Rethinking Remediation Pathways: Comparative Performance of Conventional and Adsorptive-Reactive Approaches

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Mutku Days Joensuu - 2026

CARUS REMEDIATION TECHNOLOGIES

Chemical:

- In Situ Chemical Oxidation: RemOx® Permanganates, OBC™ Activated Persulfate, OxygelPlus® Fenton like
- In Situ Chemical Reduction ABC+®

Biological (electron donors/acceptors):

- Aerobic: IXPER® Oxygel® SBC™
- Anaerobic: ABC-Olè™ , CAP18/ME®

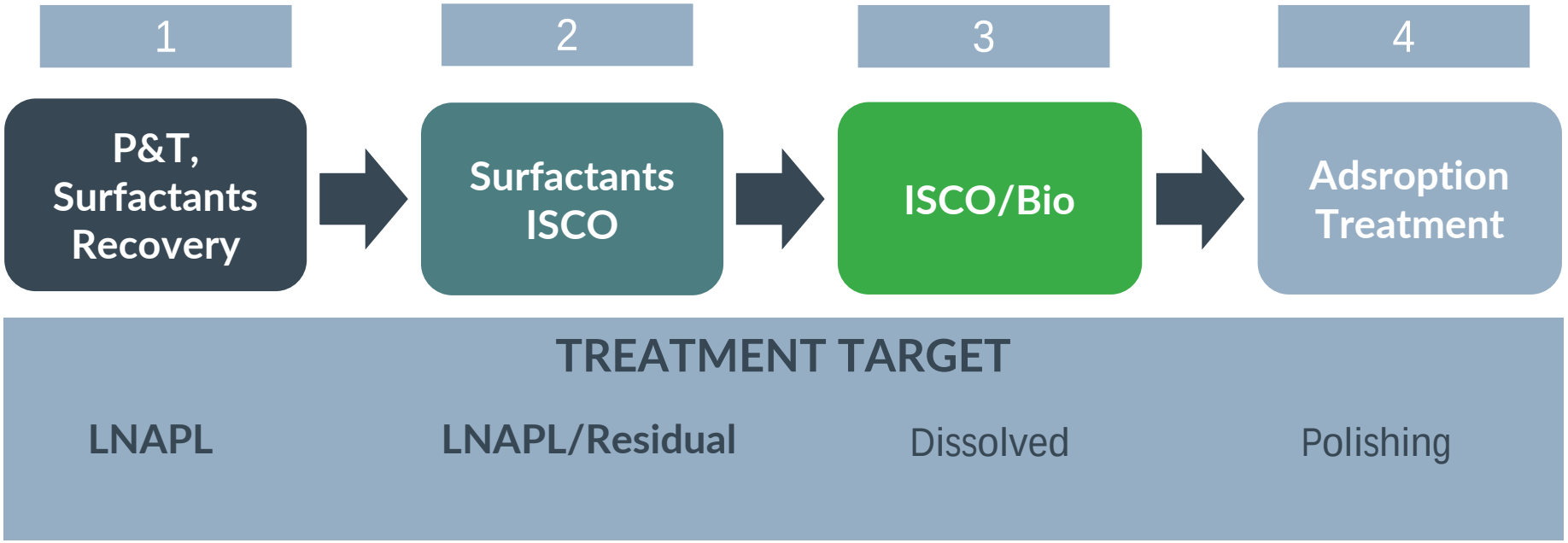
Free phase:

- Remediation Surfactant RemSurf®

Adsorption and destruction:

- RemSorb® Colloidal carbons, RemSorb®+ colloidal carvons and ZVI, RemZeo® Fe-Zeolithes, RemLock® Iron Oxides

TREATMENT TRAIN



ISCO InSitu CHEMICAL OXIDATION/REDUCTION

The Basic Premise:

Inject an oxidizing (reductant) agent into a contaminated zone in order to chemically break the carbon bond converting the contaminant from a toxic compound to naturally occurring non- hazardous compounds.

Four Design Steps

- Choose the correct reagent
- Choose the correct delivery mechanism
- Understand the site specific oxidant demand
- Create contact

OXIDIZERS

- **Permanganate RemOx® S and RemOx® L**

  $MnO_4^- + 4H^+ + 3\ e^- \rightarrow MnO_2 + 2\ H_2O$ 1.7 V (permanganate ion)

  PCE, TCE, DCE, VC, PAHs, Phenols, Aromatics (B), (TPH)

- **Fenton Modified OXYGELPLUS™**

  $H_2O_2 + 2H^+ + 2e^- \rightarrow 2\ H_2O$ 1.8 V (hydrogen peroxide)

  $2 \cdot OH + 2H^+ + 2e^- \rightarrow 2\ H_2O$ 2.8 V (hydroxyl radical)

  $\cdot HO_2 + 2H^+ + 2e^- \rightarrow 2\ H_2O$ 1.7 V (perhydroxyl radical)

  $\cdot O_2^- + 4H^+ + 3e^- \rightarrow 2\ H_2O$- 2.4 V (superoxide radical)

  $HO_2^- + H_2O + 2e^- \rightarrow 3\ OH^-$ - 0.88 V (hydroperoxide anion)

  TPH, PAHs, CVOCs, Aromatics, PFOs

- **IXPER Activated Persulphate OBC™**

  $S_2O_2^{2-} + 2\ e^- \rightarrow 2\ SO_4$ 2- 2.1 V (persulphate)

  $\cdot SO_4^- + e^- \rightarrow SO_4$ 2- 2.6 V (sulphate radical)

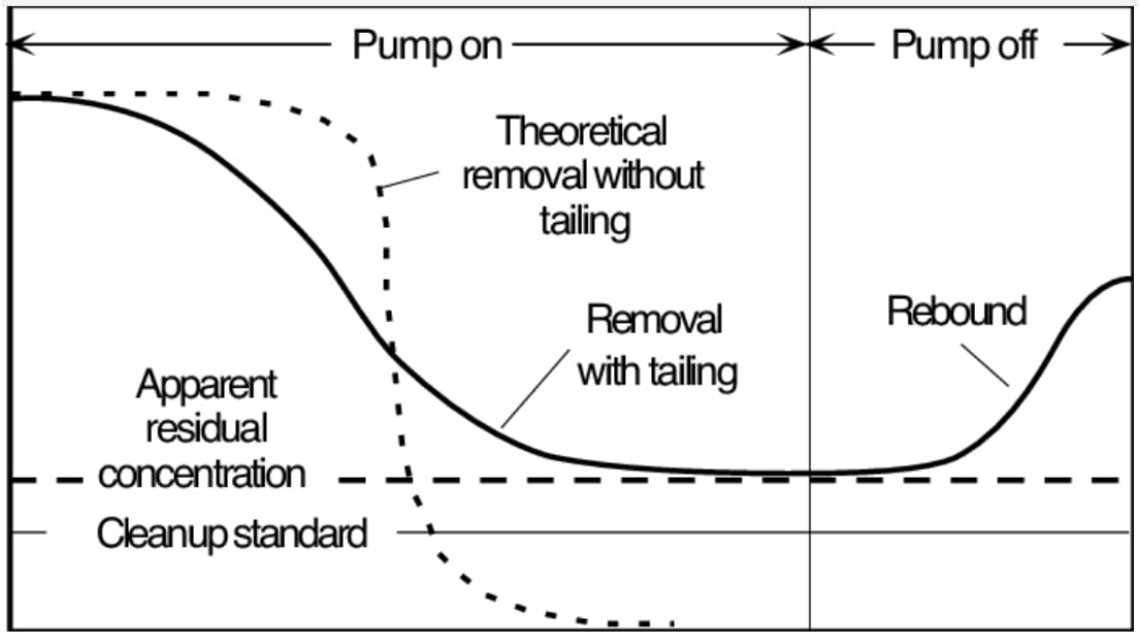
  TPH, PAHs, Aromatics, CVOCs, Chloromethanes

