Remediation of Soil & Groundwater Contaminated with Divalent Metals

Understanding Metal Sulfide Precipitation Chemistry

MetaFix® | GeoForm® ER | GeoForm® Soluble

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4 February 2026
Soil & Groundwater Remediation
Evonik Corporation

Leading Beyond Chemistry

Perspective for the Presentation

- The goal of our meeting today is to review some of the factors important in selecting an effective approach to remediation of soil and groundwater contaminated with *divalent heavy metals*.
- This presentation has been put together under the assumption that some or even many attendees are newer in the field of environmental remediation and are not be familiar with treatment methods for metals in soil and groundwater.
- In keeping with that assumption, I will be covering some basics including definitions of mechanisms involved in removal of dissolved metals, understanding phase diagrams, iron and sulfide chemistry, and biogeochemical processes.
- I will not spend too much time on case studies. Instead, I will present three brief project snapshots. If you want more detailed case studies, please reach out to me or your regional Evonik representative.

"What factors are important in the design of an effective approach to treatment of divalent heavy metals?"

Agenda

Basics

- Definitions: Adsorption, Precipitation, Coprecipitation, Occlusion
- Heavy Metal Precipitatation (sulfides, carbonates, hydroxides)
- Natural Precipitation of Metal Sulfides

Treatment Mechanisms

- Required Conditions for Effective Treatment
- Importance of Eh and pH
- Precipitate Stability Regions (phase diagrams)

MetaFix® and GeoForm® Reagents for Metals Treatment

- Composition
- Treatment Mechanisms for Divalent Metals
- Reducing Susceptibility to Rebound

Representative Performance Data & Project Snapshots

- Bench-scale Treatability Results
- Trench-type PRB for Treatment of Three Metals
- Injected PRB to Treat Divalent Metals and cVOCs
- Soil Mixing to Remove TCLP Mercury

Questions & Answers

Credit: U.S. Geological Survey

Processes & Mechanisms in Removal of Dissolved Metals

Precipitation: Conversion of a soluble metal into an insoluble form by addition of a chemical to create a supersaturated environment.

- An example of this is conversion of aqueous lead (Pb^{+2}) into lead sulfide (galena) by enriching the contaminated environment with sulfide (HS^-).

Co-precipitation: A form of adsorption in which soluble species are incorporated within a precipitating solid phase via chemical, physical, Van der Waals, or by dipole-dipole interactions.

- An example is removal of dissolved zinc by its coprecipitation with sulfide and iron to form sphalerite [(Zn,Fe)S].

Adsorption: Binding of a soluble species on the surface of a solid, driven by surface forces/charges.

- An example is removal of tetraethyl lead or methyl mercury by activated carbon.

Occlusion: Encasement of metals by formation of insoluble/low solubility layers of mineral precipitates.

- An example is physical protection of newly precipitated CdS (greenockite) species through promotion of long-term precipitation of iron sulfides.

Biogeochemical Remediation: Processes where contaminants are transformed by abiotic reactions with naturally occurring and biogenically-formed minerals (i.e., FeS_2) in the subsurface (US EPA, NAVFAC).

- Generally viewed as treatment for chlorinated organics but also applicable to removal of dissolved metals via precipitation and coprecipitation reactions. (GeoForm® reagents)

Divalent Metals

Solubility of Precipitates

Divalent Metals Precipitation Chemistry

Sulfide, Carbonate, and Hydroxide Precipitation (Pb as an Example)

Sulfide Precipitation

$Pb^{2+}_{(aq)} + HS^- \longrightarrow PbS_{(s)}\downarrow + H^+$ (Solubility = 3.8 x 10^{-6} µg/L)

Carbonate Precipitation

$Pb^{2+}_{(aq)} + HCO_3^- \longrightarrow PbCO_{3\,(s)}\downarrow + H^+$ (Solubility = 7.0 µg/L)

Hydroxide Precipitation

$Pb^{2+}_{(aq)} + 2OH^- \longrightarrow Pb(OH)_{2\,(s)}\downarrow$ (Solubility = 2,100 µg/L)

