The Evolution of Two Remediation Technologies: Combined In Situ Stabilization (ISS) and In Situ Chemical Oxidation (ISCO)

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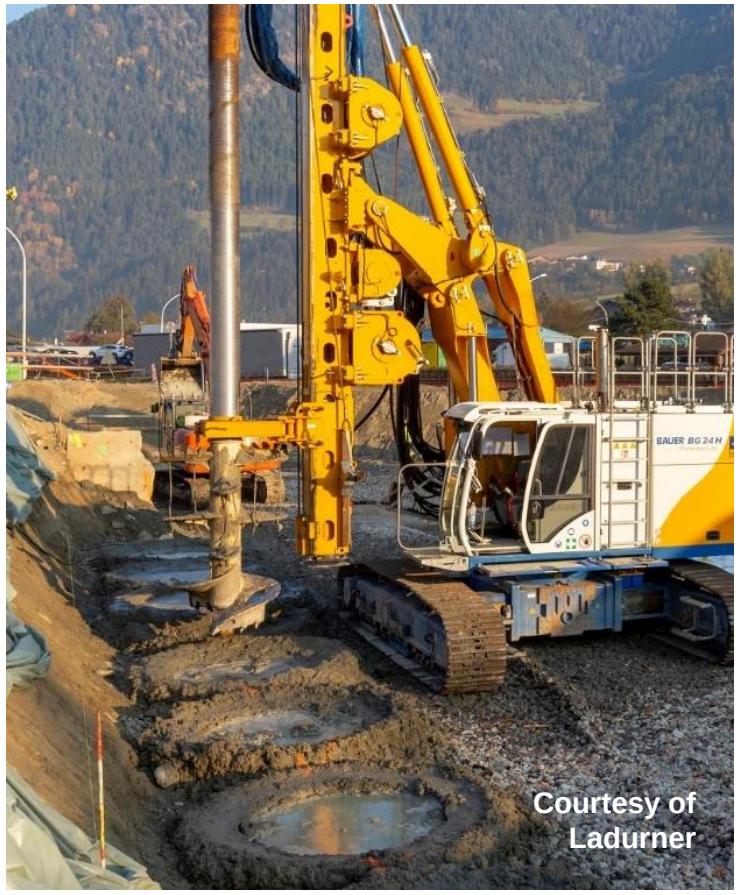
Presentation Outline

- Technology Overview
  - ISS
  - ISCO
  - Combined ISCO / ISS
- Why Combine ISCO/ISS
  - Synergies
- Case Studies



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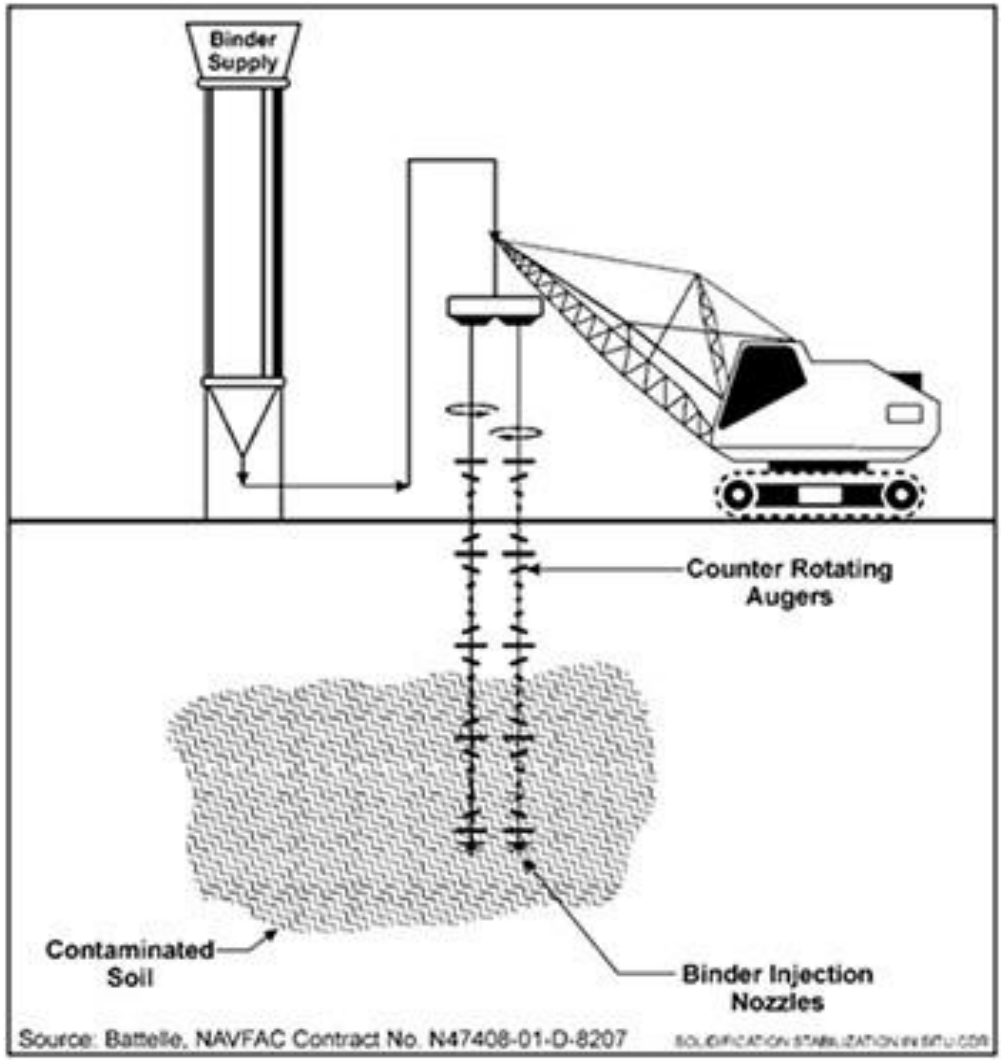
In Situ Solidification and Stabilization

- Use of soil mixing to blend binding agent(s) with contaminated soils:
  - Portland Cement
  - Blast Furnace Slag

- Common objectives:
  - Reduced hydraulic conductivity
  - Increased Unconfined Compressive Strength (UCS)
  - Lower contaminant flux and leachate concentrations