REDUCERS

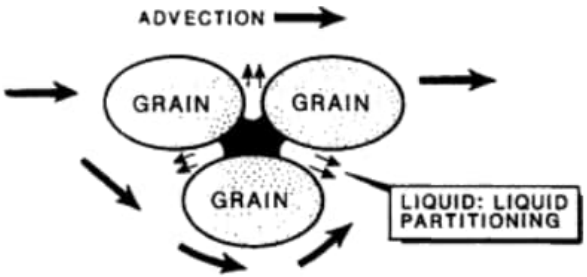
- Zero Valent Iron (ZVI) ABC™+ carbon substrate and ZVI

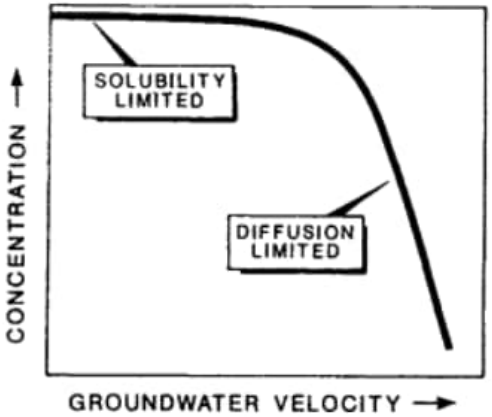
Chloroethenes, Chloroethanes, Chloromethanes, Freons, Carbon Tetrachloride, DCP, Lindane, Hexachlorobutadiene, (Pd active sites dichlorination of PCBs)

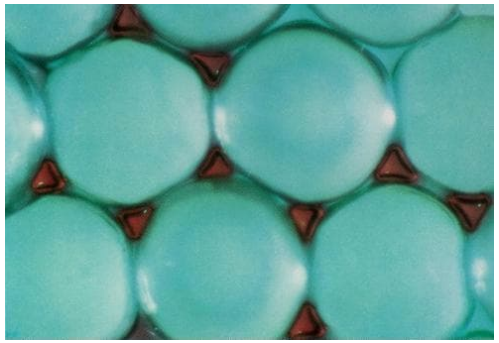
REBOUND?

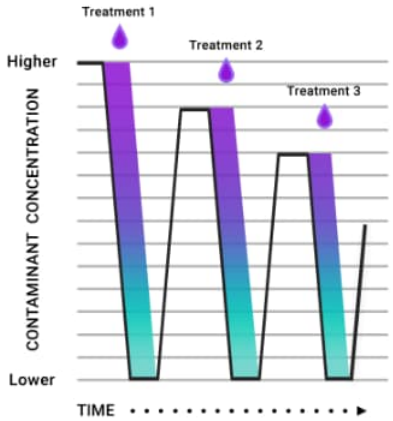


Concentration versus pumping duration or volume showing tailing and rebound effects (modified from Keely, 1989).









