General Response Action - Containment

General Response Action	Technology Type	Technology	Description	Contaminant Applicability	State of Development
Containment	Surface Barriers	Asphalt/Concrete Cap	A single layer paved surface. Designed to be impermeable to prevent surface water infiltration through the vadose zone and limit contaminant mobilization and transport to groundwater. Such barriers are designed for an operational life of a minimum of 75 years and prevent direct exposure to contaminants. Configured to route surface precipitation and run-off away from underlying subsurface contamination.	All contaminants	Technology is well established. Asphalt/concrete caps are simple to construct.
		Modified RCRA Subtitle C Barrier	A multiple-layer surface barrier with at least a low permeability layer and a drainage layer. Designed to be impermeable to prevent surface water infiltration through the vadose zone and limit contaminant mobilization and transport to groundwater. Applicable for hazardous waste, category 3 and category 1 (mixed) low-level waste. Modifications to a RCRA C barrier designed to be site specific. Number of layers can vary from 4 to 7.	All contaminants	Technology is well established. Multiple barrier designs have been developed and implemented.
		Hanford Barrier	Barriers are generally designed to be impermeable to prevent surface water infiltration through the vadose zone and limit contaminant leaching to groundwater. May also prevent direct contact to contaminants.	All contaminants	Technology is well established, although its use has been limited to the Hanford Site.
		Vegetative Cap (Evapotranspiration Cap/Cover)	Capillary barrier, which consists of a fine-grained soil layer overlying a relatively coarse-grained soil layer. The distinct textural interface in capillary evapotranspiration (ET) barriers between the fine and coarse soil layers creates a capillary break, which increases the water-holding capacity of the fine-grained soil over that associated with unimpeded vertical drainage. Water will not flow into the coarse layer until the water content approaches saturation in the fine-grained soil layer. If the textural interface is sloped, water will move laterally in the fine-soil layer above the interface, which provides an additional mechanism for water removal.	All contaminants	Technology is well established. Vegetative caps are simple to construct.

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General Response Action - Containment

General Response Action	Technology Type	Technology	Description	Contaminant Applicability	State of Development
Containment	Subsurface Barriers	Jet Grouting	Physical technology to limit interconnected porosity at a specific depth and thickness through jet grouting. High pressure injection of a grout slurry into soil in order to mix the material with grout. The resulting soil material is called "soil-crete."	All contaminants	Field scale application is fully deployable and has been performed to depths of 300 feet. There are issues over radius of influence.
		Molten Wax Injection	Injection of molten thermoplastic wax, resulting in an impermeable material. Super permeating molten wax is delivered by (1) heating the soil and (2) injecting the wax.	All contaminants	Development has occurred over the last several years at INL in radiologically contaminated environments.
		Soil Freezing	Involves placement of cooling media distribution systems into the soil layer below the contamination to freeze soil pore water and reduce mobilization of contaminants.	All contaminants	Proven application for temporary containment for dewatering during construction. Could potentially be used as containment barrier for environmental remediation.

Notes:

INL: Idaho National Laboratory

General Response Action - Removal

General Response Action	Technology Type	Technology	Description	Contaminant Applicability	State of Development
Removal[a]	Excavation	Deep Excavation with Sloping and/or Benching (Open Pit Mining)	Excavation is advanced by sloping and/or benching walls. Large lay backs are required for deeper open pit excavations. Technique can be combined with other shoring techniques to achieve greater excavation depths.	All contaminants	Excavation with sloping and/or benching is a fully mature technology. Significant lay backs or a combination of innovative and mature technologies are required for deep excavations.
		Deep Excavation using Dragline Excavators	Draglines are a primary excavating method used in many surface mining operations worldwide. Draglines are the largest single bucket excavators, capable of reaching depths up to 250 ft.	All contaminants	Fully mature technology in the construction industry that may require detailed evaluation of applicability at each specific site.
		Deep Excavation using Drilling and Soil Replacement	Drilling and soil replacement involves constructing hollow spaces using drilling techniques and replacing the existing soil with filling materials. A series of large diameter holes are drilled in the area of contamination. After the hole is drilled it is backfilled with a low strength soil-cement mixture that can backfill the hole without requiring compaction.	All contaminants	Drilling and soil replacement is a standard technique used in the construction industry throughout the world. Large diameter borings have been drilled to over 200 ft at sites that included large cobbles.
		Deep Excavation using Sheet-pilling or Sheet Pile Walls	Uses thin steel sections with interlocked watering grooves at the sides, and they are driven into soil by hammering or vibrating.	All contaminants	Fully mature technology in the construction industry that may require detailed evaluation of applicability at each specific site.
		Deep Excavation using Soldier Pile and Lagging Wall	The method is also commonly known as "Berliner Wall" when steel piles and timber lagging is used and are the most inexpensive systems compared to other retaining walls.	All contaminants	Fully mature technology in the construction industry that may require detailed evaluation of applicability at each specific site.