Divalent Metals

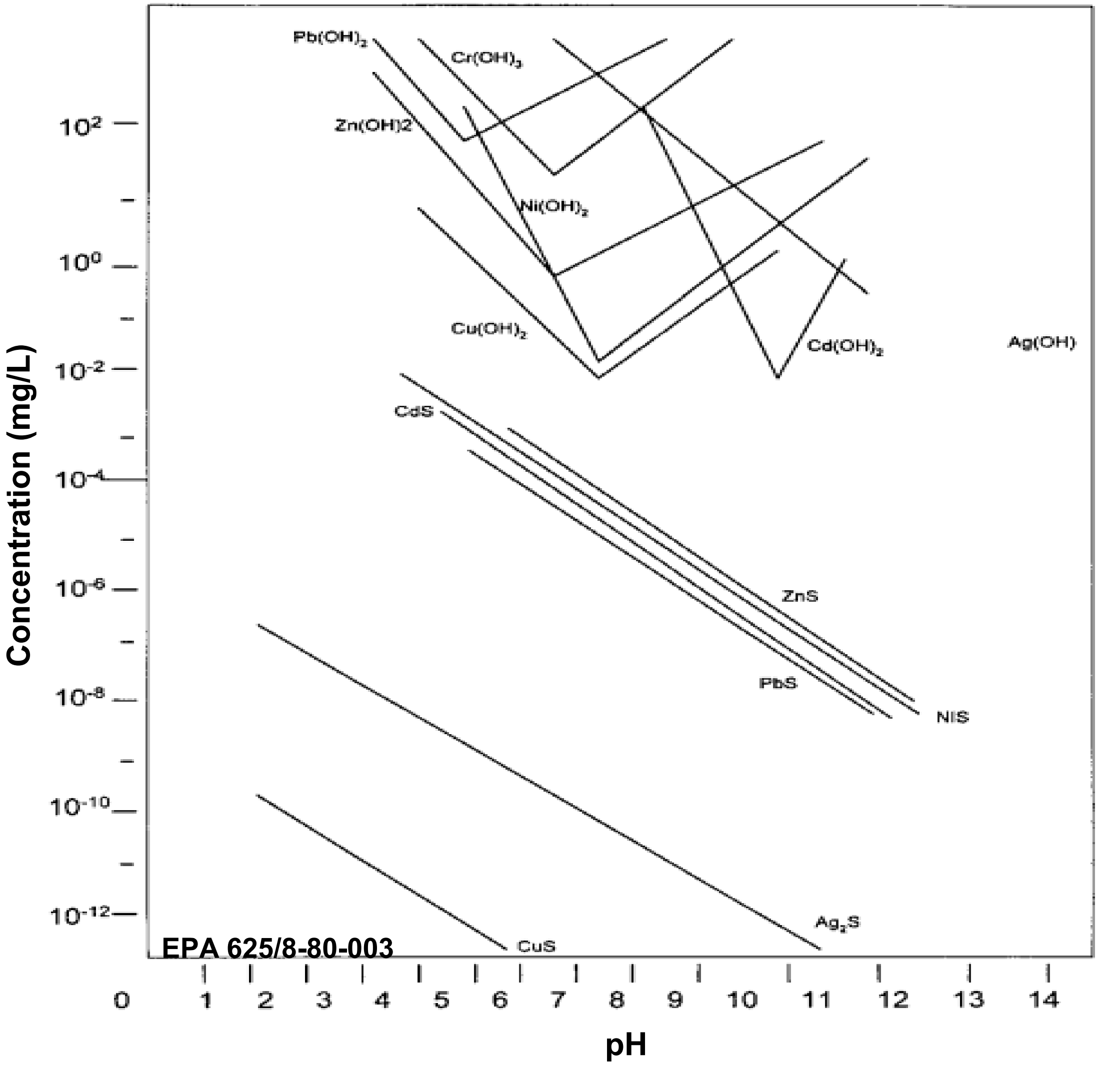
Metal sulfide solubilities are much lower than either metal carbonates or metal hydroxides

Metals	**Dissolved Species** *(of Significance)*	**Groundwater Standards**[1,2,3] (µg/L)	**TCLP** (mg/L)	**Sulfide Solubility** (µg/L)	**Carbonate Solubility** (µg/L)	**Hydroxide Solubility** (µg/L)
Cadmium	Cd^{2+}, organics	5.0[1]	1.0	6.7×10^{-7}	0.1	0.023
Cobalt	Co^{2+}, hydroxides	2.0[2]	-	1.0×10^{-5}	-	220
Copper	Cu^{2+}, organics	1,300[3]	-	5.8×10^{-15}	-	22
Lead	Pb^{2+}, organics, hydroxides	15[3,5]	5.0	3.8×10^{-6}	7.0	2,100
Manganese	Mn^{2+}, hydroxides	500[4]	-	2.1	490	1,200
Mercury	Hg^{2+}, organics, hydroxides	2.0[1]	0.2	9.0×10^{-17}	39	0.39
Nickel	Ni^{2+}, organics	100[1]	-	6.9×10^{-5}	190	6.9
Zinc	Zn^{2+}, organics	5,000[4]	-	2.3×10^{-4}	0.7	1,100

1: MCL, 2: NJDEP, 3: US EPA Action Level, 4: SMCL, 5: Canadian MCL and WHO Guideline is 10 µg/L.
Note: Due to time limitation, we are not addressing molybdenum, barium, strontium, or bromine.