APPLICATIONS & LIMITATIONS

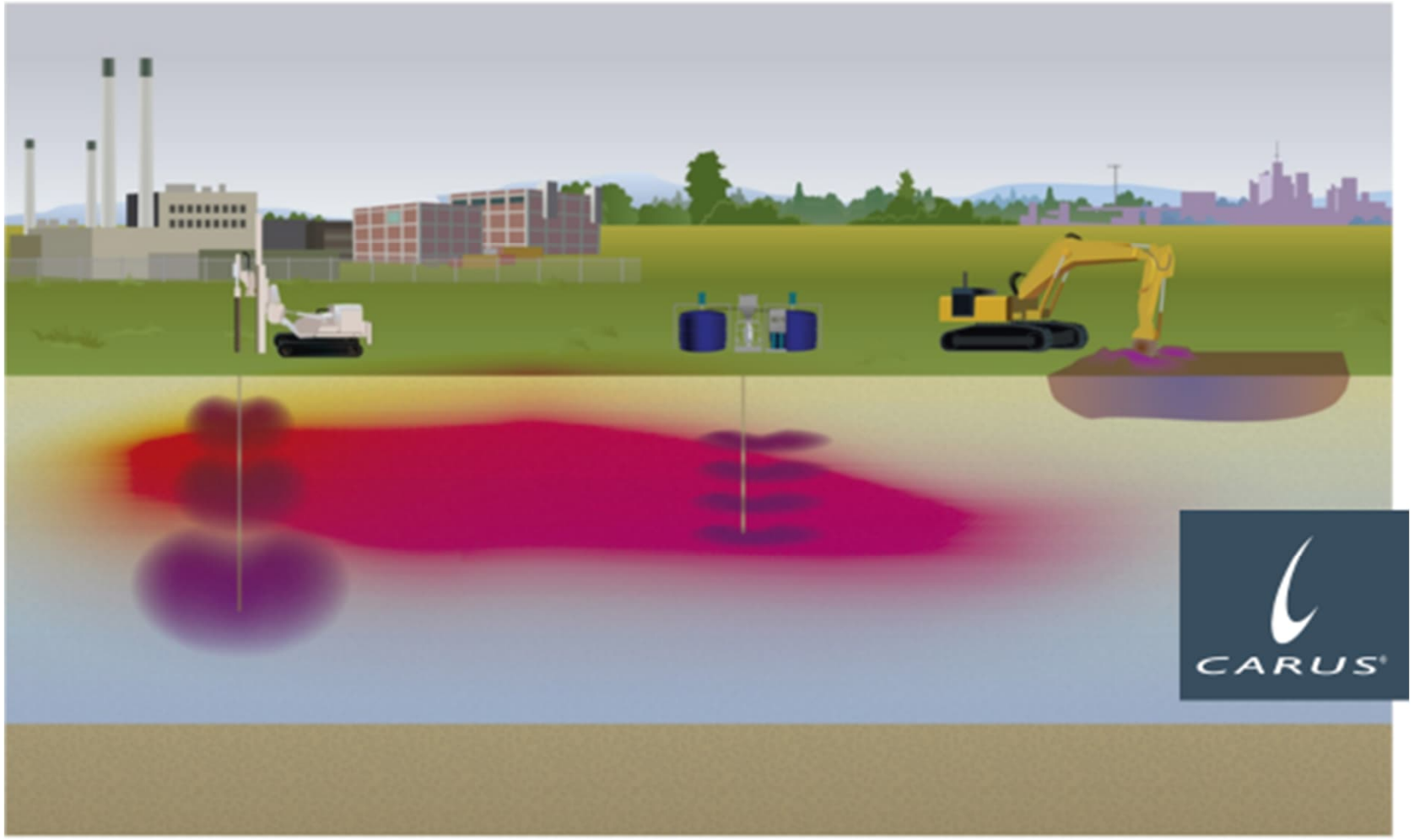
APPLICABILITY

High to medium concentrations
Small intervention volumes
Quick effect

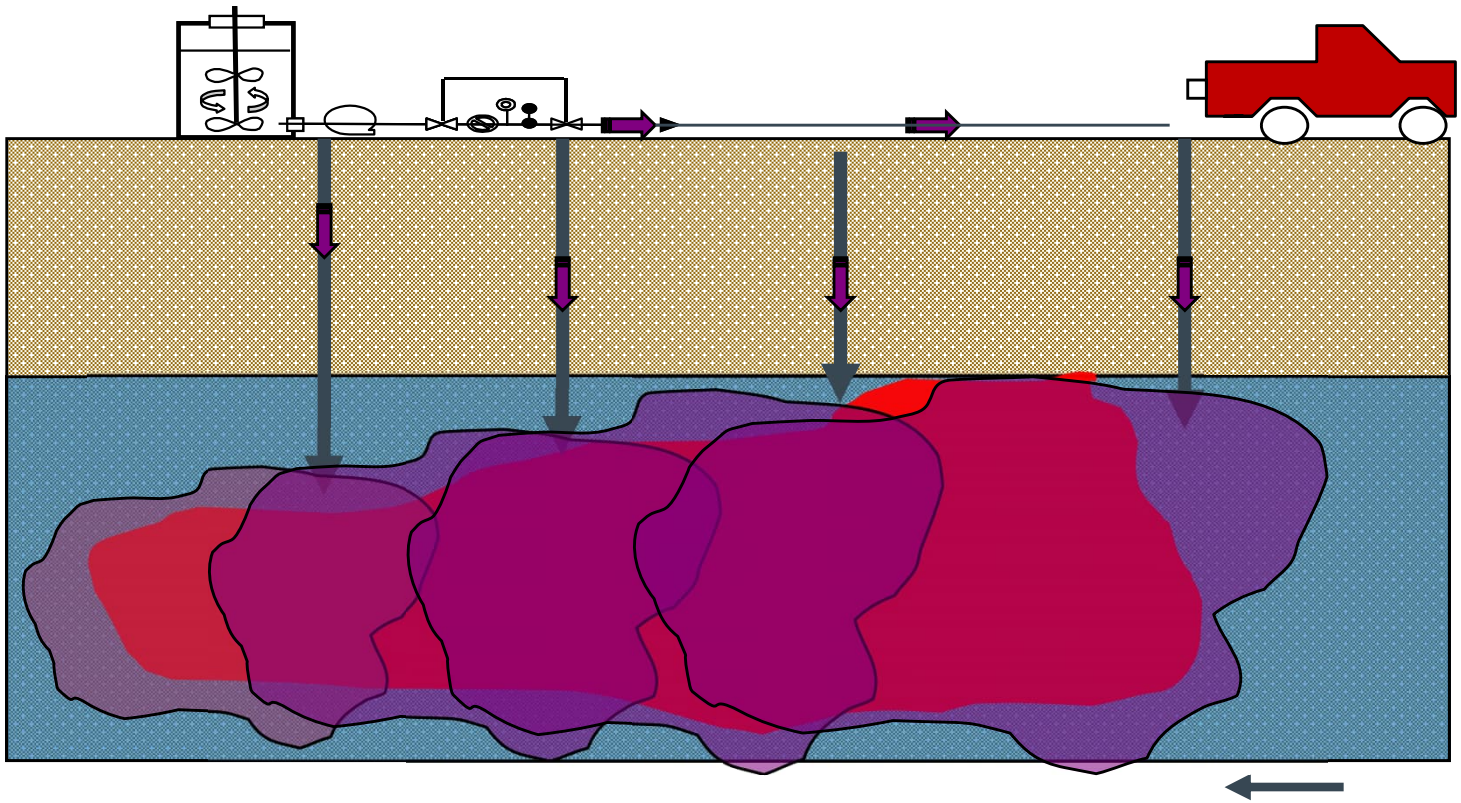
LIMITATIONS

Low permeability soils
NAPL (Non Aqueous Phase Liquid free or residual – RemSURF)
Receptors (rivers, sewer systems, waterbodies,..)

