max} [g/cm²-d] from subsurface vapor source located a distance d [cm] below ground surface (steady-state, constant source)[A]	$F_{max} = D^{eff}\frac{C_{v,eq}}{d}$	
Maximum time-averaged diffusive vapor flux $\langle F_{max}\rangle$ [g/cm²-d] from subsurface soils over period from time = 0 to time = τ, single component immiscible phase present[A]	$\langle F_{max}\rangle = \frac{\rho_s C_{soil}}{\tau}\left\{\sqrt{\left[d^2 + \frac{2C_{v,eq}D^{eff}\tau}{\rho_s C_{soil}}\right]} - d\right\}$	
Maximum combined convective and diffusive vapor flux F_{max} [g/cm²-d] from subsurface vapor source located a distance d [cm] below ground surface[A]	$F_{max} = R_v u_{v,max} C_{v,eq} - \frac{R_v u_{v,max} C_{v,eq}}{\left[1 - \exp\left(\frac{R_v u_{v,max} d}{D^{eff}}\right)\right]}$	
Vapor Emissions from Surface Soils to Open Spaces:		
Maximum time-averaged diffusive vapor flux $\langle F_{max}\rangle$ [g/cm²-d] from surface soils over period from time = 0 to time = τ, single component immiscible phase present	$\langle F_{max}\rangle = \rho_s C_{soil}\sqrt{\frac{2C_{v,eq}D^{eff}}{\rho_s C_{soil}\tau}}$	
Vapor Emissions from Surface Soils to Open Spaces:		
Maximum time-averaged diffusive vapor flux $\langle F_{max}\rangle$ [g/cm²-d] from surface soils over period from time = 0 to time = τ, no immiscible phase present[A]	$\langle F_{max}\rangle = 2\rho_s C_{soil}\sqrt{\frac{D^{eff}}{\pi R_v \tau}}$	
Maximum time-averaged diffusive vapor flux $\langle F_{max}\rangle$ [g/cm²-d] from surface soils over period from time = 0 to time = τ, volatile components from relatively nonvolatile immiscible phase (for example, benzene from gasoline)[A]	$\langle F_{max}\rangle = \frac{2D^{eff}\left(\frac{x_i P_i^v M_{w,i}}{RT}\right)}{\sqrt{\pi\alpha\tau}}$ where: $\alpha = \frac{D^{eff}}{\theta_v + \frac{\rho_s RT(C_{soil}/M_{w,T})}{P_i^v}}$	

those most commonly required for various screening level models, including:

X3.5.4.1 Soil bulk density (can be estimated ≈ 1.7 g/cm³),

X3.5.4.2 Total soil porosity (can be estimated ≈ 0.38 cm³/cm³),

X3.5.4.3 Soil moisture content can be conservatively estimated in many cases. It is approximately equal to the total soil porosity beneath the water table, and typically >0.05 cm³-H_2O/cm³-soil in the vadose zone; this can be a critical input parameter in the case of diffusion models and may require site-specific determination unless conservative values are used,

X3.5.4.4 Fraction organic matter in soil particles (=0.005 – 0.01: sandy soil is often conservatively assumed); this can

TABLE X3.1 *Continued*

Description	Mathematical Approximation	Parameters
Vapor Emissions to Enclosed Spaces: Maximum vapor emission rate E_{max} [g/cm²-d] to enclosed spaces from subsurface vapor sources located a distance d [cm] away from the enclosed spaces[A]	$E_{max} = Q_B C_{v,eq} \left(\frac{D^{eff} A_B}{Q_B d}\right) \exp\left(\frac{Q_{soil} L_{crack}}{D^{crack} A_{crack}}\right) \Big/ \exp\left(\frac{Q_{soil} L_{crack}}{D^{crack} A_{crack}}\right) + \left(\frac{D^{eff} A_B}{Q_B d}\right) + \left(\frac{D^{eff} A_B}{Q_{soil} d}\right)\left(\exp\left(\frac{D_{soil} L_{crack}}{D^{crack} A_{crack}}\right) - 1\right)\Big]$	u_w = wind speed [cm/d] V_B = volume of enclosed space [cm³] W = width of impacted soil zone [z] δ = height of breathing zone [cm]
Hydrocarbon Vapor Dispersion:		
Ambient hydrocarbon vapor concentration resulting from area vapor source $C_{outdoor}$ [g/cm³][A]	$C_{outdoor} = \frac{FL}{u_w \delta}$	
Enclosed space vapor concentration C_{indoor} [g/cm³][A]	$C_{indoor} = \frac{E_{max}}{V_B E_B}$	
Leachate Transport:		
Leaching Impact on Ground water: Ground water source area concentration C_{source} [g/cm³-H_2O] resulting from leaching trhough vadose zone hydrocarbon-impacted soils[A]	$C_{source} = C_{w,eq} \frac{q_1 W}{(K_d I M + q_1 W)}$	
Ground water source area concentraiton C_{source} [g/cm³-H_2O] resulting from hydrocarbon-impacted soils in direct contact with ground water[A]	$C_{source} = C_{w,eq}$	

[A] Equation for this parameter given in this table.

also be a critical parameter requiring site-specific determination unless conservative values are used),

X3.5.4.5 Hydraulic conductivity (generally site-specific determination required),

X3.5.4.6 Ground water gradient and flow direction (requires site-specific determination), and

X3.5.4.7 First-order decay-rate (generally requires site-specific calibration as models are very sensitive to this parameter), see Table X3.2 for a summary of measured values currently available from the literature.

X3.5.5 Depending on the models selected, other information may be required, such as meteorological information (wind speed, precipitation, temperature), soil particle size distributions, and nearby building characteristics.

