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Standard Guide for
Application of Engineering Controls to Facilitate Use or Redevelopment of Chemical-Affected Properties[1]

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INTRODUCTION

Environmental media, such as soil, groundwater, or air, are susceptible to impact by chemical releases associated with past property-use activities; or they may be affected by naturally occurring conditions. Previously developed properties may have been impacted by chemical releases associated with historical operations, chemical spill incidents, waste management practices, or other related sources of COCs. In some cases, such chemicals may remain in soil, groundwater, or other environmental media; and, depending on their toxicity, concentration, location, and migration potential in the environment, they can pose a potential health risk in the event of exposure of current or future property users. Similarly, in the absence of a chemical release caused by human activity, COCs that are naturally present in soils, groundwater, soil vapors, or other environmental media can pose an unacceptable risk to human health, depending on the chemical toxicity and exposure (e.g., radon gas emanation into indoor air space of overlying buildings). Under certain conditions, in the absence of exposure controls, human exposure to chemical-affected environmental media at residential, commercial, or industrial properties could occur via various exposure pathways, including but not limited to (*1*) surface soil direct contact, (*2*) ambient or indoor air vapor exposure, or (*3*) affected groundwater impact on subsurface structures or utilities. Other pathways or exposure mechanisms may exist, and if so, should be addressed in a similar manner to those addressed in the guide.

1. Scope

1.1 This guide presents general considerations for application of engineering controls to facilitate continued use or redevelopment of properties containing chemical-affected soil, groundwater, or other environmental media, due either to chemical releases or naturally-occurring conditions. This guide is not meant to be prescriptive but rather to present considerations for evaluating technologies capable of addressing potential human exposures associated with chemical-affected environmental media.

1.2 Table 1 lists the considerations that should be taken into account when developing an engineering control in accordance with this guide.

1.3 This guide is intended for use by real estate developers, civil/structural designers, environmental regulators, industrial parties, environmental consultants, and other persons concerned with residential, commercial, or industrial development of real properties where chemical-affected environmental media are present. The design process should involve the individuals and firms working on various aspects of the specifications for construction, operation, and maintenance. If the site is located on public property, then public participation should be considered during the design process.

1.4 This guide is directed toward properties where chemical-affected environmental media, associated with either human-influenced activities or naturally-occurring conditions, will remain in place and where active or passive engineering controls will be used to reduce or eliminate exposures that may otherwise pose an unacceptable risk to property users.

1.5 This guide identifies the exposure concerns associated with chemical-affected properties that may affect the property development plan, both in the construction phase and during the proposed use of the property; defines performance standards for control of applicable exposure pathways; and, for each exposure pathway, provides examples of engineering controls that may be applied for new or existing construction.

[1] This guide is under the jurisdiction of ASTM Committee E50 on Environmental Assessment, Risk Management and Corrective Action and is the direct responsibility of Subcommittee E50.04 on Corrective Action.

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TABLE 1 Design Considerations for Engineering Controls[A]

Task/Description	Reference[B]	Check: When Complete	Check: If Not Applicable
SITE CHARACTERIZATION			
1. Regulatory Framework			
• *Regulations:* Identify federal, state, and local laws, rules, and ordinances applicable to site characterization and engineering controls. Ensure design and installation conform to technical standards specified in regulations.	6.3.9	☐	☐
• *Guidance:* Identify relevant guidance documents.	4.6,6.3.9	☐	☐
• *Risk Limits:* Define unacceptable risk per regulatory framework or other process.	5.2	☐	☐
• *Permitting:* Complete permitting, notification, and activity and use limitations per regulatory requirements.	6.3.9	☐	☐
2. Site Conceptual Model			
• *Delineation:* Define extent of chemical-affected environmental media: soil, groundwater, air, other.	5.2.1	☐	☐
• *Chemicals of Concern:* Identify COCs, toxicity, concentrations, locations, migration potential.	5.2.1	☐	☐
• *Receptors:* Identify potential receptors, complete exposure pathways, define anticipated property use during design life of engineering control.	5.2.1	☐	☐
SITE DEVELOPMENT PLAN			
1. Considerations for Site Development Plan			
• *Human Contact:* Reduce or eliminate human contact with chemical-affected environmental media.	5.3.1	☐	☐
• *Waste:* Limit generation of hazardous waste materials.	5.3.1	☐	☐
• *COC Migration:* Prevent off-site migration of COCs.	5.3.1	☐	☐
• *Plume Expansion:* Prevent expansion of affected soil and groundwater zones.	5.3.1	☐	☐
2. Limitations on Site Development Plan			
• *Subsurface Construction:* Consider locations of structures and subsurface penetrations, consider direct contact with chemical-affected groundwater during construction.	5.3.2	☐	☐
• *Existing Facilities:* Consider need to maintain existing engineering controls.	5.3.2	☐	☐
DESIGN OF ENGINEERING CONTROLS			
1. Achievement of Performance Standard			
• *Risk Limits:* Reduce or eliminate unacceptable risk by either or both of the following: a. By preventing direct contact with chemical-affected environmental media. b. By preventing migration of COCs from chemical-affected environmental media to point of exposure.	6.1.1	☐	☐
• *Design Life:* Set design life of engineering control equal to lesser of the following: a. Expected duration of the exposure hazard. b. Expected duration of the site or structure for the specified property use.	6.1.2	☐	☐
2. Application of Engineering Controls to Specific Exposure Pathways			
• *Direct Contact:* Prevent surface soil direct contact by either or both of the following a. Obstructing human contact with chemical-affected soil. b. Impeding the release of wind-driven soil particulates into the air.	6.2.1	☐	☐
• *Soil or Groundwater Vapors:* Prevent inhalation of vapors at concentrations exceeding unacceptable risk levels by inhibiting migration of vapors to ambient or indoor air.	6.2.2	☐	☐
• *Groundwater Impacts:* Prevent impact of affected groundwater on subsurface structures or utilities by installing a barrier to flow.	6.2.3	☐	☐
3. Design Specifications			
• *Qualifications:* Prepare design specification by qualified persons having required professional or regulatory certifications.	4.5,6.3	☐	☐
• *Participation:* Solicit, consider, and incorporate input from individuals and firms working on various aspects of the design, construction, operation, and maintenance specifications.	1.3	☐	☐
• *Documentation:* Document design specifications in sufficient detail to evaluate compliance with performance criteria.	6.3	☐	☐
• *Design Basis Information:* Develop design basis information sufficient to support engineering design of components of the engineering control.	6.3.1	☐	☐
• *Effective Area:* Define effective area to address the full area or volume, or both, of the chemical-affected environmental media requiring exposure control.	6.3.2	☐	☐
• *Defining Boundary:* Specify defining boundary to physically demarcate or document engineering control or area of chemical-affected media, or both.	6.3.2	☐	☐
• *Components:* Specify design components of engineering control, including details of design, installation, and operation and maintenance.	6.3.3	☐	☐
• *Dimensions and Material Specifications:* Evaluate the properties of each design component (e.g., material strength, durability, corrosion resistance, chemical compatibility) for capability to achieve the specified performance standard for the duration of the design life under anticipated site conditions.	6.3.4	☐	☐
• *Treatment System:* Specify design for construction or installation of treatment system for soil or groundwater, including removal efficiency or required concentrations after treatment.	6.3.5	☐	☐
• *Documentation:* Prepare record drawings, drawings conforming to construction records, or other written records to document installation of engineering control.	6.3.7	☐	☐
INSTALLATION OF ENGINEERING CONTROLS			
• *QA/QC Program:* Set up system of inspections, monitoring, or testing, or combination thereof, to confirm installation in accordance with design specifications.	7.1	☐	☐
• *Qualifications:* Specify installation by persons qualified to complete work by reason of professional or regulatory certifications.	7.2	☐	☐

TABLE 1 *Continued*

Task/Description	Reference[B]	Check: When Complete	Check: If Not Applicable
MONITORING AND MAINTENANCE OF ENGINEERING CONTROLS			
• *Obligatory Requirements:* Ensure monitoring requirements comply with enforcement instruments for site (e.g., consent agreement, consent order, order, permit, etc.).	8.1	☐	☐
• *Periodic Monitoring:* Specify type (e.g., visual inspection, physical measurements, sampling and testing) and frequency, of monitoring programs needed to assess performance of engineering control and fulfill regulatory requirements. Include triggers for non-routine monitoring.	8.2	☐	☐
• *Maintenance:* Describe schedule and procedures for conducting repairs or replacements indicated by periodic monitoring.	8.3	☐	☐
• *Assessment:* Describe procedures for assessing the performance of the engineering control and implementing changes as needed to address results of the periodic monitoring.	8.4	☐	☐
• *Re-Evaluation:* Describe procedures for re-evaluating the performance of the engineering control and implementing changes as needed to address (*1*) a change in land use, regulatory criteria, or site development plan; or (*2*) a newly identified risk.	4.4,5.4,8.4	☐	☐
USE OF ACTIVITY AND USE LIMITATIONS			
• *Need for Activity and Use Limitations:* Identify the activity and use limitations to be implemented along with engineering controls in order to control risk.	9.1	☐	☐
• *Recordation:* File activity and use limitations in real property records of governmental entities having jurisdiction over the site in order to notify future owners and users of the site about the presence of engineering controls.	9.2	☐	☐

[A] Table presents design issues to be considered to demonstrate that the design of an engineering control for chemical-affected property has been developed in accordance with this guide. Consideration of the issues should be documented in accordance with the identified regulatory framework for the site.
[B] References indicate sections of this guide.

1.6 This guide will assist in identification of the optimal property development plan for a property with chemical-affected environmental media. Such a plan will address both short-term construction issues and long-term exposures of property users.

1.7 This guide does not address the broader range of environmental concerns that are not directly affected by construction measures and engineering controls (e.g., protection of water resources or ecological receptors).

1.8 Detailed specifications for site-specific application of engineering controls are not addressed in this guide. The user is referred to other related ASTM standards and technical guidelines regarding the implementation of the site evaluation and corrective action process, as well as the detailed design, installation, operation, and maintenance of these engineering controls.

1.9 The overall strategy for addressing unacceptable risks may employ either remedial actions or activity and use limitations, or both. Engineering controls are a subset of remedial actions given that (*1*) remedial actions involve cutting off the exposure pathway or reducing the concentration of COCs, or both and (*2*) that engineering controls only involve cutting off the exposure pathway. Engineering controls are briefly described in Guide E2091, which describes a broad range of options for managing risk. This guide covers implementation of engineering controls in a detailed manner, thereby providing a needed complement to the information provided in Guide E2091.

1.10 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.11 *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 to determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 The pertinent ASTM standards for development of engineering controls at chemical-affected properties are listed below. Additional standards and other non-ASTM references related to the development of engineering controls at chemical-affected properties are provided in Appendix X6.

2.2 *ASTM Standards:*[2]

C1193 Guide for Use of Joint Sealants
C1299 Guide for Use in Selection of Liquid-Applied Sealants (Withdrawn 2012)[3]
E1689 Guide for Developing Conceptual Site Models for Contaminated Sites
E1745 Specification for Plastic Water Vapor Retarders Used in Contact with Soil or Granular Fill under Concrete Slabs
E1984 Guide for Brownfields Redevelopment (Withdrawn 2012)[3]
E2081 Guide for Risk-Based Corrective Action
E2091 Guide for Use of Activity and Use Limitations, Including Institutional and Engineering Controls

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.
[3] The last approved version of this historical standard is referenced on www.astm.org.

E2121 Practice for Installing Radon Mitigation Systems in Existing Low-Rise Residential Buildings

3. Terminology

3.1 *active engineering control*—active engineering control systems involve the input of energy (e.g., electrical, mechanical, hydraulic, pneumatic, chemical, thermal, or other energy source) to remove, treat, or control chemical-affected environmental media. Examples of active engineering controls include, but are not limited to, groundwater pumping, vapor extraction, in-situ chemical or biological treatment, active sub-slab ventilation systems.

3.2 *activity and use limitations*—legal or physical restrictions or limitations on the use of, or access to, a site or facility so as to eliminate or minimize potential exposures to COCs.

3.3 *chemical(s) of concern (COCs)*—the specific compounds and their breakdown products that are identified for evaluation in the Risk-Based Corrective Action (RBCA) process or redevelopment process, based upon their current or historical use at the property; detected concentrations in environmental media; and mobility, toxicity, and persistence in the environment. COCs may include, but are not limited to, methane, petroleum hydrocarbons, radon, organic chemicals, inorganic chemicals, metals, etc.

3.4 *chemical release*—any spill or leak of COC(s) to an environmental medium.

3.5 *chemical-affected environmental medium*—environmental medium which has been physically or chemically altered or otherwise adversely impacted by one or more COCs in excess of background levels or other applicable regulatory standard or beneficial use criterion.

3.6 *engineering controls*—physical modifications to a site or facility installed to reduce or eliminate the potential for exposure to COCs.

3.7 *environmental medium*—naturally-occurring physical material in the environment, including but not limited to ambient or indoor air, air in soil pore spaces, soils, groundwater, or surface water.

3.8 *exposure pathway*—the course that a COC takes from the source area(s) to a receptor. An exposure pathway describes the mechanism by which an individual or population is exposed to a COC originating from a site. Each exposure pathway includes a source from which a release of a COC occurs, an exposure route, and a point of exposure where a human receptor may come in contact with the COC. If the exposure point is not at the source, then a transport medium or exposure medium, or both (for example, air or water), are also included in the exposure pathway.

3.9 *exposure route*—the manner in which a COC comes in contact with a receptor (for example, ingestion, inhalation, dermal contact).

3.10 *passive engineering controls*—passive engineering control systems either require no energy or chemical input or take advantage of natural conditions (e.g., barometric pressure variations) to remove or control, or both, chemical-affected environmental media. Passive controls may include those involving only physical barriers or flow controls. Examples of passive controls include, but are not limited to, groundwater seepage barriers, surface soil covers, passive vapor controls, surface covers, and polymeric membrane liners.

3.11 *potentially complete exposure pathway*—a situation with a reasonably likely chance of occurrence in which a human receptor may become directly or indirectly exposed to the COC(s).

3.12 *property*—real property, including land and associated improvements, as well as all environmental media contained within the legal boundaries. The environmental media containing COCs may extend over all or a portion of one or more properties.

3.13 *property development*—the human-influenced alteration of a property, including but not limited to the construction of improvements such as buildings, roadways, utilities, landscaped areas, parking lots or structures, recreational areas, or other such features associated with residential, commercial, or industrial land use.

3.14 *property development plan*—the short-term and long-term strategies or schemes for implementing the human-influenced alteration of a property.

3.15 *risk*—the potential for, or probability of, an adverse effect, which may be expressed either quantitatively or qualitatively.

3.16 *surface soil*—the soil zone that a human receptor could reasonably come into contact with, currently or at some time in the future. The surface soil zone extends from ground surface to the shallower of the following: (*1*) the depth specified in applicable law, rule, or ordinance, depending upon the planned land use; or (*2*) a depth extending no deeper than the top of the uppermost groundwater-bearing unit or bedrock.

3.17 *unacceptable risk*—a risk which exceeds regulatory, published, or other criteria based on site-specific considerations and a human health-risk assessment.

4. Significance and Use

4.1 *Intended Application of Guide*—This guide is intended for use at properties that are presently developed or proposed for development for residential, commercial, or industrial purposes but which contain chemical-affected soil, groundwater, air, or other environmental media, which may pose an unacceptable risk to human health. This guide can be used as a tool for planning and implementation of property reuse or redevelopment activities at former commercial/industrial facilities, "brownfield" properties, or properties containing naturally occurring, chemical-affected environmental media so as to effectively manage potential human exposures to COCs which might otherwise limit productive use of the property.

4.2 *Situations Where This Guide May Be Applied*—An engineering control may be needed as part of the development plan when: (*1*) COCs are present in soil, groundwater, or other environmental media at concentrations posing unacceptable risk(s) to human health per applicable regulatory criteria or a risk-based evaluation; (*2*) a potentially complete exposure pathway for COCs is likely to exist in the absence of an engineering control or other response measure, and (*3*) installation and maintenance of the engineering control is determined to be an applicable and cost-effective response action relative to other options. A property should not be excluded from development or redevelopment solely on the basis of chemical-affected media, in general, and chemical-affected groundwater, in particular. If no affected environmental media are identified as having COC concentrations in excess of applicable regulatory standards or risk-based criteria, then engineering controls or other response measures are not required.

4.3 *Assumptions for Use of This Guide*—For use of this guide, it is assumed that (*1*) an environmental site assessment has been completed to characterize chemical-affected environmental media, (*2*) exposures to COCs posing an unacceptable risk to the health of current or future property users have been identified based upon a risk-based corrective action analysis or other evaluation consistent with applicable regulatory requirements, and (*3*) engineering controls are being considered as a potentially effective and acceptable measure to manage exposures to chemical-affected environmental media remaining in place at the property. This guide assumes that the property is served by a public water supply or other water source so that use of on-site groundwater or surface water resources as a water supply is not necessary.