Divalent Metals

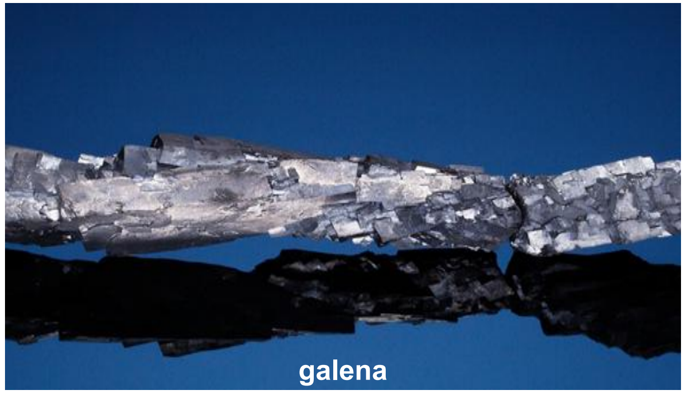
Influence of pH on Solubilities of Metal Hydroxides and Metal Sulfides



EPA 625/8-80-003

Notes

- Solubilities of most metal hydroxides are several orders of magnitude higher than their metal sulfide.
- Solubilities of some metal hydroxides are higher than their MCL.
- The influence of pH on solubility is much greater for the metal hydroxides than for the metal sulfides
- The pH range of minimum solubility for metal hydroxides is very narrow.
- Implications for rebound?



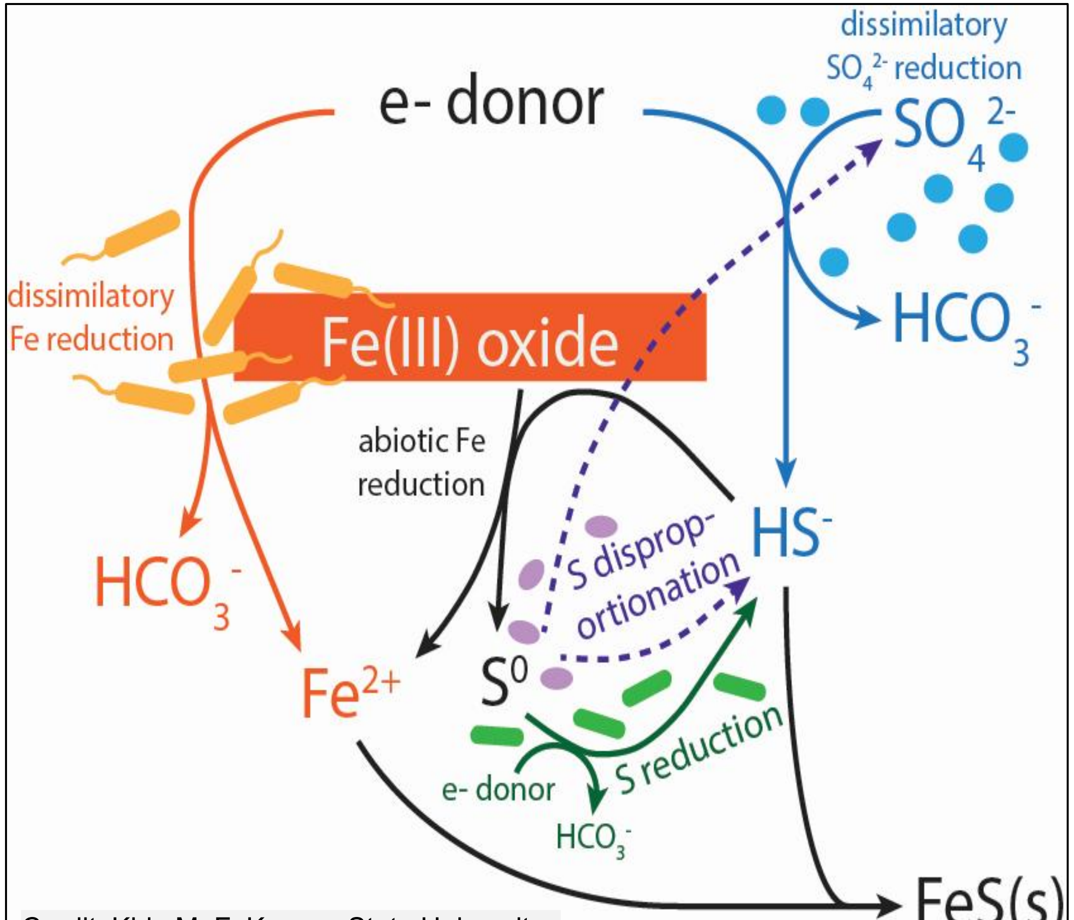
galena

cerussite

Microbial Sulfate Reduction and Metal Sulfide Precipitation

Important Natural Processes in Most Environments

- Biogenic production of iron sulfides is a major natural process in many environments.
- The process is significant where there is an adequate supply of metabolizable organic carbon, sulfate, and iron-bearing minerals.
- Estimated that 150,000,000 tons of sulfate are reduced to sulfide worldwide each year[1].
- Most of this total is by microbial sulfate reduction because abiotic sulfate reduction is very, very, slow.
- Generation of this huge mass of sulfide results in annual production of about 5,000,000 tons of FeS_2 (pyrite) in sediments[1].
- Simultaneous with precipitation of this mass of pyrite many other metals will be precipitated as metal sulfides (galena, greenockite, chalcocite) or iron-metal sulfides (chalcopyrite, $CuFeS_2$).
- HS^- is a reactive electron donor at surfaces of ferric iron minerals and can increase the release of Fe^{2+}.