X3.5.6 In most cases, measurements of the attenuation (decrease in concentration) of compounds with distance away from the petroleum source area will be required to calibrate and verify the predictive capabilities of the selected models. The amount of data required varies depending on:

X3.5.6.1 The models used,

X3.5.6.2 Their sensitivity to changes in model input parameters, and

X3.5.6.3 The contribution of the pathway of concern to the total incremental exposure and risk.

X3.5.7 Generally, site-specific physical and chemical properties for the most sensitive parameters are required for migration models. However, instead of site-specific data, conservative values selected from the literature may be used.

TABLE X3.2 Reported Degradation Rates for Petroleum Hydrocarbons

Reference	Source of Data	Chemical Decay Rates (day⁻¹, [half-life days])							
		Benzene	Toluene	Ethyl-Benzene	Xylenes	O-Xylene	MTBE	Naphthalene	Benzo(a)Pyrene
Barker et al[A]	Borden Aquifer, Canada	0.007 [99]	0.011 [63]	...	...	0.014 [50]	...	...	...
Kemblowski[B]	Eastern Florida Aquifer	0.0085 [82]	...	...	...	...	...	...	...
Chiang et al[C]	Northern Michigan Aquifer	0.095 [7]	...	...	...	...	...	...	...
Wilson et al[D]	Traverse City, MI Aquifer	0.007 to 0.024 [99] to [29]	0.067 [10]	...	0.004 to 0.014 [173] to [50]	...	...	...	...
Howard et al[E]	Literature	0.0009 [730] to 0.069 [10]	0.025 [28] to 0.099 [7]	0.003 [228] to 0.116 [6]	0.0019 [365] to 0.0495 [14]	...	0.0019 [365] to 0.0866 [8]	0.0027 [258]	0.0007 [1058] to 0.0061 [114]

[A] See Ref (23).
[B] See Ref (24).
[C] See Ref (25).
[D] See Ref (26).
[E] See Ref (27).

X3.5.8 *Migration Modeling Process*—The goal of a migration modeling exercise is to utilize, or develop, mathematical approximations of real phenomena (for example, vadose zone processes, ground water flow, contaminant transport) that can be used to interpret site characterization and monitoring data, predict future migration, determine corrective action requirements, or predict the effect of proposed corrective action measures, or combination thereof. The migration modeling process typically involves the following tasks:

X3.5.8.1 *Modeling Objectives*—Modeling objectives must first be identified (that is, the questions to be answered by the model). It is important to keep these objectives in mind during data collection, model conceptualization, model and parameter selection, and model interpretation. At this point the user defines what phenomena are to be modeled and how the results are to be used (interpret site characterization and monitoring data, predict future migration, determine corrective action requirements, or predict the effect of proposed corrective action measures, or combination thereof).

X3.5.8.2 *Conceptual Model*—Once the modeling objectives have been identified, a conceptual model is constructed. The conceptual model is a qualitative description of the characteristics of the physical system and processes involved.

X3.5.8.3 *Model Selection*—After the conceptual model has been developed, a mathematical representation is selected to simulate the physical system and processes affecting it. Types of models generally employed include physical, analytical, and numerical models. If analytical or numerical mathematical models are selected, they should be appropriately simple to fit the available data and meet the modeling objectives. Physical models, such as sand tanks, are not commonly employed for exposure/risk assessment modeling and will not be discussed further here.

X3.5.8.4 Analytical models are generally based on assumptions of uniform properties and regular geometries. Advantages include a very simple set of assumptions, quick set-up and execution (calculator, or personal computer, and sometimes pencil and paper), and they can often quickly and inexpensively answer many important questions. In some cases, however, analytical models may be so simplistic that important aspects of a given system are neglected, or demanding modeling objectives cannot be satisfied.

X3.5.8.5 Numerical models allow for more complex heterogeneous systems with distributed properties and irregular geometries. Advantages include the flexibility to simulate more complex physical systems and natural parameter variability. However, the numerical approach can be very time intensive, may require much more data and information to be collected than is practicable, and results can be difficult to interpret and communicate.

X3.5.8.6 *Model Verification*—Model results must be verified against known solutions (in most cases these are analytical model results) to ensure that the mathematical equations are being solved correctly. Many commercially available models have already undergone validation studies; when available, the results of such a study should be reviewed prior to the model use.

X3.5.8.7 *Model Calibration*—The model calibration step is performed in order to verify that the combination of the selected model and set of input parameters produces model results that are adequately representative of site characterization and historical monitoring data from a given site. This step may include iterative history matching and input value refinement.

X3.5.8.8 *Sensitivity/Uncertainty Analysis*—Once a model has been verified and calibrated, a study to define the sensitivity, or variability, of model predictions resulting from variations in input parameter values is undertaken. These results can be used in two ways: to define which parameters must be most accurately defined and that can be approximated without loss of accuracy, and to define the range of model outputs given reasonable ranges in parameter values. If model predictions are found to be highly sensitive to small changes in the value of a poorly defined input parameter, then it will be difficult to have confidence in the accuracy of model results. On the other hand, if the model results remain relatively constant or are insensitive to changes in input parameter values, then the user can be more confident that the range of possible results is relatively well-defined.

X3.5.8.9 *Model Prediction*—Once these steps have been conducted, the model is now used to satisfy the modeling objectives.

X3.6 *Risk and Exposure Assessment Models:*

X3.6.1 "Exposure models" are used to estimate the chemical uptake, or dose, while "risk assessment models" are used to relate human health or ecological impacts to the uptake of a chemical. Risk and exposure assessment models are often combined to calculate a target exposure point concentration of a compound in air, water, or soil.