4.4 *Presumptive Use of Engineering Controls*—The design basis for any engineering controls installed depends on the risk to be controlled, nevertheless, if no known risk has been identified, the guide may be implemented at the discretion of the site developer. As a conservative measure to reduce or eliminate potential unidentified exposures (e.g., migration of COCs from adjacent properties with known chemical-affected environmental media), the site developer may choose to install engineering controls in the absence of a detailed site characterization and associated risk-based corrective action analysis. Regardless, the site must be sufficiently characterized as to the types and concentrations of the COCs present in order to design and install engineering controls that will effectively mitigate the potentially complete exposure pathway(s) identified for the site. Upon change in land use, the potential for unacceptable risk should be evaluated and the engineering control modified, if so indicated by the results of the evaluation.

4.5 *Expected Qualifications for Persons Applying This Guide*—Persons applying this guide are expected to be sufficiently knowledgeable in various disciplines, including but not limited to environmental science, property development requirements, or engineering applications, or combination thereof. Such knowledge is required in order to (*1*) interpret the results of environmental site assessments and risk-based corrective action analyses and (*2*) identify applicable construction measures and engineering controls, as needed to reduce or eliminate unacceptable human exposures to chemical-affected environmental media while achieving property development goals. Persons implementing this guide are responsible for ensuring that the application of the guide, as well as design, installation, and monitoring and maintenance of engineering controls identified for a site by the guide, are performed, reviewed, or certified, or combination thereof, by persons qualified to complete work of this nature by reason of professional or regulatory certifications, or both.

4.6 *Intended Compatibility with Other ASTM Guides*—This guide is intended to be compatible with other ASTM guides related to the investigation and characterization of chemical-affected property and the management of associated human health risks. This guide is consistent with the practices set forth in these other guides but provides a more focused evaluation on engineering controls as measures to manage risk specifically associated with property development activities.

4.7 *Limitations on Use of This Guide*—This guide provides a general overview of the procedures for evaluation and selection of engineering controls for use in property development or reuse, but does not address the detailed design, installation, operation, or maintenance of these engineering controls. The user is referred to other, more detailed technical design guidelines for proper implementation of such controls on a site-specific basis.

4.8 *Situations Not Addressed*—This guide does not address other environmental issues or concerns that are not directly related to property development or reuse but which may be required under applicable laws or regulations. Such uses may include groundwater protection, surface water protection, or ecological concerns.

4.9 *Costs Associated with Engineering Controls*—The costs for engineering control systems will depend on numerous site specific factors (e.g., area and volume of chemical-affected environmental media, COCs, unacceptable risks to be reduced or eliminated). An exhaustive comparison of costs associated with various engineering control systems is beyond the scope of this guide; however, in order to illustrate the potential cost impact of site development using engineering controls, a case study example is presented in Appendix X4.

5. General Considerations for Use or Redevelopment of Chemical-Affected Property

5.1 *Overview*—Continued use or redevelopment of property containing chemical-affected environmental media may entail consideration of potential human exposure concerns, both during the construction phase and during the subsequent use of the property. To address these issues, the nature and extent of chemical-affected environmental media should first be characterized based on an environmental site assessment. Based upon this information, a risk-based corrective action analysis or other relevant evaluation should then be conducted by a competent individual to define potentially complete exposure pathways under the current or proposed land use. The site development plan should address design and construction constraints related to contact with or mobilization of chemical-affected environmental media, as well as waste production and related costs. Consideration of the following environmental factors in the planning process can facilitate safe and economical use or redevelopment, or both, of the property.

5.2 *Conceptual Exposure Model*—The conceptual exposure model is a representation of an environmental system which includes the biological, physical, and chemical processes that determine the fate and transport of COCs through environmental media to receptors within that system. The purpose of the conceptual exposure model is the characterization of exposure pathways which includes (*1*) delineation of zones of chemical-affected environmental media, (*2*) determination of fate and transport mechanisms, and (*3*) identification of potential human receptors. Procedures for development of the conceptual exposure model are provided in Guide E1689.

5.2.1 *Chemical-Affected Environmental Media*—The nature and extent of chemical-affected environmental media should be characterized sufficiently to support development of the conceptual exposure model and to support evaluation of applicable engineering control measures. Characterization may include delineation of chemical-affected environmental media; determination of unsaturated or saturated soil properties (e.g., grain size, soil type), or determination of groundwater-bearing unit properties (e.g., hydraulic conductivity, thickness, porosity), or combination thereof. This evaluation must also consider naturally occurring conditions having the potential to cause unacceptable risk to human health (e.g., radon, methane).

5.2.2 *Potentially Complete Exposure Pathways and Corrective Action Goals*—Based upon the characterization of chemical-affected environmental media, potentially complete pathways for human exposure should be defined on a site-specific basis. This information should then be used to establish corrective action goals as needed to reduce or eliminate unacceptable risks associated with chemical-affected environmental media during and after property development activities.

5.3 *Short-Term Construction Issues and Property Development Constraints*—Use and development of chemical-affected property may entail design and construction considerations not encountered at unaffected properties, including (*1*) exposure of construction workers to chemical-affected environmental media; (*2*) mobilization of chemical-affected environmental media or COCs during or after site development activities (e.g., dust, excavation, leaching to groundwater); (*3*) generation of chemical-affected environmental media classified as waste material requiring special handling, treatment, or disposal procedures; (*4*) preservation of engineering controls or activity and use limitations established in accordance with prior regulatory approval (e.g., soil leachate control systems or surface covers to control migration of chemicals via soil leaching to groundwater); or (*5*) other regulatory restrictions related to property use.

5.3.1 *Considerations for Site Development Plan*—Design and construction considerations may affect the site development plan as needed to (*1*) reduce or eliminate human contact with chemical-affected environmental media, (*2*) manage the generation, storage, and disposal of hazardous waste materials, if required, (*3*) prevent off-site migration of COCs in environmental media or the expansion of existing chemical-affected environmental media on the property, and (*4*) install new engineering controls, preserve previously installed engineering controls, or replace previously installed engineering controls. Previously installed engineering controls for reducing or eliminating potential exposure to human receptors at the property may be replaced if no longer effective, if no longer required, or if an alternative engineering control is determined to be advantageous with respect to reducing or eliminating risk, operation and maintenance, cost effectiveness, or other considerations. For projects where the community is involved in the property development, general guidelines for community outreach and input are described in Guide E1984.

5.3.2 *Limitations on Site Development Plan*—The property development plan may entail limitations on structure locations or subsurface penetrations (e.g., slab-on-grade foundations versus excavated basements, underground utilities, stormwater retention ponds); installation of engineering controls or maintenance of existing engineering controls (e.g., surface covers, vapor barriers, drainage controls); or other such measures which serve to achieve site development goals while reducing or eliminating environmental concerns and associated costs. Such constraints, if any, are site-specific in nature and depend in part upon the nature and extent of the chemical-affected environmental media, the presence and effectiveness of existing engineering controls, the applicable regulatory requirements, and the relative cost and feasibility of alternative site development measures.

5.4 *Re-Evaluation of Engineering Control for Change in Land Use*—The effectiveness of each engineering control should be re-evaluated upon a change in land use, regulatory criteria, or site development plan. Based on a proposed change in property use, the engineering control may require modification, and should be retooled or replaced in accordance with approved alternative corrective action(s) intended to continue to reduce or eliminate unacceptable risks of exposure to future property users.

6. Design of Engineering Controls

6.1 *Performance Standards for Engineering Controls*—Engineering controls serve to prevent unacceptable contact with chemical-affected environmental media by human receptors under the proposed property use. The conceptual design must therefore: (*1*) identify reasonable mechanisms whereby such exposure could occur under the proposed property use, and (*2*) define controls needed to reduce or eliminate unacceptable risk of exposure to property users and facilitate the proposed property use, if technically and economically feasible.

6.1.1 *Exposure Prevention*—Based on the Conceptual Exposure Model, the engineering control(s) should serve to reduce or eliminate exposure to COCs at concentrations exceeding unacceptable risk levels (*1*) preventing direct contact with the chemical-affected environmental media (e.g., dermal contact with affected soils) and (*2*) preventing migration of COCs from the affected medium to a point of exposure at a different location or in a different medium, or both (e.g., soil-to-air volatilization of chemical vapors). Depending on property conditions and the type of control selected, a single engineering control may serve to address one or more exposure pathways.

6.1.2 *Design Life*—While accounting for operation and maintenance, the engineering control should be designed for a time period equal to the lesser of (*1*) the expected duration of the unacceptable risk or (*2*) the expected duration of the site or structure for the specified land use. For presumptive remedies as described in 4.4, the engineering control should be designed for a time period equal to the lesser of (*1*) the expected duration of the potential unacceptable risk or (*2*) the expected duration of the use of the site or structure for the specified land use. Other considerations for determining a design lifetime will depend on the specific engineering controls evaluated for the site and may include regulatory requirements, properties of materials of construction, cost-benefit analyses, and expected or reasonable design lifetimes of the engineering control as a system.

6.2 *Application of Engineering Controls to Specific Exposure Pathways*—Performance criteria for control of selected exposure pathways and examples of applicable engineering control techniques are listed below. In all cases, existing engineering controls (e.g., pavement, soil cover) may be evaluated to assess effectiveness for exposure control and amended only as needed to achieve performance objectives. Appendix X5 provides a summary of the applicability, design considerations, and monitoring requirement for various engineering control technologies.

6.2.1 *Pathways Addressed*—The intent of this guide is to address potential exposures likely to be associated with property development or redevelopment. This guide is not a comprehensive manual for addressing every potential unacceptable risk, whether on-site or off-site. This guide describes engineering controls to address such potential unacceptable risks for three principal exposure pathways: (*1*) surface soil direct contact, (*2*) ambient or indoor air vapor exposure, and (*3*) affected groundwater impact on subsurface structures or utilities. Other exposure mechanisms may exist, and if so, should be addressed in a similar manner as described.

6.2.2 *Surface Soil Direct Contact*—In areas where chemical-affected soils are present at or near the ground surface, human exposure could occur via incidental ingestion, direct dermal contact, or inhalation of particulates. Chemical-affected soil particulates could potentially be released into the air as a result of erosion by the wind or as a result of shallow excavation for landscaping, construction, or maintenance activities. An effective engineering control would prevent surface soil direct contact by inhibiting (*1*) human contact with the chemical-affected soil and (*2*) the release of wind driven soil particulates into the air. Example technologies for controlling exposure due to surface soil direct contact include, but are not limited to, the following or combinations thereof:

Asphalt pavement,
Concrete pavement,
Flexible membrane liner (FML),
Clean soil cover,
Vegetative cover, and
Stone blankets.

Additional information regarding design, installation, and maintenance of engineering controls for chemical-affected soils is provided in Appendix X1.

6.2.3 *Ambient or Indoor Air Vapor Exposure*—In areas where chemical-affected soils or groundwater are present, human exposure could occur via inhalation of vapors released into the air as a result of volatilization of COCs from soils or groundwater. An effective engineering control would serve as a barrier to prevent COC concentrations exceeding unacceptable risk levels in ambient or indoor air. Such a barrier would prevent (*1*) migration of vapors to ambient air from chemical-affected soils or groundwater or (*2*) migration of vapors to indoor air through vapor entry routes such as basements, foundations, sumps, subsurface utility connections, or subsurface utility corridors, or both. Example technologies for controlling exposure due to inhalation of ambient or indoor air vapors include, but are not limited to, the following or combinations thereof:

Sealing soil gas entry routes,
Passive vapor barriers,
Building pressurization systems, and
Active soil depressurization.

Additional information regarding design, installation, and maintenance of engineering controls for soil or groundwater vapors is provided in Appendix X2.

6.2.4 *Affected Groundwater Impact on Subsurface Structures or Utilities*—In areas where chemical-affected groundwater is present, human exposure could occur via incidental ingestion or direct contact if groundwater enters subsurface structures, stormwater retention ponds, or utilities through cracks or leaks. In such a situation, property damage could also be sustained (e.g., fiber optic cable lines). An effective engineering control would prevent entry of groundwater to subsurface structures, stormwater retention ponds, or utilities. Example technologies for controlling exposure due to impact of chemical-affected groundwater on subsurface structures or utilities include, but are not limited to, the following or combinations thereof:

Seepage barriers.
Sealing utility lines, foundations, or utility joints,
Interceptor wells and trenches,
Slurry walls, and
Permeable reactive barriers.

Additional information regarding design, installation, and maintenance of engineering controls for chemical-affected groundwater is provided in Appendix X3.

6.3 *Development of Design Specifications*—Design specifications for the selected engineering controls should be documented in sufficient detail to ensure that the implemented control achieves the applicable performance criteria. The engineering control should be designed by persons qualified to complete work of this nature by reason of professional or regulatory certifications, or both. As applicable, design specifications may address general criteria for design, installation, and monitoring and maintenance, as summarized as follows.

6.3.1 *Design Basis Information*—Sufficient information regarding current and future site conditions should be compiled to support engineering design of all components of the proposed engineering control.

6.3.2 *Effective Area and Defining Boundary*—The engineering control must address the full area or volume, or both, of the chemical-affected environmental media requiring exposure control. As applicable, the engineering control should be equipped with a "defining boundary," serving to physically demarcate the engineering control or the area of chemical-affected environmental media, or both. Examples of such defining boundaries to be installed below grade include, but are not limited to, geofabric, horizontal plastic snow fencing, horizontal chain-link fencing, grids of warning tape, or other inert material. Signs may also be posted to delineate the defining boundary above grade. Record drawings or drawings conforming to construction records depicting the location and construction details of the engineering controls may also serve as a record of the effective area. If prepared, drawings should be available for reference, either at the site or at another location known and accessible to persons needing access to such information

6.3.3 *Design Components*—Each of the principal components of the engineering control should be defined, along with specifications for the design, installation, and operation and maintenance of each component included in the design.

6.3.4 *Dimensions and Material Specifications*—The material strength, durability, corrosion resistance, and chemical compatibility of each design component should be sufficient to achieve the specified performance standard for the design life of the control under the anticipated site conditions.

6.3.5 *Treatment System*—If an active engineering control such as a soil vapor or groundwater treatment system is to be included in the property development plan, the design specifications should address the design and operation of the equipment needed to treat the extracted soil vapor or groundwater so as to reduce concentrations of COCs to regulatory-mandated concentration levels prior to discharge. If a treatment system is already in place prior to property development or redevelopment, then the system should continue operating as needed for mitigation of chemical-affected environmental media as per applicable regulatory requirements, unless an engineering control proves to be more effective at preventing exposure to chemical-affected environmental media, subject to applicable regulatory requirements and approvals.

6.3.6 *Installation Specifications*—Requirements for installing the engineering control should specify methods, quality assurance/quality control (QA/QC) procedures, and personnel qualifications to ensure that the final installation is consistent with the design. The area to which the engineering control will be applied should be prepared as needed for an effective installation (e.g., clearing and grading for placement of surface cover).

6.3.7 *Documentation*—Record drawings, drawings conforming to construction records, or other written records, or combination thereof, should be prepared to document the installation details of the engineering control.

6.3.8 *Monitoring and Maintenance*—The design specifications should describe operations and maintenance requirements, if any, for the engineering control to ensure the best achievable effectiveness of the engineering control. The design should specify monitoring measures and monitoring frequency. The monitoring frequency will be a function of the timeframe for possible failure of the engineering control (i.e., more frequent for an active system, less frequent for a passive system) and the relative effect of such a failure on a potential receptor (more frequent for immediate impact, less frequent for a delayed impact). Design specifications may include (*1*) a monitoring frequency that varies over the operating period of the engineering control or (*2*) a provision to evaluate and modify the monitoring frequency based on data or information obtained during monitoring and maintenance. Non-routine inspections should be conducted to verify adequate and intended system performance after certain triggering events (e.g., floods, earthquakes). If applicable, the design specifications should provide for alarm of any expected condition harmful to potential receptors (e.g., percent lower explosive limit) as well as a response to the alarm.

6.3.9 *Regulatory Considerations*—Permitting, notification, and activity and use limitations should be completed per applicable regulatory requirements. The design should conform to applicable technical standards specified by regulations.

7. Installation of Engineering Controls

7.1 *QA/QC Program*—A quality assurance/quality control (QA/QC) program involving inspections, monitoring, and testing should be implemented to confirm that the engineering control has been completed in accordance with the design specifications.

7.2 *Qualifications*—The engineering control should be installed by persons qualified to complete work of this nature by reason of professional or regulatory certifications, or both.

8. Monitoring and Maintenance of Engineering Controls

8.1 *Overview of Monitoring Requirements*—Engineering controls may require routine monitoring to demonstrate the initial performance of the engineering control for the specified design objective and ensure continued performance for the duration of the property use activity. Note that monitoring requirements may be binding if they are included in an enforcement instrument (e.g., consent agreement, consent order, order, permit, no-further-action letter).

