FINAL

COST TO COMPLETE (CTC) TECHNOLOGIES REFERENCE MANUAL

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COST TO COMPLETE REFERENCE MANUAL

This Cost to Complete (CTC) Technologies Reference Manual is a technical manual prepared to support the normalized database (NORM) CTC system. Gathering information to support technology selection can require commitment of a considerable amount of time and effort. This manual is intended to help remedial project managers (RPMs) streamline the process of reviewing and selecting technologies that serve as a basis for preparing budgetary cost estimates. Each technology is described in a concise format allowing the RPM to quickly and efficiently access information about the operating characteristics, applications, limitations, maturity status, operation and maintenance duration, cost range, and work breakdown structure (WBS) correspondence. A supporting diagram is included with each technology to clearly illustrate the major inputs, process operations, outputs, and process residuals of typical applications. The guidance and supporting information provided in this manual should be used only for preliminary identification of a range of feasible alternatives. The manual is not intended to be the sole basis for final selection of a technology or treatment train to remediate a site.

The technologies are grouped as biological treatment technologies, physical chemical technologies, combined mechanism technologies, and containment or removal technologies. Information is included regarding developmental category (i.e., conventional, innovative, and emerging technologies). The use of specific trade and vendor names has been avoided where ever possible. Mention of specific trademarked products or vendors should not be construed as endorsement or recommendation of the product or vendor.

The manual provides background information on a wide variety of technologies for remediating combinations of contaminants and media that occur frequently at Navy sites. The contaminants considered are halogenated volatile and semivolatile organic compounds, nonhalogenated volatile and semivolatile organic compounds, inorganics, ordnance compounds, and polychlorinated biphenyls. The media considered are in situ and ex situ groundwater, in situ unsaturated zone soil, in situ sediment, excavated soil or dredged sediment, and off-gas.

The technology profiles support a technology selection and cost estimating system. Matrices showing the technology applicability for various contaminant and media combinations and the approach to screening to further refine technology lists is presented in a logic diagram summarizing the technology selection approach. Background information defining the cost elements included in the Cost Estimating Relationships (CERs) for 50 technologies also are provided as CER Profiles.

The information in this manual is organized into eight sections as follows:

1. Technology Profile Index and Glossary
2. Remediation Technologies (for Typical Contaminants and Media at Navy Remediation Sites)
3. Biological Treatment Methods
4. Physical/Chemical Treatment Methods
5. Combined Mechanism Treatment Methods
6. Containment or Removal Methods
7. Technology Screening Logic
8. Cost Estimating Relationship Profiles

Technology Profiles Index

Remediation Technology	Treatment Method[a]	Category[b]	Applicability[c]	Technology Profile	Technology Page No. (TP-)	CER Profile Page No. (CER-)[d]
Air Stripping	PC	C	4, 20	PC2	39	NA
Air Sparging	PC	I	1, 17, 22	PC1	36	NA
Asphalt/Concrete Cap	CR	C	27	CR1	166	NA
Base-Catalyzed Decomposition Process	PC	I	9, 14, 40	PC3a	42	57
Bioifilter	B	I	6b	B1	1	102
Biological Barrier	B	E	1, 7, 12, 17, 22	B2	4	NA
Biopile/Composting (Ordnance)	B	I	35	B3	6	46, 52
Biopile/Composting (Organics)	B	C	19, 24	B3	6	46, 52
Bioreactors	B	I	20, 25	B4	9	48
Bioreactors with Cometabolites	B	E	4, 10, 15	B4	9	48
Bioreactors with Specially Adapted Microorganisms	B	E	10, 15, 36	B4	9	48
Bioventing	B	C	18, 23	B6	15	NA
Chemical Leaching	PC	I	30	PC4	48	65
Chemical Oxidation (Organics)	PC	C	4, 10, 15, 20, 25, 36	PC6a	53	61
Chemical Reduction/Oxidation (Inorganics)	PC	C	31	PC5	51	NA
Circulating Wells	PC	E	1, 17	PC7	58	NA
Cometabolic Bioventing	B	E	2	B6	15	NA
Condensation	PC	C	6a, 6b	PC8	61	108
Confined Disposal Facilities	CR	C	3, 19, 24	CR2	169	31
Constructed Wetland	CM	I	4, 20, 25, 31, 36	CM1	154	42
Deep Soil Mixing	B	E	22	B6	18	NA
Drawdown Pumping	CR	C	38, 39	CR3	172	NA
Electrokinetic Extraction	PC	E	28, 29	PC9	63	NA
Enhanced In Situ Aerobic Bioremediation	B	I	22, 23	B5	12	28
Enhanced In Situ Aerobic Cometabolic Bioremediation	B	E	1, 7, 8	B5	12	28
Glycolate Dehalogenation	PC	I	9, 14, 40	PC3b	45	55
Granular Activated Carbon Absorption (Liquid Phase)	PC	C	4, 10, 15, 20, 25, 36	PC10a	65	NA
Granular Activated Carbon Adsorption (Vapor Phase)	PC	C	6a, 6b	PC10b	68	NA
In Situ Capping (Sediment) Contaminant	CR	C	5, 11, 16, 21, 26, 32, 37	CR4	176	NA
In Situ Heating – High Temperature (>100°C)	PC	I	7, 8, 12, 13, 23, 39	PC11	72	82, 88, 91
In Situ Heating – Low Temperature (<100°C)	PC	I	7, 8, 23, 39	PC30	135	84, 86

(a) B= Biological, CM = Combined Mechanism, CR = Containment or Removal, PC = Physical/Chemical.
(b) C = Conventional, E = Emerging, I = Innovative.
(c) Applicability indicated by cross reference to Tables of Remediation Technologies.
(d) NA = CER Profile not available.

Technology Profiles Index (continued)

Remediation Technology	Treatment Method[a]	Category[b]	Applicability[c]	Technology Profile	Technology Page No. (TP-)	CER Profile Page No. (CER-)[d]
In-Well Air Stripping	PC	I	1, 17	PC14	88	67
Incineration (On Site)	PC	C	9, 14, 24, 35, 40	PC15	91	NA
Ion Exchange	PC	C	31	PC17	97	59
Internal Combustion Engine	PC	C	6a	PC16	95	106
Land Application	B	C	19, 24	B8	20	NA
Land Tilling	B	I	23	B9	23	NA
Lasagna™ Process	CM	E	1	CM2	157	NA
Membrane Pervaporation (VOCs)	PC	E	4	PC19	103	NA
Membrane Separation (VOCs)	PC	E	6a, 6b	PC19	103	NA
Natural Attenuation	CM	I	1, 2, 5, 7, 8, 11, 12, 13, 16, 17, 18, 21, 22, 23, 26, 27, 28, 29, 32, 33, 34, 37	CM3	159	NA
Oxygen Release Compounds	B	E	17, 22	B5	12	28
Off-Site Disposal	CR	C	3, 9, 14, 19, 24, 30, 35	CR5	179	NA
Physical Separation	PC	C	30	PC23	114	76, 78
Phytoremediation	B	I	1, 2, 7, 8, 12, 13, 17, 18, 22, 23, 24, 27, 28, 29, 30, 33, 34	B10	26	44
Precipitation (Hydroxide or Sulfide)	PC	C	31	PC20	105	NA
RCRA Subtitle C and D Caps	CR	C	27	CR6	182	NA
Reverse Osmosis	PC	C	31	PC22	111	NA
Sequential Anaerobic/Aerobic Bioreactors	B	E	4, 10, 15, 36	B4	9	NA
Sequential Anaerobic/Aerobic Slurry-Phase Bioreactors	B	E	9, 14, 35	B11	30	50
Skimming	CR	C	38	CR7	186	69
Slurry-Phase Bioreactors	B	I	19, 24, 35	B11	30	50
Slurry-Phase Bioreactors with Cometabolites	B	E	3, 9, 14	B11	30	50
Slurry-Phase Bioreactors with Specially Adapted Microorganisms	B	E	3, 9, 14	B11	30	50
Soil Flushing	PC	I	8, 13, 23, 29, 34	PC24	117	NA
Soil Vapor Extraction (Ex Situ)	PC	I	3	PC25b	123	74
Soil Vapor Extraction (In Situ)	PC	C	2, 18	PC25a	120	NA
Soil Washing	PC	I	9, 14, 24, 30, 35	PC26	125	NA
Solidification/Stabilization (Ex Situ)	PC	C	30	PC12b	79	100
Solidification/Stabilization (In Situ)	PC	I	29	PC12a	76	94, 96, 98

(a) B= Biological, CM = Combined Mechanism, CR = Containment or Removal, PC = Physical/Chemical.
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(d) NA = CER Profile not available.

Technology Profiles Index (continued)

Remediation Technology	Treatment Method[a]	Category[b]	Applicability[c]	Technology Profile	Technology Page No. (TP-)	CER Profile Page No. (CER-)[d]
Solvent Extraction	PC	I	9, 14, 24, 35	PC28	130	63
Solvated Electron Treatment Process	PC	E	9, 14, 35, 40	PC27	128	NA
Sprinkler Irrigation	PC	I	4, 20	PC29	133	80
Surfactant-Enhanced Recovery	PC	E	1, 39	PC31	139	NA
Synthetic Resin Adsorption (Liquid Phase)	PC	E	4, 10, 20, 25	PC32	141	NA
Synthetic Resin Adsorption (Vapor Phase)	PC	E	6a, 6b	PC32	141	NA
Thermal/Catalytic Oxidation	PC	C	6a, 6b	PC33	143	NA
Thermal Desorption	PC	I	3, 9, 14, 19, 24	PC18	100	NA
Treatment Wall	PC	I	1, 7, 28, 33	PC21	108	NA
Two-Phase (Dual-Phase) Extraction	PC	I	1, 17	PC34	146	NA
Ultraviolet Light/Chemical Oxidation (Organics)	PC	I	4, 10, 15, 20, 25, 36	PC6b	55	NA
Ultraviolet Light Oxidation (Vapor Phase)	PC	I	6a, 6b	PC35	149	104
Use as Aggregate in Asphalt Mix	PC	C	19, 24, 30	PC36	151	NA
Vacuum-Enhanced Recovery (Bioslurping)	CM	I	38	CM4	162	NA
Vertical Cutoff Wall	CR	C	1, 7, 12, 17, 22, 27, 28, 33, 38, 39	CR8	189	38, 40
Vitrification (Ex Situ)	PC	I	30	PC13b	85	NA
Vitrification (In Situ)	PC	I	29	PC13a	82	NA
Water Harvesting Vegetation Cover	CR	I	27	CR9	192	NA
White-Rot Fungus Treatment	B	E	9, 14, 34, 35	B12	34	NA

(a) B= Biological, CM = Combined Mechanism, CR = Containment or Removal, PC = Physical/Chemical.
(b) C = Conventional, E = Emerging, I = Innovative.
(c) Applicability indicated by cross reference to Tables of Remediation Technologies.
(d) NA = CER Profile not available.

GLOSSARY OF ACRONYMS AND ABBREVIATIONS

APEG	alkaline polyethylene glycol
ATEG	potassium (or sodium) hydroxide tetraethylene glycol
BCD	base-catalyzed decomposition (process)
BTEX	benzene, toluene, ethylbenzene, and total xylenes
CAA	Clean Air Act
CDF	confined disposal facility
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFC	chlorofluorocarbon
CVOC	chlorinated volatile organic compound
CW	circulating well
DCE	dichloroethylene
DDT	dichlorodiphenyltrichloroethane
DMSO	dimethyl sulfoxide
DNAPL	dense, nonaqueous-phase liquid
GAC	granulated activated carbon
HDPE	high-density polyethylene
HE	high explosive(s)
HMX	high melting (or His Majesty's) explosive
ICE	internal combustion engine
ISV	in situ vitrification
JP-4	jet fuel 4
JP-5	jet fuel 5
KPEG	potassium polyethylene glycol
LNAPL	light, nonaqueous-phase liquid
N/A	not applicable
NAPL	nonaqueous-phase liquid
NCA	Noise Control Act
NPDES	National Pollution Discharge Elimination System
O&M	operations and maintenance
ORC	oxygen release compound
PAH	polycyclic aromatic hydrocarbon
PCB	polychlorinated biphenyl
PCE	perchloroethylene
PCP	pentachlorophenol
PEG	polyethylene glycol
ppm(v)	parts per million (by volume)
PVC	polyvinyl chloride

RBC	rotating biological contactor
RCRA	Resource Conservation and Recovery Act
RDX	research department (or Royal Demolition) explosive
redox	reduction/oxidation
RF	radiofrequency
SET™	solvated electron treatment
S/S	solidification/stabilization
SVE	soil vapor extraction
SVOC	semivolatile organic compound
TCA	trichloroethane
TCE	trichloroethylene
TCLP	Toxicity Characteristic Leaching Procedure
TI	technical impracticability
TNT	trinitrotoluene
TPH	total petroleum hydrocarbons
TSCA	Toxic Substances Control Act
UV	ultraviolet
VC	vinyl chloride
VOC	volatile organic compound
WBS	work breakdown structure

Remediation Technologies for Typical Contaminants and Media at Navy Remediation Sites

Typical Contaminants and Media at Navy Remediation Sites

(a) Contaminant: Halogenated Volatile Organic Compounds (VOCs)
Media: Groundwater - In Situ (Saturated Zone) (Table 1)
Vadose Zone Soils - In Situ (Table 2)
Excavated Soil and Dredged Sediments - Ex Situ (Table 3)
Groundwater - Ex Situ (Table 4)
Sediment - In Situ (Table 5)
Off-Gases (Table 6a)

(b) Contaminant: Halogenated Semivolatile Organic Compounds (SVOCs) and Pesticides
Media: Groundwater - In Situ (Saturated Zone) (Table 7)
Vadose Zone Soils - In Situ (Table 8)
Excavated Soil and Dredged Sediments - Ex Situ (Table 9)
Groundwater - Ex Situ (Table 10)
Sediment - In Situ (Table 11)

(c) Contaminant: Polychlorinated Biphenyls (PCBs)
Media: Groundwater - In Situ (Saturated Zone) (Table 12)
Vadose Zone Soils - In Situ (Table 13)
Excavated Soil and Dredged Sediments - Ex Situ (Table 14)
Groundwater - Ex Situ (Table 15)
Sediment - In Situ (Table 16)

(d) Contaminant: Nonhalogenated VOCs (includes gasoline and JP-4)
Media: Groundwater - In Situ (Saturated Zone) (Table 17)
Vadose Zone Soils - In Situ (Table 18)
Off-Gases (Table 6b)
Excavated Soil and Dredged Sediments - Ex Situ (Table 19)
Groundwater - Ex Situ (Table 20)
Sediment - In Situ (Table 21)

(e) Contaminant : Nonhalogenated SVOCs (includes diesel, JP-5, and other heavy fuels)
Media: Groundwater - In Situ (Saturated Zone) (Table 22)
Vadose Zone Soils - In Situ (Table 23)
Excavated Soil and Dredged Sediments - Ex Situ (Table 24)
Groundwater - Ex Situ (Table 25)
Sediment - In Situ (Table 26)

(f) **Contaminant:** Mixed (Landfill)
Media: Soil and Groundwater (Table 27)

(g) **Contaminant:** Inorganics
Media: Groundwater - In Situ (Saturated Zone) (Table 28)
Vadose Zone Soils - In Situ (Table 29)
Excavated Soil and Dredged Sediments - Ex Situ (Table 30)
Groundwater - Ex Situ (Table 31)
Sediment - In Situ (Table 32)

(h) **Contaminant:** Ordnance Compounds
Media: Groundwater - In Situ (Saturated Zone) (Table 33)
Vadose Zone Soils - In Situ (Table 34)
Excavated Soil and Dredged Sediments - Ex Situ (Table 35)
Groundwater - Ex Situ (Table 36)
Sediment - In Situ (Table 37)

(i) **Contaminant:** Light, Nonaqueous-Phase Liquid (Free-Phase LNAPL)
Media: Groundwater - In Situ (Saturated Zone) (Table 38)

(j) **Contaminant:** Dense, Nonaqueous-Phase Liquid (Free-Phase DNAPL)
Media: Groundwater - In Situ (Saturated Zone) (Table 39)

(k) **Contaminant:** Polycholrinated Biphenyls (PCBs)
Media: PCB Liquids (Table 40)

Technology Categories

Conventional – Technologies are in common use, and design and cost information is available.

Innovative – Technologies are proven but may not be in common use; however, design and cost information is available.

Emerging – Technologies are under field- or pilot-scale testing and evaluation, and show a high potential for advancing to the innovative category. Design and cost information for these technologies may not be available.

Remediation Technologies Tables

1. Contaminant: Halogenated VOCs
Media: Groundwater - In Situ (Saturated Zone)

Remediation Technology	Category	Secondary Process
Biological Treatment		
Biological Barrier	Emerging	NA
Enhanced In Situ Aerobic Cometabolic Biotreatment	Emerging	NA
Phytoremediation	Innovative	NA
Physical/Chemical Treatment		
Air Sparging (with Vapor Extraction)	Innovative	Off-gas treatment (when required)
Circulating Wells	Emerging	NA
In-Well Air Stripping	Innovative	Off-gas treatment (when required)
Treatment Wall	Innovative	NA
Surfactant-Enhanced Recovery	Emerging	NA
Two-Phase (Dual-Phase) Extraction	Innovative	Extracted groundwater and off-gas treatment
Combined Mechanism Treatment		
Lasagna™ Process	Emerging	NA
Natural Attenuation	Innovative	Long-term monitoring
Containment or Removal		
Vertical Cutoff Wall	Conventional	NA

2. Contaminant: Halogenated VOCs
Media: Vadose Zone Soils - In Situ

Remediation Technology	Category	Secondary Process
Biological Treatment		
Cometabolic Bioventing	Emerging	NA
Phytoremediation	Innovative	NA
Physical/Chemical Treatment		
Soil Vapor Extraction	Conventional	Off-gas treatment
Combined Mechanism Treatment		
Natural Attenuation	Innovative	Long-term monitoring

3. Contaminant: Halogenated VOCs
Media: Excavated Soil and Dredged Sediments - Ex Situ

Remediation Technology	Category	Secondary Process
Biological Treatment		
Slurry-Phase Bioreactors with Cometabolites	Emerging	NA
Slurry-Phase Bioreactors with Specially Adapted Microorganisms	Emerging	NA
Physical/Chemical Treatment		
Low-Temperature Thermal Desorption	Innovative	Off-gas treatment
Vapor Extraction (Ex Situ)	Innovative	Off-gas treatment
Containment or Removal		
Confined Disposal Facilities	Conventional	NA
Off-Site Disposal	Conventional	NA

4. Contaminant: Halogenated VOCs
Media: Groundwater - Ex Situ

Remediation Technology	Category	Secondary Process
Biological Treatment		
Bioreactor with Cometabolites	Emerging	NA
Sequential Anaerobic/Aerobic Bioreactors	Emerging	Sludge disposal
Physical/Chemical Treatment		
Air Stripping	Conventional	Groundwater pretreatment and off-gas treatment
Chemical Oxidation (Organics)	Conventional	Groundwater pretreatment
Ultraviolet Light (with Chemical Supplement) Oxidation (Organics)	Innovative	Groundwater pretreatment
Granular Activated Carbon Adsorption (Liquid Phase)	Conventional	Groundwater pretreatment; carbon disposal or regeneration
Membrane Pervaporation (VOCs)	Emerging	Groundwater pretreatment
Sprinkler Irrigation	Innovative	NA
Synthetic Resin Adsorption (Liquid Phase)	Emerging	Groundwater pretreatment; resin regeneration
Combined Mechanism Treatment		
Constructed Wetland	Innovative	Long-term monitoring

5. Contaminant: Halogenated VOCs
Media: Sediment - In Situ

Remediation Technology	Category	Secondary Process
Combined Mechanism Treatment		
Natural Attenuation	Innovative	Long-term monitoring
Containment or Removal		
In Situ Capping (Sediment)	Conventional	Long-term monitoring

6a. Contaminant: Halogenated VOCs, SVOCs, and PCBs
Media: Off-Gases

Remediation Technology	Category	Secondary Process
Physical/Chemical Treatment		
Condensation	Conventional	Solvent reuse or disposal
Granular Activated Carbon Adsorption (Vapor Phase)	Conventional	Carbon disposal or regeneration
Membrane Separation (VOCs)	Emerging	Treatment of concentrated stream
Synthetic Resin Adsorption (Vapor Phase)	Emerging	Resin regeneration
Thermal/Catalytic Oxidation	Conventional	NA
Ultraviolet Light Oxidation (Vapor Phase)	Innovative	NA

6b. Contaminant: Nonhalogenated VOCs and SVOCs
Media: Off-Gases

Remediation Technology	Category	Secondary Process
Biological Treatment		
Biofilter	Innovative	NA
Physical/Chemical Treatment		
Condensation	Conventional	Solvent reuse or disposal
Granular Activated Carbon Adsorption (Vapor Phase)	Conventional	Carbon disposal or regeneration
Internal Combustion Engine	Conventional	NA
Membrane Separation (VOCs)	Emerging	Treatment of concentrated stream
Synthetic Resin Adsorption (Vapor Phase)	Emerging	Resin regeneration
Thermal/Catalytic Oxidation	Conventional	NA
Ultraviolet Light Oxidation (Vapor Phase)	Innovative	NA

7. Contaminant: Halogenated SVOCs and Pesticides
Media: Groundwater - In Situ (Saturated Zone)

Remediation Technology	Category	Secondary Process
Biological Treatment		
Biological Barrier	Emerging	NA
Enhanced In Situ Aerobic Cometabolic Biotreatment	Emerging	NA
Phytoremediation	Innovative	NA
Physical/Chemical Treatment		
In Situ Heating – High Temperature (>100°C)	Innovative	Off-gas and water treatment
Treatment Wall	Innovative	NA
Steam/Water Heating – Low Temperature (<100°C)	Innovative	Off-gas and water treatment
Combined Mechanism Treatment		
Natural Attenuation	Innovative	Long-term monitoring
Containment or Removal		
Vertical Cutoff Walls	Conventional	NA

8. Contaminant: Halogenated SVOCs and Pesticides
Media: Vadose Zone Soils - In Situ

Remediation Technology	Category	Secondary Process
Biological Treatment		
Enhanced In Situ Aerobic Cometabolic Biotreatment	Emerging	NA
Phytoremediation	Innovative	NA
Physical/Chemical Treatment		
In Situ Heating – High Temperature (>100°C)	Innovative	Off-gas and water treatment
Soil Flushing	Innovative	Flushing solution recovery and treatment
Steam/Water Heating – Low Temperature (<100°C)	Innovative	Off-gas and water treatment
Combined Mechanism Treatment		
Natural Attenuation	Innovative	Long-term monitoring

9. Contaminant: Halogenated SVOCs and Pesticides
Media: Excavated Soil and Dredged Sediments - Ex Situ

Remediation Technology	Category	Secondary Process
Biological Treatment		
Sequential Anaerobic/Aerobic Slurry-Phase Bioreactors	Emerging	NA
Slurry-Phase Bioreactors with Cometabolites	Emerging	NA
Slurry-Phase Bioreactors with Specially Adapted Microorganisms	Emerging	NA
White-Rot Fungus Treatment	Emerging	NA
Physical/Chemical Treatment		
Base-Catalyzed Decomposition Process	Innovative	Off-gas treatment
Glycolate Dehalogenation	Innovative	Off-gas treatment
Incineration (On Site)	Conventional	Off-gas treatment
Thermal Desorption	Innovative	Off-gas treatment
Soil Washing	Innovative	Washing solution treatment
Solvated Electron Treatment Process	Emerging	NA
Solvent Extraction	Innovative	Solvent treatment
Containment or Removal		
Off-Site Disposal	Conventional	NA

10. Contaminant: Halogenated SVOCs and Pesticides
Media: Groundwater - Ex Situ

Remediation Technology	Category	Secondary Process
Biological Treatment		
Bioreactors with Cometabolites	Emerging	NA
Bioreactors with Specially Adapted Microorganisms	Emerging	NA
Sequential Anaerobic/Aerobic Bioreactors	Emerging	Sludge disposal
Physical/Chemical Treatment		
Chemical Oxidation (Organics)	Conventional	Groundwater pretreatment
Ultraviolet Light (with Chemical Supplement) Oxidation (Organics)	Innovative	Groundwater pretreatment
Granular Activated Carbon Adsorption (Liquid Phase)	Conventional	Groundwater pretreatment; carbon disposal or regeneration
Synthetic Resin Adsorption (Liquid Phase)	Emerging	Groundwater pretreatment; resin regeneration

11. Contaminant: Halogenated SVOCs and Pesticides
Media: Sediment - In Situ

Remediation Technology	Category	Secondary Process
Combined Mechanism Treatment		
Natural Attenuation	Innovative	Long-term monitoring
Containment or Removal		
In Situ Capping (Sediment)	Conventional	Long-term monitoring

12. Contaminant: PCBs
Media: Groundwater - In Situ (Saturated Zone)

Remediation Technology	Category	Secondary Process
Biological Treatment		
Biological Barrier	Emerging	NA
Phytoremediation	Innovative	NA
Physical/Chemical Treatment		
In Situ Heating – High Temperature (>100°C)	Innovative	Off-gas and water treatment
Combined Mechanism Treatment		
Natural Attenuation	Innovative	Long-term monitoring
Containment or Removal		
Vertical Cutoff Walls	Conventional	NA

13. Contaminant: PCBs
Media: Vadose Zone Soils - In Situ

Remediation Technology	Category	Secondary Process
Biological Treatment		
Phytoremediation	Innovative	NA
Physical/Chemical Treatment		
In Situ Heating – High Temperature (>100°C)	Innovative	Off-gas and water treatment
In Situ Vitrification	Innovative	Off-gas treatment
Soil Flushing	Innovative	Flushing solution recovery and treatment
Combined Mechanism Treatment		
Natural Attenuation	Innovative	Long-term monitoring

14. Contaminant: PCBs
Media: Excavated Soil and Dredged Sediments - Ex Situ

Remediation Technology	Category	Secondary Process
Biological Treatment		
Sequential Anaerobic/Aerobic Slurry-Phase Bioreactors	Emerging	NA
Slurry-Phase Bioreactors with Cometabolites	Emerging	NA
Slurry-Phase Bioreactors with Specially Adapted Microorganisms	Emerging	NA
White-Rot Fungus Treatment	Emerging	NA
Physical/Chemical Treatment		
Base-Catalyzed Decomposition Process	Innovative	Off-gas treatment
Glycolate Dehalogenation	Innovative	Off-gas treatment
Incineration (On Site)	Conventional	Off-gas treatment
Thermal Desorption	Innovative	Off-gas treatment
Soil Washing	Innovative	Washing solution treatment
Solvated Electron Treatment Process	Emerging	NA
Solvent Extraction	Innovative	Solvent treatment
Containment or Removal		
Off-Site Disposal	Conventional	NA

15. Contaminant: PCBs
Media: Groundwater - Ex Situ

Remediation Technology	Category	Secondary Process
Biological Treatment		
Bioreactors with Cometabolites	Emerging	NA
Bioreactors with Specially Adapted Microorganisms	Emerging	NA
Sequential Anaerobic/Aerobic Bioreactors	Emerging	Sludge disposal
Physical/Chemical Treatment		
Chemical Oxidation (Organics)	Conventional	Groundwater pretreatment
Ultraviolet Light (with Chemical Supplement) Oxidation (Organics)	Innovative	Groundwater pretreatment
Granular Activated Carbon Adsorption (Liquid Phase)	Conventional	Groundwater pretreatment; carbon disposal or regeneration

16. Contaminant: PCBs
Media: Sediment - In Situ

Remediation Technology	Category	Secondary Process
Combined Mechanism Treatment		
Natural Attenuation	Innovative	Long-term monitoring
Containment or Removal		
In Situ Capping (Sediment)	Conventional	Long-term monitoring

17. Contaminant: Nonhalogenated VOCs (including gasoline and JP-4)
Media: Groundwater - In Situ (Saturated Zone)

Remediation Technology	Category	Secondary Process
Biological Treatment		
Treatment Barrier	Emerging	NA
Oxygen Release Compounds	Emerging	NA
Phytoremediation	Innovative	NA
Physical/Chemical Treatment		
Air Sparging (with Vapor Extraction)	Innovative	Off-gas treatment (when required)
Circulating Wells	Emerging	
In-Well Air Stripping	Innovative	Off-gas treatment (when required)
Two-Phase (Dual-Phase) Extraction	Innovative	Extracted groundwater and off-gas treatment
Combined Mechanism Treatment		
Natural Attenuation	Innovative	Long-term monitoring
Containment or Removal		
Vertical Cutoff Wall	Conventional	NA

18. Contaminant: Nonhalogenated VOCs (including gasoline and JP-4)
Media: Vadose Zone Soils - In Situ

Remediation Technology	Category	Secondary Process
Biological Treatment		
Bioventing	Conventional	NA
Phytoremediation	Innovative	NA
Physical/Chemical Treatment		
Soil Vapor Extraction	Conventional	Off-gas treatment
Combined Mechanism Treatment		
Natural Attenuation	Innovative	Long-term monitoring

19. Contaminant: Nonhalogenated VOCs (including gasoline and JP-4)
Media: Excavated Soil and Dredged Sediments - Ex Situ

Remediation Technology	Category	Secondary Process
Biological Treatment		
Biopile/Composting	Conventional	Off-gas treatment (when required)
Land Application	Conventional	NA
Slurry-Phase Bioreactors	Innovative	NA
Physical/Chemical Treatment		
Thermal Desorption	Innovative	Off-gas treatment
Vapor Extraction (Ex Situ)	Innovative	Off-gas treatment
Use as Aggregate in Asphalt Mix	Conventional	NA
Containment or Removal		
Confined Disposal Facilities	Conventional	NA
Off-Site Disposal	Conventional	NA

20. Contaminant: Nonhalogenated VOCs (including gasoline and JP-4)
Media: Groundwater - Ex Situ

Remediation Technology	Category	Secondary Process
Biological Treatment		
Bioreactors	Innovative	NA
Physical/Chemical Treatment		
Air Stripping	Conventional	Groundwater pretreatment and off-gas treatment
Chemical Oxidation (Organics)	Conventional	Groundwater pretreatment
Ultraviolet Light (with Chemical Supplement) Oxidation (Organics)	Innovative	Groundwater pretreatment
Granular Activated Carbon Adsorption (Liquid Phase)	Conventional	Groundwater pretreatment; carbon disposal or regeneration
Sprinkler Irrigation	Innovative	Air monitoring
Synthetic Resin Adsorption (Liquid Phase)	Emerging	Groundwater pretreatment; resin regeneration
Combined Mechanism Treatment		
Constructed Wetland	Innovative	Long-term monitoring

21. Contaminant: Nonhalogenated VOCs (including gasoline and JP-4)
Media: Sediment - In Situ

Remediation Technology	Category	Secondary Process
Combined Mechanism Treatment		
Natural Attenuation	Innovative	Long-term monitoring
Containment or Removal		
In Situ Capping (Sediment)	Conventional	Long-term monitoring

22. Contaminant: Nonhalogenated SVOCs (including diesel fuel, JP-5, and other heavy fuels)
Media: Groundwater - In Situ (Saturated Zone)

Remediation Technology	Category	Secondary Process
Biological Treatment		
Biological Barrier	Emerging	NA
Enhanced In Situ Aerobic Biotreatment	Innovative	NA
Deep Soil Mixing	Emerging	NA
Oxygen Release Compounds	Emerging	NA
Phytoremediation	Innovative	NA
Physical/Chemical Treatment		
Air Sparging	Innovative	NA
Combined Mechanism Treatment		
Natural Attenuation	Innovative	Long-term monitoring
Containment or Removal		
Vertical Cutoff Wall	Conventional	NA

23. Contaminant: Nonhalogenated SVOCs (including diesel fuel, JP-5, and other heavy fuels)
Media: Vadose Zone Soils - In Situ

Remediation Technology	Category	Secondary Process
Biological Treatment		
Enhanced In Situ Aerobic Biotreatment	Innovative	NA
Bioventing	Conventional	NA
Land Tilling (shallow contamination)	Innovative	NA
Phytoremediation	Innovative	NA
Physical/Chemical Treatment		
In Situ Heating – High Temperature (>100°C)	Innovative	Off-gas and water treatment
Soil Flushing	Innovative	Flushing fluid recovery and treatment
Steam/Water Heating – Low Temperature (<100°C)	Innovative	Off-gas and water treatment
Combined Mechanism Treatment		
Natural Attenuation	Innovative	Long-term monitoring

24. Contaminant: Nonhalogenated SVOCs (including diesel fuel, JP-5, and other heavy fuels)
Media: Excavated Soil and Dredged Sediments - Ex Situ

Remediation Technology	Category	Secondary Process
Biological Treatment		
Biopile/Composting	Conventional	Off-gas treatment (when required)
Land Application	Conventional	NA
Phytoremediation	Innovative	NA
Slurry-Phase Bioreactors	Innovative	NA
Physical/Chemical Treatment		
Incineration (On site)	Conventional	NA
Thermal Desorption	Innovative	Off-gas treatment
Soil Washing	Innovative	Washing solution treatment
Solvent Extraction	Innovative	Solvent treatment
Use as Aggregate in Asphalt Mix	Conventional	NA
Containment or Removal		
Confined Disposal Facilities	Conventional	NA
Off-Site Disposal	Conventional	NA

25. Contaminant: Nonhalogenated SVOCs (including diesel fuel, JP-5, and other heavy fuels)
Media: Groundwater - Ex Situ

Remediation Technology	Category	Secondary Process
Biological Treatment		
Bioreactors	Innovative	NA
Physical/Chemical Treatment		
Chemical Oxidation (Organics)	Conventional	Groundwater pretreatment
Ultraviolet Light (with Chemical Supplements) Oxidation (Organics)	Innovative	Groundwater pretreatment
Granular Activated Carbon Adsorption (Liquid Phase)	Conventional	Groundwater pretreatment; carbon disposal or regeneration
Synthetic Resin Adsorption (Liquid Phase)	Emerging	Groundwater pretreatment; resin regeneration
Combined Mechanism Treatment		
Constructed Wetland	Innovative	Long-term monitoring

26. Contaminant: Nonhalogenated SVOCs (including diesel fuel, JP-5, and other heavy fuels)
Media: Sediment - In Situ

Remediation Technology	Category	Secondary Process
Combined Mechanism Treatment		
Natural Attenuation	Innovative	Long-term monitoring
Containment or Removal		
In Situ Capping (Sediment)	Conventional	Long-term monitoring

27. Contaminant: Mixed (Landfill)
Media: Soil and Groundwater

Remediation Technology	Category	Secondary Process
Biological Treatment		
Phytoremediation	Innovative	NA
Combined Mechanism Treatment		
Natural Attenuation	Innovative	Long-term monitoring
Water Harvesting Vegetative Cover	Emerging	Long-term monitoring
Containment or Removal		
Asphalt/Concrete Cap	Conventional	Long-term monitoring
RCRA Subtitle C and D Caps	Conventional	Long-term monitoring
Vertical Cutoff Walls	Conventional	NA

28. Contaminant: Inorganics
Media: Groundwater - In Situ (Saturated Zone)

Remediation Technology	Category	Secondary Process
Biological Treatment		
Phytoremediation	Innovative	NA
Physical/Chemical Treatment		
Electrokinetic Extraction	Emerging	Extracted groundwater treatment
Combined Mechanism Treatment		
Natural Attenuation	Innovative	Long-term monitoring
Treatment Wall	Innovative	NA
Containment or Removal		
Vertical Cutoff Wall	Conventional	NA

29. Contaminant: Inorganics
Media: Vadose Zone Soils - In Situ

Remediation Technology	Category	Secondary Process
Biological Treatment		
Phytoremediation	Innovative	NA
Physical/Chemical Treatment		
Electrokinetic Extraction	Emerging	Extracted groundwater treatment
Solidification/Stabilization (In Situ)	Innovative	NA
Vitrification (In Situ)	Innovative	Off-gas treatment
Soil Flushing	Innovative	Flushing solution recovery and treatment
Combined Mechanism Treatment		
Natural Attenuation	Innovative	Long-term monitoring

30. Contaminant: Inorganics
Media: Excavated Soil and Dredged Sediments - Ex Situ

Remediation Technology	Category	Secondary Process
Biological Treatment		
Phytoremediation	Innovative	NA
Physical/Chemical Treatment		
Chemical Leaching	Innovative	Extractant solution treatment
Physical Separation	Conventional	Treatment of residues
Soil Washing	Innovative	Washing solution treatment
Solidification/Stabilization (Ex Situ)	Conventional	NA
Use as Aggregate in Asphalt Mix	Conventional	NA
Vitrification	Innovative	Off-gas treatment
Containment or Removal		
Off-Site Disposal	Conventional	NA

31. Contaminant: Inorganics
Media: Groundwater - Ex Situ

Remediation Technology	Category	Secondary Process
Physical/Chemical Treatment		
Chemical Reduction/Oxidation (Inorganics)	Conventional	NA
Ion Exchange	Conventional	Disposal of resin or regeneration of chemicals
Precipitation (Hydroxide or Sulfide)	Conventional	Coagulation/flocculation; sludge management
Reverse Osmosis	Conventional	Treatment of retentate
Combined Mechanism Treatment		
Constructed Wetland	Innovative	Long-term monitoring

32. Contaminant: Inorganics
Media: Sediment - In Situ

Remediation Technology	Category	Secondary Process
Combined Mechanism Treatment		
Natural Attenuation	Innovative	Long-term monitoring
Containment or Removal		
In Situ Capping (Sediment)	Conventional	Long-term monitoring

33. Contaminant: Ordnance Compounds
Media: Groundwater - In Situ (Saturated Zone)

Remediation Technology	Category	Secondary Process
Biological Treatment		
Phytoremediation	Innovative	NA
Combined Mechanism Treatment		
Natural Attenuation	Innovative	Long-term monitoring
Treatment Wall	Innovative	NA
Containment or Removal		
Vertical Cutoff Wall	Conventional	NA

34. Contaminant: Ordnance Compounds
Media: Vadose Zone Soils - In Situ

Remediation Technology	Category	Secondary Process
Biological Treatment		
Phytoremediation	Innovative	NA
White-Rot Fungus (shallow contamination)	Emerging	NA
Physical/Chemical Treatment		
Soil Flushing	Innovative	Flushing solution recovery and treatment
Combined Mechanism Treatment		
Natural Attenuation	Innovative	Long-term monitoring

35. Contaminant: Ordnance Compounds
Media: Excavated Soil and Dredged Sediments - Ex Situ

Remediation Technology	Category	Secondary Process
Biological Treatment		
Biopile/Composting	Conventional	NA
Sequential Anaerobic/Aerobic Slurry-Phase Bioreactors	Emerging	NA
Slurry-Phase Bioreactors	Innovative	NA
White-Rot Fungus Treatment	Emerging	NA
Physical/Chemical Treatment		
Incineration (On Site)	Conventional	Off-gas treatment; ash management
Soil Washing	Innovative	Washing solution treatment
Solvated Electron Treatment Process	Emerging	NA
Solvent Extraction	Innovative	Solvent treatment
Containment or Removal		
Off-Site Disposal	Conventional	NA

36. Contaminant: Ordnance Compounds
Media: Groundwater - Ex Situ

Remediation Technology	Category	Secondary Process
Biological Treatment		
Bioreactor with Specially Adapted Microorganisms	Emerging	NA
Sequential Anaerobic/Aerobic Bioreactors	Emerging	Sludge disposal
Physical/Chemical Treatment		
Chemical Oxidation (Organics)	Conventional	Groundwater pretreatment
Ultraviolet Light (with Chemical Supplements) Oxidation (Organics)	Innovative	Groundwater pretreatment
Granular Activated Carbon Adsorption (Liquid Phase)	Conventional	Groundwater pretreatment; carbon disposal or regeneration
Combined Mechanism Treatment		
Constructed Wetland	Innovative	Long-term monitoring

37. Contaminant: Ordnance Compounds
Media: Sediment - In Situ

Remediation Technology	Category	Secondary Process
Combined Mechanism Treatment		
Natural Attenuation	Innovative	Long-term monitoring
Containment or Removal		
In Situ Capping (Sediment)	Conventional	Long-term monitoring

38. Contaminant: Light, Nonaqueous-Phase Liquid (Free-Phase LNAPL)
Media: Groundwater - In Situ

Remediation Technology	Category	Secondary Process
Combined Mechanism Treatment		
Vacuum-Enhanced Recovery (Bioslurping)	Innovative	Extracted groundwater treatment; off-gas treatment
Containment or Removal		
Drawdown Pumping	Conventional	Extracted groundwater treatment
Skimming	Conventional	NA
Vertical Cutoff Wall	Conventional	NA

39. Contaminant: Dense, Nonaqueous-Phase Liquid (Free-Phase DNAPL)
Media: Groundwater - In Situ

Remediation Technology	Category	Secondary Process
Physical/Chemical Treatment		
In Situ Heating – High Temperature (>100°C)	Innovative	Off-gas treatment
Steam/Water Heating – Low Temperature (<100°C)	Innovative	Groundwater treatment
Surfactant-Enhanced Recovery	Emerging	Groundwater treatment
Containment or Removal		
Drawdown Pumping	Conventional	Extracted groundwater treatment
Vertical Cutoff Wall	Conventional	NA

40. Contaminant: Polychlorinated Biphenyls (PCBs)
Media: PCB Liquids

Remediation Technology	Category	Secondary Process
Physical/Chemical Treatment		
Base-Catalyzed Decomposition Process	Innovative	PAH oil reuse or disposal
Glycolate Dehalogenation	Innovative	PAH oil reuse or disposal
Incineration (On Site)	Conventional	Off-gas treatment
Solvated Electron Treatment Process	Emerging	NA

Biological Technology Profiles Index

Remediation Technology	Treatment Method[a]	Category[b]	Applicability[c]	Technology Profile	Technology Page No. (TP-)	CER Profile Page No. (CER-)[d]
Bioifilter	B	I	6b	B1	1	102
Biological Barrier	B	E	1, 7, 12, 17, 22	B2	4	NA
Biopile/Composting (Ordnance)	B	I	35	B3	6	46, 52
Biopile/Composting (Organics)	B	C	19, 24	B3	6	46, 52
Bioreactors	B	I	20, 25	B4	9	48
Bioreactors with Cometabolites	B	E	4, 10, 15	B4	9	48
Bioreactors with Specially Adapted Microorganisms	B	E	10, 15, 36	B4	9	48
Bioventing	B	C	18, 23	B6	15	NA
Cometabolic Bioventing	B	E	2	B6	15	NA
Deep Soil Mixing	B	E	22	B6	18	NA
Enhanced In Situ Aerobic Bioremediation	B	I	22, 23	B5	12	28
Enhanced In Situ Aerobic Cometabolic Bioremediation	B	E	1, 7, 8	B5	12	28
Land Application	B	C	19, 24	B8	20	NA
Land Tilling	B	I	23	B9	23	NA
Oxygen Release Compounds	B	E	17, 22	B5	12	28
Phytoremediation	B	I	1, 2, 7, 8, 12, 13, 17, 18, 22, 23, 24, 27, 28, 29, 30, 33, 34	B10	26	44
Sequential Anaerobic/Aerobic Bioreactors	B	E	4, 10, 15, 36	B4	9	NA
Sequential Anaerobic/Aerobic Slurry-Phase Bioreactors	B	E	9, 14, 35	B11	30	50
Slurry-Phase Bioreactors	B	I	19, 24, 35	B11	30	50
Slurry-Phase Bioreactors with Cometabolites	B	E	3, 9, 14	B11	30	50
Slurry-Phase Bioreactors with Specially Adapted Microorganisms	B	E	3, 9, 14	B11	30	50
White-Rot Fungus Treatment	B	E	9, 14, 34, 35	B12	34	NA

(a) B = Biological.
(b) C = Conventional, E = Emerging, I = Innovative.
(c) Applicability indicated by cross reference to Tables of Remediation Technologies.
(d) NA = CER Profile not available.

B1: Biofilter

Abstract:

Biofiltration is a technology in which vapor-phase organic contaminants in an air stream are passed through a bed of porous support media where they partition into a thin water film on the media and are degraded by microorganisms.

Description:

Contaminated air is introduced into the bottom of a biofilter and moves up through the porous media that is wetted by water added on top of the media. Specific strains of bacteria may be introduced into the filter and optimal conditions may be provided to preferentially degrade specific compounds. The biofilter provides several potential advantages over conventional activated carbon adsorbers. First, bioregeneration keeps the maximum adsorption capacity available constantly; thus, the mass transfer zone remains stationary and relatively short. The filter does not require regeneration, and the required bed length is greatly reduced. These features reduce capital and operating expenses. Additionally, biofiltration both removes and destroys contaminants, unlike granular activated carbon (GAC) technologies which just remove contaminants.

Applicability:

Biofiltration is used primarily to treat aerobically biodegradeable compounds such as nonhalogenated volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs) in a gas stream. Halogenated VOCs and SVOCs also can be treated, but the process may be less effective. Additionally, biofilters have been successfully used to control odors from compost piles. Biofiltration typically is limited to treating off-gas containing between 100 and 2,000 ppmv of contaminants.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Potential for release of fugitive fungi.
- Low ambient air temperature, which may slow or stop biodegradation unless the biofilter is climate-controlled.

Status: Innovative

Operation and Maintenance Duration:

Biofiltration is used to treat off-gas from a primary treatment process. The operation and maintenance duration depends on the duration of the primary process operation.

Cost Range: $1.00 to $10.00 per pound of organic removed

The major cost items included in the cost estimate range for a biofilter are designated in Table B1-1.

Table B1-1. Major Cost Items to Implement a Biofilter

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Biofilter installation	Operating and maintenance labor Utilities Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
None	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.34.01 "Biofilter".

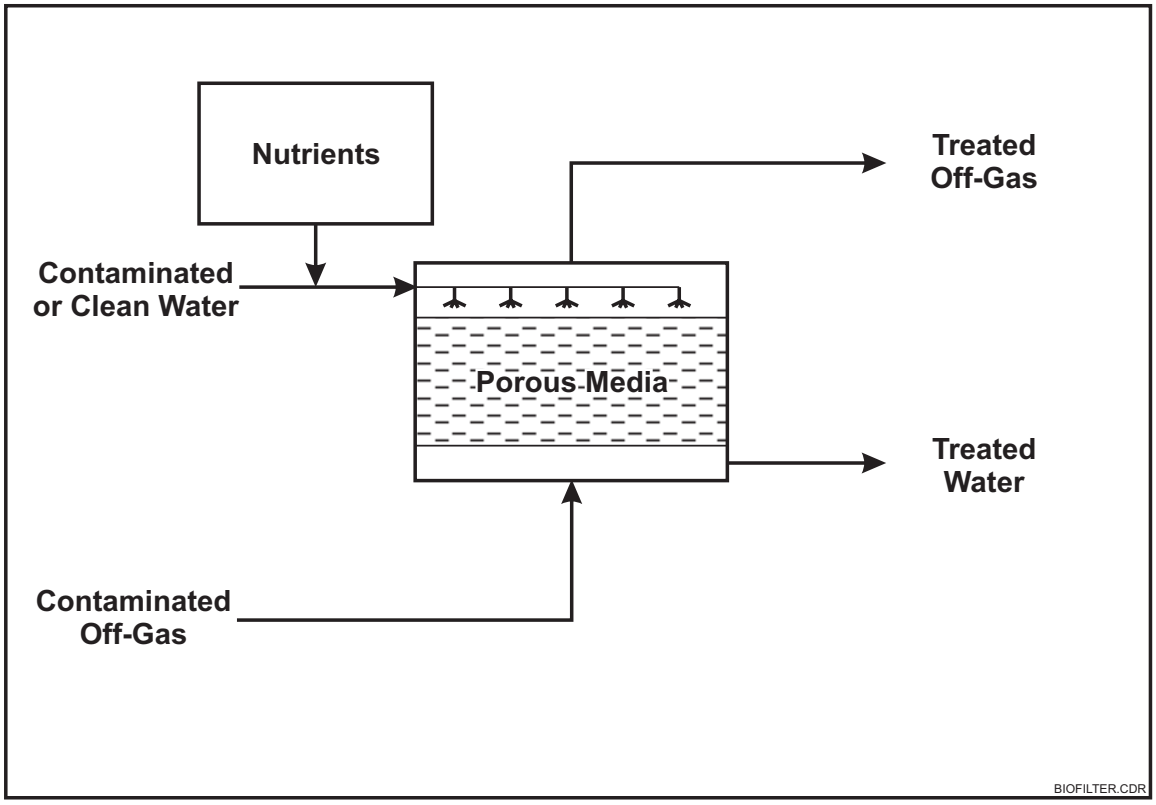


Figure B1. Biofilter

B2: Biological Barrier

Abstract:

Biological barrier technology is an in situ groundwater treatment method that involves installing a sorbent media that retains contaminants and allows biodegradation in a trench positioned to intercept and remediate a contaminant plume.

Description:

The biological barrier is installed across the flow path of a plume of contaminated groundwater, so that the plume moves through the barrier. The barrier consists of an excavated trench filled with a sorbent media that retards the movement of organics and supports microbes that biodegrade the sorbed organics. The barrier volume provides localized control of the in situ environment, by the addition of nutrients, co-substrates, and/or electron donors or acceptors, to optimize biodegradation.

Applicability:

The target contaminant groups for biological barriers are aerobically and anerobically biodegradeable compounds such as halogenated and nonhalogenated volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs) and polychlorinated biphenyls (PCBs).

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Very high contaminant concentrations may be toxic to microorganisms.
- Proximity of the plume to site boundaries or receptors.
- Depth and width of the contaminant plume.
- Cost of treatment medium.
- Generation of biomass, which may limit the permeability of the treatment barrier.
- Heavy metals are not treated by this method and can be toxic to microorganisms.

Status: Emerging

Operation and Maintenance Duration: N/A

Cost Range: N/A

The major cost items included in the cost estimate range for a biological barrier are designated in Table B2-1.

Table B2-1. Major Cost Items to Implement a Biological Barrier

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Barrier trench excavation	Site supervision
Media installation	Site quality assurance and health and safety support
Sampling well installation	Sampling and analysis for process control
Residuals Management Activities Included in Cost	
Off-site disposal of soil excavated to form media trench	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.21.01 "Biological Barriers".

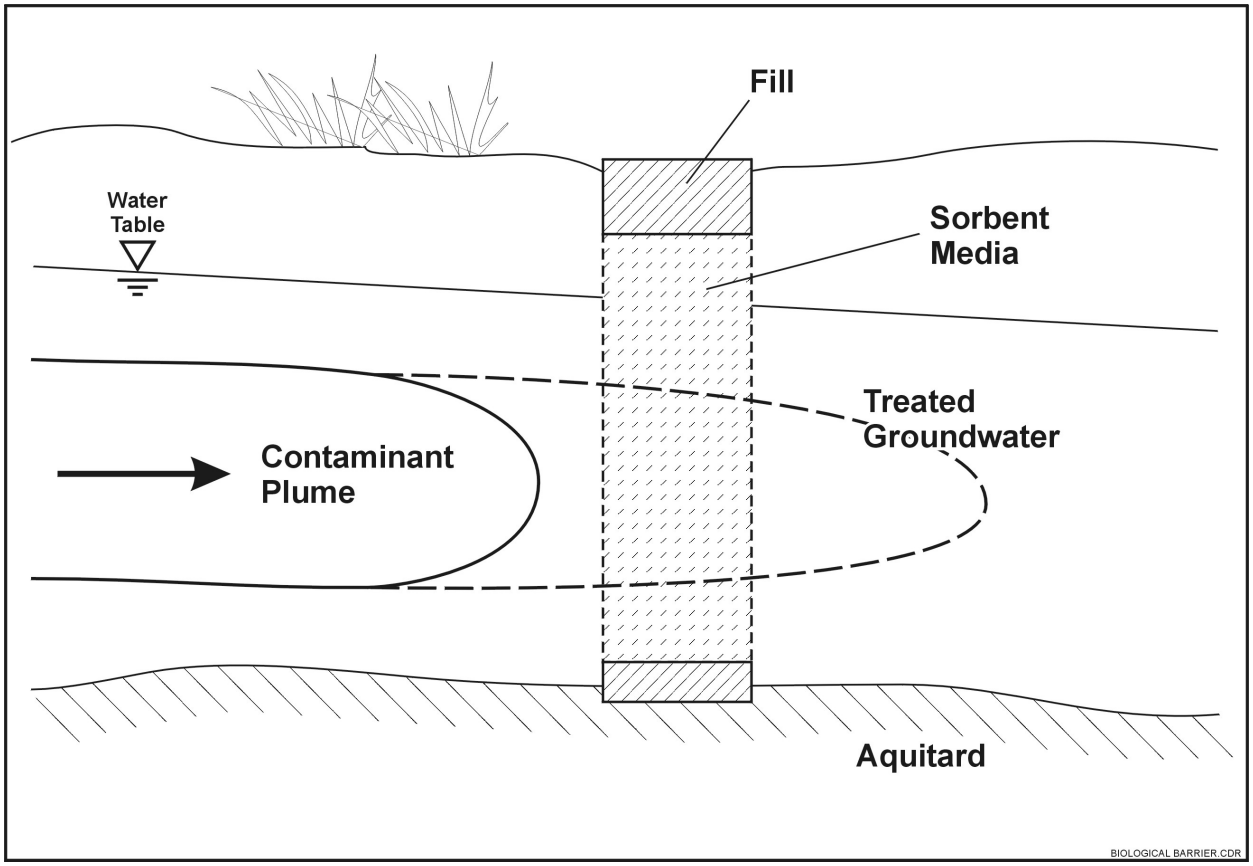


Figure B2. Cross-Sectional View of a Biological Barrier

B3: Biopile/Composting

Abstract:

Composting is a controlled, ex situ, solid-phase biological process for converting contaminants to low-toxicity byproducts.

Description:

The composting system is designed to provide optimum temperature, moisture content, aeration, and nutrient conditions to promote rapid biodegradation. In most cases, degradation is achieved by indigenous microorganisms. The compost system typically is operated so that material temperature rises as a result of heat released by biodegradation. Water content should be sufficiently high to support biological activity, but not so high as to completely fill pores and block air movement. Biopiles should be operated at a lower temperature than composting. Biopiles typically operate in the mesophilic range (<40°C [104°F]), whereas compost piles typically operate in the thermophillic range (40 to 50°C [104 to 122°F]). The material should have good structure and porosity to provide a high percentage of voids, to allow efficient air movement. Fertilizer is added to the soil to provide an optimum balance of carbon, nitrogen, and phosphorous. Bulking agents may be required if the soil porosity is low or recalcitrant contaminants (such as high explosive [HE] compounds) are being treated.

Composting can be performed using windrows, aerated static piles, or specially designed composting vessels. A windrow process involves forming long piles (windrows) turned by specially designed machines. Temperature and aeration are controlled by the natural convection currents in the windrow and the frequency of turning. The aerated static pile is constructed to allow forced air flow so that the oxygen supply can be more accurately controlled. The material is piled over perforated pipes connected to a blower to withdraw air from the pile. Contained vessel composting systems are tanks, boxes, or silos provided with equipment to aerate and mix the material. The contained systems typically allow treatment to be completed in less time than the windrow or aerated pile by providing better control of composting conditions. Rapid treatment time is offset by the high initial cost of the composting reactor.

Applicability:

Composting is used primarily to treat aerobically biodegradable organic compounds such as nonhalogenated volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs). Ordnance compounds also can be treated when the soil or sediment is mixed with a bulking agent.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Very high contaminant concentrations may be toxic to microorganisms.
- Air pollution controls may be needed to reduce emissions of volatile compounds from the compost pile.
- Substantial space may be required for static pile or windrow composting.
- Low ambient temperatures can decrease biodegradation rates.
- Composting may result in a volumetric increase if significant amounts of bulking agent are needed.
- Heavy metals are not treated by this method and can be toxic to microorganisms.
- Debris greater than 60 mm in diameter typically must be removed prior to processing.

Status: Conventional for nonhalogenated SVOCs and VOCs; innovative for ordnance compounds.

Operation and Maintenance Duration:

Biopile/composting is a short-term technology. Typical operating durations are 4 to 6 months per batch of contaminated soil. The size of the batch treated depends on the facility used. A temporary biopile typically can process about 500 cubic yards of material per batch. Permanent facilities process much larger batches. The duration of operation and maintenance for a batch is dependent on the following conditions:

- Cleanup goals
- Concentration of contaminants
- Proper temperature control, nutrient concentrations, and moisture content
- Even distribution of air.

Cost Range: $30 to $60 per cubic yard for treating VOCs and SVOCs
$100 to $300 per cubic yard for treating ordnance compounds

The major cost items included in the cost estimate range for biopile/composting are designated in Table B3-1.

Table B3-1. Major Cost Items to Implement Biopile/Composting Treatment

Pretreatment Activities Included in Cost	
Screening to remove debris	
Fixed Cost Items Included	**Variable Cost Items Included**
Base and vent system installation[(a)]	Soil excavation
Blower and off-gas treatment system installation[(a)]	Operating and maintenance labor
Base construction[(b)]	Utilities
Windrow turner purchase[(b)]	Nutrients and amendments
Composting vessel installation[(c)]	Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
On-site disposal of treated soil, sediment, or sludge	
Disposal of condensate to publicly owned treatment works via site sewer	
Off-gas treatment	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

(a) Items applicable for biopile or compost pile system.
(b) Items applicable for windrow system.
(c) Items applicable for in-vessel composting system.

WBS Correspondence: This technology corresponds to second and third level WBS elements X.22.03 "Biopile" and X.22.12 "Composting".

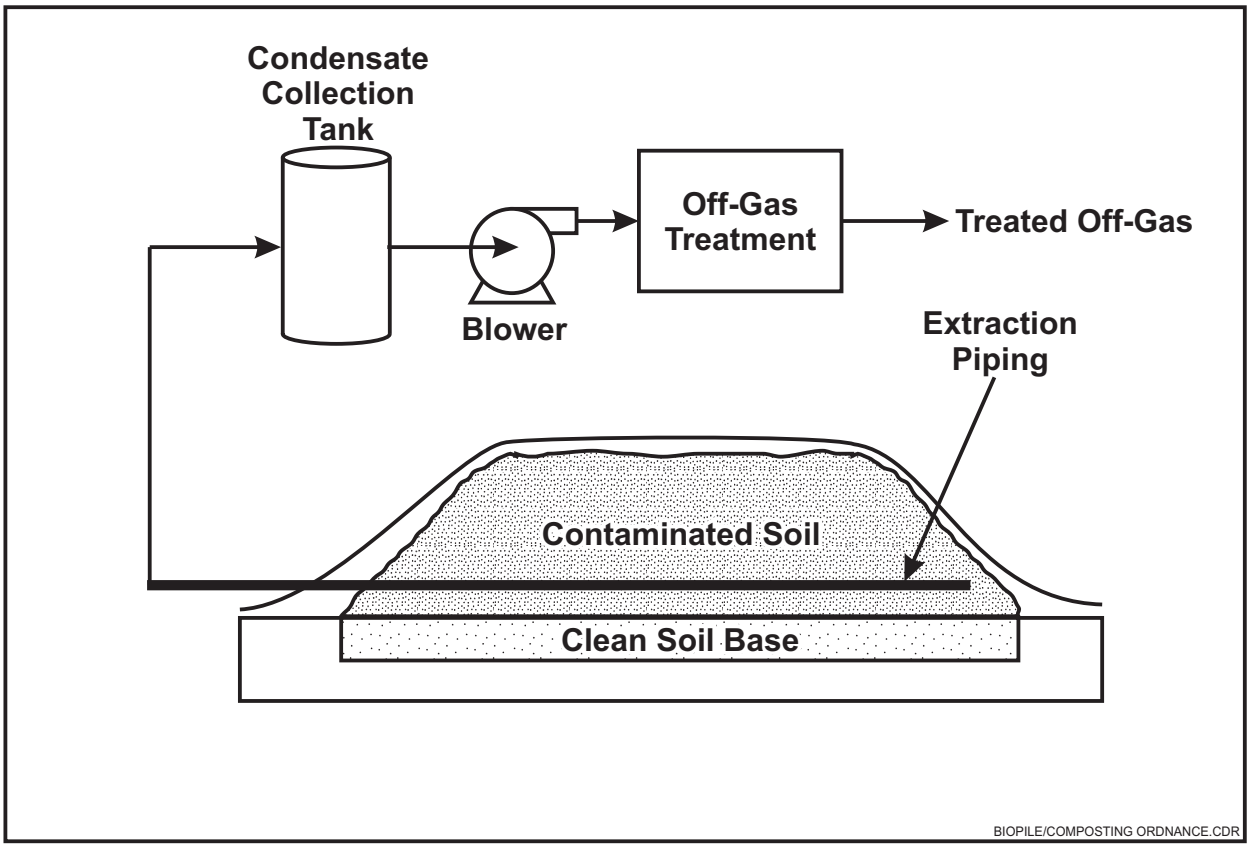


Figure B3. Biopile/Composting

B4: Bioreactors, Bioreactors with Cometabolites, Bioreactors with Specially Adapted Microorganisms, and Sequential Anaerobic/Aerobic Bioreactors

Abstract:

Bioreactors are ex situ biochemical-processing systems designed to degrade contaminants in pumped groundwater or wastewater using microorganisms.