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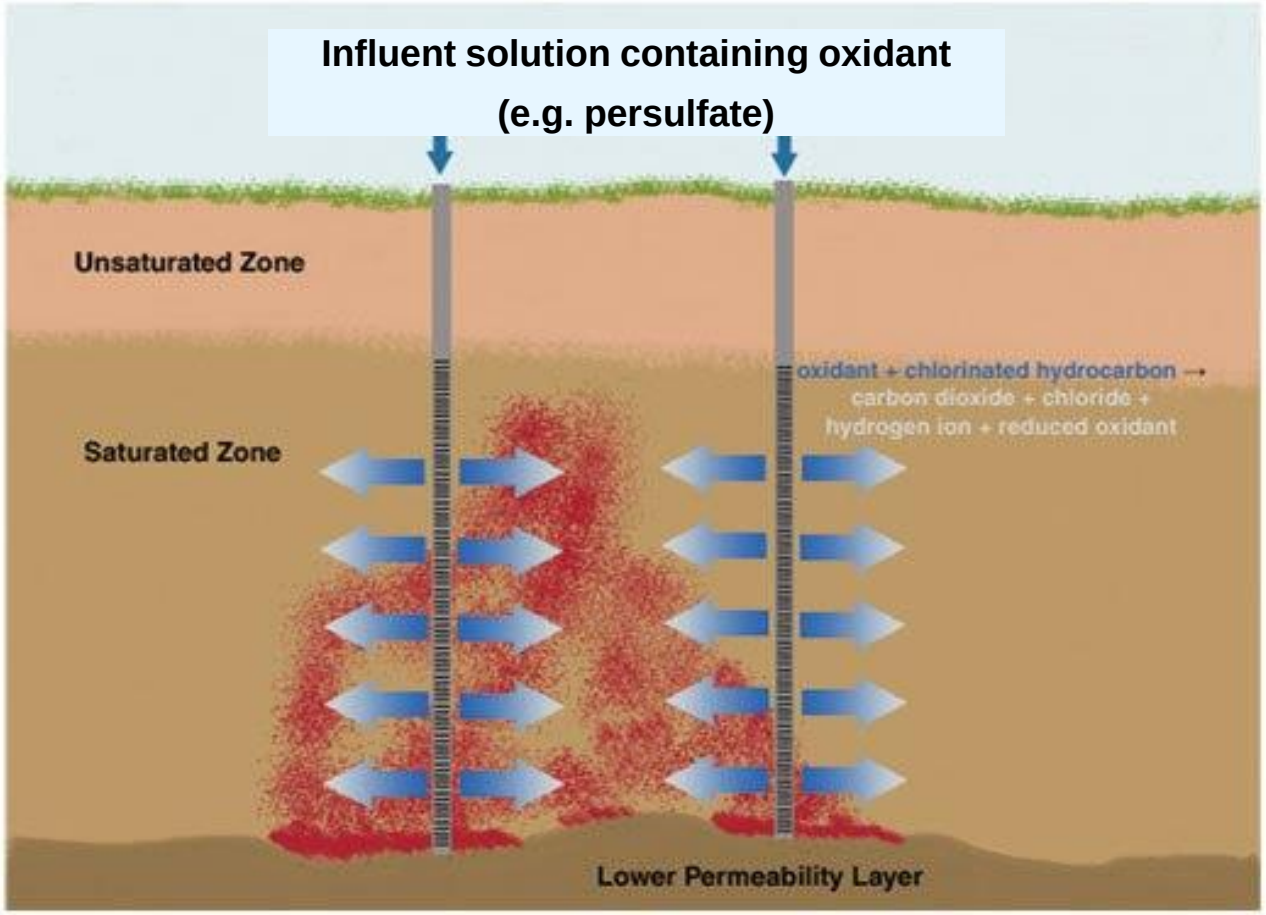
In Situ Chemical Oxidation

- What it is:
  - Oxidants are reagents that accept/take electrons from, or oxidize, contaminants of concern → CO_2
  - Typically applied via injection or soil mixing
- Objectives:
  - Contaminant destruction / mass reduction
  - Reduced concentrations in soil, groundwater, leachate and vapors

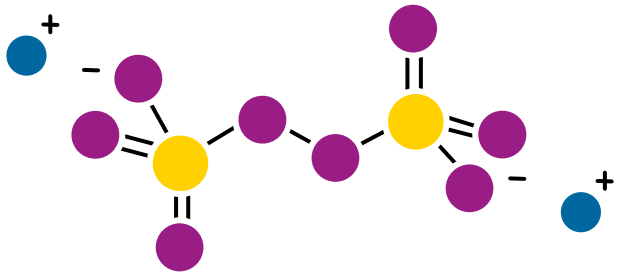


Examples (persulfate reactions):

Benzene: $15\ S_2O_8^{-2} + C_6H_6 + 12\ H_2O \rightarrow 6\ CO_2 + 30\ HSO_4^{-1}$

PCE: $2\ S_2O_8^{-2} + C_2Cl_4 + 4\ H_2O \rightarrow 2\ CO_2 + 4\ Cl^- + 4\ H^+ + 4\ HSO_4^{-1}$

Klozur® Persulfate



- Sodium and potassium persulfate are strong versatile oxidants commonly used in environmental remediation applications
- At a pH above 10.5, persulfate will be activated and form both oxidative and reductive radicals
- Common ISS binders create alkaline conditions → activates persulfate
- Oxidative and reductive pathways → applicable for treatment of very broad range of contaminants

