Table FR-2. Summary information for LNAPL remediation technologies

LNAPL Technology	Applicability Rock Types (1 to 4)				Potential Time-frame [g]					Key Considerations for Fractured Rock
	T1	T2	T3	T4	VS	S	M	L	VL	
Excavation				T4	VS					Excavation of LNAPL present in shallow Type 4 bedrock is feasible. Excavation of more consolidated bedrock types is likely not practical in most cases. Excavation in more consolidated rock types requires more aggressive approaches such as rock blasting that are not recommended for LNAPL release sites.
In-situ smoldering	Experimental Technology									In-situ smoldering has not been applied in fractured bedrock conditions as of 2017. No evaluation of the applicability in bedrock is possible and application of the technology would be considered experimental.
Fluid recovery — Total fluids, Dual Pump, LNAPL Skimming	T1	T2	T3	T4			M	L	VL	Cost for LNAPL recovery and reliability depends on complexity of fracture network. Limited applicability for source treatment, especially with LNAPL in vertical fracture network. Recovery from vertical wells is more applicable when horizontal fracturing is present. Performance in bedrock can be enhanced via hydraulic or blast fracturing. Can provide effective and rapid treatment when primary matrix is not significantly impacted.
Water flooding (incl. hot water flooding)				T4		S				Water can be applied or injected into the subsurface fracture network to increase the recoverability of LNAPL. A major consideration to consider is how effectively the water can contact the LNAPL. A good understanding of the fracture network at the site is necessary for this technology to be effective.
Fluid recovery (Multiphase extraction [MPE], vapor-entrained; Multiphase extraction, vacuum-enhanced total fluids; Multiphase extraction, vacuum-enhanced dual pump) *AKA* Bioslurping, or enhanced or total fluid recovery (EFR/TFR)	T1	T2	T3	T4			M	L	VL	Reliability of capture depends on complexity of fracture network. Inclusion of vacuum can increase robustness of hydraulic control and LNAPL removal rate as air flow preferentially propagates along transmissive fractures. There is relatively little cost and performance information for fractured bedrock applications.

Surfactant- enhanced subsurface remediation (SESR)			T3	T4	VS	S				Removes LNAPL through mobilization and demobilization in the subsurface. Success depends on contact. Relatively expensive technology. Difficult to apply on large scale.
Cosolvent flushing			T3	T4	VS	S				Addresses both residual and free phase. Addition of chemicals that may require further cleanup. Success depends on the complete contact of the NAPL solution and the injected substance. Difficult to apply on a large scale.
Steam/hot-air injection	T1	T2	T3	T4	VS					Steam and/or hot air heats the soil and bedrock and enhances the release of LNAPL from the soil matrix and fractures. Effectiveness depends on the steam or air finding the fractures and penetrating the primary matrix.
Radio-frequency heating	T1	T2	T3	T4	VS					An in-situ process that uses electromagnetic energy to heat soil and bedrock. Less dependent on a hot fluid contacting all of the primary matrix and fractures.
Three- and six-phase electrical resistance heating	T1	T2	T3	T4	VS					Electromagnetic energy can be used to heat groundwater to vaporize volatile LNAPL constituents and reduce the viscosity and interfacial tension of LNAPL for enhanced hydraulic recovery. Vapors and dissolved phase can be recovered via vapor extraction and hydraulic recovery.
Air sparging/soil vapor extraction (AS/SVE)	T1	T2	T3	T4		S	M			AS injects air into the fracture zone to volatilize residual and dissolved phase LNAPL constituents, and vapors are vacuum extracted. Effectiveness depends on the extraction penetrating all fractures and matrix containing LNAPL.
Biosparging/ bioventing	T1	T2	T3	T4			M	L		Similar process to AS/SVE except air/oxygen is injected more slowly to stimulate biological degradation in the saturated/unsaturated zone. Effectiveness depends on the extraction penetrating all fractures and matrix containing LNAPL.
In-situ chemical oxidation (ISCO)	T1	T2	T3	T4	VS	S				Residual NAPL is depleted by accelerating LNAPL solubility by the addition of a chemical oxidant into the LNAPL zone. Effectiveness depends on the extraction penetrating all fractures and matrix containing LNAPL.
Activated carbon (usually with other amendments)					VS	S				Activated carbon can be injected into bedrock to sorb dissolved phase LNAPL and provide more time for degradation processes to occur. Effectiveness depends on the extraction penetrating all fractures and matrix containing LNAPL.

Enhanced biodegradation	T1	T2	T3	T4				L	VL	Requires the injection of nutrients to enhance the degradation of residual LNAPL and dissolved phase. Effectiveness depends on the extraction penetrating all fractures and matrix containing LNAPL.
Natural source zone depletion (NSZD)	T1	T2	T3	T4				L	VL	Reliability depends on complexity of system and adequacy of CSM. Period of performance can be extended and is typically decades. Measurement of NSZD rates at surface may be challenging if near surface bedrock is present due to preferential flow also fractures. Ability for NSZD to contain LNAPL migration may differ in fractured rock conditions.
Physical or hydraulic containment (barrier wall, French drain, slurry wall)			T3	T4					VL	Pumping and treating ground water is the most common technology for hydraulic containment. To the degree that contamination is contained within accessible fractures, the existence of discrete fracture pathways can be a positive factor for remediation. If the relevant fracture pathways are sufficiently permeable and connected, contaminated ground water can be readily extracted by pumping. Often this can be done without the need to apply large gradients or pump (and treat) huge volumes of water; migration of the contaminated ground-water plume can thereby be controlled. Physical containment is less likely to be cost effective due to potential need to blast rock to achieve capture throughout a fractured rock.
In-situ soil mixing (stabilization)				T4	VS	S				In-situ soil mixing of LNAPL present in shallow Type 4 bedrock may be feasible. Soil mixing of more consolidated bedrock types is not possible.

Notes:

a. Applicability of remedial technology in: T1 – Type 1 bedrock, T2 – Type 2 bedrock, T3 – Type 3 bedrock, T4 – Type 4 bedrock

b. Timeframe for technology: VS (very short) = <1 year, S (short) = 1–3 years, M (medium) = 2–5 years, L (long) = 5–10 years, VL (very long) = >10 years