Description:

Bioreactor treatment may be performed using microorganisms growing in suspension in the fluid or attached on a solid growth support medium. In suspended growth systems, such as fluidized beds or sequencing batch reactors, contaminated groundwater is circulated in an aeration basin where a microbial population aerobically degrades organic matter and produces carbon dioxide, water, and biomass. The biomass is settled out in a clarifier, then either recycled back to the aeration basin or disposed of as sludge. In attached growth systems, such as upflow fixed film bioreactors, rotating biological contactors (RBCs), and trickling filters, microorganisms are grown as a biofilm on a solid growth support matrix and water contaminants are degraded as they diffuse into the biofilm. Support media include solids that have a large surface area for bacterial attachment. Commonly, the support matrix is an adsorptive medium, such as activated carbon, that can adsorb contaminants and slowly release them to the microorganisms for degradation. Other support media include plastic or ceramic packing and even sands and gravels have been used. The microbial population may be derived from natural selection in the reactor, from an enrichment from the contaminated media, or from an inoculum of organisms with specific contaminant-degrading capabilities.

Applicability:

Bioreactors are used primarily to treat nonhalogenated volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs), including gasoline, diesel fuel, JP-4, JP-5, and heavy fuel oil in extracted groundwater. For more specialized applications such as treatment of polychlorinated biphenyls (PCBs), halogenated VOCs, and halogenated SVOCs in extracted groundwater, addition of cometabolites may be required to provide the microorganisms with a growth substrate and/or enzyme inducer. Bioreactors employing specially adapted microorganisms can be used to treat halogenated SVOCs, pesticides, PCBs, and ordnance compounds. Sequencing anaerobic/aerobic bioreactors is an innovative approach for treating halogenated VOCs, SVOCs, pesticides, PCBs, and ordnance compounds.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Residual biomass (sludge) may require additional treatment and/or specialized disposal.
- Very high contaminant concentrations may be toxic to microorganisms.
- Air pollution controls may be needed to reduce emission of volatile compounds from aerated and/or well mixed bioreactor systems.
- Low ambient temperatures can decrease biodegradation rates.
- Bioreactors can be prone to upset and nuisance microorganisms can predominate and reduce treatment effectiveness.

- Fixed film bioreactors may not be applicable for contaminants with low diffusivities due to mass transfer limitations.
- Heavy metals are not treated by this method and can be toxic to microorganisms.

Status: Conventional (bioreactors); emerging (bioreactors with cometabolites, bioreactors with adapted microorganisms, and sequential anaerobic/aerobic bioreactors)

Operation and Maintenance Duration:

Bioreactors are used to treat pumped groundwater or wastewater residual from a treatment process. The operation and maintenance duration depends on the duration of the primary process operation.

Cost Range:

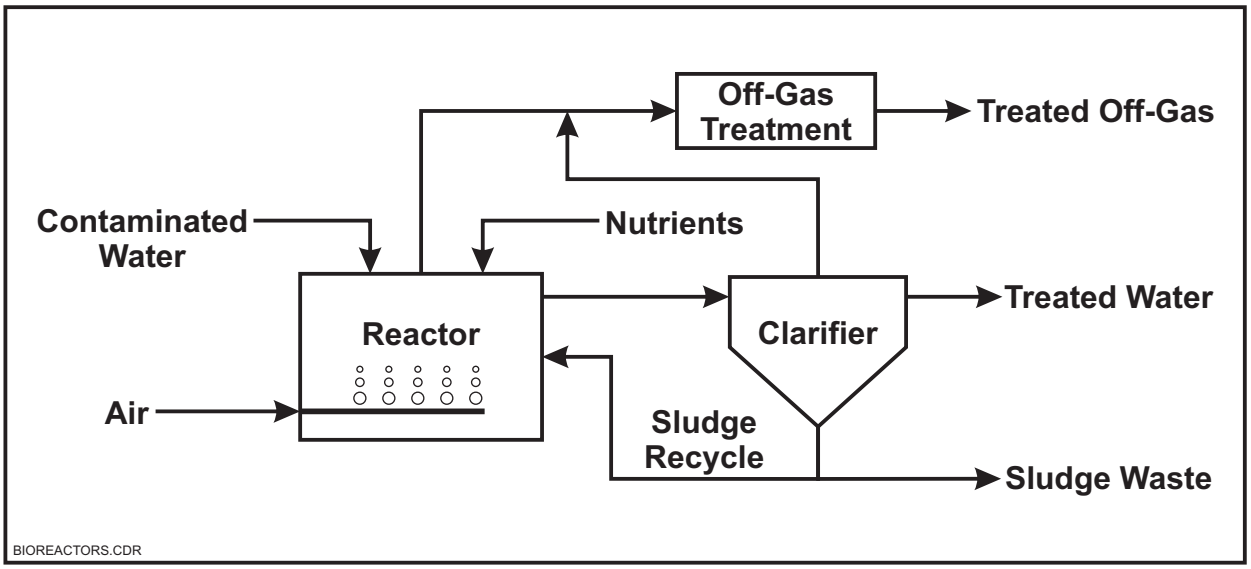
Capital, installation and setup, startup, and operation and maintenance costs associated with bioreactors can be significant and the economy of scale must be taken into account when considering using these technologies for treating contaminated groundwater. Bioreactors are more appropriate for treating larger volumes of water when contaminant destruction, not simply transfer to another medium, is required. Costs for bioreactor treatment should be competitive with alternative physical/chemical treatment technologies and should fall in the range of $0.50 to $3.00 per 1,000 gallons for mature bioreactor technology applications and $5.00 to $20.00 per 1,000 gallons for emerging bioreactor technology applications.

The major cost items included in the cost estimate range for bioreactor treatment are designated in Table B4-1.

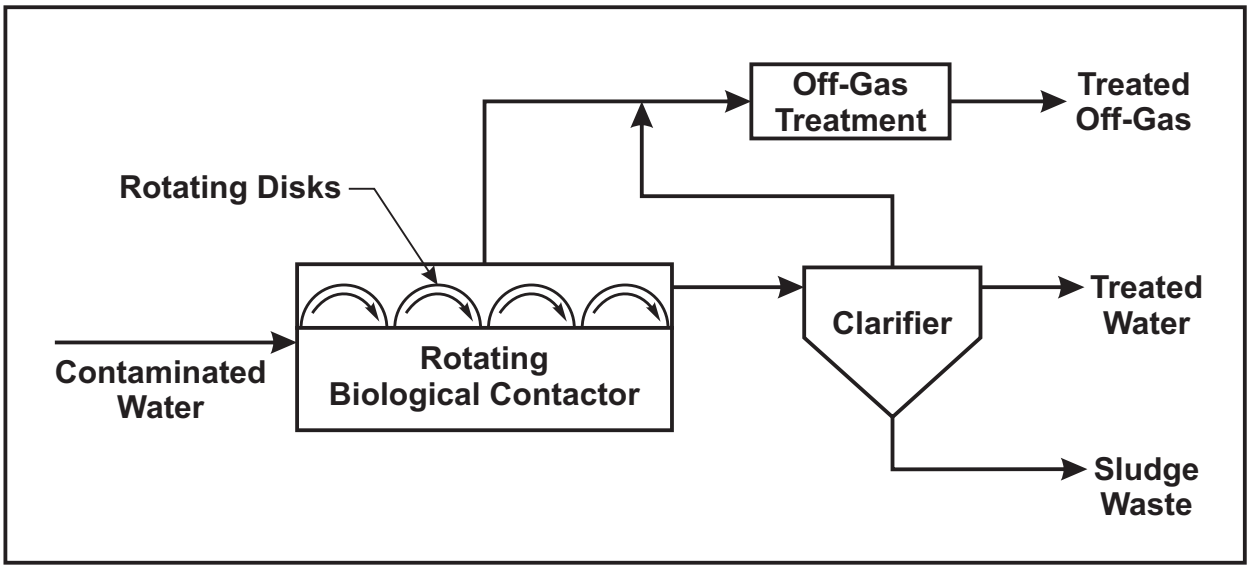
Table B4-1. Major Cost Items to Implement Bioreactor Treatment

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Bioreactor installation	Operating and maintenance labor
Clarifier installation	Utilities
Off-gas treatment system installation	Nutrients Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
Off-site disposal of sludge	
Disposal of treated water to publicly owned treatment works via site sewer	
Off-gas treatment	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.22.04 "Cometabolic Treatment", X.22.07 "Rotating Biological Contractors", X.22.09 "Trickling Filter", and X.22.10 "Biological Lagoons".



Suspended Growth



Attached Growth

Figure B4. Bioreactors

B5: Enhanced In Situ Aerobic Bioremediation/Enhanced In Situ Aerobic Cometabolic Bioremediation/Oxygen Release Compounds

Abstract:

Enhanced in situ aerobic bioremediation is the process of stimulating indigenous microorganisms to degrade contaminants in soil or groundwater.

Description:

Typically, the process involves delivery of oxygen to the aquifer and may require the addition of other nutrients and/or cometabolites. The amendments are circulated through the contaminated zone to provide mixing and intimate contact between the oxygen, nutrients, contaminant, and microorganisms. This contact is required to enhance the rate of aerobic biodegradation of the organic contaminants by the microorganisms distributed throughout the contaminated volume in the aquifer.

Common methods for oxygen delivery include air or oxygen sparging, injection of a dilute solution of hydrogen peroxide, or use of oxygen release compounds (ORCs) such as magnesium oxides. Some amendments such as the ORCs can be passively introduced in wells or trenches. Cometabolic biotreatment is unique in that a primary substrate must be added to support the growth of the microorganisms and promote degradation of contaminants.

Applicability:

Enhanced in situ aerobic bioremediation is used primarily to treat nonhalogenated semivolatile organic compounds (SVOCs) such as diesel fuel and heavy fuel oil. These contaminants readily and directly metabolizable and often require only oxygen addition to stimulate biodegradation. Cometabolic treatment is primarily used for chlorinated volatile organic compound (VOC) and SVOC contamination. Treatment of chlorinated solvents such as trichloroethylene (TCE) requires the addition of a cosubstrate such as methane, propane, or toluene. Cometabolic treatment of other SVOCs can require structural analogs for stimulation of contaminant degradation. The technology is applicable at sites where the aquifer characteristics are such as to allow effective delivery and mixing of the amendments, and where regulatory constraints do not preclude the technology.

Limitations:

The following factors may limit the applicability and effectiveness of the enhanced in situ biotreatment:

- Very high contaminant concentrations, which may be toxic to microorganisms.
- Concentrations of hydrogen peroxide greater than 100 to 200 ppm in groundwater inhibit the activity of microorganisms.
- Treatment fluid flow must be controlled to avoid contaminant escape from zones of active biodegradation.
- Subsurface heterogeneity can make it difficult to deliver amendments throughout the different zones of contamination, resulting in rapid remediation of the higher permeable zones and much slower remediation of the tighter zones where advective flow is limited.
- Low-permeability soils are difficult to treat.
- Both biotic and abiotic sinks for oxygen can increase costs and operation and maintenance duration.
- Iron precipitation and/or other changes in groundwater chemistry can cause permeability reductions and result in reduced ability to deliver amendments.

- Amended oxygen can be consumed very rapidly near the injection well, which creates two significant problems: biological growth can be limited to the region near the injection well, limiting adequate contamination/microorganism contact throughout the contaminated zone; and biofouling of wells can retard the input of nutrients.
- A surface treatment system, such as air stripping or carbon adsorption, may be required to treat extracted groundwater prior to re-injection or disposal
- Heavy metals are not treated by this method and can be toxic to microorganisms.

Status: Conventional (biotreatment of directly metabolizable contaminants); Emerging (cometabolic biotreatment).

Operations and Maintenance Duration:

The length of time required for treatment can range from 6 months to 5 years and is dependent on many site-specific factors, including the following:

- Cleanup goals
- The volume of in situ media requiring treatment
- Achievable biodegradation rates
- Contaminant concentrations and distribution
- In situ characteristics including permeability and anisotropy
- Presence of noncontaminant oxygen sinks
- Amendment delivery capacities.

Cost Range:

In many cases, enhanced in situ treatment can provide a more cost-effective alternative to pump-and-treat methods that employ technologies to achieve aboveground treatment. The costs are dependent on the specific requirements of installation such as the depth to, and the lateral extent of, the contaminant plume. The technology becomes more cost competitive with larger more concentrated plumes and when amendment delivery is not impeded by site constraints such as hydrogeologic considerations and/or surface logistical concerns such as buildings or other infrastructure. The cost for enhanced in situ biotreatment can range between $1 and $25 per pound of contaminant removed.

The major cost items included in the cost estimate range for enhanced in situ aerobic bioremediation are designated in Table B5-1.

Table B5-1. Major Cost Items to Implement Enhanced In Situ Aerobic Bioremediation

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Injection and extraction well and pump installation	Operating and maintenance labor
Sampling well installation	Utilities
Nutrient mixing equipment installation	Nutrients Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
None	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.21.04 "Cometabolic Treatment" and X.21.06 "Enhanced Bioremediation".

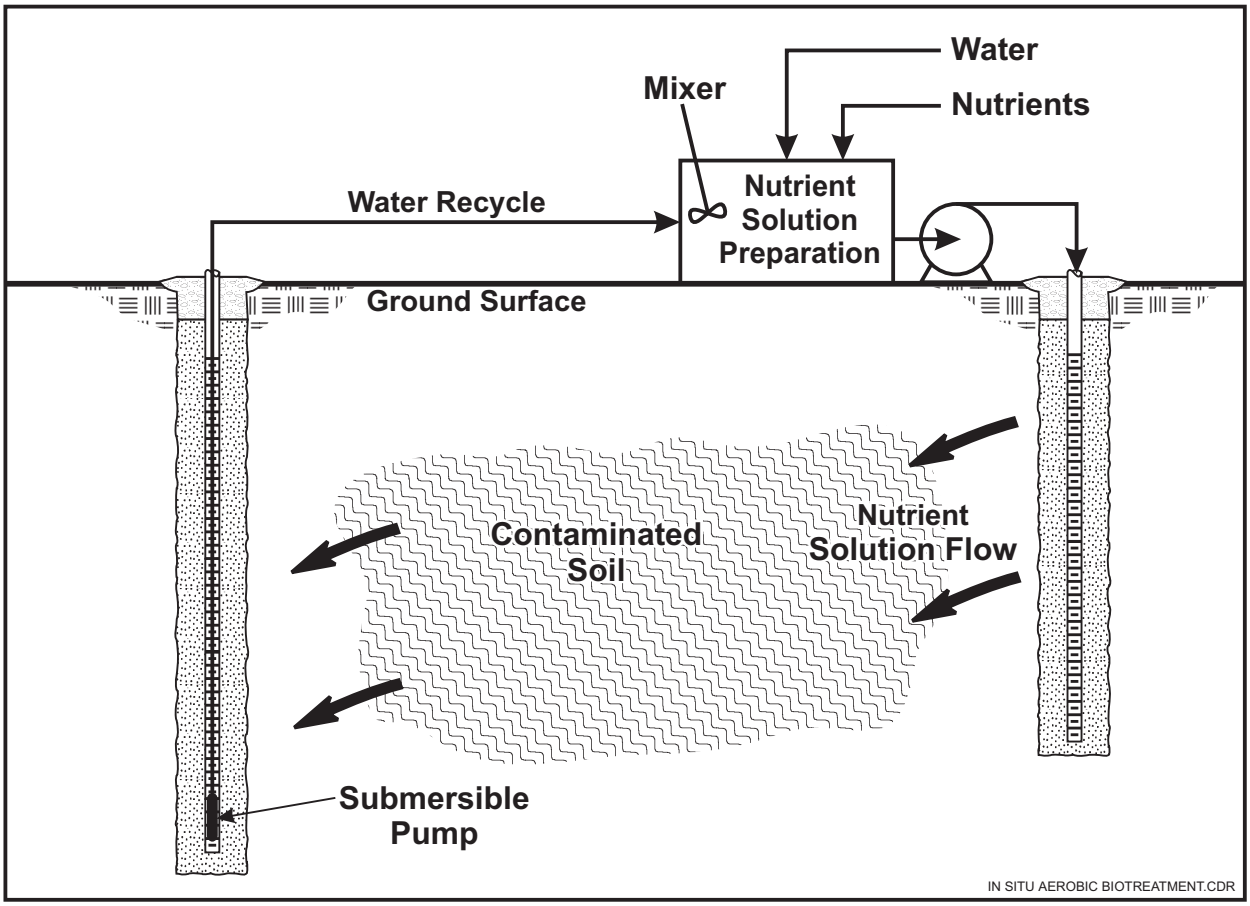


Figure B5. Enhanced In Situ Aerobic Bioremediation

B6: Bioventing and Cometabolic Bioventing

Abstract:

Bioventing is an in situ soil treatment technology that involves stimulating the natural in situ biodegradation of petroleum hydrocarbons in soil by providing oxygen to existing soil microorganisms.

Description:

During bioventing the oxygen concentration in the soil gas is increased by injecting air into the contaminated zone through drilled wells. In a few cases some air extraction wells may be used to control vapor migration. In contrast to soil vapor extraction, bioventing uses low airflow rates to provide only enough oxygen to sustain microbial activity. Oxygen is most commonly supplied by directing air flow through residual contamination in soil. In addition to degradation of adsorbed fuel residuals, volatile compounds are biodegraded as vapors move slowly through biologically active soil. Gaseous substrates can be added with the air to promote cometabolic degradation of recalcitrant compounds.

Applicability:

Conventional bioventing techniques are used primarily to treat aerobically biodegradable compounds such as nonhalogenated volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs). Compounds that have been successfully remediated include petroleum hydrocarbons, nonchlorinated solvents, some pesticides, and wood preservatives.

Cometabolic bioventing is applicable to contaminants such as trichloroethylene (TCE), trichloroethane (TCA), ethylene dibromide, and dichloroethylene (DCE) that resist direct aerobic degradation.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Very high contaminant concentrations may be toxic to microorganisms.
- Subsurface heterogeneity can interfere with efficient aeration of the contaminated zone.
- Low-permeability soils are difficult to treat.
- The presence of the water table within several feet of the surface can reduce bioventing performance.
- Vapors can build up in basements within the radius of influence of air injection wells, a problem that can be alleviated by extracting air near the structure of concern.
- Low soil moisture content may limit biodegradation and the effectiveness of bioventing, which tends to dry out the soils.
- Off-gas monitoring at the soil surface may be required when soils are aerated through air injection.
- Aerobic biodegradation of many chlorinated compounds may not be effective unless either a co-metabolite is present or an anaerobic cycle is used.
- Low ambient temperatures can significantly decrease biodegradation rates.
- Heavy metals are not treated by this method and can be toxic to microorganisms.

Status: Conventional for bioventing; emerging for cometabolic bioventing.

Operation and Maintenance Duration:

Bioventing is a medium- to long-term technology. Cleanup ranges from 6 months to 5 years. The duration of operation and maintenance is dependent on the following conditions:

- Cleanup goals
- The volume of in situ media requiring treatment
- Contaminant concentrations and distributions
- Achievable biodegradation rates
- In situ characteristics including permeability and anisotropy.

Cost Range: $10 to $50 per cubic yard

The major cost items included in the cost estimate range for bioventing and cometabolic bioventing are designated in Table B6-1.

Table B6-1. Major Cost Items to Implement Bioventing and Cometabolic bioventing

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Air injection wells and blowers installation	Operating and maintenance labor
Substrate injection system installation[(a)]	Utilities
Monitoring point installation	Cometabolic substrate[(a)] Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
None	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

(a) Items applicable to cometabolic bioventing only.

WBS Correspondence: This technology corresponds to second and third level WBS elements X.21.03 "Bioventing".

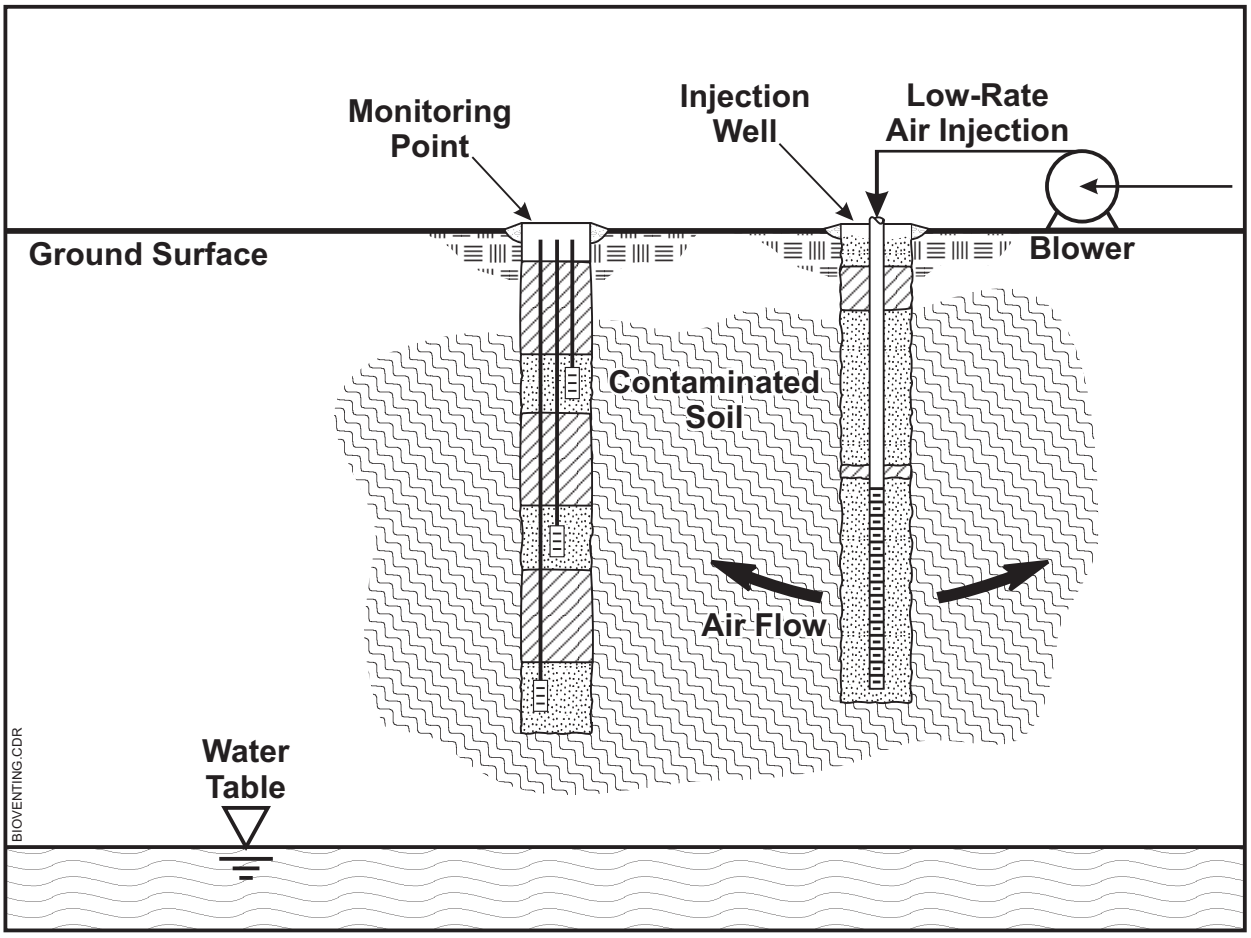


Figure B6. Bioventing

B7: Deep Soil Mixing

Abstract:

Deep soil mixing is an in situ soil biotreatment technology that involves aggressive mixing of biological treatment agents with the contaminated media.

Description:

The deep soil mixing process uses an auger system to drill down into the contaminated soil. The augers are equipped with nozzles that inject a solution into the soil while breaking up and mixing the soil. The solution contains biotreatment agents, such as oxygen release compounds (ORCs), nutrients, and microorganisms. Oxygen, water, nutrients, and/or natural bacteria, if required, are mixed into the contaminated soil as determined by a site-specific laboratory program. The soil and fluid are homogenized by the simultaneous mixing and drilling. Soil strata and pockets of contaminated soil that would otherwise remain untreated are broken up. Drilling equipment can reach a depth of 100 ft or more. The deep soil mixing technology increases the quality and acceleration of biodegradation in deep contaminated soils without the need for excavation and disposal of excavated material.

Applicability:

Deep soil mixing can be used to treat a wide variety of waste types in a number of different media. The different types of media currently treated include in situ soil and sludge. The deep soil mixing technology potentially may be applied in natural sediment; in situ groundwater; in situ dense, nonaqueous-phase liquid (DNAPL); and in situ light, nonaqueous-phase liquid (LNAPL). The different types of contaminant groups presently treated with the deep soil mixing technology include halogenated volatiles; halogenated semivolatiles; nonhalogenated volatiles; nonhalogenated semivolatiles; organic pesticides; herbicides; solvents; and benzene, toluene, ethylbenzene, and total xylenes (BTEX). This technology may potentially be applied to dioxins/furans; polychlorinated biphenyls (PCBs); polynuclear aromatic hydrocarbons (PAHs); and organometallic pesticides/herbicides.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Very high contaminant concentrations may be toxic to microorganisms.
- Large buried objects (i.e., large concrete slabs and large rocks over 18 inches) may limit the process's ability to treat 100 percent of a contaminated area.
- Treatment fluid injection and mixing must be controlled to minimize the spread of contaminants to clean areas.
- Heavy metals are not treated by this method and can be toxic to microorganisms.

Status: Emerging

Operation and Maintenance Duration: N/A

Cost Range: N/A

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.21.9X "Other".

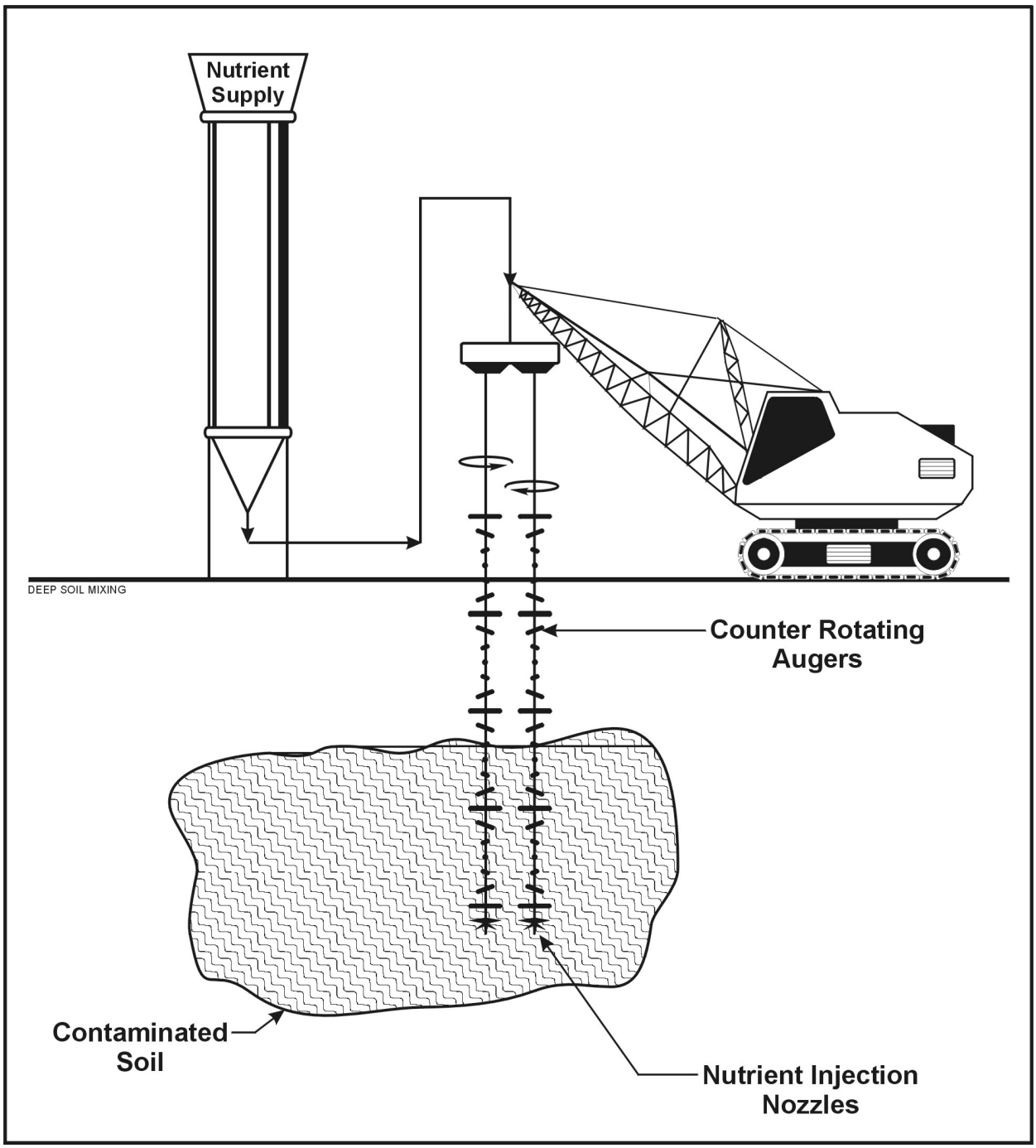


Figure B7. Deep Soil Mixing

B8: Land Application

Abstract:

Land application is an ex situ, solid-phase biotreatment technology that involves using agricultural practices to promote biodegradation of organic contaminants.

Description:

The principle behind land application technology is simple. Waste that contains low concentrations of organic contaminants is spread over a large area and is allowed to interact with the soil and climate at the site. The soil is turned periodically using equipment such as a plow or disk to expose new surfaces and aerate the matrix. Waste, soil, climate, and biological agents interact dynamically as a system to degrade, transform, and immobilize waste constituents.

Any land application site must be managed properly to prevent both on-site and off-site problems with contamination of groundwater, surface water, air, or the food chain. Leachate collection, fugitive dust emission control, adequate monitoring, and environmental safeguards are required.

Applicability:

Land application is used primarily to treat aerobically biodegradable compounds such as nonhalogenated volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs).

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Very high contaminant concentrations may be toxic to microorganisms.
- The method is not suitable for treating high hazard or toxic contaminants.
- A large amount of space is required.
- Runoff collection facilities must be constructed and monitored.
- Fine particulate in the soil may cause dust generation when tilling dry soil.
- Topography, erosion, climate, soil stratigraphy, and permeability of the soil at the site must be evaluated to determine the optimum design of the facility.
- Heavy metals are not treated by this method and can be toxic to microorganisms.
- Debris greater than 60 mm in diameter typically must be removed prior to processing.

Status: Conventional

Operation and Maintenance Duration:

Land application is a medium- to long-term technology. Operation and maintenance duration for land application ranges from 6 months to 5 years. The duration of operation and maintenance is dependent on the following conditions:

- Cleanup goals
- Concentration and types of contaminants
- Climate (i.e., temperature, winds, and rain)

- Degradation rates
- Tilling frequency.

Cost Range: $40 to $80 per cubic yard with minimal leachate control
$135 to $270 per cubic yard with extensive leachate control and treatment

The major cost items included in the cost estimate range for land application are designated in Table B8-1.

Table B8-1. Major Cost Items to Implement Land Application

Pretreatment Activities Included in Cost	
Screening to remove debris	
Fixed Cost Items Included	**Variable Cost Items Included**
Tilling and fertilizing equipment purchase	Soil excavation
Land acquisition	Operating and maintenance labor
Leachate collection system installation (if required)	Irrigation water Nutrients Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
None	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds in part to the second and third level WBS elements X.22.06 "Land Farming".

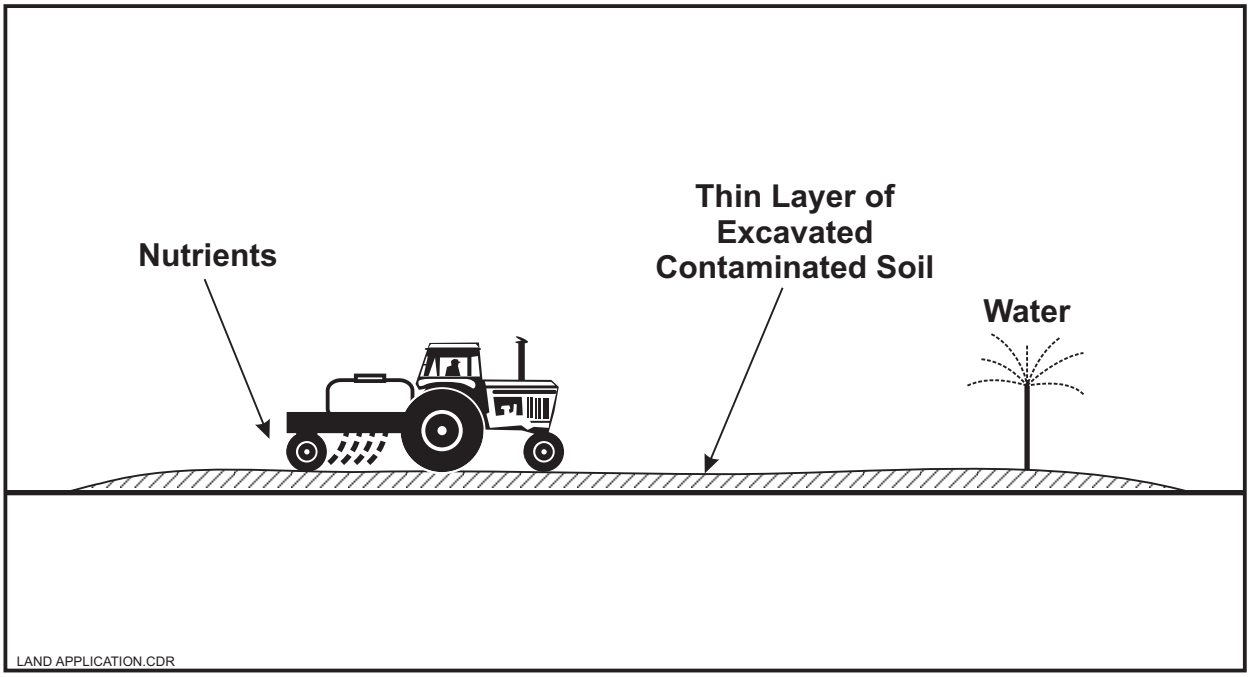


Figure B8. Land Application

B9: Land Tilling

Abstract:

Land tilling is an in situ soil biotreatment technology that involves using agricultural practices to promote biodegradation of organic contaminants.

Description:

Land tilling is a full-scale bioremediation technology in which shallow layers of contaminated soils, sediments, or sludges are periodically turned over or tilled to aerate the waste matrices. The conditions of the waste matrices are often controlled to optimize the biodegradation rate of associated contaminants. Conditions normally controlled include the following:

- Moisture content (usually by irrigation or spraying)
- Oxygen level (by mixing the soil using tilling or aerating)
- Nutrients, primarily nitrogen and phosphorus (by fertilizing)
- pH (increased slightly by adding lime)
- Soil bulking (by adding soil amendments and by mixing using tilling or aerating).

Applicability:

Land tilling is used primarily to treat aerobically biodegradable compounds such as nonhalogenated semivolatile organic compounds (SVOCs).

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Very high contaminant concentrations may be toxic to microorganisms.
- The method is not suitable for treating deep contamination.
- The method is not suitable for treating high hazard or toxic contaminants.
- Conditions advantageous for biological degradation of contaminants are largely uncontrolled, which increases the length of time to complete remediation, particularly for recalcitrant compounds.
- Low ambient temperatures can decrease biodegradation rates.
- Reduction of VOC contaminant concentrations may be caused more by volatilization than biodegradation.
- Fine particulate in the soil may cause dust generation when tilling dry soil.
- Heavy metals are not treated by this method and can be toxic to microorganisms.

Status: Innovative

Operation and Maintenance Duration:

Land tilling is a medium- to long-term technology. Operation and maintenance duration for land tilling will vary from 6 months to 5 years. The duration of operation and maintenance is dependent on the following conditions:

- Cleanup goals
- The volume of in situ media requiring treatment
- Contaminant concentrations and distribution
- Achievable biodegradation rate, which is dependent on moisture content, oxygen concentration and distribution, nutrient concentration, and pH
- Tilling frequency
- Climate (i.e., temperature, winds, and rain).

Cost Range: $30 to $70 per cubic yard

The major cost items included in the cost estimate range for land tilling are designated in Table B9-1.

Table B9-1. Major Cost Items to Implement Land Tilling

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Tilling and fertilizing equipment purchase	Operating and maintenance labor Irrigation water Nutrients Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
None	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.21.07 "Land Treatment".

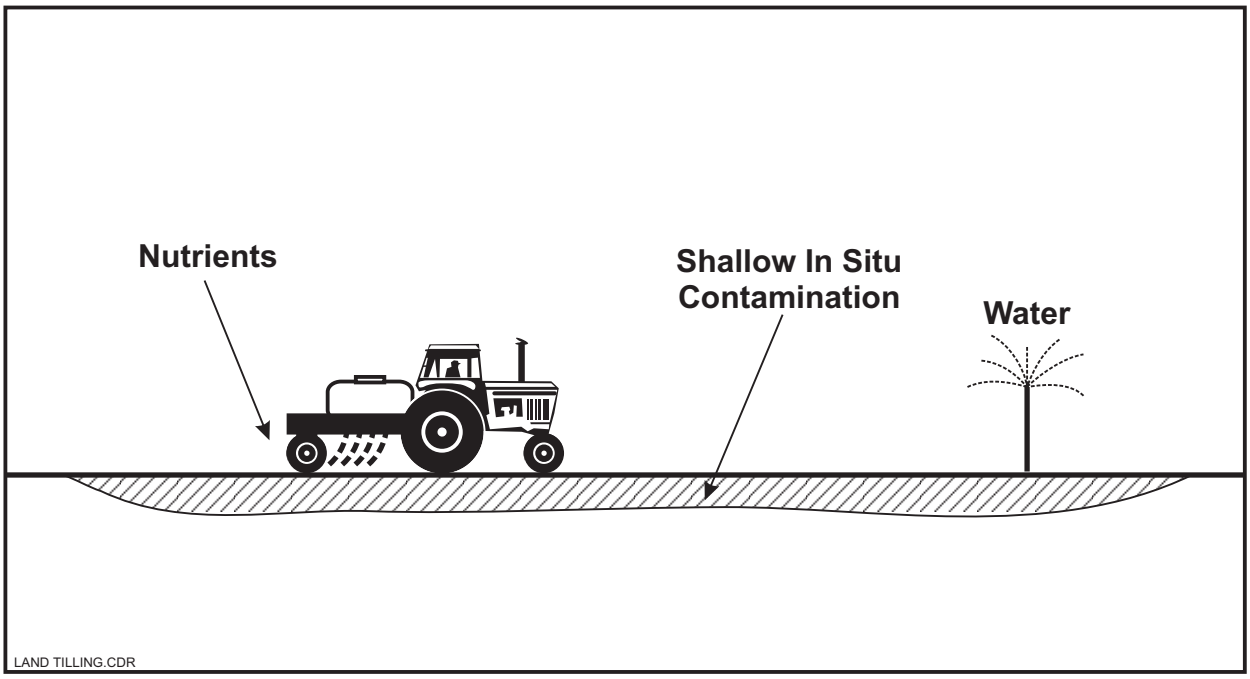


Figure B9. Land Tilling

B10: Phytoremediation

Abstract:

Phytoremediation is a soil and groundwater treatment technology that uses vegetation and its associated microbiota, soil amendments, and agronomic techniques to remove, contain, or reduce the toxicity of environmental contaminants. It is generally used as an in situ technology, but can also be used ex situ.

Description:

Phytoremediation is implemented by establishing a plant or community of plants that have been selected to provide the required remediation mechanisms. The technology exploits the natural hydraulic and metabolic processes of plants, and thus is passive and solar driven. The technology can be used in combination with mechanical treatment methods or as a "stand alone" treatment method.

Types of Phytoremediation:

Stabilization Processes

- Phytostabilization – The use of plants to increase sequestration of contaminants (usually metals) in the soil. Soil sequestration occurs as plants alter water flux and reduce contaminant mobility. Plants and microbial enzymes bind contaminants into soil (humification). Plants also incorporate free contaminants into plant roots (lignification) and prevent wind and water erosion.

Removal Processes

- Phytoaccumulation/Phytoextraction – Specific species of plants are used to absorb unusually large amounts of metals from the soil and are subsequently harvested from the growing area. The biomass is composted to recycle the metals or incinerated and the ash is sent to a landfill. Typically used for remediation of metals-contaminated soils, sediments, and groundwater.
- Rhizofiltration – Similar to phytoextraction; however, plant root systems usually are first developed to maturity in an aqueous environment within a green house. When the root system is developed, contaminated water (generally with metal contamination) is brought to the plants and circulated through their water supply.
- Phytodegradation – The process where plant enzymes completely mineralize or partially break down contaminant compounds.
- Rhizo(sphere)degradation – The symbiotic relationship that occurs between plant root systems and microorganisms in the root zone. Plant roots excrete sugars, acids, and alcohols that contain organic carbon that microorganisms use as a food source. This provision enhances microbial activity in the root zone, resulting in a microbial contribution to soil contaminant degradation.
- Organic Pumps – The use of plants to control the migration of contaminants in the groundwater by exploiting their natural hydraulic properties. Using trees for water control is estimated to cost approximately one half the cost of traditional pump-and-treat systems.
- Phytovolatilization – The use of plants to remove contaminants from the subsurface and evaporate or volatilize the contaminants from the leaf surface of the plant once it has traveled through the plant's system.

Applicability:

Phytoremediation can be used to treat a wide range of organic and inorganic contaminants. Phytoremediation has been effective for the removal of nitrates and ammonium from the groundwater. All plants require a nitrogen source to grow. Some nitrogen-containing contaminants can be used by the plants for plant growth.

Sites contaminated with heavy metals can be remediated using phytoremediation. Accumulation usually results in 1% Cu and Co and 3% Zn, Ni, Mn on a dry weight basis. The use of hyperaccumulating plants is in the beginning stages and further research is required to develop plants with greater biomass.

Phytoremediation may be useful in treating volatile organic compounds (VOCs), chlorinated VOCs (CVOCs), and trinitrotoluene (TNT). The technology is in its infancy for the treatment of contaminants of these types. Projects that target organic contaminants, such as trichloroethylene (TCE) and TNT, in the water phase have shown some promise; however, more research is needed for the less-mobile contaminants, such as polychlorinated biphenyls (PCBs) and polynuclear aromatic hydrocarbons (PAHs).

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Employing specific plant species to target particular contaminants at a site can be difficult because of adaptability problems.
- Climatic or seasonal conditions may interfere with or inhibit plant growth, slow remediation efforts, or increase the length of the treatment period.
- Phytoremediation will likely require a large area of land surface for remediation.
- Generally, phytoremediation may only be employed in areas with lower levels of contamination due to plant toxicity effects.
- The use of phytoremediation is limited by contamination depth, although there are currently studies under way which are determining the potential for fast growing, deep-rooted trees to remediate contaminated groundwater.
- More research is needed to determine the fate of various compounds in the plant metabolic cycle to ensure that plant droppings and products manufactured by plants do not contribute toxic or harmful chemicals into the food chain or increase risk exposure to the general public.

Status: Innovative

Operation and Maintenance Duration:

Operation and maintenance duration for phytoremediation will range from 2 to 20 years. The duration of operation and maintenance is dependent on the following conditions:

- Cleanup goals
- The volume of in situ media requiring treatment
- Contaminant concentrations and distribution
- Growth rate and characteristics of the remediation plantings
- Depth of contamination
- Climate (i.e., temperature, winds, and rain).

Cost Range: $75,000 to $150,000 per acre

The major cost items included in the cost estimate range for phytoremediation are designated in Table B10-1.

Table B10-1. Major Cost Items to Implement Phytoremediation

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Planting of selected species	Operating and maintenance labor Irrigation water Nutrients Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
Harvesting and disposal of biomass[(a)]	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

(a) Item applicable to phytoaccumulation, phytoextraction, and rhizofiltration only.

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.21.09 "Phytoremediation".

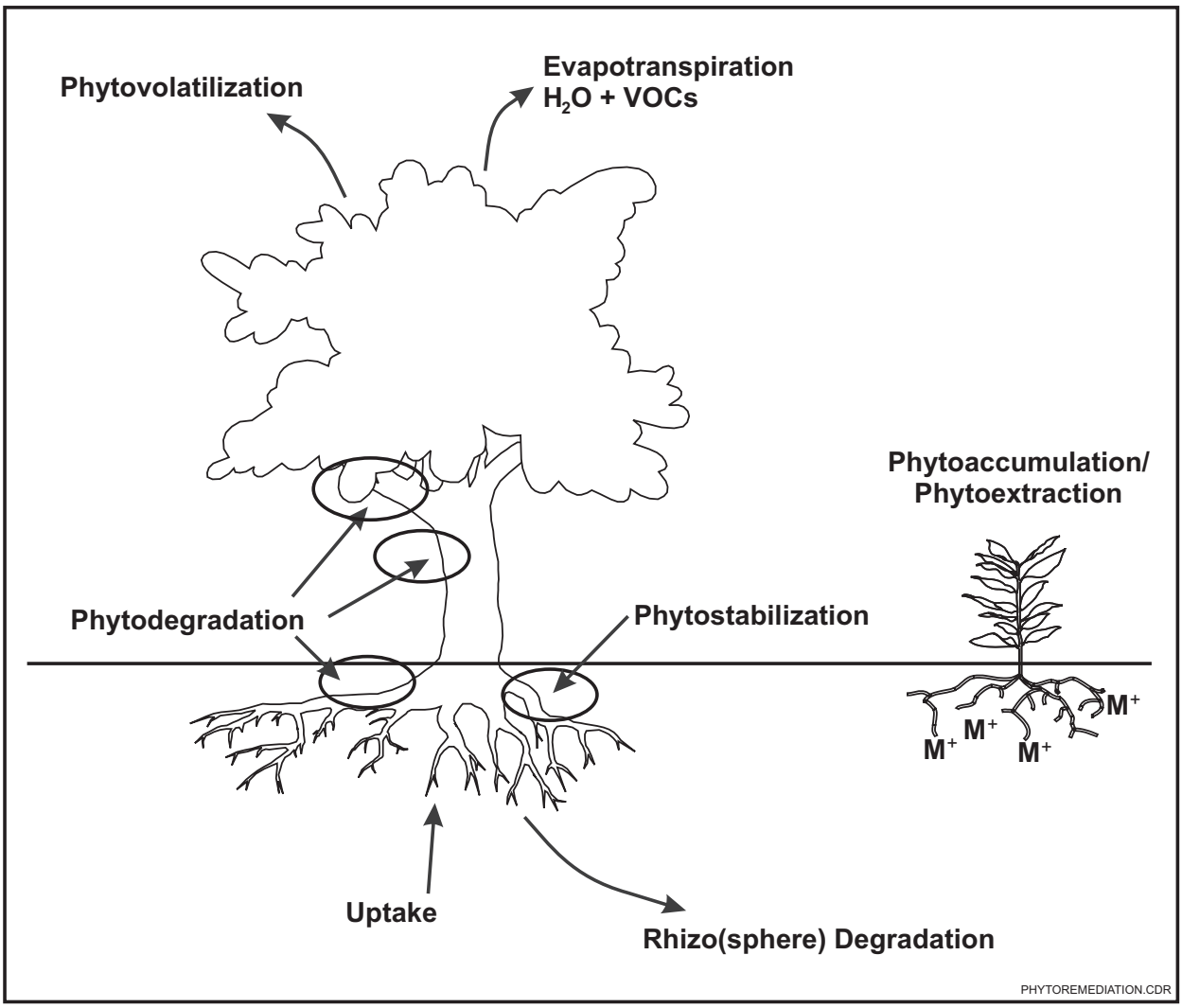


Figure B10. Phytoremediation

B11: Slurry-Phase Bioreactors, Sequential Anaerobic/Aerobic Slurry-Phase Bioreactors, Slurry-Phase Bioreactors with Cometabolites, and Slurry-Phase Bioreactors with Specially Adapted Microorganisms

Abstract:

Slurry-phase biological treatment involves the controlled treatment of a fluid mixture of water and excavated soil in a bioreactor.

Description:

To perform slurry-phase biotreatment the soil must be processed to provide a low viscosity slurry. The excavated soil is processed to physically separate stones and rubble, then mixed with a predetermined amount of water to form the slurry. The amount of water required is a function of the concentration of the contaminants, the rate of biodegradation, and the physical nature of the soil. Typically, the slurry contains 10 to 40% solids by weight. Sometimes the soil is preprocessed to concentrate the contaminants and reduce the volume of material placed in the bioreactor. Preprocessing usually involves sieving to remove larger soil particles having a small surface-to-volume ratio, and that are contaminated at or below the target cleanup concentration. This "clean" soil is removed for disposal, leaving only contaminated fines and washwater for biotreatment.

The soil is maintained in suspension in the reactor vessel and mixed with nutrients. If necessary, an acid or an alkali may be added to control pH. Microorganisms also may be added if a suitable population with the desired degrading capabilities is not present. When biodegradation is complete, the soil slurry is removed from the reactor and dewatered using clarifiers, pressure filters, vacuum filters, sand drying beds, and/or centrifuges. The soil is disposed of and the fluids are either recycled back to the reactor or treated for disposal.

Applicability:

Slurry-phase bioreactors are appropriate for treating excavated soils and sludges at sites where a relatively small volume of material requires treatment, or at sites where materials for treatment are staged and rapid throughput is not required. The technology may be favored over in situ biotreatment for heterogeneous soils, low-permeability soils, areas where underlying groundwater would be difficult to capture, or when more rapid treatment is required.

Treatment of aerobically degradable compounds such as unhalogenated semivolatile organic compounds (SVOCs) using slurry-phase bioreactors is a mature technology. Chlorinated solvents, pesticides, explosives, wood preservatives, and other organic chemicals can be treated but require more specialized applications. Cometabolites and specially adapted microorganisms may be required to effectively treat these compounds. An inexpensive and rapid bench-scale test can be conducted to determine any special requirements and to enhance biodegradation performance.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Very high contaminant concentrations may be toxic to microorganisms.
- Dewatering soil fines after treatment can be expensive.
- An acceptable method for disposing of non-recycled wastewater is required.

- Low ambient temperatures can decrease biodegradation rates.
- Heavy metals are not treated by this method and can be toxic to microorganisms.
- Debris greater than 60 mm in diameter typically must be removed prior to processing.

Status: Conventional (direct metabolic treatment); emerging (cometabolic treatment); Innovative (sequenced anaerobic/aerobic treatment, specialty organisms).

Operation and Maintenance Duration:

Slurry-phase bioreactors are used to treat excavated soil, so the operation and maintenance duration depends on the processing rate of the treatment unit and the volume of soil. The processing rate is dependent on the following:

- Cleanup goals
- Concentration of contaminants
- Temperature of reactor
- Nutrient concentration
- Proper aeration (for aerobic bioreactors).

Cost Range:

The cost of bioslurry treatment varies significantly and is dependent on the type and biodegradability of the contaminant, the volume of material requiring treatment, the amount of process control required, any special materials handling requirements, and the complexity of reactor and process design. Typically, the costs should be in the range of $10 to $200 per ton of material treated.

The major cost items included in the cost estimate range for slurry-phase bioreactors are designated in Table B11-1.

Table B11-1. Major Cost Items to Implement Slurry-Phase Bioreactors

Pretreatment Activities Included in Cost	
Screening to remove debris	
Fixed Cost Items Included	**Variable Cost Items Included**
Bioreactor installation	Soil excavation
Clarifier and filter installation	Operating and maintenance labor
Off-gas treatment system installation	Utilities Nutrients Cometabolic substrate[(a)] Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
On-site disposal of treated soil, sediment, or sludge	
Disposal of excess water to publicly owned treatment works via site sewer	
Off-gas treatment	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

(a) Item applicable to cometabolic treatment only.

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.22.08 "Slurry-Phase Biological Treatment".

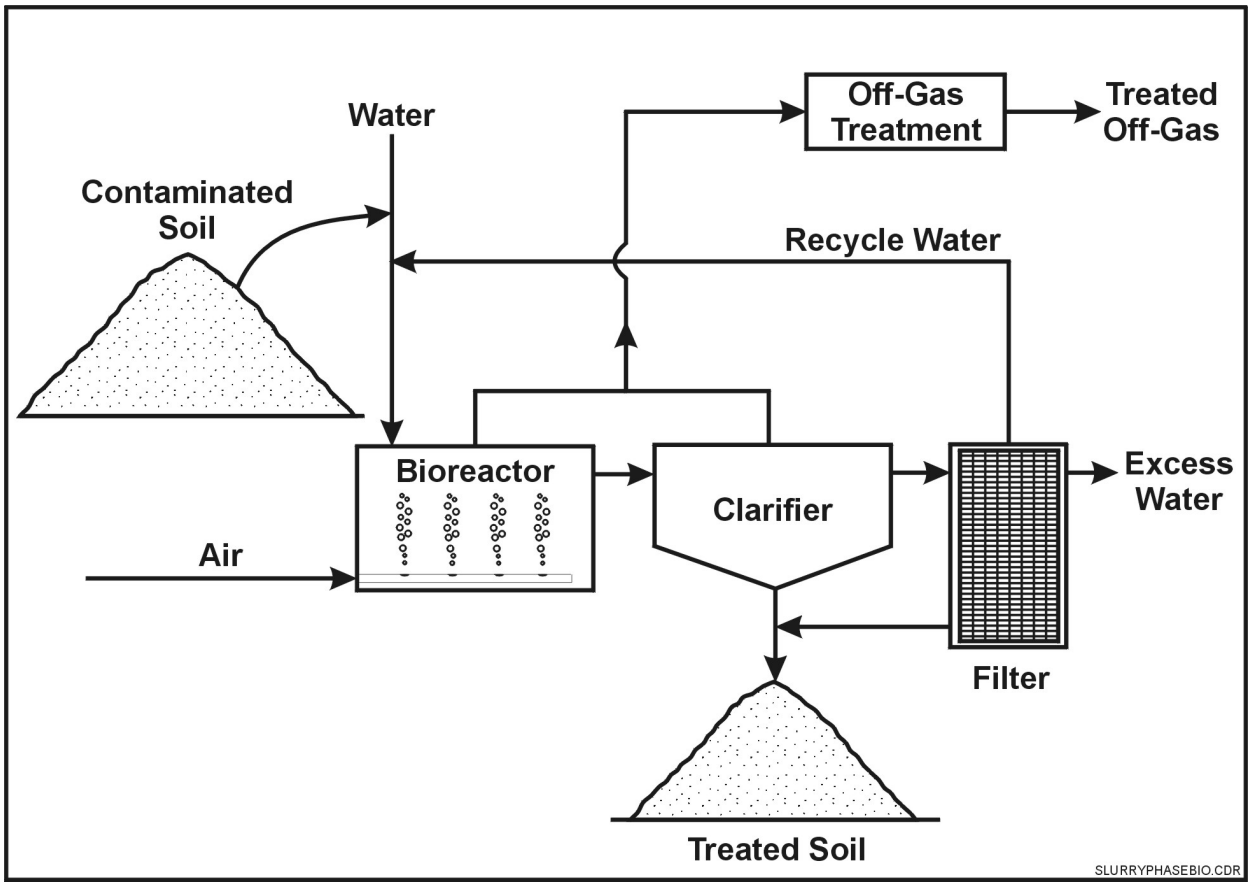


Figure B11. Slurry-Phase Reactor

B12: White-Rot Fungus Treatment

Abstract:
White-rot fungus treatment involves using fungus to biodegrade organic contaminants in soil.

Description:

White-rot fungus produces lignin-degrading (i.e., wood-rotting) enzymes that can degrade a wide variety of organic recalcitrants. Treatment involves mixing soil with fungus and a suitable substrate such as wood chips. Two different treatment configurations have been tested for white-rot fungus: bioreactor and in situ. An aerobic system using moisturized air on wood chips was used for the reactor-based biodegradation system. Alternatively, an adjustable shredder was used for making chips for an open system, which is similar to composting, with wood chips on a liner or a covered, hard-contained surface. The optimum temperature for lignin-degrading fungus ranges from 30-38ºC (86-100ºC). The heat of the biodegradation reaction helps maintain the temperature of the process near the optimum.

Although degradation of trinitrotoluene (TNT) has been reported in laboratory-scale settings using pure cultures, a number of factors increase the difficulty of using white-rot fungus for full-scale remediation. These factors include competition from native bacterial populations, toxicity inhibition, chemical sorption, and the inability to meet risk-based cleanup levels. White-rot fungus works best in a nitrogen-limited environment.

Applicability:

White-rot fungus has the ability to degrade and mineralize a number of contaminants that resist aerobic biodegradation (e.g., ordnance compounds, dichlorodiphenyltrichloroethane [DDT], polynuclear aromatic hydrocarbons [PAHs], polychlorinated biphenyls [PCBs], and pentachlorophenol [PCP]).

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- High contaminant concentrations in the soil, sediment, or sludge cannot be treated.
- Contaminant concentration may not be reduced sufficiently to meet cleanup levels.
- Competition from native bacterial populations, toxicity inhibition, and chemical sorption can reduce effectiveness.
- Low ambient temperatures can decrease biodegradation rates.
- Fungi are susceptibile to water stress.
- Heavy metals are not treated by this method and can be toxic to fungi.

Status: Emerging

Operation and Maintenance Duration: N/A

Cost Range: N/A

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.22.13 “Fungal Biodegradation (White Rot Fungus)”.