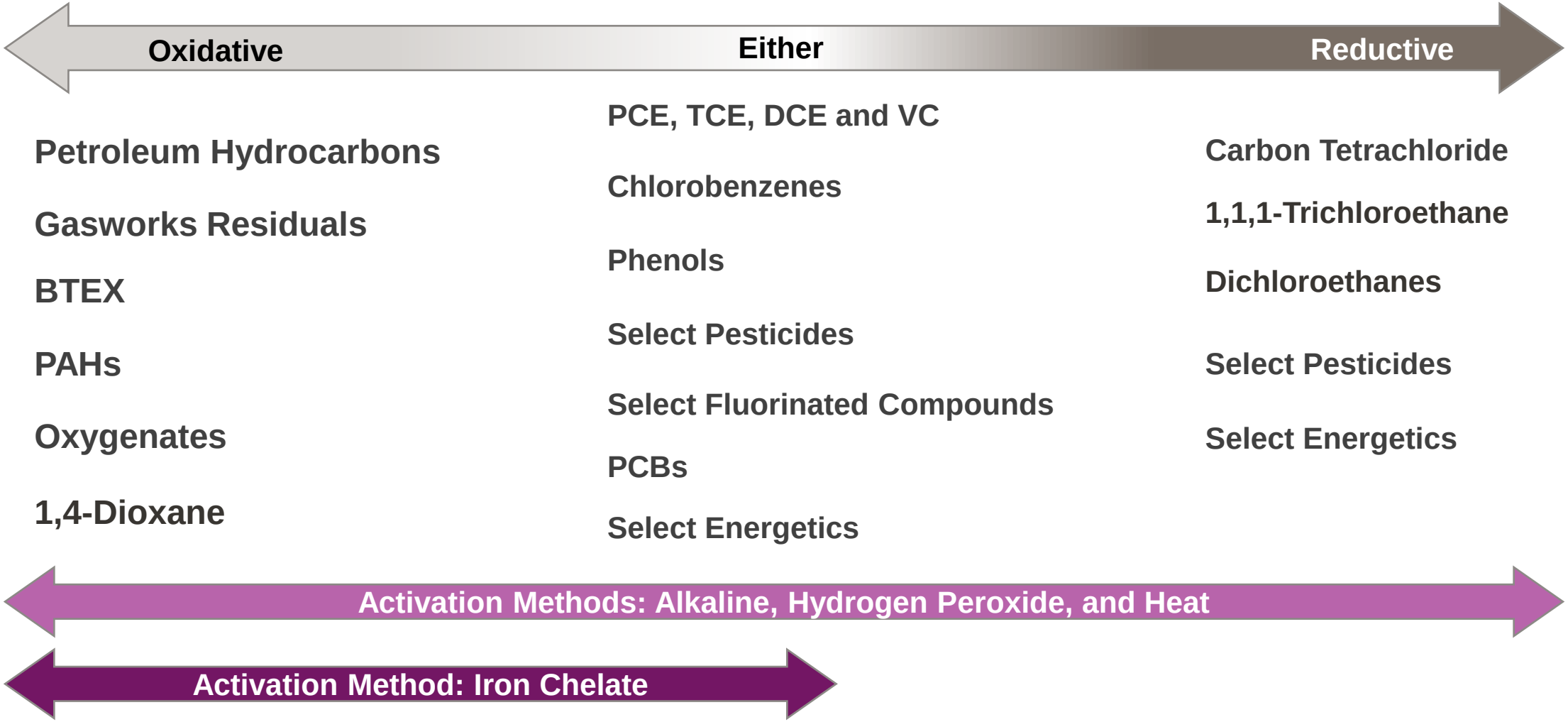
Alkaline activated persulfate:

$S_2O_8^{-2}$ + pH>10.5 → $SO_4^{\bullet-}$ + OH• + $O_2^{\bullet-}$

Oxidant	Standard Reduction Potential (V)
Hydroxyl radical (OH·)	2.59
Sulfate radical ($SO_4^{\cdot-}$)	2.43
Ozone	2.07
Persulfate anion	2.01
Hydrogen Peroxide	1.78
Permanganate	1.68
Superoxide ($O_2^{\cdot-}$)	-0.33
ZVI	-0.45

Notes: 1. Siegrist et al. (2011), 2. CRC (76th Edition)

Klozur® Persulfate Degradation Pathways / Contaminants Treated



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Single Technology Limitations

- **ISCO:**
  - Multiple applications may be needed for heavily contaminated sites → cost prohibitive
  - Contaminants that sorb strongly to the soil (low partitioning in water / Koc value) more challenging to treat, sometimes requiring multiple applications

- **ISS:**
  - Contamination is left in place maintaining environmental liability
  - Addition of binders can cause soils to swell (increase in volume), which then requires treatment or disposal

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Combining the Technologies ISCO/ISS

ISCO (sodium persulfate) and ISS reagents applied together in single application:

- Treatment of more soluble (mobile) fraction of the contamination preferentially treated via oxidation
- Remaining heavier contaminant fractions stabilized

Soil mixing using excavator with mixing attachment

Soil mixing using large diameter augers

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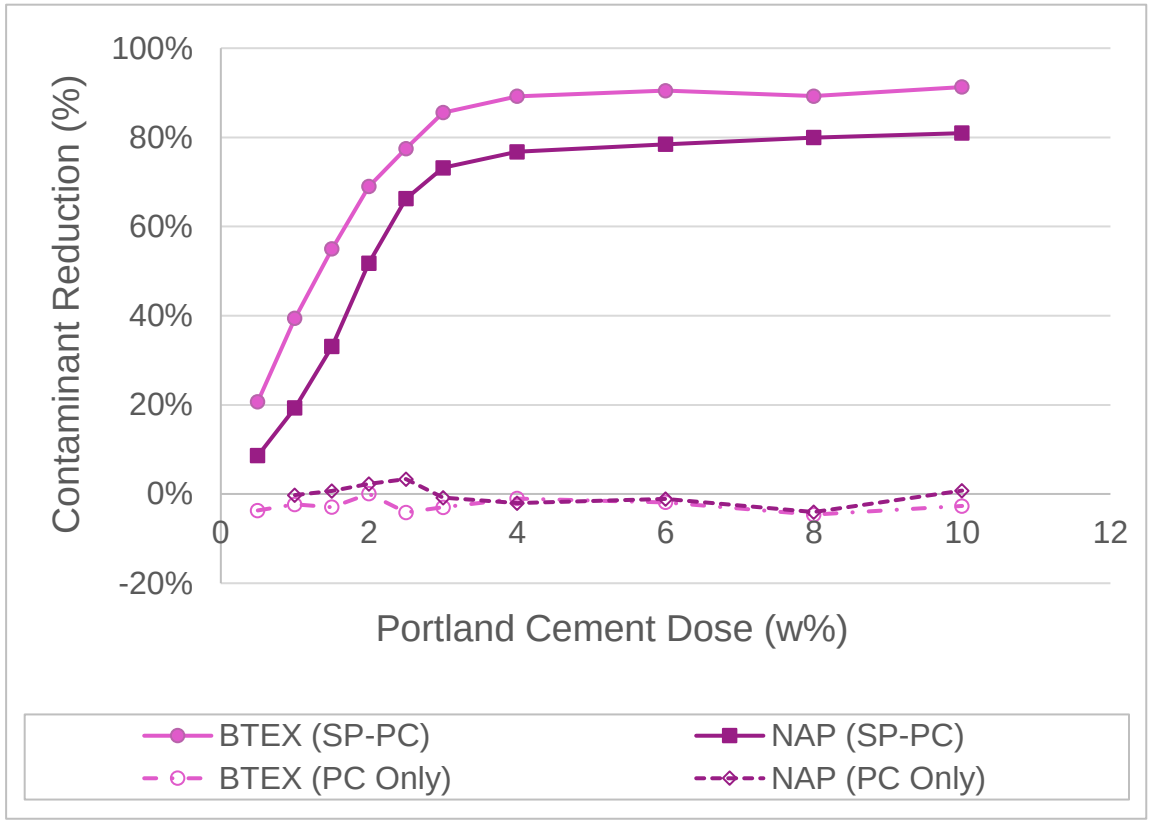
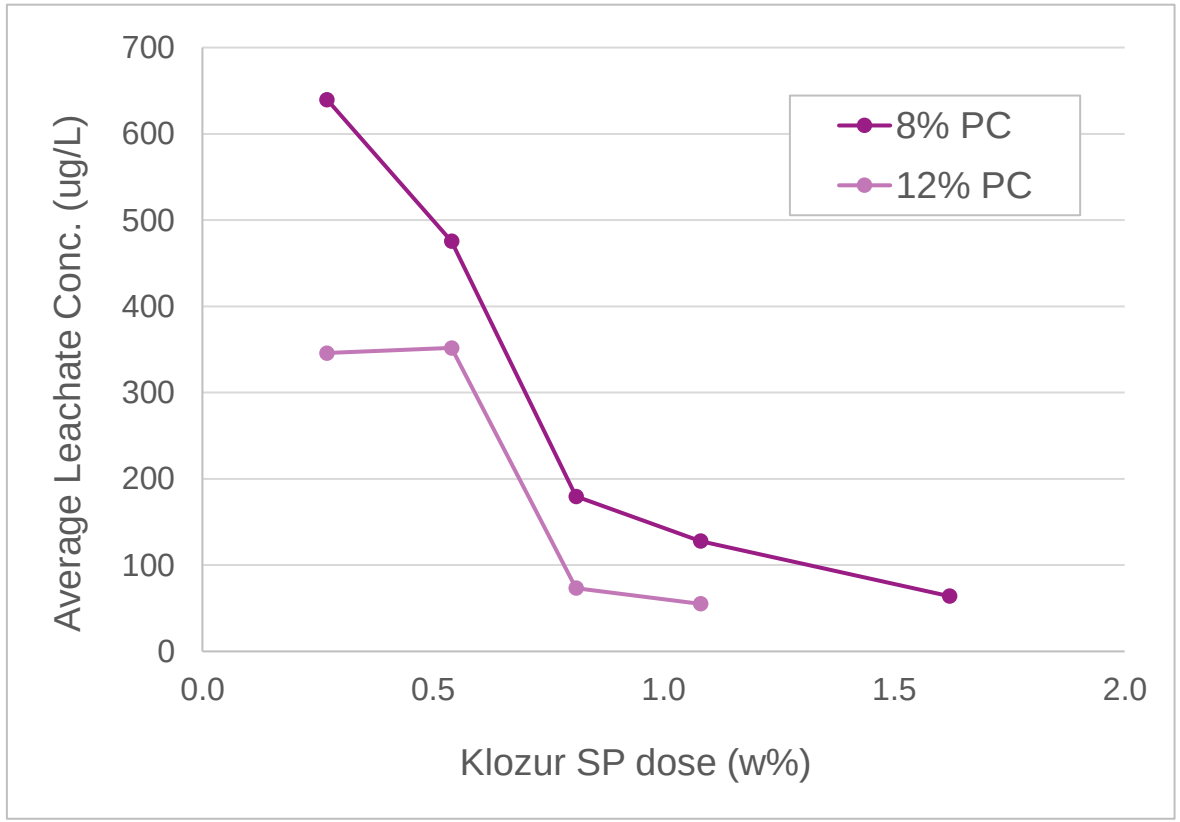
Synergistic benefits with combined approach