X3.6.1.1 In the case of compounds that have been classified as carcinogens, exposure and risk assessment models are generally linked by the expression:

$$\textit{risk} = \textit{average lifetime intake}\ [\text{mg/kg-day}] \times \textit{slope factor}\ [\text{mg/kg-day}]^{-1}$$

where the intake depends on exposure parameters (ingestion rate, exposure duration, etc.), and the concentration at point-of-exposure. The slope factor (sometimes called the "potency factor") is itself based on a model and set of underlying assumptions, that are discussed as follows:

X3.6.1.2 In the case of compounds that have not been classified as carcinogens, exposure and risk assessment models are generally linked by the expression:

$$\textit{hazard quotient} = \textit{average intake}\ [\text{mg/kg-day}]/\textit{reference dose}\ [\text{mg/kg-day}]$$

where the intake depends on exposure parameters (ingestion rate, exposure duration, etc.), and the concentration at point-of-exposure. The reference dose is itself based on a model and set of underlying assumptions, which are discussed below.

X3.6.2 *Toxicity Assessment: Dose-Response Models*—Toxicity assessments use dose-response data to identify a "safe dose" or a toxic level for a particular adverse effect. Most estimates of a "safe dose" or toxic level are based on animal studies. In some instances, human epidemiological information is available on a chemical. Toxicologists generally make two assumptions about the effects of risk agents at the low concentrations typical of environmental exposures:

X3.6.2.1 Thresholds exist for most biological effects; in other words, for noncarcinogenic, nongenetic toxic effects, there are doses below which no adverse effects are observed

in a population of exposed individuals, and

X3.6.2.2 No thresholds exist for genetic damage or carcinogenic effects. Any level of exposure to the genotoxic or carcinogenic risk agent corresponds to some non-zero increase in the likelihood of inducing genotoxic or carcinogenic effects.

X3.6.3 The first assumption is widely accepted in the scientific community and is supported by empirical evidence. The threshold value for a chemical is often called the no-observed adverse effects level (NOAEL). Scientists usually estimate NOAELs from animal studies. An important value that typically results from a NOAEL or LOAEL (lowest observed adverse effect level) value is the reference dose (RfD). A reference dose is an estimate (with an uncertainty typically spanning an order of magnitude) of a daily exposure (mg/kg/day) to the general human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime of exposure. The RfD value is derived from the NOAEL or LOAEL by application of uncertainty factors (UF) that reflect various types of data used to estimate RfDs and an additional modifying factor (MF), which is based on a professional judgment of the quality of the entire database of the chemical. The oral RfD, for example, is calculated from the following equation:

$$RfD = \frac{NOAEL}{UF \times MF}$$

X3.6.4 The second assumption regarding no threshold effects for genotoxic or carcinogenic agents is more controversial but has been adopted by the USEPA. For genotoxic and carcinogenic agents, extrapolations from high experimental doses to low doses of environmental significance requires the use of mathematical models to general low dose-response curves. It should be noted that although the EPA uses the linear multi-state model to describe carcinogenic effect, there is no general agreement in the scientific community that this is the appropriate model to use.

X3.6.5 The critical factor determined from the dose-response curve is the slope factor (SF), that is the slope of the dose-response curve in the low-dose region. The units of the slope factor are expressed as $(mg/kg\text{-}day)^{-1}$ and relate a given environmental intake to the risk of additional incidence of cancer above background.

X3.6.6 The RfD or SF values are generally obtained from a standard set of reference tables (for example, Ref (6) or Ref (7)). It is important to note that the information in IRIS has typically only been peer-reviewed within the EPA and may not always have support from the external scientific community. Whereas the information in IRIS has been subject to agency-wide data quality review, the information in the HEAST tables has not. The user is expected to consult the original assessment documents to appreciate the strengths and limitations of the data in HEAST. Thus, care should be exercised in using the values in HEAST. Some state and local agencies have toxicity factors they have derived themselves or preferences for factors to use if neither IRIS nor HEAST lists a value. Values for a range of hydrocarbons typically of interest are presented in Appendixes X1 and X2.

X3.6.7 It is important to note that in extrapolating the information obtained in animal studies to humans, a number of conservative assumptions are made.

X3.6.7.1 For noncarcinogens, an arbitrary system of default safety and uncertainty factors, as discussed above, (in multiples of ten) is used to convert observation in animals to estimates in humans.

X3.6.7.2 For carcinogens, some of the most important assumptions include: the results of the most sensitive animal study are used to extrapolate to humans, in general, chemicals with any carcinogenic activity in animals are assumed to be potential human carcinogens, and no threshold exists for carcinogens.

X3.6.8 The uncertainty in the RfD and SF values are often neglected in deference to single point values which are then typically summarized in databases such as IRIS and HEAST and are used subsequently as absolute estimates of risk. Further, many of these extremely conservative assumptions described above are risk-management policy decisions made by the USEPA. These assumptions are not explicitly defined and further obscure the conservatism in the safe dose estimate. Thus, care must be exercised in interpreting results which has as a basis these conservative toxicity evaluations.

X3.6.9 *Exposure Assessment Modeling*—The goal of exposure assessment modeling is to estimate the chemical uptake that occurs when a receptor is exposed to compounds present in their environment. In principal, the process for developing and using migration models presented in 6.5 is directly applicable to exposure assessment modeling. In this case the user:

X3.6.9.1 Develops a conceptual model by identifying significant exposure pathways and receptors,

X3.6.9.2 Selects a model to describe the contact rate and subsequent uptake of the chemical(s),

X3.6.9.3 Performs a sensitivity analysis to identify critical parameters,

X3.6.9.4 Selects appropriate exposure parameters (breathing rates, etc.),

X3.6.9.5 Generates estimates of exposure and uptake, and

X3.6.9.6 Assesses the uncertainty in the estimates.