8.2 *Periodic Monitoring*—In order to assess key performance criteria of the engineering control, monitoring programs may involve one or more of the following: visual inspection, physical measurements, or sampling and testing. The nature and frequency of such monitoring will depend on the type of engineering control employed: active controls may, but not necessarily will, require more frequent and detailed inspections than passive controls. Municipal or state requirements will likely require monitoring to demonstrate that (*1*) related activity and use limitations remain in the active public record, and (*2*) post-installation construction or maintenance activities by other parties have not adversely impacted the engineering control.

8.3 *Maintenance*—Repairs or replacements (e.g., replacement of topsoil, sealing of asphalt cracks, vegetation type and cover) should be completed as indicated based on the results of periodic monitoring.

8.4 *Engineering Control Assessment and Modification*—The performance of the engineering control should be re-evaluated based on the results of periodic monitoring. Inadequate performance of the engineering control may require corrective actions or modification of the property development plan, as needed to reduce or eliminate unacceptable risk to human health via exposure to COCs. Regular inspections should include a provision to review the actual uses of the property with respect to the design of the engineering control to ensure the continued applicability of the control.

9. Use of Activity and Use Limitations

9.1 *Need for Activity and Use Limitations*—Guidelines for application of activity and use limitations are provided in Guide E2091. For some sites, activity and use limitations other than engineering controls may be the only type of control required to reduce or eliminate unacceptable exposure to COCs in chemical-affected environmental media. However, in many cases, it may be necessary to implement engineering controls along with other activity and use limitations at the site.

9.2 *Purpose for Activity and Use Limitations*—In order to notify future property owners and users of the presence of engineering control(s) on the property and to ensure the proper maintenance of the engineering control(s), it may be necessary to file institutional control(s) in the real property records of the governmental entity or entities having jurisdiction over the property.

9.3 *Types of Activity and Use Limitations*—Guide E2091 gives the following examples of activity and use limitations: (*1*) proprietary controls, such as deed restrictions or restrictive covenants; (*2*) state and local government controls, such as zoning restrictions, building permits, well drilling prohibitions, and water advisories; (*3*) statutory enforcement tools, such as orders and permits; (*4*) information devices such as deed notices, geographic information systems, Registry Act requirements, and Transfer Act requirements; and (*5*) environmental easements.

10. Keywords

10.1 activity and use limitations; Brownfields; chemical releases; corrective action; engineering controls; environment; environmental media ; exposure controls; human exposure; property development; site assessment

APPENDIXES

(Nonmandatory Information)

X1. ENGINEERING CONTROLS FOR CHEMICAL-AFFECTED SOILS: DESIGN, INSTALLATION, AND MAINTENANCE GUIDELINES

X1.1 *Introduction*— Engineering controls may be employed as part of the use or redevelopment of chemical-affected properties to reduce or eliminate potential exposure to COCs in surface and subsurface soils. The engineering controls discussed in this appendix focus on managing risks from chemical-affected soil that occur by direct dermal contact, incidental ingestion, or inhalation of particulates. Although not the focus of this appendix, such controls may also provide a secondary benefit of managing risks by (*1*) controlling vapors from surface soils, subsurface soils, or groundwater, or (*2*) controlling migration of residual COCs to groundwater. In addition to design and installation considerations, this appendix discusses monitoring and maintenance initiatives for engineering controls for chemical-affected soils.

X1.2 *Performance Objectives and Available Technologies*—An engineering control for chemical-affected soil should reduce or eliminate the potential for human health risk by (*1*) preventing direct contact with the chemical-affected soil, (*2*) preventing incidental ingestion of the soil, and by (*3*) preventing the release of soil particulates into the air. Typical soil engineering controls may include either structural elements or thickness elements, or both. Structural elements rely on inherent physical strength to minimize contact, and include, but are not limited to, asphalt pavement, concrete pavement, building slabs, and associated foundations. Thickness elements rely on the thickness, depth, or volume characteristics of the control to minimize contact. Thickness elements include, but are not limited to, compacted clay, landscaping, and non-differentiated "clean" soil. The literature refers to engineering controls for chemical-affected soils by various terms such as engineered barriers, caps or covers. Although the literature is not consistent in the use of these terms, the term "barrier" more commonly refers to structural elements such as asphalt and concrete. The terms "cap" and "cover" are more frequently used to refer to thickness elements.

X1.3 *Design and Construction Considerations:*

X1.3.1 *Design and Construction Overview*—Design and construction of engineering controls for chemical-affected soil should account for the end use of the property in addition to addressing risk management objectives. Engineering controls for chemical-affected soil are often associated with construction for the end use of the property, including, but not limited to, parking lots, floor slabs, park surfaces, and roadways. In these applications, engineering controls are either placed directly onto the ground surface or comprise a portion of the surface soils of the site. Additional project-specific considerations may be associated with a design requirement of the control or with regulatory requirements. For example, the design requirements for a high-traffic roadway are more extensive than for a parking lot, although each system may be sufficient to manage the risks from chemical-affected soils. Also, the design should account for requirements needed to conform to local customary practices or additional regulatory requirements (e.g., Massachusetts has a draft comprehensive design guidance document for engineering controls based on meeting minimum RCRA-like requirements for all sites, irrespective of whether the site is in the RCRA program).

X1.3.1.1 This appendix provides guidance on the risk-management aspect of the engineering controls for chemical-affected soils. A detailed discussion of additional project-specific considerations related to end uses is beyond the scope of this appendix.

X1.3.1.2 Professional services providers (e.g., professional engineers, landscape architects, state certified brownfield specialists, etc.) may be required for the actual design and oversight of the construction. The design effort should solicit, consider, and incorporate input from individuals and firms working on various aspects of the design, construction, operation, and maintenance specifications

X1.3.2 *Design Basis Information*—Studies should be conducted at the property to characterize the shallow soil as needed for the design of the engineering control. Design basis information should be obtained concerning site characteristics (e.g., soil types, existing structures, topography) and the concentration and nature of COCs present in chemical-affected soils. The site investigation should delineate the lateral and vertical extent of chemical-affected soil. Materials used in construction of the engineering control should be evaluated for chemical compatibility with the COCs present in soil to ensure that materials will not be susceptible to degradation or adverse reaction after installation.

X1.3.3 *Effective Areas and Defining Boundary*— Engineering controls for chemical-affected soil placed at the ground surface should cover an area containing COCs at concentrations exceeding unacceptable risk levels. The area of coverage for an engineering control should be based on a sufficient number of sampling points to ensure that the entire volume of chemical-affected soil is addressed by the engineering control. The total area to be addressed, the number of data points, and the variability of data should be considered in identifying the effective area.

X1.3.3.1 Record drawings or drawings conforming to construction records or project reports, or both, may also serve to document the demarcation of engineering controls. Physical demarcation of surface soil engineering controls by colored tapes, fabrics or membranes is not commonly employed given the surface visibility of design elements. However, application of demarcation techniques should be considered for future applications in order to document and identify engineering controls and to comply with regulatory requirements, if any.

X1.3.4 *Design Components*—Engineering controls for chemical-affected soils are physical elements of construction selected on the basis of existing site conditions, availability of materials, and anticipated function. As with any physical element of construction, the design of a specific soil engineering control is based on the following: (*1*) a minimum structural integrity, (*2*) reasonable design life, and (*3*) non-excessive maintenance. More than one engineering control may be used in concert to address additional exposure pathways. For example, if inhalation of soil vapor (see Appendix X2) was identified as a exposure pathway in addition to direct contact with chemical-affected soils, then a concrete floor slab could be combined with a flexible membrane liner, an underfloor vapor collection system, or a soil cover in order to reduce or eliminate risks via both exposure pathways. Commonly available soil engineering controls include:

X1.3.4.1 *Asphalt Pavement*—Asphalt pavement, or an asphaltic barrier, may also be referred to as "bituminous concrete" in many State Department of Transportation (DOT) specifications. Asphalt is a designed mix of graded sand and gravel combined with a bituminous asphalt liquid which is applied in layers using specially constructed machines. A thick layer placed in one pass is referred to as full-depth asphalt; full depth asphalt is sometimes placed directly on a prepared natural soil surface. Alternatively, asphalt may be applied in thin layers (e.g., 2.5 to 5 cm thick) referred to as courses (e.g., surface or binder) to achieve the desired thickness. Layers of asphalt are typically applied over a several-centimetres thick layer of aggregate, generally coarser than the aggregate for the top layer, with an asphalt binder (i.e., the base course) to transfer loads to the underlying soils.

X1.3.4.2 *Concrete Pavement*—Concrete is a designed mix of graded sand and gravel mixed with cement and water. Concrete is commonly used for building floor slabs and for many exterior pavements. Concrete is typically placed over a several-centimetres thick layer of sand or gravel (i.e., the base course) to transfer loads to underlying soils. Concrete usually has wire mesh, reinforcing steel, or other admixtures (e.g., synthetic fibers) to control cracks that may occur during initial curing or over the long-term as a result of plastic shrinking, drying shrinking, thermal cracking, or loss of support. Concrete slabs intended to support heavy loads also have steel reinforcing bars. Exterior concrete slabs should include an air-entrainment additive to minimize surface erosion (i.e., spalling), which can occur due to inclement weather and frost conditions.

X1.3.4.3 *Flexible Membrane Liner (FML)*—FMLs are thin, low-permeability membranes installed to minimize the migration of gases and liquids. FMLs are synthetic layers that are installed from rolls of manufactured materials, or sprayed onto a surface to harden to a semi-flexible layer. FMLs are hydrocarbon-based and have a wide range of chemical compatibility. Commonly used FMLs include: PVC (polyvinyl chloride), PCE (polychlorethylene), HDPE (high density polychlorethylene), and several others. FML rolls require special seaming equipment to seal edges; spray-applied FMLs form a seamless monolithic membrane. FLM rolls have a more consistent thickness. Application of any FML requires experienced qualified installers. FMLs are generally placed in conjunction with a structural element since they have no structural strength on their own. A cover sufficient to block UV radiation should be installed atop FMLs susceptible to degradation by exposure to UV radiation.

X1.3.4.4 *Clean Soil Cover*—Clean soil covers may be constructed of soils ranging from high-permeability gravels and sands to low-permeability clays. Permeability requirements, if any, should be evaluated early on in the design of the engineering control. The thickness of a clean soil cover is dependent on the performance objective for the engineering control. If the intent is primarily to minimize contact or ingestion of underlying materials, then the thickness of the control layer should be one that is difficult to hand excavate by a home owner, child, or gardener; the material type can be any clean soil available (i.e., non-differentiated). Establishment of a vegetative cover is important to minimize erosion; therefore, soils conducive to plant growth are typically placed as the top layer of an engineering control. Such soils are commonly referred to as "top soil" and should have a significant portion of natural organic matter to promote plant growth. Landscapers typically suggest a minimum of 6 in. of topsoil to promote adequate plant growth; however, the soil thickness should also consider performance objectives for an engineering control for chemical-affected soil.

X1.3.4.5 *Stone Blankets*—Stone blankets are a passive means of exposure control comprising a layer of small stones or recycled concrete installed to isolate chemical-affected soil from direct contact. Stone blankets may be particularly suited to preventing exposure and erosion in arid locations where establishment of a vegetative cover may be challenging due to the lack of precipitation.

X1.3.5 *Dimensions and Material Specifications*— The objective of minimizing soil contact can be achieved by providing a thickness that can not be easily excavated by hand (e.g., 0.6 to 0.9 m of soil), or by providing a structural element that can not be penetrated by hand excavation (e.g., asphalt or concrete). Additionally, the control should not have excessive openings, cracks, or non-uniformity, such that the control loses its integrity. The range of specifications provided in this document is solely intended to guide developers and constructors prior to design of soil engineering controls.

X1.3.5.1 *Dimensions*—Table X1.1 provides general design considerations and dimensions for engineering controls to reduce or eliminate risks from chemical-affected soil that occur via the direct contact pathway (i.e., dermal contact, incidental ingestion, or inhalation of soil particulates). Table X1.1 also notes which of the engineering controls may be effective for reducing or eliminating risks associated with (*1*) inhalation of vapors and (*2*) leaching of COCs from the soil to groundwater and subsequent groundwater ingestion.

X1.3.5.2 *Soil Properties*—The type of soil used for an engineering control can vary widely depending on the property use or reuse. Most soil covers, irrespective of the type of soil will provide risk mitigation from potential contact when placed in a thickness that restricts contact. Landscaping topsoils intended to support a vegetative cover; non-differentiated "clean" soils, and a "stone blanket' to provide structural stability, are suitable to restrict contact.

X1.3.5.3 *Layer Thicknesses*—A thickness that will minimize contact with chemical-affected soils is considered in several states to be 91.4 cm. This thickness is required since soil can be relatively easily moved (i.e., compared to concrete or asphalt) or penetrated (e.g., as in gardening or landscaping). For petroleum hydrocarbons in soil, a soil cover thickness of less than 91.4 cm may be adequate for minimizing vapor to outdoor air. Some regulatory agencies have accepted 76.2 cm or less. The minimum structural integrity of a design element must also be considered. For example, although a 5-cm thick concrete slab may restrict direct contact, a 5-cm thick concrete slab would likely be insufficient as a construction element to endure typical use throughout the design life. Therefore, concrete may need to be installed in a thickness of 7.6 cm or more upon considering the anticipated use, design life, and reasonable maintenance.

X1.3.5.4 *Other Considerations*—Other issues may also need to be considered in the selection of a soil engineering control, including, but not limited to, the following:

TABLE X1.1 Engineering Controls for Chemical-Affected Soils: General Design Considerations

Soil Engineering Control	Exposure Pathway[A] Direct Contact	Inhalation of Vapors	Soil Leaching to Groundwater	Thickness Required to Achieve Performance Objective[B]	Comments
1. *Asphalt*	P	S	S	2.5 to 7.6 cm asphalt atop 10 to 15 cm base course; or 10 to 15 cm full depth asphalt	Requires adequate subbase
2. *Concrete*	P	S	S	7.6 to 10 cm concrete atop 10 to 15 cm base course	Requires adequate base
3. *Flexible Membrane Liner (FLM)*	S	P	P	FML liner plus structural element	Must be installed with structural element
4. *Soil Material Covers*					
• Clay	P	P	P	45.7 to 91.4 cm	Low permeability (approx. 1E-06 cm/s or lower)
• Non-differentiated clean soil	P	S	—	45.7 to 91.4 cm	Soils range from clayey to sandy (approx. 1E-03 to 1E-06 cm/s)
• Non-differentiated clean soil	P	P	S	91.4 to 152.4 cm	Soils range from clayey to sandy (approx. 1E-03 to 1E-06 cm/s)
• Vegetative soil	P	S	—	45.7 to 91.4 cm	Soils likely include organic topsoil
• Vegetative soil	P	P	S	91.4 to 152.4 cm	Soils likely include organic topsoil
• Sand/Stone blanket	P	—	—	45.7 to 91.4 cm	Typically porous, higher permeability materials (<1E-03 cm/s)

[A] P = Primary intent of engineering control; S = Secondary intent of engineering control; — = Not an appropriate use of this engineering control.
[B] Values listed here represent reasonable dimensions in the absence of design constraints or regulations. Regulatory design criteria would apply, if available.

Settlement of the control layer due to underlying materials (e.g., landfill, soft soils),
Seismic conditions,
Frost depth,
Runoff and erosion control,
Steep slopes (i.e., greater than 3 horizontal to 1 vertical),
Compatibility with toxic underlying materials, and
Gas management emanating from underlying materials.

X1.3.6 *Treatment Systems*—Some soil engineering controls can be used for treatment of residual constituents (e.g., phytoremediation or wetland treatment systems). These treatment systems are advanced treatment techniques requiring specific technical experience and are beyond the scope of this appendix.

X1.3.7 *Installation Specifications*—Numerous industry standards directly applicable to construction of engineering controls for surface and subsurface soils have been developed to verify construction quality. Key aspects relating to the performance of engineering controls for chemical-affected soils include preparation of the subgrade, and the joining of two different barriers or covers.

X1.3.7.1 *Subgrade Preparation Requirements*—The grade on which the soil engineering control is placed must be capable of supporting the design elements. Prior to placing an engineering control, the area should be cleared and grubbed of vegetation. The surface of the subgrade should be graded to the lines and grades provided by the construction specifications. Surface grading must consider whether affected soils are present to prevent spreading contamination. A soft or wet subgrade should be proof-rolled after grading. The proof-rolled surface should be observed for signs of rutting or pumping. Soft or wet soils that excessively pump or rut should be removed, replaced, and compacted prior to approval of the subgrade.