Common ISS reagents create alkaline conditions

→ Low-cost activator for persulfate



Adding persulfate to ISS reduces binder loading to reach leach targets → Less soil bulking



Srivastava et al (2016)

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Former MGP Site – Stockholm, Sweden

This project is a collaboration between multiple parties, incl City of Stockholm, PEAB, Golder, Elander Miljöteknik, RGS, Sheeba, Arkil, Evonik, Geomind

City of Stockholm Technical Project Contacts:
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Helen Österberg helen.osterberg@extern.stockholm.se

- Klozur Persulfates are being employed to remediate a former MGP site in Stockholm
  - Using Injection and ISCO/ISS
- The old MGP area is being redeveloped into a residential area
- Soil and groundwater impacted by coal tar residue, incl. Polycyclic Aromatic Hydrocarbons (PAHs)
- Goal with soil and groundwater remediation is to limit vapor intrusion to new residential buildings
- Bench and pilot testing in 2017-2020
- Full-scale implementation started March 2021

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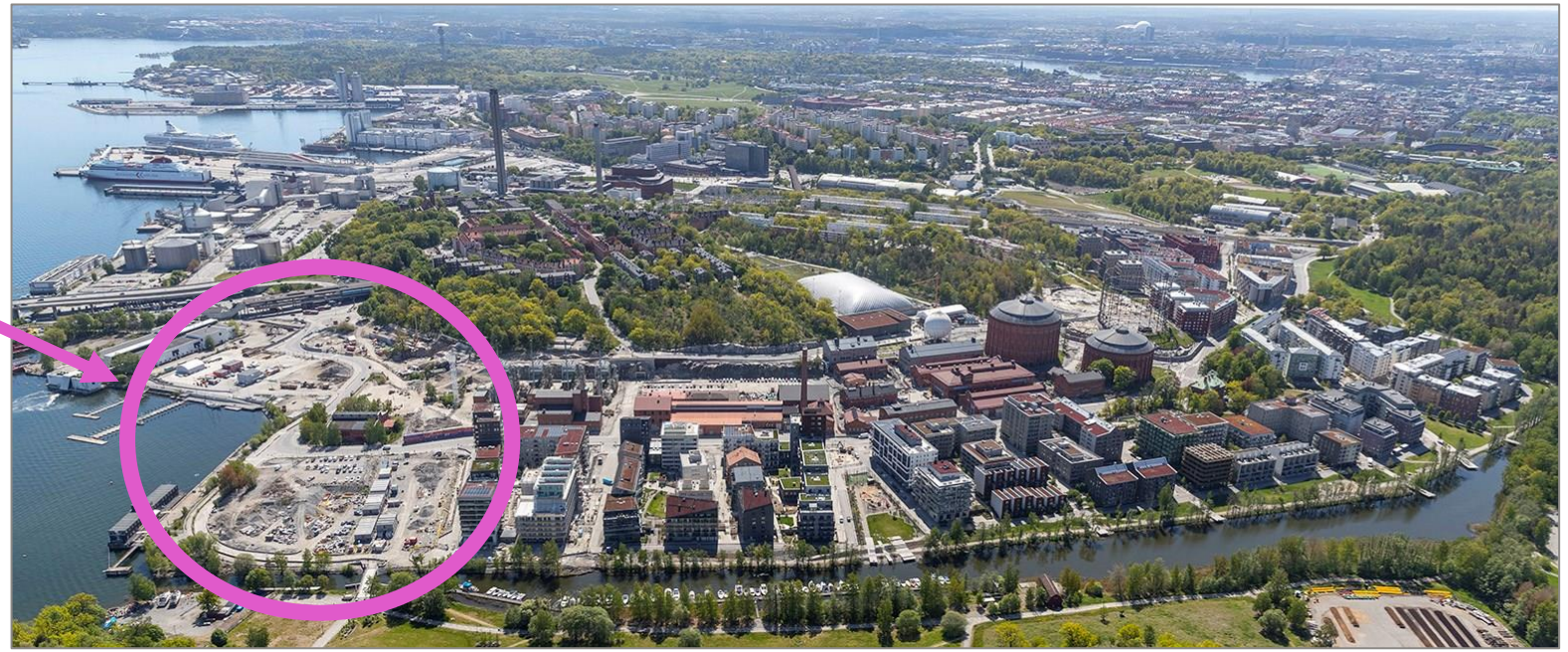
Aerial View of Stockholm Royal Seaport