X3.6.10 There are differences between the process outlined in X3.6.5 and that which can be practically applied to exposure assessment modeling. For example, with the exception of exposures and impacts to environmental resources, it is difficult to calibrate exposure assessment models unless very expensive epidemiological studies are conducted.

X3.6.11 Typically, the models used to estimate uptake are simplistic algebraic expressions, such as those contained in Ref (1). Application of these equations is illustrated in Appendix X2.

X3.6.12 In many cases, exposure parameter values are available in Ref (8), but other more-recent information is also available in peer-reviewed publications, and all sources should be carefully reviewed. While point values are often selected for simplicity, statistical distributions for many of the exposure parameters are readily available for Tier 3 analyses.

X3.6.13 It is common for USEPA reasonable maximum exposure (RME) values to be used in exposure assessment calculations, as is done for the example Tier 1 Look-Up Table discussed in Appendix X2. The RME value is generally defined as a statistical upper limit of available data (generally 85 to 90 % of all values are less than the RME

value). Therefore, by consistently selecting and multiplying conservative RME values the user models a scenario that is very improbable and always more conservative than the "true" RME exposure scenario. Thus, great care must be exercised, when using combinations of these default values in risk assessments, to avoid a gross overestimation of exposure for a specific site.

X4. INSTITUTIONAL CONTROLS

X4.1 *Introduction:*

X4.1.1 The purpose of this appendix is to provide a review of generally used institutional controls. For purposes of this appendix, "institutional controls" are those controls that can be utilized by responsible parties and regulatory agencies in remedial programs where, as a part of the program, certain levels of contamination will remain on site in soil or ground water. Referenced in this appendix are examples of programs from California, Connecticut, Illinois, Indiana, Iowa, Massachusetts, Michigan, Missouri, and New Jersey. In addition, federal programs, such as Superfund settlements and RCRA closure plans have utilized the techniques described below for some years as a mechanism to ensure that exposure to remaining contamination is reduced to the degree necessary.

X4.1.2 The types of institutional controls discussed in this appendix are as follows:

X4.1.2.1 Deed restrictions, or restrictive covenants,

X4.1.2.2 Use restrictions (including well restriction areas),

X4.1.2.3 Access controls,

X4.1.2.4 Notice, including record notice, actual notice, and notice to government authorities,

X4.1.2.5 Registry act requirements,

X4.1.2.6 Transfer act requirements, and

X4.1.2.7 Contractual obligations.

X4.1.3 Institutional controls for environmental remedial programs vary in both form and content. Agencies and landowners can invoke various authorities and enforcement mechanisms, both public and private, to implement any one or a combination of the controls. For example, a state could adopt a statutory mandate (see X4.2) requiring the use of deed restrictions (see X4.3) as a way of enforcing use restrictions (see X4.4) and posting signage (a type of access control, see X4.5). Thus, the institutional controls listed as follows are often used as overlapping strategies, and this blurs the distinctions between them.

X4.2 *Statutory Mandates*—Some states' emergency response programs mandate post-remediation institutional controls and impose civil penalties for noncompliance. The schemes vary from state to state, but all impose obligations on landowners to use one or more institutional controls listed in this appendix.

X4.3 *Deed Restrictions:*

X4.3.1 Deed restrictions place limits and conditions on the use and conveyance of land. They serve two purposes: informing prospective owners and tenants of the environmental status of the property and ensuring long-term compliance with the institutional controls that are necessary to maintain the integrity of the remedial action over time. Restraining the way someone can use their land runs counter to the basic assumptions of real estate law, so certain legal rules must be satisfied in order to make a deed restriction binding and enforceable.

X4.3.2 There are four requirements for a promise in a deed restriction (also called a "restrictive covenant") to be held against current and subsequent landowners: (*a*) a writing, (*b*) intention by both original parties that particular restrictions be placed on the land in perpetuity; (*c*) "privity of estate," and (*d*) that the restrictions "touch and concern the land."

X4.3.2.1 The first requirement is that of a writing. It is a rule of law that conveyances of land must be documented in a writing. The same rule holds for deed restrictions affecting land. Ideally, a deed restriction used as an institutional control would be written down with particularity and then recorded in the local land records office, in much the same fashion as the documentation and recordation of a sale of land. Parties may also encounter the requirement that the deed restriction be executed "under seal," a legal formality that has been abandoned in most states.

X4.3.2.2 The second requirement is that the deed restriction should precisely reflect what the parties' intentions are in regard to the scope and the duration of the restrictions. Explicitly stating in the deed restriction that the parties intend the restriction to "run with the land" (that is, last forever and bind subsequent owners) is strongly recommended.

X4.3.2.3 The third requirement, privity of estate, arises from a concern that only persons with a certain relationship to the land should be able to enforce a deed restriction. Normally, deed restrictions are promises between buyer and seller or between neighbors; therefore, the state or a third party may not enforce a deed restriction. However, even in states that require privity of estate, this concern is addressed if the landowner took the land with knowledge that the restrictions existed and might be enforced by these third parties. Thus, it is also strongly recommended that the deed restriction explicitly state that the states environmental authority may enforce the restriction. Recording of the deed restriction serves as notice to anyone who later purchases or acquires an interest in the land. Therefore, privity of estate should not be a barrier to state enforcement of the deed restriction if the proper steps are taken.