General Response Action - Removal

General Response Action	Technology Type	Technology	Description	Contaminant Applicability	State of Development
Removal[a]	Excavation	Deep Excavation using Diaphragm Walls	Diaphragm walls (similar to slurry walls) provide structural support and water tightness. It is commonly used for many deep excavations. The wall is constructed panel by panel in full depth.	All contaminants	Fully mature technology in the construction industry that may require detailed evaluation of applicability at each specific site.
		Deep Excavation using Soil Nail Walls	Excavation is made step by step. Shotcrete (concrete projected at high velocity through a hose) is common for facing; wire mesh may be used. Soft facing may be also possible using geotextiles. A hole is drilled, ordinary steel bars are lowered, and grout is placed without pressure. Requires cohesive soil and unsaturated or minimal water flow conditions.	All contaminants	Fully mature technology in the construction industry that may require detailed evaluation of applicability at each specific site.
		Deep Excavation using Secant Pile Wall	Secant pile walls are formed by constructing intersecting reinforced concrete piles. The piles are reinforced with either steel rebar or with steel beams and are constructed by either drilling under mud or augering.	All contaminants	Fully mature technology in the construction industry that may require detailed evaluation of applicability at each specific site.
		Deep Excavation using Tangent Pile Wall	Tangent pile walls are a variation of secant pile walls and soldier pile walls. However, tangent pile walls are constructed with no overlap and ideally one pile touches the other.	All contaminants	Fully mature technology in the construction industry that may require detailed evaluation of applicability at each specific site.

General Response Action - Removal

General Response Action	Technology Type	Technology	Description	Contaminant Applicability	State of Development
Removal[a]	Excavation	Deep Excavation using Reinforced Concrete Walls	It is a type of stage excavation wall usually supported by ground anchors. Soils with some cohesion are suitable because each stage is first excavated before formwork and concrete placement.	All contaminants	Fully mature technology in the construction industry that may require detailed evaluation of applicability at each specific site.
		Deep Excavation using Caissons	Land caisson is an open concrete section at the top and bottom, and it is lowered into its position by excavating inside and adding in-situ concrete section on top. Caissons can be used in cases where the soil contains large boulders which obstruct penetration of piler or bored piles, and large lateral forces may needed.	All contaminants	Fully mature technology in the construction industry that may require detailed evaluation of applicability at each specific site.
		Deep Excavation using Jet Grout Walls	Retaining walls are made by single to triple row of jet grout columns or deep mixed columns. Single reinforcing bar is placed in the central hole opened for jet grout columns. Anchors, nails or struts may be used for support.	All contaminants	Fully mature technology in the construction industry that may require detailed evaluation of applicability at each specific site.
		Deep Excavation using Deep Mixed Walls	Similar to Jet Grout walls but uses a technique specially developed for wall construction where H sections are used for reinforcement.	All contaminants	Fully mature technology in the construction industry that may require detailed evaluation of applicability at each specific site.
		Deep Excavation using Reinforced Concrete Walls	A type of stage excavation wall usually supported by ground anchors. Soils with some cohesion are suitable because each stage is first excavated before formwork and concrete placement.	All contaminants	Fully mature technology in the construction industry that may require detailed evaluation of applicability at each specific site.