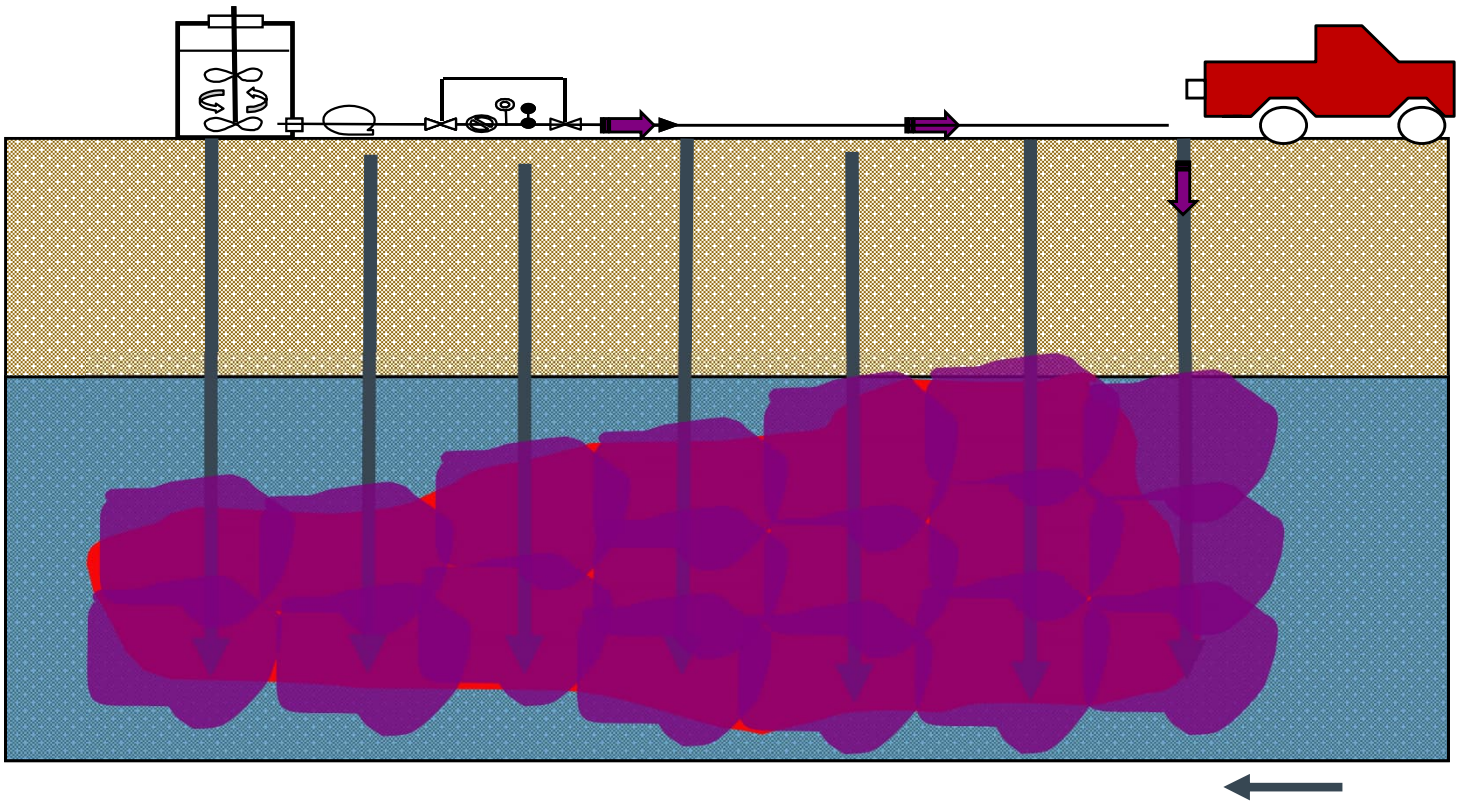
IMPLEMENTATIONS



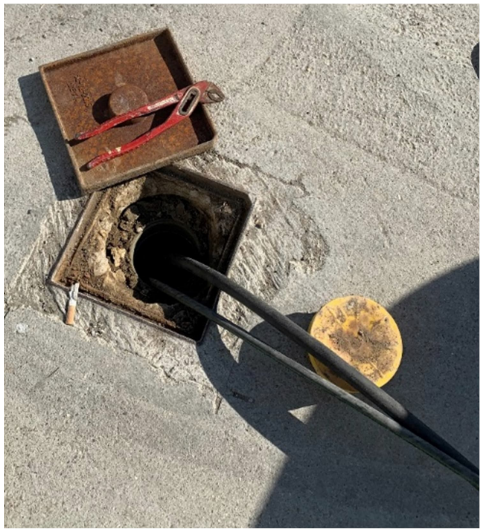
WELLS SIMPLIFIED INJECTION



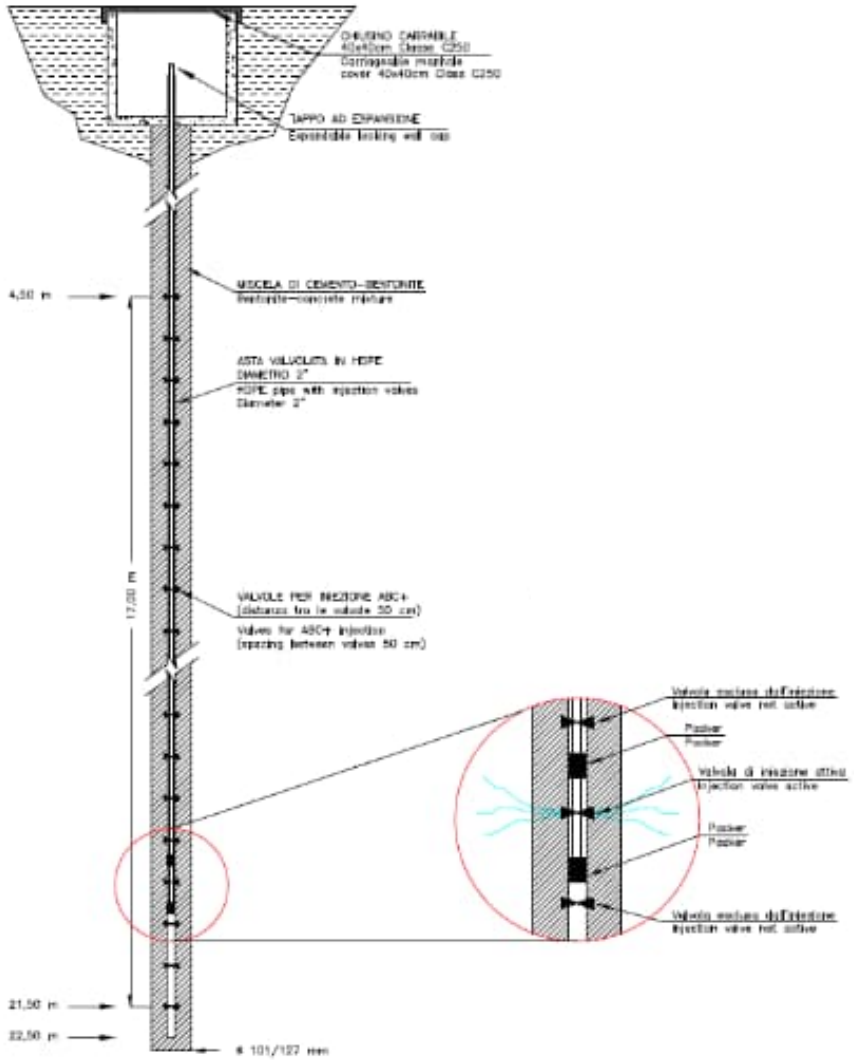
SIMPLIFIED DIRECT PUSH INJECTION



INJECTIONS IN FIXED INJECTORS



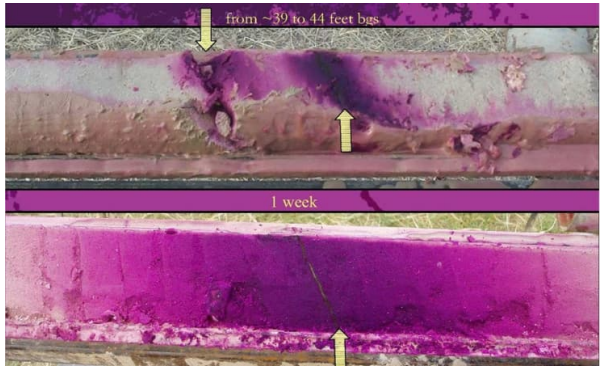
FIXED INJECTORS, VALVED PIPE, CANNE A MANCHETTE



REMOX S PERMANGANATE APPLICATIONS

Injection

Hydraulic Slurry Emplacement



Soil Blending

SOIL MIXING

Milan RemOx S

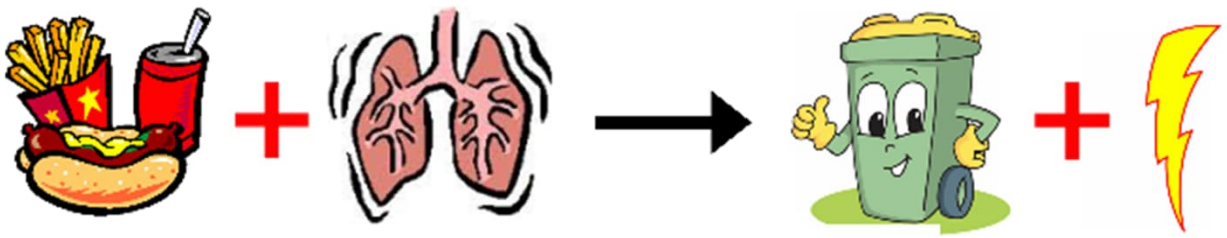
WHAT IS BIOREMEDIATION?

MNA – Monitored Natural Attenuation

Bio-Stimulation: optimize environmental parameters in order to increase degradation rate (destruction/transformation into less hazardous chemicals)