X4.3.2.4 Finally, a deed restriction is only enforceable if the promise "touches and concerns the land." A rough rule of thumb to decide this point is whether the landowner's legal interest in the land is decreased in value due to the deed restriction. If the land is devalued in this way, then the restriction could be said to "touch and concern the land." Note that the focus of the inquiry is on the land itself; promises that are personal in nature and merely concern human activities that happen to take place on the land are least likely to be enforceable. Thus, any deed restriction used

as an institutional control should be written so that it centers on the land and the use of the land.

X4.3.3 Due to the potential enforcement hurdles encountered by a governmental agency in enforcing a deed restriction, it may be appropriate for an individual state to seek statutory and regulatory amendments to ensure that such authority exits in regard to all deed restrictions for environmental purposes.

X4.3.4 Remedies for noncompliance with deed restrictions comes in two forms: persons or agencies may sue to obtain a court order (injunction) requiring compliance or if the state statute allows for it, the state's attorney general can seek enforcement of civil penalties, such as fines, for noncompliance.

X4.3.5 A state program can require a landowner to continue monitoring activities and to allow state environmental officials access to the site to monitor compliance with institutional controls. These arrangements may have to be put in a deed restriction in order to run with the land from owner to owner, but responsible parties can also be required to sign a contract making these promises. Of course, almost every state has authority to issue administrative orders to accomplish some or all of the above.

X4.3.6 The above arrangements can also set out procedures that will be followed if some emergency requires that the remediation site be disturbed. If, for example, underground utility lines must be repaired, the landowner would follow this protocol for handling the soil and alerting the state authority.

X4.4 *Use Restrictions:*

X4.4.1 Use restrictions are usually the heart of what is in a deed restriction. Use restrictions describe appropriate and inappropriate uses of the property in an effort to perpetuate the benefits of the remedial action and ensure property use that is consistent with the applicable cleanup standard. Such techniques also prohibit any person from making any use of the site in a manner that creates an unacceptable risk of human or environmental exposure to the residual contamination.

X4.4.2 Use restrictions address uses that may disturb a containment cap or any unremediated soils under the surface or below a building. A prohibition on drinking on-site (or off-site by means of well restriction areas discussed below) ground water may also be appropriate.

X4.4.3 As an example, a program may allow a restriction of record to include one or more of the following:

X4.4.3.1 Restriction on property use;

X4.4.3.2 Conditioning the change of use from nonresidential to residential on compliance with all applicable cleanup standards for a residential property;

X4.4.3.3 Restricting access; or

X4.4.3.4 Restricting disturbance of department-approved remedial effects.

X4.4.4 Well restriction areas can be a form of institutional control by providing notice of the existence of contaminants in ground water, and by prohibiting or conditioning the construction of wells in that area.

X4.4.4.1 This technique preserves the integrity of any ground water remedial action by prohibiting or conditioning the placement and use of any or all types of wells within the area.

X4.4.4.2 Well restrictions of this nature would be subject to agency approval, public notice, and may include the restriction on constructing or locating any wells within a particular designated area. Notice of the well restriction is recorded on the land records and with various health officials and municipal officials. The restrictions can only be released upon a showing that the contamination in the well restriction area is remediated in accordance with state standards.

X4.5 *Access Controls:*

X4.5.1 Another subset of institutional controls is the control of access to any particular site. The state uses the following criteria to determine the appropriate level and means of access control:

X4.5.1.1 Whether the site is located in a residential or mixed use neighborhood;

X4.5.1.2 Proximity to sensitive land-use areas including day care centers, playgrounds, and schools; and

X4.5.1.3 Whether the site is frequently traversed by neighbors.

X4.5.2 Access can be controlled by any of the following: fencing and gates, security, posting or warnings.

X4.6 *Notice:*

X4.6.1 Regulations of this type generally provide notice of specific location of contamination on the site, and disclose any restrictions on access, use, and development of part or all of the contaminated site to preserve the integrity of the remedial action.

X4.6.2 *Record Notice:*

X4.6.2.1 Some states require that sites having releases of hazardous waste file a notice on the land records providing to any subsequent purchaser of the property information regarding the past or current activities on the site.

X4.6.2.2 The record notice requirement may be broad; the program may require any property subject to a response action to obtain a professional opinion and then prepare and record a Grant of Environmental Restriction that is supported by that opinion.

X4.6.2.3 The record notice requirement can be ancillary to a transfer act (see X6.8), in which case recording of an environmental statement is only required in conjunction with a land transaction.

X4.6.3 *Actual Notice:*

X4.6.3.1 States may require direct notice of environmental information to other parties to a land transaction. These laws protect potential buyers and tenants, and they also help ensure that use restrictions and other institutional controls are perpetuated.

X4.6.3.2 Actual notice of an environmental defect or failure to provide notice may give a party the right to cancel the transaction and result in civil penalties. For example, landlords and sellers who do not give notice as required by the state may be liable for actual damages plus fines. Nonresidential tenants who fail to notify landowners of suspected or actual hazardous substance releases can have their leases canceled and are subject to fines.

X4.6.4 *Notice to Government Authorities*—Parties to a land transaction may also be required to file the environmental statement with various environmental authorities. Notice to the government may be required before the transaction takes place.

X4.7 *Registry Act Requirements:*

X4.7.1 Some states have registry act programs that provide for the maintenance of a registry of hazardous waste disposal sites and the restriction of the use and transfer of listed sites.

X4.7.2 A typical registry act provides that the state environmental agency establish and maintain a registry of all real property which has been used for hazardous substance disposal either illegally or before regulation of hazardous waste disposal began in that state.