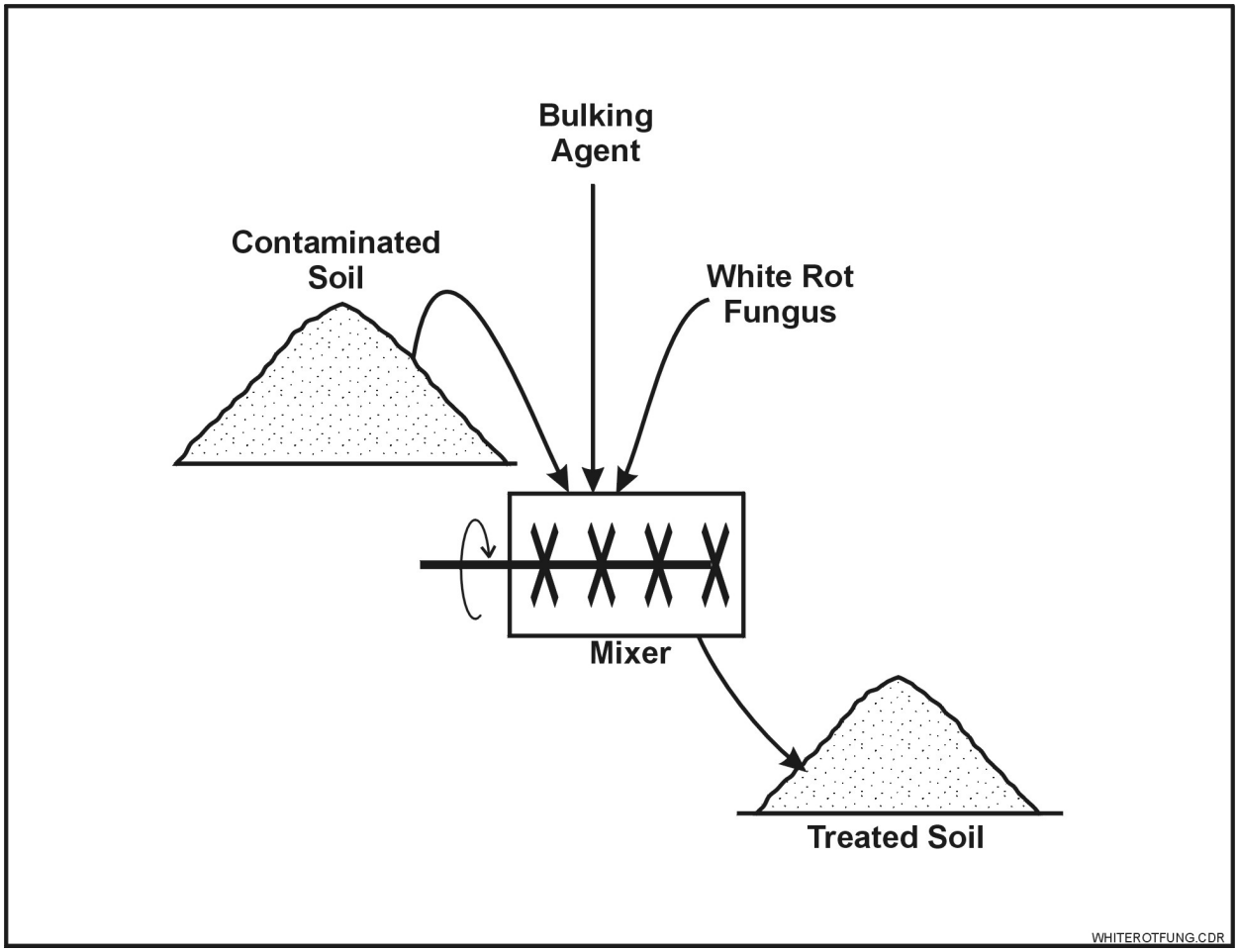


Figure B12. Diagram of White-Rot Fungus Treatment

Physical/Chemical Technology Profiles Index

Remediation Technology	Treatment Method[a]	Category[b]	Applicability[c]	Technology Profile	Technology Page No. (TP-)	CER Profile Page No. (CER-)[d]
Air Stripping	PC	C	4, 20	PC2	39	NA
Air Sparging	PC	I	1, 17, 22	PC1	36	NA
Base-Catalyzed Decomposition Process	PC	I	9, 14, 40	PC3a	42	57
Chemical Leaching	PC	I	30	PC4	48	65
Chemical Oxidation (Organics)	PC	C	4, 10, 15, 20, 25, 36	PC6a	53	61
Chemical Reduction/Oxidation (Inorganics)	PC	C	31	PC5	51	NA
Circulating Wells	PC	E	1, 17	PC7	58	NA
Condensation	PC	C	6a, 6b	PC8	61	108
Electrokinetic Extraction	PC	E	28, 29	PC9	63	NA
Glycolate Dehalogenation	PC	I	9, 14, 40	PC3b	45	55
Granular Activated Carbon Absorption (Liquid Phase)	PC	C	4, 10, 15, 20, 25, 36	PC10a	65	NA
Granular Activated Carbon Adsorption (Vapor Phase)	PC	C	6a, 6b	PC10b	68	NA
In Situ Heating – High Temperature (>100°C)	PC	I	7, 8, 12, 13, 23, 39	PC11	72	82, 88, 91
In Situ Heating–Low Temperature (<100°C)	PC	I	7, 8, 23, 39	PC30	135	84, 86
In-Well Air Stripping	PC	I	1, 17	PC14	88	67
Incineration (On Site)	PC	C	9, 14, 24, 35, 40	PC15	91	NA
Ion Exchange	PC	C	31	PC17	97	59
Internal Combustion Engine	PC	C	6a	PC16	95	106
Membrane Pervaporation (VOCs)	PC	E	4	PC19	103	NA
Membrane Separation (VOCs)	PC	E	6a, 6b	PC19	103	NA
Physical Separation	PC	C	30	PC23	114	76, 78
Precipitation (Hydroxide or Sulfide)	PC	C	31	PC20	105	NA
Reverse Osmosis	PC	C	31	PC22	111	NA
Soil Flushing	PC	I	8, 13, 23, 29, 34	PC24	117	NA
Soil Vapor Extraction (Ex Situ)	PC	I	3	PC25b	123	74
Soil Vapor Extraction (In Situ)	PC	C	2, 18	PC25a	120	NA
Soil Washing	PC	I	9, 14, 24, 30, 35	PC26	125	NA
Solidification/Stabilization (Ex Situ)	PC	C	30	PC12b	79	100
Solidification/Stabilization (In Situ)	PC	I	29	PC12a	76	94, 96, 98
Solvent Extraction	PC	I	9, 14, 24, 35	PC28	130	63
Solvated Electron Treatment Process	PC	E	9, 14, 35, 40	PC27	128	NA
Sprinkler Irrigation	PC	I	4, 20	PC29	133	80
Surfactant-Enhanced Recovery	PC	E	1, 39	PC31	139	NA
Synthetic Resin Adsorption (Liquid Phase)	PC	E	4, 10, 20, 25	PC32	141	NA

Physical/Chemical Technology Profiles Index (continued)

Remediation Technology	Treatment Method[a]	Category[b]	Applicability[c]	Technology Profile	Technology Page No. (TP-)	CER Profile Page No. (CER-)[d]
Synthetic Resin Adsorption (Vapor Phase)	PC	E	6a, 6b	PC32	141	NA
Thermal/Catalytic Oxidation	PC	C	6a, 6b	PC33	143	NA
Thermal Desorption	PC	I	3, 9, 14, 19, 24	PC18	100	NA
Treatment Wall	PC	I	1, 7, 28, 33	PC21	108	NA
Two-Phase (Dual-Phase) Extraction	PC	I	1, 17	PC34	146	NA
Ultraviolet Light/Chemical Oxidation (Organics)	PC	I	4, 10, 15, 20, 25, 36	PC6b	55	NA
Ultraviolet Light Oxidation (Vapor Phase)	PC	I	6a, 6b	PC35	149	104
Use as Aggregate in Asphalt Mix	PC	C	19, 24, 30	PC36	151	NA
Vitrification (Ex Situ)	PC	I	30	PC13b	85	NA
Vitrification (In Situ)	PC	I	29	PC13a	82	NA

(a) PC = Physical/Chemical.
(b) C = Conventional, E = Emerging, I = Innovative.
(c) Applicability indicated by cross reference to Tables of Remediation Technologies.
(d) NA = CER Profile not available.

PC1: Air Sparging

Abstract:

Air sparging is an in situ technology for treating organic contaminants in groundwater by using air as a stripping gas.

Description:

Air sparging is implemented by injecting pressurized air into a contaminated aquifer so that air streams traverse horizontally and vertically through the soil column, creating an underground stripper that removes contaminants by volatilization. The air carries the contaminants to a vapor extraction system that removes the generated vapor-phase contamination. This technology is designed to operate at high flowrates to maintain increased contact between groundwater and soil, and to strip more groundwater by sparging.

In addition to removal of contaminants by volatilization, an increased level of dissolved oxygen would enhance aerobic biodegradation of the contaminants. Reducing the air sparging flowrate to emphasize biodegradation in contrast to stripping is sometimes called biosparging.

Applicability:

Air sparging is used primarily to treat compounds with moderate to high Henry's law constants (i.e., high vapor pressure and low solubility) such as halogenated and nonhalogenated volatile organic compounds (VOCs) and nonhalogenated semivolatile organic compounds (SVOCs).

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Subsurface heterogeneity can interfere with uniform air distribution.
- Low-permeability soils are difficult to treat.
- Contaminants with low Henry's law constants are difficult to treat.
- Only a limited number of high-quality field studies of air sparging have been conducted.

Status: Innovative

Operation and Maintenance Duration:

Air sparging has a medium- to long-term duration typically requiring 6 months to 2 years to remediate a site. The duration of operation and maintenance is dependent on the following conditions:

- Cleanup goals
- The volume of contaminated groundwater
- Contaminant concentration and distribution
- Aquifer characteristics including permeability and anisotropy
- Henry's law constant of contaminants
- Radial influence of air sparging well
- Achievable biodegradation rates
- Diffusion and desorption rates.

Cost Range: $150,000 to $350,000 per acre

The major cost items included in the cost estimate range for air sparging are designated in Table PC1-1.

Table PC1-1. Major Cost Items to Implement Air Sparging

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Sparging well and compressor installation	Operating and maintenance labor
Vapor collection wells and blower installation	Utilities
Off-gas treatment system installation	Site supervision
Sampling point installation	Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
Disposal of condensate to publicly owned treatment works via site sewer	
Off-gas treatment	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.25.02 "Air Sparging".

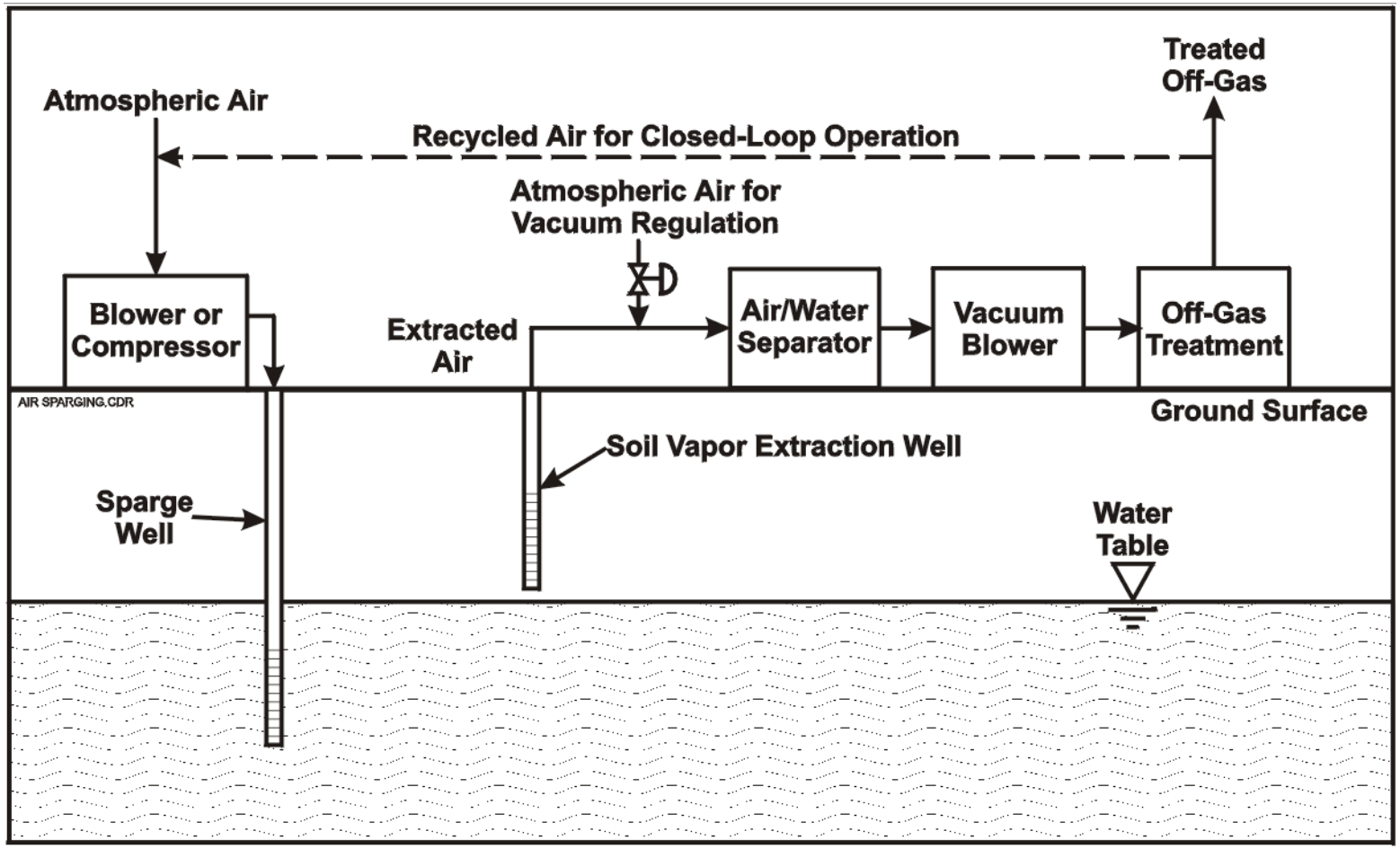


Figure PC1. Diagram of Air Sparging

PC2: Air Stripping

Abstract:

Air stripping is an ex situ technology that partitions volatile organics from pumped groundwater or wastewater by exposing a large surface area of contaminated water to clean air flow.

Description:

Air stripping involves the mass transfer of volatile contaminants from water to air. For groundwater remediation, this process is typically conducted in a packed tower or a low-profile aeration system. The typical packed tower air stripper includes a spray nozzle at the top of the tower to distribute contaminated water over the packing in the column, a fan to force air countercurrent to the water flow, and a sump at the bottom of the tower to collect decontaminated water. Low-profile air strippers are available in horizontal tray or vertical box designs. Baffles are used to route contaminated water two or more times along the length of the tray or height of the box. Air sparged through the bottom of the tray or through a vent pipe in the bottom of the box passes up through the water to strip out volatile compounds. Several trays or boxes can be used to increase flow capacity or stripping efficiency. Auxiliary equipment that can be added to the basic air stripper includes an air heater to improve removal efficiencies; automated control systems with sump level switches and explosion-proof components; and air emission control and treatment systems, such as activated carbon units, catalytic oxidizers, or thermal oxidizers. Packed tower air strippers are installed either as permanent installations on concrete pads or on a skid or a trailer. Low-profile air strippers are small package units suitable for skid or floor mounting.

Aeration tanks strip volatile compounds by bubbling air into a tank through which contaminated water flows. A forced air blower and a distribution manifold are designed to ensure air-water contact without the need for any packing materials. The baffles and multiple units ensure adequate residence time for stripping to occur. Aeration tanks are typically sold as continuously operated skid-mounted units. The advantages offered by aeration tanks are considerably lower profiles (less than 2 meters or 6 feet high) than packed column towers (5 to 12 meters or 15 to 40 feet high) where height may be a problem, and the ability to modify performance or adapt to changing feed composition by adding or removing trays or chambers. The discharge air from aeration tanks can be treated using the same technology as for packed tower air discharge treatment.

Air strippers can be operated continuously or in a batch mode where the air stripper is intermittently fed from a collection tank. The batch mode ensures consistent air stripper performance and greater energy efficiency than continuously operated units, because mixing in the storage tanks eliminates any inconsistencies in feed water composition.

Applicability:

Air stripping is used to separate halogenated and nonhalogenated volatile organic compounds (VOCs) from water, but is ineffective for contaminants with low vapor pressure or high solubility such as inorganic salts. The Henry's law constant is used to determine whether air stripping will be effective. Generally, organic compounds with constants greater than 0.01 atmospheres (m^3/mol) are considered amenable to stripping. Some compounds that have been successfully separated from water using air stripping include benzene, toluene, ethylbenzene, and xylenes (BTEX); chloroethane; trichloroethylene (TCE); dichloroethylene (DCE); and perchloroethylene (PCE).

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Suspended solids or solids formed by precipitation of reduced iron or manganese species can foul packing or trays, requiring pretreatment to remove the fouling agents.
- High concentrations of dissolved calcium or magnesium can react with carbon dioxide in the air, forming carbonate scale on the packing or trays.
- Biological growth can foul the trays or packing, requiring periodic column cleaning.
- Consideration should be given to the Henry's law constant of the VOCs in the water stream, and the type and amount of packing used in the tower.
- Compounds with low volatility at ambient temperature may require preheating of the groundwater.
- Off-gases will require treatment if the mass emission rate exceeds locally allowed limits.

Status: Conventional

Operation and Maintenance Duration:

Air stripping is used to treat pumped groundwater or wastewater residual from a treatment process. The operation and maintenance duration depends on the duration of the primary process operation.

Cost Range: $0.05 to $0.25 per 1,000 gallons

The major cost items included in the cost estimate range for air stripping are designated in Table PC2-1.

Table PC2-1. Major Cost Items to Implement Air Stripping

Pretreatment Activities Included in Cost	
Filtration to remove suspended solids	
Fixed Cost Items Included	**Variable Cost Items Included**
Stripping system installation	Operating and maintenance labor
Off-gas treatment system installation	Packing/tray cleaning and/or replacement Utilities Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
Disposal of treated water to publicly owned treatment works via site sewer	
Off-gas treatment	
Comments	
Iron and manganese oxidation and removal, which may be needed at some site, is not included in cost range Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.26.04 "Air Stripping".

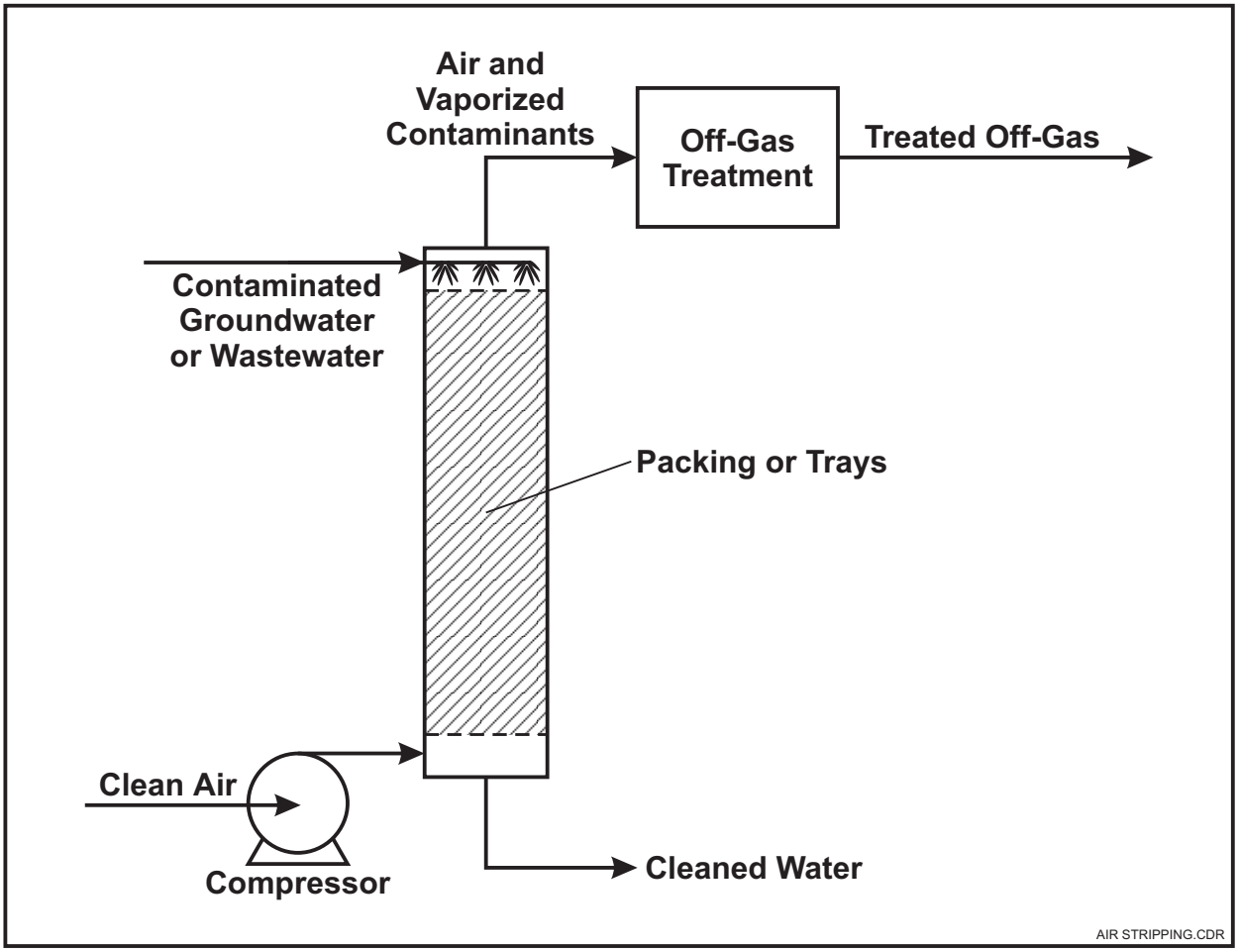


Figure PC2. Air Stripping Using a Packed Tower

PC3a: Base-Catalyzed Decomposition Process

Abstract:

The base-catalyzed decomposition (BCD) process in an ex situ treatment technology that remediates soils contaminated with chlorinated organic compounds, especially polychlorinated biphenyls (PCBs), dioxins, and furans.

Description:

The technology involves a two-stage process to remove chlorinated organics from soil and dechlorinate them to reduce their toxicity. Contaminated soil is screened, processed with a crusher and pug mill, and mixed with sodium bicarbonate. The mixture is heated to about 350°C (660°F) in a rotary reactor to volatilize the contaminants (Stage 1). The volatilized contaminants are captured, condensed, and treated (Stage 2) by reaction with sodium hydroxide and a hydrogen donor oil in the presence of a catalyst.

Applicability:

The BCD process is used primarily to treat halogenated semivolatile organic compounds (SVOCs) and PCBs. The technology also can be used to treat halogenated volatile organic compounds (VOCs), but will generally be more expensive than alternative technologies.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- High clay, humic material, or moisture content increases treatment costs.
- The organic contaminants volatilized in the Stage 1 reactor must be collected and treated in the Stage 2 reactor.
- Process off-gas must be collected and treated.
- Process condensate must be collected and treated.
- Debris greater than 60 mm in diameter typically must be removed prior to processing.

Status: Innovative

Operation and Maintenance Duration:

The BCD process is used to treat excavated soil, so the operation and maintenance duration depends on the processing rate of the treatment unit and the volume of soil. Processing typically would be performed on site using a mobile unit. The throughput of a mobile unit is expected to range from 30 to 200 cubic yards per day.

Cost Range: $100 to $350 per cubic yard

The major cost items included in the cost estimate range for base-catalyzed decomposition are designated in Table PC3a-1.

Table PC3a-1. Major Cost Items to Implement Base-Catalyzed Decomposition

Pretreatment Activities Included in Cost	
Screening to remove debris	
Fixed Cost Items Included	**Variable Cost Items Included**
BCD system installation	Soil excavation Operating and maintenance labor Utilities Chemicals Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
On-site disposal of treated soil, sediment, or sludge	
Disposal of treated water to publicly owned treatment works via site sewer	
Off-gas treatment	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: The technology corresponds to the second and third level WBS elements X.24.02 "Base-Catalyzed Decomposition Process".

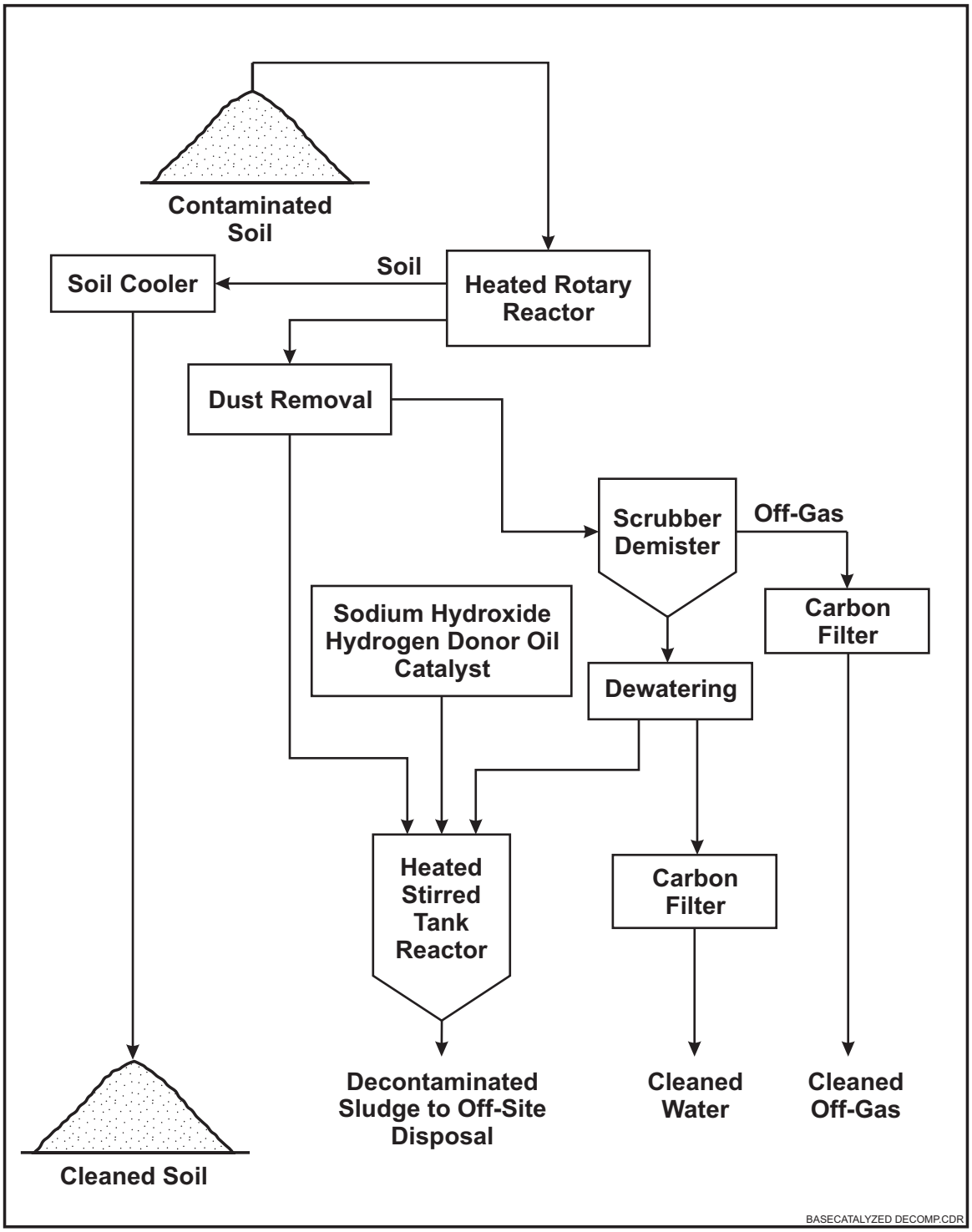


Figure PC3a. Base-Catalyzed Decomposition Process

PC3b: Glycolate Dehalogenation

Abstract:

Glycolate dehalogenation is an ex situ soil treatment technology in which an alkaline polyethylene glycol (APEG) reagent is used to dehalogenate halogenated aromatic compounds.

Description:

Glycolate dehalogenation is implemented by mixing contaminated soil and the reagent in a heated treatment vessel. Potassium polyethylene glycol (KPEG) is the most common APEG treatment reagent. In the APEG process, the reaction causes the polyethylene glycol to replace halogen molecules and render the compound nonhazardous or less toxic. For example, the reaction between chlorinated organics and KPEG causes replacement of a chlorine molecule and results in a reduction in toxicity. Dehalogenation (APEG/KPEG) is generally considered a standalone technology; however, it can be used in combination with other technologies. Treatment of the wastewater generated by the process may include chemical oxidation, biodegradation, carbon adsorption, or precipitation.

The metal hydroxide that has been most widely used for this reagent preparation is potassium hydroxide (KOH) in conjunction with polyethylene glycol (PEG) (typically, average molecular weight of 400) to form a polymeric alkoxide referred to as KPEG. Sodium hydroxide has also been used in the past, however, and most likely will find increasing use in the future because of patent applications that have been filed for modification to this technology. This new approach will expand the technology's applicability and efficacy and should reduce chemical costs by facilitating the use of less costly sodium hydroxide. A variation of this reagent is potassium hydroxide or sodium hydroxide/tetraethylene glycol, referred to as ATEG, which is more effective on halogenated aliphatic compounds. In some KPEG reagent formulations, dimethyl sulfoxide (DMSO) is added to enhance reaction rate kinetics, presumably by improving rates of extraction of the haloaromatic compounds. Using DMSO as a solvent increases safety concerns because DMSO increases the ability of the contaminants to be absorbed through the skin.

Previously developed dehalogenation reagents involved dispersion of metallic sodium in oil or the use of highly reactive organosodium compounds. The reactivity of metallic sodium and the other reagents with water presented a serious limitation to treating many waste matrices; therefore, these other reagents are not discussed here and are not considered APEG processes.

The reagent (APEG) dehalogenates the pollutant to form a glycol ether and/or a hydroxylated compound and an alkali metal salt, which are water-soluble byproducts.

Applicability:

Glycolate dehalogenation is used primarily to treat halogenated semivolatile organic compounds (SVOCs) and polychlorinated biphenyls (PCBs). Although the technology can be used against selected halogenated volatile organic compounds (VOCs), it may be less effective. APEG dehalogenation is one of the few processes available other than incineration that has been successfully field tested in treating PCBs. The technology is amenable to small-scale applications.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- The technology is generally implemented as a batch process and is not cost-effective for large waste volumes.
- Media water content above 20% requires excessive reagent volume.
- Concentrations of chlorinated organics greater than 5% require large volumes of reagent.
- Regeneration and reuse of reagents may be difficult.
- Debris greater than 60 mm in diameter typically must be removed prior to processing.

Status: Innovative

Operations and Maintenance Duration:

Glycolate dechlorination is used to treat excavated soil, so the operation and maintenance duration depends on the processing rate of the treatment unit and the volume of soil. Processing typically would be performed on site in a mobile unit. The throughput of a mobile unit is expected to range from 30 to 200 cubic yards per day.

Cost Range: $200 to $500 per cubic yard

The major cost items included in the cost estimate range for glycolate dehalogenation are designated in Table PC3b-1.

Table PC3b-1. Major Cost Items to Implement Glycolate Dehalogenation

Pretreatment Activities Included in Cost	
Screening to remove debris	
Fixed Cost Items Included	**Variable Cost Items Included**
Glycolate dehalogenation system installation	Soil excavation Operating and maintenance labor Utilities Chemicals Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
On-site disposal of treated soil, sediment, or sludge	
Disposal of treated water to publicly owned treatment works via site sewer	
Off-gas treatment	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.24.01 "Glycolate/Alkali Metal/Polyethylene Glycol (A/PEG) Process".

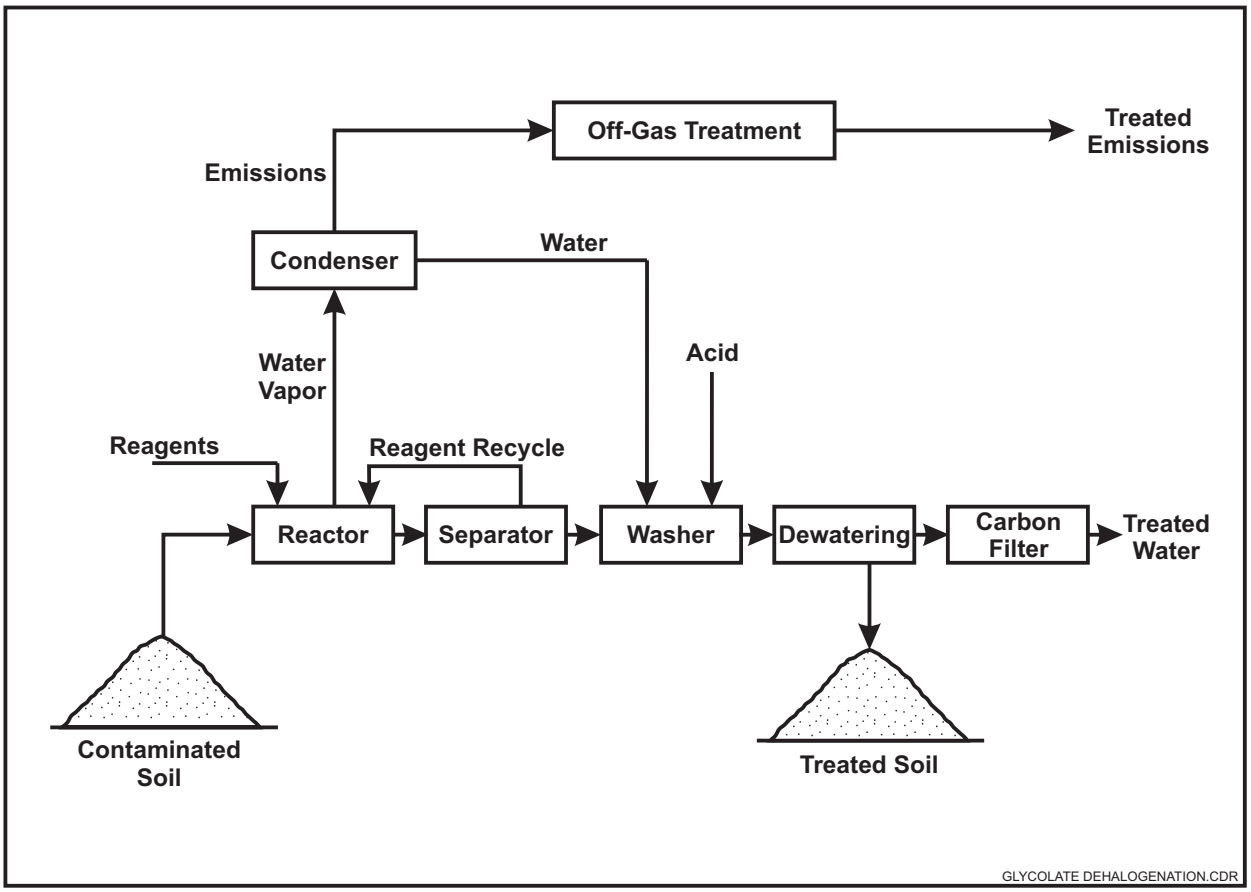


Figure PC3b. Glycolate Dehalogenation Process

PC4: Chemical Leaching

Abstract:

Chemical leaching is an ex situ technology for treating metal-contaminated soil by selectively dissolving the contaminants.

Description:

Chemical leaching involves mixing contaminated soil with a chemical solution to transfer metals from a solid matrix into the leaching solution. The cleaned soil and leaching solution are separated and solution processing methods are used to regenerate the leachant and recover a useful metal or salt. The combination of chemical leaching and leachant regeneration is known as hydrometallurgical processing, and typically includes one or more of the following four steps:

- Dissolution of the desired metal
- Purification and/or concentration of the metal
- Recovery of the metal or a metal salt
- Regeneration and reuse or treatment and disposal of the leaching solution.

Applicability:

Chemical leaching is used primarily to treat inorganic contaminants. Wastes containing a high concentration of one metal in one valence state are preferred. Waste streams processed include wastewater treatment sludges (e.g., plating operations, metal finishing, and electronic circuit board etching), baghouse dust, and spent catalyst. The metals reclaimed include chromium, nickel, copper, zinc, lead, cadmium, tin, cobalt, vanadium, titanium, molybdenum, gold, silver, palladium, and platinum.

Chemical leaching for mercury recovery is a new and growing technology area. Several chemical leaching formulations have been developed to remove mercury from contaminated soils. Processes to recover lead by acid leaching followed by electrowinning are being developed.

Products are often metal salts. For example, hydroxide plating or etching sludge can be converted to metal salts such as copper chloride, copper ammonium chloride, or nickel carbonate. For catalysts, metals and substrate materials can be converted by leaching and solution processing into products such as nickel-copper-cobalt concentrate, alumina trihydrate, chromium oxide, molybdenum trioxide, and vanadium pentoxide.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Large volumes of leaching solution or long contact time may be required for materials with a high clay content.
- Leaching of materials with a high clay content leaves fine, suspended particulate in the leachant, which may be difficult to remove.
- If particulate metals are present, physical separation to remove elemental metals is necessary to conserve leachant and reduce contact time.
- Leachant must be regenerated or treated for disposal.
- Specialized corrosion-resistant equipment often is needed to withstand the leachant.

- Complex waste mixtures (e.g., many different metals and/or chemical species) increase the difficulty of formulating a leaching solution.
- Debris greater than 60 mm in diameter typically must be removed prior to processing.

Status: Innovative

Operation and Maintenance Duration:

Chemical leaching is used to treat excavated soil, so the operation and maintenance duration depends on the processing rate of the treatment unit and the volume of soil. Soil processing may be performed on site using a mobile unit, or the soil may be moved to a central facility. The throughput of a mobile unit is expected to range from 10 to 100 cubic yards per day.

Cost Range: $15,000 to $25,000 fixed mobilization cost plus $135 to $450 per cubic yard operating cost

The major cost items included in the cost estimate range for chemical leaching are designated in Table PC4-1.

Table PC4-1. Major Cost Items to Implement Chemical Leaching

Pretreatment Activities Included in Cost	
Screening to remove debris	
Fixed Cost Items Included	**Variable Cost Items Included**
Crew and equipment mobilization	Soil excavation
Treatment pad installation	Equipment leasing Operating and maintenance labor Utilities Chemicals Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
On-site disposal of treated soil, sediment, or sludge	
Off-site disposal of sludge residual from water treatment	
Disposal of treated water to publicly owned treatment works via site sewer	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.24.18 "Chemical Extraction (Solvent/Acid/Alkaline Extraction)".

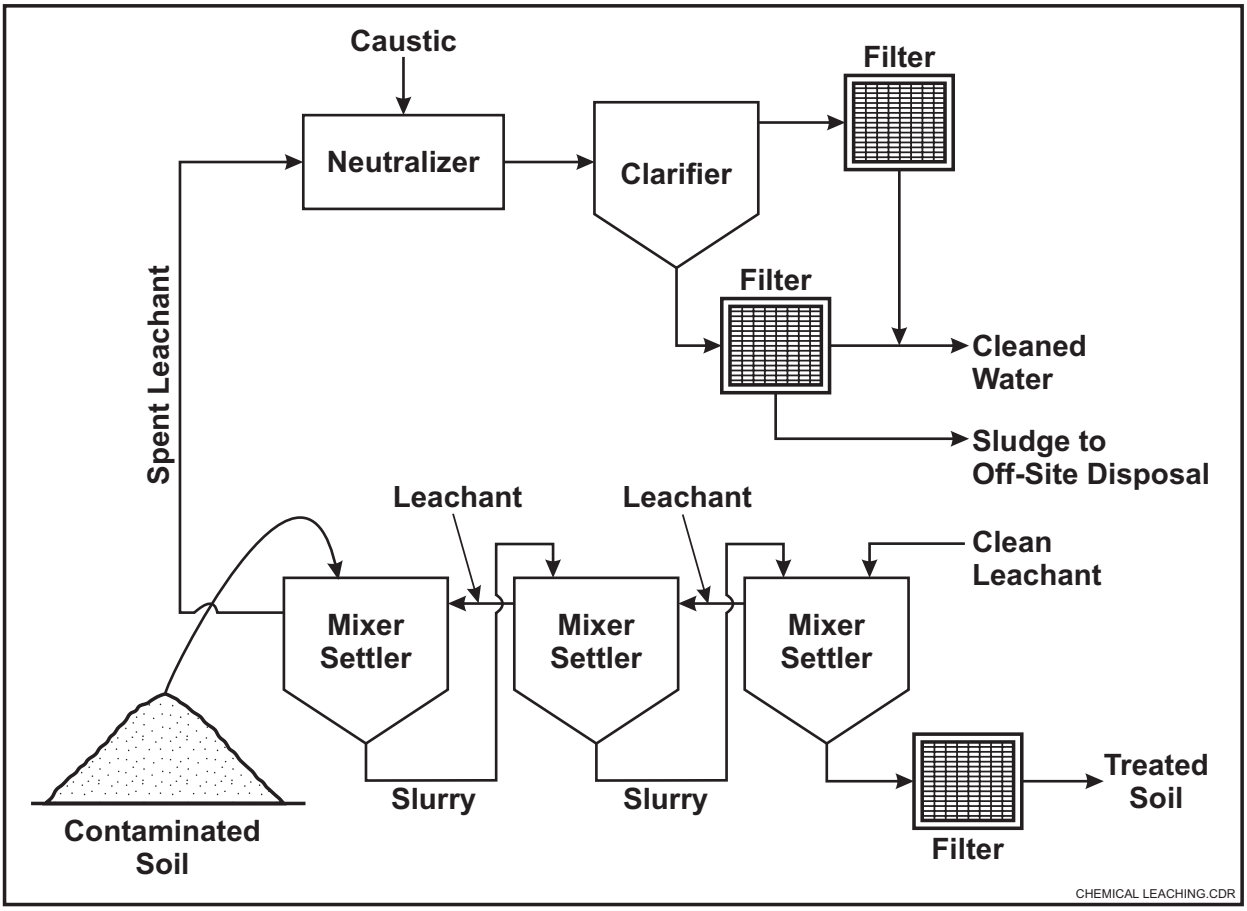


Figure PC4. Chemical Leaching

PC5: Chemical Reduction/Oxidation (Inorganics)

Abstract:

Reduction/oxidation (redox) treatment is a technology for treating pumped groundwater or wastewater contaminated with metals. It involves using chemical reactions to convert hazardous contaminants to nonhazardous or less toxic compounds that are more stable, less mobile, and/or inert.

Description:

Chemical redox treatment is implemented by mixing treatment chemicals with the water stream to promote a redox reaction. Redox reactions involve the transfer of electrons from one compound to another. Specifically, one reactant is oxidized (loses electrons) and one is reduced (gains electrons). The oxidizing agents most commonly used for treatment of hazardous waste are ozone, hydrogen peroxide, hypochlorite, chlorine, and chlorine dioxide. The reducing agents most commonly used for treatment of hazardous waste are ferrous sulfate, sodium bisulfite, and sodium hydrosulfite.

Applicability:

In remediation applications, chemical redox of inorganic contaminants usually is a wastewater pretreatment step performed to prepare a specific contaminant for removal or to reduce the toxicity of a contaminant by altering its chemical form. The most common applications of chemical reduction are reducing chromium (VI) to chromium (III) in preparation for hydroxide precipitation, oxidizing arsenic (III) to arsenic (V) to reduce toxicity and improve removal by subsequent processes, and oxidizing cyanide to produce CO_2 and N_2.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- The process may not be cost-effective for high contaminant concentrations because of the large amounts of redox agent required.
- Redox chemicals will be consumed by noncontaminant species, which increases treatment cost and creates the potential for forming undesirable byproducts.

Status: Conventional

Operation and Maintenance Duration:

Chemical redox is used to treat pumped groundwater or wastewater residual from a treatment process. The operation and maintenance duration depends on the duration of the primary process operation.

Cost Range: $0.60 to $1.00 per 1,000 gallons

The major cost items included in the cost estimate range for chemical reduction/oxidation of inorganics are designated in Table PC5-1.

Table PC5-1. Major Cost Items to Implement Chemical Reduction/Oxidation of Inorganics

Pretreatment Activities Included in Cost	
Filtration to remove suspended solids	
Fixed Cost Items Included	**Variable Cost Items Included**
Redox system installation	Operating and maintenance labor Utilities Chemicals Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
Disposal of treated water to publicly owned treatment works via site sewer	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.24.08 "Chemical Oxidation/Reduction".

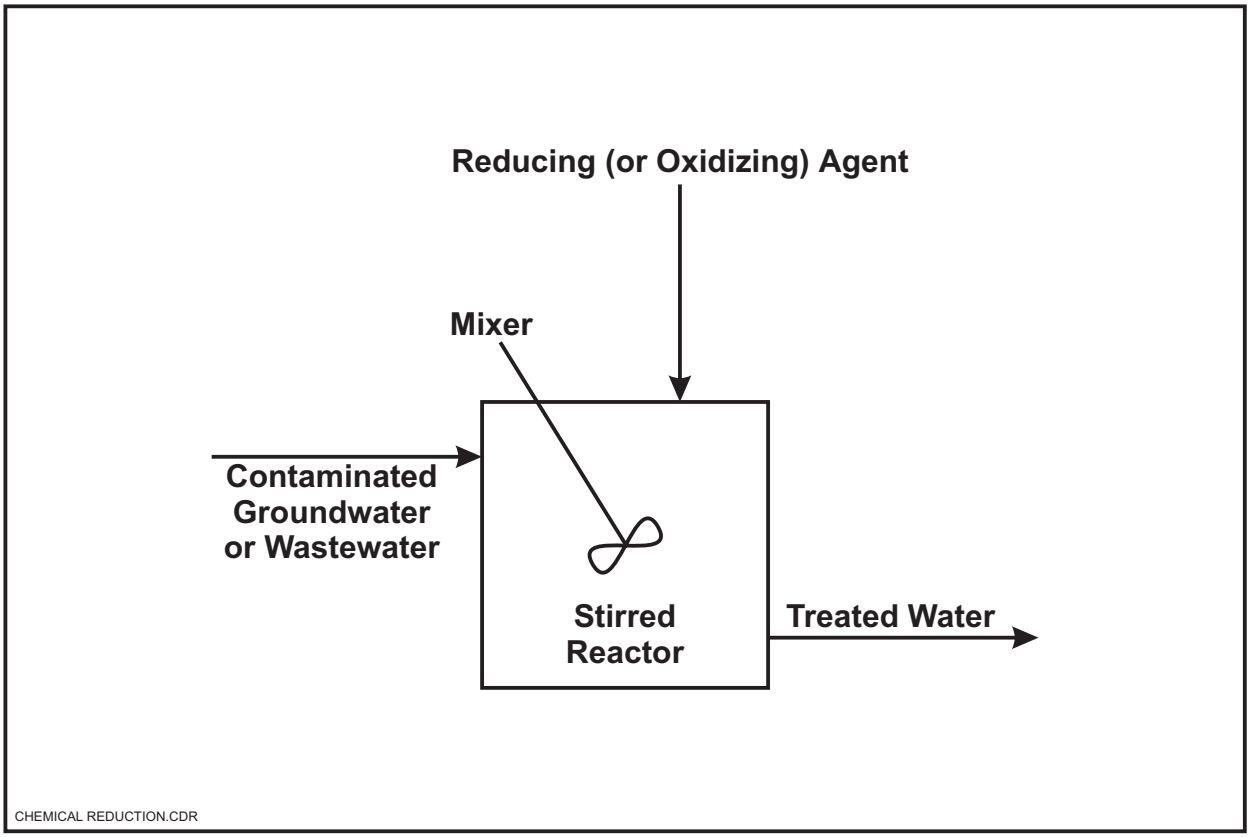


Figure PC5. Chemical Reduction/Oxidation (Inorganics)

PC6a: Chemical Oxidation (Organics)

Abstract:

Chemical oxidation is a technology for treating pumped groundwater or wastewater contaminated with organics using chemical oxidizing agents to mineralize the organics.

Description:

Chemical oxidation involves mixing the oxidation agent with groundwater in a vessel that allows sufficient residence time for oxidation. The oxidation agent can be a solution (e.g., sodium hypochlorite in water) or a gas (e.g., ozone). The oxidizing agents most commonly used for chemical treatment of organic contaminants are ozone, hydrogen peroxide, hypochlorites, chlorine, and chlorine dioxide. The treatment chemicals typically mineralize most organic compounds to carbon dioxide, water, and salts.

Applicability:

The technology can be used to treat halogenated and nonhalogenated volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs), polychlorinated biphenyls (PCBs), and ordnance compounds.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Incomplete oxidation or formation of intermediate contaminants may occur depending upon the contaminants and oxidizing agents used.
- The process is not cost-effecive for high contaminant concentrations because of the large amounts of oxidizing agent required.
- When chlorine is used for oxidation, undesirable substitution products such as chloromethanes can form.
- Oxidation chemicals will be consumed by noncontaminant species, which increases treatment cost and creates the potential for forming undesirable byproducts.

Status: Conventional

Operation and Maintenance Duration:

Chemical oxidation is used to treat pumped groundwater or wastewater residual from a treatment process. The operation and maintenance duration depends on the duration of the primary process operation.

Cost Range: $0.35 to $2.00 per 1,000 gallons

The major cost items included in the cost estimate range for chemical oxidation of organics are designated in Table PC6a-1.

Table PC6a-1. Major Cost Items to Implement Chemical Oxidation of Organics

Pretreatment Activities Included in Cost	
Filtration to remove suspended solids	
Fixed Cost Items Included	**Variable Cost Items Included**
Oxidation system installation	Operating and maintenance labor
Peroxide addition or ozone generation system installation	Utilities
Off-gas treatment system installation	Chemicals Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
Disposal of treated water to publicly owned treatment works via site sewer	
Off-gas treatment	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to second and third level WBS elements X.24.08 "Chemical Oxidation/Reduction".

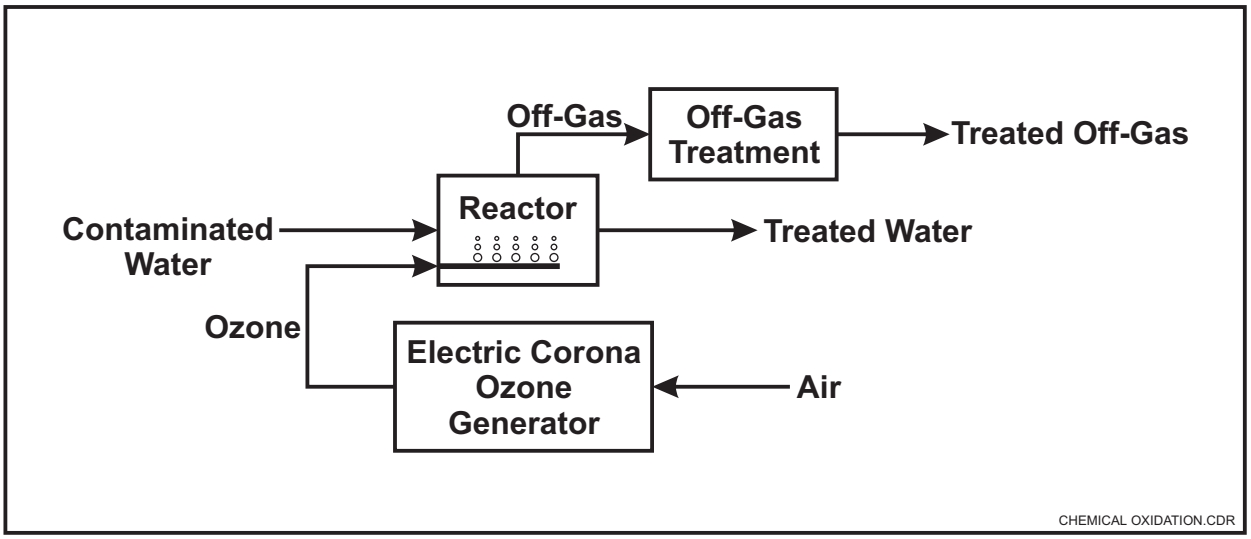


Figure PC6a. Chemical Oxidation (Organics)

PC6b: Ultraviolet Light/Chemical Oxidation (Organics)

Abstract:

Ultraviolet light/chemical oxidation is a technology for treating pumped groundwater or wastewater contaminated with organics using photochemical reactions supplemented by chemical oxidants to mineralize organics.

Description:

Ultraviolet (UV) light/chemical oxidation is a destruction process that oxidizes organic contaminants in wastewater by irradiation with UV light supplemented by the addition of chemical oxidizing agents. The most commonly used chemicals are hydrogen peroxide or ozone. Hydrogen peroxide is injected into the UV light treatment unit as an aqueous solution. Ozone is electrolytically generated and injected as a gas. The process involves passing groundwater with added chemicals in close proximity to a strong source of UV light. A quartz sleeve over the light source provides a barrier to contain the water, but is transparent to UV light. The oxidation reactions are achieved through the synergistic action of UV light, in combination with ozone and/or hydrogen peroxide to produce active hydroxyl radicals that typically mineralize contaminants to carbon dioxide, water, and salts. The main advantage of UV oxidation is that it is a destruction process, as opposed to air stripping or carbon adsorption processes in which contaminants are extracted and concentrated in a separate phase. UV oxidation processes can be configured in batch or continuous flow modes, depending on the throughput under consideration.

Applicability:

UV light/chemical oxidation can be used to treat halogenated and nonhalogenated volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs), polychlorinated biphenyls (PCBs), and ordnance compounds. Practically any organic contaminant that is reactive with the hydroxyl radical can potentially be treated. A wide variety of organic and explosive contaminants are susceptible to destruction by UV oxidation, including petroleum hydrocarbons; chlorinated hydrocarbons used as industrial solvents and cleaners; and ordnance compounds such as trinitrotoluene (TNT), Research Department Explosive (RDX), and His Majesty's Explosive (HMX). In many cases, chlorinated hydrocarbons that are resistant to biodegradation may be effectively treated by UV oxidation. Typically, easily oxidized organic compounds, such as those with double bonds (e.g., trichloroethylene [TCE], perchloroethylene [PCE], and vinyl chloride [VC]), as well as simple aromatic compounds (e.g., toluene, benzene, xylene, and phenol), are rapidly destroyed by UV oxidation processes.

Limitations:

The following factors may limit the applicability and effectiveness of the processes:

- The aqueous stream being treated must permit good transmission of UV light (high turbidity causes interference), a factor that can be more critical for UV/hydrogen peroxide than UV/ozone.
- Free radical scavengers can inhibit contaminant destruction efficiency, because chemical additives, in high concentrations, may act as scavengers.
- The aqueous stream to be treated by UV oxidation should be relatively free of heavy metal ions (less than 10 mg/L) and insoluble oil or grease to minimize the potential for fouling of the quartz sleeves.
- When UV/ozone is used on volatile organics such as trichloroethane (TCA), contaminants that are volatilized (i.e., "stripped") rather than destroyed have to be removed from the off-gas by activated carbon adsorption or catalytic oxidation.

- Suspended solids or solids formed by precipitation of reduced iron or manganese species can occlude the quartz sleeves, requiring pretreatment to remove the fouling agents.
- Handling and storage of oxidizers require special safety precautions.
- Byproduct generation must be addressed when treating halogenated compounds.

Status: Innovative

Operation and Maintenance Duration:

UV oxidation is used to treat pumped groundwater or wastewater residual from a treatment process. The operation and maintenance duration depends on the duration of the primary process operation.

Cost Range: $0.70 to $10.00 per 1,000 gallons

The major cost items included in the cost estimate range for UV light/chemical oxidation of organics are designated in Table PC6b-1.

Table PC6b-1. Major Cost Items to Implement UV Light/Chemical Oxidation of Organics

Pretreatment Activities Included in Cost	
Filtration to remove suspended solids	
Fixed Cost Items Included	**Variable Cost Items Included**
UV/chemical oxidation system installation	Operating and maintenance labor
Peroxide addition or ozone generation system installation	Utilities
Off-gas treatment system installation	Chemicals Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
Disposal of treated water to publicly owned treatment works via site sewer	
Off-gas treatment	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to second and third level WBS elements X.24.14 "UV Oxidation".

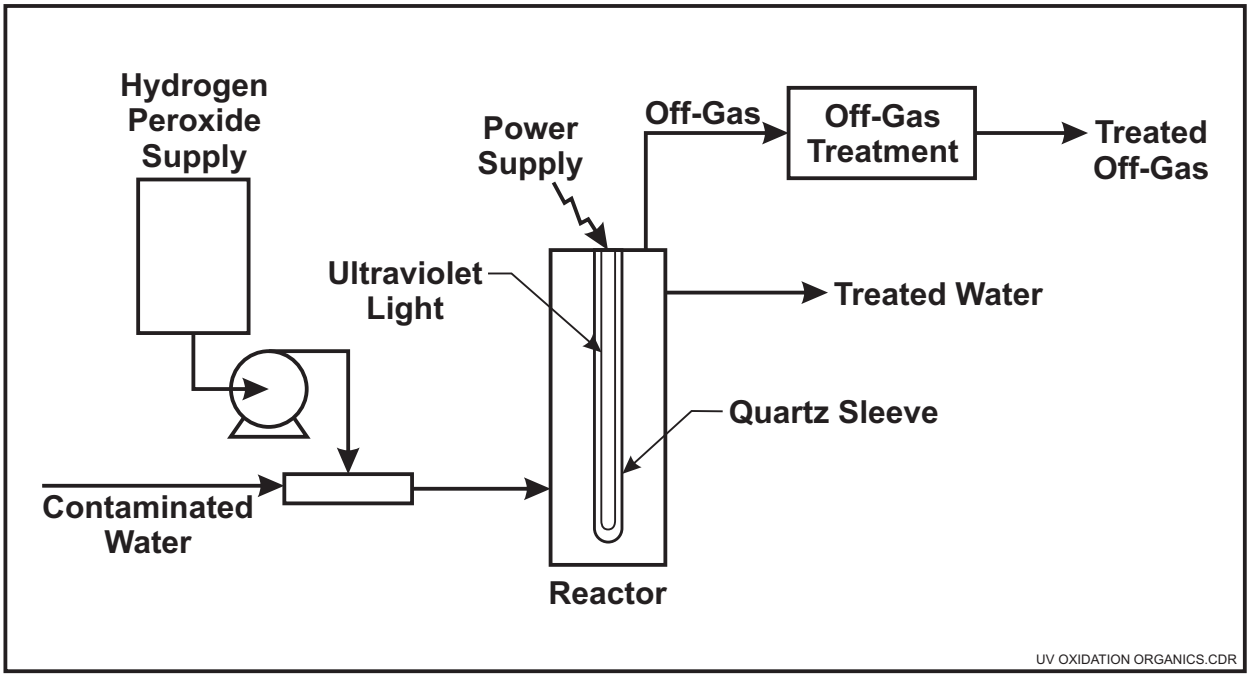


Figure PC6b. Ultraviolet Light/Chemical Oxidation (Organics)

PC7: Circulating Wells

Abstract:

Circulating well treatment is a process for moving groundwater around a well to allow in situ remediation of contaminants in and around the well.

Description:

Circulating well (CW) treatment is implemented by pumping in a well to form a three-dimensional circulation pattern of the groundwater around the well that moves contaminated water into a treatment zone in the well. Groundwater is drawn into a well through one screened section and is moved upward or downward in the well to a second screened section where it is reintroduced to the aquifer. The movement of water is driven by a mechanical or air lift pump and is sometimes supplemented by a vacuum applied to the well. The flow direction in the well can be either upward or downward, to accommodate site-specific conditions, depending on the location of packers in the well. Because groundwater is not pumped above ground, pumping costs are reduced and permitting issues eliminated. Also, the problems associated with storage and discharge are removed. In addition to groundwater treatment, CW systems can provide simultaneous vadose zone treatment in the form of bioventing or soil vapor extraction (SVE).

CW systems can provide treatment inside the well, in the aquifer, or a combination of both. For effective in-well treatment, the contaminants must be adequately soluble and mobile so they can be transported by the circulating groundwater. Currently, in-well treatments include air stripping, activated carbon adsorption, and biodegradation. Commonly, air stripping is provided by air-lift pumping, which simultaneously pumps and treats groundwater. In situ treatment is typically achieved by enhancing aerobic biodegradation in the formation with the addition of oxygen and nutrients. The combination of in-well and in situ treatment is best demonstrated by a CW equipped with an air stripping mechanism. In-well air stripping removes volatile contaminants and enriches the groundwater with oxygen before reintroducing it to the formation. The oxygen-rich groundwater promotes aerobic in situ biodegradation. Because CW systems provide a wide range of treatment options, they provide some degree of flexibility to a remediation effort.

Applicability:

In general, CW systems are most effective at treating sites with volatile contaminants with relatively high aqueous solubility and strong biodegradation potential, e.g., halogenated and nonhalogenated volatile organic compounds (VOCs). CWs operate more efficiently with horizontal conductivities greater than 10^{-3} cm/sec and a ratio of horizontal to vertical conductivities between 3 and 10. A ratio of less than 3 indicates short circulation times and a small radius of influence. If the ratio is greater than 10, the circulation time may be unacceptably long.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Subsurface heterogeneity can interfere with uniform flow in the aquifer around the well.
- Effective CW installations require a well-defined contaminant plume to prevent the spreading or smearing of the contamination.
- CWs are limited to sites with horizontal hydraulic conductivities greater than 10^{-5} cm/sec.
- Extremely thick plumes may prevent cost-effective treatment with a CW system.