Bio-Augmentation: use of selected bacteria strains

WHICH BIOREMEDIATION?



Aerobic

Contaminant (e.g. BTEX, Benzene) + Oxygen → Waste Products (CO_2 and H_2O) + Energy

IXPER

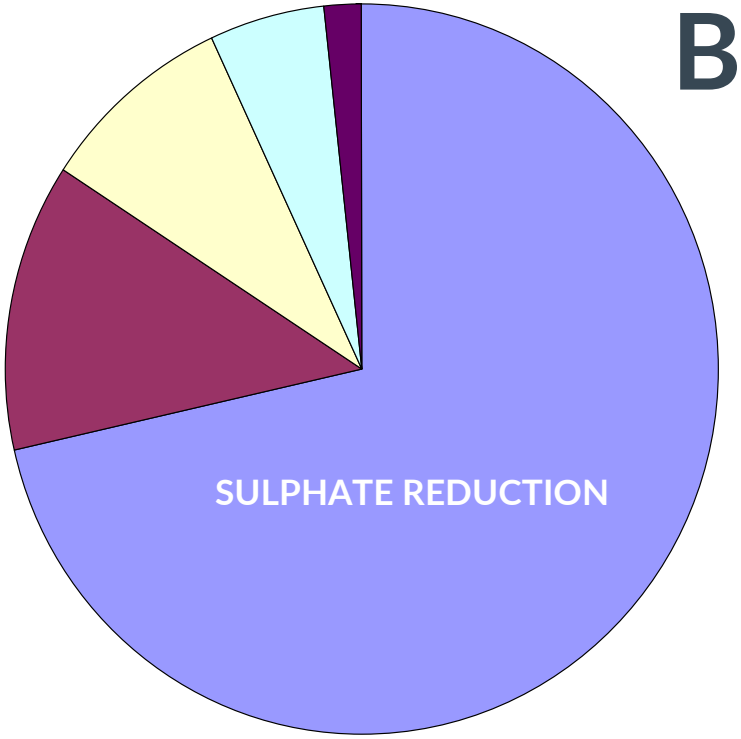
Anaerobic

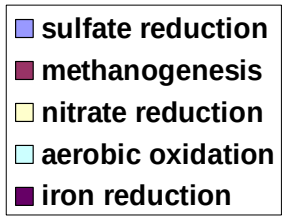
Organic Substrate (e.g. molasses, vegetable oil, H_2) + Contaminant (e.g. PCE, TCE) → Waste Products (ethene, ethane, CO_2 and H_2O) + Energy

CAP18
CAP18 ME

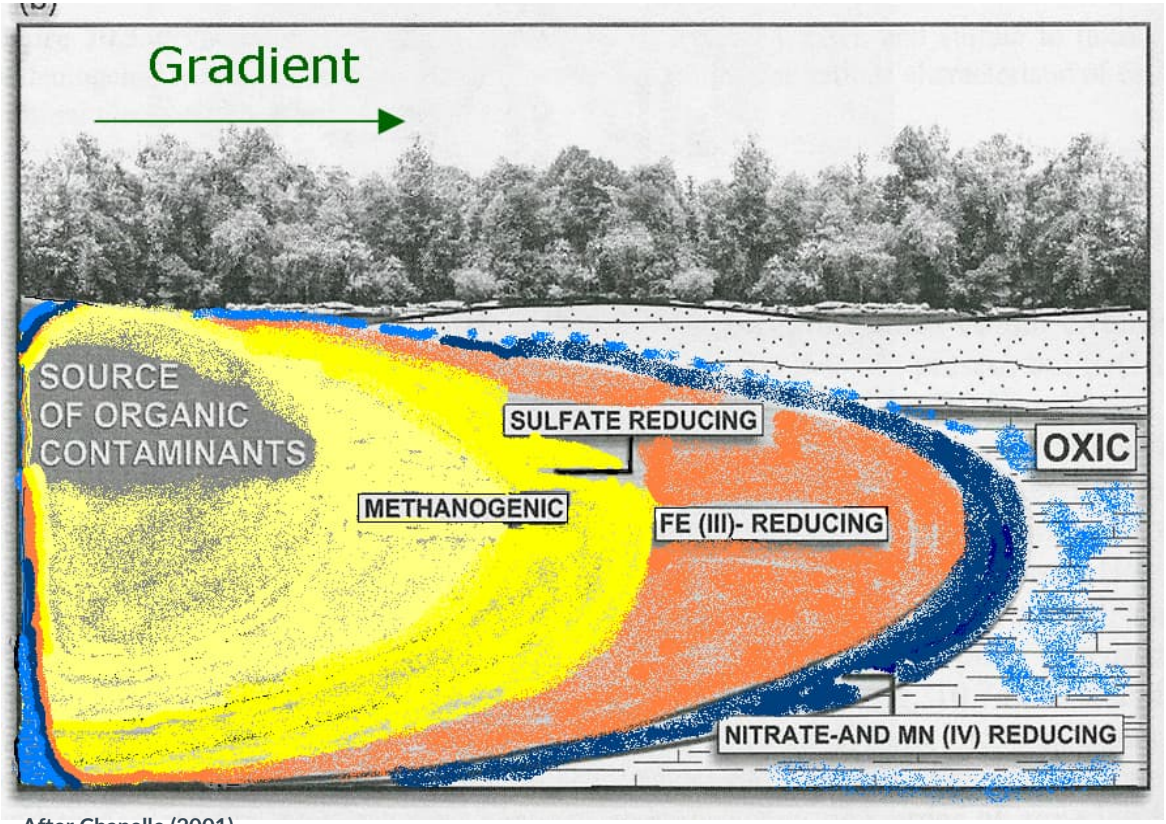
Adapted from Todd Wiedemeier

BIODEGRADATION ZONES





BP & EPA in 1994 evaluated 74 sites impacted by gasoline before any treatment.