X4.7.3 The state agency is responsible for investigating potential sites for inclusion on the registry. The registry includes the location of the site and a listing of the hazardous wastes on the property, and may also include a classification of the level of health or environmental danger presented by the conditions on the property. The state agency may be required to perform detailed inspections of the site to determine its priority relative to other registered sites.

X4.7.4 Owners of sites proposed for inclusion on the registry have rights of hearing and appeal, and owners of sites on the registry have rights to modify or terminate their listing. In some cases, the owner of a site proposed for inclusion on the registry may obtain the withdrawal of the proposed registration by entering into a consent agreement with the state. Such a consent agreement establishes a timetable and responsibility for remedial action.

X4.7.5 When a site appears on the state registry, the owner must comply with regulatory requirements in regard to use and transfer of the site. The use of a site listed on the registry may not be changed without permission of the state agency. In negotiations for a conveyance of a registered site, the owner may be obligated to disclose the registration early in the process, and permission of the state agency may be required to convey a registered property. Under other schemes, permission to convey is not required, but the seller must notify the state agency of the transaction.

X4.7.6 Finally, registry acts require that the listing of a property on a hazardous materials site registry be recorded in the records of the appropriate locality so that the registration will appear in the chain of title.

X4.8 *Transfer Act Requirements:*

X4.8.1 Some states have transfer act programs that require full evaluation of all environmental issues before or after the transfer occurs. It may be that within such program, institutional controls can be established by way of consent order, administrative order, or some other technique that establishes implementation and continued responsibility for institutional controls.

X4.8.2 A typical transfer act imposes obligations and confers rights on parties to a land transaction arising out of the environmental status of the property to be conveyed. Transfer acts impose information obligations on the seller or lessor of a property (see X4.6.3). That party must disclose general information about strict liability for cleanup costs as well as property-specific information, such as presence of hazardous substances, permitting requirements and status, releases, and enforcement actions and variances.

X4.8.3 Compliance with transfer act obligations in the manner prescribed is crucial for ensuring a successful conveyance. Sometimes the transfer act operates to render a transaction voidable before the transfer occurs. Failure to give notice in the required form and within the time period required or the revelation of an environmental violation or unremediated condition will relieve the transferee and the lender of any obligation to close the transaction, even if a contract has already been executed. Moreover, violation of the transfer act can be the basis for a lawsuit to recover consequential damages.

X4.9 *Contractual Obligations:*

X4.9.1 One system for ensuring the future restriction on use of a site, or the obligation to remediate a site, is to require private parties to restrict use by contract. While this method is often negotiated among private parties, it will be difficult, if not impossible, to institutionalize some control over that process without interfering with the abilities and rights of private parties to freely negotiate these liabilities.

X4.9.2 Another avenue is for the landowner or responsible party to obligate itself to the state by contract. The state may require a contractual commitment from the party to provide long-term monitoring of the site, use restrictions, and means of continued funding for remediation.

X4.10 *Continued Financial Responsibility*—Another aspect of institutional controls is the establishment of financial mechanisms by which a responsible party ensures continued funding of remediation measures and assurance to the satisfaction of the state.

X4.11 *References:*

X4.11.1 The following references serve as examples and are current as of the fourth quarter of 1993:

X4.11.1.1 *References for Deed Restrictions:*

24 N.J. Reg. 400 (1992) (N.J. Admin. Code § 7.26D-8.2 (e) (2)).
24 N.J. Reg. 400-02 (1992) (N.J. Admin. Code §§ 7.26D-8.1–8.4).
24 N.J. Reg. 401 (1992) (N.J. Admin. Code § 7.26D Appendix A, Model Document, Declaration of Environmental Restrictions and Grant of Easement, Item 8)
Illinois Responsible Property Transfer Act § 7(c) (1985)
Massachusetts Regulations Code Title _____ § 40.1071 (2) (1) & (k)
Mass. Regs. Code, Title _____ § 40.1071(4).
Mich. Admin. Code 299.5719 (3) (e) (1990)
Michigan Rules 299.5719 (2), (3) (d)

X4.11.1.2 *References for Use Restrictions:*

24 N.J. Reg. 400 (N.J. Admin. Code § 7.26D-8.2 (d))
Mich. Admin. Code 299.5719 (3) (a), (b), (g)
New Jersey Regulation 7.26D-8.4, that uses the above approach

X4.11.1.3 *References for Access Controls:*

Iowa Admin. Code r. 133.4 (2) (b)
Michigan Rule 299.5719 (3) (f)
New Jersey Regulations § 7.26D-8.2

X4.11.1.4 *References for Notice:*

Cal. Health and Safety Code § 25359.7 (1981)
Illinois Responsible Property Transfer Act (1985)
Indiana Code §§13-7-22.5-1–22 (1989) ("Indiana Environmental Hazardous Disclosure and Responsible Party Transfer Law")
Mass. Regs. Code Title _____ §§ 40.1071-1090 (1993)
Michigan Rule 299.5719 (3) (c)

X4.11.1.5 *References for Registry Act Requirements:*

Iowa Code Ann. §§ 455B.426–455B.432, 455B.411 (1) (1990)
Missouri Code Regs. Title 10, §§ 25-10.010, 25-3.260 (1993)

X4.11.1.6 *References for Transfer Act Requirements:*

Conn. Gen. Stat. §22a-134 *et seq*
Illinois Responsible Property Transfer Act (1985)
Indiana Code §§ 13-7-22.5-1–22 (1989) ("Indiana Environmental Hazardous Disclosure and Responsible Party Transfer Law")
New Jersey Senate Bill No. 1070, the Industrial Site Recovery Act, amending the environmental cleanup Responsibility Act, N.J.S.A. 13:1K-6 *et seq*
New Jersey Spill Compensation and Control Act, N.J.S.A. 58:10-23.11 *et seq*

X4.11.1.7 *Reference for Contractual Obligations:*

Michigan rule 299.5719 (2)

X4.11.1.8 *Reference for Continued Financial Responsibility:*

Michigan Rule 299.5719 (2)

X5. EXAMPLE APPLICATIONS OF RISK-BASED CORRECTIVE ACTION

X5.1 *Introduction*—The following examples illustrate the use of risk-based corrective action (RBCA) at petroleum-release sites. The examples are hypothetical and have been simplified in order to illustrate that RBCA leads to reasonable and protective decisions; nevertheless, they do reflect conditions commonly encountered in practice.