X1.3.7.2 *Joining of Two Different Engineering Control Systems*—Consideration must be given to the joining of different barriers or covers in order to form an adequate seal between the two elements. For example, in locations where asphalt and concrete engineering controls will abut, the concrete barrier should be constructed first so that the asphalt has a stable, straight-edged feature to be formed against. Adjoining of soil covers to asphalt, concrete, or another soil barrier should be designed to minimize potential erosion and maintenance. Seeding, sodding, or other planting will help minimize erosion near the interface, as well as reduce maintenance activities. Gradual transitioning should be incorporated into construction between engineering control areas and adjacent areas. For example, the ground surface beyond the extent of a thick clean soil engineered cover could be sloped gradually to meet the original elevation.

X1.3.8 *Documentation*—Owners may be required to submit record drawings or drawings conforming to construction records for the soil engineering controls constructed under applicable regulatory programs. The documentation may include, but not be limited to, the following: surface grade surveys before and after engineering control placement; photographs of the control; soil, asphalt and concrete physical tests (as appropriate); or a plat of survey identifying the soil engineering control location and area, or combination thereof. Documentation and record keeping similar to that required for regulatory programs should be considered for projects not specifically under regulatory purview. This consideration is based on the likelihood that questions regarding the performance of designated soil engineering controls, especially if it is recorded on the deed, could arise during future a property transfer.

X1.4 *Performance Monitoring*—The integrity of a soil engineering control must be maintained throughout the design life of the control. Planned and scheduled inspection and maintenance should be anticipated and conducted as part of the documentation of the performance of the soil engineering control.

X1.5 *Maintenance Issues*—Soil engineering controls should undergo routine inspections as part of a general maintenance program. Large cracks or openings within the soil engineering control or at adjoining areas of two controls could compromise the integrity of the control's intended use. For these conditions, a joint sealer compatible with the soil engineering control (e.g., rubberized asphalt, grout, additional fill soil) should be used for improvements or repairs.

X1.5.1 If it is necessary to disrupt the engineering control (e.g., for utility line placement) various barrier or cover replacement materials should be considered for patching. The replacement materials should be similar to, or more rigorous than, the original materials. The replacement materials should be applied to the entire utility corridor. Adequate replacement of disrupted flexible membranes is especially important, because flexible membrane liners are thin and rely on full continuity for successful performance.

X1.5.2 Soil engineering control maintenance activities should be completed in accordance with Occupational Safety and Health Administration (OSHA) and site risk-related requirements. Site inspectors and utility construction workers should be the focus of safety-related maintenance programs.

X1.5.3 A summary of common frequencies of inspection, action levels and typical maintenance actions is provided in Table X1.2.

TABLE X1.2 Engineering Controls for Chemical-Affected Soils: Performance Monitoring and Maintenance

Cover Type	Typical Design Life[A]	Inspection Frequency[B]	Action Level	Typical Maintenance Action
1. *Asphalt*	10 - 15 yr	annual	Open, wide cracks or extensive alligator crack patterns	Asphalt crack sealer treatment
2. *Concrete*	20 – 30 yr	biennial	Open joints having damaged sealant or no sealant Open, wide cracks	Replace sealant, grout or seal cracks
3. *Flexible Membrane Liner (FLM)*	50 – 100 yr[C]	annual	Disturbed soil atop the FML Differential movement of structural elements	Replace soil Correct condition causing differential settlement, if possible Replace damaged FML, if needed Consider alternative control if condition recurs
4. *Soil Material Covers*				
• Clay	20 yr[D]	semi-annual	Excessive erosion	Repair any cracks or erosion channels
• Non-differentiated clean soil	20 yr[D]	semi-annual	Excessive erosion	Repair any cracks or erosion channels
• Non-differentiated clean soil	20 yr[D]	semi-annual	Excessive erosion	Repair any cracks or erosion channels
•Vegetative soil	20 yr[D]	semi-annual	Excessive erosion plus lack of anticipated growth Vegetation present consistent with design specifications	Repair any cracks or erosion channels Reassess vegetation type and replant
•Stone blanket	15 yr[D]	semi-annual	Gaps or sparse areas resulting from settling or differential movement of the underlying soil	Add filler materials to “choke” off openings

[A] Typical design life considering routine inspection and maintenance; actual life may significantly exceed this value.
[B] The frequency of maintenance inspections and action levels must be specific to the location, climate, post-installation land use, and the degree of future site access controlled by the owner of the environmental liability.
[C] FMLs have performed as intended for 30 years; therefore, a reasonable design life of a minimum of 50 years may be expected.
[D] Although the overall design life may be 50 years for soil covers and stone blankets, significant maintenance is typically required at approximately 20-year intervals for soil covers and 15 years for stone blankets.

X2. ENGINEERING CONTROLS FOR SOIL OR GROUNDWATER VAPORS: DESIGN, INSTALLATION, AND MAINTENANCE GUIDELINES

X2.1 *Introduction*—The phenomenon of vapor intrusion, as it relates to chemical-affected soil and groundwater has recently received a significant increase in attention. This appendix deals with engineering controls to prevent intrusion of vapors from chemical-affected soil and groundwater into occupied buildings at concentrations which may pose an unacceptable risk. Many of the mitigation technologies used to control volatile organic COCs have been adapted from technologies originally developed to control radon, because both radon and volatile organic COCs are airborne and may be controlled using a subslab system. Across the United States, more than 500,000 existing houses have been retrofitted with radon-control systems. In addition, about 2 million homes have been constructed using radon-resistant construction techniques. Consequently, much of the literature cited in this appendix relates to experiences with diagnosing and mitigating radon problems. Additional references can be found in the documents cited in the references (**1-6**).

Professional services providers (e.g., professional engineers, landscape architects, state certified brownfield specialists, etc.) may be required for the actual design and oversight of the construction. The design effort should solicit, consider, and incorporate input from individuals and firms working on various aspects of the design, construction, operation, and maintenance specifications.

X2.2 *Performance Objectives and Available Technologies:*

X2.2.1 *Performance Objective*—In order for COC concentrations in indoor vapors to present unacceptable risks, the following three conditions must exist: (*1*) COCs must be present in the soil gas near the foundation of the building, (*2*) one or more entry routes must be present, and (*3*) driving forces must act to induce movement of the COCs through the entry routes. The performance objective for an effective engineering control will be to remove one or more of these three conditions, thus preventing COC entry into a structure or reducing COC concentrations to levels below unacceptable risk.

X2.2.2 *Available Technologies*—Methods for reducing indoor COC concentrations fall into two categories: (*1*) methods aimed at preventing the COC from entering the building, and (*2*) methods aimed at removing COCs after entry into the building. In most cases, the preferred strategy is to prevent COCs from entering the indoor space.

X2.2.2.1 *Entry Prevention*—Techniques that prevent COC entry include (*1*) sealing soil gas entry routes; (*2*) passive vapor barriers; (*3*) building pressurization systems that reduce or reverse the driving force for soil gas entry; and (*4*) active soil depressurization (ASD), which dilutes or diverts soil gas away from the building before it can enter. Sub-categories of ASD include sub-slab depressurization (SSD), block wall/stem wall depressurization, drain tile depressurization (DTD), and sub-membrane depressurization (SMD). In addition to these methods, direct evacuation of a crawl space is a viable method of preventing COC entry, thereby reducing risk. The negative pressure created within the crawl space may potentially pull vapors from the soil; however, such a vacuum would be very small due to the reservoir effects of the crawl space and the volume of air available within the crawl space.

X2.2.2.2 *COC Removal after Entry*—Techniques that remove the COCs after entry include (*1*) ventilation of the building, with or without heat recovery, and (*2*) air cleaning using adsorbents, scrubbers, or photo-catalytic oxidation.

X2.2.3 *Performance of Available Technologies*— In many instances, some COCs may need to be reduced by as much as 99.95 % to be less than the level of unacceptable risk. This performance is quite challenging for any of the available technologies. Experience has shown that sealing entry routes in existing buildings seldom yields a reduction greater than 80 %, with a range from 30 to 90 % (**7, 8, 9, 10**). Even heat recovery with ventilation seldom achieves greater than a 75% reduction (**11**). On the other hand, building pressurization and soil depressurization methods typically result in much greater reductions in COC concentrations. Maintaining a positive pressure in the entire building, which is difficult for long periods of operation, is not necessary for preventing the entry of COCs into a building. Pressurization of the area immediately above the basement, although difficult as well, is capable of preventing the entry of COCs into a building.

X2.2.3.1 If COC reductions greater than 80 % must be achieved, some type of ASD approach will usually be required. ASD is the most effective method that has been fully demonstrated to date for reducing concentrations of COCs in indoor air. ASD works through two mechanisms: (*1*) by reversing the direction of the driving forces, ensuring that air movement is from indoors into the soil, and (*2*) by diluting COC concentrations in the soil gas.

X2.2.3.2 The effectiveness of alternative techniques has been less well demonstrated for achieving reductions in COC concentrations in indoor air on the order of 80 %. When lower levels of reduction are sufficient, other reduction techniques can be considered (e.g., heat recovery ventilators, sealing of entry routes, or perhaps passive soil ventilation). For new construction, passive barriers may be a possibility. For crawl-space houses with exposed soil, the reduction system used most often is referred to as a sub-membrane depressurization (SMD) system. In this case, a vapor retarding membrane covers the soil surface and plays the role of a slab in the normal sub-slab depressurization (SSD) system. Performance of these systems has been well documented for radon applications (**1, 12-18**).

X2.2.3.3 Given the effectiveness of ASD systems for reducing COC concentrations in indoor air and soil vapor, this appendix focuses on the design, installation, monitoring, and maintenance of ASD systems. This appendix also refers to other systems that may be judged more suitable based on site-specific design basis information, cost considerations, or other factors.

X2.3 *Design and Construction Considerations:*

X2.3.1 *Design Overview*—In general, the development of design specifications presented below follows the outline of 6.3 of this guide. More or less information has been provided for each topic addressed in accordance with availability and relevance of information to the design of engineering controls for soil or groundwater vapors.

X2.3.2 *Design Basis Information*—The selection and design of a cost effective system for reducing COC concentrations in indoor air in a specific building will depend upon a number of factors specific to that building, including, but not limited to, (*1*) initial COC concentrations and the degree of reduction required to attain specified COC concentrations; (*2*) whether the structure already exists or will be newly constructed, (*3*) the desired confidence in system performance; (*4*) the design and construction features of the structure; and (*5*) the results of the pre mitigation diagnostic testing. Additional design considerations are discussed below for entry routes, driving forces, and existing versus new construction.

X2.3.2.1 *Entry Routes*—Probable soil gas entry routes must be characterized in order to evaluate various methods of controlling vapor intrusion. In order to design optimum control methods, the principles of vapor intrusion must be understood. These principles of entry are important whether designing control systems for existing buildings or designing new structures to resist soil gas entry.

(a) Pressure Differential—Soil gas containing COCs can enter a building through any opening between the building and the soil. The pressure inside a building is often slightly lower than the pressure in the surrounding soil, so that the soil gas flows into the building as a result of the pressure difference.

(b) Diffusion—Diffusion may be a secondary entry mechanism. The steady indoor concentration of a specific COC when soil gas is the only source will be determined by a equilibrium between the rate of entry from the soil and the rate of removal by ventilation or other process such as adsorption or chemical reactions.

(c) Groundwater—If a house receives water from an individual or small community well, indoor concentrations can also occur as a result of COCs being released from water used in the house. In this document, it will be assumed that the water in the building is not contaminated.

(d) Other Sources—Other potential sources of COCs include consumer products, paints, building materials, cleaning products, attached garages with automobiles, lawn mowers,

and stored chemicals, etc. The presence of COCs in indoor air from such products can greatly complicate the interpretation of indoor measurements of the COC concentrations. This appendix deals only with issues relating to preventing or removing COCs that originated from chemical-affected soil or groundwater.

X2.3.2.2 *Driving Force*—In addition to identifying soil gas entry routes, features contributing to the driving force causing soil gas to flow into the house should be characterized. The contributors can be divided into those associated with the weather, with building design features, and with occupant activities.

(a) Weather Effects—Pressure differentials induced by temperature differences between the inside and outside of the building serve as a driving force for air movement in a building. Cold temperatures outdoors are an important contributor to negative pressures indoors. Warm, buoyant indoor air tends to rise. The warm air leaks out of the house through openings in the upper levels (e.g., around upstairs windows and through penetrations into unheated attics). To compensate for the loss of warm air, outdoor air and soil gas leak into the building around doors and windows at the lower levels and through the seam between the building frame and the foundation wall. Once inside, the infiltrating air and soil gas become heated, rise, and leak out through the upper levels, thereby continuing the process. The shell of a closed house might thus be pictured as a chimney through which air is constantly moving upward whenever the temperature is warmer indoors. Because of the similarity of this process to warm air rising up a chimney or smoke stack, the process is commonly referred to as the thermal stack effect. In addition to indoor/outdoor temperature differences, wind is another weather-related contributor to the driving force for soil-gas entry. Winds create a low-pressure zone along the roofline and on the downwind side of the building. Depending upon the air exfiltration routes existing at the roof and on the downwind side, portions of the house can become depressurized

(b) Building Design Effects—Heated air produced by a furnace induces convective air currents that result in warm air leaving the building and cooler air entering the building from the outside. A building may be designed or modified so as to reduce such air flow patterns which are conducive to infiltration of outdoor air and soil gas. If the upper portion of a house can be pictured as a cap over a figurative chimney, then the floors between stories might be pictured as dampers in this chimney. Just as openings through the upper building shell permit rising warm air to escape, openings through the floors facilitate the upward flow of warm air inside the building, thus also facilitating the ultimate escape of the air through the shell. Such openings through the floors are referred to as internal airflow bypasses, because they permit the rising warm air to bypass the damper. Where major airflow bypasses can be closed, the upward air movement can be reduced and the exfiltration of warm air along with the corresponding infiltration of outdoor air and soil gas can be reduced.

(c) The building sub-structure plays an important role in determining the number and type of entry routes. The three basic types of substructures are (*1*) basement, in which the floor (slab) is below grade level; (*2*) slab on grade, in which the floor (slab) is at grade level; and (*3*) crawl space, in which the floor is above grade level, and the enclosed region between the floor and the soil (the crawl space) is not livable area. There are many variations and combinations of these three basic substructure types. For example, some common combinations of these basic substructures include a basement with an adjoining slab on grade, or a slab on grade with an adjoining crawl space. Some buildings include different wings representing all three sub-structure types. Sometimes the distinction between the substructure types becomes blurred, as when the lowest level of a building has a front foundation wall completely below grade, thus having the characteristics of a full basement, and a rear foundation wall totally above grade, similar to a slab on grade.

(d) A number of factors (i.e., COC concentrations in the soil gas, soil permeability, the degree of house depressurization, number and type of entry routes, and the house's ventilation rate) affect the indoor concentration of soil gas COCs. Basement houses provide the greatest amount of contact with the soil, and thus offer the greatest opportunity for entry routes to exist, although the real nature of the entry routes will vary with specific design features and construction methods. Thus, one might anticipate that basement houses would tend to have greater risks from vapor intrusion. By comparison, a crawl space house where the crawl space does not open into the living area, and where vents for natural circulation are kept open, will have a ventilated, pressure-neutralized buffer space between the living area and the soil. Crawl-space houses with ventilated crawl spaces would be expected to offer the least risk from vapor intrusion. Houses with slab-on-grade foundations would be intermediate in risk. Generally, this pattern between basement, slab-on-grade, and crawl-space houses is observed in the field; however, the idealized condition of a well-ventilated crawl space is often not realized. Consequently, some crawl-space houses have higher levels of COCs than basement houses next door. Similarly, some slab-on-grade houses also have higher levels of soil gas COCs than adjacent basement houses.

(e) Occupant Activity Effects—There are a number of appliances that remove air from the building, thereby contributing to building depressurization. Fans that draw air from indoors and exhaust it outdoors are present in most buildings (e.g., window fans, attic fans, range hoods, and bathroom exhaust fans). A clothes drier is a form of exhaust fan when the moist air leaving the drier is exhausted outdoors. A stove, fireplace, furnace, or boiler inside the building also exhausts air in order to burn the fuel and to maintain the proper draft up the flue. This air, including products of combustion, goes up the flue and is exhausted outdoors.

X2.3.2.3 *Existing Building versus New Construction*— Each building is a unique structure having many variables that influence entry of soil gas and the choice of a mitigation system. For existing buildings, a variety of observations and measurements known as diagnostic tests can be made prior to mitigation in order to aid in the selection and design of the engineering control. Some of the more important diagnostic tests include the following:

(a) Visual Survey—A visual survey is an essential diagnostic component of the design. A visual survey should be conducted to identify possible soil gas entry routes, features possibly contributing to the driving force, and structural features which could influence mitigation selection and design.

(b) Gas Movement—If sub-slab depressurization is being considered as an engineering control, then communication (i.e., the ease of gas movement) and pressure field extension should be measured beneath the concrete slab. Such measurements can provide substantial information to aid in the selection of sub slab ventilation pipe location, fan capability, and pipe diameter.