General Response Action - Removal

General Response Action	Technology Type	Technology	Description	Contaminant Applicability	State of Development
Removal[a]	Excavation	Deep Excavation using Cofferdams	A cofferdam is a temporary earth retaining structure to be able to make excavation for construction activities. Use to support heavy vertical and horizontal loads (e.g., typically used near water bodies). Contiguous, tangent, secant piles or diaphragm walls are constructed in circular shapes, and no internal bracing or anchoring is used to form the cofferdam.	All contaminants	Fully mature technology in the construction industry that may require detailed evaluation of applicability at each specific site.
		Deep Excavation using Tunneling	Completely enclosed tunnel except for openings for egress, commonly at each end. Tunnel is created by cut-and-cover, boring, pipe jacking, or box jacking.	All contaminants	Fully mature technology in the construction industry that may require detailed evaluation of applicability at each specific site. Large cobbles and boulders will impact the selection of tunneling equipment/techniques.
	Contaminated Water Removal	Perched Water Removal	Water perched above low-permeability areas within the vadose zone is pumped before it migrates to groundwater. Wells must be correctly placed to adequately capture the extent of the perched water.	Mobile contaminants	Technology is well developed. Currently planned to be deployed in the B Area Complex at Hanford.
		Pore Water Extraction	Subsurface water within the unsaturated zone containing mobile contaminants is extracted. Soil gas with entrained water is extracted from the subsurface through a well using high vacuum to induce high vapor extraction rates.	Mobile contaminants	Technology is still being developed for full scale field operation. Currently being pilot tested at Hanford for mobile contaminants.

General Response Action - Removal

General Response Action	Technology Type	Technology	Description	Contaminant Applicability	State of Development
Removal[a]	Soil Flushing and Contaminant Recovery	Soil Flushing - Vadose Zone with Water	Mobilization of contaminants with water so they can be removed and treated or disposed. This technology has been widely used in the mining industry. Can only be applied where soil has sufficient permeability to allow circulation and recovery of flushing solution.	Contaminants with high/moderate solubility, e.g., Uranium (U(VI)) and Technetium-99 (Tc(VII))	Mature technology, in-situ field deployment for shallow vadose zone has taken place.
		Soil Flushing - Vadose Zone, Chemical Enhanced	Identical to soil flushing with water, except for addition of chemicals (e.g., surfactants) to enhance mobilization of contaminants with lower solubility.	Contaminants with moderate solubility	Conceptual technology that has been subjected to limited study. Treatment uniformity and contaminant recovery issues exist.
		In-Situ Uranium Recovery	Recovers uranium by dissolving it with a solution and pumping the solution to the surface for removal. This technology is most widely used for uranium mining in saturated conditions.	Uranium	This technology is currently being deployed in the uranium mining industry in the USA, Kazakhstan, and Australia under saturated conditions.

Notes:

a: All soil removal technologies require ex-situ treatment and disposal.

General Response Action - Ex-Situ Treatment and Disposal

General Response Action	Technology Type	Technology	Description	Contaminant Applicability	State of Development
Ex-Situ Treatment	Thermal Treatment	Ex-Situ Vitrification	Process that converts excavated soil and other materials into stable crystalline substances. The thermal treatment process is typically performed inside a chamber using plasma torches or electric arc furnaces to melt the soil.	All contaminants	Uses furnaces that have evolved from the glass industry. Implementability is higher than for in-situ application given use of proven technology.
	Physical/Chemical Treatment	Solidification / Stabilization	Contaminants are physically bound or enclosed within a stabilized mass, or chemical reactions are induced between the stabilizing agent and contaminants to reduce their mobility.	Mobile to Semi-mobile contaminants (Uranium (U(VI)), Tc-99 (Tc(VII))	Well-established technology. Site-specific studies need to be completed to evaluate equipment required and appropriate solidification.
		Soil Washing	Separation of soil particles followed by mechanical abrasion or washing to remove surface contamination. Final contaminated fraction is typically treated by technologies such as solidification/stabilization prior to disposal.	Possibly Uranium, Tc-99, I-129, Nitrate	Conventional aggregate washing and screening technology is used to separate soil particles. Mobile contaminants are captured in the wash water.
		Soil Sorting/Screening	Clean soil fractions are separated from the contaminated based upon radioactive energy emissions from the soil. Soil passes under an array of radiation detectors that are used to determine the radioactivity present. Software algorithms are then used to determine if the soil exceeds defined release criteria, and those portions that exceed the criteria are identified and flagged for mechanical separation from the clean soil.	Radionuclides	Fully functional prototype has been developed and deployed.