X5.2 *Example 1—Corrective Action Based on Tier 1 Risk-Based Screening Levels*

X5.2.1 *Scenario*—A [illegible] from the underground storage tank (UST), piping and dispenser system at a service station is discovered during a tank [illegible] assessment. It is known that there are petroleum-impacted surficial soils in the area of the tank fill ports; however, the extent to which the soils are impacted is unknown. In the past, both gasoline and diesel have been sold at the facility. The new owner plans to continue operating the service station facility.

X5.2.2 *Step 1—Initial Site Assessment*—The responsible party completes an initial site assessment focussed on potential source areas (for example, tanks, lines, dispensers) and receptors. Based on historical knowledge that gasoline and diesel have been dispensed at this facility, chemical analyses of soil and ground water are limited to benzene, toluene, ethylbenzene, xylenes, and naphthalene. Site assessment results are summarized below:

X5.2.2.1 Field screening instruments and laboratory analyses indicate that the extent of petroleum-impacted soils is confined to the vicinity of the fill ports for the tanks. A tank and line test reveals no leaks; therefore, evidence suggests that soils are impacted due to spills and overfills associated with filling the storage tank,

X5.2.2.2 The current tanks and piping were installed five years ago,

X5.2.2.3 The concrete driveway is highly fractured,

X5.2.2.4 No other sources are present,

X5.2.2.5 The site is underlain by layers of fine to silty sands,

X5.2.2.6 Ground water, that is first encountered at 32 ft (9.7 m) below ground surface, is not impacted,

X5.2.2.7 Maximum depth at which hydrocarbons are detected is 13 ft (3.9 m) maximum detected soil concentrations are as follows:

Compound	Depth, ft below ground surface (m)	Concentration, mg/kg
Benzene	8 (2.4)	10
Ethylbenzene	4 (1.2)	4
Toluene	6.5 (1.9)	55
Xylenes	3.5 (1.01)	38
Naphthalene	2 (0.6)	17

X5.2.2.8 A receptor survey indicates that two domestic water wells are located within 900 ft (273.6 m) of the source area. One well is located 500 ft (152.4 m) hydraulically down-gradient from the impacted soil zone, the other well is hydraulically up-gradient. Both wells produce water from the first encountered ground water zone.

X5.2.3 *Step 2—Site Classification and Initial Response Action*—Based on classification scenarios given in Table 3, this site is classified as a Class 3 site because conditions are such that, at worst, it is a long-term threat to human health and environmental resources. The appropriate initial response is to evaluate the need for a ground water monitoring program. At most, this would consist of a single well located immediately down-gradient of the impacted petroleum soils. The responsibility party recommends deferring the decision to install a ground water monitoring system until the Tier 1 analysis is complete, and justifies this recommendation based on no detected ground water impact, the limited extent of impacted soils, and the separation between impacted soils and first-encountered ground water. The regulatory agency concurs with this decision.

X5.2.4 *Step 3a—Tier 1—Exposure Pathway Evaluation*—Based on current and projected future use, the only two potential complete exposure pathways at this site are: the inhalation of ambient vapors by on-site workers, or the leaching to ground water, ground water transport to the down-gradient drinking-water well, and ingestion of ground water.

X5.2.5 *Step 3b—Tier 1—Risk-Based Screening Level (RBSL) Selection*—Assumptions used to derive example Tier 1 RBSL in Table 4 are reviewed and presumed valid for this site. A comparison of RBSLs for both pathways of concern indicates that RBSLs associated with the leaching pathway are the most restrictive of the two. As this aquifer is currently being used as a drinking water supply, RBSL values based on meeting drinking water MCLs are selected. In the case of naphthalene, for which there is no MCL, the RBSL value corresponding to a residential scenario and a hazard quotient of unity is used.

X5.2.6 *Step 3c—Tier 1—Comparison of Site Conditions With Tier 1 RBSLs*—Based on the data given in X5.2.3.7 and the RBSLs given in Look-Up Table 4 of the main body of text, exceedences of Tier 1 RBSLs are noted only for benzene and toluene.

X5.2.7 *Step 4—Evaluation of Tier 1 Results*—The responsible party decides to devise a corrective action plan to meet Tier 1 standards after considering the following factors:

X5.2.7.1 The shallow aquifer is not yet affected,

X5.2.7.2 Quick (relative to rate of chemical migration) removal of the source will eliminate the need for ground water monitoring,

X5.2.7.3 The new owner plans to install new tanks within six months,

X5.2.7.4 Limited excavation of soils to meet Tier 1 criteria could be performed quickly and inexpensively when the tanks are removed, relative to the cost of proceeding to a Tier 2 analysis, and

X5.2.7.5 An excavation proposal will facilitate the real estate deal.

X5.2.8 *Step 5—Corrective Action Plan*—Excavate all impacted soils with concentrations above the Tier 1 RBSLs when the current tanks are replaced. Subsequently resurface the area with the new concrete pavement to reduce future infiltration and leaching potential through any remaining impacted soils. It is agreed that ground water monitoring is

not necessary and the governing regulatory agency agrees to issue a No Further Action and Closure letter following implementation of the corrective action plan.