Credit: Kirk, M. F. Kansas State University

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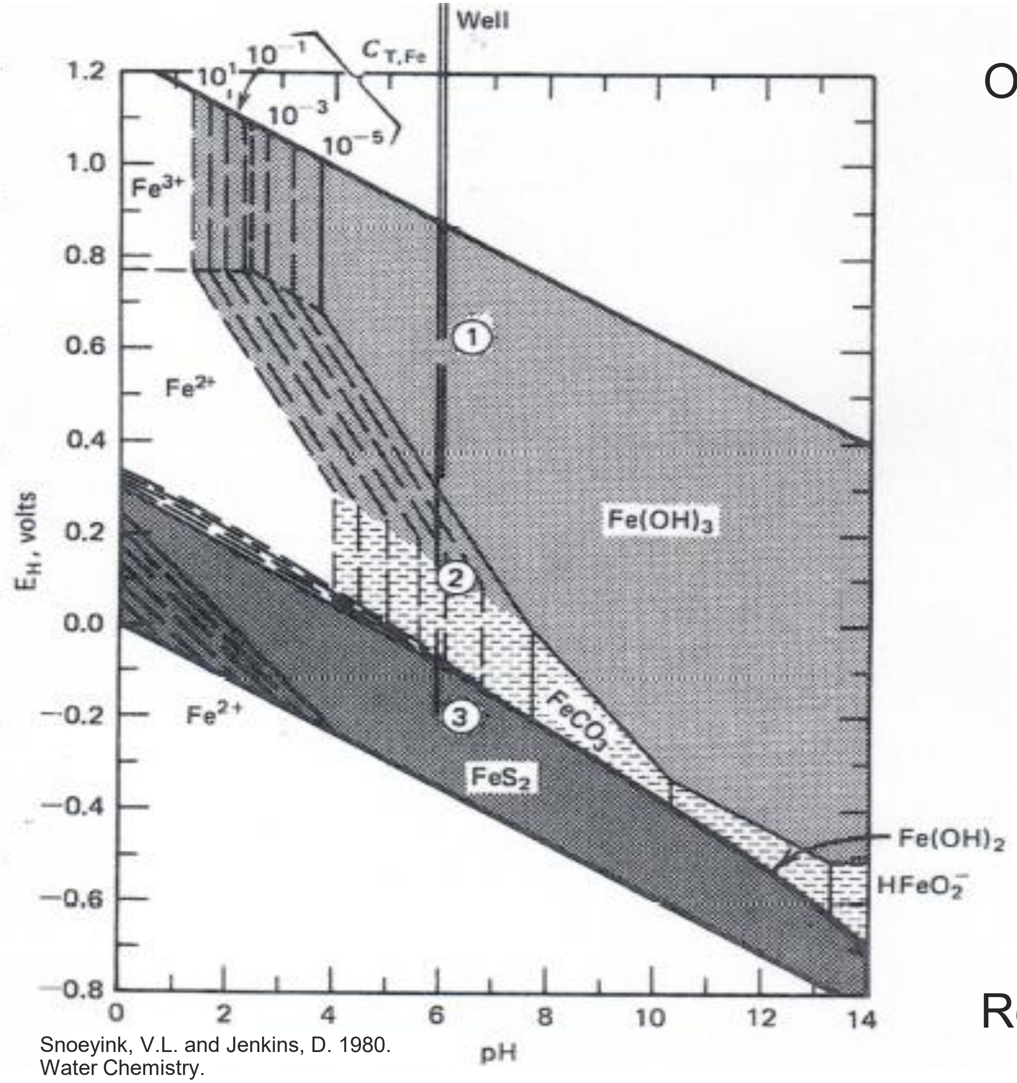
1. Rickard, D. and Luther, G.W. III. 2007.

Divalent Metals

Stability Regions for Sulfide, Carbonate, and Hydroxide Precipitates

Understanding Eh/pH Phase Diagrams

Using Iron as an Example



Snoeyink, V.L. and Jenkins, D. 1980.
Water Chemistry.