After Chapelle (2001)

SITE CLOSURE !!

New adsorption/treatment options:

- PRB for off site migration control
- Rebound control
- Long term source treatment

ISCO and Bioremediation limitations

- Sites impacted by low levels of contamination
- Off site migration control (PRBs, more effective with ABC+)
- Rebound when regents are depleted
- Minor effect on heavy metals

New adsorption - destruction technologies

- High efficiency in off site migration control, replace Pump&Treat
- Effective on low levels of contamination to achieve stringent targets (ppbs)
- Long activity in the subsoil (decades) allowing excellent rebound control
- Effective on commingled contamination and heavy metals
- Immediate effect (weeks)
- Allow immediate risk reduction and **quick site closure**

RemSorb® COLLOIDAL ACTIVATED CARBONS

Developed and patented by UFZ (German Federal Research Center for Environment - Leipzig) in 2004. Can be used in PRBs and for source control in combination with an oxidant or Bioremediation-

- Specific activation for In Situ Treatment
- Can be injected in existing wells, direct push or valved pipes
- Distribution can be controlled via a mobility coating to achieve RoI up to 20m in ideal conditions, no wash-out
- Grain size: 1 micron
- BET: 1800 m^2/g
- Delivered as a stable suspension 200 kg of carbons per m^3 of suspension
- Effective on any kind of organics (Hydrocarbons, Chlorinated, Aromatics, PAHs….)

RemSorb®

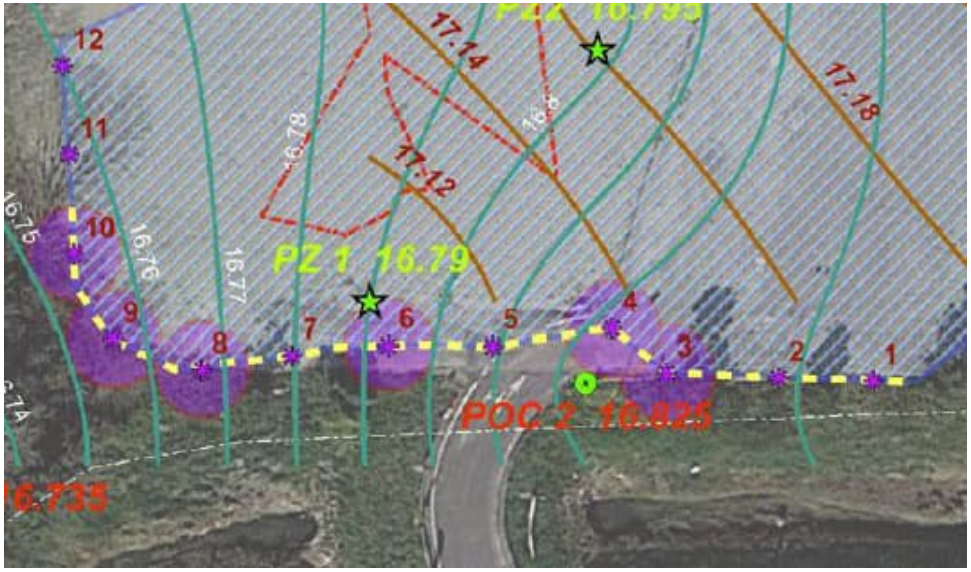
CASE STUDY

Northern Italy

Active gas stations

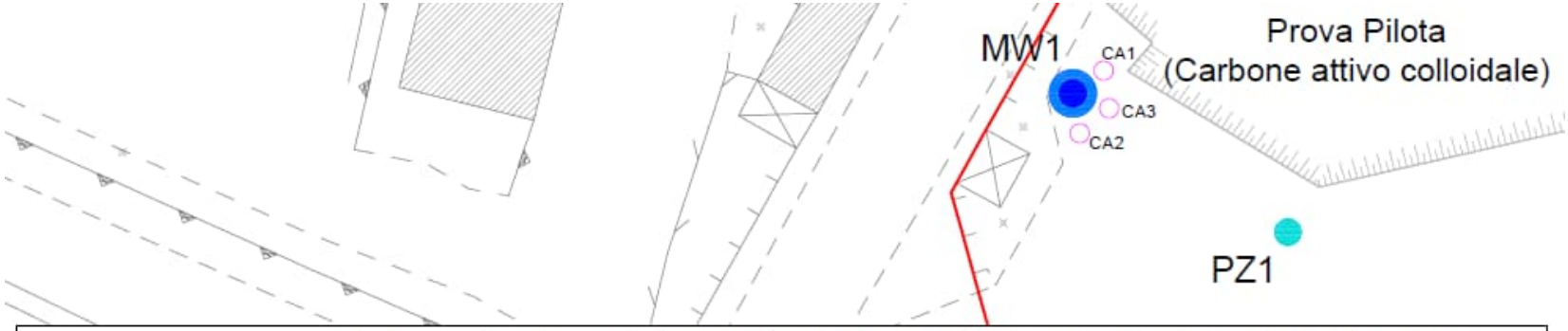
Dose: 200 kg Carbons distributed in 10 m^3 of injection fluid in 5 in direct push injection points

Site Activities: 1 day



Contaminant	Before treatment (average previous year)	1 month after treatment
Benzene	27	bdl
ETBE	2515	bdl
MTBE	6520	bdl
TPH	1250	2 ug/l

RemSorb®



	baseline	Injection	1°monit. (15gg)	2° monit. (30gg)	3°monit. (2 mesi)	4°monit. (3 mesi)	5°monit. (4 mesi)	6°monit. (5 mesi)	
MW1	11/03/2024	08-29/04/24	21/05/2024	03/06/2024	24/06/2024	29/07/2024	30/08/2024	24/09/2024	
Ferro	222		51	33.8	44.4	6.7	610	1680	µg/L
Manganese	101		89	60	26.1	12.4	239	530	
Solfati	429		223	290	207	213	212	190	
Benzene	< l.r.		< l.r.	< l.r.	< l.r.	< l.r.	< l.r.	0.41	
Benzo[a]antracene	0.046		0.160	0.115	< l.r.	< l.r.	0.0065	< l.r.	
Benzo[a]pirene	0.039		0.135	0.067	< l.r.	< l.r.	0.0045	0.00126	
Benzo[b]fluorantene	0.031		0.116	0.065	< l.r.	< l.r.	< l.r.	< l.r.	
Benzo[g,h,i]perilene	0.0228		0.084	0.0306	< l.r.	< l.r.	0.0032	< l.r.	
Benzo[k]fluorantene	0.0196		0.070	0.036	< l.r.	< l.r.	< l.r.	< l.r.	
Dibenzo[a,h]antracene	0.0056		0.028	0.0068	< l.r.	< l.r.	< l.r.	< l.r.	
Indeno[1,2,3-cd]pirene	0.0204		0.091	0.0276	< l.r.	< l.r.	< l.r.	< l.r.	
Σ IPA	0.0938		0.36	0.159	< l.r.	< l.r.	0.003	< l.r.	
pH	7.28		7.40	7.1	7.35	6.78	7.29	7.10	
Cond. Elettrica	1094		2090	2160	1782	1533	1418	1415	
O2 (mg/l)	1.7		2.45	2.5	1.85	2.5	2.5	2.8	
ORP	118		205	185	238	240	-71	-61	