- Part of one of Europe's most extensive urban development areas
- A total of 12,000 new homes and 35,000 new workplaces are planned for greater Royal Seaport Area:
  - 1500 new apartments planned at the former MGP area
- This is one of the city's designated sustainability profile areas:
  - Treating soil in place was the chosen sustainable remedial approach

Project site



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Residential Development Completed along the Channel

Aerial view from 2013

Current view

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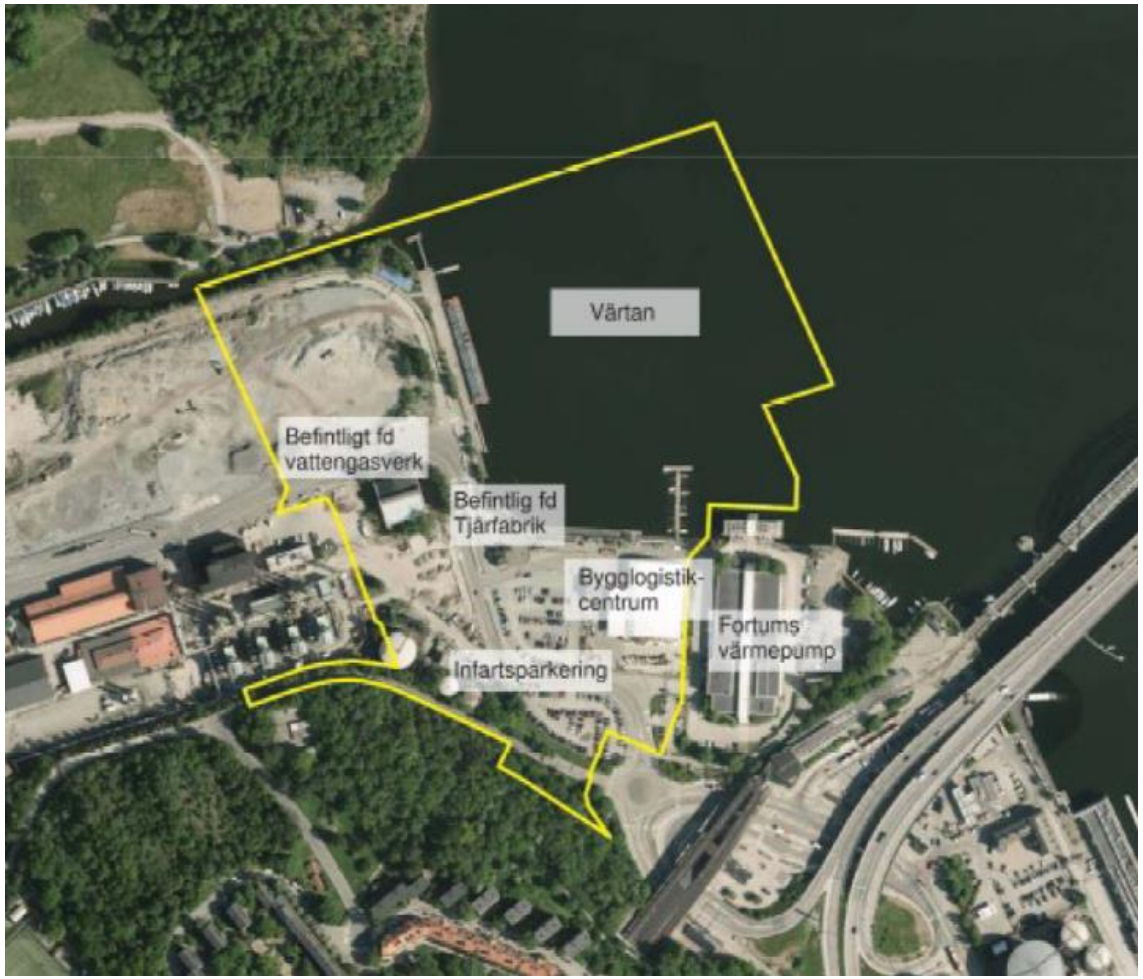
ISCO/ISS Remediation Area – area next to former tar factory



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And this is what is planned.. 1500 new apartments being built in the area.

Pictured: An early-stage visionary illustration of the final Stockholm Royal Seaport district.

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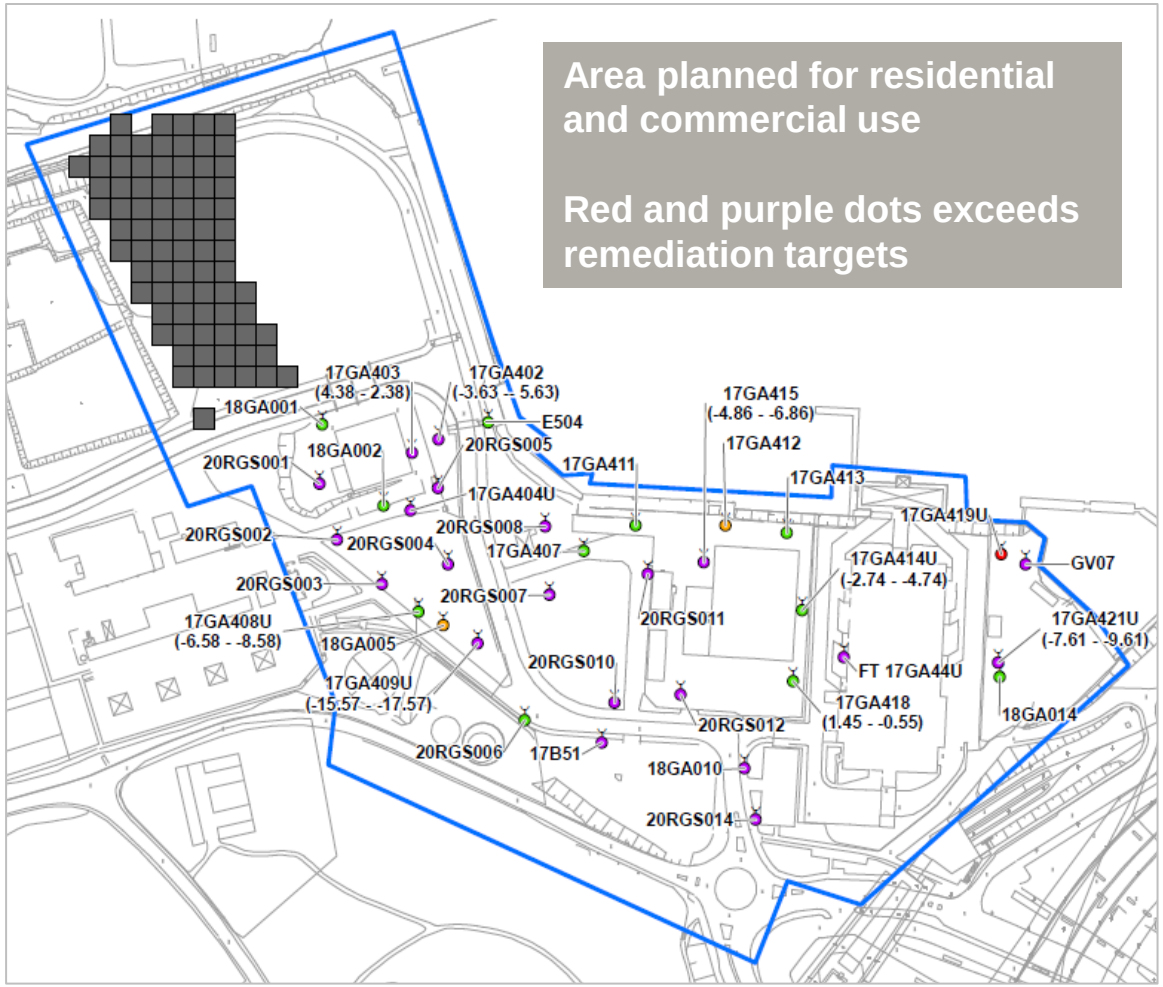
Before construction can begin the soil needs to be treated