Oxidizing

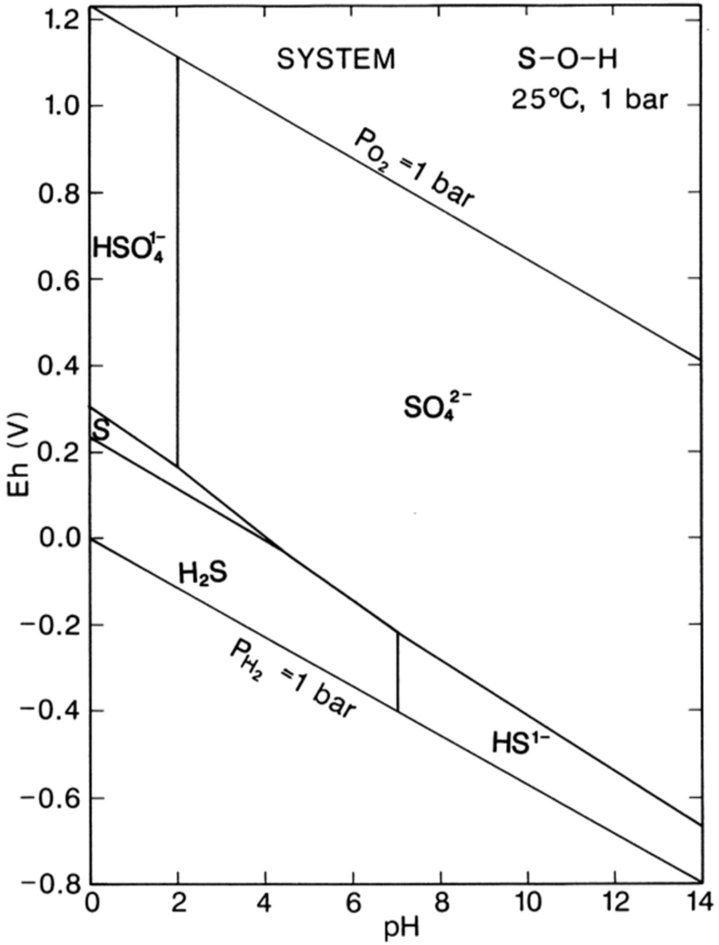
Reducing

Aqueous Iron/Sulfur System as Influenced by pH and Eh

- Each region shows the most thermodynamically stable and therefore likely most abundant species under specific Eh/pH conditions
- Horizontal lines indicate electron transfer.
- Vertical lines indicate proton transfer (acid acid-base equilibrium).
- Diagonal lines indicate a redox equilibrium involving hydrogen or hydroxide ions.
- Note that total iron concentration influences the pH at which iron will begin to precipitate as $Fe(OH)_3$, $Fe(OH)_2$, or $FeCO_{3.}$
- Higher [soluble iron] ⟶ precipitation begins at a lower pH
- Phase diagrams provide no information about kinetics of formation or dissolution.

Sulfide Chemistry in Soil & Groundwater

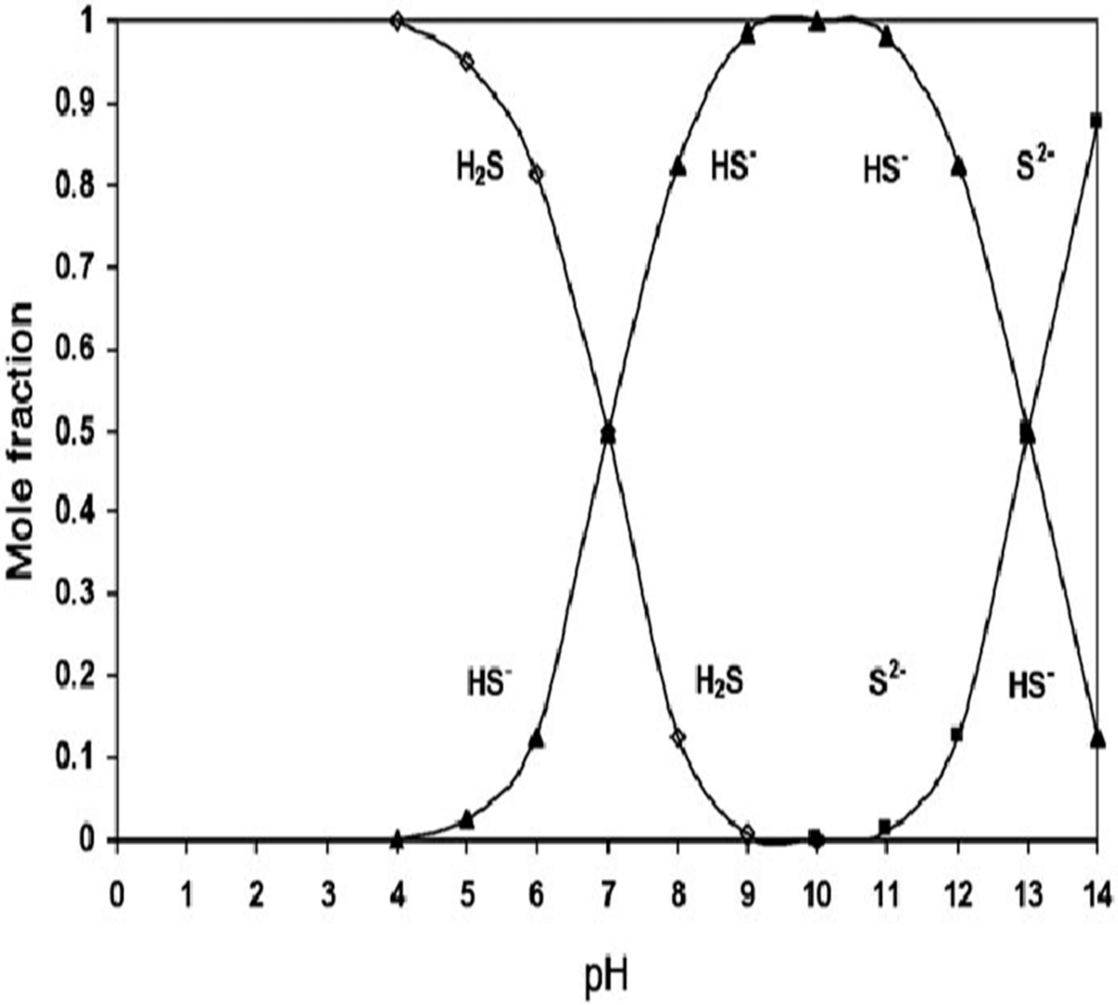
Sulfur Speciation with pH and Eh: Sulfidology