CASE STUDY Pilot

Italy

Residual PAHs contamination with low target levels

Dose: 200 kg Carbons distributed in 7 m^3 of injection volume in wells **Site Activities:** 2 day

RemSorb® SOURCE TREATMENT

Data	20/12/2021	20/12/2021	20/12/2021	20/12/2021
Punto	PZ6*	PZ7*	W1	W2
MTBE	< 2,0	2,36	< 2,0	3,27
ETBE	< 2,0	26,2	931	469
TPH	4350	1490	108	181
Data	06/05/2022	06/05/2022	06/05/2022	06/05/2022
Punto	PZ6*	PZ7*	W1	W2
MTBE	8,68	20,1	4,98	2,92
ETBE	2,75	207	617	850
TPH	< 35	36,2	45,9	363
Data	09/06/2022	09/06/2022	09/06/2022	09/06/2022
Punto	PZ6*	PZ7*	W1	W2
MTBE	3,85	3,73	2,61	3
ETBE	24,3	26,5	841	359
TPH	43,3	< 35	40,7	234
Data	08/08/2022	08/08/2022	08/08/2022	08/08/2022
Punto	PZ6	PZ7	W1	W2
MTBE	< 2,0	20,1	< 2,0	< 2,0
ETBE	< 2,0	< 2,0	< 2,0	< 2,0
TPH	645	94,2	< 35	< 35
Data	06/09/2022	06/09/2022	06/09/2022	06/09/2022
Punto	PZ6	PZ7	W1	W2
MTBE	< 2,0	< 2,0	< 2,0	< 2,0
ETBE	< 2,0	74,5	< 2,0	< 2,0
TPH	45,8	< 35	< 35	54,8
Data	05/10/2022	05/10/2022	05/10/2022	05/10/2022
Punto	PZ6	PZ7	W1	W2
MTBE	< 2,0	< 2,0	< 2,0	< 2,0
ETBE	< 2,0	192	< 2,0	< 2,0
TPH	< 35	< 35	< 35	< 35

July: Carus activated carbon injection

RemSorb®+ CARBONS & ZVI

CARUS ACTIVATED CARBONS & ZVI

- Micro Colloidal carbons (1 micron)
- Embedded particles ZVI 50 nm
- BET: 600 – 800 m^2/g
- **Demonstrated dehalogenation by ZVI with end products (ethene/ethane/methane/propane)**

	0 g/l Cl	1 g/L Cl	5 g/L Cl	10 g/L Cl
Chloromethane (µg/l)	<1	<1	<1	<1
Trichloromethane (Chloroform) (µg/l)	<1	<1	<1	<1
Vinyl chloride (µg/l)	<1	<1	<1	<1
1,2-Dichloroethane (µg/l)	<1	<1	<1	<1
1,1-Dichloroethylene (µg/l)	30	<1	<1	<1
Trichloroethylene (µg/l)	60	<1	<1	<1
Tetrachloroethylene (µg/l)	<1	<1	<1	<1
Hexachlorobutadiene (µg/l)	<1	<1	<1	<1
1,1-Dichloroethane (µg/l)	<1	<1	<1	<1
1,2-Dichloroethylene (µg/l)	<1	<1	<1	<1
1,2-Dichloropropane (µg/l)	7	<1	<1	<1
1,1,2-Trichloroethane (µg/l)	<1	<1	<1	<1
1,2,3-Trichloropropane (µg/l)	<1	<1	<1	<1
1,1,2,2-Tetrachloroethane (µg/l)	<1	<1	<1	<1
Sum of ethane/ethylene/ethene (µg/l)	<1	16	16	16
Propane/propene sum (µg/l)	<1	2.9	2.9	2.9

RemLock® COLLOIDAL IRON OXIDES

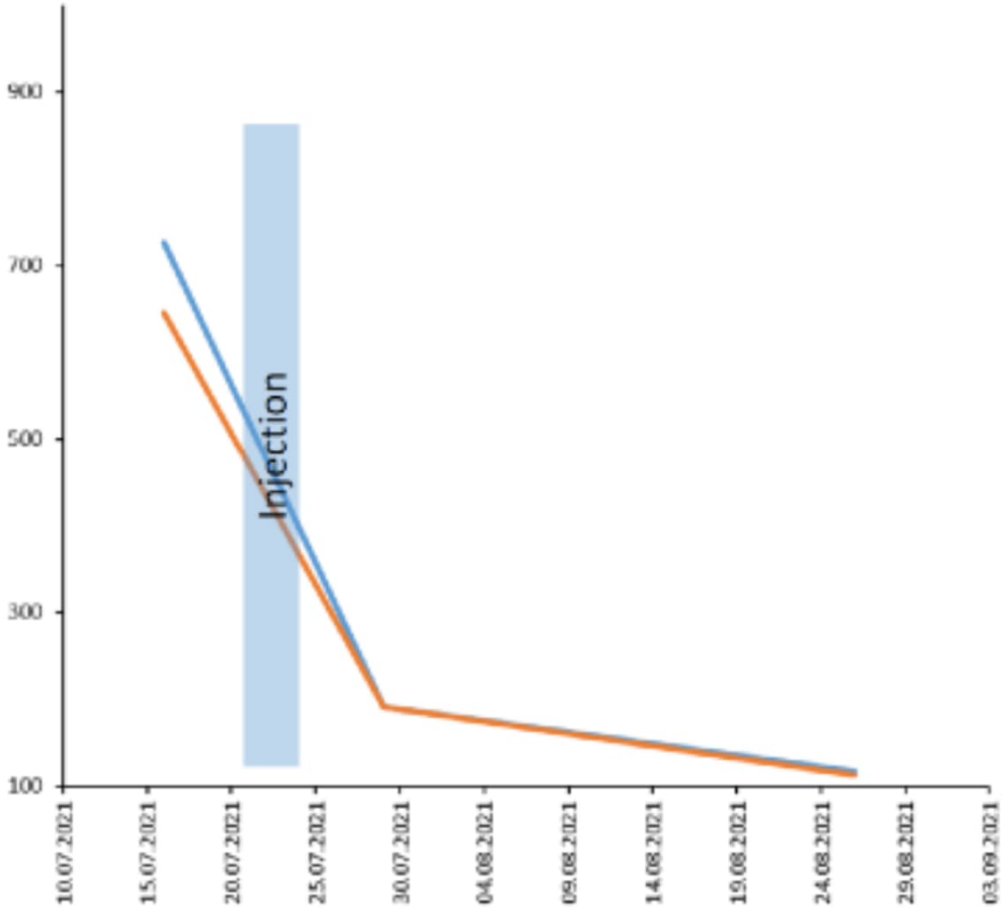
RemLock consists of specially prepared iron oxides (goethite) particles that are stabilized in colloidal form and injected into the subsoil. After controlled dispersion, they attach themselves to the soil matrix and thus form an in situ adsorption zone