- CW systems should not be applied to sites containing nonaqueous-phase liquids (NAPLs) to prevent the possibility of smearing the contaminants.

Status: Emerging

Operation and Maintenance Duration: N/A

Cost Range: N/A

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.25.9 "Other".

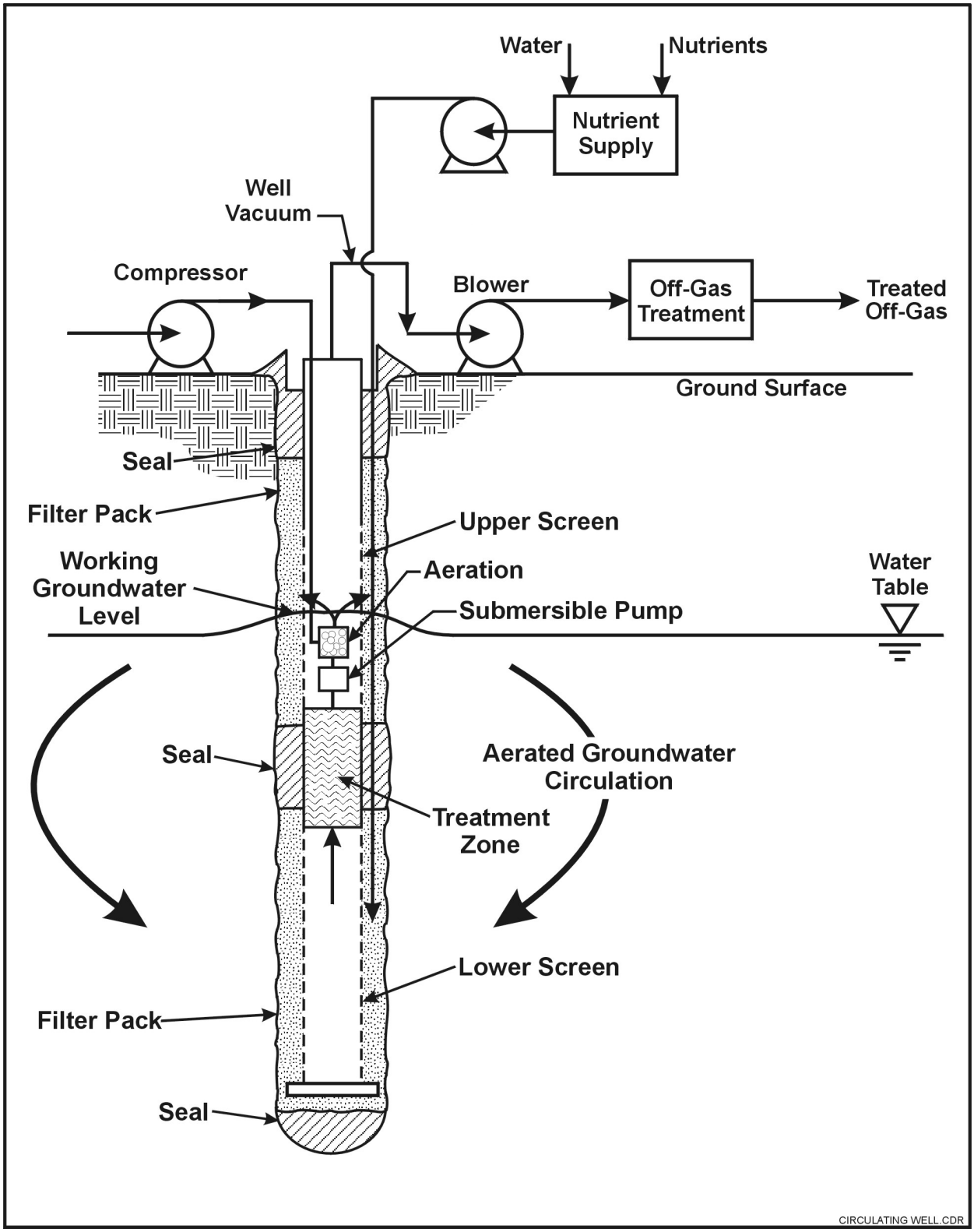


Figure PC7. Circulating Wells

PC8: Condensation

Abstract:

Condensation is the process of removing condensable organics from a noncondensable gas stream by reducing the gas stream temperature.

Description:

Organic vapor condensation from a gas stream may be performed by lowering the gas stream temperature at a constant pressure in a heat exchanger or increasing the gas stream pressure at a constant temperature (or combination of both).

There are two popular types of condensers: surface and direct contact. Surface condensers are generally shell-and-tube heat exchangers where coolant flows inside the tubes to condense the organics in a gas stream flowing outside the tubes. Contact condensers operate by spraying a cool liquid directly into a gas stream to cool it and condense the organics. In both types of condensers, the organics may be collected and reused. Coolants used to condense organics include chilled water, brine solutions, and cryogenic fluids.

Applicability:

Condensation is used primarily to treate halogenated and nonhalogenated volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs) and polychlorinated biphenyls (PCBs) in a gas stream. Condensation is most efficiently applied when the contaminant concentration is greater than 5,000 ppmv.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Readily available technologies, such as granular activated carbon (GAC) may be more cost-effective for low-concentration streams.
- Capital cost of the condenser and associated chilled water supply.
- Particulate in the gas stream may foul the condenser surfaces.

Status: Conventional

Operation and Maintenance Duration:

Condensation is used to treat off-gas from a primary treatment process. The operation and maintenance duration depends on the duration of the primary process operation.

Cost Range: $1.00 to $10.00 per pound of organic removed

The major cost items included in the cost estimate range for condensation are designated in Table PC8-1.

Table PC8-1. Major Cost Items to Implement Condensation

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Condenser installation	Operating and maintenance labor
Chiller installation	Utilities Cooling coil cleaning Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
None	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.34.17 "Condensation".

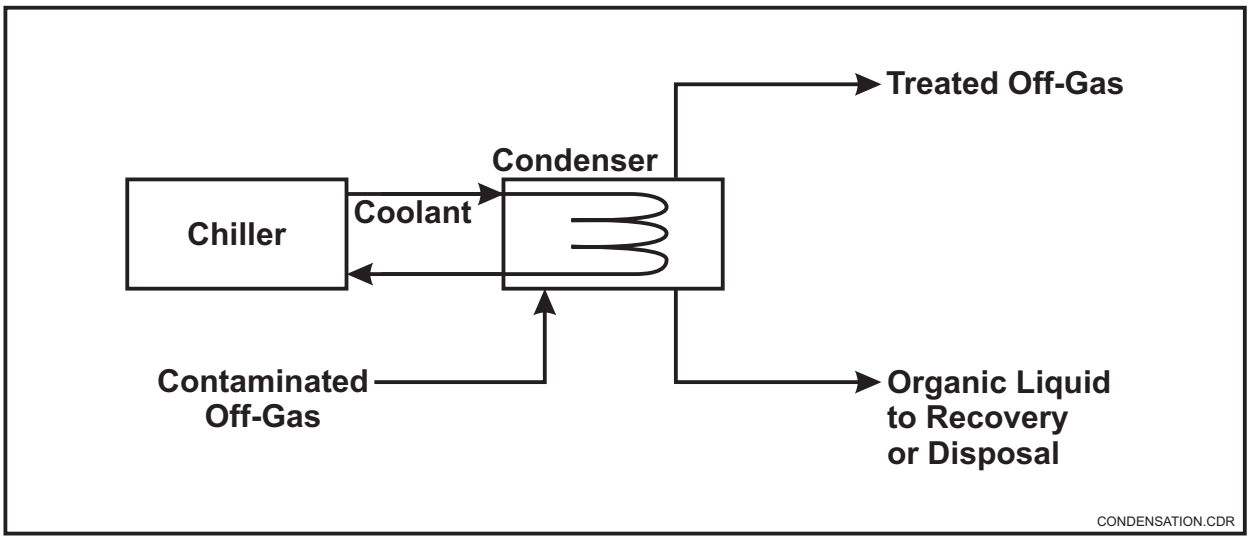


Figure PC8. Condensation

PC9: Electrokinetic Extraction

Abstract:

Electrokinetic extraction is an in situ process that separates and extracts metals and polar organic contaminants from saturated or unsaturated soils, sludges, and sediments.

Description:

Electrokinetic extraction is performed by applying a low voltage direct current across electrode pairs that have been implanted in the ground on each side of the contaminated soil mass. The electrical current causes electroosmosis and ion migration. The aqueous phase or contaminants desorbed from the soil surface are transported towards respective electrodes depending on their charge. The contaminants may then be extracted to a recovery system or deposited at the electrode. Surfactants and complexing agents can be used to increase solubility and assist in the movement of the contaminant. Also, reagents may be introduced at the electrodes to enhance contaminant removal rates.

Electrokinetics has been used for decades in the oil recovery industry and to remove water from soils, but in situ application of electrokinetics to remediate contaminated soil is new. Recently, attention has focused on developing in situ electrokinetic techniques for the treatment of low permeability soils, which are resistant to remediation with traditional technologies because of their low hydraulic conductivity.

Applicability:

The target contaminants groups for electrokinetic technology are dissolved polar species such as metal ions, anions, and water soluble organics. Electrokinetics is being used commercially in Europe to remove heavy metal contaminants such as uranium, mercury, and metal mixtures.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- The process must be operated long enough to acidify the entire contaminated volume.
- Solutions must be extracted from the electrode installation wells to control in situ conditions and treated prior to reinjection or disposal.
- Works best in soils with high clay content.
- Chloride in the groundwater can be converted to chloride at the anode, resulting in the formation of trihalomethanes.

Status: Emerging

Operation and Maintenance Duration: N/A

Cost Range: N/A

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.25.16 “Electrokinetics”.

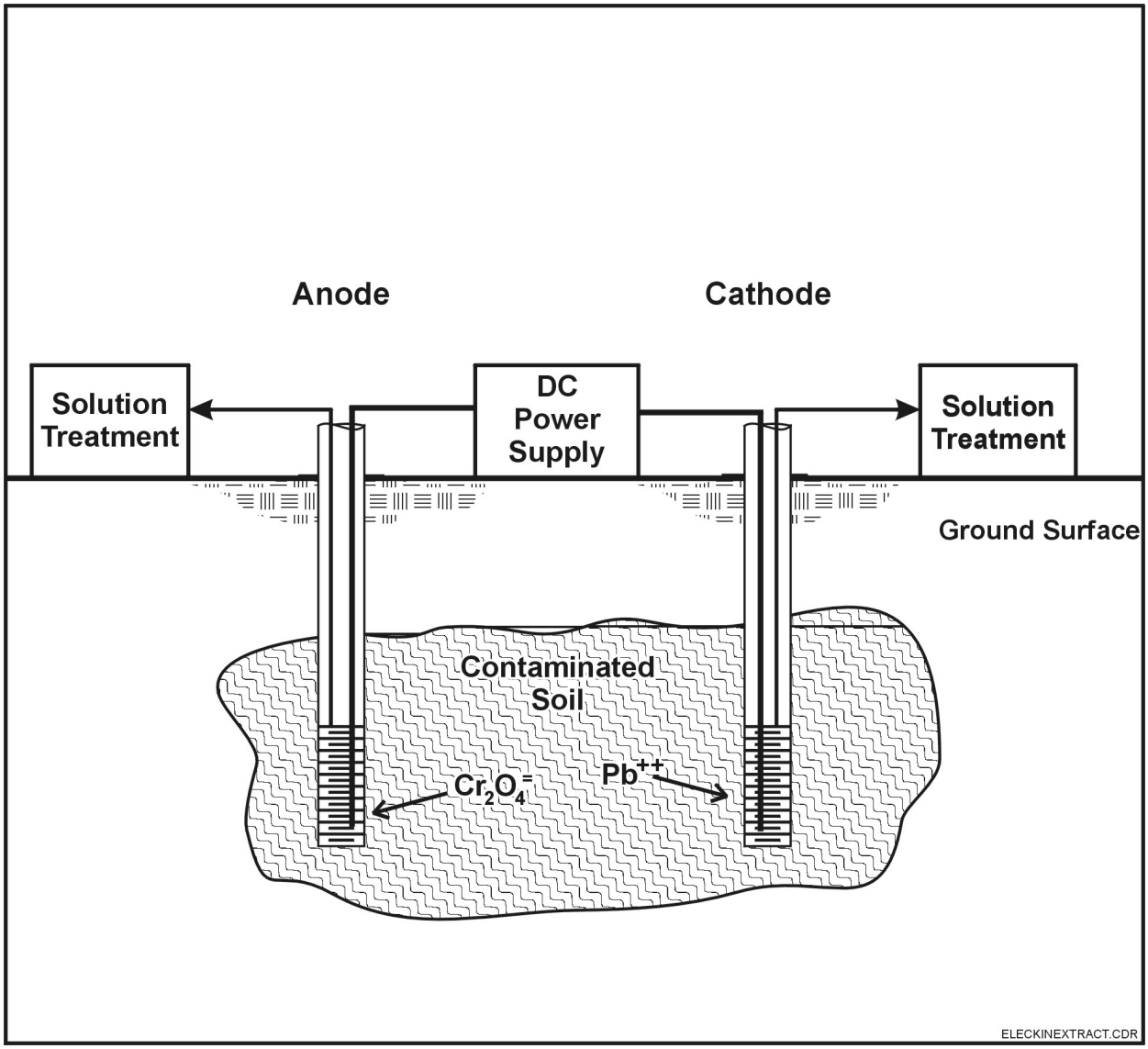


Figure PC9. Electrokinetic Extraction

PC10a: Granular Activated Carbon (GAC) Adsorption (Liquid Phase)

Abstract:

Liquid-phase GAC adsorption is an ex situ treatment technology for removing organics from pumped groundwater or wastewater.

Description:

Liquid-phase GAC treatment is performed by pumping groundwater through one or more vessels containing activated carbon, which removes contaminants from the water stream by sorption until available active sites are occupied. Carbon is "activated" for this purpose by being processed to create porous particles with a large internal surface area (300 to 2,500 square meters or 3,200 to 27,000 square feet per gram of carbon) that attracts and adsorbs organic molecules as well as certain metal and inorganic molecules. As the available surface sites become occupied, the contaminant concentration in the bed effluent increases. When the concentration of contaminants in the effluent from the bed exceeds a specified action level, the carbon can be regenerated in place, removed and regenerated at an off-site facility, or removed for disposal. Adsorption by activated carbon has a long history of use in treating municipal, industrial, and hazardous wastewaters.

The two most common reactor configurations for carbon adsorption systems are the fixed bed and the pulsed or moving bed. The fixed-bed configuration is the most widely used for adsorption from liquids. Suspended solids in a liquid stream may accumulate in the column, causing further pressure drop. When the pressure drop becomes too great, the accumulated solids must be removed, for example, by backwashing. The solids removal process necessitates adsorber downtime and may result in carbon loss and disruption of the mass transfer zone. Pretreatment for removal of solids from streams to be treated is, therefore, an important design consideration.

Applicability:

Liquid-phase GAC can be used to treat halogenated and nonhalogenated volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs), polychlorinated biphenyls (PCBs), and ordnance compounds. The target contaminant groups for carbon adsorption are SVOCs and explosives. Limited effectiveness may be achieved on some halogenated VOCs, such as vinyl chloride or dichloroethylenes. Liquid-phase carbon adsorption is effective for removing contaminants at low concentrations (less than 1 mg/L) from water at nearly any flowrate, and for removing higher concentrations of contaminants from water at low flowrates (typically 40 liters per minute or 10 gpm). Carbon adsorption systems are particularly effective for polishing water discharges from other remedial technologies to attain regulatory compliance. Carbon adsorption systems can be deployed rapidly, and contaminant removal efficiencies are high. Logistic and economic disadvantages arise from the need to transport and decontaminate spent carbon.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Spent carbon may be a Resource Conservation and Recovery Act (RCRA) hazardous waste.
- Spent carbon must be regenerated or disposed of and the adsorbed contaminants must be destroyed, often by incineration.

- The presence of multiple contaminants can affect the process performance due to competitive adsorption of different classes of compounds. Single component isotherms may not be applicable for mixtures. Bench tests may be conducted to estimate carbon usage for mixtures.
- Some common chlorinated contaminants are weakly sorbed, causing low GAC capacity.
- Suspended solids or solids formed by precipitation of reduced iron or manganese species in solution can foul a GAC bed, requiring pretreatment to remove the fouling agents.
- Type and pore size of the carbon, as well as the operating temperature, must be carefully selected to optimize contaminant removal.
- Carbon used for explosives-contaminated groundwater is not regenerated and must be properly disposed of .
- Water-soluble compounds and small molecules are not adsorbed well.

Status: Conventional

Operation and Maintenance Duration:

Liquid-phase GAC adsorption is used to treat pumped groundwater or wastewater residual from a treatment process. The operation and maintenance duration depends on the duration of the primary process operation.

Cost Range: $0.50 to $5.00 per 1,000 gallons

The major cost items included in the cost estimate range for GAC adsorption (liquid phase) are designated in Table PC10a-1.

Table PC10a-1. Major Cost Items to Implement GAC Adsorption (Liquid Phase)

Pretreatment Activities Included in Cost	
Filtration to remove suspended solids	
Fixed Cost Items Included	**Variable Cost Items Included**
GAC system installation	Operating and maintenance labor Utilities Replacement carbon Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
Off-site disposal or regeneration of spent carbon	
Disposal of treated water to publicly owned treatment works via site sewer	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.26.23 "Granular Activated Carbon Adsorption—Liquid".

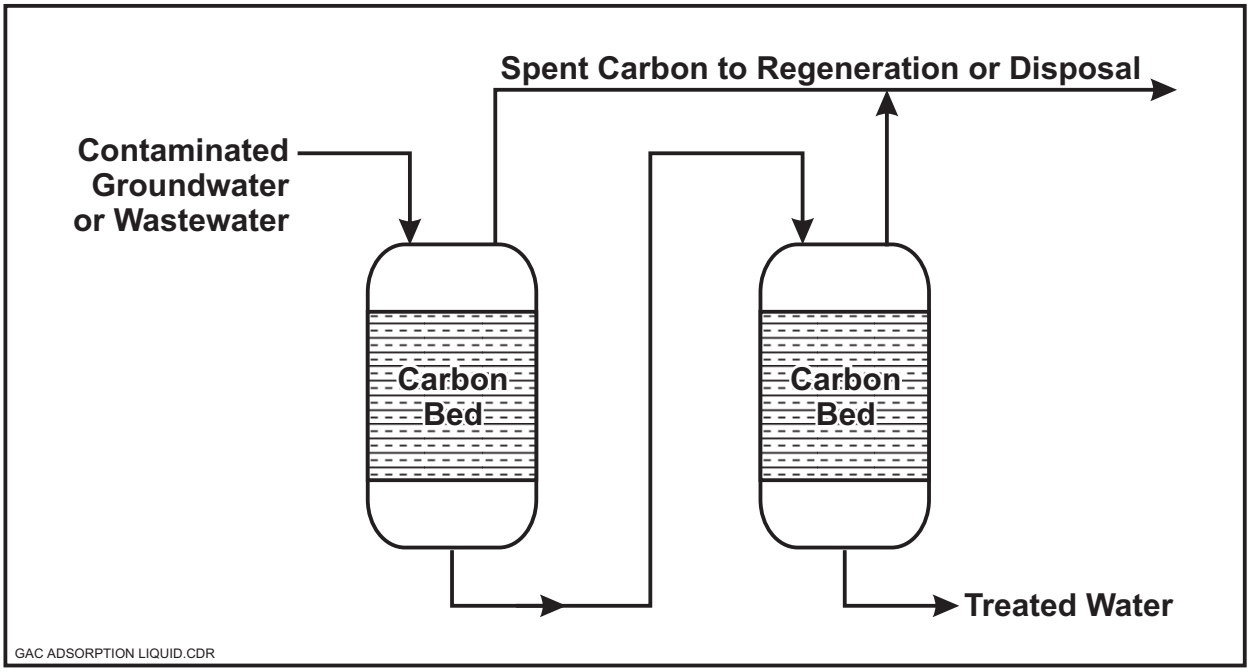


Figure PC10a. Granular Activated Carbon Adsorption (Liquid Phase)

PC10b: Granular Activated Carbon (GAC) Adsorption (Vapor Phase)

Abstract:

Vapor-phase GAC adsorption is a treatment technology in which pollutants are removed from air by physical adsorption onto activated carbon grains.

Description:

Vapor-phase GAC treatment is performed by passing an off-gas stream through one or more vessels containing activated carbon, which removes contaminants from the gas stream by sorption until available active sites are occupied. Carbon is "activated" for this purpose by being processed to create porous particles with a large internal surface area (300 to 2,500 square meters or 3,200 to 27,000 square feet per gram of carbon) that attracts and adsorbs organic molecules as well as certain metal and inorganic molecules.

Commercial grades of activated carbon are available for specific use in vapor-phase applications. The granular form of activated carbon is typically used in packed beds through which the contaminated air flows until the concentration of contaminants in the effluent from the carbon bed exceeds an acceptable level. GAC systems typically consist of one or more vessels filled with carbon connected in series and/or parallel operating under atmospheric, negative, or positive pressure. The carbon can then be regenerated in place, regenerated at an off-site regeneration facility, or disposed of, depending upon economic considerations.

The capacity of carbon to adsorb contaminants depends on the properties of the contaminants. In particular large, polar molecules tend to adsorb more strongly than small, nonpolar molecules. Some common chlorinated solvents, such as vinyl chloride, are poorly adsorbed (see Table PC10b-1).

Table PC10b-1. Capacities for Gas-Phase Adsorption on Activated Carbon

Contaminant	Q at 10 ppmv	Q at 100 ppmv	Q at 1,000 ppmv
Octane	17.4	24.6	32.8
Hexane	11.2	16.7	22.9
Benzene	11.9	19.6	29.0
Toluene	20.1	28.2	36.1
o-Xylene	28.7	35.7	41.4
Trichloroethylene	19.9	33.2	49.4
Tetrachloroethylene	39.2	54.7	69.4
Vinyl chloride	0.43	1.5	4.2
1,1-Dichloroethylene	6.4	12.2	21.9
1,2-Dichloroethylenes	6.9	14.3	26.2

(a) Q = g compound/100g GAC.

Applicability:

Vapor-phase carbon adsorption is used primarily to treat halogenated and nonhalogenated volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs) and polychlorinated biphenyls (PCBs)

in a gas stream. GAC treatment is most efficiently applied when the contaminant concentration is less than 200 ppmv or the off-gas flowrate is low.

Limitations:

The following factors may limit the effectiveness of this process:

- Spent carbon may be a Resource Conservation and Recovery Act (RCRA) hazardous waste.
- Spent carbon must be regenerated or disposed of and the adsorbed contaminants must be destroyed, often by incineration.
- Relative humidity greater than 50% can reduce carbon capacity.
- Elevated temperatures from soil vapor extraction (SVE) pumps (greater than 38°C or 100°F) inhibit adsorption capacity.
- Some common chlorinated contaminants are weakly sorbed, causing low GAC capacity.
- Biological growth on carbon or high particulate loadings can reduce flow through the bed.
- Some compounds, such as ketones, may cause carbon bed fires because of their high heat release upon adsorption.

Status: Conventional

Operation and Maintenance Duration:

Vapor-phase adsorption is used to treat off-gas from a primary treatment process. The operation and maintenance duration depends on the duration of primary process operation.

Cost Range: $4.00 to $20.00 per pound of organic removed

The major cost items included in the cost estimate range for GAC adsorption (vapor phase) are designated in Table PC10b-2.

Table PC10b-2. Major Cost Items to Implement GAC Adsorption (Vapor Phase)

Pretreatment Activities Included in Cost	
Preheat to reduce relative humidity to <50% (if needed)	
Fixed Cost Items Included	**Variable Cost Items Included**
GAC system installation	Operating and maintenance labor Utilities Replacement carbon Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
Off-site disposal or regeneration of spent carbon	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.34.10 "Granular Activated Carbon Adsorption—Gas/Vapor".

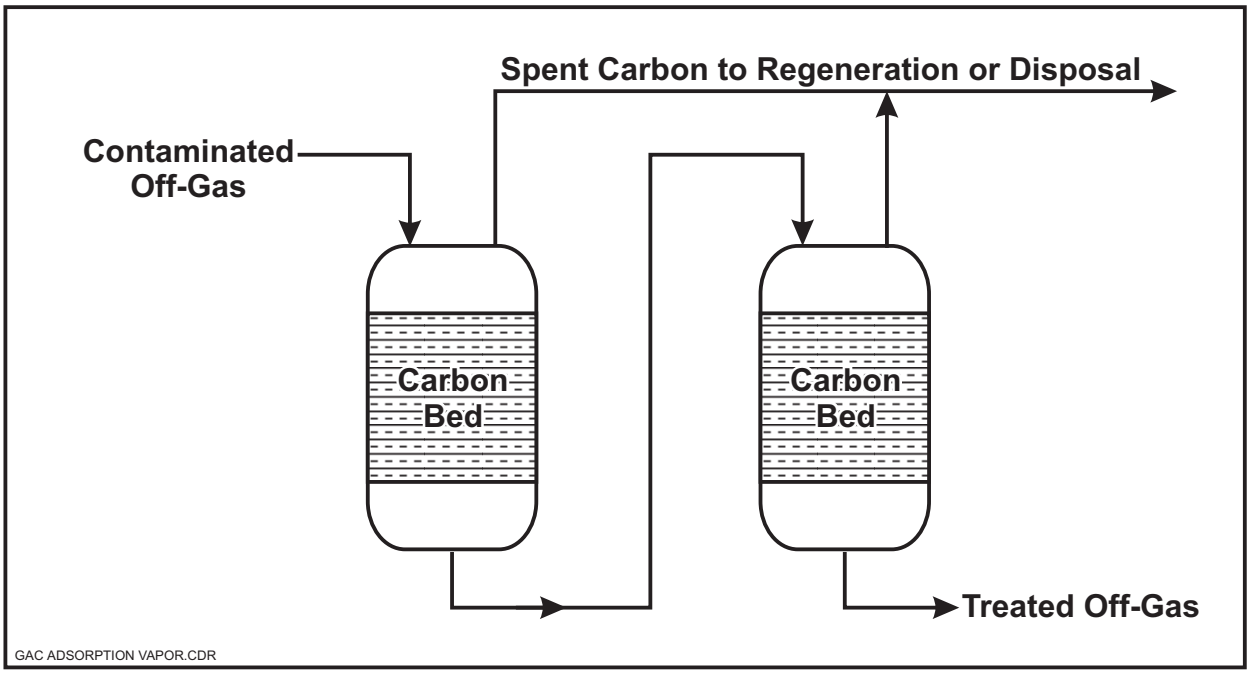


Figure PC10b. Granular Activated Carbon (GAC) Adsorption (Vapor Phase)

PC11: In Situ Heating – High Temperature (>100°C)

Abstract:

In situ heating (supplemented by vacuum extraction) to temperatures above the boiling point of water is a technology for vaporizing high-boiling-point organics from in situ soil or groundwater for collection and management above ground.

Description:

In situ heating to above 100°C can be implemented using electrical heat input by conduction (i.e., thermal wells and blankets) or radiation (i.e., radiofrequency [RF] heating). In situ temperatures higher than 1000°C can be reached with these heating methods in the vadose zone.

These high temperatures can also be reached in the saturated zone if the groundwater flowrate is low enough that the system heat input rate is more than sufficient to boil all of the incoming water. Vaporized water and contaminants are collected by vapor extraction wells and blowers similar to those used for a standard soil vapor extraction (SVE) system, but designed for very high temperature operation.

Conduction heating (also referred to as in situ thermal desorption) can be implemented using surface heating blankets to treat soil from the surface down to abut 3 ft bgs or heating elements installed in wells for deeper contamination.

The thermal blanket system uses modular electrically heated blankets that are placed on top of the contaminated ground surface. The blankets can operate at temperatures up to 1,000°C. Heat from the blankets is conducted down into the soil to vaporize contaminants in the upper 3 ft. Each blanket module is covered with an impermeable membrane and is provided with an exhaust port giving access to the space under the blanket. The exhaust ports for the blankets covering a treatment area are connected to a common manifold leading to the suction of a blower. Soil heating causes contaminants to vaporize and migrate to the surface because of the negative pressure caused under the blanket by the blower. The vaporized contaminants are withdrawn from under the blanket and enter a thermal treatment unit where they are oxidized. The high temperature gas stream is then cooled to protect the blower and passed through a carbon bed that collects any trace levels of organics not oxidized prior to release to the atmosphere.

The thermal well system involves an arrangement of electrical immersion heating elements placed in vertical wells spaced about 7 to 10 ft apart. The heating elements operate at up to 1,000°C to heat the surrounding soil. Similar to the thermal blanket system, heat transfer from the wells into the soil occurs by conduction. The wells are installed with an outer perforated screen. The top outlets of all of the wells used in a particular application are connected to a common manifold. Similar to the blanket modules, vacuum applied to the manifold removes air and desorbed contaminants for treatment by thermal oxidation and carbon adsorption.

RF heating is accomplished by use of electromagnetic energy in the RF band. The heating process does not rely on the thermal conductivity of the soil. The energy is introduced into the soil matrix by electrodes inserted into drilled holes. The mechanism of heat generation is similar to that of a microwave oven. A modified radio transmitter serves as the power source, and the industrial, scientific, and medical band provides the frequency at which the modified transmitter operates. The exact operational frequency is obtained from an evaluation of the real extent of contamination and the dielectric properties of the soil matrix.

Full implementation of an RF heating system at a contaminated hazardous waste site requires four major subsystems.

- A RF energy radiation array
- RF power generating, transmitting, monitoring, and control systems
- A vapor barrier and containment system
- A vapor recovery and treatment system.

Applicability:

High-temperature in situ heating is used primarily to treat halogenated and nonhalogenated semivolatile organic compounds (SVOCs), polychlorinated biphenyls (PCBs), and dense, nonaqueous-phase liquid (DNAPL).

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Subsurface heterogeneity can interfere with uniform treatment of in situ media.
- Performance in extracting less volatile contaminants varies depending upon the maximum temperature achieved in the process selected.
- The heating and vapor collection systems must be designed and operated so as to limit the spread of contaminants to clean areas.
- The soil structure at the site may be modified by the high temperature.
- The high energy input required to boil water increases the cost significantly when the saturated zone is treated.
- Soil that has a high clay or humic content has a high sorption capacity of volatile organic compounds (VOCs), which results in reduced removal rates.
- Off-gas collection and treatment are required.

Status: Innovative

Operation and Maintenance Duration:

Soil remediation by in situ heating typically can be done in a treatment period of 3 to 6 months, depending on the following conditions:

- Cleanup goals
- The volume of in situ media requiring treatment
- Contaminant concentrations and distribution
- In situ characteristics including permeability and anisotropy
- Physical characteristics of contaminants including vapor pressure and Henry's law constant
- Moisture content of the soil.

Cost Range: $10,000 to $20,000 fixed mobilization cost plus $90 to $290 per cubic yard operating cost

The major cost items included in the cost estimate range for in situ heating – high temperature are designated in Table PC11-1.

Table PC11-1. Major Cost Items to Implement In Situ Heating – High Temperature

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Well installation	Heating system leasing
Sampling point installation	Off-gas treatment system leasing
Crew and equipment mobilization	Operating and maintenance labor Utilities Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
Off-gas treatment	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.27.01 "Thermal Blanket (with Vacuum Extraction)", X.27.08 "RadioFrequency/Electomagnetic Heating", and X.27.90 "Thermal Wells". Note that thermal wells typically are used with thermal blankets.

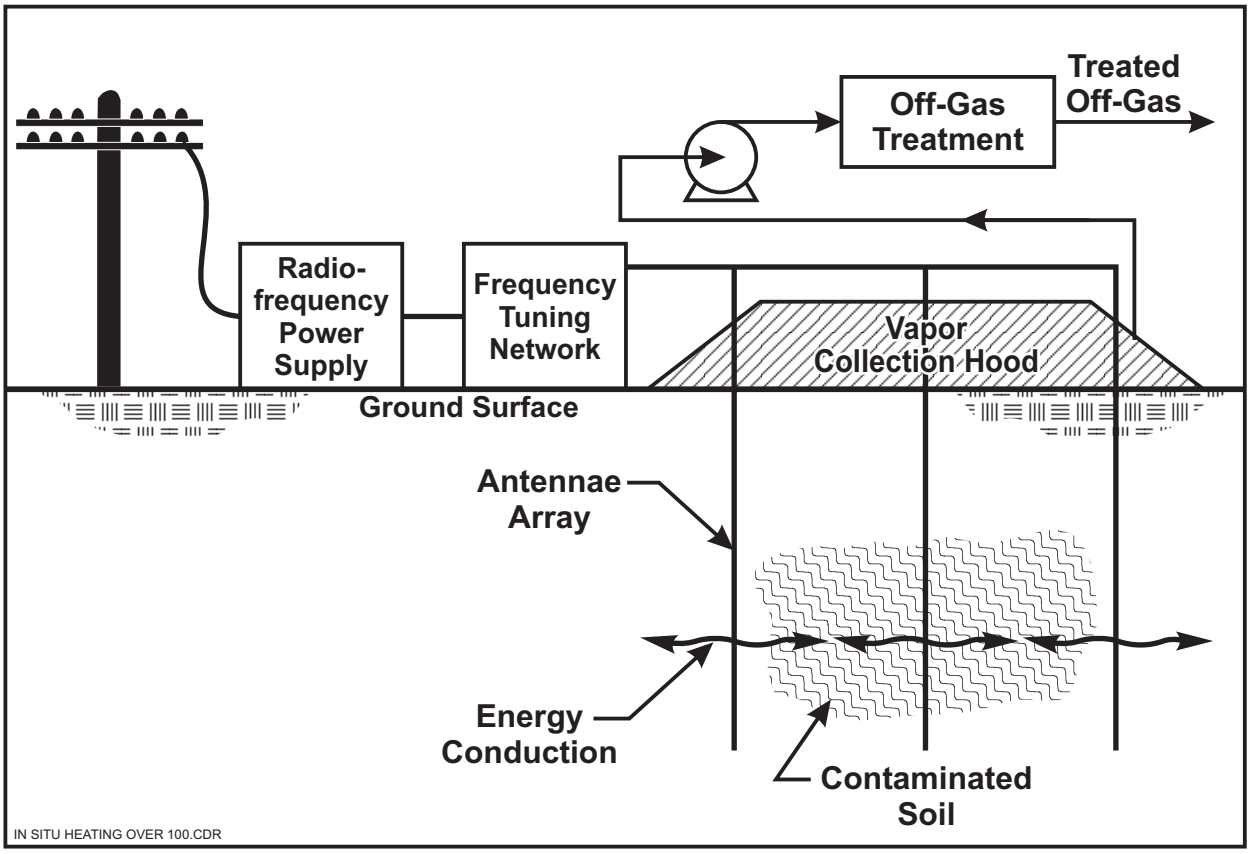


Figure PC11. In Situ Heating >100°C

PC12a: Solidification/Stabilization (In Situ)

Abstract:

Solidification/stabilization (S/S) is a remediation process for in situ soil that reduces the mobility of hazardous substances and contaminants in the environment using a binding agent.

Description:

S/S treatment is designed to immobilize contaminants within the contaminated matrix, instead of removing them through chemical or physical treatment. Soil is mixed with a binder, (such as portland cement) to reduce contaminant mobility by a combination of physical entrapment (e.g., encapsulation or purosity reduction) and chemical reaction (e.g., hydroxide precipitation). Leachability testing is typically performed to measure the immobilization of contaminants. In situ S/S techniques use auger systems or grout injection systems to apply S/S agents to in situ soils.

Auger mixing involves using large soil augers to mix binder into in situ soil. Binder is applied through nozzles at the bottom on the augers as they turn, mixing and drilling into the soil. Grout injection involves forcing binder into the soil porosity using high-pressure grout injection pipes forced into the soil.

Applicability:

In situ S/S is used primarily to treat inorganics. The technology has limited effectiveness against semivolatile organic compounds (SVOCs) and pesticides; however, binder formulations designed to be more effective in treating organics are being developed and tested.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Long-term effectiveness has not been demonstrated for many contaminant/process combinations.
- A high proportion of rocks or debris in situ can interfere with binder injection or mixing.
- Depth of contaminants may limit some types of application processes.
- Binder injection and mixing must be controlled to minimize the spread of contaminants to clean areas.
- Exposure to water or freeze/thaw cycles may reduce immobilization of contaminants.
- It can be difficult to formulate an effective binder for complex waste.
- Reagent delivery and effective mixing are more difficult and costly than for ex situ applications.
- VOCs generally are not immobilized.
- Auger mixing is limited to depths less than 150 ft.

Status: Innovative

Operation and Maintenance Duration:

In situ S/S typically can be performed in a treatment period of 3 to 6 months, depending on the following conditions:

- Cleanup goals
- The volume of in situ media requiring treatment

- Contaminant concentration and distribution
- Subsurface soil characteristics including particle size distribution and density.

Cost Range: $10,000 to $20,000 fixed mobilization cost plus $90 to $290 per cubic yard operating cost

The major cost items included in the cost estimate range for in situ S/S are designated in Table PC12a-1.

Table PC12a-1. Major Cost Items to Implement In Situ S/S

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Crew and equipment mobilization	Equipment leasing Operating and maintenance labor Utilities Binder Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
None	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.29.03 "Pozzolan Process (Lime/Portland Cement)".

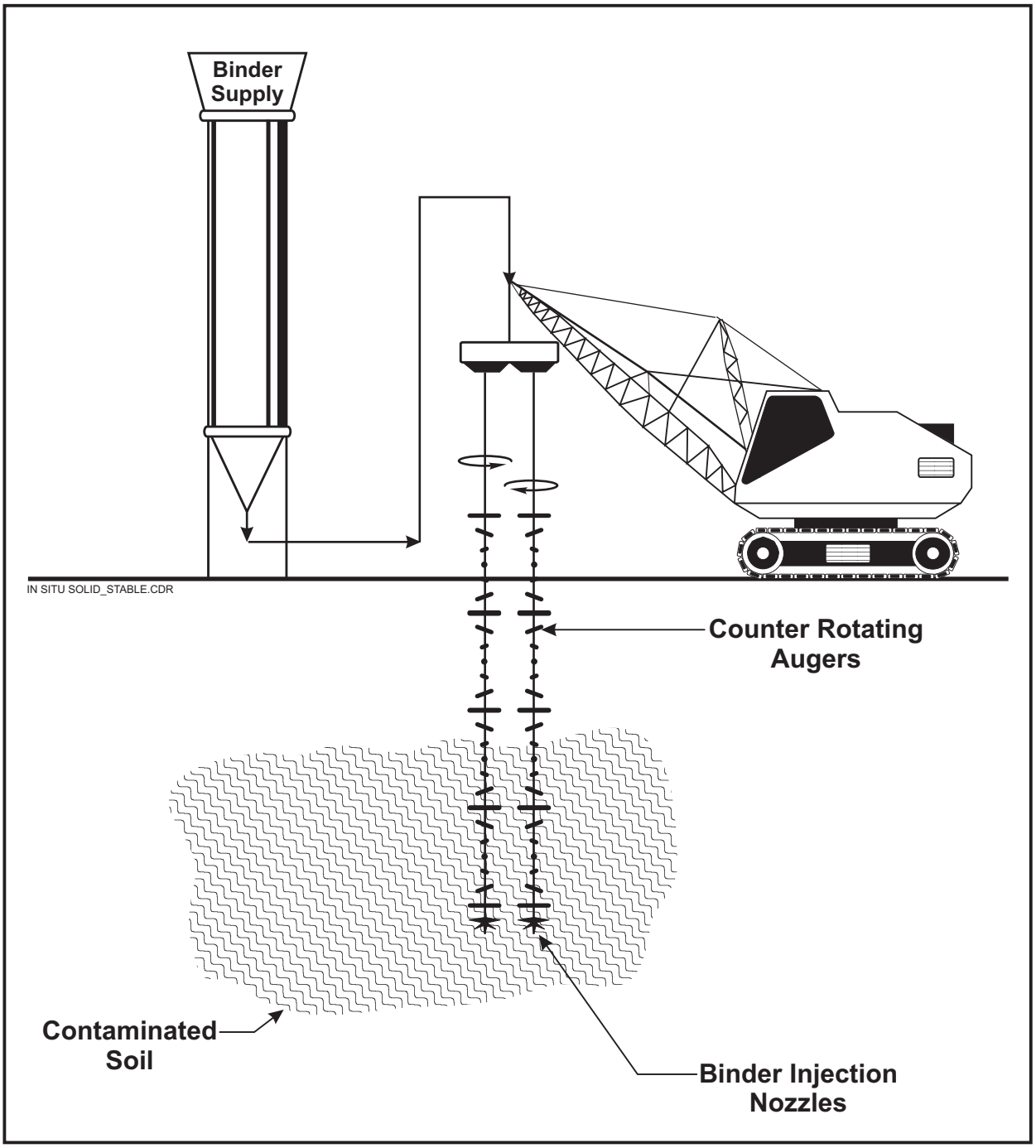


Figure PC12a. In Situ Solidification/Stabilization

PC12b: Solidification/Stabilization (Ex Situ)

Abstract:

Ex situ solidification/stabilizaiton (S/S) is a treatment process for excavated soil that relies on reducing the mobility of contaminants using a binding agent.

Description:

Contaminant mobility reduction is achieved by mixing soil with a binder that provides a combination of physical entrapment (e.g., encapsulation or porosity reduction) and chemical reaction (e.g., hydroxide precipitation). A wide variety of materials are used as S/S binders including portland cement, pozzolans, silicates, bitumen, and polymers. Portland cement and related aluminosilicate pozzolans (e.g., blast furnace slag or fly ash) are the most commonly used binders. Cement and water are mixed with soil using a pug mill, rotating drum mixer, or other slurry mixing apparatus. Additives may also be included in the mixture to improve the immobilization of specific contaminants or off-set negative affects of contaminants on setting time or ultimate strength.

Applicability:

Ex situ S/S is used primarily to treat inorganics. The technology has limited effectiveness against semivolatile organic compounds (SVOCs) and pesticides; however, binder formulations designed to be more effective against organic contaminants are being developed and tested.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Long-term effectiveness has not been demonstrated for many contaminant/process combinations.
- Environmental conditions in the final disposal site may affect the long-term immobilization of contaminants.
- Some processes result in a significant increase in volume (up to double the original volume).
- Organics can interfere with binder setting.
- Volatile organic compounds (VOCs) generally are not immobilized and can escape during mixing.
- It can be difficult to formulate an effective binder for complex waste.
- Debris greater than 60 mm in diameter typically must be removed prior to processing.

Status: Conventional

Operation and Maintenance Duration:

Ex situ S/S is used to treat excavated soil, so the operation and maintenance duration depends on the processing rate of the treatment unit and the volume of soil. Processing typically would be done on site in a mobile unit. The throughput of a mobile unit is expected to range from 10 to 500 cubic yards per day.

Cost Range: $10,000 to $20,000 fixed mobilization cost plus $90 to $290 per cubic yard operating cost

The major cost items included in the cost estimate range for ex situ S/S are designated in Table PC12b-1.

Table PC12b-1. Major Cost Items to Implement Ex Situ S/S

Pretreatment Activities Included in Cost	
Screening to remove debris	
Fixed Cost Items Included	**Variable Cost Items Included**
Crew and equipment mobilization	Soil excavation
Treatment pad installation	Equipment leasing Operating and maintenance labor Utilities Binder Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
On-site disposal of treated soil, sediment, or sludge	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.30.04 "Pozzolan Process (Lime/Portland Cement)".

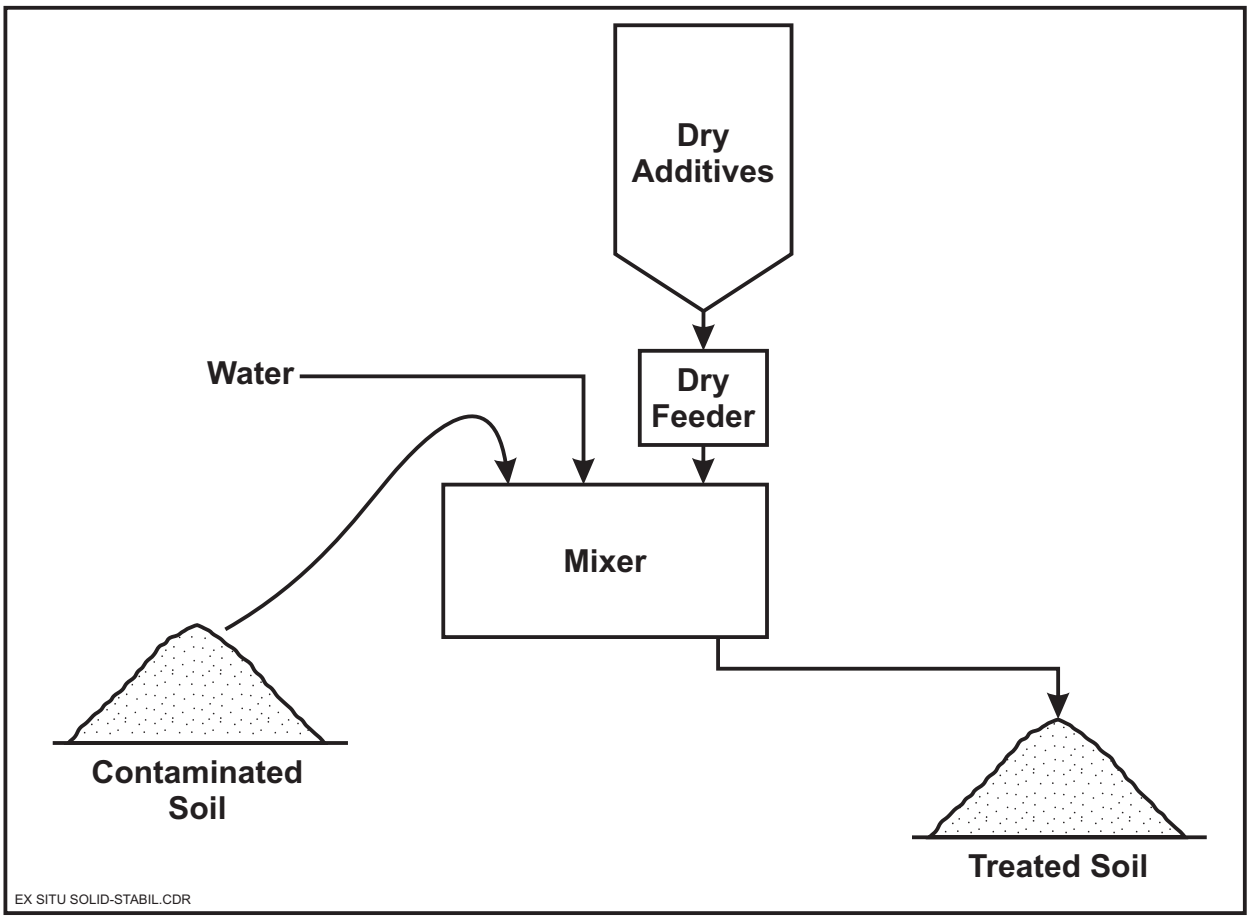


Figure PC12b. Solidification/Stabilization (Ex Situ)

PC13a: Vitrification (In Situ)

Abstract:

In situ vitrification (ISV) is a treatment process for in situ soil that immobilizes contaminants in a glassy matrix formed by melting soil.

Description:

ISV involves using an electric current to melt soil or other earthen materials at extremely high temperatures (1,600-2,000°C or 2,900-3,650°F). Organics are pyrolyzed and vaporized by the high temperature. Water vapor and organic pyrolysis combustion products are captured in a hood, which draws the contaminants into an off-gas treatment system that removes particulates and other pollutants from the gas. Upon cooling, the melt solidifies to form a glassy solid, immobilizing most inorganics.

High temperatures are achieved using a square array of four graphite electrodes. To initiate the process, a path of conducting material (graphite) is placed on the surface of the soil so that current can flow in the soil beyond the boiling temperature of water (dry soil is not conductive after the conduction path in soil pore water is boiled off) to the melting point of the soil. The joule heating of the starter path achieves temperatures high enough to melt the soil (value is dependent on the soil's alkali metal oxide content), at which point the soil becomes conductive. The molten soil zone grows downward and outward. New designs incorporate a moving electrode mechanism to achieve a greater process depth. A vacuum pressurized hood is placed over the vitrification zone to contain and process any contaminants emanating from the soil during vitrification. The vitrification product is a chemically stable, leach-resistant, glass and crystalline material similar to obsidian or basalt rock. The process destroys and/or removes organic materials. Radionuclides and heavy metals are retained within the molten soil.

Applicability:

The ISV process can destroy or remove organics and immobilize most inorganics in contaminated soils, sludges, other earthen materials. The process has been tested on a broad range of volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs), other organics including dioxins and polychlorinted biphenyls (PCBs), and on most priority pollutant metals and radionuclides.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Buried electrical conduction paths (e.g., pipes or drums).
- Rubble exceeding 20% by weight.
- Heating the soil may cause subsurface migration of contaminants into clean areas.
- Large accumulations of flammable or explosive materials.
- Combustible organics in the soil or sludge exceeding 5 to 10 weight percent (wt%), depending on the heating value.
- The solidified material may hinder future site use.
- Processing of contamination below the water table may require some means to limit recharge.
- High moisture content increases cost.

Status: Innovative

Operation and Maintenance Duration:

ISV typically can be performed in a treatment period of 6 to 24 months, based on the following conditions:

- Cleanup goals
- The volume of in situ soil requiring treatment
- Contaminant concentration and distribution
- Soil moisture content.

Cost Range: $40,000 to $80,000 fixed mobilization cost plus $450 to $900 per cubic yard operating cost

The major cost items included in the cost estimate range for in situ vitrification are designated in Table PC13a-1.

Table PC13a-1. Major Cost Items to Implement In Situ Vitrification

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Crew and equipment mobilization	Power supply and electrode system leasing Hood and off-gas treatment system leasing Operating and maintenance labor Utilities Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
Off-gas treatment	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.29.04 "In Situ Vitrification".

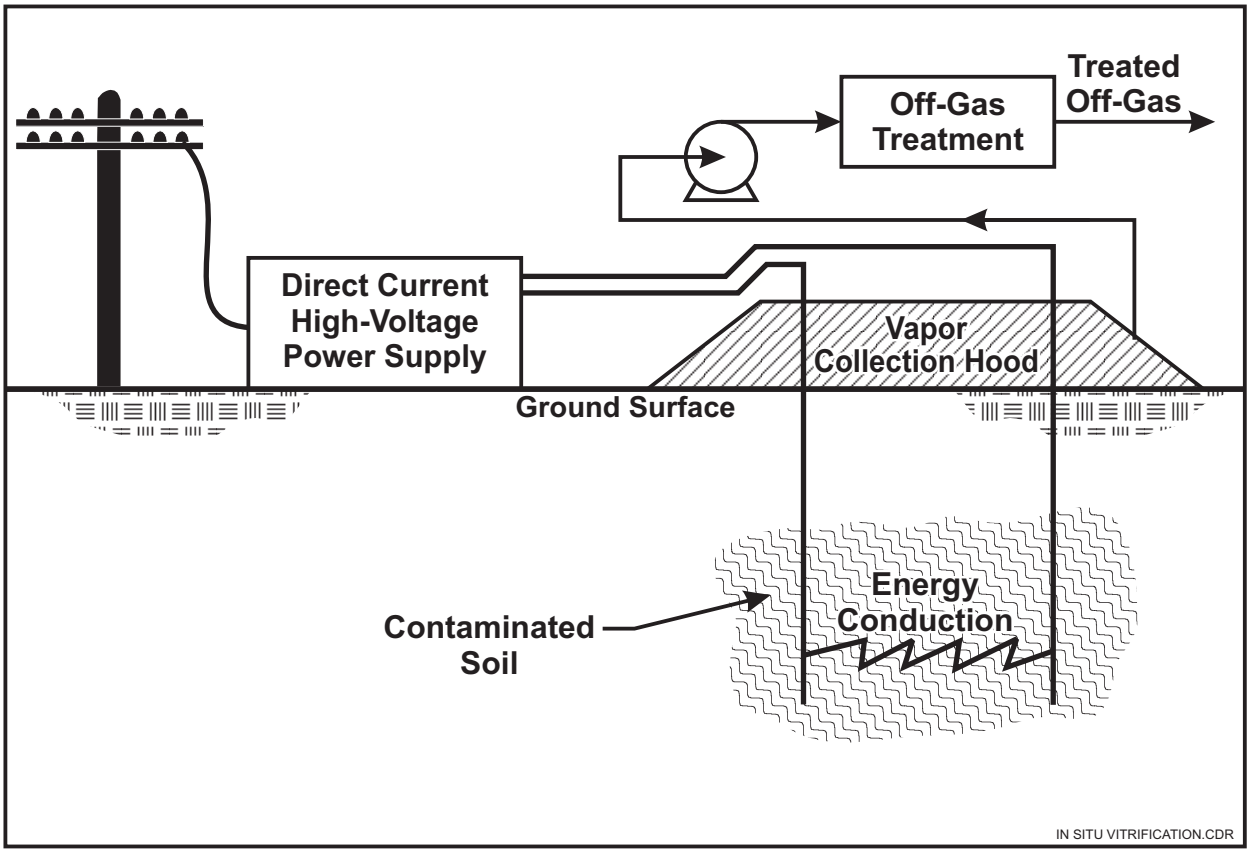


Figure PC13a. In Situ Vitrification

PC13b: Vitrification (Ex Situ)

Abstract:

Ex situ vitrification is a treatment process for excavated soil that immobilizes contaminants by melting soil.

Description:

Ex situ vitrification is performed using a plasma torch, an electrical current, or other heat source to melt soil or other contaminated matrices at extremely high temperatures (1,600 - 2,000°C or 2,900 - 3,650°F). Organics are pyrolyzed and vaporized by the high temperatures. Water vapor and pyrolysis products are captured by an off-gas treatment system for additional processing prior to discharge. The melt exits the vitrification unit where it cools to form a glassy solid that immobilizes inorganics.

Ex situ vitrification is effective in reducing the mobility of the contaminated wastes within a media. The vitrified mass has high strength and resistance to leaching. The strength properties of material vitrified by different systems can vary widely. Systems in which the vitrified mass is quench-cooled may produce a more easily fractured mass than systems in which the mass is allowed to air cool. In addition, systems in which fluxing agents are used will have different strength properties. The composition of the soil that is vitrified may also affect the strength properties of the vitrified material.

Ex situ vitrification is normally considered a stand-alone technology; however, its potential for use in treating the solid residuals from other technologies, such as incinerator ash, is receiving increasing attention.

Applicability:

Ex situ vitrification can destroy or remove organics and immobilize most inorganics in contaminated soils, sludges, or other earthen materials.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Organic contaminants in the off-gas need to be controlled, and some volatile heavy metals may volatilize and require treatment in the off-gas system.
- Use or disposal of the resultant vitrified slag is required.
- High moisture content increases costs.
- Debris greater than 60 mm in diameter typically must be removed prior to processing.

Status: Innovative

Operation and Maintenance Duration:

Ex situ vitrification is used to treat excavated soil, so the operation and maintenance duration depends on the processing rate of the treatment unit and the volume of soil. Processing typically would be performed on site in a mobile unit. The throughput of a mobile unit is expected to range from 5 to 30 cubic yards per day.

Cost Range: $500 to $1,000 per cubic yard

The major cost items included in the cost estimate range for ex situ vitrification are designated in Table PC13b-1.

Table PC13b-1. Major Cost Items to Implement Ex Situ Vitrification

Pretreatment Activities Included in Cost	
Screening to remove debris	
Fixed Cost Items Included	**Variable Cost Items Included**
Vitrification system installation	Soil excavation
Off-gas treatment system installation	Operating and maintenance labor Utilities Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
On-site disposal of vitrified soil, sediment, or sludge	
Off-gas treatment	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.30.07 "Vitrification/Molten Glass".

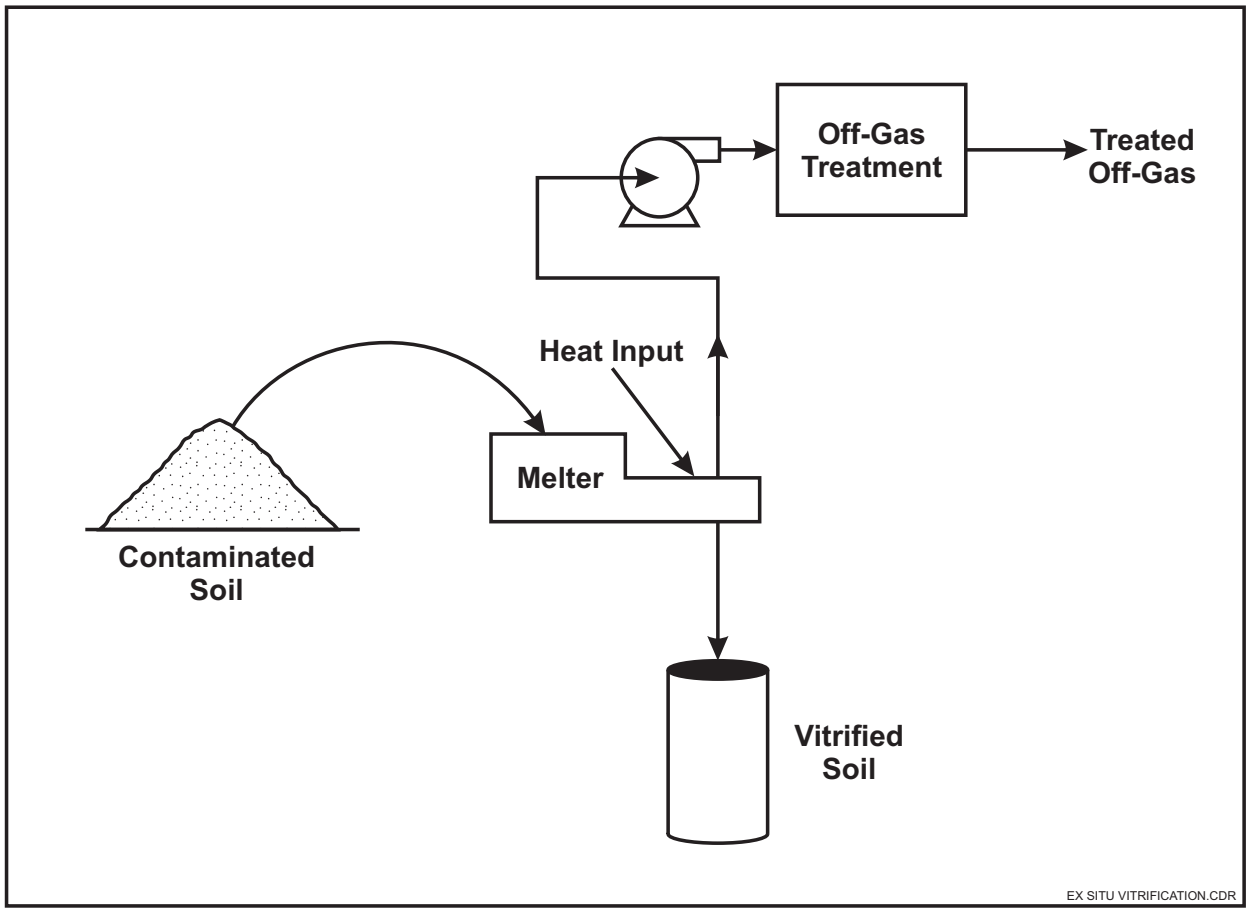


Figure PC13b. Ex Situ Vitrification

PC14: In-Well Air Stripping

Abstract:

In-well air stripping is an in situ remediation process for using airlift pumping to move groundwater around a well and to air strip volatile organics from water in the well.

Description:

The in-well air stripping process involves injecting gas, usually air, into a well, resulting in an in-well airlift pump effect. Air injection in the well at a level below the water table decreases the average fluid density in the deeper portions of the well. The lower density of the newly formed air/water mixture causes it to rise above the higher density water table. At a level in the well above the water table, the air (and contained volatiles) separates from the groundwater and exits the well. The groundwater flows out of the upper screened portions of the well above the water table and migrates down to the lower screened portion of the well. The air injection removes volatiles through air stripping, and provides an airlift pumping effect to establish a circulation pattern of oxygen-saturated water in the aquifer that may enhance the biodegradation rate. In-well air stripping has the potential to be more cost-effective and efficient than conventional pump-and-treat technology, but will be subject to similar limitations. Much remains to be learned about specific applications of in-well aeration, particularly regarding the questions of radius of influence and groundwater flow regime around the well.