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General Response Action - Ex-Situ Treatment and Disposal

General Response Action	Technology Type	Technology	Description	Contaminant Applicability	State of Development
Disposal	Onsite	Backfill Treated Soil	Excavation and ex-situ treatment followed by onsite disposal (backfill).	All contaminants that can be treated ex situ	Fully mature technology.
		Onsite Landfill	Disposal of excavated soil at onsite landfill (e.g. ERDF). Treatment performed at the facility as required to meet land disposal restrictions.	All contaminants depending on concentrations	Fully mature technology.
	Offsite	Offsite Landfill/Repository	Disposal of excavated soil at offsite landfill. Required for wastes that onsite disposal is not acceptable.	All contaminants depending on concentrations	Fully mature technology.

General Response Action - In-Situ Treatment

General Response Action	Technology Type		Technology	Description	Contaminant Applicability	State of Development
In-Situ Treatment	Thermal Treatment		In-Situ Vitrification	Thermal treatment process that converts soil and other materials into stable crystalline substances. Contaminants are incorporated into the glass structure, which is generally strong, durable, and resistant to leaching. Particularly suitable for sites with high concentrations within 6 to 9 meters (m) (20 to 29 feet [ft]) of soil surface.	All contaminants	In-situ vitrification has been subjected to several pilot studies to test its effectiveness.
			In-Situ Thermal Desorption	Direct application of heat (e.g., using electrical heater elements, electrical resistive heating, injection of hot air, steam or hot water, radio frequency, etc.) to increase the temperature of soil and destroy or volatilize organic compounds. Volatile Organic Compound (VOC) capture required.	Organics	DOE has developed and tested several thermally enhanced remediation systems combining Soil Vapor Extraction (SVE).
	In-Situ Physical/Chemical Treatment	Delivery Method	Gas-phase Delivery	A gaseous mixture of chemical reagent is injected into and drawn through the vadose zone to reduce or stabilize mobile contaminants. Gaseous delivery to the deep vadose zone has advantages because of the ease of transport through the sediments with minimal effect from gravitational and capillary forces.	All contaminants	Studies for gas-phase reagents are planned for the Hanford Site. Gaseous electron donor vadose zone demonstration and validation ongoing under Strategic Environmental Research and Development Program (SERDP) Department of Defense (DoD) support.
			Foam Delivery	Surfactant foam could be used for flushing, liquid chemical deliver, or delivery of nanoparticles to minimize the gravitational effects impacting reagent distribution.	All contaminants	Microfoam formulas applicable for Deep Vadose Zone (DVZ) delivery and tank-scale testing are being conducted in coordination with corresponding modeling and monitoring development. Under research and development (R&D) by DOE-EM DVZ-AFRC.
			Shear Thinning Fluid Injection	Shear thinning fluids could be used to enhance amendment and/or reagent delivery to low permeability zones.	All contaminants	Tested primarily for groundwater applications. Can be utilized during periods of rising groundwater table and rewetting of contaminated areas near the groundwater table. Development activities supported by SERDP (DoD).
			Jet Grouting	Similar to jet grouting under the containment technology response action, high pressure injection of a reactive grout slurry into soil in order to hydraulically mix the soil with the slurry. Fluidization of the soil is preferred.	All contaminants	Field scale application is fully deployable and has been performed to depths of 300 ft (91.5 m). There are issues concerning the radius of influence.