(c) Infiltration Rate—Measurements of the natural infiltration rate (i.e., the effective leakage area through the building shell). This measurement is useful to evaluate engineering controls that increase the ventilation rate (e.g., a heat recovery ventilator). The effectiveness of ventilation techniques in reducing exposure will depend upon what the infiltration rate is before the system is installed. Knowing the ventilation rate is also helpful in determining whether the soil gas entry rate adequately accounts for observed indoor concentrations.

(d) Differential Pressure—Measurements of differences in pressure between indoors and outdoors, between points indoors, or between the soil and indoors during diagnostic procedures help to determine whether the driving forces for entry are high or low during diagnostic tests. Such measurements can give an indication of the pressures for which the mitigation system will have to compensate.

X2.3.2.4 *New Construction*—Steps can be taken during building construction to reduce the risk for elevated levels of soil gas COCs. In addition, measures can be installed to facilitate the activation of an effective engineering control if elevated concentrations of COCs are measured after the structure is built. These steps can be implemented with less expense (i.e., 20 to 44 % of the retrofit value), and with greater effectiveness, during the construction stage than is possible after the building is completed. If the potential has been identified for elevated levels of soil gas COCs, the following steps should be considered:

(a) Eliminate Soil Gas Entry Routes—Attempt to eliminate soil gas entry routes by taking steps to avoid cracks in the concrete floor slab by (*1*) using proper water content and plasticizers, (*2*) sealing around utility penetrations through the slab and foundation walls, (*3*) capping the top of hollow block foundation walls, and (*4*) sealing the top of sumps.

(b) Avoid Thermal Bypasses—Attempt to reduce the house depressurization and house air exfiltration that can increase soil gas influx by (*1*) avoiding thermal bypasses throughout the house, (*2*) providing an external air supply for certain combustion appliances, and (*3*) ensuring the presence of adequate vents in crawl spaces (**19**).

(c) Install Standpipe Rough-Ins—As a further precaution, provisions can be made during construction that will enable effective sub slab suction after the house is built if COC levels turn out to be elevated despite the preventive steps mentioned previously(**20**). These provisions include a 10-cm deep layer of clean crushed rock under the slab, with an exterior or interior drain tile loop that drains into a sump or which is stubbed up and capped outside the house or through the slab. Alternatively, one or more 30-cm lengths of PVC pipe can be embedded into the aggregate through the slab and capped at the top. If needed, these standpipes can later be uncapped and connected to a fan in suction or to a passive convection stack which is less effective than a fan system.

X2.3.3 *Effective Area and Defining Boundary*— Record drawings or drawings conforming to construction records should be prepared to document the location and construction details of the engineering control. In order to provide a warning in the event that chemical-affected soils are excavated, the area of chemical-affected soil may also need to be physically demarcated using geofabric, horizontal plastic snow fencing, horizontal chain-like fencing grids of warning tape, or other inert material.

X2.3.4 *Design Components, Dimensions, Material Specifications, and Installation Specifications*—If an evaluation of site-specific design basis information indicates that an ASD system will adequately reduce risks associated with soil or groundwater vapors, then completing the design will involve sizing mechanical components and determining the number and placement of suction holes. The primary mechanical components of an ASD system are the fan, the collection piping, and the alarm devices. Detailed steps for estimating the fan capacity and the pipe diameter are provided in Henschel (**1**) and Fowler et al. (**21**).

X2.3.4.1 The principal design question concerns how many suction holes are needed and where they should be located (**1**,**21**). The most useful information for estimating the slab area that can be treated by a single suction point comes from slab-slab pressure field extension measurements (**1**,**21**). In the case of sub-membrane depressurization (SMD) for crawl-space houses, areas as large as 186 m^2 have been treated with good success. Generally, one suction point was sufficient for these crawl-space houses. The largest area that can be effectively treated with one suction point is not known. For houses with slabs, if the sub-slab communication is good, corresponding to a thick layer of clean gravel, one suction point has been effective in treating houses up to 251 m^2 and schools and commercial buildings up to 4645 m^2. When sub-slab communication is marginal or poor, many more suction points may be required. Detailed steps for estimating the number of suction points needed based on sub-slab pressure field extension measurements are described by Henschel (**1**) and by Fowler et al. (**21**).

X2.3.5 *Treatment System*—Treatment systems are not typically installed in conjunction with ASD systems. However, techniques that remove the COCs after entry may involve air treatment using adsorbents, scrubbers, or photo-catalytic oxidation.

X2.3.6 *Documentation*—The system should be labeled so that those responsible for future maintenance can readily understand the parts of the system and their proper operation. An operating manual, including record drawings or drawings conforming to construction records, should be prepared to inform maintenance personnel how to interpret readings of any gages or other measurement devices and alarms. The manual should also include information about the system installer(s) (**1, 4**).

X2.4 *Performance Monitoring:*

X2.4.1 *Post Installation Diagnostic Tests*—After installation of any mitigation system, tests should be conducted to ensure that the engineering control is operating properly. Some components of such diagnostic tests include, but are not limited to, the following:

X2.4.1.1 *Visual Inspections*—Perform a visual inspection of the system to verify proper installation. For ASD systems, check all pipe joints for leaks. A smoke stick is sometimes useful for this purpose. A smoke stick releases a small stream of smoke that can reveal air movement. The smoke stick can be used, for example, to confirm whether pipe joints and slab/wall closures are adequately sealed.

X2.4.1.2 *Mechanical System Operation*—Perform pressure and flow measurements in the pipes of ASD systems and heat-recovery ventilators. Such measurements can reveal installation and operating problems of various types.

X2.4.1.3 *Sub-Slab Measurements*—Perform sub-slab pressure field measurements, where a sub-slab depressurization system has been installed. Such measurements will reveal whether the system is maintaining the desired pressure reduction underneath the entire slab.

X2.4.1.4 *Flow Measurements*—Perform flow measurements with and without the mitigation fan running in the flues of existing furnaces, water heaters, and other combustion appliances when an ASD system has been installed, in order to ensure that house air being removed by the system is not depressurizing the house enough to cause back drafting of the combustion appliances (**1, 6, 22**).

X2.4.1.5 *Fire Breaks*—Check to ensure that fire breaks have been installed where pipes penetrate a fire wall (**4**).

X2.4.1.6 *Membrane Installation*— Check to ensure that the membrane has been properly installed and sealed in the case of crawl-space SMD systems.

X2.4.1.7 *Alarms*—Check to ensure that an appropriate gauge and alarm have been properly installed and are operating correctly.

X2.4.1.8 *Documentation*—Check to ensure that the system has been labeled such that those responsible for future maintenance can readily understand the parts of the system and how it is supposed to work. The labeling should inform the maintenance personnel how to interpret the readings of the gages and alarms as well as who installed the system (**1, 4**).

X2.4.2 *COC Concentrations*—After the mitigation system is installed, a few-day measurement of the COCs of concern should be made to give an initial indication of the success of the system. One or a few grab samples, by themselves, are not recommended for the purpose of determining reduction performance because a sampling period of a few minutes is considered too brief to provide a reliable measure. Measurements to document the performance of the system must deal with the issue of background. Background refers to indoor COCs of concern originating from sources other than the soil gas. The best evidence for the performance of the system is provided by a consistent reduction of a number of different COCs of concern. If the initial short-term measurement indicates sufficient reductions, then it should be followed up by a long-term measurement that includes a winter to obtain a measure of sustained system performance under the challenging conditions that cold weather presents. Periodic follow-up measurements are recommended every couple of years.

X2.5 *Maintenance and Operating Issues*—The primary mechanical components of an ASD system are the fan and the alarm devices that indicate when the fan is not working properly. The warning devices (e.g., lights and buzzers attached to sensors) should be inspected frequently to ensure that the fan has not stopped. However, it is possible that the fan could be running, but not performing adequately, especially if the fan uses an electrolytic capacitor to help with its startup phase. It has been observed that when the electrolytic capacitor fails, the fan can sometimes continue to operate for a considerable length of time with limited effectiveness. This ineffectiveness can often be observed as a reduced pressure in the suction pipe or a reduced flow rate in the pipe. The installer of the system should always provide a description of any required maintenance as well as a description of the system operation. Routine maintenance should include some of the following procedures:

X2.5.1 Check to see if alarms (lights or buzzers) have been activated.

X2.5.2 Check to see that the alarms are working correctly.

X2.5.3 Check to see that the fan is operating (feel for vibrations and heat, listen for worn bearings).

X2.5.4 Check flow or pressure sensor to confirm they are operating properly.

X2.5.5 Inject tracer gases in sump, sub-slab region, or basement and detect it in the system exhaust.

X2.5.6 Inspect pipes for cracks and leaky joints.

X2.5.7 Check system operation during cold weather to avoid blocked lines due to freezing.

X2.5.8 Check exhaust to ensure its free of dirt, spider webs, bird and insect nests, etc.

X3. ENGINEERING CONTROLS FOR CHEMICAL-AFFECTED GROUNDWATER: DESIGN, INSTALLATION, AND MAINTENANCE GUIDELINES

X3.1 *Introduction*—Chemical-affected groundwater may potentially impact a property, an existing building, or new construction on a property when the water table rises due to natural conditions or when groundwater filters through the building foundation. Excavations associated with construction activities may also encounter chemical-affected groundwater owing to a consistently high or a seasonally high water table. This appendix discusses commercially available technologies proven and effective for mitigating potential exposure to chemical-affected groundwater that could occur via incidental ingestion or direct contact if groundwater enters buildings, stormwater retention ponds, or utilities through cracks or leaks.

X3.1.1 Professional services providers (e.g., professional engineers, landscape architects, state certified brownfield specialists, etc.) may be required for the actual design and oversight of the construction. The design effort should solicit, consider, and incorporate input from individuals and firms working on various aspects of the design, construction, operation, and maintenance specifications.

X3.2 *Performance Objective and Available Technologies:*

X3.2.1 *Performance Objective*—In areas where chemical-affected groundwater is present, human exposure could occur via incidental ingestion or direct contact if groundwater enters subsurface structures, stormwater retention ponds, or utilities through cracks or leaks. In such a situation, property damage could also be sustained (e.g., to fiber optic cable lines). An effective engineering control would prevent entry of such groundwater to subsurface structures, stormwater retention ponds, or utilities.

X3.2.2 *Available Technologies*—In general, engineering controls for preventing entry of chemical-affected groundwater into subsurface structures involve installation of (*1*) a barrier or sealant directly on the building or utility or (*2*) an interceptor or cut-off mechanism placed within the groundwater bearing zone. The technologies considered in detail in this appendix include seepage barriers, sealing utility lines, interceptor wells or trenches, slurry wells, and permeable reactive barriers (PRBs). A brief summary of each technology is provided as follows.

X3.2.2.1 *Seepage Barriers*—An impermeable curtain wall or geosynthetic clay liner (GCL) may be installed in order to prevent seepage of chemical-affected groundwater into a foundation. Seepage of groundwater or stormwater runoff, or both, through foundation walls presents an engineering challenge that can potentially threaten building foundations regardless of whether the water has been chemical-affected. Such seepage may be caused by one or a combination of the following conditions: negative slope influence, perched upgradient groundwater tables, or persistent flooding.

X3.2.2.2 *Sealing Utility Lines*—Various liquid or membrane sealants may be employed in order to prevent utility lines, or the trenches or vaults in which they are installed, from serving as potential conduits for chemical-affected groundwater or stormwater, or both. Utility lines such as subgrade electrical lines and communications lines (e.g. cable, telephone, network) are typically enclosed in metal or concrete "vaults" that prevent infiltration of soil or groundwater and allow for easy access for repair or maintenance. Electrical vaults such as subgrade transformer vaults are typically enclosed rooms constructed with poured concrete floors, poured/reinforced concrete or concrete block walls, and concrete or steel ceilings with at least one access hatch. Over time, these conduits will break down due to water damage, corrosive soils, or contaminants that may potentially degrade the lines or vaults. In other instances, the vaults may act as conduits themselves, diverting chemical-affected groundwater or stormwater seepage towards a building or into subterranean vaults, thereby presenting a potential risk to site workers.

X3.2.2.3 *Interceptor Wells and Trenches*—Permanent groundwater recovery wells or trenches may be installed hydraulically upgradient of potential receptors to intercept or divert chemical-affected groundwater away from such receptors. Groundwater recovery wells intercept COCs via active pumping, thereby preventing chemical-affected groundwater from reaching potential receptors. Trenches divert the COCs away from potential receptors to an area in which no unacceptable exposure is expected to occur.

X3.2.2.4 *Slurry Walls*—A slurry wall is a narrow and deep excavation backfilled with an inert and relatively impermeable substance surrounding the perimeter of the chemical-affected groundwater plume. A slurry wall serves as a cut-off barrier to limit migration of chemical-affected groundwater or to divert chemical-affected groundwater away from building foundations. Typically, slurry walls are excavated to an impermeable substratum or bedrock, and slurries are either mixed off-site in a central plant and transported to the site in a cement mixing truck or mixed onsite in enclosed beds or portable grout plants.

X3.2.2.5 *Permeable Reactive Barriers (PRB)*–PRBs provide passive in-situ remediation of chemical-affected groundwater. In addition, PRBs may also serve to divert or contain, or both, chemical-affected groundwater. PRBs are constructed by excavating and filling a trench with a biologically or organically active permeable or semi-permeable medium through which chemical-affected groundwater flows. Organic chemicals in the groundwater are degraded by nascent microorganisms or oxidative/reductive chemicals. Dozens of media and additives are available to enhance the efficiency of a PRB, and many ASTM-based tests that may be used to ensure that optimum treatability is achieved.

X3.3 *Design and Construction Considerations:*

X3.3.1 *Design Basis Information*—In order to evaluate potential technologies for control of chemical-affected groundwater, design basis information must be obtained concerning site characteristics and the concentration and nature of COCs present in environmental media. Additionally, the appropriate engineering control, if applicable, should be chosen based on site characterization using an appropriate remedial investigation scheme (see Guide E2081). A summary of information relevant to the selection and design of engineering controls is provided as follows.

X3.3.1.1 *Shallow Site Stratigraphy*—Detailed studies of the soil and groundwater-bearing units at the property should be conducted. These studies should include soil profile and bedrock geology assays, soil permeability and percolation tests, hydraulic conductivity studies, and groundwater fluctuation studies (i.e., monitoring precipitation or tidal influences, or both, on groundwater elevation and flow). Geophysical characteristics of the property will influence the type and effectiveness of a particular seepage barrier.

X3.3.1.2 *Chemicals of Concern*—The specific COCs and their concentrations in soil and groundwater should be characterized in order to ensure that any material used in construction of the engineering control will not be susceptible to degradation or adverse reaction after installation. The site investigation should delineate the plume of chemical-affected soil or groundwater, or both.

X3.3.1.3 *Pilot Testing*—A pilot test may be useful for the design of a seepage barrier or other technology to ensure that the materials of construction will be capable of achieving the desired performance standard and to evaluate the projected effectiveness of an engineering control. In addition, the test should be designed so that the pilot test portion of the engineering may be removed, if needed, and the test site restored to original conditions.

X3.3.2 *Design Overview*—The design specifications presented below follow the general outline of 6.3 of the guide for each available technology identified previously (i.e., seepage barriers, sealing utility lines, interceptor wells and trenches, slurry walls, and PRBs). More or less information is provided for each topic addressed in accordance with availability and relevance of information to the design of each type of engineering control for chemical-affected groundwater.

X3.3.3 *Seepage Barriers:*

X3.3.3.1 *Effective Area and Defining Boundary*— A seepage barrier will generally be effective throughout the cross-sectional area of chemical-affected groundwater that could contact the subgrade portion of a building or other potential receptor. Record drawings or drawings conforming to construction records or other descriptive records regarding the location and construction details of the seepage barrier may serve as a record of the effective area. Signs may also be used to indicate the presence of a slurry wall beneath a site.

X3.3.3.2 *Design Components, Dimensions, Material Specifications, and Installation Specifications*—A seepage barrier consists of an impermeable wall or membrane that diverts groundwater away from the subgrade portion of a building. In order to account for fluctuations of groundwater flow due to weather-related or tidal influence, the barrier is typically installed to a depth below the foundation of a building. A seepage barrier may also be combined with virtually any other of the before-mentioned technologies to further enhance its effectiveness. If installed according to ASTM or other applicable engineering standards, a seepage barrier can last decades. The type of seepage barrier, including installation method, structural components, and barrier dimensions will vary from site to site, as will the associated cost. Other technologies such as French drains, trenches, or the "Funnel and Gate" may also be combined with the seepage barrier to further enhance the diversion of groundwater from a building substructure. Two types of seepage barriers are available: curtain walls and membranes.