Applicability:

In-well air stripping is used primarily to treat halogenated and nonhalogenated volatile organic compounds (VOCs) and nonhalogenated semivolatile organic compounds (SVOCs). Typically, in-well air stripping systems are more cost-effective for remediating VOC-contaminated groundwater at sites with deep water tables because the water does not need to be brought to the surface.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- In-well air strippers generally are more effective at sites with high concentrations of contaminants with high Henry's law constants.
- Subsurface heterogeneity can interfere with uniform aquifer treatment.
- Low-permeability soils are difficult to treat.
- Oxidized constituents in the groundwater may foul the system.
- Shallow aquifers may limit process effectiveness.

Status: Innovative

Operation and Maintenance Duration:

The duration of in-well air stripping is short- to long-term, dependent on the following conditions:

- Cleanup goals
- The volume of groundwater requiring treatment
- Contaminant concentrations and distribution
- Aquifer characteristics including permeability and anisotropy
- The Henry's law constants of the contaminants present at the site

- The radius of influence and the groundwater flow regime.

Cost Range: $75,000 to $200,000 per acre

The major cost items included in the cost estimate range for in-well air stripping are designated in Table PC14-1.

Table PC14-1. Major Cost Items to Implement In-Well Air Stripping

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Well and compressor installation	Operating and maintenance labor
Off-gas treatment system installation	Utilities
Sampling point installation	Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
Off-gas treatment	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.25.01 "In-Well Air Stripping".

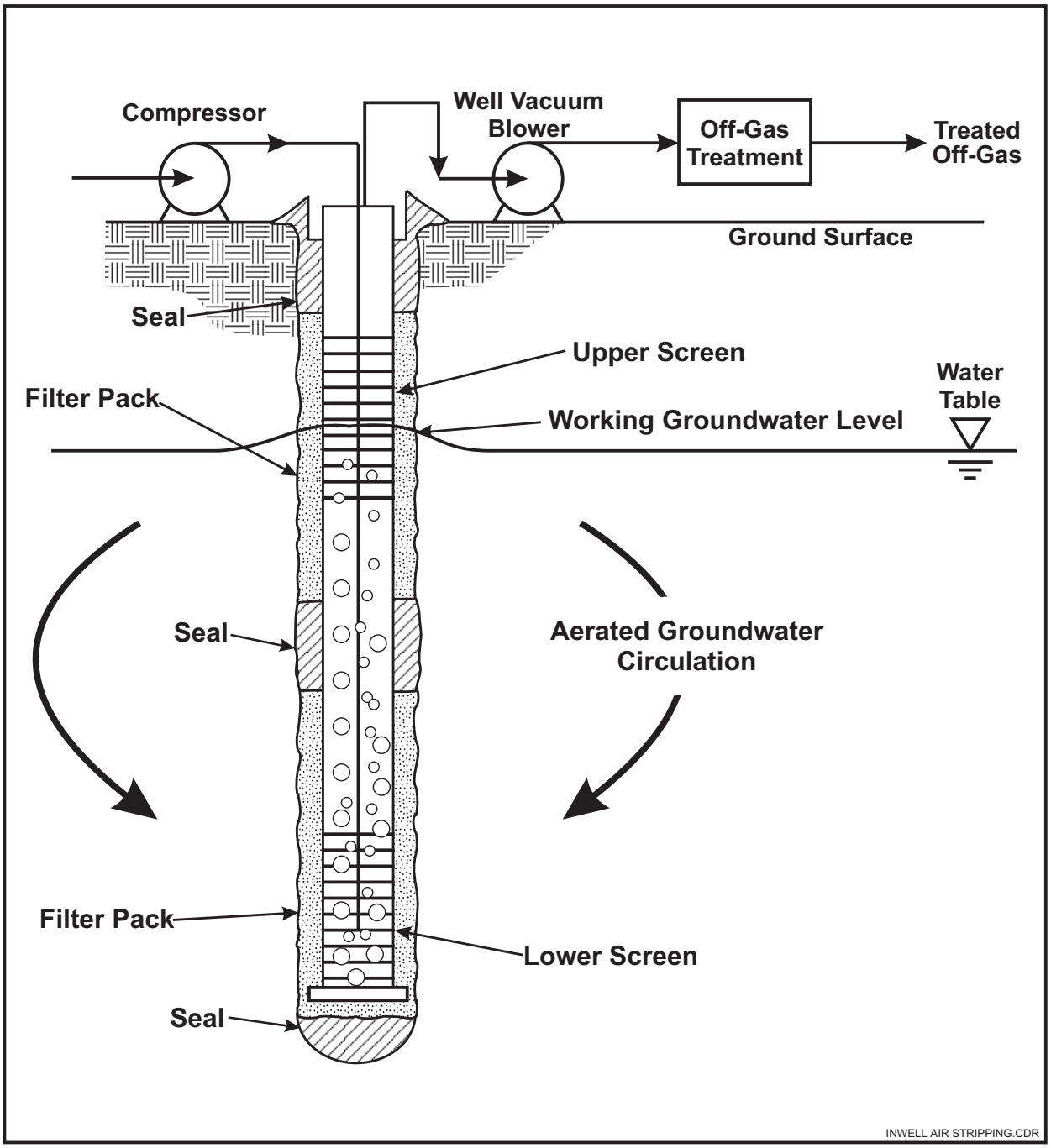


Figure PC14. In-Well Air Stripping

PC15: Incineration (On Site)

Abstract:

Incineration is a treatment process for excavated soil that uses oxidation at elevated temperatures to mineralize organic contaminants.

Description:

Incineration is performed by supplying heat from fuel combustion or electrical input to cause thermal decomposition of organic contaminants through cracking and oxidation reactions at high temperatures (usually between 760 - 1,550°C or 1,400 - 3,000°F). The organic contaminants primarily are converted into carbon dioxide and water vapor. Other products of incineration can include nitrite oxides, nitrates, and ammonia (for nitrogen-containing wastes); sulfur oxides and sulfate (for sulfur-containing wastes); and halogen acids (for halogenated wastes). Contaminated soils typically are treated in a rotary kiln or a fluidized bed incinerator.

Rotary kiln and fixed hearth incineration technologies involve two chambers in the incineration process. Organic constituents in the waste are volatilized in the primary chamber. During this volatilization process, some of the organic constituents oxidize to form carbon dioxide and water vapor. High temperatures then cause the organic constituents to react with oxygen in the second chamber, forming carbon dioxide and water vapor.

Fluidized bed incinerators involve a single chamber that contains the fluidizing sand and a freeboard section above the bed. The fluidized bed aids in the volatilization and combustion of the organic waste constituents. The solid particulate in the bed provides a sufficient heat capacity to volatilize organic constituents. The forced air used to fluidize the bed provides sufficient oxygen and turbulence to enhance the reactions of organics with oxygen to form carbon dioxide and water vapor. Additional time for conversion of the organic constituents is provided by the freeboard above the fluidized bed.

Incinerator off-gas requires treatment by an air pollution-control system to remove particulates and neutralize and remove acid gases (HCl, NO_X, and SO_X). Baghouses, venturi scrubbers, and wet electrostatic precipitators remove particulates; packed-bed scrubbers and spray driers remove acid gases.

Ash discharged from the incinerator is cooled and collected for disposal. Ash remaining after incineration may require treatment (e.g., solidification/stabilization to reduce metal leachability) prior to disposal.

Incineration processes are subject to a series of technology-specific regulations, including the Clean Air Act (CAA) for air emissions; the Toxic Substances Control Act (TCSA) for polychlorinated biphenyl (PCB) treatment and disposal; the Resource Conservation and Recovery Act (RCRA) for hazardous waste generation, treatment, storage, and disposal; regulations of the National Pollution Discharge Elimination System (NPDES) for discharge to surface waters; and the Noise Control Act (NCA) for noise.

Applicability:

Incineration is used primarily to treat halogenated and nonhalogenated semivolatile organic compounds (SVOCs), PCBs, and ordnance compounds.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- A permit to operate an on-site incinerator typically is very difficult to obtain.
- Heavy metals may remain in a bottom ash or fly ash, producing a waste that requires solidification/stabilization treatment prior to disposal.
- Volatile heavy metals, including lead, cadmium, mercury, and arsenic, may leave the combustion unit with the flue gases, thus requiring the installation of gas cleaning systems for their removal.
- Sodium and potassium form low melting point ashes that can attack the brick lining and form a sticky particulate that fouls gas ducts.
- Metals can react with other elements (such as chlorine and sulfur) in the feed stream, forming more volatile and toxic compounds than the original substances designated for incineration; such compounds are likely to be short-lived reaction intermediates that can be destroyed in a caustic quench.
- Dust in the soil increases the difficulty of treating off-gas.
- Debris greater than 60 mm in diameter typically must be removed prior to processing.

Status: Conventional

Operation and Maintenance Duration:

Incineration is used to treat excavated soil, so the operation and maintenance duration depends on the processing rate of the treatment unit and the volume of soil. Processing will be performed on site using a mobile unit. The throughput of a mobile unit is expected to range from 30 to 200 cubic yards per day.

Cost Range: $300,000 to $500,000 fixed mobilization cost plus $100 to $500 per cubic yard operating cost

The major cost items included in the cost estimate range for on site incineration are designated in Table PC15-1.

Table PC15-1. Major Cost Items to Implement On Site Incineration

Pretreatment Activities Included in Cost	
Screening to remove debris	
Fixed Cost Items Included	**Variable Cost Items Included**
Crew and equipment mobilization	Soil excavation
Treatment pad installation	Equipment leasing Operating and maintenance labor Utilities Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
On-site disposal of treated soil, sediment, or sludge	
Off-gas treatment	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.28.02 "Incineration".

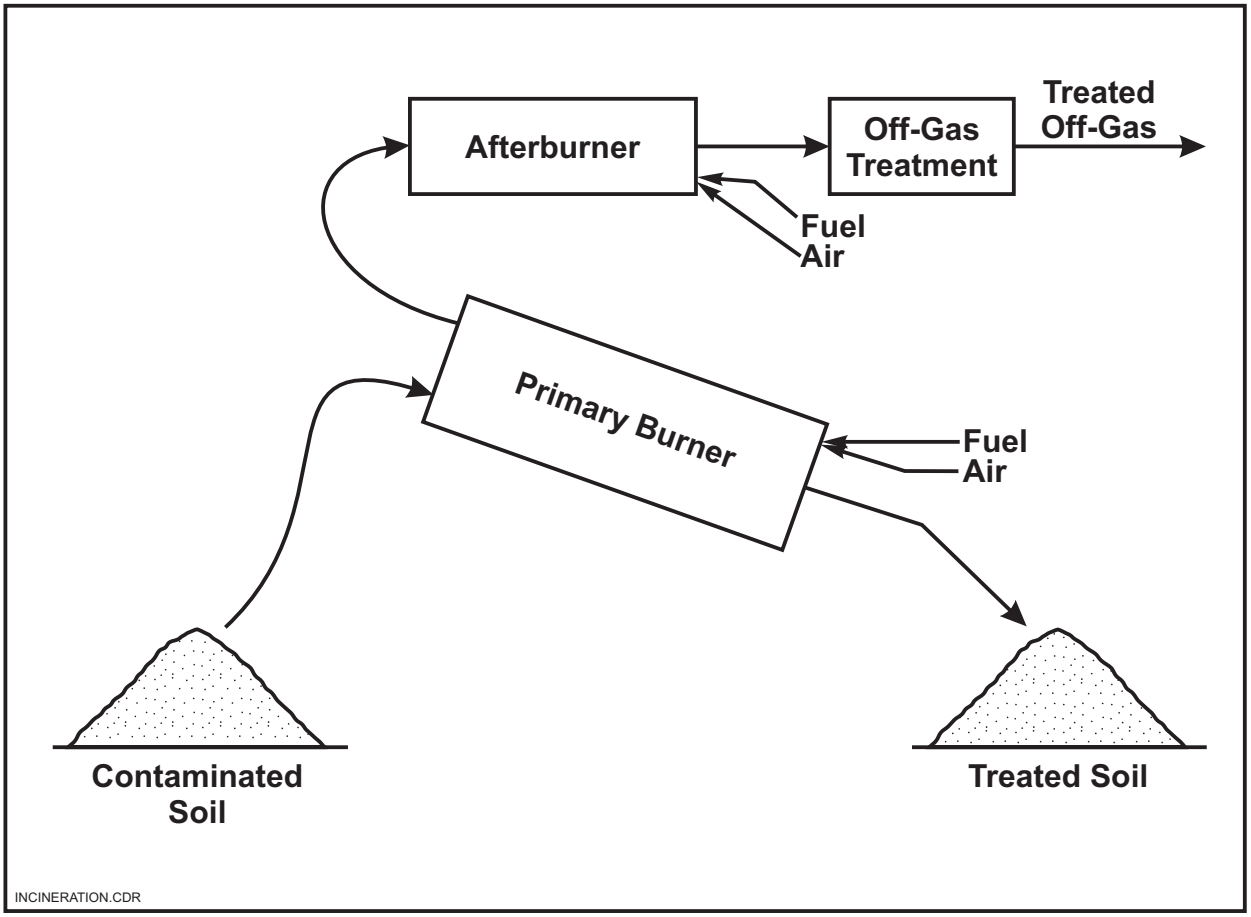


Figure PC15. Incineration (On Site)

PC16: Internal Combustion Engine

Abstract:

Internal combustion engine (ICE) treatment is a process for destroying combustible organic contaminants in an off-gas stream using thermal oxidation induced by compression heating and spark ignition in a combustion chamber.

Description:

ICE treatment is done using ordinary automotive engines with their manifold throttle bodies modified to accept petroleum hydrocarbons in the vapor phase rather than in the liquid phase. Each ICE unit is equipped with a valve that bleeds in ambient air to maintain the required fuel/air mixture, because the soil vapor may contain very low concentrations of oxygen, especially during the initial stages of operation. Ambient air is added to the engine through an intake valve at a ratio sufficient to bring the oxygen content up to the stoichiometric requirement for combustion.

ICEs are capable of destruction efficiencies of greater than 99%. ICEs are especially useful for treating vapor streams with high concentrations of total petroleum hydrocarbons (TPH) (up to 30% by volume). Tests of destruction of benzene, toluene, ethylbenzene, and xylenes (BTEX) components by ICE treatment show that nondetectable levels of contaminants can be achieved in the exhaust gas, and outlet contaminant concentrations below 1 ppm can be achieved in many cases.

Applicability:

ICE systems are used primarily to treat nonhalogenated volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs) in a gas stream. ICEs are most efficiently applied when the contaminant concentration is greater than 3,000 ppmv.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Capital cost of the ICE system.
- ICEs cannot handle vapor streams with moderate to high concentrations of chlorinated organic compounds.
- The consumption of supplemental fuel can be substantial if TPH concentrations in the off-gas from the remedial system are not high enough.
- The unit may require manual adjustment to achieve the proper fuel/air mixture at start up.

Status: Conventional

Operation and Maintenance Duration:

ICE systems are used to teat off-gas from a primary treatment process. The operation and maintenance duration depends on the duration of the primary process.

Cost Range: $1 to $10 per pound of organic removed

The major cost items included in the cost estimate range for internal combustion engine treatment of vapors are designated in Table PC16-1.

Table PC16-1. Major Cost Items to Implement Internal Combustion Engine Treatment of Vapors

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
ICE installation	Operating and maintenance labor Utilities Catalyst replacement Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
Off-site disposal of spent catalysts	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.34.09 "Internal Combustion Engine".

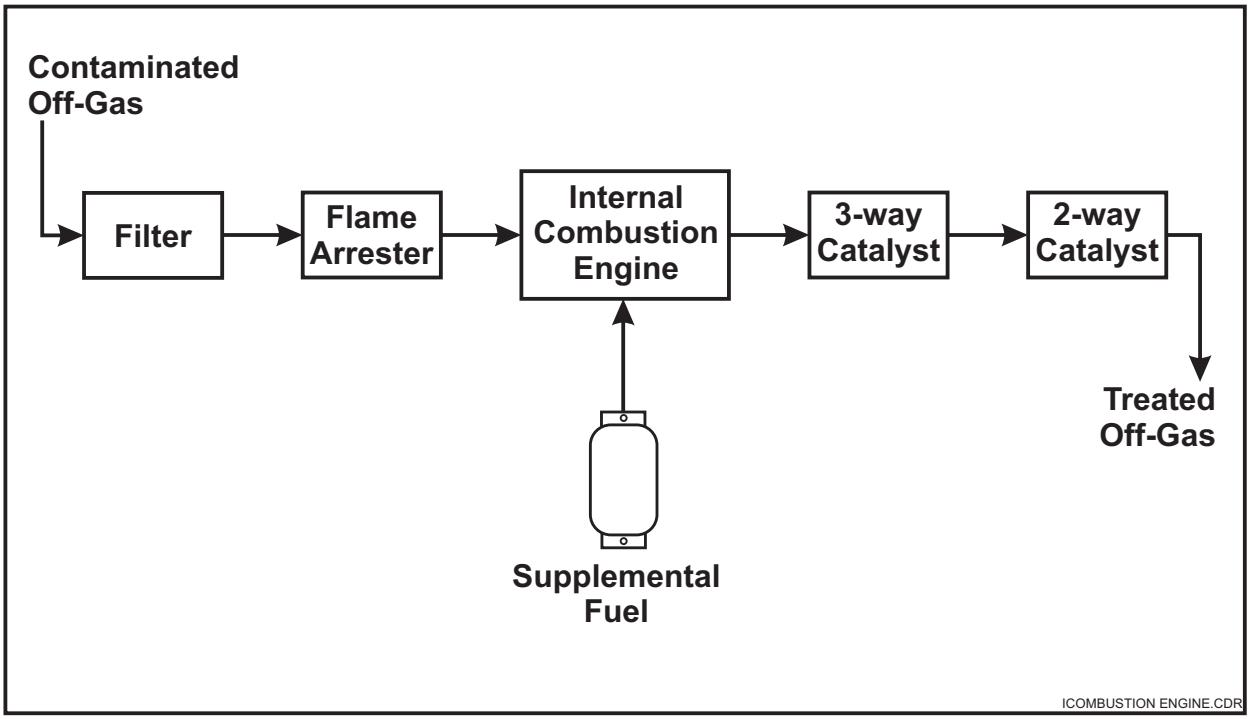


Figure PC16. Internal Combustion Engine

PC17: Ion Exchange

Abstract:

Ion exchange is an ex situ water treatment process for removing ions from solution by exchanging cations or anions between the dissolved phase and counter ions on a resin matrix.

Description:

Ion exchange treatment involves passing contaminated water through an ion exchange resin so that contaminants exchange onto sites on the media, exhausting its capacity. After resin capacity has been exhausted, resins can be regenerated for reuse. Ion exchange materials usually consist of synthetic organic polymers that contain ionic functional groups to which exchangeable ions are attached. Inorganic or natural polymeric materials, such as zeolites, may also exhibit useful ion exchange properties.

Applicability:

Ion exchange is used primarily to treat inorganics by removing dissolved ionic contaminants such as metals (e.g., lead and copper) or anions (e.g., nitrate and ammonia) from aqueous solutions.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Different resins are needed to remove cations and anions.
- Oil and grease can foul the exchange resin.
- Suspended solids or solids formed by precipitation of reduced iron or manganese species in solution can foul the exchange resin.
- The pH of the influent water may affect the ion exchange resin selection.
- Oxidants in groundwater may damage the ion exchange resin.
- Wastewater is generated during the regeneration step and will require additional treatment and disposal.
- Concentrations of dissolved solids greater than 4,000 mg/L will rapidly exhaust bed capacity. The technology typically is used to treat concentrations up to about 200 to 500 mg/L.

Status: Conventional

Operation and Maintenance Duration:

Ion exchange is used to treat pumped groundwater or wastewater residual from a treatment process. The operation and maintenance duration depends on the duration of the primary process operation.

Cost Range: $0.30 to $0.80 per 1,000 gallons

The major cost items included in the cost estimate range for ion exchange are designated in Table PC17-1.

Table PC17-1. Major Cost Items to Implement Ion Exchange

Pretreatment Activities Included in Cost	
Filtration to remove suspended solids	
Fixed Cost Items Included	**Variable Cost Items Included**
Ion exchange system installation	Operating and maintenance labor
Regeneration system installation	Replacement resin Utilities Regeneration chemicals Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
Off-site disposal of regeneration wastes	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.24.07 "Ion Exchange".

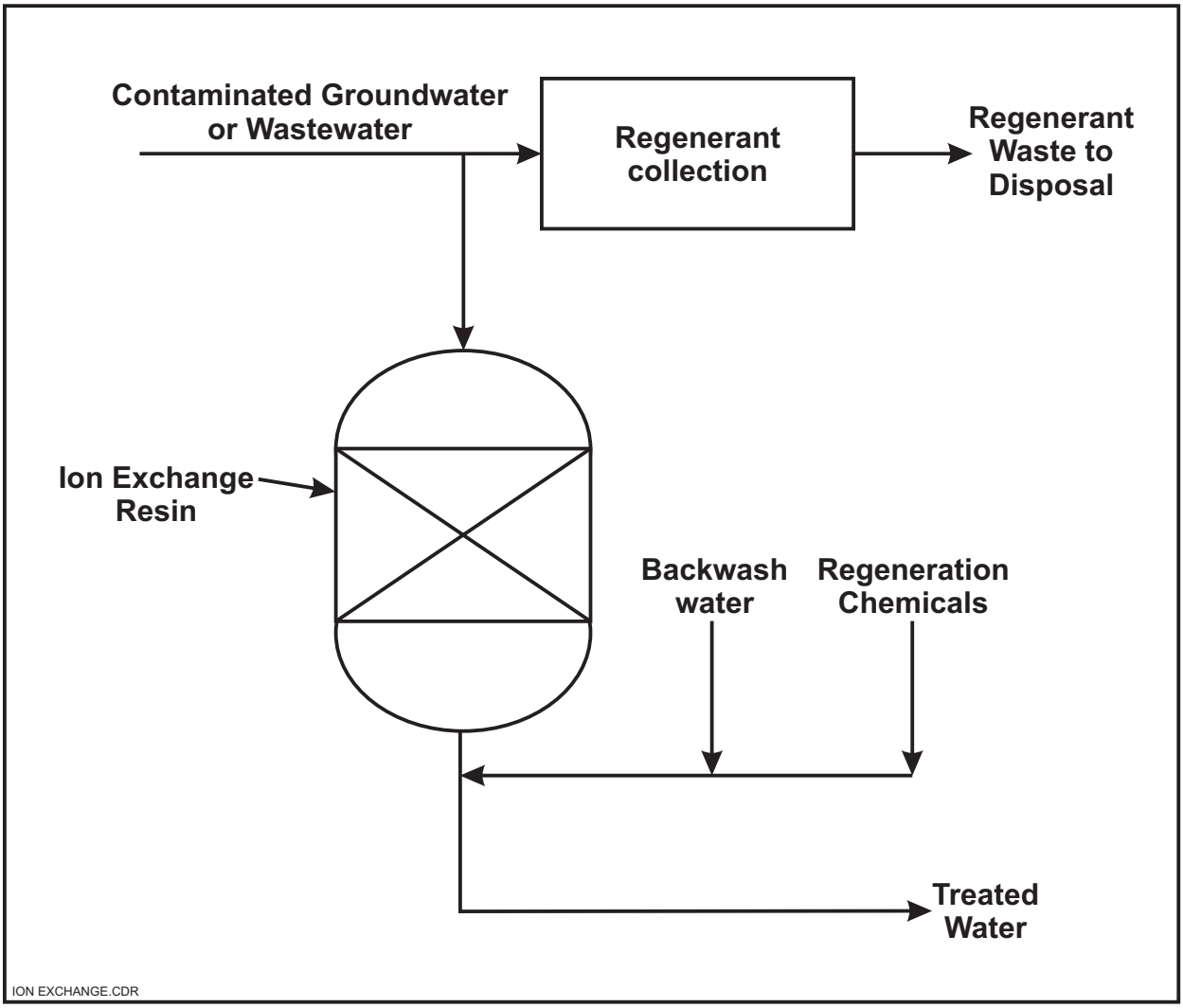


Figure PC17. Ion Exchange

PC18: Thermal Desorption

Abstract:

Thermal desorption is a physical separation process that applies heat to volatize water and organic contaminants in waste at temperatures of 90-540°C (200-1,000°F).

Description:

Thermal desorption is implemented by heating and agitating soil while it is exposed to a carrier gas or vacuum that transports volatilized water and organic contaminants to the gas treatment system. The bed temperatures and residence times designed into these systems will volatilize selected contaminants but typically will not oxidize or destroy them. Thermal desorption is a full-scale technology that has been proven successful for remediating all types of soil.

Two common thermal desorption designs are the rotary dryer and thermal screw. Rotary dryers are horizontal cylinders that can be indirect- or direct-fired. The dryer is normally inclined and rotated. For the thermal screw units, screw conveyors or hollow augers are used to transport the medium through an enclosed trough. Hot oil or steam circulates through the auger to indirectly heat the medium. All thermal desorption systems require treatment of the off-gas to remove particulates and contaminants. Particulates are removed by conventional particulate removal equipment, such as wet scrubbers or fabric filters. Contaminants are removed through condensation followed by carbon adsorption, or they are destroyed in a secondary combustion chamber or a catalytic oxidizer. Most of these units are transportable.

Applicability:

The target contaminant groups for thermal desorption systems are halogenated and nonhalogenated volatile organic compounds (VOCs). The technology can be used to treat semivolatile organic compounds (SVOCs) and polychlorinated biphenyls (PCBs) when a temperature near the high end of the normal operating range and long residence time is used.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Site-specific feed size and materials handling requirements can affect applicability or cost.
- High clay, humic material, or moisture content increases costs.
- Highly abrasive feed potentially can damage the processor unit.
- Dust and organic matter in the soil increases the difficulty of treating off-gas.
- Debris greater than 60 mm in diameter typically must be removed prior to processing.

Status: Innovative

Operation and Maintenance Duration:

Thermal desorption is used to treat excavated soil, so the operation and maintenance duration depends on the processing rate of the treatment unit and the volume of soil. Processing typically would be performed on site in a mobile unit. The throughput of a mobile unit is expected to range from 50 to 400 cubic yards per day.

Cost Range: $10,000 to $20,000 fixed mobilization cost plus
$25 to 55 per cubic yard for petroleum-contaminated soil or
$95 to $195 per cubic yard for other organic contaminants operating cost

The major cost items included in the cost estimate range for thermal desorption are designated in Table PC18-1.

Table PC18-1. Major Cost Items to Implement Thermal Desorption

Pretreatment Activities Included in Cost	
Screening to remove debris	
Fixed Cost Items Included	**Variable Cost Items Included**
Crew and equipment mobilization	Soil excavation
Treatment pad installation	Equipment leasing Operating and maintenance labor Utilities Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
On-site disposal of treated soil, sediment, or sludge	
Off-gas treatment	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.28.01 "High Temperature Thermal Desorption" and X.28.03 "Low-Temperature Thermal Desorption".

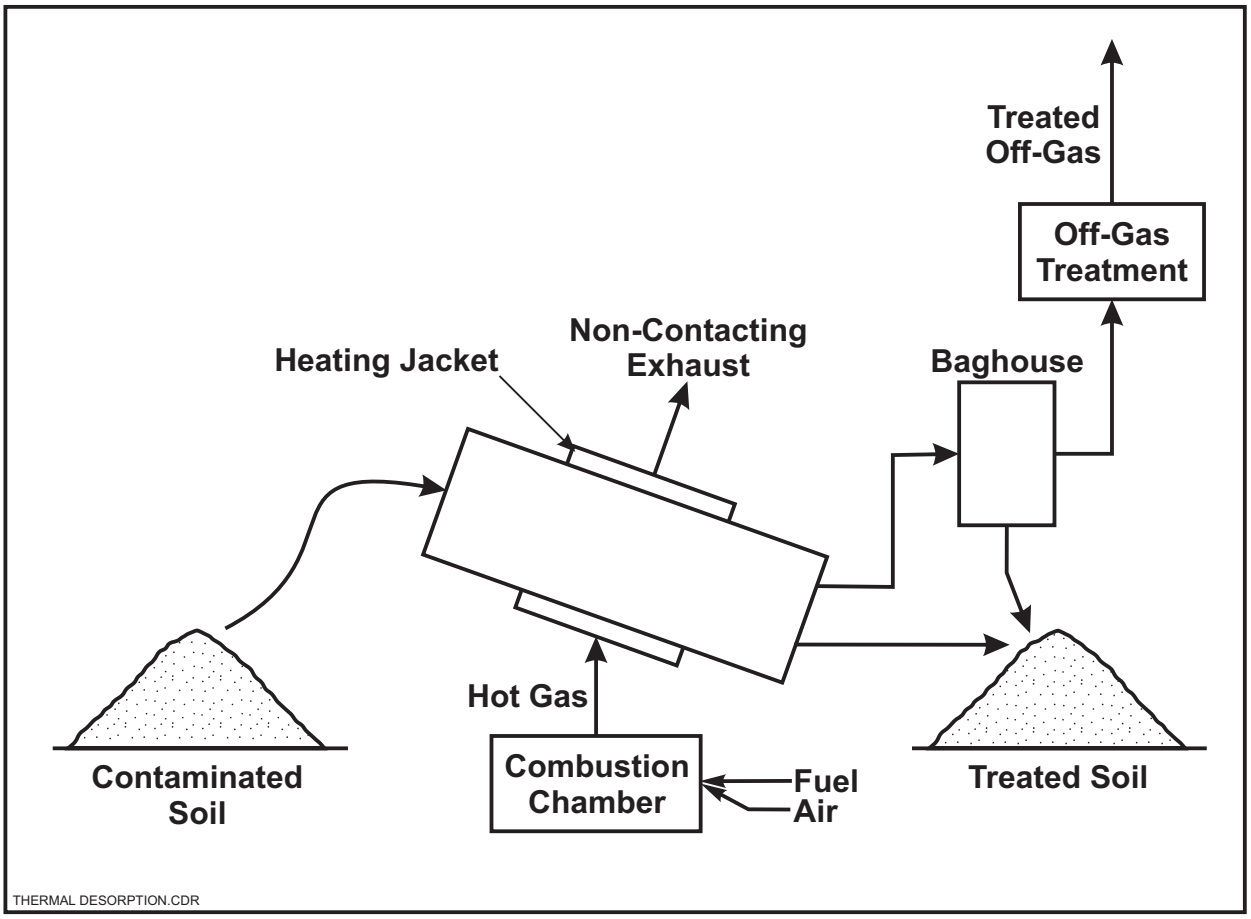


Figure PC18. Thermal Desorption

PC19: Membrane Separation/Membrane Pervaporation (VOCs)

Abstract:

Membrane separation or pervaporation for treatment of volatile organic compounds (VOCs) refers to the use of a semi-permeable membrane to concentrate VOCs in an off-gas stream (separation) or remove and concentrate VOCs from a water stream (pervaporation).

Description:

Membrane-based organic vapor/air separation technology involves the preferential transport of organic vapors through a nonporous gas separation membrane (a diffusion process analogous to pumping saline water through a reverse osmosis membrane). The synthetic polymer membrane is permeable to VOC molecules, but retains oxygen and nitrogen. In this system, the feedstream is compressed and sent to a condenser where the liquid solvent is recovered. The condenser bleed stream, which contains approximately 5,000 ppm of VOC, is then sent to the membrane module.

The membrane module is comprised of spiral-wound modules of thin film membranes separated by plastic mesh spacers. The membrane and the spacers are wound spirally around a central collection pipe. In the membrane module the stream is further concentrated to 3% VOC. The concentrated stream is then returned to the compressor for further recovery in the condenser.

Membrane pervaporation is a process that uses permeable membranes that preferentially adsorb VOCs from contaminated water. Contaminated water first passes through a heat exchanger, raising the water temperature. The heated water then enters the pervaporation module, containing membranes composed of a nonporous organophilic polymer, similar to silicone rubber, formed into capillary fibers. VOCs diffuse by vacuum from the membrane-water interface through the membrane wall. Treated water exits the pervaporation module, while the organic vapors travel from the module to a condenser where they return to the liquid phase.

Applicability:

The targeted contaminants are halogenated and nonhalogenated VOCs such as benzene, carbon tetrachloride, and chloroform in gas or liquid streams.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Particulates in the water or gas stream can foul the membrane.
- System is unable to handle large fluctuations in VOC concentrations.

Status: Emerging

Operation and Maintenance Duration: N/A

Cost Range: N/A

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.26.45 “Membrane Pervaporation” and X.34.04 “Membrane Separation”.

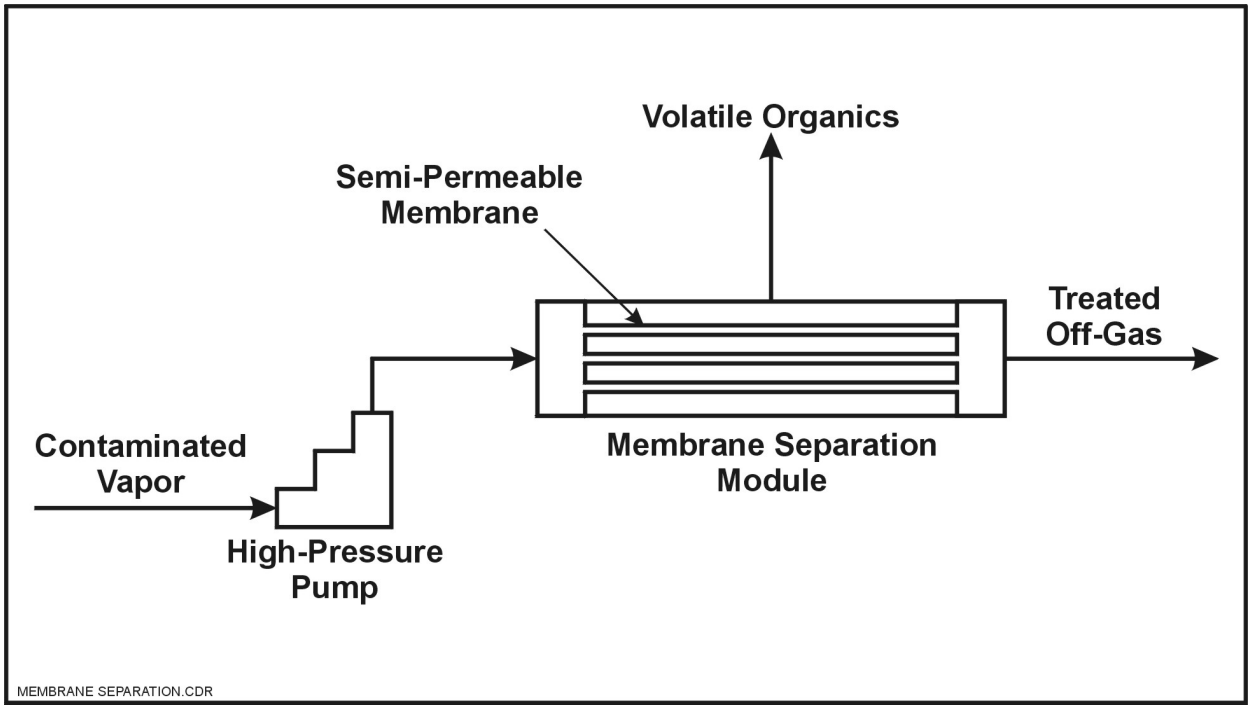


Figure PC19. Membrane Separation/Membrane Pervaporation (VOCs)

PC20: Precipitation (Hydroxide or Sulfide)

Abstract:

Precipitation is an ex situ treatment technology used to remove metal contaminants from water.

Description:

Precipitation involves the addition of a chemical to the contaminated water that converts dissolved contaminants to insoluble solids. The most commonly used precipitation agent is a basic chemical that is mixed with the water to increase the pH, causing cationic metals to precipitate as hydroxides. Commonly used bases include lime [$Ca(OH)_2$] or caustic (NaOH). Lime is less expensive than caustic, but produces a larger volume of sludge. Sulfide addition is the next most common precipitation approach. Many metal sulfides have a very low solubility in water. Sodium sulfide (Na_2S) is the most commonly used agent for sulfide precipitation. Sulfide precipitation is more expensive and complex compared to hydroxide precipitation due to the potential for release of hydrogen sulfide (H_2S) gas. Less commonly used precipitation agents include soda ash (Na_2CO_3) and phosphate (PO_4^{3-}).

The precipitation process requires mixing the precipitation agent with the contaminated water; adding flocculating agents and allowing residence time to promote crystal growth; settling, to reduce the water content of the precipitated solid sludge; and filtration, to produce a semisolid sludge cake for disposal.

Applicability:

Precipitation is used primarily to treat inorganics by removing cationic metal contaminants from water.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- The presence of multiple metal species may lead to removal difficulties as a result of amphoteric natures of different compounds (i.e., optimization on one metal species may prevent removal of another).
- Metal-containing sludges produced by precipitation may be a Resource Conservation and Recovery Act (RCRA) hazardous waste.
- Reagent addition must be carefully controlled to preclude unacceptable concentrations of the reagent or contaminant in treatment effluent.
- Efficacy of the system relies on adequate solids separation techniques (e.g., clarification, flocculation, and/or filtration).
- Dissolved salts are added to the treated water as a result of pH adjustment.
- Polymer may be added to the water to achieve adequate settling of solids.
- Treated water will often require pH adjustment.

Status: Conventional

Operation and Maintenance Duration:

Precipitation is used to treat pumped groundwater or wastewater residual from a treatment process. The operation and maintenance duration depends on the duration of the primary process operation.

Cost Range: $0.50 to $1.00 per 1,000 gallons

The major cost items included in the cost estimate range for precipitation are designated in Table PC20-1.

Table PC20-1. Major Cost Items to Implement Precipitation

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Chemical addition system installation	Operating and maintenance labor
Mixer settler installation	Utilities
Sludge filter installation	Chemicals Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
Off-site disposal of metal hydroxide or sulfide sludge residual from precipitation	
Disposal of treated water to publicly owned treatment works via site sewer	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.24.15 "Coagulation/Flocculation/Precipitation".

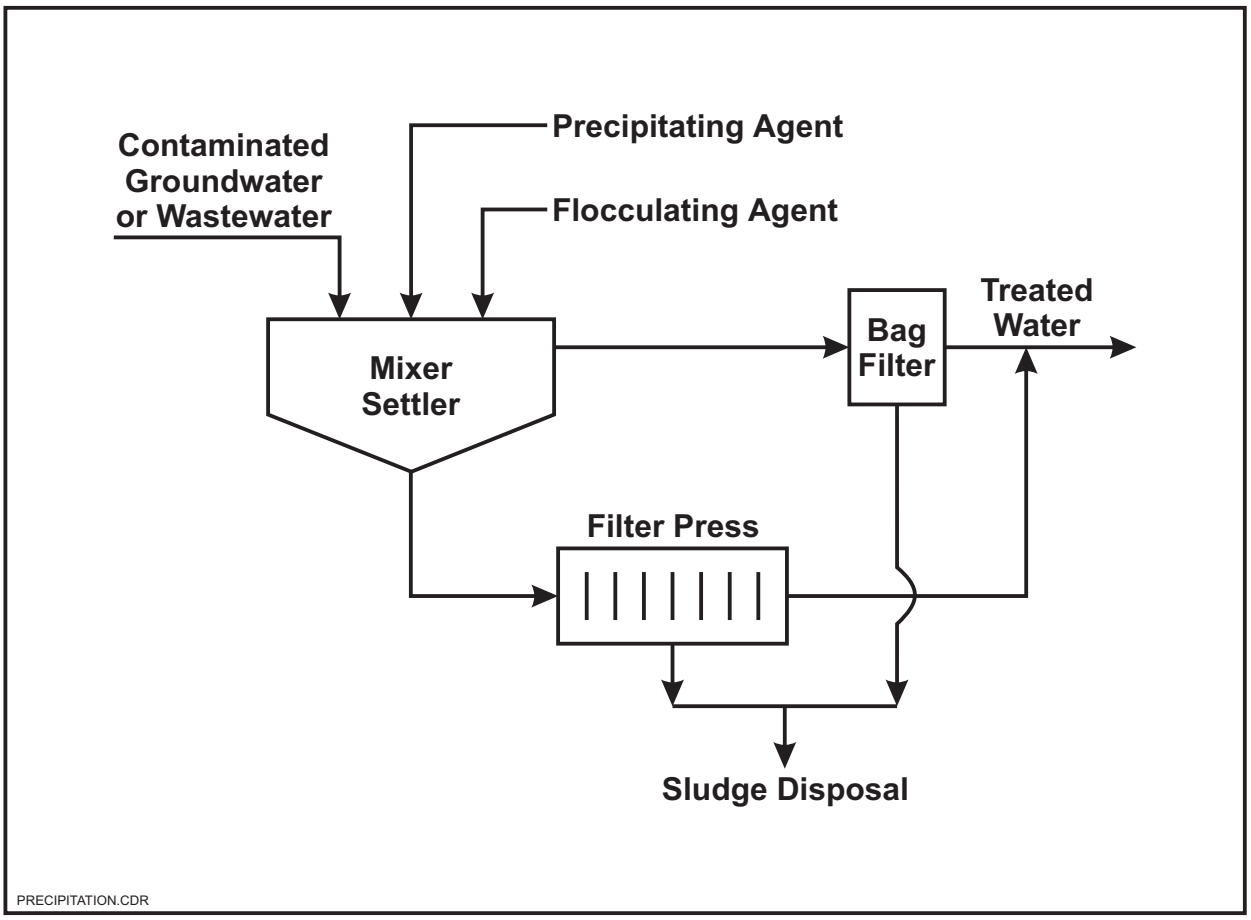


Figure PC20. Precipitation (Hydroxide or Sulfide)

PC21: Treatment Wall

Abstract:

Treatment wall technology is an in situ groundwater treatment method that involves installing a vertical barrier containing a reactive or passive media to intercept and remediate a contaminant plume.

Description:

In its simplest form, a treatment barrier consists of a trench placed in the path of a dissolved contaminant plume. This trench is filled with a reactive material, such as granular iron to reduce Cr(VI) or to declorinate halogenated organics, chelators to sequester selected metals, or other treatment media. As the groundwater passes through the treatment barrier, the contaminants react with the media. For example, chlorinated organics that come in contact with an elemental iron treatment wall are degraded to potentially nontoxic dehalogenated organic compounds and inorganic chloride. The main advantage of this system is that no pumping or aboveground treatment is required; the contaminated water passively moves through the barrier. Because there are no aboveground installed structures, the affected property can be put to productive use while it is being cleaned up.

A common treatment barrier configuration is the funnel-and-gate system. Wider plumes or heterogeneously distributed contamination can be captured by using impermeable funnel walls or wings on either side of the treatment trench, to direct the plume towards the permeable reactive cell, or gate. At some sites, a funnel-and-gate configuration can provide better control over reactive zone emplacement and plume capture.

Although a variety of reactive media could be used to treat groundwater contaminants, the most commonly used media are zero-valent metals, particularly granular iron. As the zero-valent metal in the reactive cell corrodes, the resulting electron activity can reduce the chlorinated compounds to potentially nontoxic products. Granular iron is the only reactive medium that has been used so far in field applications and the mechanism of chlorinated solvent degradation with zero-valent iron has been the most widely studied and reported to date. Other zero-valent metals may exhibit similar reactions with differing reaction rates.

Applicability:

Reactive barriers are used primarily to treat halogenated volatile organic compounds (VOCs) and to reduce Cr (VI) to Cr (III). Depending on the site conditions, a funnel-and-gate system can be installed to handle large volumes of contaminated water without hydraulic control via pumping.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Proximity of the plume to site boundaries or receptors.
- The cost to install a treatment wall increases significantly at depths greater than 80 feet.
- Size of the plume, as large plumes would be difficult and expensive to contain.
- Geotechnical considerations, such as underground utility lines, rocks, or consolidated sediments, can increase the difficulty of installing a barrier.

Status: Innovative

Operation and Maintenance Duration:

The treatment barrier remains in place indefinitely and is designed to remain effective for treating contaminants as long as the concentration of contaminants in groundwater is expected to remain above action limits. Operation and maintenance duration typically ranges from 3 to 30 years. The duration of operation and maintenance is dependent on the following conditions:

- Cleanup goals.
- The volume of aquifer requiring treatment.
- Contaminant concentrations and distribution.
- Aquifer characteristics including porosity and groundwater movement rate.
- The reactive cell wall may have to be flushed or the reactive medium replaced periodically if precipitates build up to the point that reactivity or hydraulic performance is affected. Based on experience at existing sites, the incorporation of proper safety factors in the design may make it possible to keep the frequency of such maintenance as low as once in several years, if at all.

Cost Range: $300 to $1,500 per square foot of reactive barrier installed (assuming a barrier thickness of 2 to 4 feet)

The major cost items included in the cost estimate range for a treatment wall are designated in Table PC21-1.

Table PC21-1. Major Cost Items to Implement a Treatment Wall

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Barrier trench excavation	Site supervision
Media installation	Site quality assurance and health and safety support
Sampling well installation	Sampling and analysis for process control
Residuals Management Activities Included in Cost	
Off-site disposal of soil excavated from treatment wall trench	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.25.09 "Passive/Reactive Treatment Wall".

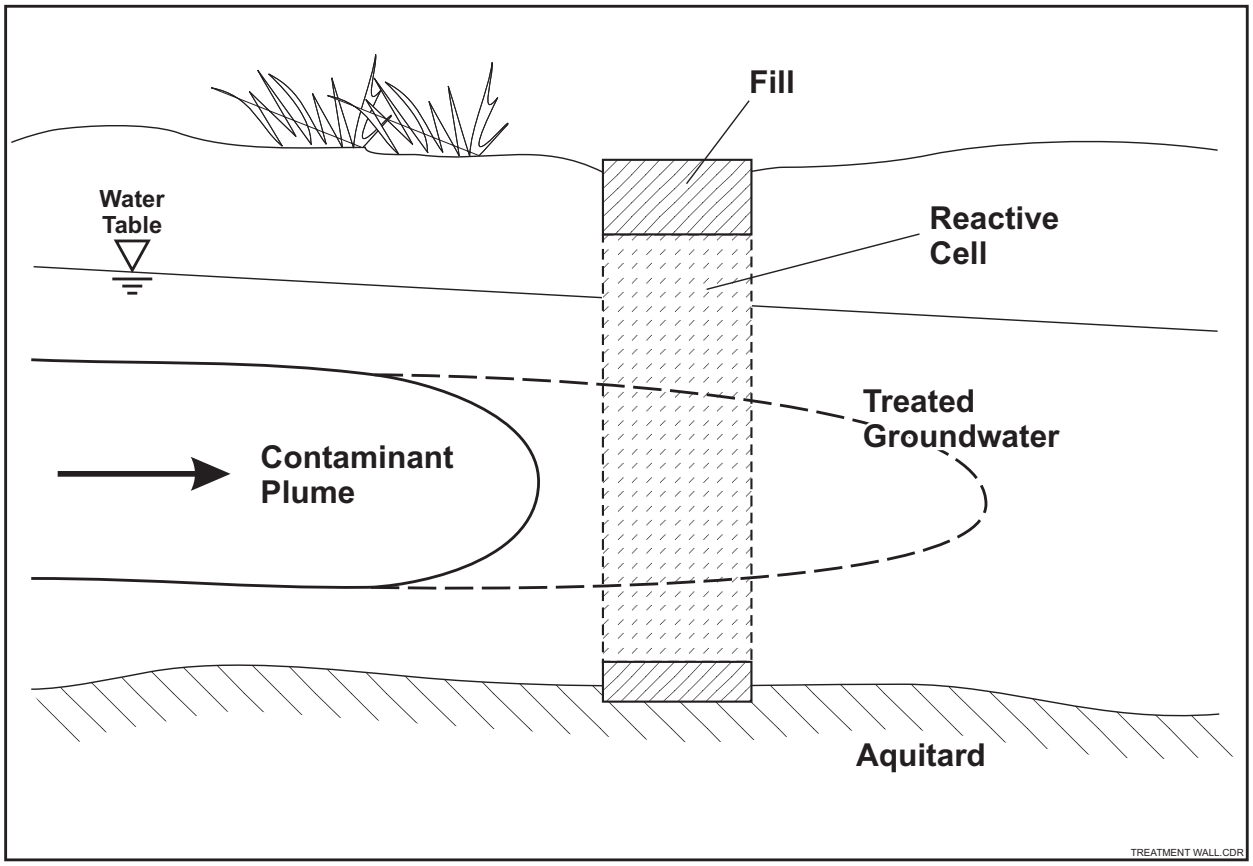


Figure PC21. Cross-Sectional View of a Treatment Wall

PC22: Reverse Osmosis

Abstract:

Reverse osmosis is an ex situ treatment technology for contaminated water that involves using a semipermeable membrane to produce a clean water stream and a smaller volume of a concentrated solution of contaminants.

Description:

Osmosis is the movement of a solvent (typically water) through a membrane that is impermeable to a solute (dissolved ions). The normal direction of solvent flow is from the more dilute to the more concentrated solution. Reverse osmosis reverses the normal direction of flow by applying pressure on the concentrated solution. The semipermeable membrane acts as a filter to retain the ions and particles on the concentrate side while allowing the water to pass through. The cleaned water passing through the membrane is called the permeate. The liquid containing the constituents that do not pass through the membrane (i.e., metals) is called the concentrate. Metal or salt products are recovered from the concentrate by techniques such as evaporation, electrowinning, or precipitation.

For reverse osmosis applications, membranes that have high water permeability and low salt permeability are ideal. The three most commonly used reverse osmosis membrane materials are cellulose acetate, aromatic polyamide, and thin-film composites, which consist of a thin film of a salt-rejecting membrane on the surface of a porous support polymer.

Applicability:

Reverse osmosis is used primarily to treat inorganics by concentrating dissolved metal salts in aqueous solution. Electrolytes and water-soluble organics with molecular weights greater than 300 are stopped by the membrane and collect in the concentrate. Most metals in solution (e.g., nickel, copper, cadmium, and zinc) can be concentrated to about 2 to 5 percent in the concentrate. Waste solutions containing high-suspended solids, high or low pH, oxidizers, or nonpolar organics typically are not suitable for reverse osmosis processing.

Limitations:

Factors that may limit the applicability and effectiveness of the process include the following:

- Membranes are sensitive to degradation, so pretreatment may be required to condition the waste to reduce membrane attack.
- Suspended solids or solids formed by precipitation of reduced iron or manganese species in solution can foul the membrane, requiring pretreatment to remove the fouling agents.
- Extreme pH conditions or oxidizers in the waste solution will degrade the membrane.
- The ability of the membrane to retain dissolved contaminants is based on molecule size, weight, and electrical charge, as well as variations of maximum pore size of the membrane; therefore retention may be difficult to predict.

Status: Conventional

Operation and Maintenance Duration:

Reverse osmosis is used to treat pumped groundwater or wastewater residual from a treatment process. The operation and maintenance duration depends on the duration of the primary process operation.

Cost Range: $0.50 to $2.00 per 1,000 gallons

The major cost items included in the cost estimate range for reverse osmosis are designated in Table PC22-1.

Table PC22-1. Major Cost Items to Implement Reverse Osmosis

Pretreatment Activities Included in Cost	
Filtration to remove suspended solids	
Fixed Cost Items Included	**Variable Cost Items Included**
Reverse osmosis system installation	Operating and maintenance labor
Membrane cleaning system installation	Utilities Membrane replacement Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
Off-site disposal of retentate	
Disposal of treated water to publicly owned treatment works via site sewer	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: The technology corresponds to the second and third level WBS elements X.26.29 "Reverse Osmosis".

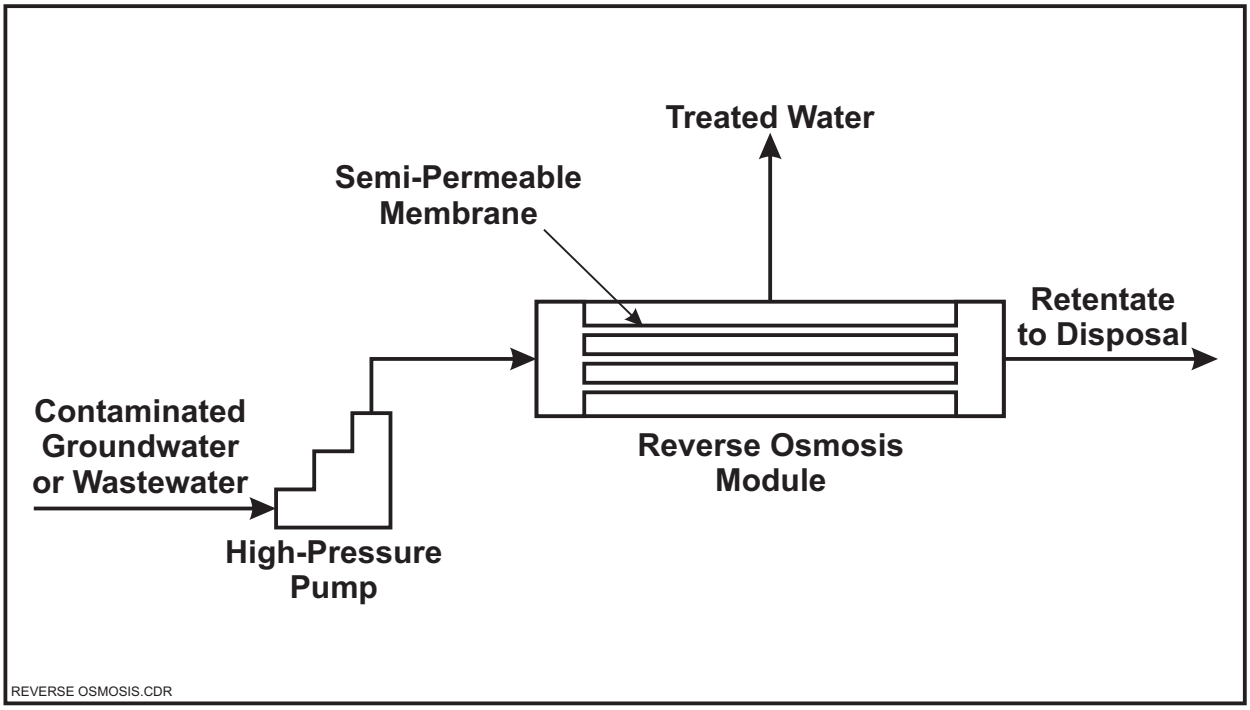


Figure PC22. Reverse Osmosis

PC23: Physical Separation

Abstract:

Physical separation is a treatment process for excavated soil that involves separating different types of particles based on physical characteristics.

Description:

Most physical separation operations are based on one of four characteristics:

- Particle size (filtration or microfiltration)
- Particle density (sedimentation or centrifugation)
- Magnetic properties (magnetic separation)
- Surface properties (flotation).

Equipment used to perform physical separation ranges from simple dry screens to complex hydrodynamic separation equipment such as hydrocyclones.

Applicability:

Physical separation is used primarily to treat inorganics by recovering or concentrating metals from soils, sediments, or slags in either of two situations.

First, discrete metal particles in soil can be recovered based on size, density, or other properties. For example, mercury metal can be recovered by gravity separation, lead fragments can be separated by screening or by gravity methods, and high-value metals (e.g., gold or silver) can be recovered by membrane filtration. The most common applications are size and gravity recovery of lead in firing range or battery breaking site soils and gravity recovery of elemental mercury from contaminated soils.

Second, metals present in elemental or salt form may be sorbed or otherwise associated with a particular size fraction of soil material. Materials tend to sorb onto the fine clay and silt in soil. Physical separation can divide sand and gravel from clay and silt, yielding a smaller volume of material with a higher contaminant concentration. The upgraded material can then be processed by techniques such as pyrometallurgy or chemical leaching to recover products.

Limitations:

Factors that may limit the applicability and effectiveness of the process include the following:

- Physical separation requires that the desired component be present in higher concentrations in a phase having different physical properties than the bulk material.
- Separation methods applied to dry the material (e.g., screening) generate dust.
- Aqueous wastestream and fines fraction of the solid matrix usually require subsequent treatment.

Status: Conventional

Operation and Maintenance Duration:

Physical separation is used to treat excavated soil, so the operation and maintenance duration depends on the processing rate of the treatment unit and the volume of soil. Processing typically would be performed on site in a mobile unit. The throughput of a mobile unit is expected to range from 10 to 500 cubic yards per day.

Cost Range: $10,000 to $20,000 fixed mobilization cost plus $5 to $90 per cubic yard operating cost

The major cost items included in the cost estimate range for physical separation are designated in Table PC23-1.

Table PC23-1. Major Cost Items to Implement Physical Separation

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Crew and equipment mobilization	Soil excavation
Construction of a treatment pad	Equipment leasing
	Operating and maintenance labor Utilities Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
On-site disposal of sand and gravel fraction	
Comments	
Additional treatment or disposal of clay fraction (if needed) is not included Cost or credit for recovered metal (if any) is not included Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.26.24 "Heavy Media Separation", X.26.27 "Magnetic Separation", X.26.31 "Sedimentation", X.26.33 "Sieving (Size Separation, Screening, Physical Separation)", and X.26.41 "Gravity Separation".

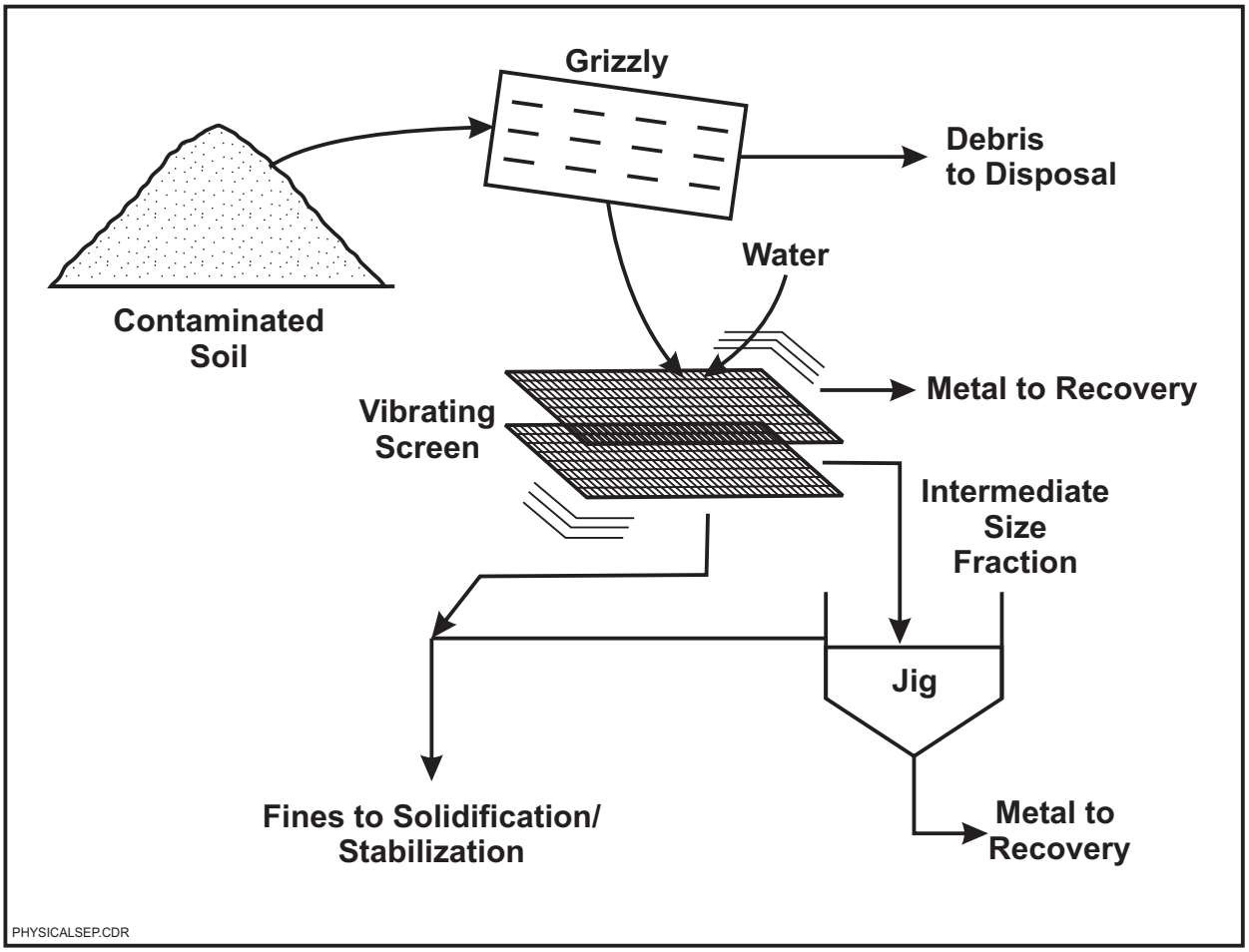


Figure PC23. Physical Separation

PC24: Soil Flushing

Abstract:

Soil flushing is the extraction of contaminants from in situ soil with water or other suitable aqueous solutions.