General Response Action - In-Situ Treatment

General Response Action	Technology Type		Technology	Description	Contaminant Applicability	State of Development
In-Situ Treatment	In-Situ Physical/Chemical Treatment	Delivery Method	Injection/Extraction Wells (Horizontal)	Delivery of amendments or extraction of soil vapor using horizontal wells. Wells are installed using horizontal drilling techniques.	All contaminants	Technology is well proven at shallow depths and certain geological conditions.
			Injection/Extraction Wells (Vertical)	Delivery of amendments using conventional vertical wells.	All contaminants	Technology is well proven. Distribution of liquid amendments can be highly ineffective due to presence of gravelly and cobbly lithologies.
			Surface Infiltration	Reagent is applied to ground surface to treat contaminants within the vadose zone. Surface infiltration can be done through drip irrigation, trenches, and shallow basin systems. Systems are generally designed to be 12 inches (0.3 m) below the surface and covered to be protected. Can be applied to bottom of excavations to target deeper vadose zone and smear zone soils more effectively.	All contaminants	Technology is well proven for shallow depths, but would need additional testing to make it applicable to the deeper vadose zone.
			Deep Soil Mixing	Large mixing augers (1.5 to 3 m [5 to 10 ft] in diameter) or horizontally rotating heads are used to blend and homogenize reactants with soil. The reactants may be chemical reductants, biological substrate, or solidification/stabilization agents.	All contaminants	Technology is proven for shallow deployment in fairly homogeneous soils. May be effective in combination with other technologies (e.g., excavation).
		Reagent Approach	Chemical Oxidation	Subsurface delivery of chemical oxidant (e.g., hydrogen peroxide, ozone, permanganate, persulfate, percarbonate) to degrade organic contaminants. Oxidants cause chemical destruction of toxic organic chemicals. Petroleum hydrocarbons and polycyclic aromatic hydrocarbons (PAHs) can be treated with a variety of oxidants (including peroxide, percarbonate, persulfate, and ozone).	Organics	Technology is proven for shallow deployment in fairly homogeneous soils. Chemical oxidants can be delivered using soil mixing, horizontal injections wells, or vertical injection wells.
			Soil Vapor Extraction (SVE)	Soil vapor is extracted through vertical or horizontal extraction wells to induce contaminant mass transfer from soil to soil vapor, and remove contaminant mass from soil vapor. Vapor is treated separately (granular activated carbon [GAC], thermal oxidizer, etc.) or directly discharged to atmosphere, if appropriate.	Volatile Organics	Technology is proven for remediating soils contaminated by volatile organics.
			Biological Reductive Dechlorination	Bioremediation, via the addition of an organic substrate, will reductively dechlorinate carbon tetrachloride. The substrate must be distributed to contact the carbon tetrachloride and allow reaction to occur.	Carbon Tetrachloride (CCl_4)	Pilot-scale and laboratory bench-scale testing have been performed for reduction of carbon tetrachloride.

General Response Action - In-Situ Treatment

General Response Action	Technology Type		Technology	Description	Contaminant Applicability	State of Development
In-Situ Treatment	In-Situ Physical/ Chemical Treatment	Reagent Approach	Electrokinetic Mobilization and Recovery	Application of an electric field in the soil induces contaminant mobilization through electromigration, electroosmosis, or electrophoresis. This application is attractive for low-permeability soils that are difficult to flush.	Uranium, nitrate	Method has been implemented in selected shallow vadose zone contaminant areas.
			Hybrid Electrokinetic Delivery of Treatment Chemicals	Mobilization of fluids to target areas by application of electric fields.	Depends on the type of treatment chemicals being applied.	Laboratory testing performed for reduction of chromate. Control of subsurface chemical conditions is critical.
			Sodium Dithionate	Inject sodium dithionate to reduce ferric iron, Fe(III), to ferrous iron, Fe(II), to create a reductant barrier for Cr(VI) in saturated systems.	Hexavalent Chromium (Cr(VI))	Application to the vadose zone has not been demonstrated. Effective delivery is the challenge.
			Sulfide Salts and Minerals	Calcium polysulfide is an effective reductant for Cr(VI) but mobilization by the dithionate solution is likely to occur so some impacts on groundwater can be expected. Polysulfide can also reduce uranium and technetium but those elements are more easily reoxidized in the vadose zone than chromium.	Hexavalent Chromium (Cr(VI)), Uranium (U(VI)), Tc(VII)	Field deployment for Cr(VI) remediation has taken place at a number of sites, including Hanford.
			Ferrous Iron	Can reduce Cr(VI), Tc(VII), or potentially other contaminants. The reduction mechanism may be through a homogeneous reaction solution or be a surface-mediated heterogeneous reaction.	Hexavalent Chromium (Cr(VI)) and Tc(VII)	Treatments have been effective on source plumes in the saturated zone.
			Gaseous Reductant	Gas-phase reductants such as hydrogen sulfide are easily transported through the vadose zone and can reduce contaminants in the vadose zone.	Uranium (U(VI)), Tc(VII)	Field-scale demonstration of Cr(VI) remediation in the vadose zone has been successful.