- **Soil and Groundwater impacted by MGP residual contamination including Polycyclic Aromatic Hydrocarbons (PAHs)**
- **PAHs present in two subsurface units:**
  - Clay unit down to ~7 m below ground surface
    - Volume: 50,000 m^3
  - More permeable “Moraine” layer (sand, gravels, and rock) beneath the clay
    - Volume 70,000 m^3



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Site Specific Remedial Targets

Site Specific Remedial Targets developed to prevent vapor intrusion

Clay unit remediation goal:

- <250 mg/kg PAH-16

Groundwater remediation goals:

- Naphthalene <6200 ug/L
- Fluoranthene <12 ug/L
- Benzene <300 ug/L

16 Priority PAH (PAH-16) by molecular weight (low, medium, and high)

PAH-L	PAH-M	PAH-H
naftalen	fluoren	benso(a)antracen
acenaften	fenantren	krysen
acenaftylen	antracen	benso(b)fluoranten
	fluoranten	benso(k)fluoranten
	pyren	benso(a)pyren
		dibens(ah)antracen
		benso(ghi)perylen
		indeno(123cd)pyren

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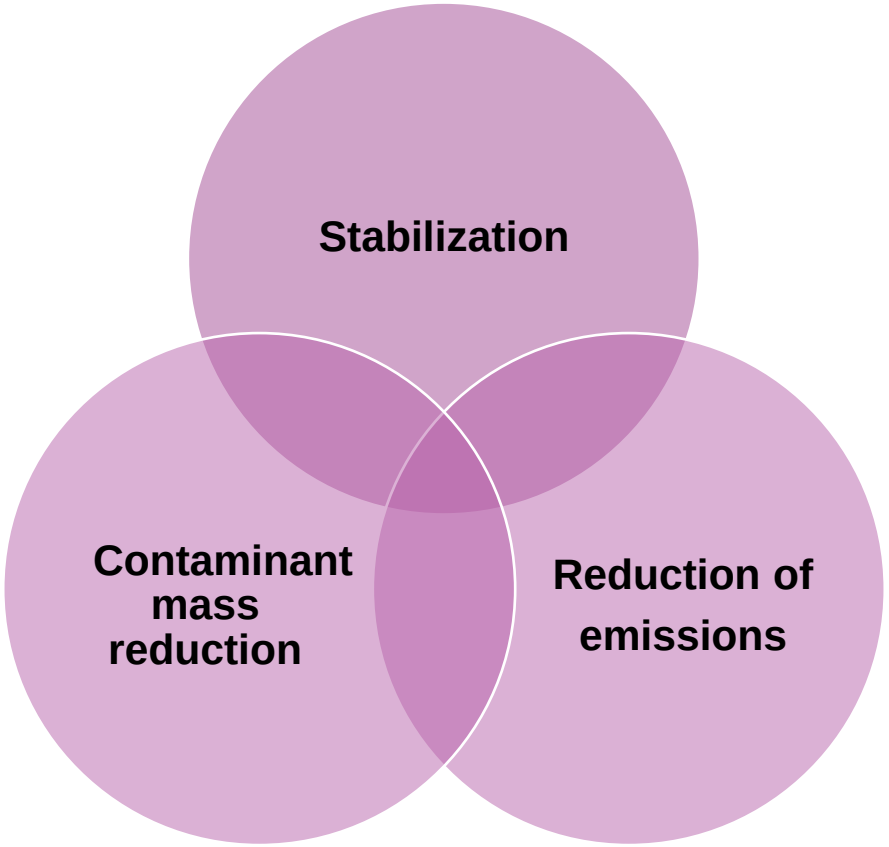
Remediation Approach

- **After several years of bench and pilot field scale testing, Klozur SP selected to treat both the clay and moraine layer units:**
  - Clay unit treated with ISCO/ISS to both degrade and solidify contaminants in a soil mixing strategy (~50,000 m^3).
  - Underlying moraine layer treated via injection of Klozur SP solution (~70,000 m^3).