Curtain Walls—The barrier may be constructed as a curtain wall consisting of solid, buried materials such as corrosion-resistant steel sheeting or pre-cast concrete/bentonite slabs that are driven into place. The barrier may also be poured in-place in the manner of a slurry wall. This type of seepage barrier would require disruption of the property only along the line of installation, and, provided that the barrier is located a sufficient distance from the building, no reconstruction of the building or its substructure would be required.

Membranes—Installation of sheet membrane waterproofing involves the adhesion of an impermeable membrane to below-grade walls to prevent infiltration of chemical-affected groundwater through the substructure. The membrane is similar to that of a geosynthetic membrane liner such as butyl or ethylene propylene diene monomer (EPDM) used in landfills for leachate control. The membrane is typically adhered to the exterior of the foundation wall with powerful waterproof glues or mastic, and will typically last for many years.

X3.3.3.3 *Treatment Systems*—Collection and treatment of chemical-affected groundwater is not required for proper operation of seepage barriers.

X3.3.4 *Sealing Utility Lines:*

X3.3.4.1 *Effective Area and Defining Boundary*— Sealing utility lines will generally be effective on the vault, piping, or other utility conduit. Record drawings, drawings conforming to construction records, or other descriptive records regarding the location and installation details of the seals may serve as a record of the effective area.

X3.3.4.2 *Design Components, Dimensions, and Material Specifications*—Trench sealants must resist erosion and deterioration by groundwater flow. They must also be installed so as to fill any void spaces and prevent incidental infiltration of chemical-affected groundwater or stormwater. For example, the elasticity of the bentonite used in a trench saddle must be such that it expands to fill every available void of the pipeline in which it has been installed. The materials used for sealing should not react adversely with the COCs identified in the chemical-affected groundwater or stormwater runoff in utility trenches. Sealant permeabilities must be sufficient to prevent entry of groundwater or stormwater into the utility trench. Trenches may be surrounded by impermeable membranes such as EPDM or butyl liners surrounded by clayey or other low permeability soils, or they may be constructed of steel trenches with waterproof grout seals.

X3.3.4.3 *Treatment Systems*—Collection and treatment of chemical-affected groundwater is not required for properly sealing utility lines.

X3.3.4.4 *Installation Specifications*—Pipe or utility trenches are typically backfilled with impermeable material to prevent chemical-affected groundwater from impacting the lines or pipes. One of the more versatile technologies used for utility line sealing is the "trench plug." A trench plug is a permanent or temporary barrier that is installed at regular intervals in pipe trenches. They are typically required if a trench's slope exceeds a certain percent or if a particular length of trench is open at any one time. Trench plugs may be installed as trench breakers or trench saddles, as described as follows:

(a) Trench Breaker—A trench breaker involves the emplacement of semipermeable fill material that prevents erosion of the trench caused by the lateral movement of groundwater. Temporary emplacements such as soil berms, hay bales, or sand bags, can be used during installation or maintenance of utility lines, and can be easily removed and replaced as needed. Impermeable materials such as clay, cement, or bentonite slurries are installed as permanent erosion barriers, as well as stabilizing structures to prevent subsidence, once the utility line(s) have been laid. A trench breaker may also be installed to isolate water in particular areas that may be accessed for dewatering.

(b) Trench Saddle—A trench saddle is an impermeable structure, installed in similar fashion to a trench breaker, that prevents infiltration of groundwater after a subgrade utility line has been backfilled. Trench saddles are typically composed of bentonite or clay slurries, and have excellent sealing qualities.

X3.3.5 *Interceptor Wells and Trenches:*

X3.3.5.1 *Effective Area and Defining Boundary*— Interceptor wells and trenches are usually designed to be effective over a specified area of chemical-affected groundwater that could migrate either on-site or off-site to impact a potential receptor. Record drawings or drawings conforming to construction records are typically prepared to document the installation of mechanical systems, such as wells and trenches.

X3.3.5.2 *Design Components*—Interceptor wells are installed in such a configuration as to maximize the capture of the contaminant plume. Typically, an interceptor well or group of wells is fitted with in-situ or ex-situ active or passive remediation system. An interceptor trench, whether open or enclosed, is installed to capture chemical-affected groundwater in a lined, impermeable trench which employs pumping or gravity flow to divert chemical-affected groundwater away from potential receptors. The trench may simply divert groundwater away from the property within the groundwater-bearing unit, or the trench may divert groundwater to a passive remediation system such as a permeable reactive barrier.

X3.3.5.3 *Material Specifications*—Materials of construction must be compatible with COCs identified in the recovered groundwater as well as meet standards specified by local codes or regulations.

X3.3.5.4 *Treatment Systems*—Collection and treatment of chemical-affected groundwater is an integral component of a system of interceptor wells. Interceptor trenches may also involve recovery of chemical-affected groundwater in the event that the chemical-affected groundwater is not routed away from potential receptors under gravity flow. In addition to groundwater recovery pumps and collection piping, a treatment system will include some means for removing COCs from the recovered groundwater (e.g., air stripping, granular active carbon) and discharge via a permitted outfall.

X3.3.5.5 *Installation Specifications*—For wells, installation details should include number and location of wells; drilling method; well total depths; screened intervals; well screen and casing materials, diameter, slot size; well development procedures; and surface completion details. For trenches, installation details should include excavation method; dimensions (depth, width, and length); and backfill material and grain size. For both wells and trenches, as needed, installation information should include pump size, type, connections, and installed depth as well as collection piping materials, supports, and testing. Installation, startup, and testing of the treatment train, if any, should be specified.

X3.3.6 *Slurry Walls:*

X3.3.6.1 *Effective Area and Defining Boundary*— A slurry wall will generally be effective throughout the cross-sectional area of chemical-affected groundwater that could contact the subgrade portion of a building or other potential receptor. As-built drawings or other descriptive records regarding the location and construction details of the slurry wall may serve as a record of the effective area. Signs may also be used to indicate the presence of a slurry wall beneath a site. Slurry wall installations are typically installed to manage the flow of chemical-affected groundwater in unconfined groundwater bearing units and are not used for confined or bedrock situations. Fractures in bedrock can allow chemical-affected groundwater to migrate vertically, thereby contaminating deeper groundwater bearing units.

X3.3.6.2 *Design Components*—Slurry walls involve excavating and backfilling a narrow trench with an impermeable slurry such as a mixture of soil removed from the excavation mixed and bentonite. If a slurry wall completely encompasses a plume of chemical-affected groundwater, one or more groundwater recovery wells may need to be installed inside the slurry wall. A limited number of recovery wells serve to maintain an inward hydraulic gradient, thereby reducing hydraulic mounding inside the slurry wall and preventing COCs from moving through the slurry wall.

X3.3.6.3 *Dimensions and Material Specifications*— The slurry material should have a minimum 10 to 15 cm "slump" to facilitate placement into the trench. The slurry should have a relative permeability of approximately 1.0E-05 cm/s and an unconfined compressive strength (UCS) of at least 103.4 kPa when cured.

(a) Permeability—Generally, higher percentages of Portland cement will increase the permeability of the slurry mixture. As water is added to create an adequate "slump," pore sizes are increased as the cement's shrink-swell potential increases. Additives may be included in the slurry to reduce permeability; however, this may increase the cost of the operation. Additionally, the slurry wall should be layered in a lower permeability substrate to avoid bypass (i.e., groundwater that goes around the slurry wall through higher permeability native soil).

(b) UCS—A higher percentage of cement will typically yield a higher UCS. However, a higher percentage of cement will also decrease the flexibility of the barrier, which may lead to cracks caused by crushing or shear loads, such as that which may be encountered in high-clay soils.

X3.3.6.4 *Treatment Systems*—If one or more recovery wells are installed in association with a slurry wells, then collection and treatment of chemical-affected groundwater will be required. Design considerations for recovery wells are provided in X3.3.5.

X3.3.6.5 *Installation Specifications*—During installation, the depth and dimensions of the slurry wall should be verified. In addition, field-testing of the backfill should be conducted to verify the permeability and UCS of the installation. Slurry walls may be constructed using one of five techniques, as described as follows.

(a) Soil-Bentonite (SB) Walls—SB walls are backfilled with a mixture of soils excavated from the trench and bentonite to form an impervious backfill. The low permeability results from both the native clay in the excavated soil and the addition of bentonite to the mixture to form a "filter cake." The amount of bentonite required in the slurry is inversely proportional to the percent clay present in the native fill. Permeabilities have been achieved from 1.0E 06 cm/s to 1.0E-07 cm/s. This slurry mixture is associated with lower costs, as materials being removed (i.e., the excavated soil from the trench) are being recycled in the slurry.

(b) Cement-Bentonite (CB) Walls—CB walls are constructed similarly to SB walls; however, rather than native soil, portland cement is mixed with the bentonite to form a stiff, clay-like slurry that expands to fit into the trench into which it is poured. The material has lower plasticity than SB slurry mixtures, resulting in a permeability which is usually an order of magnitude greater than in a typical SB slurry wall. Permeability is also proportional to the amount of cement, bentonite, and flyash used in the mix. CB walls are typically used when logistics preclude the use of SB walls due to restrictive site conditions, as well as the unavailability of suitable bentonite-based products to be used in SB walls. Similarly, CB walls are useful in areas of highly permeable, loosely compacted soils. The expansion of the CB wall will fill most voids in sandy or gravelly soils through which chemical-affected groundwater could easily migrate.

(c) Soil-Cement-Bentonite (SCB) Walls—A more recent development in slurry wall technology, SCB walls combine the engineering aspects of both SB and CB walls in an attempt to combine lower permeability with higher strength. The wall is constructed similarly to an SB wall, and cement is added to the soil-bentonite mixture to enhance the strength of the wall and to allow for greater expansion into soil voids. Typical permeabilities are in the vicinity of 1.0E 06 cm/sec, and UCS values may be as high as 1379 kPa.

(d) Plastic Concrete Cutoff (PCC) Walls—In cases where deeper trenches are required (e.g., coastal plain areas where confined substratum or bedrock is typically deeper), a PCC wall is useful. Plastic concrete is a lower strength concrete with a small percentage of bentonite that uses sand or flyash, or both, instead of soil for the base ingredient. Plastic concrete expands rapidly to prevent the collapsing of the soil trench and the accumulation of sediment on the bottom of the wall. The walls are constructed in alternating jointed panels to form strong seals.

(e) Deep Soil Mixed (DSM) Walls—DSM cutoff walls use a mixture of cement and bentonite, and have similar strength and permeability to SCB walls. However, a DSM slurry must be added fluidly rather than solidly so as to allow for the limitations of the grout workability.

X3.3.7 *Permeable Reactive Barriers:*

X3.3.7.1 *Effective Area and Defining Boundary*— A PRB will generally be effective throughout the cross-sectional area of chemical-affected groundwater that could contact the subgrade portion of a building or other potential receptor. Record drawings, drawings conforming to construction records, or other descriptive records regarding the location and construction details of the PRB may serve as a record of the effective area. Signs may also be used to indicate the presence of a PRB beneath a site.

X3.3.7.2 *Design Components*—PRBs are installed as a trench system whereby a permeable or semi-permeable substrate is backfilled into a trench along with materials that will react with COCs in groundwater to remove or degrade volatile organic chemicals, semivolatile organic compounds, or heavy metals.

X3.3.7.3 *Dimensions and Material Specifications*— Substrates used for construction of PRBs depend on the COCs being treated and include soil mixed with iron filings, peat moss, oxidative/reductive material, chelators, zero-valent bonding material, granular activated carbon (GAC), or bioreactive slurry. The trench may be as wide or as deep as necessary based on the concentrations of COCs in the chemical-affected groundwater and the required lifespan of the installation. Higher volumes of substrate will not necessarily guarantee longer PRB life.

X3.3.7.4 *Treatment Systems*—As described previously, the PRB itself serves as a treatment system when chemical-affected groundwater flows into the upgradient side of the PRB and treated groundwater flows out of the downgradient side of the PRB.

X3.3.7.5 *Installation Specifications*—Considerations for installation of PRBs are provided as follows.

Buried Installations—A buried installation is a one-time PRB installation in which a trench is constructed and filled with the chemically or biologically reactive backfill. The trench is not replenished with new backfill or altered after installation except in extreme situations where engineering aspects of the property are considered.

Replaceable Installations—Replaceable, also called "cassette," installations involve the installation of a structure such as a slotted tank or interceptor wells where cassettes of reactive substrates can be inserted so as to treat chemical-affected groundwater.

Funnel and Gate Installations—A funnel-and-gate installation involves constructing an impermeable barrier, such as a slurry wall, and a select number of "gates" where chemical-affected groundwater may be "funneled" through for passive remediation. The slurry wall must be proven impermeable through percolation tests or enhanced via the use of such materials as specialized bacteria or high carbon fly ash to reduce permeability even further and ensure that no chemical-affected groundwater is permitted to bypass the treatment "gates."

X3.4 *Performance Monitoring and Maintenance Issues:*

X3.4.1 *Seepage Barriers*—A seepage barrier is a one-time installation that requires virtually no operation and maintenance. Considerations for each type of seepage barrier are as follows:

(a) Curtain Walls—The performance of curtain wall barriers should be monitored by measuring groundwater elevations in piezometers or wells placed hydraulically upgradient and downgradient of the barrier. The measured potentiometric surface contours should demonstrate that groundwater flow continues to be diverted away from potential receptors identified during the design phase as well as any new receptors that may be present.

(b) Membranes—Given that membrane barriers are installed below grade, no inspection will be possible; however, repair or replacement may be required in the event of damage due to excavation adjacent to the building.

X3.4.2 *Sealing Utility Lines*—If possible, any above-ground portions of the utility lines should be inspected to evaluate the continued integrity of the seals. The proper operation of leak detection sensors, if installed, should be verified.

X3.4.3 *Interceptor Wells and Trenches*—The operation of pumps and treatment system, if installed, should be checked periodically. Groundwater samples should be periodically collected and analyzed to assess system effectiveness and continuing need for operation. Recovery wells should be redeveloped as needed to maintain groundwater recovery rates.

X3.4.4 *Slurry Walls*—The performance of slurry walls should be monitored by measuring groundwater elevations in piezometers or wells placed hydraulically upgradient and downgradient of the barrier. The measured potentiometric surface contours should demonstrate that groundwater flow continues to be diverted away from potential receptors identified during the design phase as well as any new receptors that may be present. The operation of pumps and treatment system, if installed, should be checked periodically. Groundwater samples should be periodically collected and analyzed to assess system effectiveness and continuing need for operation. Recovery wells should be redeveloped as needed to maintain groundwater recovery rates.

X3.4.5 *Permeable Reactive Barriers (PRB)*—PRBs are low maintenance and very effective in the passive remediation of groundwater if so required. There are no aboveground facilities required, no active pumping or treatment, and no disposal costs associated with the in-situ treatment of chemical-affected groundwater through this technology. Replaceable installations require the replacement of cassettes; therefore, a moderate amount of O&M and expenditure is required for this technology. Additionally, shutoff valves and pipe connections may also be required, which can increase the cost of this technology. Funnel-and-gate installations must be tested thoroughly to ensure the impermeability of the cutoff wall so that no chemical-affected groundwater is allowed to bypass the "gate" where the remediation media is located. This requires significant forward planning and engineering research.

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X4. CASE STUDY EXAMPLE OF SITE DEVELOPMENT PLAN USING ENGINEERING CONTROLS FOR CHEMICAL-AFFECTED PROPERTY

X4.1 *Introduction*— This case study example reviews the use of engineering controls to address exposure concerns at a chemical-affected property and compares this approach to remediation by removal/treatment technologies. For a hypothetical site condition, the scope and cost of these two approaches are compared.

X4.2 *Chemical-Affected Environmental Media*—A site assessment conducted at a commercial property, which formerly contained both a gasoline service station and a dry cleaning operation, has discovered a chemical release to shallow soil and groundwater beneath the property. Results of the site assessment are illustrated in Fig. X4.1.

X4.2.1 *Site Development Plan Options*—In general, plans for the site include demolishing and removing the service station and strip mall and constructing an office building. Parking for the office building will include a subgrade parking garage. In order to develop the site in the most cost-effective manner, the developers reviewed options for construction of the office building and parking garage in consideration of alternative engineering controls, as well as remediation by removal/treatment technologies. By consideration of these issues in the early planning stages, the developer is able to balance the costs of construction and engineering controls with future leasing revenues. The two site development scenarios are described in Table X4.1.