Conditions: total dissolved S = 10^{-3} molal

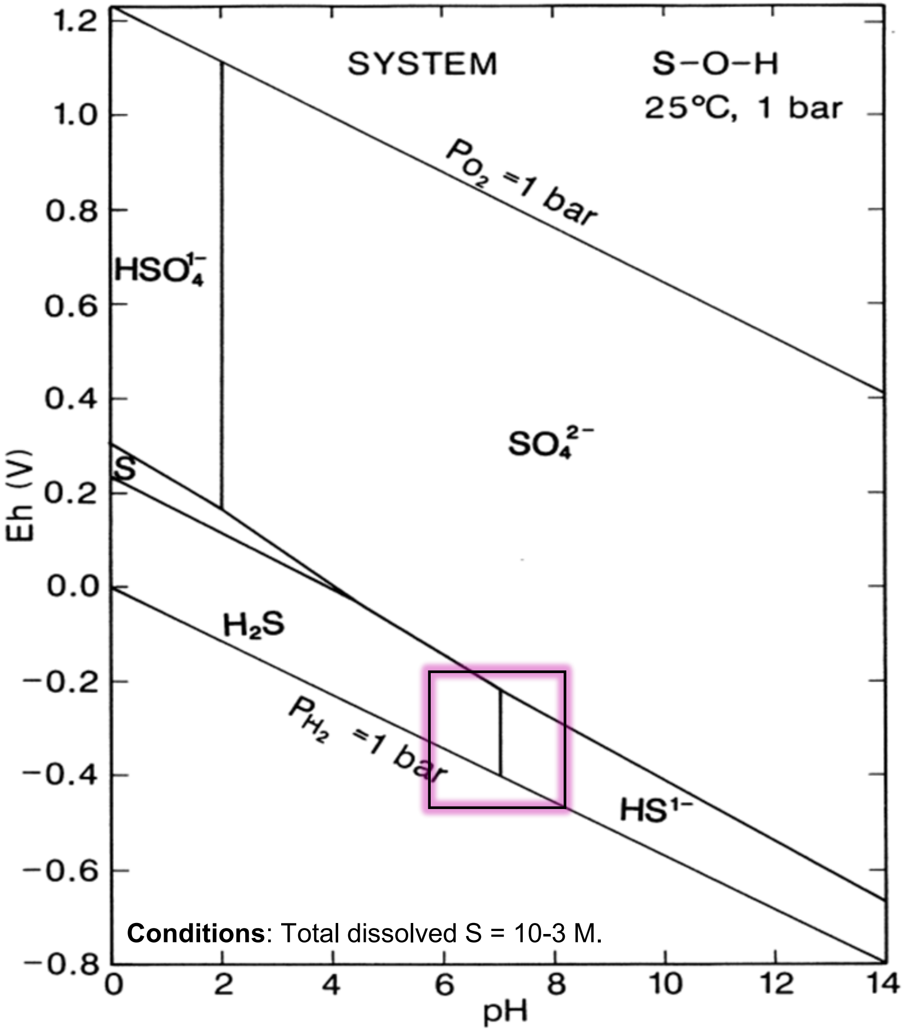
Notes

- Below neutral pH the dominant form is volatile H_2S (can be lost)
- To preserve free sulfide pH should be maintained above 6.0
- Note that HS^- is more reactive than H_2S and readily serves as an electron donor.
- Hence, the formation of desired insoluble metal sulfides is more reliable when pH is in the range that favors HS^-.
- Should target near-neutral pH and solidly reducing Eh.