Description:

Soil flushing is accomplished by passing the extraction fluid through in-place soils using an injection or infiltration process. Contaminants in the soil partition into the flushing solution by mechanisms such as solubilization, emulsification, or chemical reaction. The contaminant-laden solution must be recovered to prevent uncontrolled transport of contaminants. For biodegradable contaminants, it may be possible to add nutrients and distribute the flushing solution on the soil to promote contaminant bioremediation. However, in most cases, treatment will be required to allow reuse of the fluid for continued flushing or release to local, publicly owned wastewater treatment works or receiving streams. To the maximum extent practical, recovered fluids should be reused in the flushing process. The separation of surfactants from recovered flushing fluids, for reuse in the process, is a major factor in the cost of soil flushing. Treatment of the recovered fluids results in process sludges and residual solids, such as spent carbon and spent ion exchange resin, which must be appropriately treated before disposal. Air emissions of volatile contaminants from recovered flushing fluids should be collected and treated, as appropriate, to meet applicable regulatory standards. Residual flushing additives in the soil may be a concern and should be evaluated on a site-specific basis.

Applicability:

Soil flushing is used primarily to treat halogenated and nonhalogenated semivolatile organic compounds (SVOCs), polychlorinated biphenyls (PCBs), and ordnance compounds from in situ materials. Water soluble inorganic contaminants may also be removed using soil flushing.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- The flushing solution must be compatible with the in situ environment.
- Subsurface heterogeneity can interfere with uniform distribution of flushing solutions.
- Low-permeability soils are difficult to treat.
- Surfactants can adhere to soil and reduce effective soil porosity.
- The flushing solution injection and collection systems must be designed and operated to limit the spread of contaminants to clean areas.
- The flushing solution must be recovered and treated.
- Complex waste mixtures (e.g., multiple contaminant classes) increase the difficulty of formulating a flushing solution.

Status: Innovative

Operation and Maintenance Duration:

Soil flushing is expected to achieve clean up in an operation and maintenance duration of 4 to 9 months, depending on the following conditions:

- Cleanup goals
- The volume of in situ media requiring treatment
- Contaminant concentrations and distribution
- In situ characteristics including permeability and anisotropy
- Flushing solution delivery capacity.

Cost Range: $100 to $300 per cubic yard

The major cost items included in the cost estimate range for soil flushing are designated in Table PC24-1.

Table PC24-1. Major Cost Items to Implement Soil Flushing

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Injection and recovery well and pump installation	Operating and maintenance labor
Sampling wells installation	Utilities
Flushing solution preparation system installation	Chemicals
Flushing solution treatment system installation	Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
Off-site disposal of sludge residual from flushing solution treatment	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.23.05 "In Situ Chemical Soil Flushing (Surfactant/Solvent)" and X.25.11 "In Situ Physical Soil Flushing (Surfactant/Solvent)".

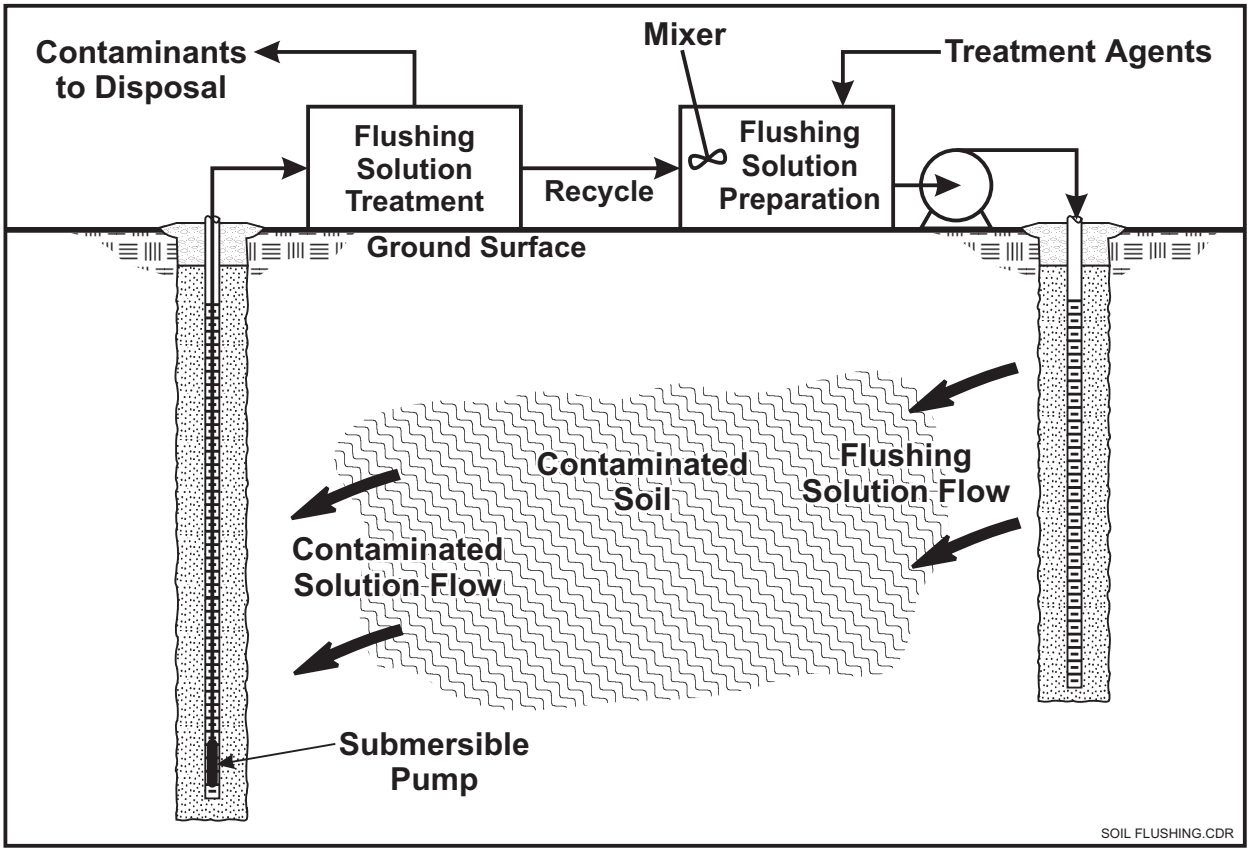


Figure PC24. Soil Flushing

PC25a: Soil Vapor Extraction (In Situ)

Abstract:

Soil vapor extraction (SVE) is an in situ unsaturated (vadose) zone soil remediation technology in which a vacuum is applied to the soil to induce the controlled flow of air and to remove volatile and some semivolatile contaminants from the soil.

Description:

To perform in situ SVE, air flow is induced through soil pores by applying a vacuum to extraction wells screened in the unsaturated zone. Volatile and semivolatile contaminants tend to partition into the clean air as it moves through the soil to the extraction wells. The gas leaving the soil may be treated to recover or destroy the contaminants, depending on local and state air discharge regulations. Vertical extraction vents are typically used at depths of 1.5 meters (5 feet) or greater and have been successfully applied as deep as 91 meters (300 feet). Horizontal extraction vents (installed in trenches or horizontal borings) can be used as warranted by contaminant zone geometry, drill rig access, or other site-specific factors.

Groundwater depression pumps may be used to reduce groundwater upwelling induced by the vacuum or to increase the depth of the vadose zone. Air injection is effective for facilitating extraction of deep contamination, contamination in low-permeability soils, and contamination in the saturated zone (see PC1: Air Sparging).

Applicability:

SVE is used primarily to treat halogenated and nonhalogenated volatile organic compounds (VOCs). The technology is typically applicable only to volatile compounds with a Henry's law constant greater than 0.01 or a vapor pressure greater than 0.5 mm Hg (0.02 in. Hg). Other factors such as moisture content, organic content, and air permeability of the soil will also influence the effectiveness of this treatment technology. SVE will not remove heavy oils, metals, polychlorinated biphenyls (PCBs), or dioxins. Because the process involves the continuous flow of air through the soil, however, SVE often promotes the in situ biodegradation of low-volatility organic compounds that may be present.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Subsurface heterogeneity can interfere with uniform distribution of air flow.
- Low-permeability soils are difficult to treat.
- The presence of the water table within several feet of the surface can reduce SVE performance.
- Large screened intervals are required in extraction wells for soil with low-permeability layers.
- Soil that has high clay or humic content or is extremely dry has a high sorption capacity of VOCs, which results in reduced removal rates.
- Air emissions may require treatment.
- SVE is not effective in the saturated zone; however, lowering the water table can expose more media to SVE.

Status: Conventional

Operation and Maintenance Duration:

In situ SVE is expected to achieve clean up in an operation and maintenance duration of 6 to 12 months, depending on the following conditions:

- Cleanup goals
- The volume of in situ soil requiring treatment
- Contaminant concentrations and distribution
- In situ characteristics including permeability and anisotropy
- Contaminant volatility, solubility, and sorption characteristics
- Air extraction capabilities.

Cost Range: $20 to $60 per cubic yard

The major cost items included in the cost estimate range for in situ soil vapor extraction are designated in Table PC25a-1.

Table PC25a-1. Major Cost Items to Implement Soil Vapor Extraction

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Extraction well and blower installation	Operating and maintenance labor
Off-gas treatment system installation	Utilities
Monitoring point installation	Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
Off-gas treatment	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.25.17 "Soil Vapor Extraction (In Situ)".

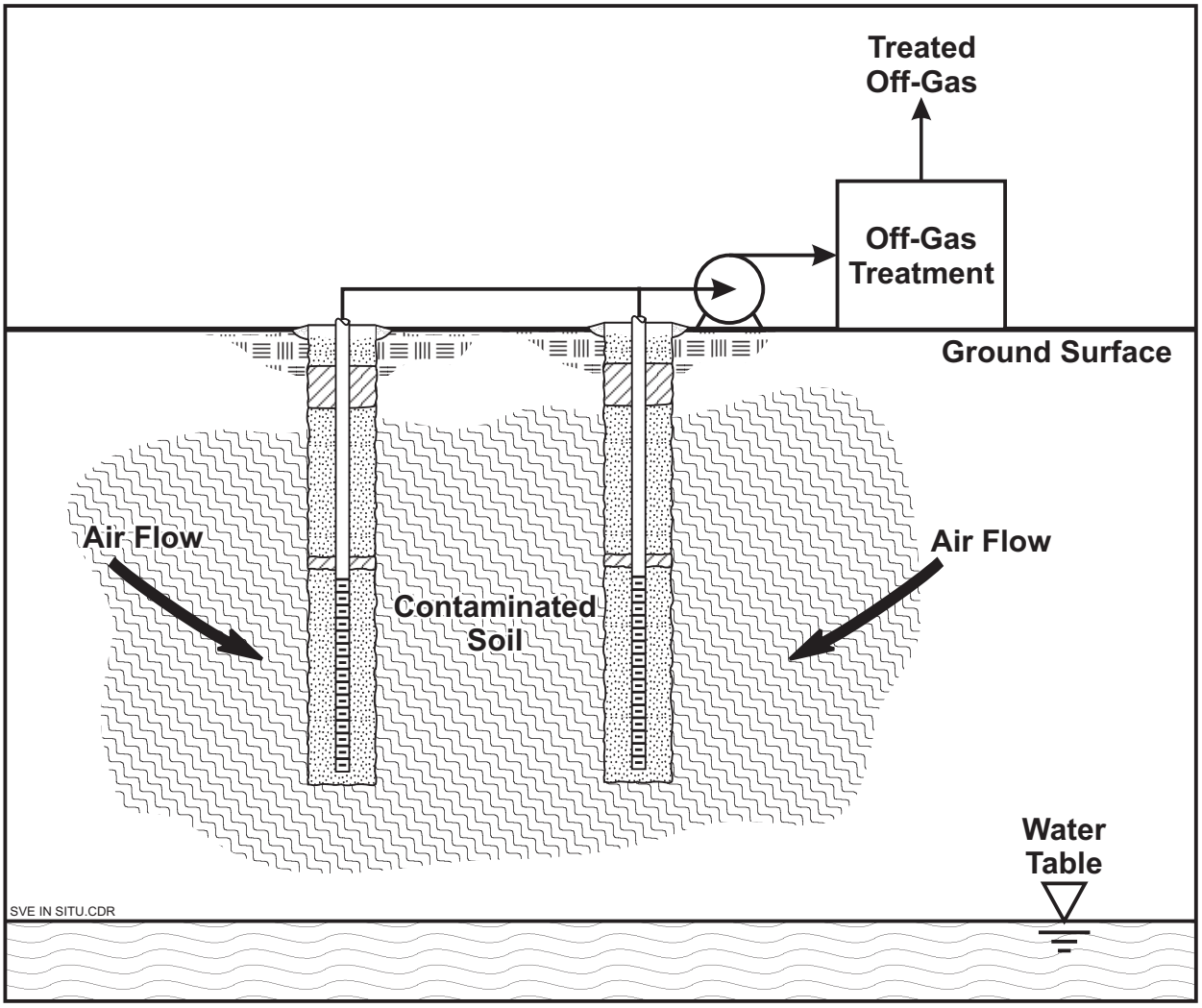


Figure PC25a. Soil Vapor Extraction (In Situ)

PC25b: Soil Vapor Extraction (Ex Situ)

Abstract:

Ex situ soil vapor extraction (SVE) is a technology in which excavated soil is treated by inducing a controlled flow of air through the soil to vaporize volatile organic compounds (VOCs).

Description:

Ex situ SVE is performed by placing excavated soil over a network of slotted piping and applying a vacuum to the pipes to cause airflow through the soil pile. Volatile and semivolatile contaminants tend to partition into the clean air as it moves through the pile. The process includes a system for handling off-gases. Ex situ SVE enjoys several advantages over its in situ counterpart. First, the excavation process forms an increased number of passageways through which the clean air can flow. Second, shallow groundwater does not limit the treatment process. Third, collection of leachate is possible. And fourth, the treatment process is more easily monitored and more uniform.

Applicability:

Ex situ SVE is used primarily to treat halogenated and nonhalogenated VOCs.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Air emissions may occur during excavation and materials handling.
- High clay or humic content soils inhibit volatilization.
- A large amount of space is required.
- Debris greater than 60 mm in diameter typically must be removed prior to processing.

Status: Innovative

Operation and Maintenance Duration:

Ex situ SVE is a batch process used to treat excavated soil, so the operation and maintenance duration depends on the processing rate and the volume of soil. The processing rate of a batch process is a function of the batch operating time and the batch size. Typical operating times range from 4 to 6 months per batch of contaminated soil. The size of the batch treated depends on the facility used. A temporary treatment pile typically processes about 500 yd^3 of material per batch. Permanent facilities can be designed to process much larger batches, depending on the following conditions:

- Cleanup goals
- Concentration and volatility of VOCs in the excavated soils
- Soil properties including particle size distribution and porosity.

Cost Range: $30 to $60 per cubic yard

The major cost items included in the cost estimate range for ex situ soil vapor extraction are designated in Table PC25b-1.

Table PC25b-1. Major Cost Items to Implement Ex Situ Soil Vapor Extraction

Pretreatment Activities Included in Cost	
Screening to remove debris	
Fixed Cost Items Included	**Variable Cost Items Included**
Base and vent system installation	Soil excavation
Blower installation	Operating and maintenance labor
Off-gas treatment system installation	Utilities
	Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
Disposal of condensate to publicly owned treatment works via site sewer	
Off-gas treatment	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.26.18 "Soil Vapor Extraction (Ex Situ)".

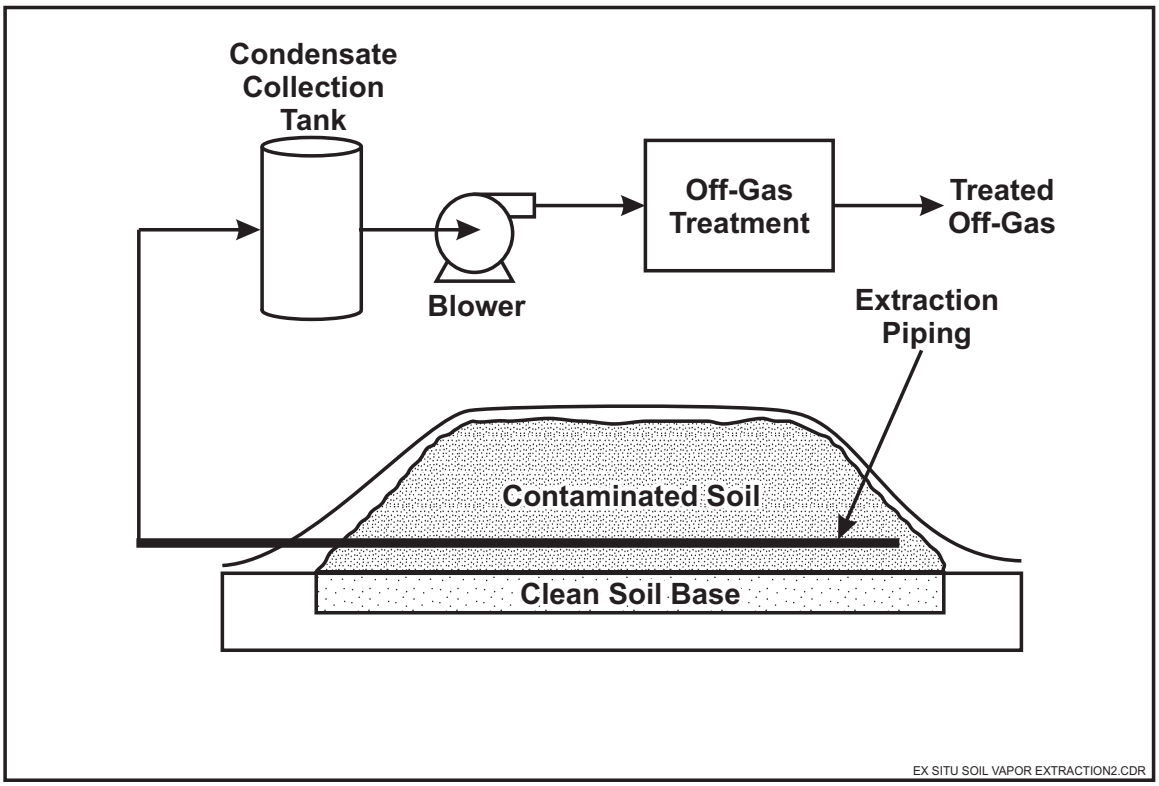


Figure PC25b. Soil Vapor Extraction (Ex Situ)

PC26: Soil Washing

Abstract:

Soil washing is a treatment technology for removing contaminants from excavated soil that involves scrubbing soil with a water-based solution.

Description:

Soil washing is accomplished by contacting soil with a wash solution, separating the soil and solution, and treating the solution. The solution is contacted with the soil and vigorously agitated to transfer contaminants into the wash solution. The process removes contaminants from soils by dissolving or suspending them in the wash solution (which is later treated by conventional wastewater treatment methods). Surfactants or similar mild solvents are often used to improve the removal of petroleum hydrocarbons and a wide variety of other organic contaminants from soils.

Soil washing typically incorporates particle size separation during washing. The use of particle size separation to reduce the amount of solids requiring treatment is based on the tendency of many organic and inorganic contaminants to bind to clay, silt, and organic soil particles. The silt and clay, in turn, are attached to sand and gravel particles by physical processes, primarily compaction and adhesion. Washing separates fine clay and silt particles from the coarser sand and gravel soil particles, effectively separating and concentrating the contaminants into a smaller volume consisting of the clay and silt fraction. This fraction can be managed by further treatment or disposal. The cleaned sand and gravel fraction can be returned to the site.

Applicability:

The target contaminant groups for soil washing are typically semivolatile organic compounds (SVOCs), fuels, and inorganics. The technology can be used on selected volatile organic compounds (VOCs) and pesticides. The technology typically is most effective with coarse-grained soils containing low clay content.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Fine soil particles (e.g., silt and clay) may be difficult to separate from the washing fluid.
- Complex waste mixtures (e.g., metals with organics) make formulating washing fluid difficult.
- Clay and humic materials tend to retain contaminants by sorption and often are difficult to treat by soil washing.
- The aqueous washing solution stream will require treatment.
- Debris greater than 60 mm in diameter typically must be removed prior to processing.

Status: Innovative

Operation and Maintenance Duration:

Soil washing is used to treat excavated soil, so the operation and maintenance duration depends on the processing rate of the treatment unit and the volume of soil. Processing typically would be performed on

site in a mobile unit. The throughput of a mobile unit is expected to range from 20 to 200 cubic yards per day.

Cost Range: $10,000 to $20,000 fixed mobilization cost plus $90 to $400 per cubic yard operating cost

The major cost items included in the cost estimate range for soil washing are designated in Table PC26-1.

Table PC26-1. Major Cost Items to Implement Soil Washing

Pretreatment Activities Included in Cost	
Screening to remove debris	
Fixed Cost Items Included	**Variable Cost Items Included**
Crew and equipment mobilization	Soil excavation
Treatment pad installation	Equipment leasing
	Operating and maintenance labor
	Washing additive
	Utilities
	Site supervision
	Site quality assurance and health and safety support
	Sampling and analysis for process control
Residuals Management Activities Included in Cost	
On-site disposal of treated soil	
Off-site disposal of sludge from washing solution treatment	
Disposal of treated washing solution to publicly owned treatment works via site sewer	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the "Surfactant" portion of the second and third level WBS elements X.26.35 "Soil Washing (Surfactant/Solvent)".

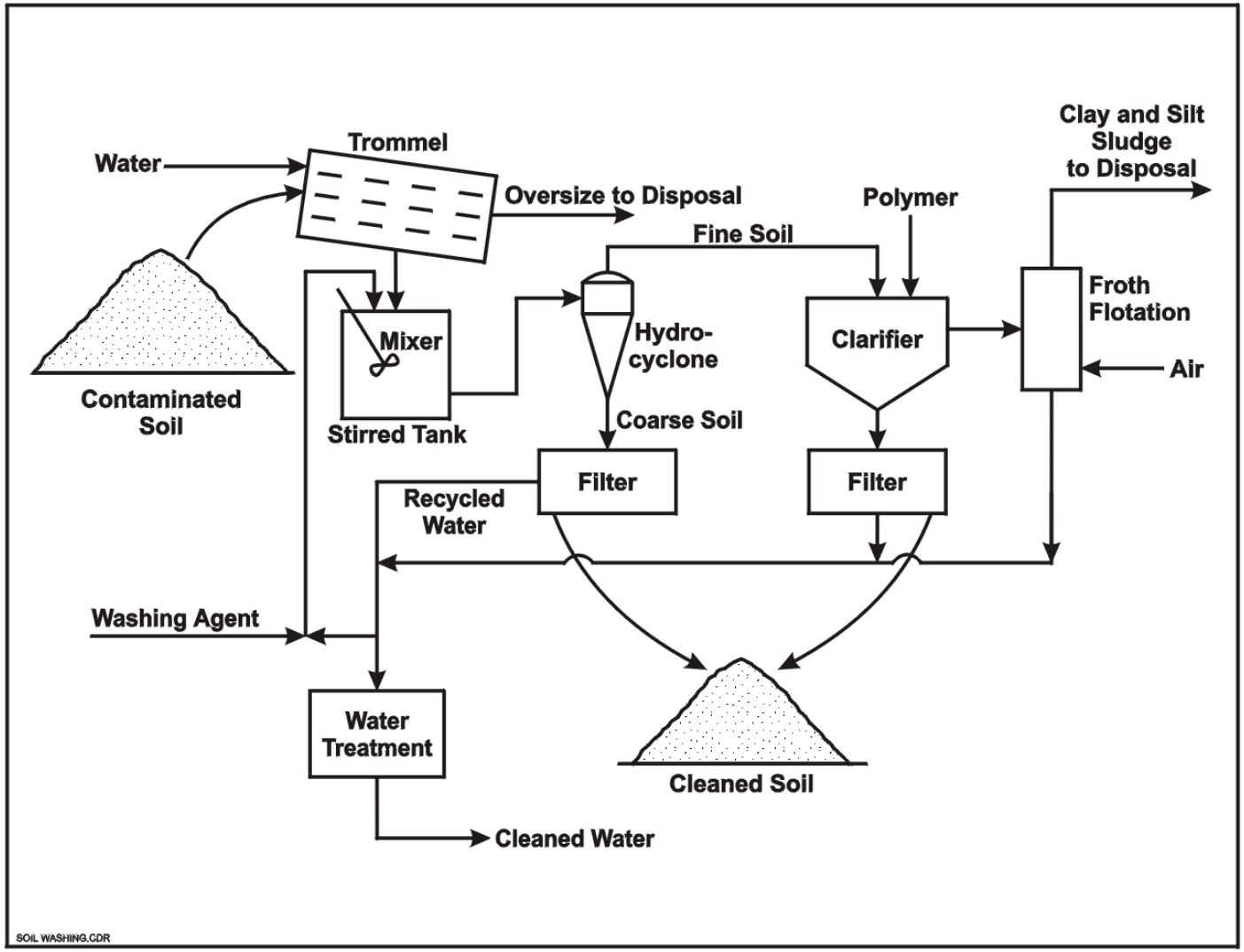


Figure PC26. Soil Washing

PC27: Solvated Electron Treatment Process

Abstract:

The solvated electron treatment (SET™) process is a method for treating ex situ soils with a powerful chemical reducing agent.

Description:

The SET™ process uses sodium- or calcium-generated solvated electrons as a reducing agent. Solvated electrons are formed when alkali or alkaline earth metals dissolve, with no net reaction, in solvents such as ammonia, amines, and ethers, forming metal ions and free electrons.

Soil is prepared by excavation, screening to remove debris, and dewatering to <30% (if required). The prepared soil is placed into the treatment vessel; liquid ammonia is added to the sealed vessel at room temperature; and the vessel rotates, tumbling the soil like a cement mixer.

After mixing to form a soil/ammonia slurry, elemental calcium or sodium is added to the slurry and mixing continues until the slurry conductivity indicates the reaction is complete.

The reacted slurry is transferred to an ammonia/soil separation vessel where the ammonia is separated from the soil as a liquid until most of the ammonia is removed. The separator is then rotated, warming the soil and driving off the remaining ammonia as a vapor. The vapor then is collected along with the liquid, in the ammonia/water separator.

Water is separated from the ammonia for return to the cleaned soil. The ammonia is returned to the main ammonia storage tank for reuse.

Applicability:

The SET™ process has been tested for dechlorination of halogenated semivolatile organic compounds (SVOCs) and polychlorinated biphenyls (PCBs) and reduction of ordnance compounds.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Cannot be applied to wastewater streams.
- Soil or sediments containing >30% water must be dewatered.
- Handling of anhydrous ammonia and sodium metal is required.
- Debris greater than 60 mm in diameter typically must be removed prior to processing.

Status: Emerging

Operation and Maintenance Duration: N/A

Cost Range: N/A

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.24.9X "Ex Situ Chemical Treatment–Other".

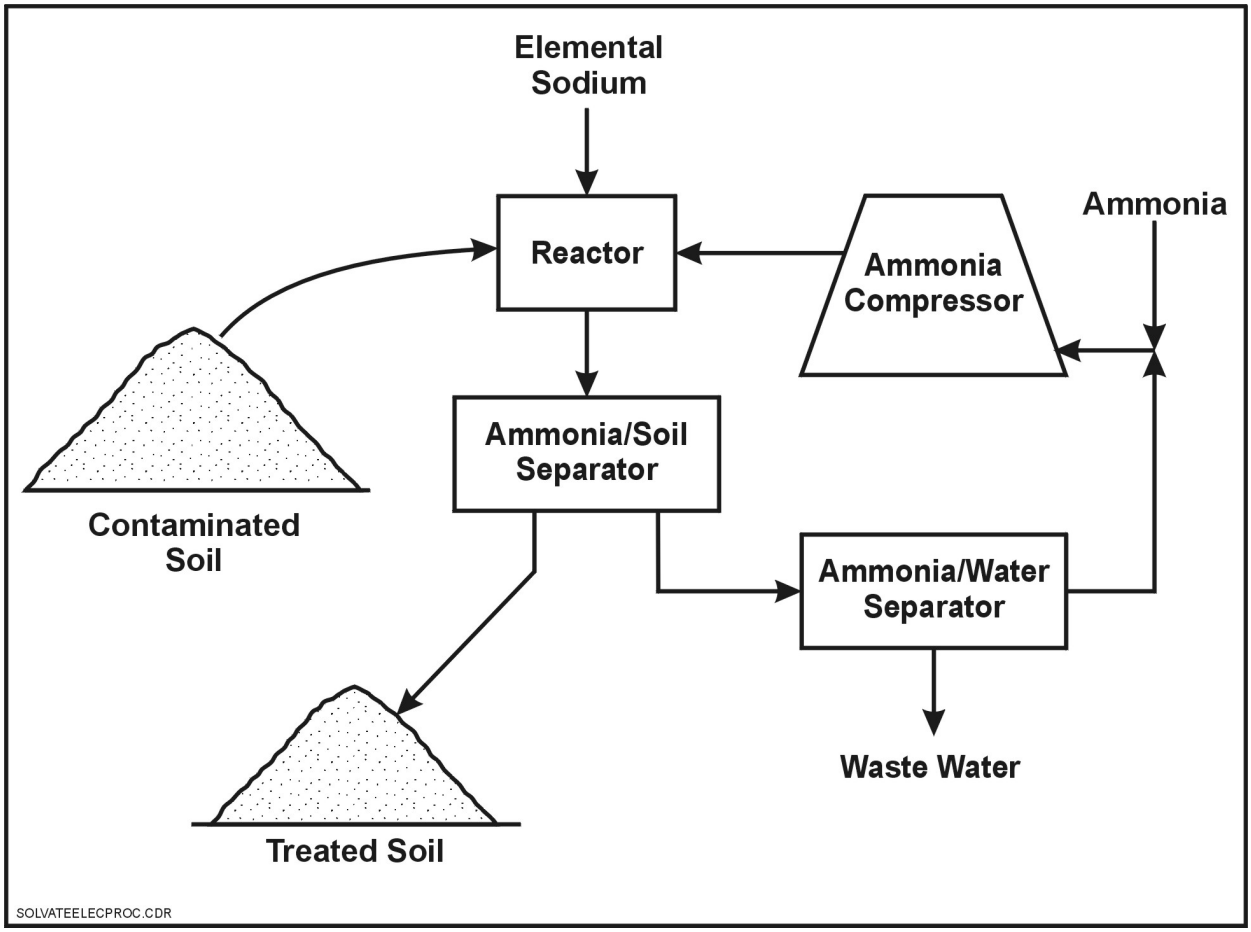


Figure PC27. Solvated Electron Treatment (SET™) Process

PC28: Solvent Extraction

Abstract:

Solvent extraction is a treatment process for excavated soil that involves preferential removal of organic contaminants into a solvent.

Description:

Solvent extraction is accomplished by contacting soil with a solvent, separating the soil and solvent, and regenerating the solvent for reuse. To be successful, the extraction solvent should have a high solubility for the contaminant and low solubility in the waste matrix. Typical solvents include liquefied gas (propane or butane), supercritical carbon dioxide fluid, triethylamine, or proprietary organic fluids. The extraction solvent is well mixed with the contaminated matrix to allow contaminants to transfer to the solvent. The clean matrix and solvent are then separated by physical methods, such as gravity decanting or centrifuging. Distillation regenerates the solvent, which is then returned for reuse in the extraction process.

Extraction typically is mass transfer limited, so thorough mixing of the solvent and contaminated matrix is required. Some solvent extraction systems require the addition of water if the waste is a dry, nonflowing solid. In other systems, extraction fluid is added to make the waste flow.

The extraction solvent typically is purified by distillation. In systems that use pressurized solvents, such as liquefied gas or supercritical carbon dioxide, vaporization occurs by pressure release, which causes the solvent to boil. With higher-boiling solvents, distillation tanks or towers may be used to separate the extraction solvent from the organic contaminants.

The triethylamine system extracts both water and organics. The contaminant/water/solvent mixture is heated to 55°C (130°F), where separate water and organic phases form. The phases are separated by decanting, and the contaminant and solvent are separated by distillation.

Applicability:

Solvent extraction is used primarily to treat halogenated and nonhalogenated semivolatile organic compounds (SVOCs), polychlorinated biphenyls (PCBs), and ordnance compounds. The technology is generally not used for extracting inorganics (i.e., acids, bases, salts, or heavy metals). Inorganics usually do not have a detrimental effect on the extraction of the organic components, and metals that pass through the solvent extraction process in the treated soil sometimes benefit by being changed into a less toxic or leachable form. The process has been shown to be applicable for the separation of the organic contaminants in paint wastes, synthetic rubber process wastes, coal tar wastes, drilling muds, wood-treatment wastes, separation sludges, pesticide/insecticide wastes, and petroleum refinery oily wastes.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Spent solvent must be regenerated and reused.
- Organically bound metals can be extracted along with the target organic pollutants, which restricts handling of the residuals.
- The presence of detergents and emulsifiers can unfavorably influence the extraction performance.

- Traces of solvent may remain in the treated solids, so the toxicity of the solvent is an important consideration.
- Solvent extraction is generally least effective on very high molecular weight organic and very hydrophilic substances.
- High moisture content reduces process efficiency and increases complexity of residuals management.
- Debris greater than 60 mm in diameter typically must be removed prior to processing.

Status: Innovative

Operation and Maintenance Duration:

Solvent extraction is used to treat excavated soil, so the operation and maintenance duration depends on the processing rate of the treatment unit and the volume of soil. Processing typically would be performed on site in a mobile unit. The throughput of a mobile unit is expected to range from 20 to 200 cubic yards per day.

Cost Range: $10,000 to $20,000 fixed mobilization cost plus $90 to $400 per cubic yard operating cost

The major cost items included in the cost estimate range for solvent extraction are designated in Table PC28-1.

Table PC28-1. Major Cost Items to Implement Solvent Extraction

Pretreatment Activities Included in Cost	
Screening to remove debris	
Fixed Cost Items Included	**Variable Cost Items Included**
Crew and equipment mobilization	Soil excavation
Treatment pad installation	Equipment leasing Operating and maintenance labor Extraction solvent Utilities Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
On-site disposal of treated soil	
Off-site disposal of sludge from solvent recycling	
Off-site disposal of spent solvent remaining at the end of processing	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.24.11 "Solvent Extraction".

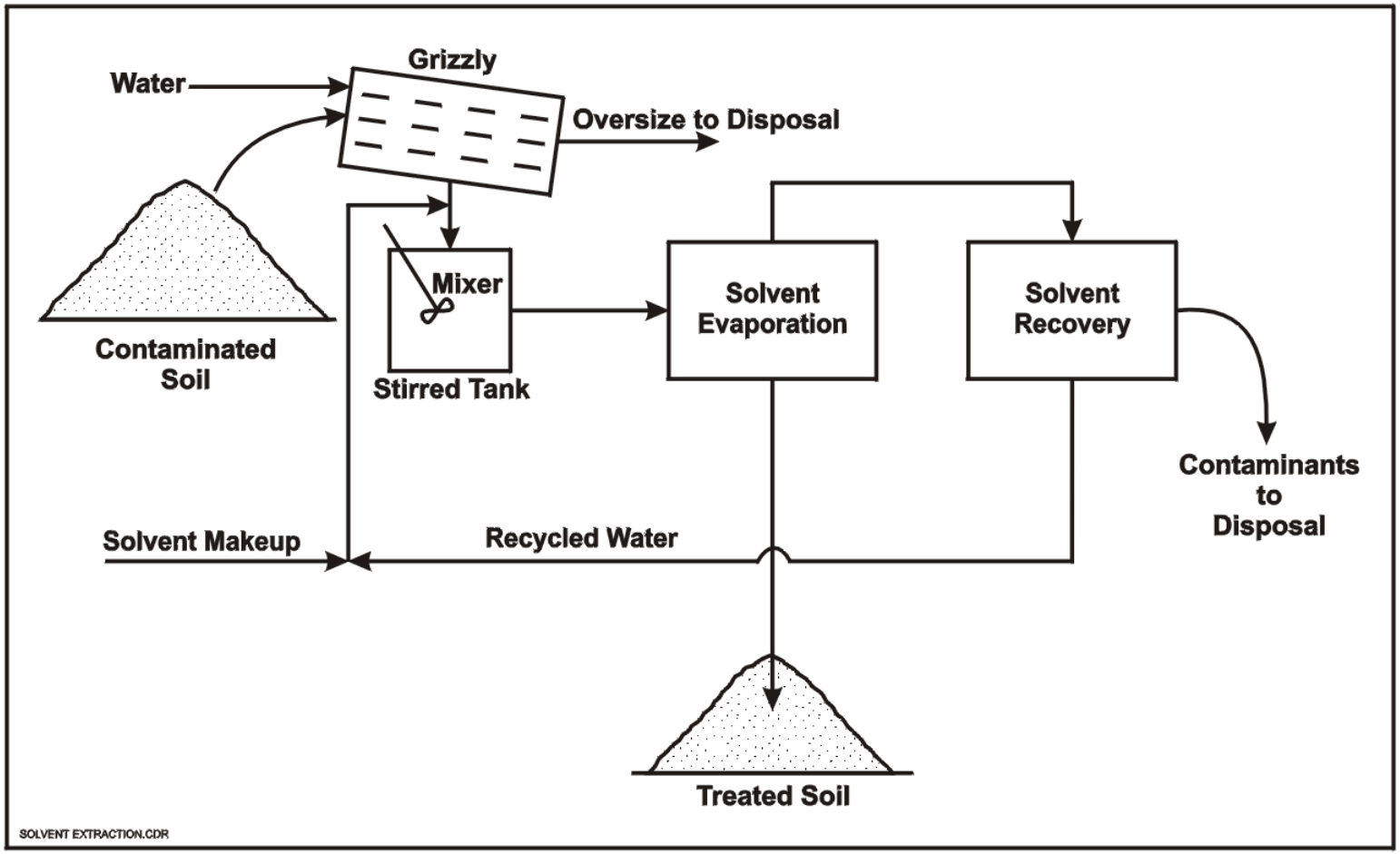


Figure PC28. Solvent Extraction

PC29: Sprinkler Irrigation

Abstract:

Sprinkler irrigation is a treatment technology used to volatilize volatile organic compounds (VOCs) from pumped groundwater or wastewater using conventional spray irrigation equipment.

Description:

Treating water using sprinkler irrigation involves the pressurized distribution of VOC-laden water through spray nozzles. The high surface area caused by forming the spray promotes the transfer of VOCs from the dissolved aqueous phase to the vapor phase, whereby the VOCs are released directly to the atmosphere.

Applicability:

Sprinkler irrigation is used primarily to treat contaminants that readily transfer from the dissolved phase to the vapor phase such as halogenated or nonhalogenated VOCs.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Regulatory approval may be difficult to obtain because of the potential for excessive release of contaminants to the atmosphere.
- A large amount of space is required.
- Added surface water flow may promote ponding in low areas and runoff and erosion on slopes.
- Suspended solids or solids formed by precipitation of reduced iron or manganese species in solution can plug spray nozzles, requiring pretreatment to remove the solids.

Status: Innovative

Operation and Maintenance Duration:

Sprinkler irrigation is used to treat pumped groundwater or wastewater from a treatment process. The operation and maintenance duration depends on the duration of the primary process operation.

Cost Range: $0.05 to $0.10 per 1,000 gallons

The major cost items included in the cost estimate range for sprinkler irrigation are designated in Table PC29-1.

Table PC29-1. Major Cost Items to Implement Sprinkler Irrigation

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Piping and sprinkler system installation	Operating and maintenance labor
Land acquisition	Site supervision
	Site quality assurance and health and safety support
	Sampling and analysis for process control
Residuals Management Activities Included in Cost	
None	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.26.37 "Sprinkler Irrigation".

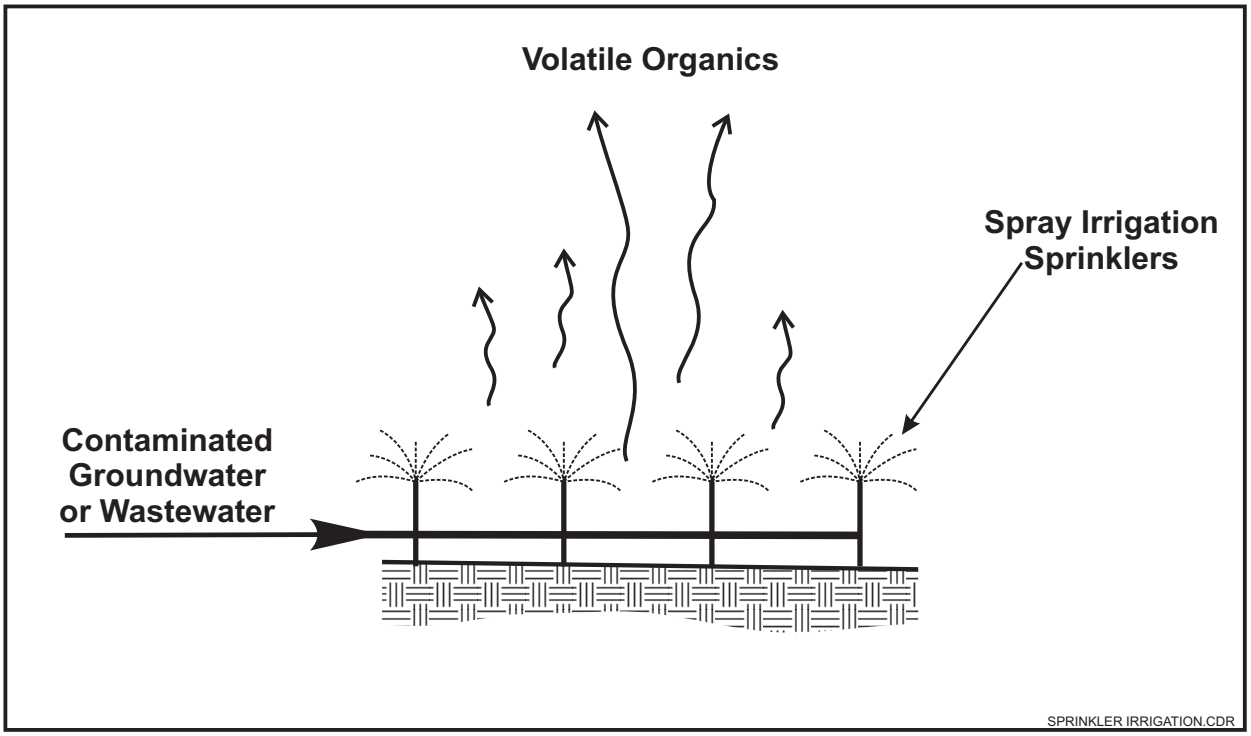


Figure PC29. Sprinkler Irrigation

PC30: In Situ Heating – Low Temperature (<100°C)

Abstract:

In situ heating (supplemented by vacuum extraction) to the boiling point of water is a technology for steam stripping semivolatile organic compounds (SVOCs) from in situ soils or groundwater for collection and management above ground.

Description:

In situ heat to 100°C can be implemented using steam injection wells, steam injection augers, hot water flooding, or in situ steam generation by electrical resistance heating (e.g., Six Phase Heating®).

Steam injection can be done using a fixed system of wells or a mobile system with augers that drill into the soil. With a fixed system, low-moisture-content steam is injected into vertical wells to heat the formation, vaporizing contaminants and mobilizing nonaqueous-phase liquid (NAPL) (if present) to extraction wells where fluids are collected by submersible pumps. Vapors are collected for treatment by applying vacuum to the extraction wells. With a mobile system, augers equipped with steam injection nozzles are advanced downward into the soil. Low-moisture-content steam discharged through the nozzle mixes with the soil. Vaporized moisture and contaminants are collected in a vacuum hood maintained over the augers.

Hot water flooding uses hot water and low-quality (high-water-content) steam injection to enhance and control contaminant mobility. The heat of the water and steam flow reduces the viscosity of the oily contaminants encountered, and the flow displaces and floats the NAPLs toward the extraction wells.

The water flooding system requires a complex well system to simultaneously inject low-quality steam, hot water, and cool water at three separate elevations. Low-quality steam is injected below the contamination to heat the DNAPL. At elevated temperature the DNAPL density is lower than the water density, and the DNAPL is mobilized upward by the hot water. Hot water is injected around the periphery of the contaminated zone to provide lateral confinement and displace the DNAPL toward extraction wells. Cool water is injected above the contaminated zone to create an absorption layer or cold cap. This absorption layer provides vertical confinement of rising pore fluids and condenses any vapors emanating from the heated contaminated zone.

With electrical resistance heating, direct resistive heating (also called Joule or ohmic heating) is a potentially efficient method to deposit heat directly in the contaminated soil mass by the conduction of electric current. The technology is implemented by placing electrodes in the ground and applying sufficient voltage to produce an electric current. Ohmic heating occurs when electric current flows through the soil. Moisture in the soil is the main conduction path for the electricity. Heating vaporizes water from the formation so a continual supply of water is required. Because of the need to maintain water in the soil, the maximum temperature achieved by resistive heating is below 100°C. Volatile organic compounds (VOCs) and SVOCs are vaporized by a combination of steam stripping action and increased vapor pressure. The water vapor and organics are collected by vacuum extraction wells and treated.

Applicability:

Low-temperature in situ heating is used primarily to treat halogenated and nonhalogenated SVOCs and dense, nonaqueous-phase liquid (DNAPL). VOCs also can be treated by this technology, but there are more cost-effective processes for sites contaminated with VOCs.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Subsurface heterogeneity can interfere with uniform fluid flow.
- Low-permeability soils are difficult to treat.
- Gravity override may cause the steam front to bypass DNAPL contaminants.
- Buried electrical conductors can interfere with the application of in situ ohmic heating.
- The fluid injection and fluid and vapor collection systems must be designed and operated to limit the spread of contaminants to clean areas.
- Steam, water, and organic liquids must be recovered and treated.
- Off-gas collection and treatment are required.

Status: Innovative

Operation and Maintenance Duration:

In situ heating is expected to achieve clean up in an operation and maintenance duration of 3 to 6 months, depending on the following conditions:

- Cleanup goals
- The volume of in situ media requiring treatment
- Contaminant concentration and distribution
- In situ characteristics including permeability and anisotropy
- Fluid delivery and collection capacity
- Physical characteristics of contaminants, including vapor pressure, solubility, and density.

Cost Range: $10,000 to $20,000 fixed mobilization cost plus $90 to $290 per cubic yard operating cost

The major cost items included in the cost estimate range for in situ heating – low temperature are designated in Table PC30-1.

Table PC30-1. Major Cost Items to Implement In Situ Heating – Low Temperature

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Well installation	Heating system leasing
Sampling point installation	Off-gas treatment system leasing
Crew and equipment mobilization	Condensate handling system leasing Operating and maintenance labor Utilities Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
Off-site disposal of organic liquids	
Off-gas treatment	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.27.02 "Six-Phase Heating and Extraction" and X.27.04 "Steam/Hot Water Injection—Vacuum Extraction".

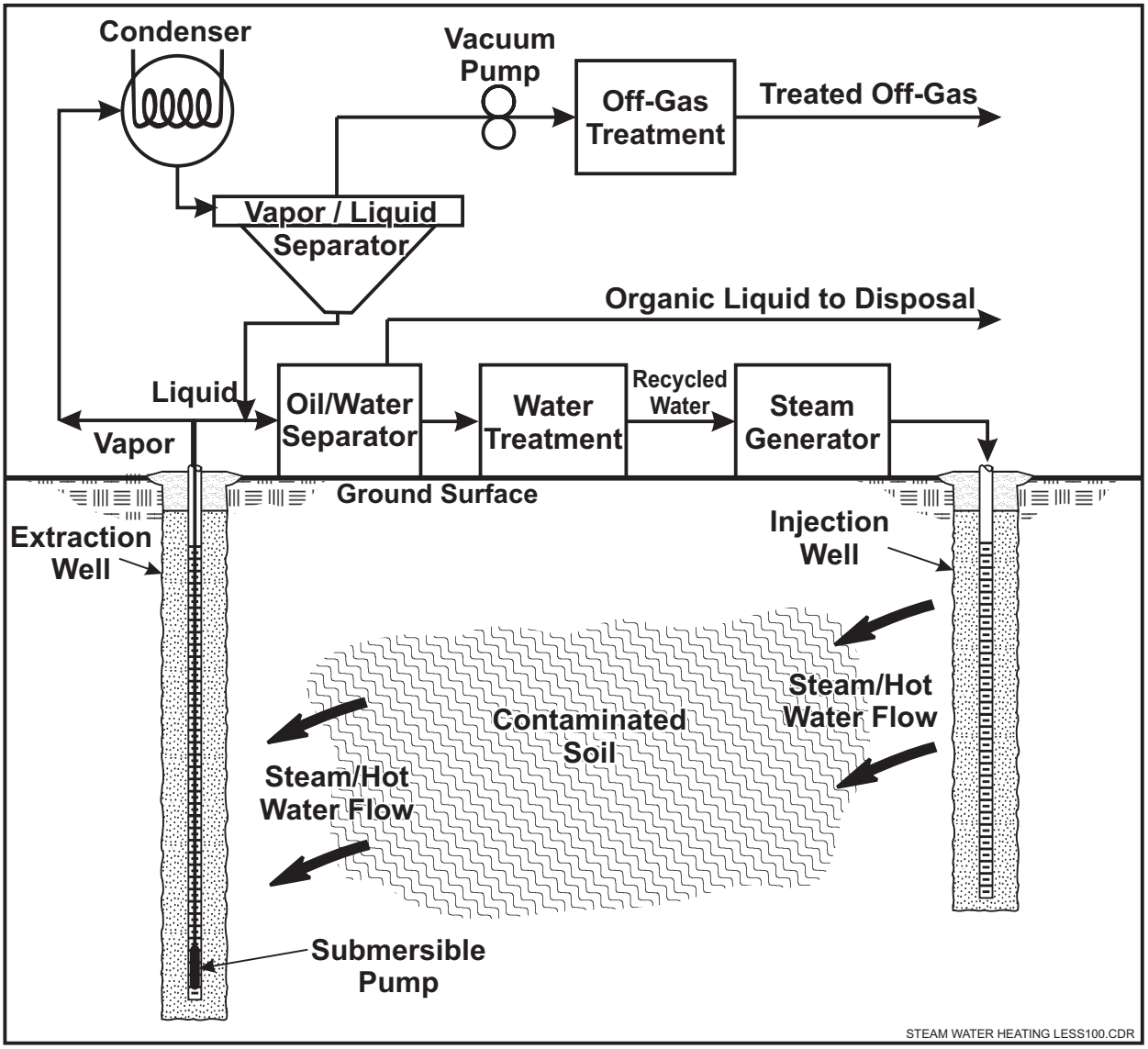


Figure PC30. In Situ Heating <100°C

PC31: Surfactant-Enhanced Aquifer Remediation (SEAR)

Abstract:

Surfactant-enhanced aquifer remediation (SEAR) is an in situ treatment process for enhancing organic contaminant solubility to increase the efficiency of pump-and-treat systems.

Description:

Surfactant-enhanced aquifer remediation (SEAR), also known as in situ surfactant flooding, targets the removal of residual nonaqueous-phase liquids (NAPLs) that become trapped in the pore spaces of the aquifer. The removal of NAPL contaminants is frequently inefficient and expensive using conventional technologies such as pump-and-treat, due to the low solubilities and rates of dissolution of NAPL contaminants. If not addressed, NAPL will persist as a source of contamination to surrounding soils and groundwater, prolonging attenuation of a groundwater plume. SEAR is designed to enhance the removal of NAPL from the subsurface by increasing the effective aqueous solubility of the NAPL and by reducing the interfacial tension between the water and NAPL phases. The technology has most often been applied at sites contaminated by free-phase chlorinated solvents, or dense nonaqueous-phase liquids (DNAPLs). DNAPLs present a unique remediation problem because they are more dense than water and will migrate downward within an aquifer until retarded by a low permeability layer. Therefore, they can reach depths that are not amenable to remediation by conventional methods such as excavation.

SEAR is conducted by injecting a surfactant solution into the contaminated zone while simultaneously extracting water to maintain hydraulic control over the movement of the surfactant solution and the mobilized contaminants. Surfactant flooding is followed by water flooding to remove residual contaminants and injected chemicals. Conventional wastewater treatment technologies may be used to process the extracted effluent so long as surfactant foaming can be controlled, such as with the addition of an anti-foaming agent. The design of a surfactant flood requires comprehensive site data to identify the location and distribution of NAPL, measurement of aquifer permeability and hydraulic gradients, and determination of the integrity and thickness of any underlying layer of low permeability (i.e., aquitard). If an aquitard is not present, SEAR must be specially designed to avoid downward movement of mobilized contaminants; this can be accomplished by adjusting the surfactant composition.

Applicability:

The majority of demonstrations for this emerging technology residual-phase NAPL-contaminated sites. SEAR has been applied to remove chlorinated solvents, creosote, gasoline, jet fuels, Navy special fuel oil, and polychorinated biphenyls (PCBs) from the subsurface.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Subsurface heterogeneities can interfere with effective delivery of the surfactant solution to contaminated zones.
- Injected surfactants must be food-grade or biodegradable.
- Low-permeability soils are difficult to treat.
- Careful design is required to prevent undesired movement of contaminant and injected chemicals away from the treatment zone. Maintaining hydraulic control is necessary.
- Surfactant solution must be recovered and treated.

Status: Emerging

Operation and Maintenance Duration: Duration is dependent on the soil permeability. A full-scale application of SEAR can require from three weeks to four months. Aquifer characterization activities recommended for SEAR design can be conducted in 3 to 12 days. Any readily mobile free-phase NAPL in the system should be removed prior to surfactant injection.

Cost Range: Costs vary with soil permeability, heterogeneities in permeability, and scale of application, and range from hundreds to thousands of dollars per cubic yard of contaminated soil treated.

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.23.05 "In Situ Chemical Soil Flushing (Surfactant/Solvent) and X.25.11 "In Situ Physical Soil Flushing (Surfactant/Solvent)".

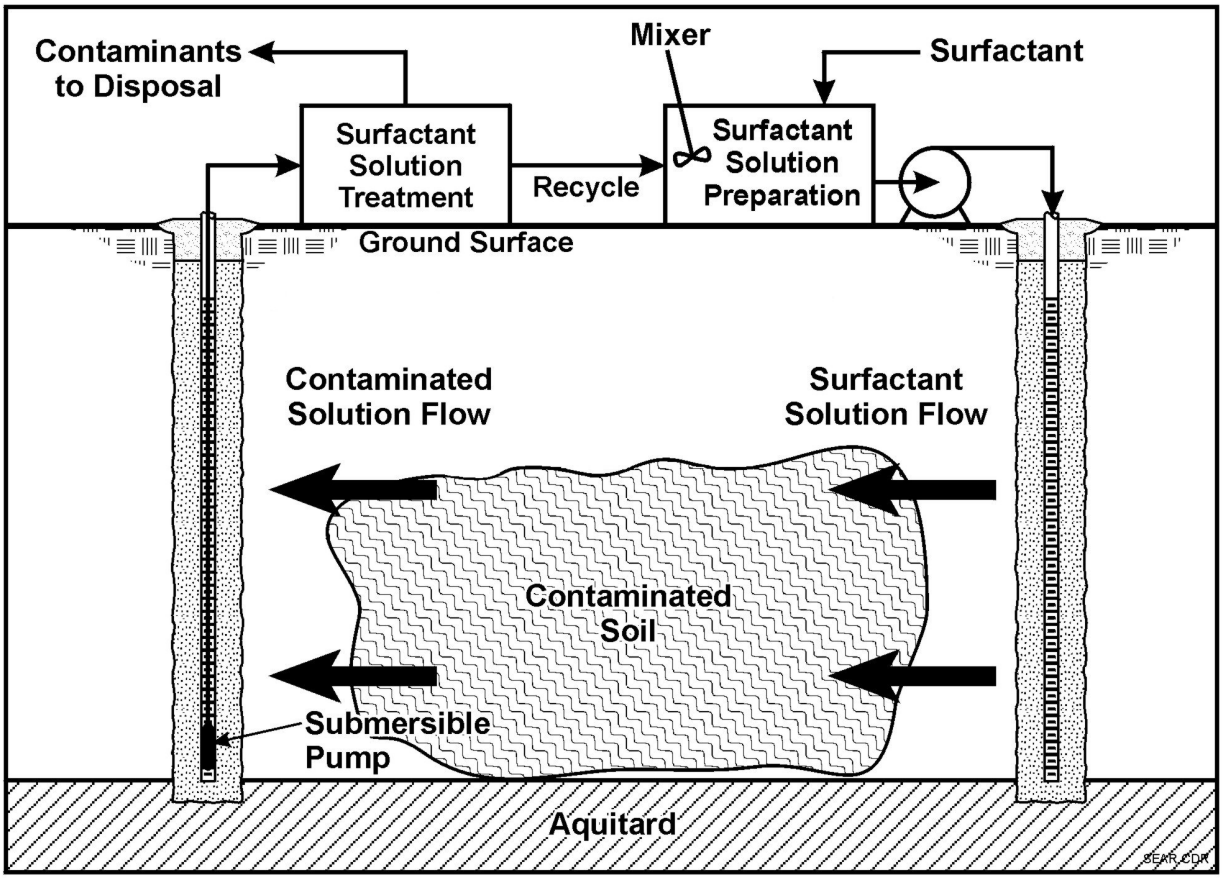


Figure PC31. Surfactant-Enhanced Recovery

PC32: Synthetic Resin Adsorption (Liquid Phase and Vapor Phase)

Abstract:

Synthetic resin adsorption is a process for remediation of contaminants from water or gas streams by sorption phenomena on synthetic resins.

Description:

Synthetic resin adsorption involves passing contaminated fluid through a bed of resin so that contaminants sorb onto active sites. The synthetic resins are hard, spherical, microporous beads manufactured to provide high effective surface area and a high adsorption capacity for organic molecules.

Applicability:

Synthetic resin adsorption is applicable for removing halogenated and nonhalogenated volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs), polychlorinated biphenyls (PCBs), and ordnance compounds from water or gas streams. The synthetic resins provide 5 to 10 times higher mass loading of contaminants than does granular activated carbon (GAC) when the contaminant concentration in the wastestream is low. The synthetic resin allows higher flow loading per unit area than GAC beds.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Oil and grease in the water may clog the sorbent resin.
- Unit cost of resin is higher than GAC, typically requiring resin regeneration.
- Economic trade off of higher capacity at higher cost has not been fully explored.
- Suspended solids or solids formed by precipitation of reduced iron and manganese species in solution can foul a resin bed, requiring pretreatment to remove the fouling agents.

Status: Emerging

Operation and Maintenance Duration: N/A

Cost Range: N/A

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.26.40 "Synthetic Resin Adsorption".