TABLE X4.1 Site Development Scenarios

Action Item	Scenario A: Use of Engineering Controls	Scenario B: Use of Removal/Treatment Technologies
Development Plan	Office building with underground parking garage	Office building with underground parking garage
Soil Action	Partial excavation, apply engineering controls	Complete excavation of chemical-affected soil
Groundwater Action	No treatment, apply engineering controls	Pump-and-treat to achieve full remediation

X4.2.2 *Potentially Complete Exposure Pathways and Corrective Action Goals*—Potentially complete exposure pathways during construction of the subgrade parking garage include exposure of construction workers via: (*1*) direct soil contact, and (*2*) inhalation of ambient vapors. Potentially complete exposure pathways for property users after construction include: (*1*) direct soil contact, (*2*) inhalation of ambient or indoor vapors, and (*3*) affected groundwater impact on subsurface structures or utilities in the event of a high-water table. Engineering controls and conventional removal/treatment technologies will be evaluated to determine the most cost-effective method for eliminating these potentially complete exposure pathways.

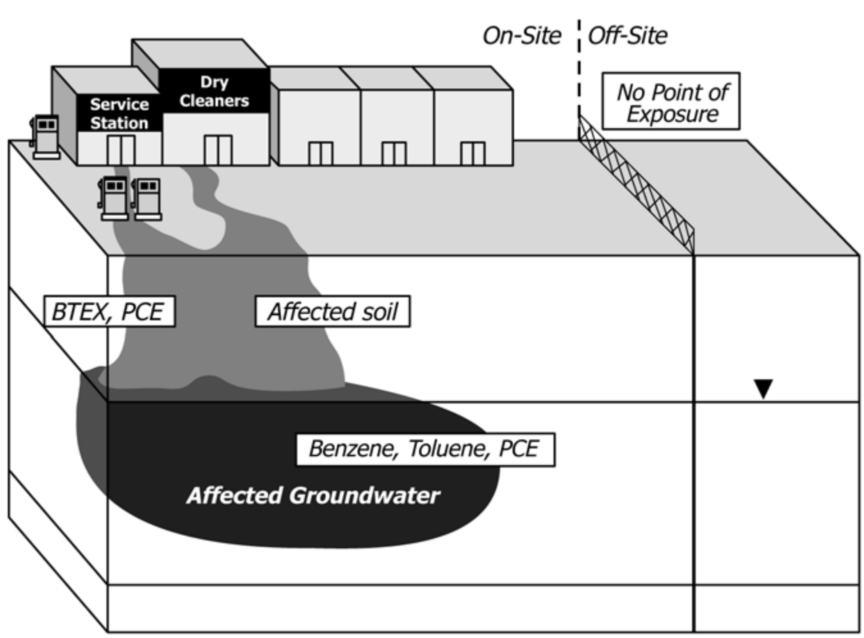

FIG. X4.1 Former Property Use and Results of Site Assessment

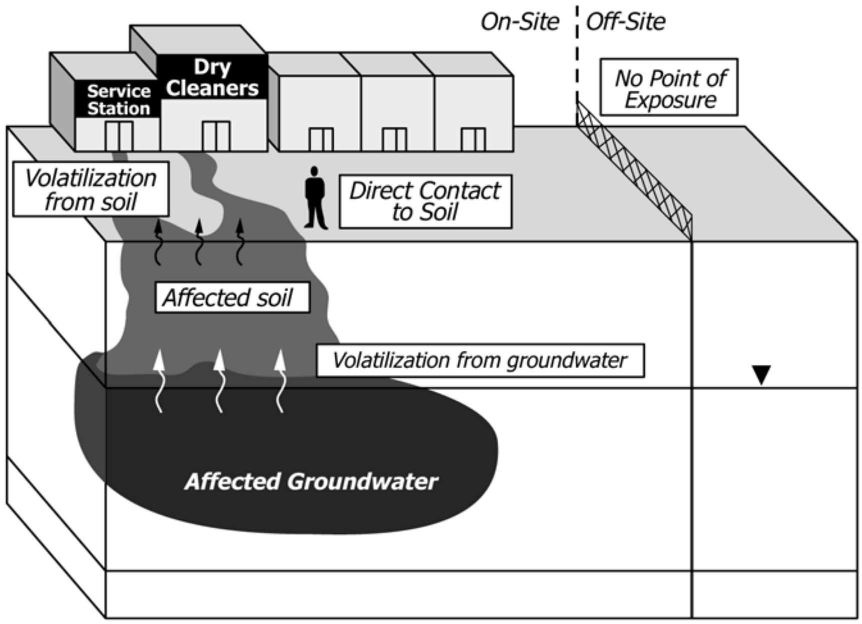

FIG. X4.2 Potentially Complete Exposure Pathways

X4.2.3 *Development of Design Specifications*—Proposed exposure controls for each site development scenario are summarized on Table X4.2 and illustrated on Figs. X4.3 and X4.4.

X4.2.4 *Cost Comparison*—Approximate costs for Scenario A and Scenario B have been estimated based on the design basis information provided on Table X4.2, and are summarized in Table X4.3. Costs for site characterization and routine

TABLE X4.2 Site Development Specifications

Design Specification	Scenario A: Use of Engineering Controls	Scenario B: Use of Removal/ Treatment Technologies
Design Basis Information	Partial excavation of the chemical-affected soil during installation of parking garage. Some affected soil will remain at surface and along two sides of parking garage. Chemical-affected groundwater will not be treated.	All chemical-affected soil will be removed. A pump-and-treat system will be installed to remediate chemical-affected groundwater.
Effective Area and Defining Boundary	Engineering controls will be installed atop chemical-affected soil at surface and on sides and floor of parking garage. Defining boundary will consist of warning tape installed between engineering control and affected soil.	Not applicable to a complete removal and treatment scenario.
Design Components	Polymeric vapor barrier will be installed on two sides and floor of parking garage. Polymeric vapor barrier and vegetative soil cover will be installed atop affected surface soil. A dewatering system will surround parking garage to prevent infiltration in the event of a high water table. Six monitoring wells will be installed within the plume and at the downgradient property boundary.	All chemical-affected soil (1452.7 cubic metres) will be excavated. The pump-and-treat system will include 6 recovery wells, 6 pneumatically powered pumps, an air compressor, collection piping, and treatment. Six monitoring wells will be installed within the plume and at the downgradient property boundary.
Dimensions and Material Specifications	Polymeric vapor barrier will be high-density polyethylene. Dewatering system will consist of a french drain constructed of polyvinyl chloride, and a sump with sump pump. Monitoring wells will be constructed of polyvinyl chloride.	Recovery wells, collection piping, and monitoring wells will be constructed of polyvinyl chloride.
Treatment System	For high water table events, groundwater will be collected in a sump, and discharged to the publicly owned treatment works (POTW).	Recovered groundwater will be treated using a granular activated carbon (GAC) system.
Installation Specifications	Polymeric vapor barrier will be installed to achieve good contact between the barrier and concrete. Utility openings will be sealed with spray-on barrier. Monitoring wells will be installed to a depth of 7.6 m below ground surface	Recovery wells and monitoring wells will be installed to a depth of 7.6 m below ground surface and connected to a common header pipe connected to two GAC units piped in parallel.
Monitoring and Maintenance	Ambient and indoor air will be analyzed upon installation, and every 5 years thereafter. Engineering controls will be inspected annually. Groundwater from the monitoring wells will be analyzed annually.	Treated groundwater will be analyzed upon installation and monthly thereafter. Groundwater from the recovery wells and monitoring wells will be analyzed annually. The pump-and-treat system will be inspected monthly, and GAC will be reactivated semi-annually.
Regulatory Considerations	Appropriate manifesting and disposal will be completed during installation of parking garage. An institutional control will be implemented to notify future owners of the presence of chemical-affected soil at the property.	Appropriate manifesting and disposal will be completed during remediation. A permit will be obtained for discharging treated groundwater to the POTW.

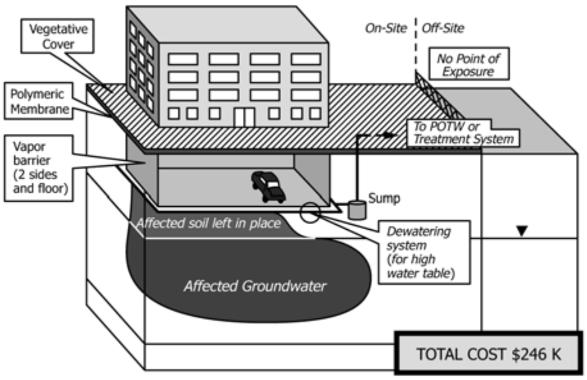

FIG. X4.3 Scenario A: Use of Engineering Controls for Exposure Control

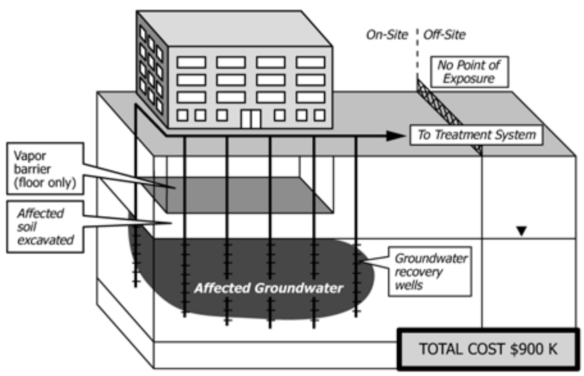

FIG. X4.4 Scenario B: Use of Removal/ Treatment Technologies for Exposure Control

reporting, which would be required for each of these scenarios have not been included. Totals have been calculated assuming a 4 % annual discount rate based on 2004 costs.

X4.2.5 *Discussion*—Engineering controls or remediation by removal/treatment technologies can be employed to control exposure to chemical-affected soil and groundwater during the renovation and reuse of this property. The decision to use engineering controls rather than conventional treatment depends on several factors including: (*1*) the nature and extent of chemical-affected media and potentially complete exposure pathways, (*2*) the presence of existing engineering controls, (*3*) the applicable regulatory requirements, and (*4*) the relative cost and feasibility of alternative site-development measures. For the hypothetical site presented in this example, both site development scenarios are protective of potential exposure to chemical-affected media and are consistent with applicable regulatory requirements; therefore, the cost of implementing and maintaining each site development option is the primary factor considered to determine which scenario is more advantageous. Significant costs are associated with implementation of either site development scenario, such as installation of engineering controls for Scenario A or soil removal and installation of the groundwater recovery system for Scenario B; however, use of engineering controls is much less costly compared to complete soil removal and installation of a pump-and-treat system. When long-term monitoring and maintenance obligations are included in the cost comparison, even greater cost savings are realized for site development utilizing engineering controls rather than conventional removal and treatment.

TABLE X4.3 Cost Comparison of Site Development Scenarios

SCENARIO A: USE OF ENGINEERING CONTROLS			
Task/Description	*Unit Cost*[A]	*Units*	*Total Cost*
• ***Excavate affected soil***, haul, and dispose portion of affected soil in landfill as non-hazardous waste	$ 104 per CY[B]	1,100 CY	**$ 114,400**
• ***Excavate unaffected soil*** and haul	$ 10 per CY	2,000 CY	**$ 20,000**
• ***Install vapor barrier*** on sides and floor of parking garage (spray-applied membrane)	$ 200 per CSF[C]	122 CSF	**$ 24,400**
• ***Install vegetative cover*** and top soil atop vapor barrier at ground surface	$ 1 per SF[D]	2,000 SF	**$ 2,000**
• ***Install dewatering system*** for high water table events, includes underground french drain, sump, sump pump, and piping	$ 13,000	1	**$ 13,000**
• ***Install groundwater monitoring wells***, includes drilling and installation, materials, and oversight	$ 1,700	6	**$ 10,200**
• ***Collect air samples*** of ambient and indoor air from parking garage and analyze for site constituents	$ 3,000	1	**$ 3,000**
• ***Conduct annual inspection*** of engineering controls for thirty years, conduct annual groundwater monitoring for thirty years, and collect and analyze ambient and indoor air samples every 5 years to verify exposure control	$ 3,400 per year	30 years	**$ 58,800**[E]
		TOTAL	***$ 246,000***

SCENARIO B: USE OF REMOVAL/TREATMENT TECHNOLOGIES			
Task/Description	*Unit Cost*	*Units*	*Total Cost*
• ***Excavate affected soil***, haul, and dispose of all affected soil in landfill as non-hazardous waste	$ 104 per CY	1,900 CY	**$ 198,000**
• ***Excavate unaffected soil*** and haul	$ 10 per CY	2,000 CY	**$ 20,000**
• ***Install vapor barrier*** on floor of parking garage	$ 200 per CSF	122 CSF	**$ 24,400**
• ***Install recovery wells***, includes drilling, materials, and oversight	$ 6,100 per well	6 wells	**$ 36,600**
• ***Install groundwater monitoring wells***, includes drilling and installation, materials, and oversight	$ 1,700	6	**$ 10,200**
• ***Install treatment system***, includes pumps, compressor, 2 granular activated carbon units, and associated piping	$ 54,000	1	**$ 54,000**
• ***Operate treatment system*** for thirty years, includes monthly inspection, maintenance, and effluent sampling, and annual groundwater monitoring of the recovery and monitoring wells	$ 32,200 per year	30 years	**$ 557,000**[E]
		TOTAL	***$ 900,000***

[A] Unit costs estimated from *RS Means Environmental Remediation Cost Data*, 10th Edition, ECHOS, L.L.C., 2004.
[B] CY = cubic yard
[C] CSF = hundred square feet
[D] SF = square foot
[E] Net present value calculated assuming 4 % annual discount rate.

X5. APPLICABILITY, DESIGN CONSIDERATIONS, AND MONITORING REQUIREMENTS FOR ENGINEERING CONTROL TECHNOLOGIES

X5.1

TABLE X5.1

Engineering Control Technology	Active or Passive?	Description/Means of Exposure Control	Applicable to: New Constr	Applicable to: Existing Bldg	Possible Monitoring and Maintenance Procedures	Design Considerations and Specifications (see Note 2)	Refs
PREVENTION OF DIRECT CONTACT WITH CHEMICAL-AFFECTED SOIL							
Asphalt Pavement	Passive	A layer of hot-mix asphalt installed to isolate chemical-affected soil from direct contact.	✓		• ***Start-Up:*** Verify proper installation. • ***Routine O&M:*** Verify integrity and presence on periodic basis. Repair cracks, potholes, or other degradation as needed.	• ***Effective Area and Defining Boundary:*** Specify extent and location of asphalt and defining boundary. • ***Dimensions and Material Specifications:*** Specify stability and durability requirements considering use (e.g., parking lot, recreation) and type, frequency, and weight of traffic. Consider availability/proximity of batch plant (e.g., not available in winter in cold climates). • ***Installation Specifications***: Prepare underlying soil as needed by amending or modifying prior to asphalt placement. Grade site for proper drainage of stormwater runoff. Specify air voids, workability, compaction, and in-place thickness; binder and aggregate details; and temperature leaving batch plant and at installation.	(23, 24)
Concrete Pavement	Passive	A layer of concrete pavement installed to isolate chemical-affected soil from direct contact.	✓		• ***Start-Up:*** Verify proper installation. • ***Routine O&M:*** Verify integrity and presence on periodic basis. Repair cracks, potholes, or other degradation as needed.	• ***Effective Area and Defining Boundary:*** Specify extent and location of concrete placement and defining boundary. • ***Dimensions and Material Specifications:*** Specify stability and durability requirements considering use (e.g., parking lot, building foundation) and type, frequency, and weight of traffic, if applicable, or structural loading requirements. Consider availability/proximity of batch plant. • ***Installation Specifications:*** Prepare underlying soil as needed by amending or modifying prior to concrete placement. Grade site for proper drainage of stormwater runoff. Specify cement type, fine and coarse aggregate, and/or admixtures; thicknesses of concrete and base course, if specified; and strength, air content, slump, and surface finish.	(23)
Flexible Liners	Passive	A flexible membrane liner typically installed beneath a protective layer of soil, or other structural element, to isolate chemical-affected soil from direct contact.	✓		• ***Start-Up:*** Verify proper installation. • ***Routine O&M:*** Verify integrity and presence of liner. Verify that protective soil layer is present and in good condition. Add additional soil as needed to replace eroded material.	• ***Effective Area and Defining Boundary:*** Specify extent and location of liner and defining boundary. • ***Dimensions and Material Specifications:*** Specify liner thickness, tensile strength, tear resistance, puncture resistance, impact resistance, resistance to ultraviolet light, and compatibility with chemicals in soil. • ***Installation Specifications:*** Specify optional protective soil layer, including thickness, soil type, and compaction requirements.	E1745
Clean Soil Cover	Passive	A layer of clean soil installed to prevent direct contact with chemical-affected soil.	✓	✓	• **Start-Up:** Verify proper installation. • ***Routine O&M:*** Periodically verify integrity and presence, and examine for erosion. Add additional soil as needed to replace eroded material.	• ***Effective Area and Defining Boundary:*** Specify extent and location of soil cover and defining boundary. • ***Installation Specifications:*** Grade site for proper drainage of stormwater runoff. Consider availability of suitable soils close to site. Specify thickness of soil layer and whether allowance for erosion is to be included; placement requirements (e.g., clod size, lift thickness); compaction requirements; soil type (e.g., clay), and final topographic contours. Specify frequency and location of topographic surveys.	(23)
Vegetative Cover	Passive	A layer of clean soil planted with vegetation installed to prevent direct contact with chemical-affected soil.	✓	✓	• ***Start-Up:*** Verify proper installation. • ***Routine O&M:*** Periodically verify integrity and presence, and examine for erosion or lack of vegetation. Add additional soil as needed to replace eroded material and replant. Mow and fertilize as needed.	• ***Design Basis Information:*** Consider availability of suitable soils close to site. May not be suitable for sites with COCs that are water soluble or incompatible with fertilizers. • ***Effective Area and Defining Boundary***: Specify extent and location of vegetative cover and defining boundary. • ***Installation Specifications:*** Grade site for proper drainage of stormwater runoff. Consider whether site characteristics will support healthy vegetative cover (e.g., topography, rainfall, climate, pests, compatibility with COCs). Specify placement requirements (e.g., clod size, lift thickness, final thickness); compaction specifications; soil type (e.g., clay), and final topographic contours. Specify type of vegetation; density and type of planting (e.g., seeds or slips); and fertilization, mowing, and watering requirements.	(23)