Sulfide Chemistry in Soil & Groundwater

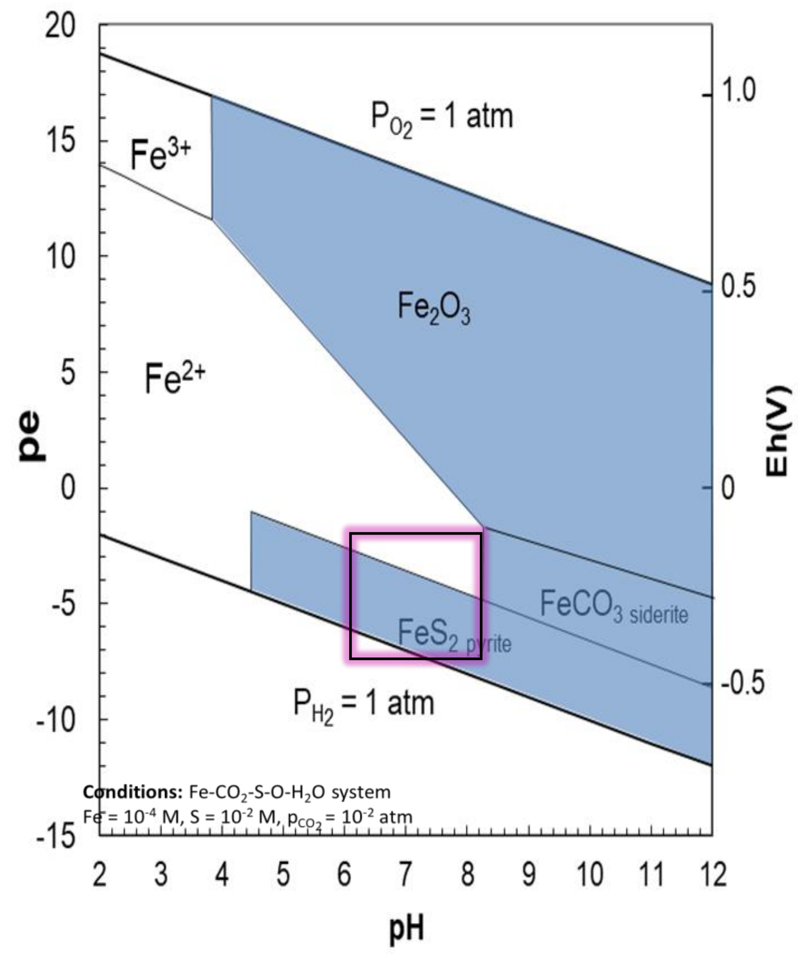
Sulfur and Iron Stability Regions



Conditions: Total dissolved S = 10-3 M.

Notes

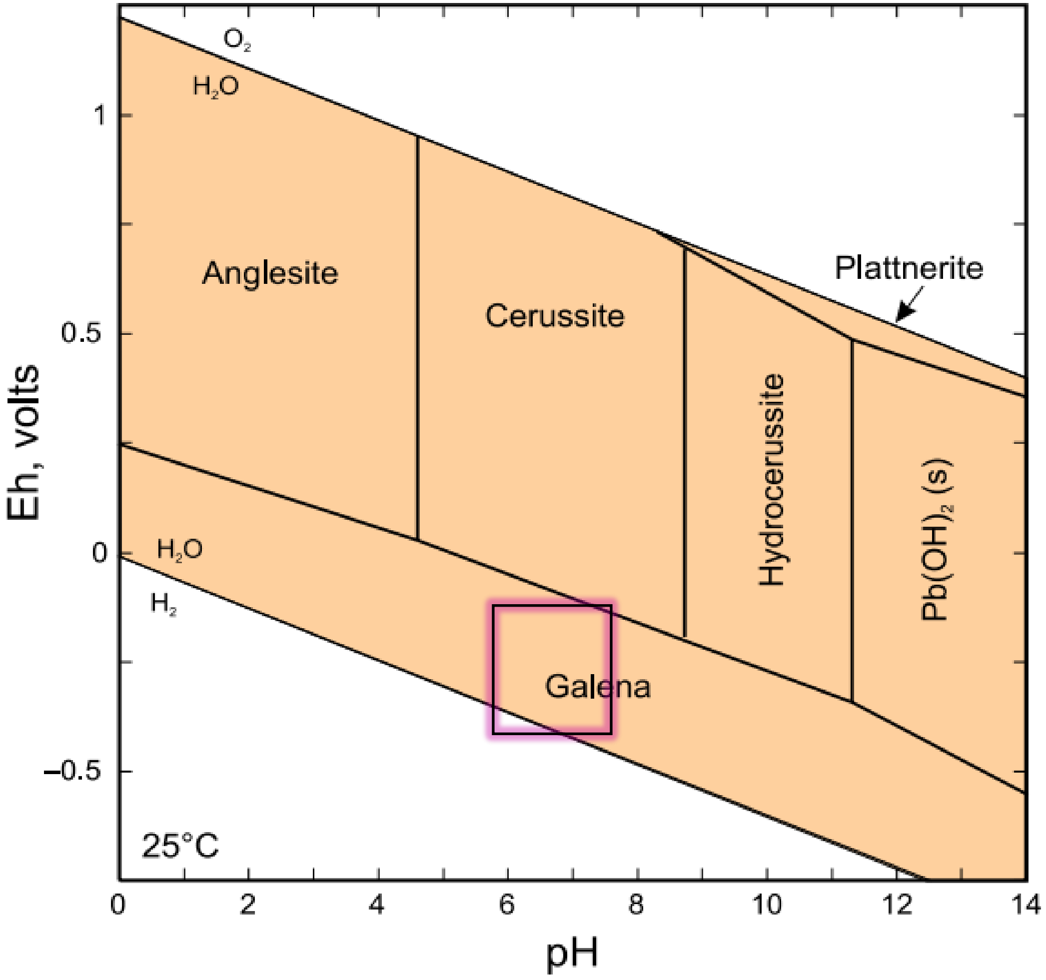
- Compare pH/Eh regions in which HS^- and FeS_2 are stable.
- Moderately to highly reducing Eh.
- Recall that HS^- is substantially more reactive than H_2S.
- This Eh/pH region is also favorable to activity of sulfate reducing bacteria (SRB) required to ensure good conversion of SO_4^{2-} to HS^-.
- Good availability of phosphorus when pH between 6.0 and 7.5.
- Phosphorus availability essential to good activity of SRB.