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Why these Technologies used at Stockholm

- **Klozur® Persulfate: Powerful oxidant capable to degrading full suite of contaminants found at site (MGP residuals and PAHs)**

- **Clay unit - ISCO-ISS:**
  - Soil mixing more effective for establishing contact between the reagents and contaminants in the low permeability soils
  - ISS increases clay compressive strength to allow for above ground construction of roads and buildings

- **Moraine layer – Injection of persulfate solution:**
  - Injection strategy more effective in more permeable soils
  - Rocks prevents soil mixing

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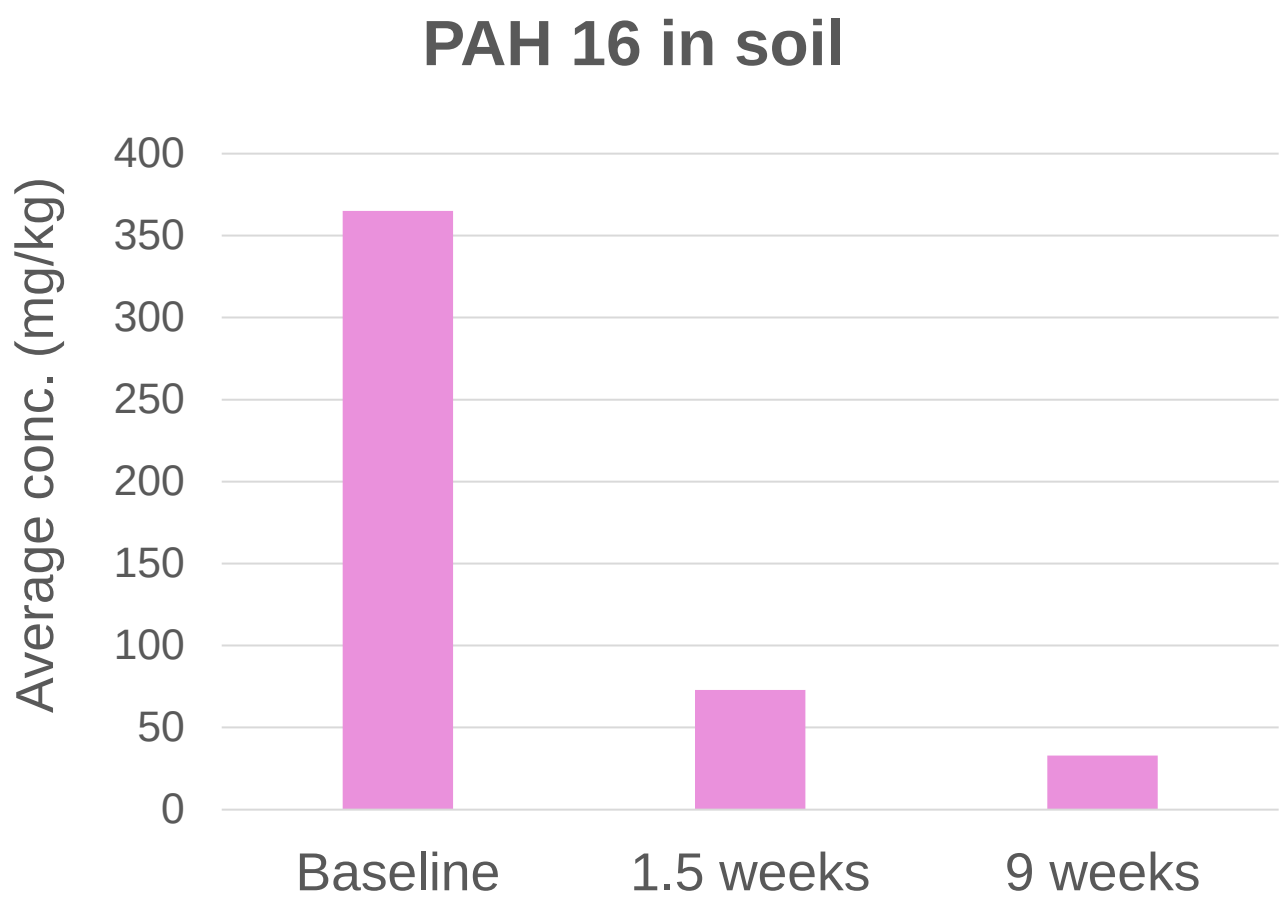
Full-Scale Installation of ISCO/ISS to Clay Unit

Dose applied:

- Cement: 4-8 wt%
  - Higher dosing for areas with roads.
- Klozur SP: 1.8 wt%
- Water: 4-7 wt%

Full-Scale Results – Contaminant Destruction – PAH 16



PAH 16 concentrations:

Baseline:

- Average: 365 mg/kg
- Range: 1-2700 mg/kg

9 weeks post treatment:

- Average: 33 mg/kg
- Range: 5-120 mg/kg
- All samples below remedial goal of 250 mg/kg

Reference: Uppföljning av föroreningshalter i pelare efter stabilisering och kemisk oxidation av lera (ISS-ISCO), Golder, Jan 2022

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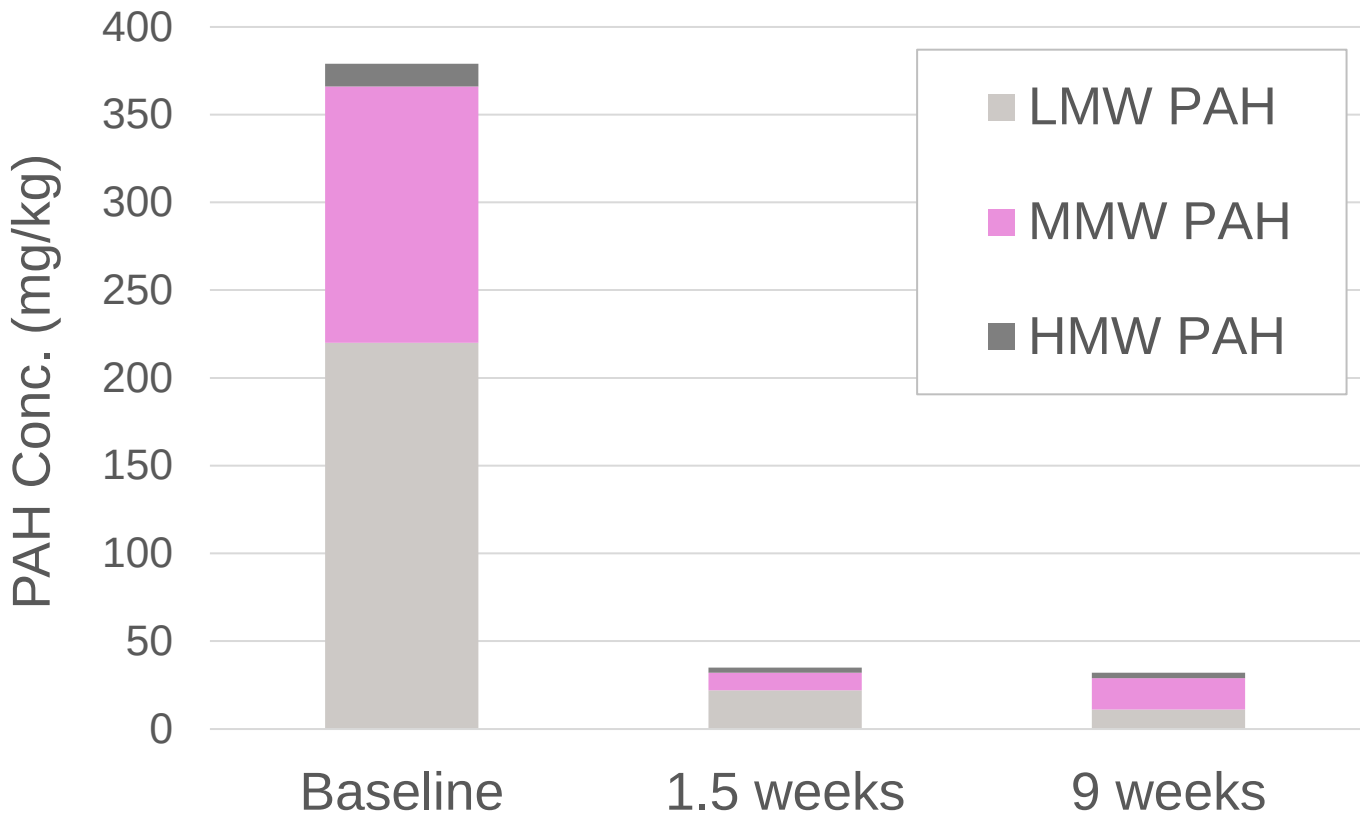
Full-Scale Results – Contaminant Destruction