TABLE X5.1 *Continued*

Engineering Control Technology	Active or Passive?	Description/Means of Exposure Control	Applicable to: New Constr	Applicable to: Existing Bldg	Possible Monitoring and Maintenance Procedures	Design Considerations and Specifications (see Note 2)	Refs
Stone Blankets	Passive	A layer of small stones or recycled concrete installed to isolate chemical-affected soil from direct contact.	✓		• ***Start-Up:*** Verify proper installation. • ***Routine O&M:*** Verify integrity and presence on periodic basis. Repair as needed.	• ***Effective Area and Defining Boundary:*** Specify extent and location of stone blanket and defining boundary. • ***Dimensions and Material Specifications:*** Specify size range and composition of stones, and whether recycled concrete (with or without steel after processing) is acceptable. • ***Installation Specifications:*** Prepare underlying soil as needed by amending or modifying prior to stone blanket installation. Grade site for proper drainage of stormwater runoff. Generally not considered applicable for slopes greater than 2 horizontal to 1 vertical or in areas susceptible to erosion. Specify thickness of stone blanket, sequence of installation of underlayment, filter fabric, stones, and grout.	(**25**)
PREVENTION OF EXPOSURE TO AMBIENT OR INDOOR VAPORS							
Sealing Soil Gas Entry Routes	Passive	Vapor entry points are sealed to prevent intrusion of soil vapors to indoor air space.	✓	✓	• ***Start-Up:*** Verify proper installation. • ***Routine O&M:*** Periodically inspect to identify new openings that may have opened due to movement and shifting of the structure and to ensure that installed seals are still in place and no gaps or apparent leaks have developed, perhaps as a result of foundation and/or soil settling, damage from physical contact, degradation, or water. Install new seals or repair as needed.	• ***Design Basis Information:*** Identify all possible vapor entry points: sumps, floor drains, French drains, uncapped hollow block walls, utility penetrations, electrical junction boxes, slab/wall cracks, block wall pore openings, and others. • ***Dimensions and Material Specifications:*** Consider compatibility of caulks and sealants with materials to be sealed (e.g., urethane caulks are more effective for cement than silicone caulks) and need for primers or other surface preparation to assure good adhesion. • ***Installation Specifications:*** Consider method of application: membranes, bead-caulk, flowable sealants, or spray-on sealants. A backing rod may be needed for deep cracks. Match sealant to application. For small cracks, consider silicone or urethane caulk or non-shrink grout with binder. For large cracks, consider silicone caulk; spray foam; expanding urethane foam; or two-part urethane foam, silicone liquid, spray foam, or flowable urethane. For pore openings, consider HDPE, polymer, PVC, or polyethylene membranes or sheeting; surface bonding cement; two-part furan, polysulfide, water-based epoxy. For design openings (e.g., utility entrances), consider two-part urethane, spray foam; flowable urethane; or spray foam.	C1193, C1299 (**26**)
Passive Vapor Barriers	Passive	Flexible sheet materials and/or coatings placed beneath or on the sides of building foundation to prevent intrusion of soil vapors to indoor air space.	✓		• ***Start-Up:*** Verify proper installation. Conduct air sampling to verify effectiveness of liner. • ***Routine O&M:*** Conduct air sampling to verify on-going effectiveness of liner.	• ***Effective Area and Defining Boundary:*** Specify location of vapor barrier installation (e.g., beneath slab, on foundation walls) and defining boundary. • ***Dimensions and Material Specifications:*** Specify vapor barrier thickness, tensile strength, tear resistance, puncture resistance, impact resistance, resistance to ultraviolet rays in sunlight if left uncovered, compatibility with chemicals in soil, and impermeability to vapors identified on site. Examples: flexible sheet materials (i.e., metal foils, laminated foils, and polyethylene, PVC, or EPDM films) or coatings (i.e., paint, semi-fluid mastic, spray, or hot melt applications).	E2121, (**26-34**)
Building Pressurization Systems	Active	Indoor air pressure is maintained at a level greater than ambient so as to prevent intrusion of soil vapors to indoor air space.	✓	✓	• ***Start-Up:*** Verify proper installation and alarm operation.	• ***Design Basis Information:*** Consider impact of potential interference or influence from air handling systems in adjacent spaces. Consider desired number of air changes per hour, volume to be ventilated, and estimated vapor concentrations.	(**35**)
					• ***Routine O&M:*** Inspect and service HVAC components, and change filters as specified by manufacturer or as indicated by conditions of use. Maintain and test alarm system.	• ***Installation Specifications:*** Specify size of HAVC unit, whether operation will be continuous or dependent on alarm condition, and source of unaffected air for system intake.	

TABLE X5.1 *Continued*

Engineering Control Technology	Active or Passive?	Description/Means of Exposure Control	Applicable to: New Constr	Applicable to: Existing Bldg	Possible Monitoring and Maintenance Procedures	Design Considerations and Specifications (see Note 2)	Refs
Active Soil Depressurization	Active	Remove contaminated soil vapor using a system of fans and collection piping and vent to the atmosphere.	✓	✓	• ***Start-Up:*** Verify that no vapors are entering building. Verify proper alarm operation, if present. • ***Routine O&M:*** Periodically verify that no vapors are entering building. Maintain and test alarm system, if present.	• ***Design Basis Information:*** Consider how to seal building penetrations and protect piping from damage within the building (i.e., within walls or chases). • ***Dimensions and Material Specifications:*** Specify pump capacity, piping diameter, materials of construction, and termination details. Specify number and location of suction points. • ***Installation Specifications:*** Specify location, depth, and length for piping. Specify one-way valve details for suction points. Specify stenciling, labeling, or marking of piping.	(36)
CONTROL OF CHEMICAL-AFFECTED GROUNDWATER IMPACTS ON SUBSURFACE STRUCTURES OR UTILITIES							
Seepage Barriers	Passive	A vertically excavated trench filled with an impermeable medium is installed hydraulically upgradient of the point of exposure to route groundwater away from the subsurface structure or utility.	✓	✓	• ***Start-Up:*** Verify proper installation. • ***Routine O&M:*** Periodically monitor potentiometric surface to verify continuing effectiveness of barrier. Periodically collect and analyze groundwater samples to assess continuing need for system.	• ***Design Basis Information:*** Consider site characteristics including depth to groundwater, thickness and continuity of groundwater bearing zone, hydraulic gradient, hydraulic conductivity, groundwater flow direction, and distance to point of exposure. Configure barrier to route chemical-affected groundwater around or away from point of exposure without impacting other potential receptors. Depth should be sufficient to reduce or eliminate groundwater impact on any downgradient structures or utilities. • ***Dimensions and Material Specifications:*** Options for impermeable medium include geomembranes, geosynthetic clay liners, and bentonite slurries. • ***Installation Specifications:*** Specify location, depth, and width of seepage barrier. Install piezometers for monitoring potentiometric surface and sampling groundwater.	—
Sealing Utility Lines	Passive	Utility lines are sealed to prevent entry of chemical-affected groundwater.	✓		• ***Start-Up***: Verify proper installation. • ***Routine O&M***: Periodically inspect utility lines, if possible. Leak detection sensors may be needed if lines cannot be visually inspected.	• ***Design Basis Information:*** Identify all possible groundwater entry points: sumps, floor drains, French drains, utility penetrations, electrical junction boxes, and others. Specify primers or other surface preparation needed to assure good adhesion. • ***Dimensions and Material Specifications:*** Select caulks and sealants compatible with materials to be sealed. Consider silicone or urethane caulks; spray foams; expanding urethane foams; or two-part urethane foam, silicone liquid, spray foam, or flowable urethane. Consider silicone or urethane caulks; spray foams; expanding urethane foams; or two-part urethane foam, silicone liquid, spray foam, or flowable urethane. • ***Installation Specifications*** : Methods of application include bead-caulk, flowable sealants, or spray-on sealants.	C1193, C1299 (26, 28, 34)
Interceptor Wells	Active	An array of vertical or horizontal groundwater recovery wells equipped with pumps and installed to intercept and collect chemical-impacted groundwater hydraulically upgradient of the potential point of exposure.	✓	✓	• ***Start-Up:*** Verify proper installation. • ***Routine O&M***: Periodically check operation of pumps and treatment system, if installed. Periodically collect and analyze groundwater samples to assess continuing need for system. Redevelop wells as needed to maintain recovery rates.	• ***Design Basis Information:*** Consider site characteristics including depth to groundwater, thickness and continuity of groundwater bearing zone, hydraulic gradient, hydraulic conductivity, and groundwater flow direction, and distance to point of exposure. Estimate minimum pumping rate needed to intercept chemical affected groundwater but not create a cone of depression deeper than needed to reduce or eliminate exposure. Evaluate vertical vs. horizontal wells based on thickness and continuity of groundwater bearing zone. • ***Dimensions and Material Specifications:*** Specify materials of construction, filter pack characteristics, open area and slot or hole size, and filter fabric details.	—

TABLE X5.1 *Continued*

Engineering Control Technology	Active or Passive?	Description/Means of Exposure Control	Applicable to: New Constr	Applicable to: Existing Bldg	Possible Monitoring and Maintenance Procedures	Design Considerations and Specifications (see Note 2)	Refs
						• ***Treatment System:*** Consider need for treatment of recovered groundwater (e.g., granular activated carbon). • ***Installation Specifications:*** Specify depth of screened interval, number of wells and diameter of wells. • ***Regulatory Considerations:*** Obtain permit to discharge groundwater, if needed.	
Interceptor Trenches	Active	A vertically excavated trench filled with a permeable medium and perforated pipe installed hydraulically upgradient of the potential point of exposure. Sumps equipped with pumps at one or more locations along the trench collect and remove affected groundwater.	✓	✓	• ***Start-Up:*** Verify proper installation. • ***Routine O&M:*** Periodically check operation of pumps and treatment system, if installed. Periodically collect and analyze groundwater samples to assess continuing need for system.	• ***Design Basis Information:*** Consider site characteristics including depth to groundwater, thickness and continuity of groundwater bearing zone, hydraulic gradient, hydraulic conductivity, and groundwater flow direction, and distance to point of exposure. Estimate the minimum pumping rate needed to intercept chemical affected groundwater but not create a cone of depression deeper than needed to reduce or eliminate exposure. • ***Dimensions and Material Specifications:*** Specify diameter, materials of construction, and open area and slot or hole size of perforated collector pipe. Specify material and grain size of permeable media and filter fabric. • ***Treatment System:*** Consider need for treatment of recovered groundwater (e.g., granular activated carbon). • ***Installation Details:*** Specify location, depth, width, and required bottom slope of trench. Specify number and location of sumps and pump capacities. • ***Permitting and Regulatory Considerations:*** Obtain permit to discharge groundwater, if needed.	—
Slurry Walls	Active/ Passive	A vertically excavated trench filled with a impermeable medium. Recovery wells may be installed inside the slurry wall.	✓	✓	• ***Start-Up:*** Verify proper installation. • ***Routine O&M:*** Periodically check operation of pumps and treatment system, if installed. Periodically measure GW elevations, and collect and analyze GW samples to assess continuing need for system.	• ***Design Basis Information:*** Consider site characteristics including depth to groundwater, thickness and continuity of groundwater bearing zone, hydraulic gradient, hydraulic conductivity, and groundwater flow direction, and distance to point of exposure. Estimate the minimum pumping rate needed to maintain inward hydraulic gradient. • ***Dimensions and Material Specifications:*** Specify length, width, and depth of trench. Specify materials of construction, filter pack characteristics, open area and slot or hole size of wells, if needed. • ***Treatment System:*** Consider need for treatment of recovered groundwater (e.g., granular activated carbon). • ***Installation Details:*** Specify location of slurry wall. Specify material and installation procedure for impermeable media. Specify number and location of recovery wells. • ***Permitting and Regulatory Considerations:*** Obtain permit to discharge treated groundwater, if needed.	—
Permeable Reactive Barriers (PRBs)	Passive	A vertically excavated trench filled with a reactive medium to degrade or remove COCs.	✓	✓	• ***Start-Up:*** Verify proper installation. • ***Routine O&M:*** Periodically measure GW elevations, and collect and analyze GW samples to assess continuing need for system. Replace treatment cassettes, if needed.	• ***Design Basis Information:*** Consider site characteristics including depth to groundwater, thickness and continuity of groundwater bearing zone, hydraulic gradient, hydraulic conductivity, and GW flow direction, and distance to point of exposure. Determine optimum reactive medium for COCs to be treated or removed. • ***Dimensions and Material Specifications:*** Specify length, width, and depth of trench. Specify reactive medium. • ***Treatment System:*** Consider single installation vs. cassettes.	—

TABLE X5.1 *Continued*

Engineering Control Technology	Active or Passive?	Description/Means of Exposure Control	Applicable to:		Possible Monitoring and Maintenance Procedures	Design Considerations and Specifications (see Note 2)	Refs
			New Constr	Existing Bldg			
						• ***Installation Details:*** Specify location of PRB. Specify materials and installation procedure for reactive medium.	

X6. ADDITIONAL REFERENCES RELATED TO DEVELOPMENT OF ENGINEERING CONTROLS AT CHEMICAL-AFFECTED PROPERTIES

ASTM Standards:

D6235 Practice for Expedited Site Characterization of Vadose Zone and Ground Water Contamination at Hazardous Waste Contaminated Sites

E1527 Practice for Environmental Site Assessments: Phase 1 Environmental Site Assessment Process

E1739 Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites

E1903 Guide for Environmental Site Assessments: Phase II Environmental Site Assessment Process

E1912 Guide for Accelerated Site Characterization for Confirmed or Suspected Petroleum Releases

E1943 Guide Remediation of Ground Water by Natural Attenuation at Petroleum Release Sites

NFPA Standards:[4]

National Electrical Code, NFPA 70

Other Relevant Guidelines:

ASHRAE, "Ventilation for Acceptable Indoor Air Quality," American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, Georgia, 1990.

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Pennsylvania Department of Environmental Protection, "Guidance on Vapor Intrusion into Buildings from Groundwater and Soil under the Act 2 Statewide Health Standard," Final Draft, Online, Available: http://www.dep.state.pa.us/dep/deputate/airwaste/wm/landrecy/facts/VaporGuidance062303.pdf.

Pennsylvania Department of Environmental Protection, "Land Recycling Program Technical Guidance Manual-Section IV.A.4 Vapor Intrusion into Buildings from Groundwater and Soil under the Act 2 Statewide Health Standard," January 24, 2004, Online, Available: http://www.dep.state.pa.us/dep/deputate/airwaste/wm/landrecy/manual/Guidance.htm.

US Department of Highways, "Hot Mix Asphalt for the Undergraduate," Federal Highway Administration, http://www.fhwa.dot.gov/asphtech/sophomore/lectures/slect2.htm.

City of Los Angeles, "Methane Seepage District Regulations," LAMC 91.7100, Los Angeles, CA, Online, Available: http://lacodes.lacity.org.

"Passive Soil Vapor Extraction," Lawrence Livermore National Laboratory, Industrial Partnership and Commercialization, Online, Available: http://www.llnl.gov/IPandC/technology/profile/environment/PassiveSoilVaporExtraction/index.php.

U.S. Environmental Protection Agency, "EPA Policy on ASTM International E2121 Standard Practice for Radon Mitigation Systems in Existing Low-Rise Residential Buildings," Office of Air and Radiation, Office of Radiation and Indoor Air, Indoor Environments Division, March 12, 2003, Online, Available: http://www.epa.gov/radon/images/final_e2121policy.pdf.

U.S. Environmental Protection Agency, "Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils (Subsurface Vapor Intrusion Guidance)," Draft, EPA530-F-02-052, Office of Solid Waste and Emergency Response, November 2002, Online, Available: http://www.epa.gov/correctiveaction/eis/vapor.htm.

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