X5.3 *Example 2—[illegible] Based on Tier 2 Assessment:*

X5.3.1 *S[illegible]*—During the installation of new double-contained [illegible] lines, petroleum-impacted soils are discovered in the vicinity of a gasoline dispenser at a service station located close to downtown Metropolis. In the past, both gasoline and diesel have been sold at this facility, which has been operating as a service station for more than twenty years.

X5.3.2 *Step 1—Initial Site Assessment*—The owner completes an initial site assessment, [illegible] of potential source areas (for example, tanks, lines, dispensers, and receptors). Based on historical knowledge that gasoline and diesel have been dispensed at this facility, chemical analyses of soil and ground water are limited to benzene, toluene, ethylbenzene, xylenes, and naphthalene. Results of the site investigation are as follows:

X5.3.2.1 The extent of petroleum-impacted soils is confined to the vicinity of the tanks and dispensers. A recent tank and line test revealed no leaks; therefore, evidence suggests that the releases occurred sometime in the past.

X5.3.2.2 The current tanks, lines, and dispensers were installed three years ago,

X5.3.2.3 The asphalt driveway is competent and not cracked,

X5.3.2.4 Another service station is located hydraulically down gradient, diagonally across the intersection,

X5.3.2.5 The site is underlain by silty sands with a few thin discontinuous clay layers,

X5.3.2.6 Ground water, which is first encountered at 32 ft (9.7 m) below ground surface, is impacted, with highest dissolved concentrations observed beneath the suspected source areas. Dissolved concentrations decrease in all directions away from the source areas, and ground water samples taken hydraulically down gradient from a well located in the center divider of the street (about 100 ft (30.4 m) from the source area) do not contain any detectable levels of dissolved hydrocarbons,

X5.3.2.7 Ground water flow gradient is very shallow, and ground water flow velocities are at most tens of feet per year,

X5.3.2.8 Ground water yield from this aquifer is estimated to be in excess of 5 gal/min (18.9 L/min), and total dissolved solids levels are less than 700 mg/L. Based on this information, this aquifer is considered to be a potential drinking water supply,

X5.3.2.9 A shallow soil gas survey indicates that no detectable levels of hydrocarbon vapors are found in the utility easement running along the southern border of the property, or in soils surrounding the service station kiosk,

X5.3.2.10 Impacted soils extend down to the first encountered ground water. Maximum concentrations detected in soil and ground water are as follows:

Compound	Soil [mg/kg]	Ground water [mg/L]
Benzene	20	2
Ethylbenzene	4	0.5
Toluene	120	5
Xylenes	100	5.0
Napthalene	2	0.05

X5.3.2.11 A receptor survey indicates that no domestic water wells are located within one-half mile of the site; however, there is an older residential neighborhood located 1200 ft (365.7 m) hydraulically down-gradient of the site. Land use in the immediate vicinity is light commercial (for example, strip malls). The site is bordered by two streets and a strip mall parking lot.

X5.3.3 *Step 2—Site Classification and Initial Response Action*—Based on classification scenarios given in Table 3, this site is classified as a Class 3 site because conditions are such that, at worst, it is a long-term threat to human health and environmental resources. The appropriate initial response is to evaluate the need for a ground water monitoring program. The owner proposes that the ground water monitoring well located hydraulically down-gradient in the street divider be used as a sentinel well, and be sampled yearly. The regulatory agency concurs, provided that the well be sampled every six months.

X5.3.4 *Step 3(a)—Tier 1—Exposure Pathway Evaluation*—Based on current and projected future use, and the soil gas survey results, there are no potential complete exposure pathways at this site. The down-gradient residential neighborhood is connected to a public water supply system, and there is no local use of the impacted aquifer. However, being concerned about future uncontrolled use of the aquifer, the regulatory agency requires that the owner evaluate the ground water transport to residential drinking water ingestion pathway, recognizing that there is a low potential for this to occur.

X5.3.5 *Step 3(b)—Tier 1—Risk-Based Screening Level (RBSL) Selection*—Assumptions used to derive example Tier 1 RBSL in Table 4 are reviewed and presumed valid for this site. Due to the very low probability of the exposure pathway actually being completed in the future, MCLs are not used and the site owner is able to negotiate Tier 1 RBSLs based on a 10^{-5} risk to human health for carcinogens and hazard quotients equal to unity for the noncarcinogens (based on ground water ingestion).

X5.3.6 *Step 3(c)—Tier 1—Comparison of Site Conditions With Tier 1 RBSLs*—Based on the data given in X5.3.2.10 and the RBSLs given in example in Table 4, exceedences of Tier 1 soil and ground water RBSLs are noted only for benzene.

X5.3.7 *Step 4—Evaluation of Tier 1 Results*—The responsible party decides to proceed to a Tier 2 analysis for benzene and the pathway of concern, rather than devise a corrective action plan to meet Tier 1 standards after considering the following factors:

X5.3.7.1 The shallow aquifer is impacted, but the dissolved plume appears to be stable and ground water movement is very slow,

X5.3.7.2 Excavation of soils to meet Tier 1 criteria would be expensive, due to the depth of impacted soils. Excavation would shut down the facility, and require all tanks and new lines to be removed and reinstalled,

X5.3.7.3 Costs for application of other conventional treatment methods, such as vapor extraction and pump and treat are estimated to exceed $300 000 over the life of the remediation, and

X5.3.7.4 A tier 2 analysis for this site is estimated to require minimal additional data, and is anticipated to result in equally protective, but less costly corrective action.