Higher % reduction in lower molecular weight PAH fractions.

Reduction in PAH conc. following 9 weeks:

- ~95% reduction in PAH-L
- ~90% reduction in PAH-M
- ~80% reduction in PAH-H

Reference: Uppföljning av föroreningshalter i pelare efter stabilisering och kemisk oxidation av lera (ISS-ISCO), Golder, Jan 2022

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Stockholm Site Case Study Summary

- Phases thus far have been a success:
  - ISCO-ISS portion was completed between March 2021 and April 2022 has achieved goals for less than proposed budget
  - Injection portion initiated in January 2022 and completed in February 2023:
    - Monitoring is currently ongoing
    - Preliminary results are very positive – most cells met remedial targets after the first application round, only a few cells needed a second injection round

- More work to come:
  - New area using injection strategy has already started in 2023
  - New ISCO-ISS area is anticipated for 2024, although that area is still being characterized

Working with Evonik's Soil and Groundwater Group since 2017; City of Stockholm has successfully developed strategies that address the needs and concerns at their site.

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ISCO-ISS Successfully Remediates PCE DNAPL at Former Dry Cleaner in Residential Neighborhood

Location: Former Kent Cleaners, Lansing, Michigan

Lead Consultant: Hamp Mathews & Associates

Contractor: Lang Tool

Regulator: EGLE

Contaminants: PCE (up to >1,000 mg/kg)

Goal: Reduce vapor intrusion risk

Treatment volume: 12,354 cy soil,

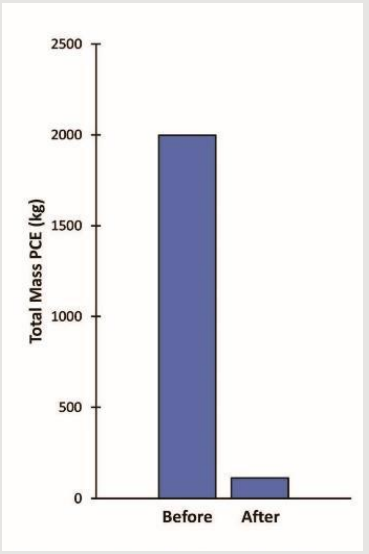
Reagent Dose (w/w soil):

- Klozur SP: 1-2% (440K lbs)
- Portland Cement: 4% (1.6M lbs)

Results

- 94% reduction in PCE mass
- UCS of 25-50 psi (Day 60)
- Underlying GW conc. reduced by 90 to 99%

Saved client >$2.5 Million compared to excavation estimate



ISCO-ISS Successfully Remediates Petroleum Contaminated Soils for Site Redevelopment

Location: Bolzano, Italy

Lead Consultant: Ladurner Bonifiche S.r.l.

Contaminants: Petroleum Hydrocarbons

Goals: Combination of contaminant reduction, soil stability targets, limit soil bulking

Treatment volume: 3,500 m^3, from 3-8 m bgs

Dose (w/w soil):
- Klozur SP: 0.7-1%
- Portland Cement: 4-8%

Installation: 556 columns w. large diameter auger

ISCO Results & Goals:
- Benzene: 100% samples < 2 mg/Kg
- TPH (C4-C12): 100% samples <250 mg/Kg
- TPH (C13-C40): Over 50% samples <750 mg/Kg

ISS / Geotechnical Goals Achieved:
- UCS: 30 to 70 psi
- Permeability: 2.8 x 10^{-6} to 7.3 x 10^{-7} cm/sec

Less than 15% soil bulking

ISCO-ISS Successfully Remediates TCE Contaminated Soils Achieving Clean-Up Goals in One Week

Site: Former Industrial Site / Redevelopment

Location: Västerås, Sweden

Contaminants: TCE source area (up to >500 mg/kg)

Lead Consultant: Wescon

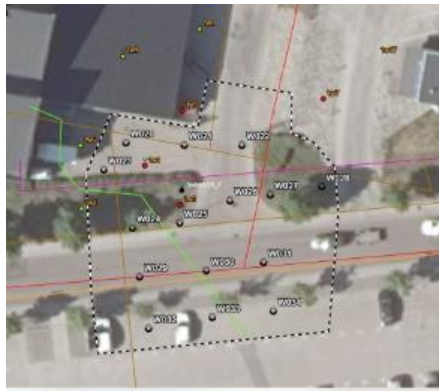
Soil Mixing Contractor: SMG

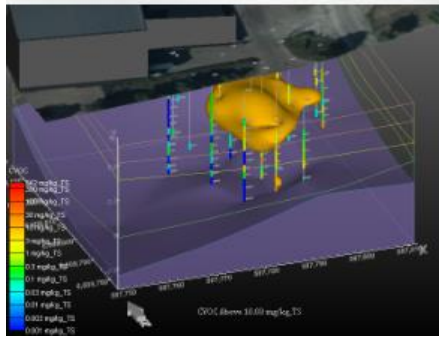
Goal: Reduce TCE mass by 50%

Treatment volume: 600 m^3 soil

Reagent Dose (w/w soil):

- Klozur SP: 0.8% (8 tons)
- Portland Cement: 7% (70 tons)





Results:

- Goals reached after 1 week and confirmed after 5 weeks
- The stability of the soil was improved
- Infrastructure was minimally affected

Significant cost savings (~70%) relative estimated excavation and disposal costs

	Baseline: CVOCs before treatment	Results: CVOCs 5 weeks post treatment	Reduction
Maximum conc (mg/kg)	542	16.5	97%
Average conc (mg/kg)	45	4.5	90%
Estimated CVOC mass (kg)	35-40	7-9	74 to 83%

Thank You!

Questions?

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