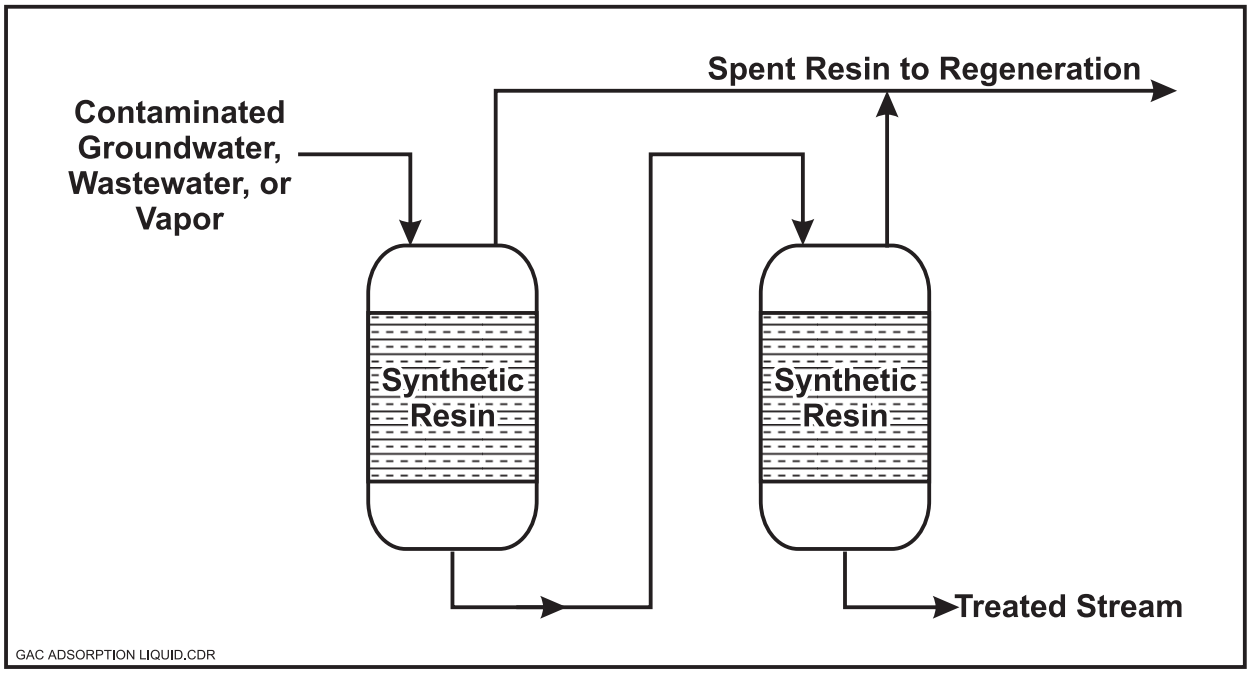


Figure PC32. Synthetic Resin Adsorption

PC33: Thermal/Catalytic Oxidation

Abstract:

Thermal/catalytic oxidation is a treatment technology in which combustible organics are removed from air by reaction with oxygen at high temperature.

Description:

Thermal oxidation is accomplished by heating the contaminated off-gas stream by direct exposure to a fossil fuel flame. The air is preheated, thoroughly mixed, and combusted at high temperatures so that organics burn to form carbon dioxide and water. A thermal combustion unit typically consists of a fan to move volatile organic compound (VOC)-laden air; a filter-mixer to mix the VOC-laden air; a fan to supply combustion air; a combustion unit consisting of a refractory-lined chamber and one or more burners; heat recovery equipment; and a stack for atmospheric release of the treated exhaust. Thermal oxidation systems require supplemental fuel to sustain the combustion temperature, which is normally about 650 to 870°C (1,200 to 1,600°F) when treating low-concentration streams.

When treating off-gas streams with an inlet concentration lower than 2,000 ppmv, catalytic oxidation typically becomes economically favorable because of the high fuel consumption required for thermal oxidation. A catalytic oxidation unit is essentially a thermal oxidation unit with a catalyst module at the combustion chamber exit. Many thermal oxidation units allow for conversion to catalytic operation by the addition of a catalyst module. Exposing the heated gas to a catalyst allows for acceptable destruction of organics at a lower temperature (e.g., 315 to 540°C [600 to 1,000°F]). Operating the combustion chamber at a lower temperature improves fuel economy when treating dilute gas streams.

Applicability:

Thermal oxidation units typically are used to treat halogenated and nonhalogenated VOCs and semivolatile organic compounds (SVOCs) and polychlorinated biphenyls (PCBs) in a gas stream. Thermal oxidation is most efficiently applied for treating off-gas containing 1,000 to 5,000 ppmv of combustibles. Catalytic oxidation is best used for concentrations in the range of 100 to 3,000 ppmv. Dilution air must be added when the combustible vapor concentration exceeds 25% of the lower explosive limit (LEL).

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Capital cost of the thermal combustion systems.
- Low-concentration VOC streams may require large amounts of supplemental fuel.
- Inlet VOC concentrations must be less than 25% of the LEL for the contaminant.

Status: Conventional

Operation and Maintenance Duration:

Thermal oxidation is used to treat off-gas from a primary treatment process. The operation and maintenance duration depends on the duration of the primary process operation.

Cost Range: $1.00 to $10.00 per pound of organic removed

The major cost items included in the cost estimate range for thermal/catalytic oxidation are designated in Table PC33-1.

Table PC33-1. Major Cost Items to Implement Thermal/Catalytic Oxidation

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Oxidation system installation	Operating and maintenance labor Utilities Catalyst replacement[(a)] Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
Off-site disposal of spent catalyst[(a)]	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

(a) Applicable only for catalytic operation

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.34.05 "Catalytic Oxidation", and X.34.06 "Thermal Oxidation".

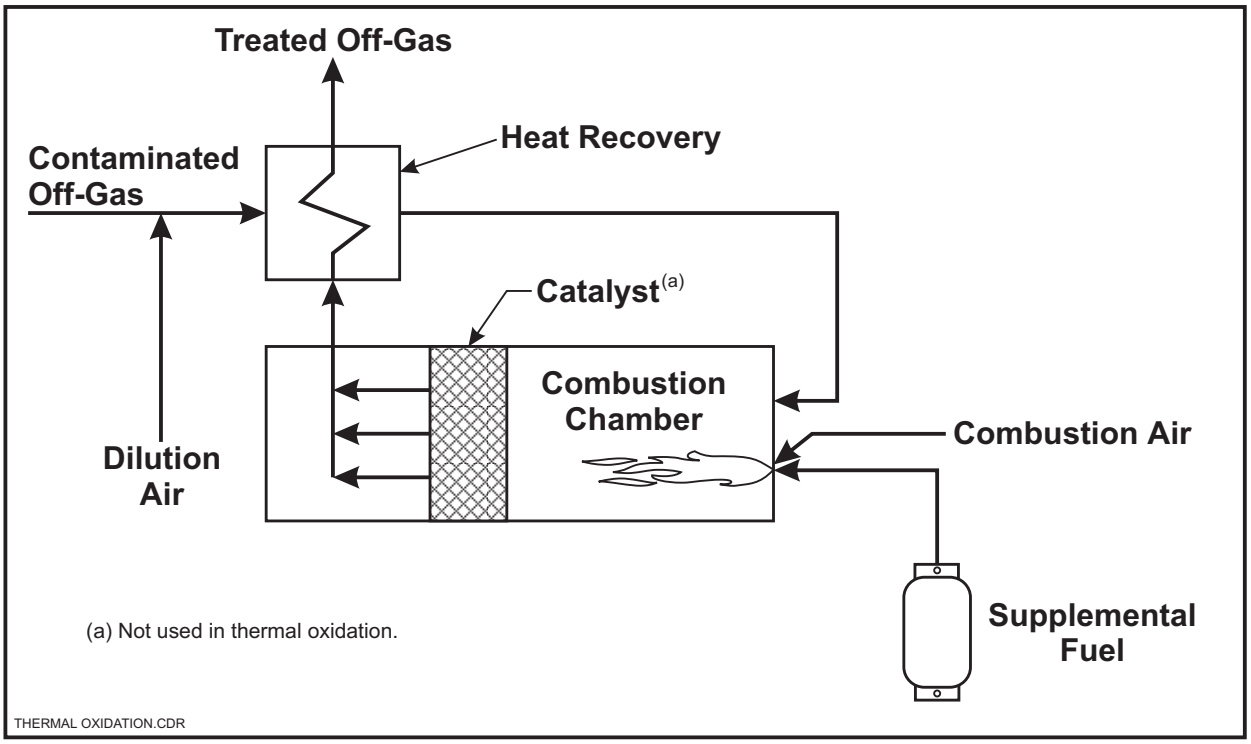


Figure PC33. Thermal/Catalytic Oxidation

PC34: Two-Phase (Dual-Phase) Extraction

Abstract:

In two-phase (dual-phase) extraction, a high-vacuum system is applied to simultaneously remove liquid and gas from low permeability or heterogeneous formations.

Description:

Two-phase extraction provides air flow through the unsaturated zone to remediate volatile organic compounds (VOCs) and fuel contaminants by vapor extraction and/or bioventing. The air flow also extracts groundwater for treatment above ground. The screen in the two-phase extraction well is positioned in both the unsaturated and saturated zones. A vacuum applied to the well, using a drop tube near the water table, extracts soil vapor. The vapor movement entrains groundwater and carries it up the tube to the surface. Once above grade, the extracted vapors and groundwater are separated and treated. The drop tube is located below the static water level, so the water-table elevation is lowered, exposing more contaminated soil to remediation by the air flow. When containment of vapors/liquids is necessary, the results are better than those obtained through air sparging.

Applicability:

Two-phase extraction is used primarily to treat halogenated and nonhalogenated VOCs and nonhalogenated semivolatile organic compounds (SVOCs). Two-phase vacuum extraction enhances air flow to remediate contaminants in unsaturated soil and, at the same time, collects groundwater for aboveground treatment.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Subsurface heterogeneity can interfere with uniform collection of contaminated groundwater and aeration of contaminated soil.
- Combination with complementary technologies (e.g., pump-and-treat) may be required to recover groundwater from high-yielding aquifers.
- Two-phase extraction requires both water treatment and vapor treatment.

Status: Innovative

Operation and Maintenance Duration:

Operation and maintenance duration for this technology varies from a 6 months to years, and is dependent on the following conditions:

- Cleanup goals
- The volume of in situ media requiring treatment
- Contaminant concentrations and distribution
- In situ characteristics including permeability and anisotropy
- The radius of influence of groundwater extraction
- The groundwater extraction rate.

Cost Range: $100,000 to $250,000 per acre

The major cost items included in the cost estimate range for two-phase extraction are designated in Table PC34-1.

Table PC34-1. Major Cost Items to Implement Two-Phase Extraction

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Extraction well and vacuum system installation	Operating and maintenance labor
Off-gas treatment system installation	Utilities
Monitoring well installation	Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
Disposal of treated water to publicly owned treatment works via site sewer	
Off-gas treatment	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.25.22 "Dual-Phase Extraction (Multi-Phase)".

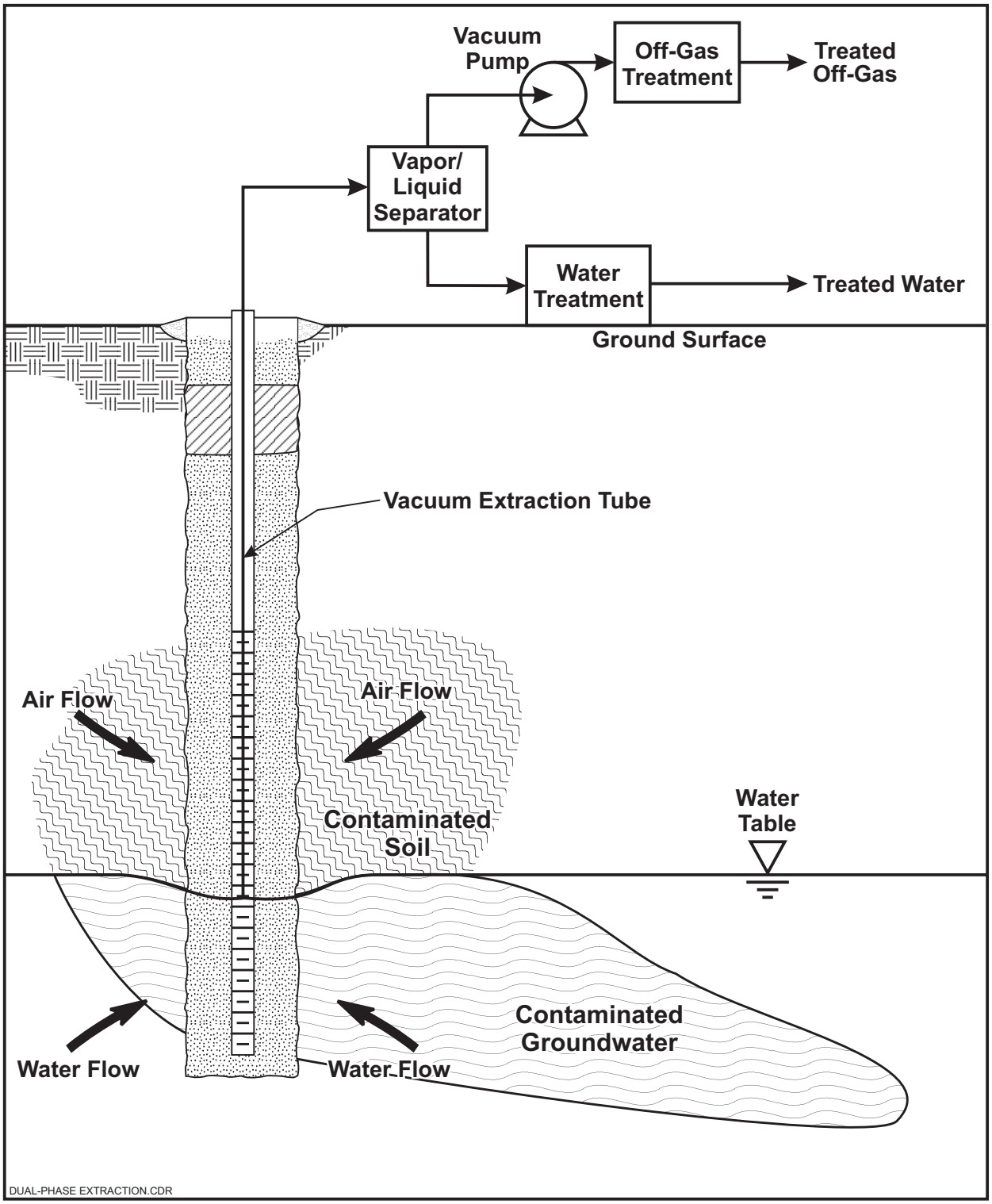


Figure PC34. Two-Phase (Dual-Phase) Extraction

PC35: Ultraviolet Light Oxidation (Vapor Phase)

Abstract:

Ultraviolet (UV) light oxidation is an organic destruction process that oxidizes organic constituents in off-gas by exposure to UV light in the presence of an oxidizing agent or a catalyst.

Description:

UV light oxidation of vapor-phase contaminants is accomplished by passing the off-gas stream in close proximity to a powerful UV light source. Oxidation occurs as a result of reactions with hydroxyl radicals produced by the UV light. The photo-oxidation usually is supplemented by a gaseous chemical oxidant (e.g., ozone) or a solid catalyst (e.g., TiO_2).

Applicability:

UV light oxidation can be used to treat halogenated and nonhalogenated volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs) and polychlorinated biphenyls (PCBs). The process is best used to treat easily oxidized organic compounds, such as those with double bonds (e.g., trichloroethylene [TCE], perchloroethylene [PCE], and vinyl chloride [VC]), as well as simple aromatic compounds (e.g., toluene, benzene, xylene, and phenol).

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Capital cost of the UV treatment system.
- The UV light frequency must be selected for maximum VOC removal based on the properties of the VOCs in the off-gas stream.
- Costs may be higher than competing technologies because of energy requirements.
- Pretreatment of the off-gas stream may be required to minimize ongoing cleaning and maintenance of UV reactor and quartz sleeves.
- Catalyst can be fouled by long-chain organics.

Status: Innovative

Operation and Maintenance Duration:

UV oxidation is used to treat off-gas from a primary treatment process. The operation and maintenance duration depends on the duration of the primary process operation.

Cost Range: $1.50 to $15.00 per pound of organic removed.

The major cost items included in the cost estimate range for UV oxidation (vapor phase) are designated in Table PC35-1.

Table PC35-1. Major Cost Items to Implement UV Oxidation (Vapor Phase)

Pretreatment Activities Included in Cost	
Filtration to remove particulates	
Fixed Cost Items Included	**Variable Cost Items Included**
UV oxidation system installation	Operating and maintenance labor Utilities Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
None	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.34.07 "Ultraviolet Oxidation".

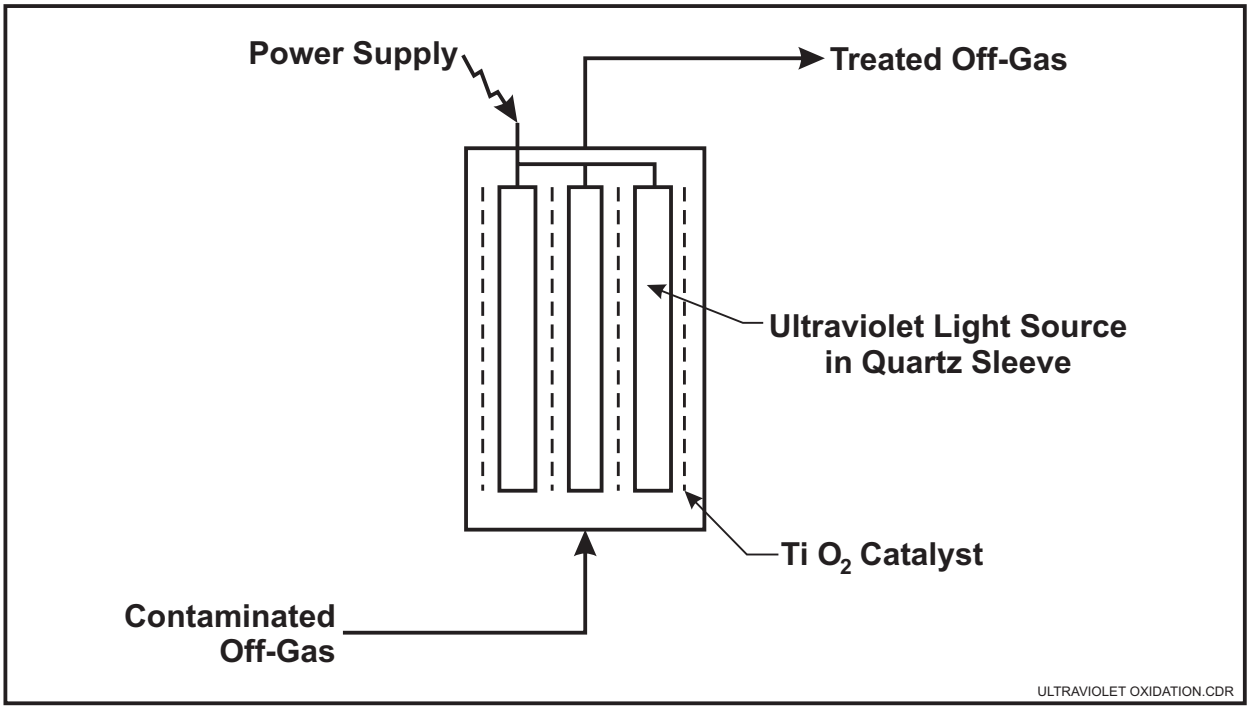


Figure PC35. Ultraviolet Light Oxidation (Vapor Phase)

PC36: Use as Aggregate in Asphalt Mix

Abstract:

Suitable granular matrices contaminated with petroleum hydrocarbons or non-hazardous concentrations of metals may be managed by reuse as aggregate in asphalt paving.

Description:

Use as aggregate is a recycling approach for managing granular soils and solids such as abrasive blasting media. This approach involves using the waste as the fine aggregate in asphalt. The waste matrix replaces some or all of the sand used to prepare an asphalt paving mixture. The bitumen binder that forms the paving also immobilizes the contaminants. The waste can be used in hot mix or cold mix asphalt. Hot mix asphalt is prepared by blending and drying fine aggregate and coarse aggregate. The dried blend is then mixed with bitumen at 150 to 180°C (300 to 350°F). Cold mix asphalt is prepared by blending sand, gravel, and a bitumen/water emulsion at ambient temperature. A typical finished paving mixture using the hot or cold mix method contains about 45% fine aggregate, 50% coarse aggregate, and 5% bitumen. The contaminated soil or sand usually replaces about half or less of the fine aggregate.

A wide variety of wastes containing petroleum hydrocarbons or moderate to low concentrations of metal contaminants can be used to make asphalt. For the reuse option to be acceptable, the asphalt prepared using the contaminated matrix must provide adequate paving performance and immobilize the contaminants. Sandy soils containing petroleum contaminants and metal-contaminated sand are particularly suitable for reuse in asphalt. Petroleum contaminants are similar to the bitumen binder and are easily accommodated in the asphalt mixture. Foundry casting sand and spent sand blasting grit contain metal contaminants that can be effectively immobilized in the bitumen and sand matrix by replacing some of the clean sand normally used in asphalt. Resource Conservation and Recovery Act (RCRA) hazardous wastes and/or highly toxic wastes are unlikely to be acceptable for reuse in asphalt.

Applicability:

Soils or granular silica materials contaminated with non-halogenated volatile organic compounds (VOCs), semivolatile organic compounds (SVOCs), or low concentrations of metals can be recycled as asphalt aggregate.

Limitations:

Factors that may limit the applicability and effectiveness of the process include the following:

- Materials containing solvents or other particularly hazardous or toxic constituents should not be recycled in this manner.
- Materials with high metal contents (percent level or greater) may pose hazards either to workers at the asphalt plant due to dust exposure or to the public in the asphalt product because of metals leaching.
- High concentrations of silt and smaller-size particles are undesirable because they have poor wetting characteristics in the bitumen binder and may generate dust.
- Highly rounded aggregates are not compatible with good vehicular traction in the asphalt concrete product.
- The presence of sulfate or metallic iron is undesirable because these materials swell upon hydration of sulfates or oxidation of iron. Reduced forms of trace metals may cause similar problems, which,

however, may be avoidable by recycling the materials into a base coarse layer, where there is minimal contact with air.

Status: Conventional

Operation and Maintenance Duration:

Use as aggregate is used to treat excavated soil or contaminated granular material, so the operation and maintenance duration depends on the processing rate of the treatment unit and the volume of soil. Processing will be performed at a central facility (i.e., asphalt plant). The facility's capacity to accept waste will depend on the volume of construction in the area.

Cost Range: $1.00 to $25.00 per cubic yard for nonhazardous waste

The major cost items included in the cost estimate range for use in aggregate in asphalt mix are designated in Table PC36-1.

Table PC36-1. Major Cost Items to Implement Use in Aggregate in Asphalt Mix

Pretreatment Activities Included in Cost	
Screening to remove debris	
Fixed Cost Items Included	**Variable Cost Items Included**
None	Transportation to the asphalt plant Toll fee for accepting material at asphalt plant Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
None	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.30.9X "Ex Situ Stabilization/Fixation/Encapsulation—Other".

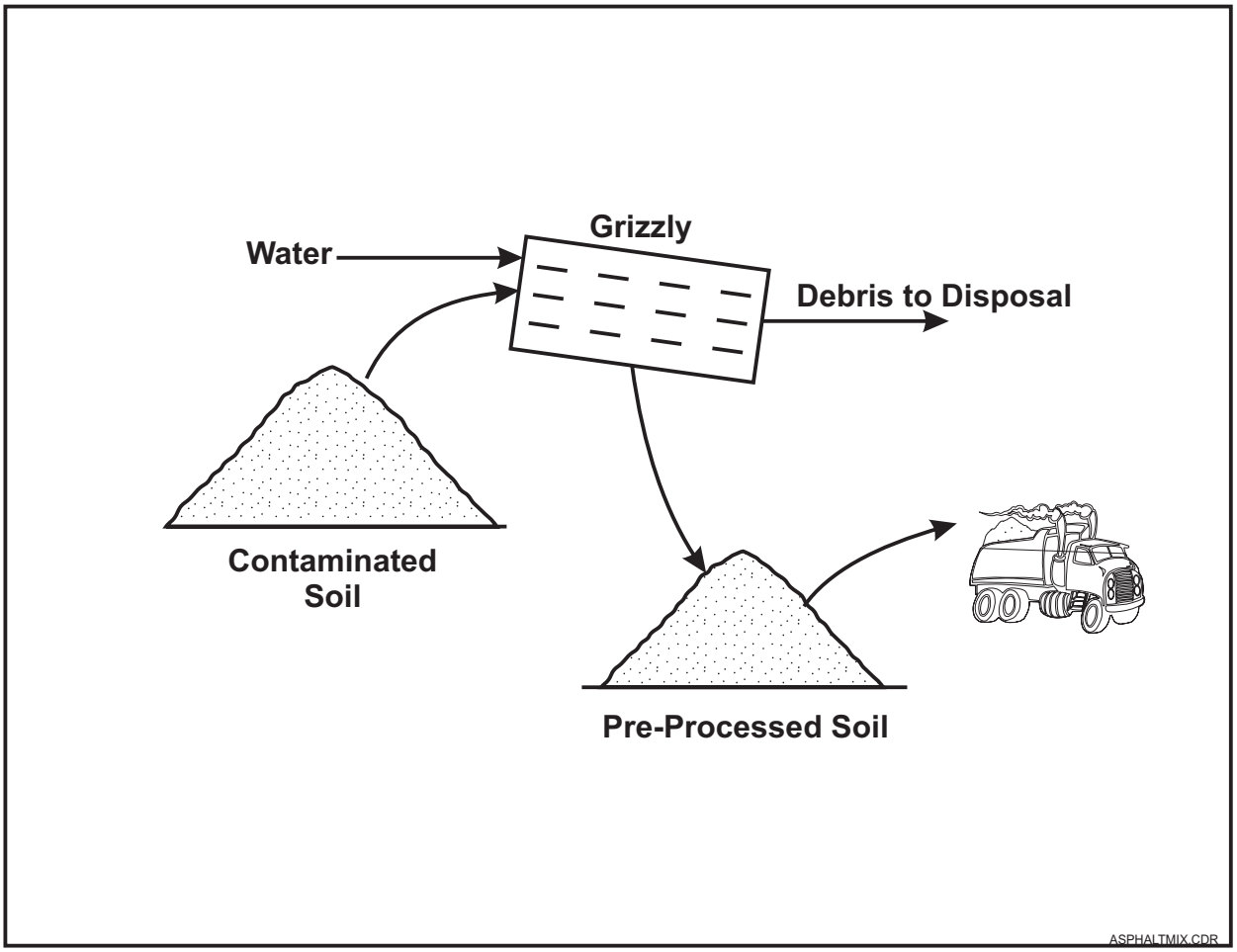


Figure PC36. Use as Aggregate in Asphalt Mix

Combined Mechanism Technology Profiles Index

Remediation Technology	Treatment Method[a]	Category[b]	Applicability[c]	Technology Profile	Technology Page No. (TP-)	CER Profile Page No. (CER-)[d]
Constructed Wetland	CM	I	4, 20, 25, 31, 36	CM1	154	42
Lasagna™ Process	CM	E	1	CM2	157	NA
Natural Attenuation	CM	I	1, 2, 5, 7, 8, 11, 12, 13, 16, 17, 18, 21, 22, 23, 26, 27, 28, 29, 32, 33, 34, 37	CM3	159	NA
Vacuum-Enhanced Recovery (Bioslurping)	CM	I	38	CM4	162	NA

(a) CM = Combined Mechanism.
(b) C = Conventional, E = Emerging, I = Innovative.
(c) Applicability indicated by cross reference to Tables of Remediation Technologies.
(d) NA = CER Profile not available.

CM1: Constructed Wetland

Abstract:

Constructed wetland treatment is a method of constructing an environment that promotes the action of natural processes to mineralize organic contaminants and immobilize inorganic contaminants.

Description:

A constructed wetland treatment system incorporates principal ecosystem components found in wetlands, including organic materials (substrate), microbial fauna, and algae. Influent waters, with organic contaminants, low pH and/or contaminated with high metal concentrations, flow through the aerobic and anaerobic zones of the wetland ecosystem. Large hydrophobic organics and metals are removed by ion exchange, adsorption, absorption, and precipitation through geochemical and microbial oxidation and reduction. Sorption occurs as metals in the water contact humic or other organic substances in the soil medium. Oxidation and reduction reactions that occur in the aerobic and anaerobic zones, respectively, transform or degrade organics and precipitate metals as hydroxides and sulfides. Precipitated and adsorbed metals settle in quiescent ponds, or are filtered out as the water percolates through the soil or substrate.

Applicability:

Constructed wetlands are used primarily to treat halogenated and nonhalogenated volatile organic compounds (VOCs), nonhalogenated semivolatile organic compounds (SVOCs), and inorganics. Constructed wetlands have most commonly been used in wastewater treatment for controlling organic matter; nutrients, such as nitrogen and phosphorous; and suspended sediments (e.g., agricultural runoff. The wetlands-based treatment process is also suitable for controlling trace metals and other toxic materials (e.g., acid mine drainage). Constructed wetlands have been used to treat acid mine drainage that has extreme acid conditions and high concentrations of iron, sulfate, and other trace metals. Constructed wetlands not only show a reduction in iron and sulfate concentrations, but also show a recovery in pH levels. In the area of stormwater treatment, wetlands have shown the ability to remove fecal coliform bacteria, total petroleum hydrocarbons, and metals including lead, chromium, and zinc.

Wetland treatment has been applied with some success to wastewater in the eastern United States. The process may have to be adjusted to account for differences in geology, terrain, trace metal composition, and climate in the metal mining regions of the western United States.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- The long-term effectiveness of constructed wetland treatment is not well known. Wetland aging may be a problem that may contribute to a decrease in contaminant removal rates over time.
- The cost of building an artificial wetland varies considerably depending on such site conditions as topography, soil permeability, and climate.

Status: Innovative

Operation and Maintenance Duration:

Wetland treatment is a long-term technology intended to operate continuously for 10 to 30 years or longer. Factors that affect the duration of wetland operation and maintenance include the following:

- Cleanup goals
- The amount and concentration of the contaminants
- Sediment erosion patterns
- Surrounding land use
- Wetland water balance
- Slope
- Local climate (i.e., aridity, rainfall, temperature)
- Organism type and density.

Cost Range: $0.15 to $1.00 per 1,000 gallons

The major cost items included in the cost estimate range for constructed wetland treatment are designated in Table CM1-1.

Table CM1-1. Major Cost Items to Implement Constructed Wetland Treatment

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Land acquisition	Long-term inspection
Grade, fill, and weir construction to form wetland	Site supervision
Establishing wetland plant growth	Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
None	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.21.05 "Constructed Wetlands".

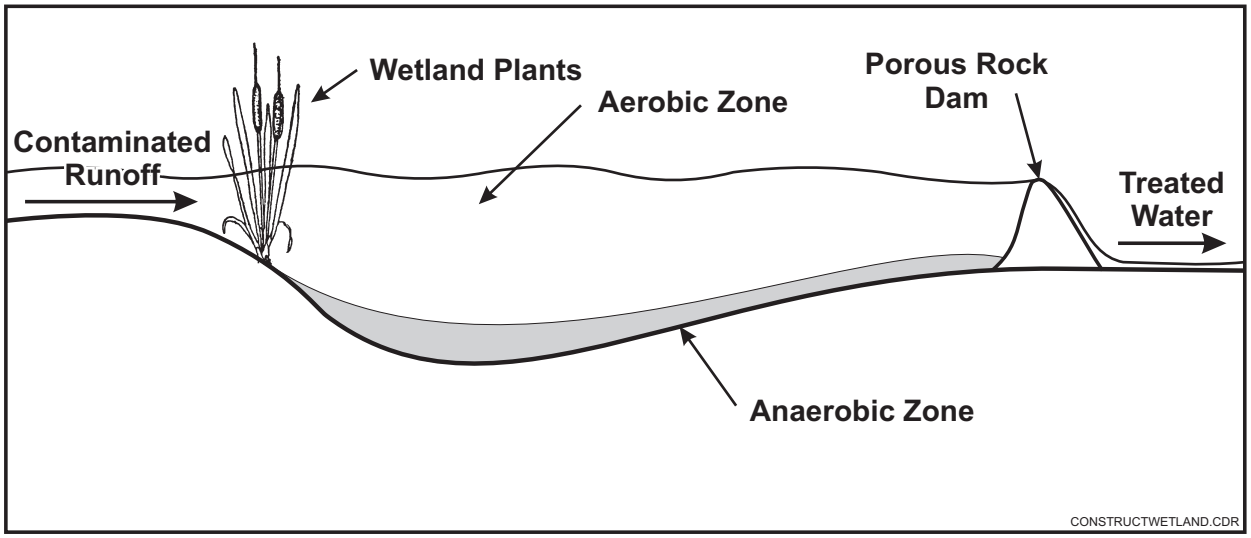


Figure CM1. Constructed Wetland

CM2: Lasagna™ Process

Abstract:

The Lasagna™ process is an in situ treatment technology that remediates soils and soil pore water contaminated with soluble organic compounds.

Description:

The Lasagna™ process uses electrokinetics to move contaminants in soil pore water into treatment zones where the contaminants can be captured or decomposed. The process is especially suited to sites with low-permeability soils, where electroosmosis can move water faster and more uniformly than hydraulic methods, and with very low power consumption. Both vertical and horizontal configurations have been conceptualized, but fieldwork to date is more advanced for the vertical configurations. Major features of the technology are as follows:

- Electrodes are energized by direct current, which causes the water and soluble contaminants to move into or through the treatment layers and also heats the soil.
- Treatment zones contain reagents that decompose the soluble organic contaminants or adsorb contaminants for immobilization or subsequent removal and disposal.
- A water management system recycles the water that accumulates at the cathode (high pH) back to the anode (low pH) for acid-base neutralization. Alternatively, electrode polarity can be reversed periodically to reverse electroosmotic flow and neutralize pH.

Applicability:

Low-permeability soils with water-soluble contaminants (organics, inorganic, or mixed wastes) could be remediated using the Lasagna™ technology. Field experiments have been staged to quantify performance and variables and determine cost-effectiveness for in situ trichloroethylene (TCE) remediation. Initial results indicate the electroosmosis can remove residual TCE from soil, with concentrations reduced to approximately 1 ppm after 4 months of operation. Future tests will evaluate in situ degradation of TCE by reaction with zero-valent iron and the compatibility of this process with electroosmotic transport.

Limitations:

The following factor may limit the applicability and effectiveness of the process:

- The need for a water management system to neutralize pH near the cathode and anode
- Chloride ions in the groundwater can be converted to chlorine at the anode, resulting in the formation of trihalomethanes.

Status: Emerging

Operation and Maintenance Duration: N/A

Cost Range: N/A

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.25.06 "Lasagna™ Process".

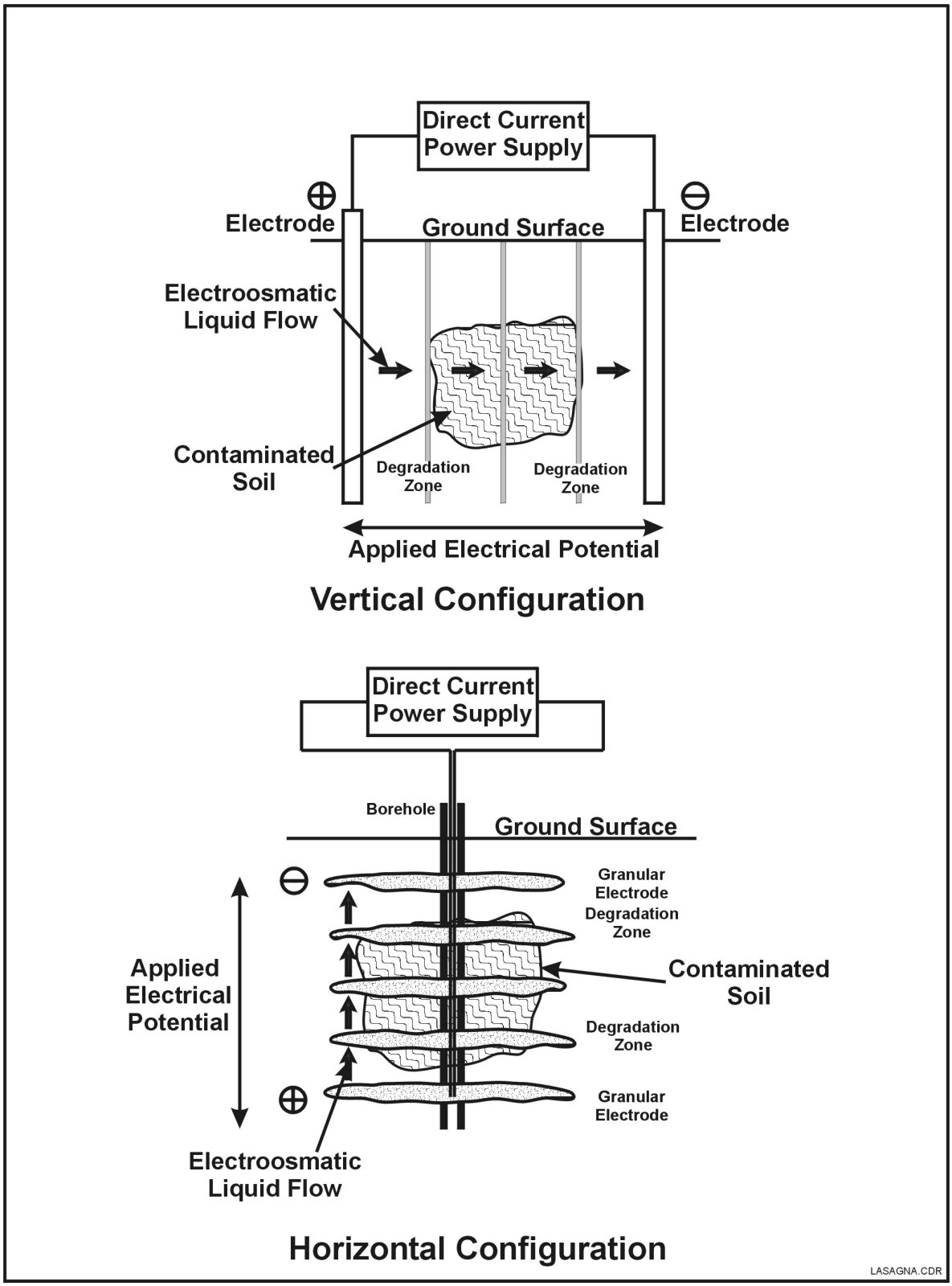


Figure CM2. Lasagna™ Process

CM3: Natural Attenuation

Abstract:

Natural attenuation is an in situ remediation technology where naturally occurring physical, chemical, and biological processes attenuate contaminant concentrations in soil and groundwater sufficiently to protect human health and the environment and achieve remedial goals within a time frame that is reasonable in comparison with active remediation.

Description:

For natural attenuation, natural subsurface processes such as dilution, volatilization, biodegradation, adsorption, and chemical reactions with subsurface materials are allowed to reduce contaminant concentrations to acceptable levels. Consideration of this option requires modeling and evaluation of contaminant degradation rates and pathways. The primary objective of site modeling is to demonstrate that natural processes of contaminant degradation will reduce contaminant concentrations below regulatory standards before potential exposure pathways are completed. In addition, sampling and sample analysis must be conducted throughout the process to confirm that degradation is proceeding at rates consistent with meeting cleanup objectives.

Natural attenuation is not the same as "no action," although it often is perceived as such. The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) requires evaluation of a "no action" alternative but does not require evaluation of natural attenuation. Natural attenuation is considered in the Superfund program on a case-by-case basis, and guidance on its use is still evolving. It has been selected at Superfund sites where, for example, polychlorinated biphenyls (PCBs) are strongly sorbed to deep subsurface soils and are not migrating; where removal of dense, nonaqueous-phase liquids (DNAPLs) has been determined to be technically impracticable (Superfund is developing technical impracticability [TI] guidance); and where it has been determined that active remedial measures would be unable to significantly speed remediation time frames. Where contaminants are expected to remain in place over long periods of time, as in the first two examples, TI waivers must be obtained. In all cases, extensive site characterization is required.

The attitude toward natural attenuation varies among agencies. The U.S. Air Force carefully evaluates the potential for use of natural attenuation at its sites; however, the U.S. Environmental Protection Agency accepts its use only in certain special cases.

Applicability:

Natural attenuation can be used to treat halogenated and nonhalogenated volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs), polychlorinated biphenyls (PCBs), ordnance compounds, and inorganics. Halogenated VOCs, halogenated SVOCs, pesticides, and ordnance compounds tend to resist natural degradation mechanisms, so natural attenuation may be less effective and may be applicable to only some compounds within these contaminant groups.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Extensive amounts of data must be collected and analyzed to determine plume behavior.
- Natural attenuation typically is not applicable when the plume is expanding.
- Natural attenuation should be used only where there are no impacts on potential receptors.

- Contaminants may migrate before they are degraded.
- The site may have to be fenced and may not be available for re-use until contaminant levels are reduced.
- If source material exists, it may have to be removed.
- Some inorganics, such as mercury, can be immobilized by natural mechanisms, but are not degraded.
- Halogenated organics may be relatively resistant to natural degradation processes.
- Intermediate degradation products may be more mobile or more toxic than the original contaminant.

Status: Innovative

Operation and Maintenance Duration:

The operation and maintenance duration is determined from natural attenuation evaluation and regulatory requirements. The process is expected to continue for 2 to 10 years until desired degradation levels are achieved. The duration of operation and maintenance is dependent on the following conditions:

- Cleanup goals
- The volume of the in situ media requiring treatment
- Contaminant concentrations and distribution
- In situ characteristics such as permeability and anisotropy
- Availability of nutrients, moisture, and reactive compounds
- Degradation processes that are occurring naturally in situ.

Cost Range: $50,000 to $250,000 per acre

The major cost items included in the cost estimate range for natural attenuation are designated in Table CM3-1.

Table CM3-1. Major Cost Items to Implement Natural Attenuation

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Sampling well installation	Site supervision
Evaluation of plume behavior	Site quality assurance and health and safety support Periodic evaluation of progress
Residuals Management Activities Included in Cost	
None	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.21.08 "Natural Attenuation".

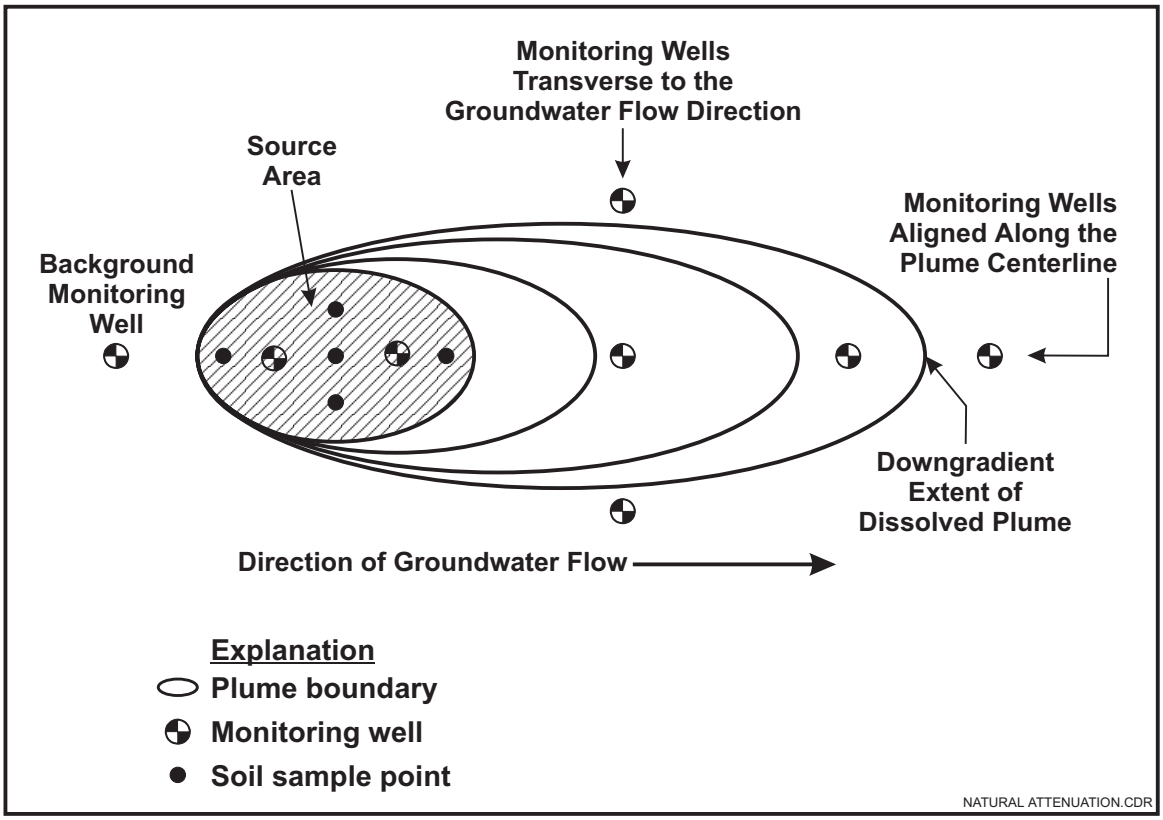


Figure CM3. Natural Attenuation

CM4: Vacuum-Enhanced Recovery (Bioslurping)

Abstract:

Bioslurping is a treatment technology that involves using a vacuum in a sealed extraction well to recover light, nonaqueous-phase liquid (LNAPL) and induce airflow through the unsaturated zone.

Description:

Bioslurping is performed using a tube positioned in a well so the end of the tube is near the water-table level in the formation. Vacuum is applied to the well using a single aboveground vacuum pump, and LNAPL and groundwater are removed from the well by air entrainment. The depth of the tube can be adjusted manually, if needed. The negative pressure established in the well depends on the air withdrawal rate and the permeability of the surrounding formation. The reference to biological processes in the term "bioslurping" results from the possibility that aerobic biological degradation of the hydrocarbons will be enhanced as a result of the introduction of air into the unsaturated zone. Slurping is used as the term to describe the air entrainment and aerodynamic dragging action that lifts fluids up the slurping tube.

The bioslurper system pulls a vacuum of up to 20 in. Hg on the recovery well to create a pressure gradient to force movement of LNAPL into the well. The system is operated to cause very little drawdown of the water-table level, thus reducing the problem of free-product entrapment in soils when pumping is ceased.

Aeration of the unsaturated zone soils is achieved by withdrawing soil gas from the recovery well. The slurping action of the bioslurper system cycles between recovering liquid (free product and/or groundwater) and soil gas. The rate of soil-gas extraction is dependent on the recovery rate of liquid into the well. When free-product removal activities are complete, the bioslurper system can be converted to a conventional bioventing system to complete remediation of the unsaturated zone soils.

A significant feature of the bioslurping process is the induced airflow, which in turn induces LNAPL flow toward the well. The pressure gradient created in the air phase results in a driving force on the LNAPL that can be significantly greater than the driving force that can be induced by pumping the LNAPL with no airflow. Also of importance is the fact that the vacuum extraction mechanism pulls LNAPL along more permeable horizontal zones. In addition, the continuity of the LNAPL phase is better maintained by eliminating the cone of depression formed during drawdown recovery, thus increasing the relative permeability for LNAPL. For these reasons, bioslurping has the potential for removing more LNAPL and at greater rates than do other pumping mechanisms.

Applicability:

Bioslurping is used primarily to recover LNAPL and can help to remediate nonhalogenated volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs) in the unsaturated zone. Bioslurping combines physical recovery of LNAPL, removal of LNAPL constituents by vaporization (SVE), and mineralization of LNAPL constituents by biological action (bioventing). The rate of mass removal due to each mechanism is site dependent. The bioventing component can be a strong contributor to the total mass removal at sites with low-volatility fuel, whereas vaporization may be relatively high at sites with high-volatility fuel. The combined mechanisms applied in bioslurping allow effective removal of LNAPL in the capillary fringe and LNAPL floating on the water table, while the residual organic in the unsaturated zone is mineralized by biological action and removed by vapor extraction.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- At some sites, bioslurper systems can extract large volumes of water that may need to be treated depending on the concentration of contaminants in the process water.
- Since the fuel, water, and air are removed from the subsurface in one stream, mixing of the phases occurs. These mixtures may require special oil/water separators or treatment methods before the process water can be discharged.
- Subsurface heterogeneity can interfere with LNAPL flow to the well and uniform aeration of contaminated soil.
- At sites having low-permeability soils, such as glacial tills, it may be difficult to mobilize the free product to the extraction well.
- Frequently, the off-gas from the bioslurper system requires treatment before discharge. However, treatment of the off-gas may only be required shortly after the startup of the system. As fuel recovery rates decrease, contaminant concentrations in the off-gas decrease as well.
- Frequently, the process water needs to be treated prior to discharge. As with the off-gas, the contaminant concentrations in the process water will decrease as the fuel recovery rate decreases.

Status: Innovative

Operation and Maintenance Duration:

Operations and maintenance duration for this technology varies from a few months to years. It is most cost-effective to limit the duration to less than 2 years. The duration of operation and maintenance is dependent on the following conditions:

- Cleanup goals
- The volume of free product present at the site
- Contaminant concentrations and distribution in the unsaturated zone
- In situ characteristics, including permeability and anisotropy
- The radius of influence of the bioslurper system on the free product
- The achievable rate of free-product extraction.

Cost Range: $100,000 to $500,000 per acre

The major cost items included in the cost estimate range for bioslurping are designated in Table CM4-1.

Table CM4-1. Major Cost Items to Implement Bioslurping

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Wells and vacuum pump installation	Operating and maintenance labor
Sampling points installation	Utilities
Oil/water separator installation	Site supervision
Off-gas treatment system installation	Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
Off-site disposal of organic liquid	
Disposal of treated water to publicly owned treatment works via site sewer	
Off-gas treatment	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.25.21 "Bioslurping".

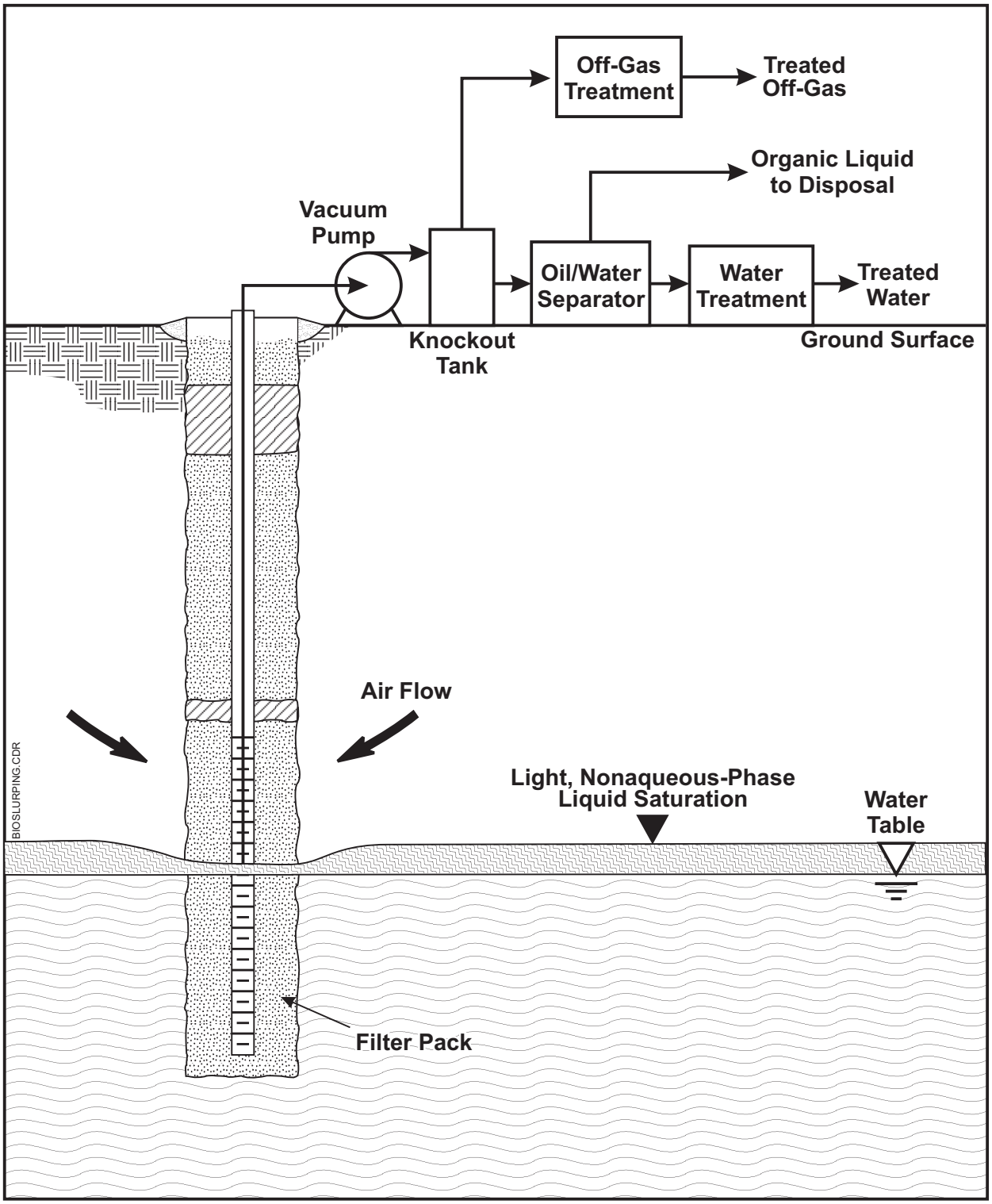


Figure CM4. Vacuum-Enhanced Recovery (Bioslurping)

Containment or Removal Technology Profiles Index

Remediation Technology	Treatment Method[a]	Category[b]	Applicability[c]	Technology Profile	Technology Page No. (TP-)	CER Profile Page No. (CER-)[d]
Asphalt/Concrete Cap	CR	C	27	CR1	166	NA
Confined Disposal Facilities Containment	CR	C	3, 19, 24	CR2	169	31
Drawdown Pumping	CR	C	38, 39	CR3	172	NA
In Situ Capping (Sediment) Contaminant	CR	C	5, 11, 16, 21, 26, 32, 37	CR4	176	NA
Off-Site Disposal	CR	C	3, 9, 14, 19, 24, 30, 35	CR5	179	NA
RCRA Subtitle C and D Caps	CR	C	27	CR6	182	NA
Skimming	CR	C	38	CR7	186	69
Vertical Cutoff Wall Containment	CR	C	1, 7, 12, 17, 22, 27, 28, 33, 38, 39	CR8	189	38, 40
Water Harvesting Vegetation Cover Containment	CR	I	27	CR9	192	NA

(a) CR = Containment or Removal.
(b) C = Conventional, I = Innovative.
(c) Applicability indicated by cross reference to Tables of Remediation Technologies.
(d) NA = CER Profile not avalable.

CR1: Asphalt/Concrete Cap

Abstract:

Asphalt/concrete (e.g., hard-surface) capping is a containment technology that involves using modified paving construction practices to reduce contaminant mobility and protect groundwater.

Description:

Hard-surface capping works by maintaining a high-strength, low-permeability cover over the waste to stabilize surface soil and reduce infiltration of surface water. The low-permeability layer can be made from either asphalt or concrete. Asphalt usually is selected in favor of concrete because the bitumen binder in asphalt provides some flexibility, making the cover more resistant to cracks that tend to form as a result of temperature cycling and/or differential settling. A top coat of bitumen or rubberized-bitumen mastic may be applied to further decrease permeability. For a cap applied in a high-traffic area, gravel may be mixed with the mastic to provide a wear resistant surface. The low-permeability layer typically is placed on a high-permeability foundation layer. The foundation helps reduce the negative effects of differential settling and allows drainage. Drainage under the low-permeability layer is needed to prevent ponding of small amounts of water that may leak through the low-permeability layer or migrate upward from the soil. Ponded water can freeze and expand during cold weather, causing frost heave damage to the cover. If gas generation in the waste volume must be controlled, a permeable vent layer can be placed on the surface as the first layer of the cap. Vapor extraction by applying a vacuum to the vent layer at points along the edge of the cap allows collection of gas for treatment.

Materials and methods used to place a hard-surface cap are similar to conventional road paving, but include modifications to reduce permeability and increase durability of the paving that forms the low-permeability element. For example, an asphalt layer used for capping consists of bitumen mixed with fine and coarse aggregate to give a specified well-graded aggregate mix as in paving. However, an asphalt paving mixture used for capping will require a more tightly controlled particle size distribution and a higher bitumen content in comparison to a standard road paving mixture. Concrete for capping typically will be an air-entrainment mixture (to increase freeze-thaw durability and workability) having a water-to-cement ratio less than 0.45 (to reduce porosity and increase strength).

Applicability:

An asphalt or concrete cap is used to contain in situ waste and can be applied to contain halogenated and nonhalogenated volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs), polychlorinated biphenyls (PCBs), ordnance compounds, and inorganics. These hard surface caps are alternatives to a multilayer cap and provide equivalent performance to a Resource Conservation and Recovery Act (RCRA) Subtitle C or D cap at similar to higher cost. Hard surface caps typically are selected only when required to limit vertical relief or provide a paved surface for traffic.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Contaminants remain in place at the site.
- Actual operating life is uncertain.
- Requires long-term monitoring and maintenance.
- Cannot be installed during frozen or saturated ground conditions.

Status: Conventional

Operation and Maintenance Duration:

Installation time for an asphalt or concrete cap typically ranges from 1 to 4 months. Inspections may be conducted frequently in the first 6 months because problems are most likely to appear during this period. After several years of service, the integrity of the cap becomes uncertain and should be investigated regularly. The period of time requiring active monitoring and maintenance is expected to be 20 years or longer.

Cost Range: $220,000 to $1,200,000 per acre

The major cost items included in the cost estimate range for asphalt/concrete caps are designated in Table CR1-1.

Table CR1-1. Major Cost Items to Implement Asphalt/Concrete Caps

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Site clearing	Long-term inspection
Crew and equipment mobilization	Repair of frost heave damage
Initial surface compaction	Site supervision
Surface preparation	Site quality assurance and health and safety support
Hard surface cap layer placement	
Edge drainage swale preparation	
Residuals Management Activities Included in Cost	
None	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.19.06 "Asphalt/Concrete Layer".