- High affinity of heavy metals and semi-metals (e.g. As): contaminants are immobilized on site without energy and cost-intensive measures such as pump and treat, excavation or soil washing.
- Iron oxides as goethite are naturally occurring minerals
- Stable adsorption no release of adsorbed compounds
- RemLock is ecotoxicologically safe as is made of food anddrinking water grade natural occurring constituents of the soils.
- RemLock can be used for adsorption barriers to prevent off site migration or in source areas
- RemLock can be blended with RemSorb or RemSorb+ for mixed contamination

RemLock® COLLOIDAL IRON OXIDES

Reduction of the arsenic concentration downstream of an RemLock in situ barrier

RemLock is injected into the subsoil as a~1% (m/V) suspension



RemZeo® FE-ZEOLITHES

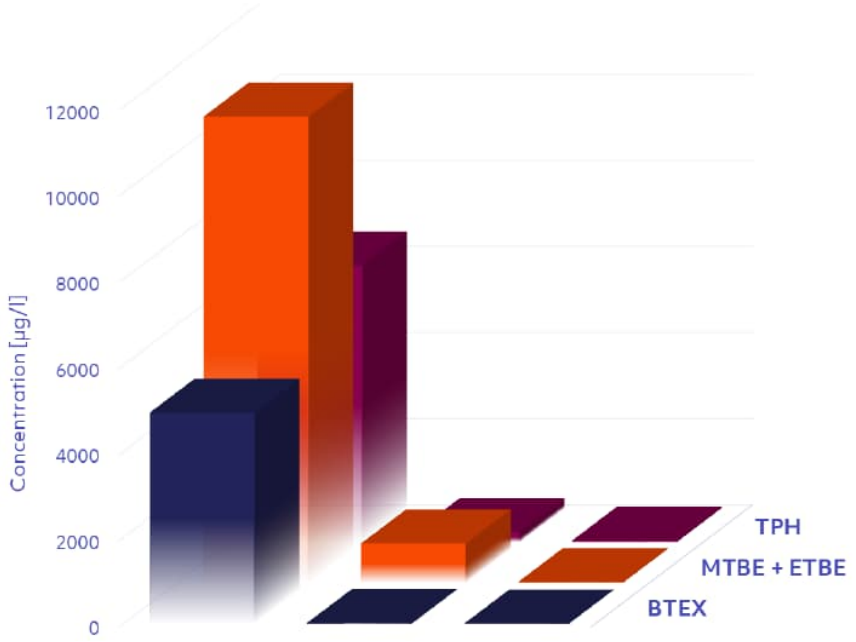
FIRST STEP

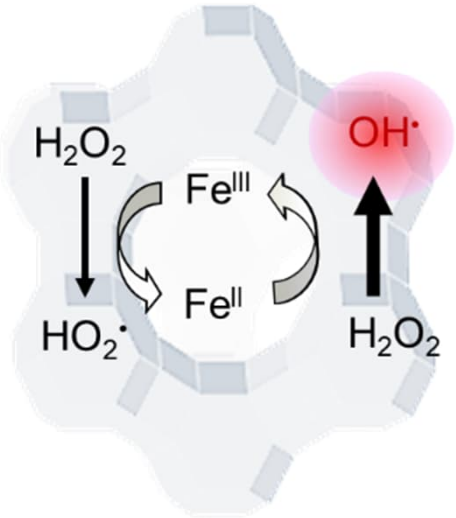
- Micro Colloidal Fe-Zeolithes for adsorption (1 micron)

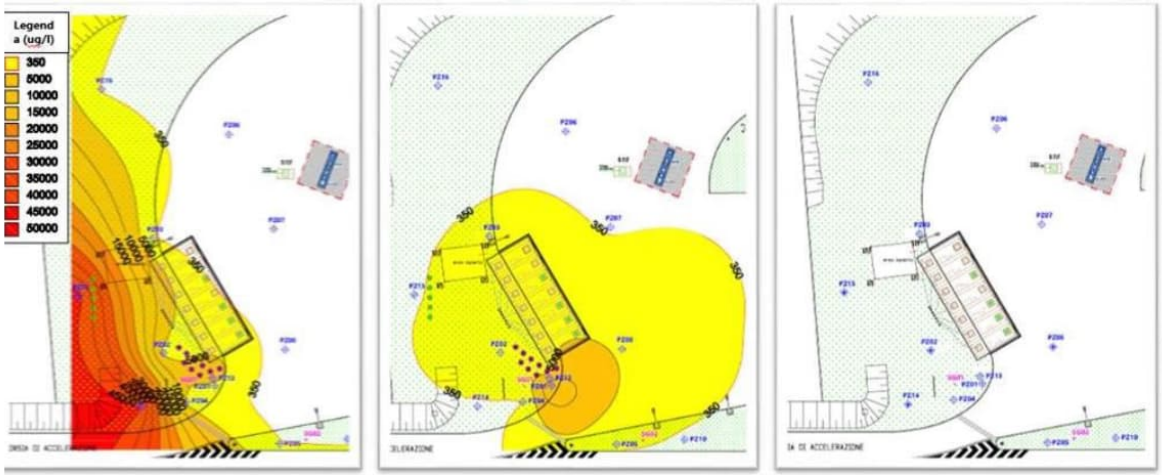
SECOND STEP

- Injection of stabilised H_2O_2 for oxidation on Fe active sites (can be repeated)

Applicable to any organic







CONCLUSIONS

As traditional technologies (ISCO, Bioremediation) have a consolidate application frame, new adsorption technologies can be an efficient complement in the following situations:

- Sites with low levels of contamination or very close to remediation targets
- Need of fast reduction of concentrations (weeks)
- Rebound control
- Off site migration prevention as Permeable Reactive Barriers (PRB)
- Closure of Pump&Treat and installation of adsorption barrier (in particular in case of tailing)
- Fast site closure
- Complex mixtures of contaminants including heavy metals

CONTACT INFORMATION

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