General Response Action - In-Situ Treatment

General Response Action	Technology Type		Technology	Description	Contaminant Applicability	State of Development
In-Situ Treatment	In-Situ Physical/ Chemical Treatment	Reagent Approach	Gaseous Ammonia	Involves the injection of ammonia gas to increase pH to dissolve silica. The pH naturally decreases to ambient conditions over time and aluminosilicate minerals precipitate and possibly coat and immobilize various contaminants.	Mobile contaminants	Effectiveness is being studied as part of a laboratory-scale investigation. Field testing is being planned for the Hanford Site.
			Phosphate Sequestration (Apatite)	Stabilization of metals by chemically binding them into new stable phosphate phases (apatite minerals) and other relatively insoluble phases in the soil, sediment or in a permeable reactive groundwater barrier. Phosphates are a viable form for uranium sequestration (fixing in place) and can promote sequestration by iron and aluminum oxides.	Mobile contaminants; Uranium (U(VI)), Tc(VII), Hexavalent Chromium (Cr(VI))	Field-scale testing for sequestration of uranium in phosphate phases (apatite) is being performed in saturated conditions at the Hanford Site.
			Carbonate Sequestration	Substitution into rhombohedral (e.g., calcite) or orthorhombic (e.g., aragonite) carbonate minerals can sequester the contaminants. Solid solutions tend to be more stable than pure end members. Carbonate minerals are often near saturation in the vadose zone.	Uranium, chromium	Substitution of strontium, uranium and chromium into carbonates has been shown but not developed into remediation technology.
		Other	Soil Desiccation	Removing water from vadose zone by injecting hot dry air or nitrogen gas and removing moist air to create a capillary barrier that impedes migration of contaminants by preventing their aqueous-phase transport.	Mobile contaminants	A pilot test is being performed at the Hanford Site.
	Biological Treatment		In-Situ Biological Reduction	Biological reduction of contaminants may occur as part of metabolic processes, or reduced as a microbial response to the toxicity of the contaminant. Microbially reduced species (e.g., iron and sulfur) may also reduce contaminants. Specific microbial groups mediate U(VI) reduction and nitrate attenuation in subsurface sediments co-contaminated with U(VI) and nitrate.	Uranium (U(VI)), Tc(VII), Hexavalent Chromium (Cr(VI)), Nitrate (NO_3^-)	Field scale application has occurred for some of the target contaminants in the saturated zone. DOE-SC supporting effort to study the long-term stability of uranium sequestration by sulfate-reducing bacteria.
	Natural Attenuation		Monitored Natural Attenuation	Reliance on natural processes to achieve remediation objectives within a designated time frame. Contaminants are often monitored in order to track progress and make sure that contamination does not spread or increase.	Contaminants are dependent on time frame to reach remediation objectives	Mature technology

Notes

DOE-EM DVZ AFRC: U.S. Department of Energy Office of Environmental Management, Deep Vadose Zone Applied Field Research Center

DOE-SC: U.S. Department of Energy Office of Science