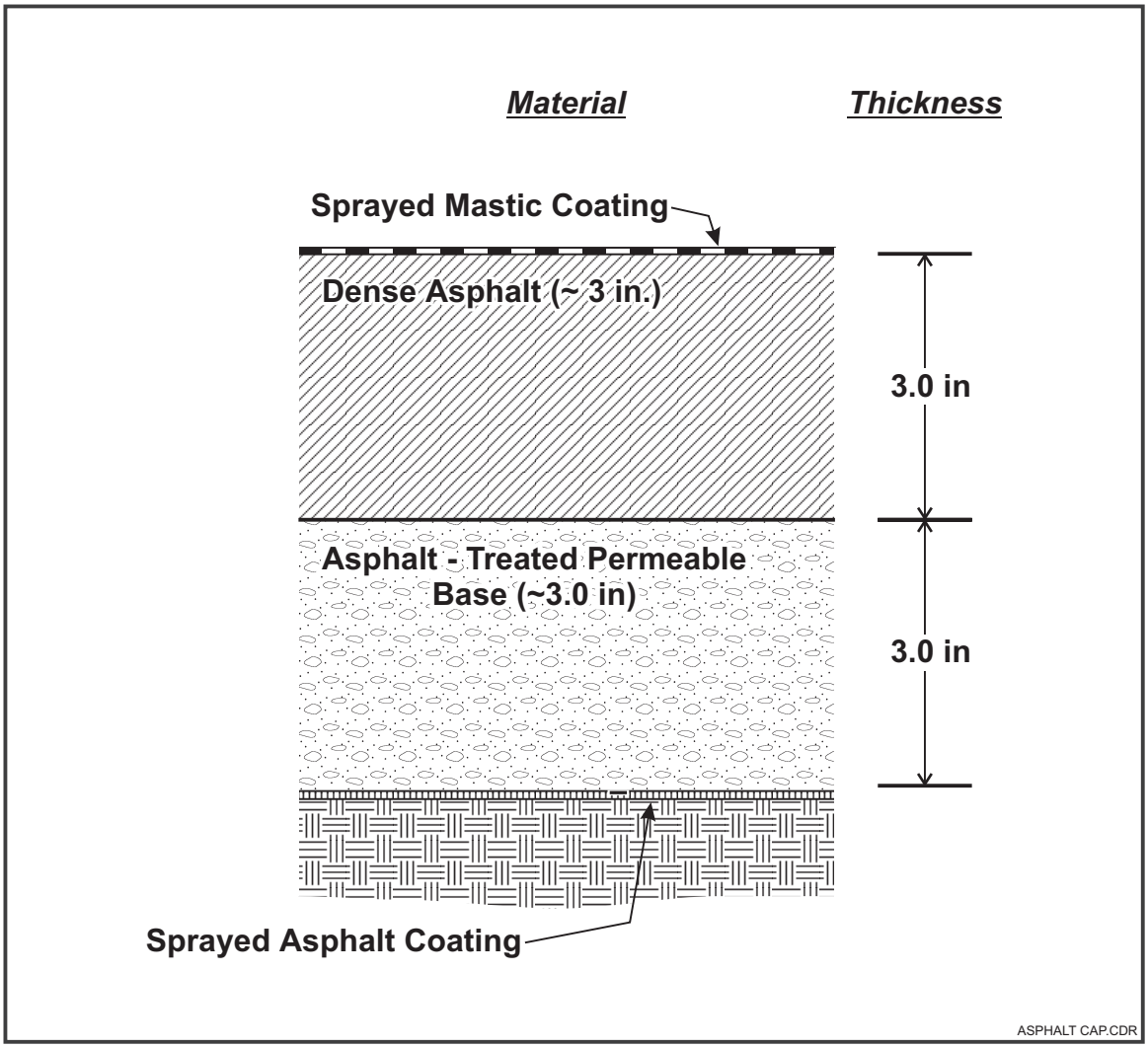


Figure CR1. Asphalt Cap

CR2: Confined Disposal Facilities (CDFs)

Abstract:

Confined disposal facilities (CDFs) are disposal areas formed by engineered dikes that are used to retain moderately contaminated sediment dredged from the bottoms of streams, rivers, lakes, and coastal waters.

Description:

The dikes needed to form CDF cells may be constructed at an upland location (above the water table), partially in the water near shore, or completely surrounded by water. A CDF may contain a large cell for material disposal, and adjoining cells for retention and decantation of turbid, supernatant water. A variety of linings have been used to reduce seepage through the dike walls. The most effective linings are clay or bentonite-cement slurries, but sand, soil, and sediment linings have also been used.

Three key factors normally will influence the development and implementation of CDF technology at a given site: location, design, and monitoring. First, the location of a CDF will depend on physical site parameters (such as the relationship sizes of the site and the CDF technology required for remediation, and proximity to a navigable waterway); construction parameters (such as geology and hydrology of a site); and environmental effects of the CDF on the site). Second, the design of a CDF should be directed toward the goal of minimizing contaminant loss. Potential contaminant pathways therefore must be identified, followed by the selection of controls and structures that will limit contaminant release through these pathways. Common contaminant pathways include leaching through the bottom of a CDF, seepage through CDF dikes, volatilization to the air, and uptake by plants and animals. Caps are a potentially effective method of minimizing contaminant loss through pathways associated with CDFs, but selection of proper CDF liner material is also an important method. Finally, continuous monitoring is required to ensure the structural integrity of a CDF.

Applicability:

CDFs are used to contain dredged sediments and can be applied to contain halogenated and nonhalogenated volatile organic compounds (VOCs) and nonhalogenated semivolatile organic compounds (SVOCs).

Limitations:

The following factors may limit the applicability and effectiveness of the technology:

- Contaminants can potentially migrate from the CDF along several pathways, including effluent discharges to surface water during filling operations and subsequent settling and dewatering, rainfall surface runoff, leachate into groundwater, volatilization to the atmosphere, and direct uptake.
- Contaminant losses from CDFs may also occur due to low pH conditions caused by bacterial oxidation of sulfur-containing sediments during crust management operations.
- Without proper design and maintenance, CDFs can develop odor problems as well as mosquito and insect problems.

Status: Conventional

Operation and Maintenance Duration:

Installation time for a CDF typically ranges from 6 to 12 months. Operations and maintenance duration lasts as long as the contained sediment requires management. The period of time requiring active monitoring and maintenance is expected to be 20 years or longer. Several media may require monitoring, such as groundwater, surface water, air emissions, soils, and leachate.

Cost Range: $15 to $50 per cubic yard

The major cost items included in the cost estimate range for confined disposal facilities are designated in Table CR2-1.

Table CR2-1. Major Cost Items to Implement Confined Disposal Facilities

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Containment area construction	Long-term inspection
Dike and weir construction	Site supervision
Settling basin construction	Site quality assurance and health and safety support
Monitoring well installation	Sampling and analysis for process control
Residuals Management Activities Included in Cost	
None	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.13.10 "Confined Disposal Facilities".

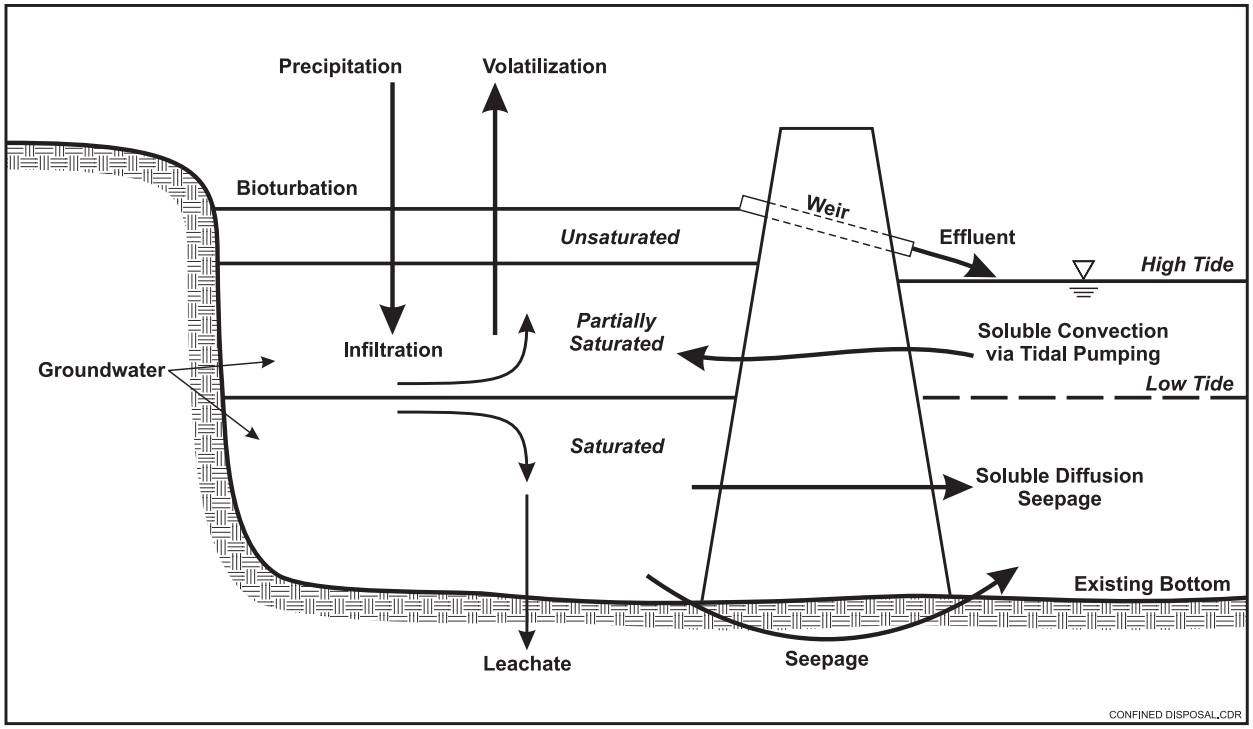


Figure CR2. Confined Disposal Facilities (CDFs)

CR3: Drawdown Pumping

Abstract:

Drawdown pumping is designed to pump free-product liquid (light, nonaqueous-phase liquid [LNAPL] or dense, nonaqueous-phase liquid [DNAPL]) and groundwater from recovery wells or trenches.

Description:

Pumping removes water and lowers the water table near the extraction area to create a cone of depression. The cone of depression around the extraction well reduces the local water head. The driving force caused by the cone of depression typically causes the nonaqueous-phase liquid (NAPL)-layer thickness to increase at the well and provides a head difference that pushes NAPL toward the extraction point. LNAPL saturation collected in the capillary fringe will tend to accumulate in the cone of depression. DNAPL will tend to upwell in response to the reduced water head.

Pumping may be accomplished with one or two pumps. In the single-pump configuration, one pump withdraws both water and NAPL. The two-pump configuration uses one pump located below the water table to remove water and a second located in the NAPL layer to recover NAPL. A single-pump system reduces capital and operating costs and allows simpler control systems and operation, but produces a stream of mixed water and NAPL that must then be separated.

Applicability:

Drawdown pumping is effective for LNAPL or DNAPL recovery when the aquifer has moderate to high hydraulic conductivity and a measurable layer of low-visocity NAPL. An aquifer with high hydraulic conductivity gives less flow resistance of NAPL into the well. A thick layer of NAPL allows the pumping system to collect a high proportion of NAPL in relation to the amount of groundwater. For best operation, the NAPL thickness should be sufficient to completely cover the pump suction port.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Drawdown pumping generally produces large volumes of water in the process of recovering the free product.
- The production of a cone depression in the water table can smear the free product or trap the fuel in the saturated zone when the water table returns to its original level.

Status: Conventional

Operation and Maintenance Duration:

Operation and maintenance durations are from 6 months to 5 years, depending on product volume and site-specific factors such as the following:

- Cleanup goals.
- The volume of free product present at the site.
- In situ characteristics including permeability and anisotropy.
- The radius of influence for free-product collection.
- The achievable rate of free-product extraction.

- The amount of drawdown that can be produced at the site. Significant drawdown cannot be accomplished at sites with thin aquifers; therefore, at such sites the radius of influence produced by each recovery well is relatively small.

Cost Range: $100,000 to $500,000 per acre

The major cost items included in the cost estimate range for drawdown pumping are designated in Table CR3-1.

Table CR3-1. Major Cost Items to Implement Drawdown Pumping

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Extraction wells and pump installation	Operating and maintenance labor
Monitoring well installation	Utilities
Oil/water separation equipment installation	Site supervision
	Site quality assurance and health and safety support
	Sampling and analysis for process control
Residuals Management Activities Included in Cost	
Off-site disposal of organic liquid	
Disposal of treated water to publicly owned treatment works via site sewer	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.25.23 "Draw-Down Pumping" and X.25.24 "DNAPL Extraction".

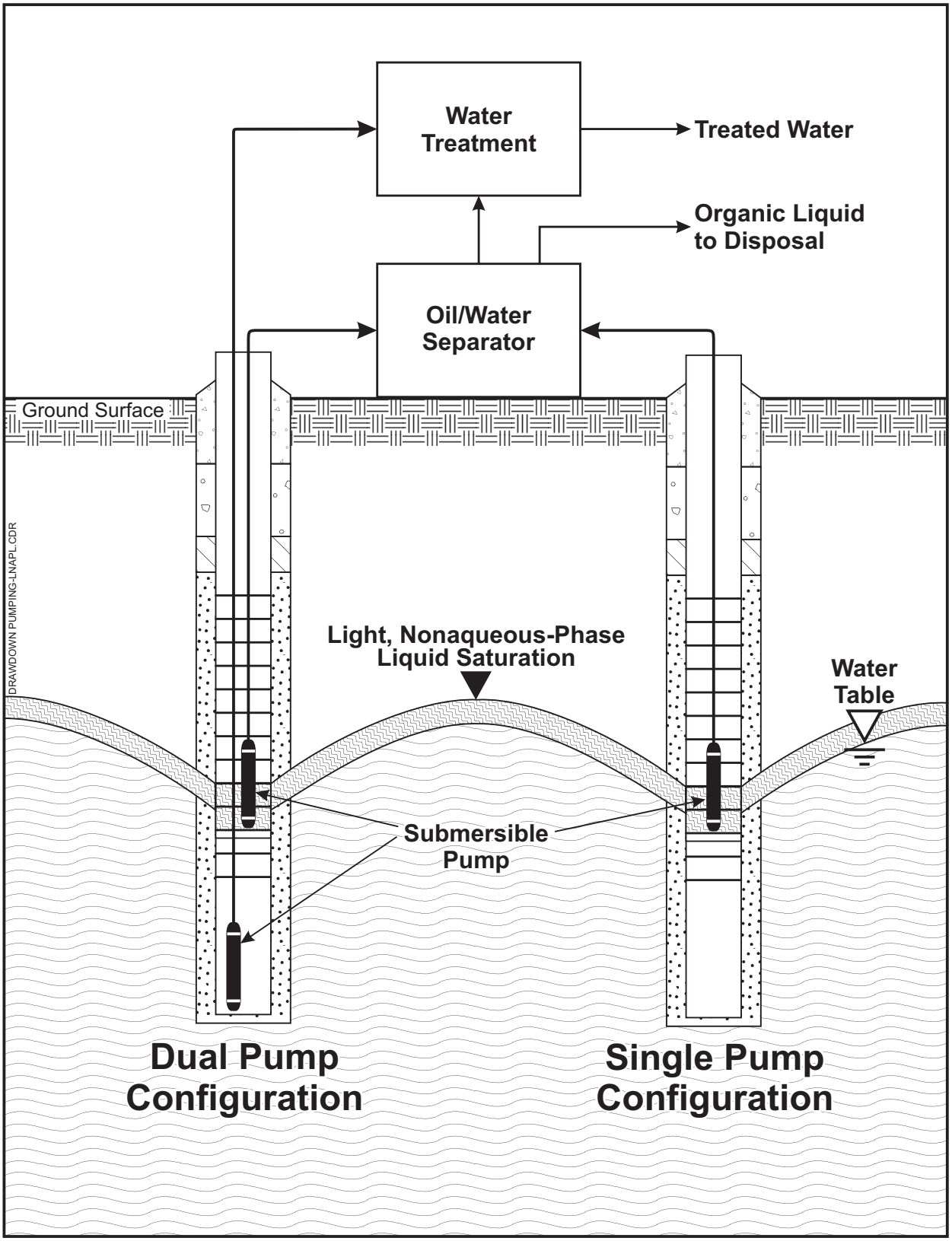


Figure CR3a. Drawdown Pumping (LNAPL)

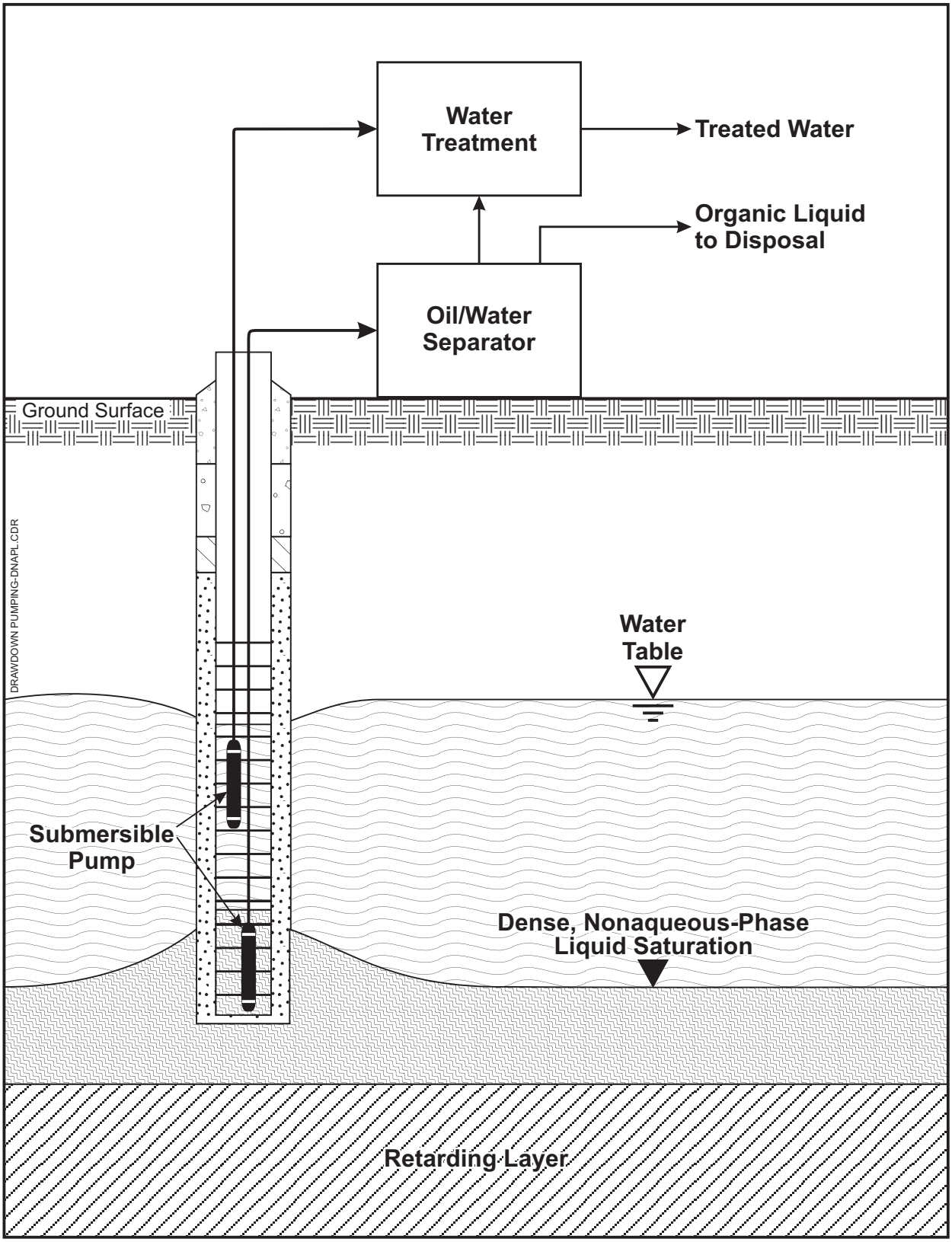


Figure CR3b. Drawdown Pumping (DNAPL)

CR4: In Situ Capping (Sediment)

Abstract:

In situ capping is a containment technology that involves isolating contaminated sediments from the surrounding aquatic environment using layers of geologic and synthetic materials.

Description:

In situ capping involves using underwater containment of contaminated sediments with a stable cover formed using layers of sediment, gravel, rock, and/or synthetic materials. The cap reduces contaminant mobility and interaction between aquatic organisms and the contaminants. Capping is appropriate if the following circumstances apply:

- The "no action" alternative does not provide sufficient protection from contaminants.
- Original point source discharges have been halted.
- The costs and environmental effects of moving/treating contaminated sediment are too great.
- Suitable capping materials are available.
- Hydrologic conditions will not disturb the site.
- The bottom of the water body at the site will support the cap.
- The area is amenable to dredging.

Although it is technically feasible to cap contaminated sediments in place and at their original location, at times the use of the waterway may conflict with reduction in available draft caused by the cap and therefore may dictate that contaminated sediments be moved from their original site of deposition. The tendency for sediments to flow because of the momentum generated during placement and slope impact should be considered to prevent sediment displacement and contaminant release.

If contaminated sediment must be moved, it may be possible to deposit sediments in a natural depression or a depression formed by dredging clean sediment. The preferred deposition methods are by hydraulic pipeline with or without a submerged diffuser, direct placement with a clamshell, or release from a bottom-dump scow. The success of capping operations depends on the following:

- Careful selection and operation of the dredging equipment.
- Transportation of the contaminated material to the disposal site in the same device from which it will be discharged.
- Choice of the disposal and capping site: The effects of the water body at the site (such as currents, water depth, and bottom contours) can affect the placement accuracy and the integrity of the mound.
- Selection of capping material: Thickness, integrity, and capability to fall quickly and directly over the material to be capped are important criteria.
- Placement techniques (accuracy of placement).
- Effectiveness of monitoring: Monitoring of the cap is essential to ensure that its integrity has not been compromised by currents or other effects.

Applicability:

In situ capping is used to contain in situ sediment and can be applied to contain halogenated or nonhalogenated volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs), polychlorinated biphenyls (PCBs), ordnance compounds, and inorganics.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Contaminants remain in place at the site.
- Actual operating life is uncertain.
- Requires long-term monitoring and maintenance.
- Moving contaminated sediment (if required) and placing the first layer of capping material can suspend sediment in the water column.
- Capping materials reduce available clearance for water traffic.
- Strong currents can displace capping materials.

Status: Conventional

Operation and Maintenance Duration:

Installation time for an in situ cap typically ranges from 1 to 4 months. Inspections may be conducted frequently in the first 6 months because problems are most likely to appear during this period. After several years of service, the integrity of the cap becomes uncertain and should be investigated regularly. The cap should be designed to provide containment for as long as the contaminated sediment requires management. The period of time requiring active monitoring and maintenance is expected to be 20 years or longer.

Cost Range: $120,000 to $500,000 per acre

The major cost items included in the cost estimate range for confined in situ capping are designated in Table CR4-1.

Table CR4-1. Major Cost Items to Implement In Situ Capping

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Sediment, sand, gravel, and/or geotextile layer placement	Long-term inspection Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
None	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.17.91 "In Situ Isolation Contaminated Sediments (Containment)".

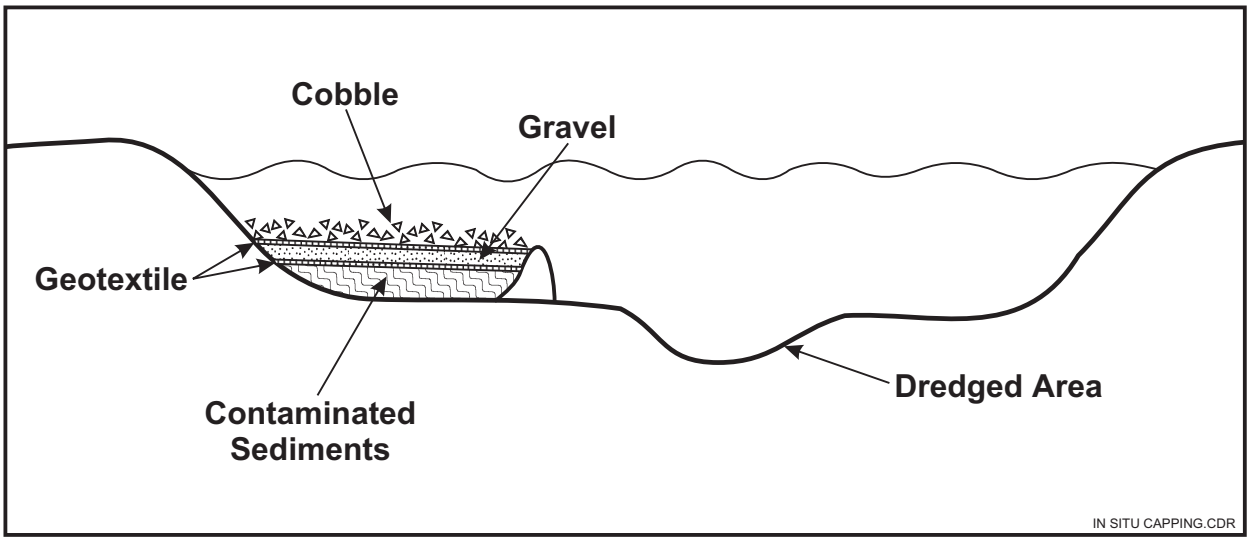


Figure CR4. In Situ Capping (Sediment)

CR5: Off-Site Disposal

Abstract:

Off-site disposal is a management approach for excavated drums, debris, or soil that involves transfer to and management at a permitted facility such as an incinerator or land disposal unit.

Description:

Off-site disposal is implemented by purchasing services for transportation, treatment, and land disposal of waste. Treatment can include processing such as incineration or solidification/stabilization to meet land ban requirements.

For off-site incineration, the contaminated material is first excavated and then transported to an approved facility. Contaminants will be destroyed using high temperature thermal oxidation. Ash will be managed as appropriate depending on the source and the types and concentrations of contaminants present after incineration.

For disposal at an off-site landfill, the contaminated material is first excavated and then transported to an approved facility. Pretreatment will be performed when required to meet land disposal restrictions. This off-site disposal can reduce human health risk by reducing the risk of direct contact with the contaminated material. An engineered landfill reduces the migration of the contaminants by using liners and caps. Regulatory agencies generally prefer remedial alternatives that permanently reduce the volume or toxicity of contaminants over disposal options that reduce the mobility of contaminants.

Hazardous wastes typically are sorted according to their compatibility and then placed below ground in control cells. Control cells usually are separated by an earthen berm or other separation method. Each control cell is constructed by placing and compacting about 2 to 3 feet of waste in a lined earthen pit. A 1-ft layer of cover soil is placed over the wastes at the end of each day. Waste is added to approximately 16 to 20 feet above grade. Hazardous waste landfills are designed to control leachate, gaseous emissions, runoff and drainage, and settling. Data needs for the selection of disposal at a landfill depend on permitting requirements of the landfill, but probably would include the following:

- Contaminant type and concentration
- Toxicity Characteristic Leaching Procedure (TCLP) test
- Volume of waste.

Applicability:

Landfill disposal is used to contain halogenated and nonhalogenated volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs), polychlorinated biphenyls (PCBs), ordnance compounds, and inorganics provided that the wastes meet land disposal restriction treatment standards or have been treated to meet these standards prior to disposal.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Least desirable management option
- High unit cost.

Status: Conventional

Operation and Maintenance Duration:

Off-site disposal is used to manage ex situ material, so the operation and maintenance duration depends on the shipping and waste-handling capabilities of the site infrastructure. Long-term monitoring and maintenance of containment systems for buried waste is controlled by the conditions of the disposal facility permit.

Cost Range: $50 to $150 per cubic yard for soil disposal (including transportation and land disposal)

$150 to $300 per cubic yard for soil disposal (including transportation, solidification/stabilization, and land disposal)

$500 to $2,000 per cubic yard for soil incineration (including transportation, off gas treatment, and ash management)

$5 to $20 per gallon for hazardous liquid incineration (including transportation, off gas treatment, and ash management)

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.33.01 "Container Handling", X.33.02 "Transport Waste to Commercial Disposal Facility", and X.33.03 "Tipping Charges and Taxes (Landfill)".

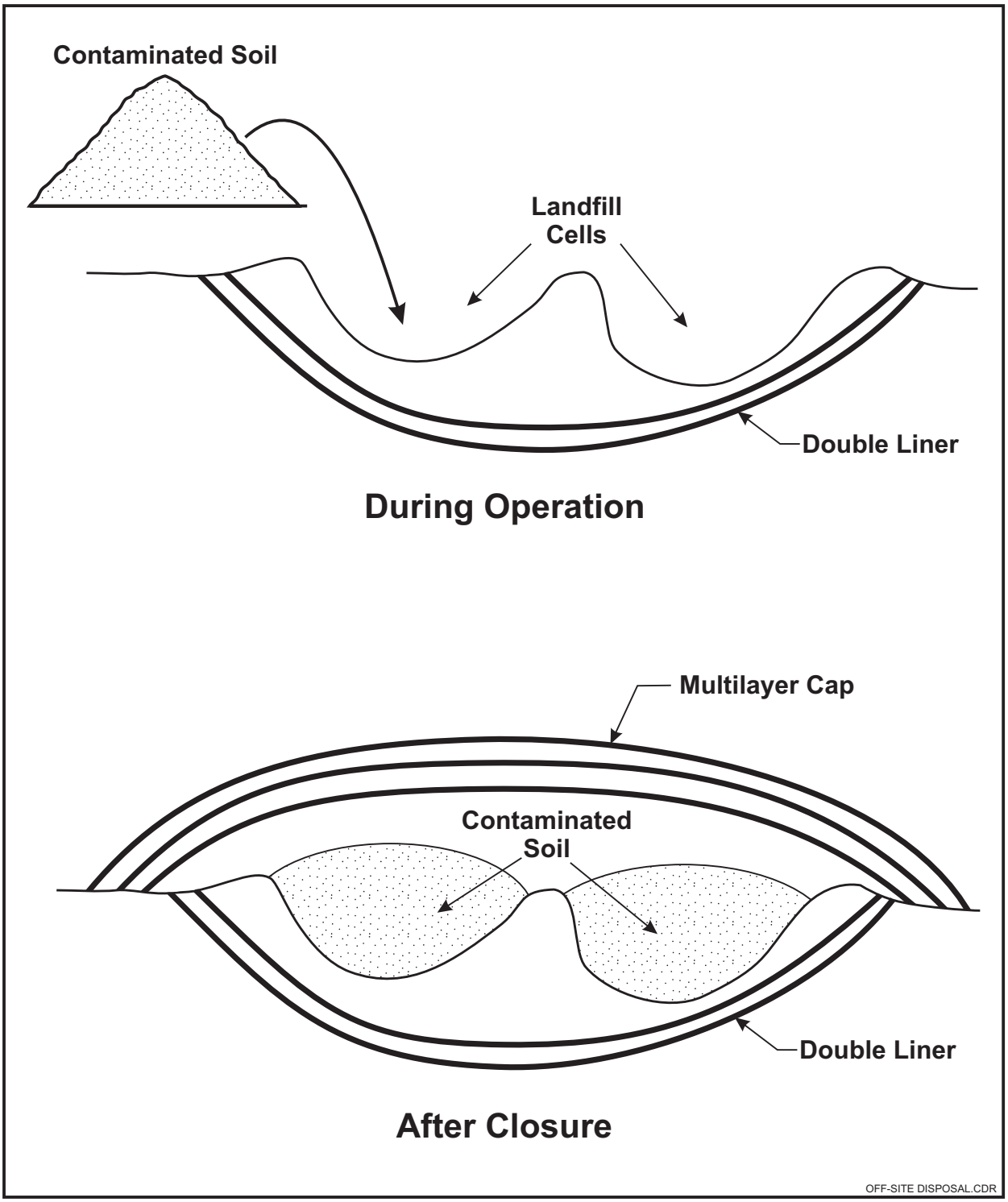


Figure CR5. Off-Site Disposal

CR6: RCRA Subtitle C and D Caps

Abstract:

Resource Conservation and Recovery Act (RCRA) capping is a containment technology that involves using multiple layers of earthen and synthetic materials to reduce contaminant mobility and protect groundwater.

Description:

RCRA capping works by maintaining a multi-layer, low-permeability cover over the waste to stabilize surface soil and reduce surface water infiltration. Performance standards for caps typically require minimum liquid migration through the wastes, low cover maintenance requirements, efficient site drainage, high resistance to damage by settling or subsidence, and a permeability lower than or equal to the underlying liner system or natural soils. These performance standards may not always be appropriate, particularly in instances where the cap is intended to be temporary, where there is very low precipitation, and when the capped waste is not leached by infiltrating rainwater.

Subtitles C and D of RCRA provide criteria for hazardous waste treatment, storage, and disposal facilities and municipal solid waste landfills, respectively. The typical requirements for Subtitle C and D caps are summarized below.

Typical Requirements for RCRA Subtitle C and D Caps

Cap Element[(a)]	Subtitle C Cap[(b)]	Subtitle D Cap[(b)]
Vegetative and protective layer	A 24-in.-thick layer of earthen material	A 6-in.-thick layer of earthen material
Drainage layer	A 12-in.-thick layer of sand (permeability $>1\times10^{-2}$ cm/sec)	N/A
Synthetic barrier	Synthetic membrane (>20 mil thickness)	N/A
Geological material barrier	A 24-in.-thick layer of low-permeability compacted clay (permeability $<1\times10^{-7}$ cm/sec)	A 18-in.-thick layer of earthen material (permeability $< 1\times10^{-5}$ cm/sec)
Gas vent layer	A 12-in.-thick layer of native soil or sand to act as a foundation for the cap[(c)]	N/A

(a) Cap elements are tabulated in order from the surface down.
(b) Final cover must be designed and constructed to have a permeability less than or equal to the bottom liner system or natural subsoils.
(c) Requirement for the gas vent layer depends on site-specific conditions.

There are a variety of cap designs and capping materials available. Most cap designs are multi-layered to conform to the above-mentioned design standards; however, single-layered designs are also used for special purposes. The selection of capping materials and a cap design is influenced by specific factors,

such as local availability and costs of cover materials, desired functions of cover materials, the nature of wastes being covered, local climate and hydrogeology, and projected future use of the site in question. Capping is often performed with groundwater extraction or containment technologies to prevent, or significantly reduce, further plume development; thus reducing the time needed to complete groundwater cleanup operations. In addition, groundwater monitoring wells are often used in conjuction with caps to detect any unexpected migration of the capped wastes. A gas collection system should always be incorporated into a cap when wastes may generate gases. Capping is also associated with surface water control technologies, such as ditches, dikes, and berms, because these structures are often designed to accept rainwater drainage from the cap. Two other surface water control technologies, grading and revegetation, are incorporated into multi-layered caps.

Applicability:

A multilayer RCRA cap is used to contain in situ waste and can be applied to contain halogenated and nonhalogenated volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs), polychlorinated biphenyls (PCBs), ordnance compounds, and inorganics.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Contaminants remain in place at the site.
- Actual operating life is uncertain.
- Root or animal intrusion can increase the permeability of the clay barrier layer.
- Requires long-term monitoring and maintenance.
- The clay barrier layer can be subject to dessication cracking in semiarid or arid environments.
- Cannot be installed during frozen or saturated ground conditions.
- Unusual events (e.g., fire or strong storm) can damage large areas of the cap surface.

Status: Conventional

Operation and Maintenance Duration:

Installation time for a RCRA cap typically ranges from 1 to 4 months. Long-term operation and maintenance is required to monitor cap integrity and leaks through the cap. The period of time requiring active monitoring and maintenance is expected to be 20 years or longer. The duration of operation and maintenance is dependent on the following conditions:

- Invasion by deep-rooted vegetation or burrowing animals
- Settling or subsidence of cap
- Erosion.

Cost Range: $200,000 to $1,000,000 per acre for a RCRA Subtitle C cap
$100,000 to $300,000 per acre for a RCRA Subtitle D cap

The major cost items included in the cost estimate range for RCRA C and D caps are designated in Table CR6-1.

Table CR6-1. Major Cost Items to Implement RCRA C and D Caps

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Site clearing	Long-term inspection
Crew and equipment mobilization	Repair of erosion damage
Borrow pit identification and testing	Site supervision
Initial surface compaction Ventilation layer placement Clay layer placement Synthetic liner placement Vegetative and protective layer placement Edge drainage swale preparation	Site quality assurance and health and safety support
Residuals Management Activities Included in Cost	
None	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.19.04 "RCRA C" and X.19.05 "RCRA D".

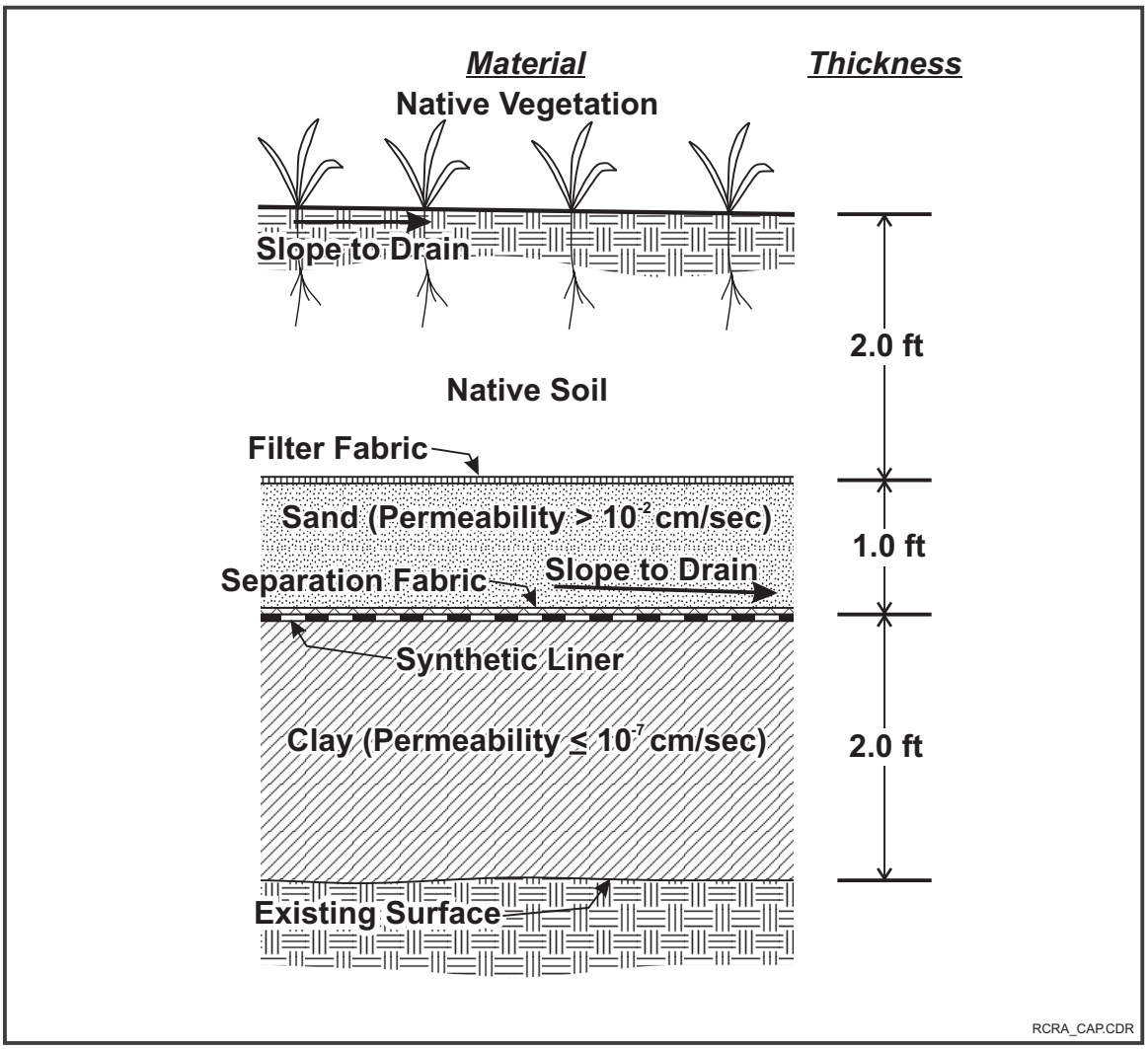


Figure CR6. RCRA Subtitle C Cap

CR7: Skimming

Abstract:

Skimming recovery systems use selective collection devices (skimmers) to collect light, nonaqueous-phase liquid (LNAPL) floating on the water table.

Description:

Skimming typically is done using a floating filter of oleophilic/hydrophobic mesh with a high affinity for nonpolar hydrocarbons and the ability to reject polar molecules such as water. A mesh cylinder is designed to float in the LNAPL layer in a recovery well. LNAPL floating on the water surface in the well passes through the mesh while water is prevented from entering by the mesh. The LNAPL runs down into a collection pot and periodically is discharged by air pressure to a central holding tank on the surface. The pressurization cycle may be controlled by a timer, by high- and low-level switches, or manually.

Shallow wells with low recovery rates can use rope wick or belt skimmers. The rope wick or belt skimmer uses a continuous loop of rope or belt made of an oleophilic/hydrophobic material. The rope or belt is strung through the LNAPL layer and up through a pair of compression rollers. The rollers provide the motive force for the rope or belt while squeezing out any retained LNAPL into a small container. LNAPL collected in the container periodically is pumped to a central holding tank. Large trench recovery points can be fitted with drum or disk skimmers that are too large to fit into a well.

Applicability:

Skimmer systems are effective at removing LNAPL from the well while withdrawing little or no water and producing little or no drawdown; thus they have limited pressure head to move LNAPL toward the recovery point. Skimmers will recover LNAPL when the thickness of the floating layer is too thin to allow efficient recovery with a pump. A skimmer can recover LNAPL even when the floating layer in the well is less than ¼-in. thick.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- The rate of recovery is low because the skimmer relies on the passive movement of LNAPL into the product recovery wells or trenches.
- The passive action results in a small radius of influence out from the recovery point.
- Biofouling of the oleophilic filter can occur frequently at some sites.

Status: Conventional

Operation and Maintenance Duration:

Skimming is a long-term technology typically requiring 1 to 5 years of operation and maintenance. The duration of the operation and maintenance is dependent on the following conditions:

- Cleanup goals.
- The volume of free product present at the site.
- In situ characteristics including permeability and anisotropy.

- The radius of influence for free-product collection.
- The achievable rate of free-product extraction.
- The frequency with which the oleophilic filter becomes fouled. If the filter is frequently fouled, the system will often be shut down for maintenance and it will take longer to meet cleanup goals.

Cost Range: $100,000 to $500,000 per acre

The major cost items included in the cost estimate range for skimming are designated in Table CR7-1.

Table CR7-1. Major Cost Items to Implement Skimming

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Extraction well and skimmer installation	Operating and maintenance labor
Air compressor installation	Utilities
Monitoring well installation	Site supervision Site quality assurance and health and safety support Sampling and analysis for process control
Residuals Management Activities Included in Cost	
Off-site disposal of organic liquid	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.25.10 "Skimming".

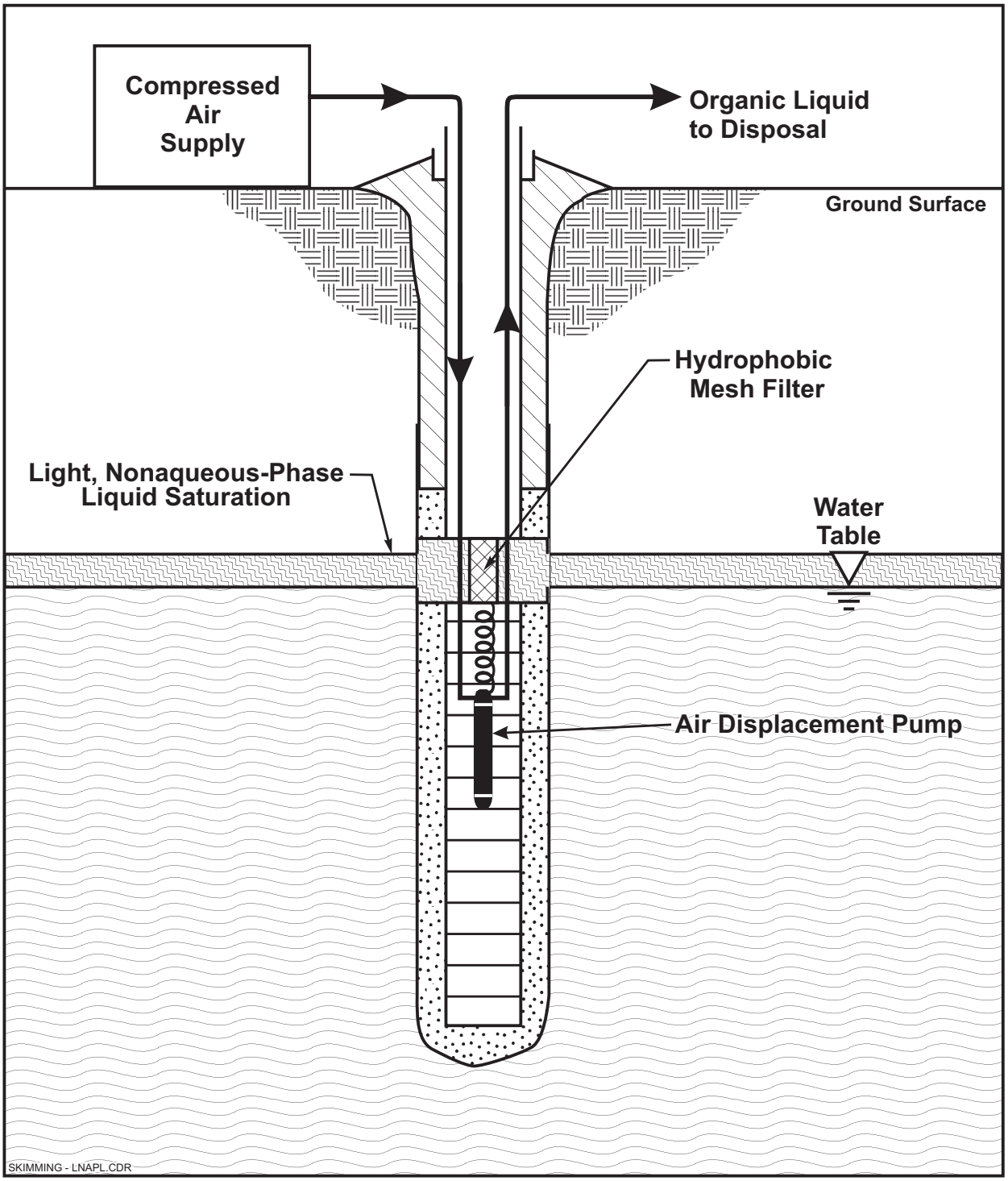


Figure CR7. Skimming

CR8: Vertical Cutoff Wall

Abstract:

A vertical cutoff wall is a structure that acts as a barrier to prevent horizontal flow of contaminated groundwater or nonaqueous-phase liquids (NAPLs).

Description:

There are several approaches that have been used to control groundwater flow.

- Sheet pile cutoff walls are constructed by driving interlocking steel or high-density polyethylene (HDPE) into the ground. The joints between individual sheets are typically plugged with a clay slurry (steel sheets) or an expanding gasket (HDPE sheets). The steel piles can be driven directly into the ground, while the synthetic piles need to be driven with a steel backing that is removed once the synthetic sheet is in place.
- Slurry walls can be constructed using several different methods. For example, with the trench method, a trench is dug and back filled with a slurry mixture of bentonite and native materials. With a vibrating beam method, a steel plate is forced into the ground. As the plate is removed, bentonite is injected to fill the space of the beam. A typical slurry wall installed by trenching ranges in width from about 0.5 to 2 m and can be installed to depths of up to approximately 50 m, depending on the site geology. Slurry walls created with the vibrating beam method are much narrower and are typically installed at shallower depths.
- Grouting is another direct method to control the migration of contaminated groundwater. A grout wall is constructed by injecting fluids under pressure into the ground. The grout moves away from the zone of injection, fills pores in the formation, and solidifies, which reduces the hydraulic conductivity of the formation. Typical grouting compounds include cement, bentonite, and silicate.
- Geomembranes are synthetic sheets installed in open or slurry-supported trenches to control contaminant spread. Geomembranes can provide very low hydraulic conductivity. The sheets generally are constructed of either HDPE or polyvinyl chloride (PVC). This technology is still in the development stage and there are concerns regarding long-term performance.

Applicability:

Vertical cutoff walls are installed to limit the migration of contaminated groundwater and can be applied to remediate halogenated and nonhalogentated volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs); polychlorinated biphenyls (PCBs); ordnance compounds; inorganics; light, nonaqueous-phase liquid (LNAPL); and dense, nonaqueous-phase liquid (DNAPL). In many cases barriers can be installed very quickly, thus providing additional time before remedial action is required. Vertical cutoff walls can be used in conjunction with pump-and-treat systems to reduce the volume of water that must be extracted to maintain hydraulic control around a contaminant source.

Limitations:

The following factors may limit the applicability and effectiveness of the process:

- Contaminants remain in place at the site.
- All of the methods described above, except grouting, become significantly more costly or impossible to install at depths greater than 80 feet.
- Most of the approaches involve a large amount of heavy construction.
- For best performance, the wall should be keyed several feet into a low-permeability layer.

- The location of sheet pile walls requires planning to avoid existing structures or underground utilities.
- Generally, vertical cutoff walls cannot be installed at sites that contain construction rubble or cobbles in the subsurface.
- Long-term performance of cutoff walls is not proven.

Status: Conventional

Operation and Maintenance Duration:

Installation time for a vertical cutoff wall typically ranges from 1 to 2 months. Long-term operation and maintenance is required to monitor cutoff wall integrity. The period of time requiring active monitoring and maintenance is expected to be 20 years or longer. The duration of operation and matenance is dependent on the following conditions:

- Cleanup goals
- Geohydrologic setting
- Chemical nature of the contaminants
- Concentration of the contaminants.

Cost Range: $25 to $80 per square foot of barrier – steel sheet pile with grouted joints (Depth 0 – 60')
$2 to $10 per square foot of barrier – soil bentonite slurry wall (Depth 0 – 80')
$6 to $15 per square foot of barrier – soil bentonite slurry wall (Depth 80 – 150')
$40 to $200 per square foot of barrier – grout wall (Depth 0 – 400')
$8 to $25 per square foot of barrier – geomembrane (Depth 0 – 80')

The major cost items included in the cost estimate range for a vertical cutoff wall are designated in Table CR8-1.

Table CR8-1. Major Cost Items to Implement a Vertical Cutoff Wall

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Barrier trench excavation[(a)]	Site supervision
Barrier installation	Site quality assurance and health and safety support
Sampling well installation	Sampling and analysis for process control
Residuals Management Activities Included in Cost	
Off-site disposal of soil excavated from treatment wall trench[(a)]	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

(a) Applicable only for slurry walls.

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.18.04 "Slurry Walls", X.18.05 "Grout Curtain", and X.18.06 "Sheet Piling".

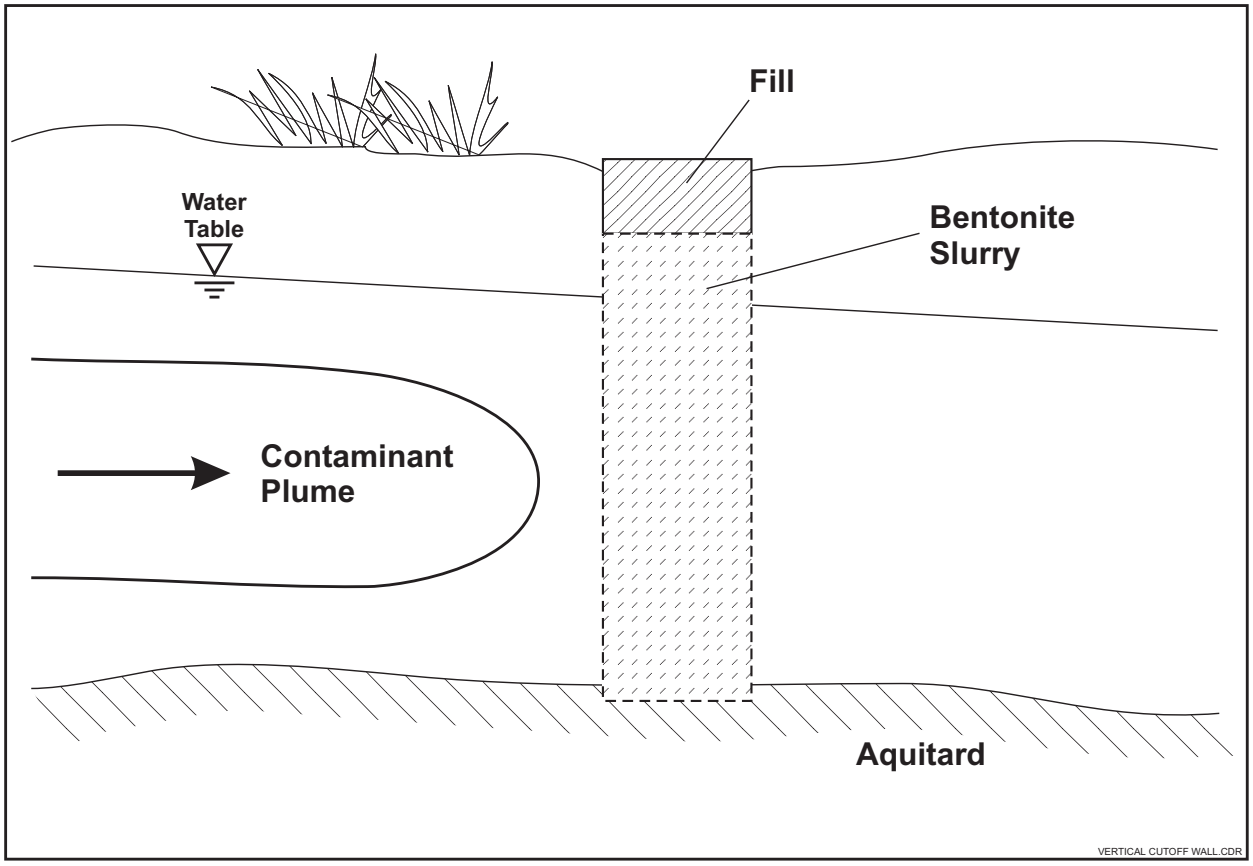


Figure CR8. Vertical Cutoff Wall

CR9: Water Harvesting Vegetation Cover

Abstract:

Water harvesting vegetation covering is a containment technology that involves using plants and earthen materials to reduce contaminant mobility and protect groundwater.

Description:

Water harvesting vegetation covers work by maintaining a high evapotranspiration rate to remove surface water, and by using a stable vegetation cover to maximize runoff while limiting erosion. A vegetation cover consists of a topsoil root zone supporting selected plants. Criteria for plant selection include the following:

- Hardy to the area
- High evapotranspiration rate
- A root structure that provides a stable surface to promote runoff.

The plants' natural growth processes maximize removal of precipitation falling on or around the surface over the in situ waste. The topsoil cover may be sloped and/or provided with trenches or drains to maximize runoff. Capillary barrier layers usually are included under the topsoil to store and distribute excess water during wet seasons or heavy precipitation events. The stored water maintains continued plant growth during dry seasons and resists downward movement of water.

A water harvesting vegetation cover is used to improve contaminant containment by reducing water movement from the surface downward through waste left in place at a site. The vegetation cover may be used alone or as the top layer of a multilayer cap. Water harvesting vegetation covers are particularly useful for semiarid and arid sites where conventional caps that rely on a compacted clay layer are strongly subject to dessication cracking.

If gas generation in the waste volume must be controlled, a permeable vent layer can be placed on the surface as the first layer of the cap. Vapor extraction by applying a vacuum to the vent layer at points along the edge of the cap allows collection of gas for treatment.

Applicability:

A water harvesting cover is used to contain halogenated and nonhalogenated volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs), polychlorinated biphenyls (PCBs), ordnance compounds, and inorganics. Water harvesting covers are alternatives to a conventional multilayer cap and provide equivalent performance to a Resource Conservation and Recovery Act (RCRA) Subtitle C or D cap at similar or lower cost. Water harvesting covers are particularly applicable for use in semiarid or arid environments.

Limitations:

The following factors may limit the applicability and effectiveness of the technology:

- Contaminants remain in place at the site.
- Actual operating life is uncertain.
- Requires long-term monitoring and maintenance.

- Water removal rate may vary with the seasons.
- Several growing seasons may be needed to fully establish the cover.
- Cannot be installed during frozen or saturated ground conditions.
- Unusual events (e.g., fire or strong storm) can damage large areas of the cap surface.

Status: Innovative

Operation and Maintenance Duration:

Installation time for a water harvesting vegetation cover typically ranges from 1 to 4 months. Long-term operation and maintenance is required to monitor cover integrity and maintain healthy vegetation. The period of time requiring active monitoring and maintenance is expected to be 20 year or longer.

Cost Range: $200,000 to $1,000,000 per acre

The major cost items included in the cost estimate range for water harvesting covers are designated in Table CR9-1.

Table CR9-1. Major Cost Items to Implement Water Harvesting Covers

Pretreatment Activities Included in Cost	
None	
Fixed Cost Items Included	**Variable Cost Items Included**
Site clearing	Long-term inspection
Crew and equipment mobilization	Repair of erosion damage
Borrow pit identification and testing	Site supervision
Initial surface compaction Capillary barrier placement Soil layer placement Water harvesting vegetation placement Edge drainage swale preparation	Site quality assurance and health and safety support
Residuals Management Activities Included in Cost	
None	
Comments	
Indirect costs such as project management, design and engineering, vendor selection, home office support, permit preparation and fees, regulatory interaction, site characterization, treatability testing, performance bond, and contingencies are not included in the estimated cost range.	

WBS Correspondence: This technology corresponds to the second and third level WBS elements X.19.03 "Upper Vegetative (Topsoil) Layer".

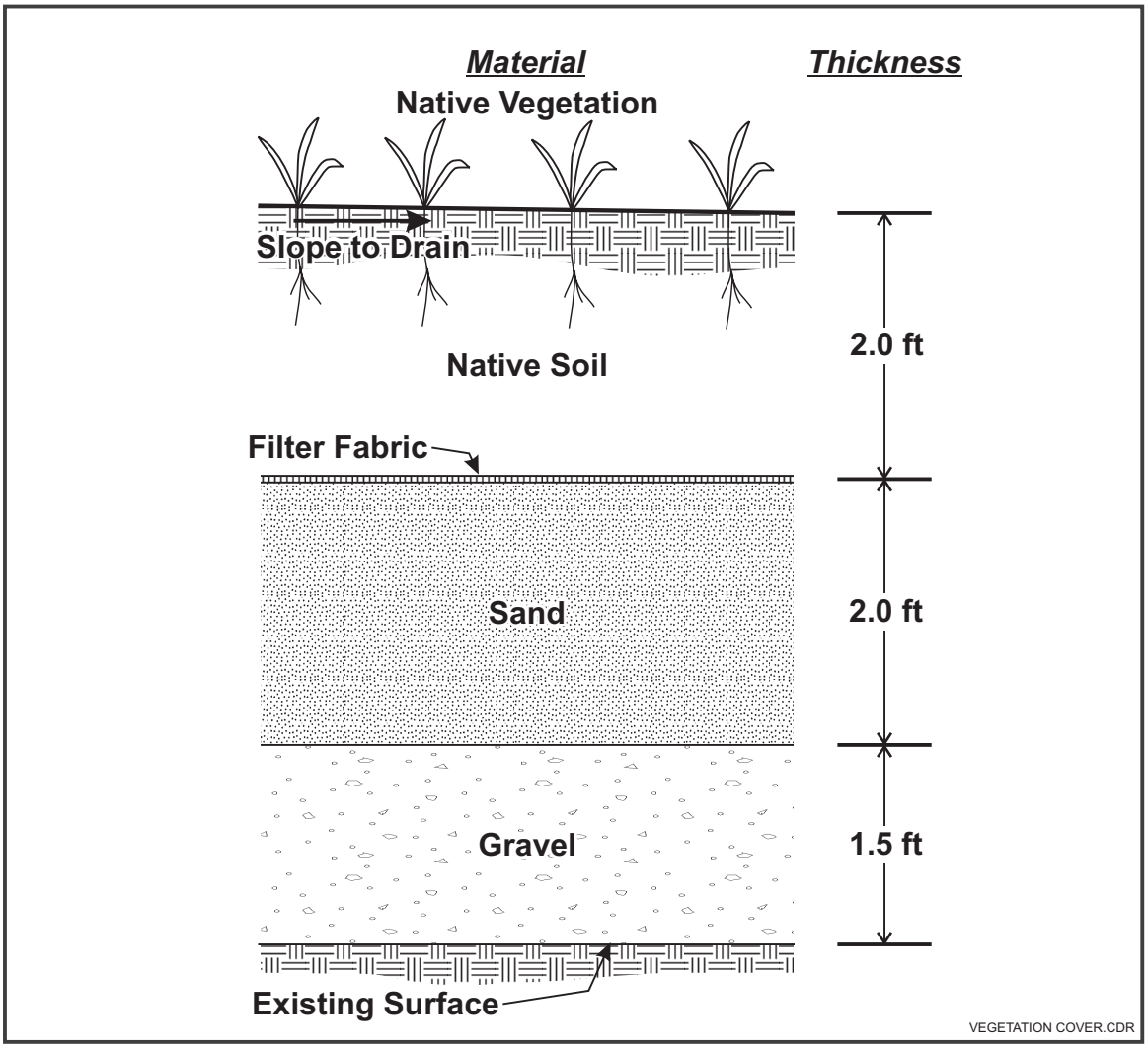


Figure CR9. Water Harvesting Vegetation Cover