Conditions: $Fe\text{-}CO_2\text{-}S\text{-}O\text{-}H_2O$ system
$Fe = 10^{-4}$ M, $S = 10^{-2}$ M, $p_{CO_2} = 10^{-2}$ atm

Lead Stability Regions with Carbonate & Sulfide

Treatment Mechanisms for Metals



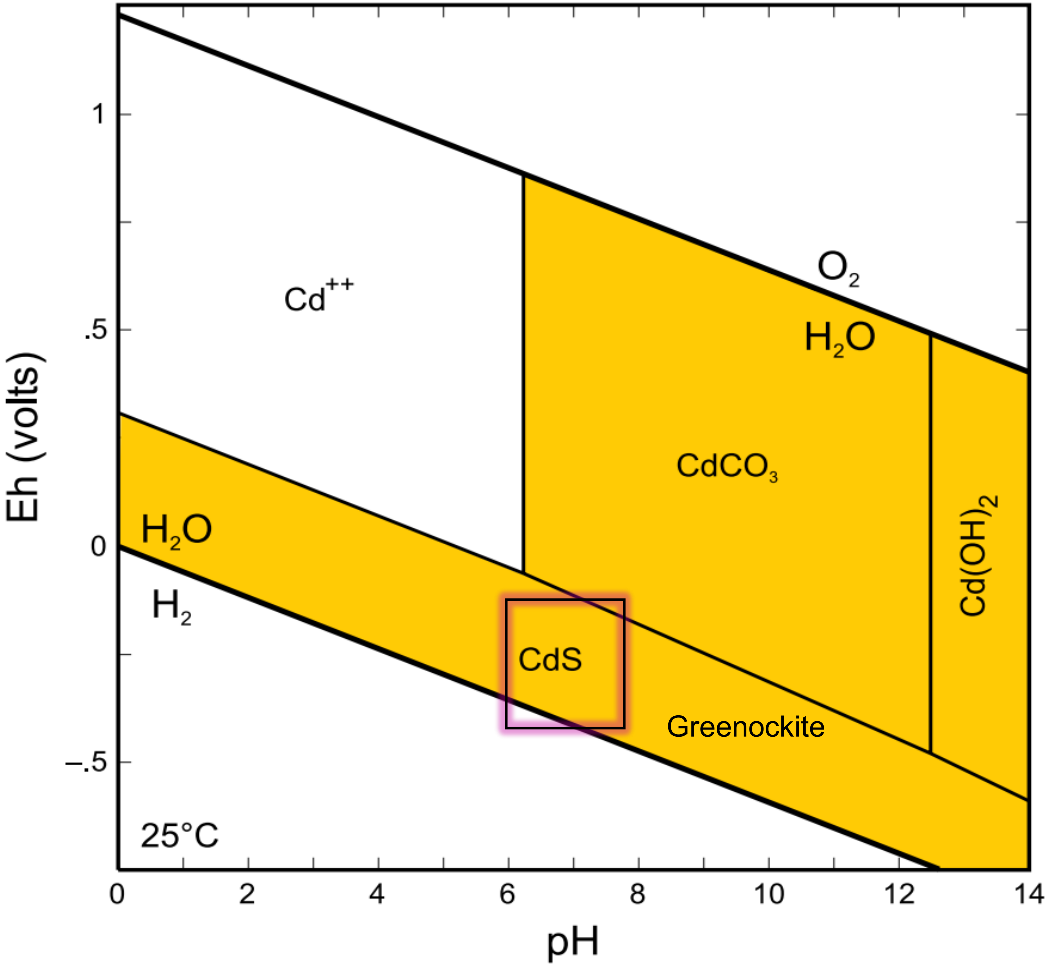
Conditions: Total Pb = 10^{-5} molal, Total C = 10^{-3} molal, Total S = 10^{-3} molal, Organo-lead species are not considered. **From: EPA/600/R-07/140**

Notes

- Lead carbonate (cerussite, hydrocerussite) has a broad stability field and low solubility above pH = 8.0, but becomes increasingly soluble, even above the MCL, as pH becomes more acidic.
- Lead sulfide (galena) has very low solubility, well below the MCL, regardless of pH.
- Lead hydroxide is only stable above pH = 11.5.
- Lead sulfate (anglesite) is broadly stable at low pH and oxidizing conditions but has solubility well above the MCL.
- Substantial portion of total dissolved lead is often present in organometallic forms where dissolved organic carbon is high.

Cadmium Stability Regions with Carbonate & Sulfide

Treatment Mechanisms for Metals



Conditions: Total Cd = 10^{-5} molal, Total C = 10^{-3} molal, Total S = 10^{-3} molal, Organo-cadmium species are not considered. **From: EPA/600/R-07/140**

Notes

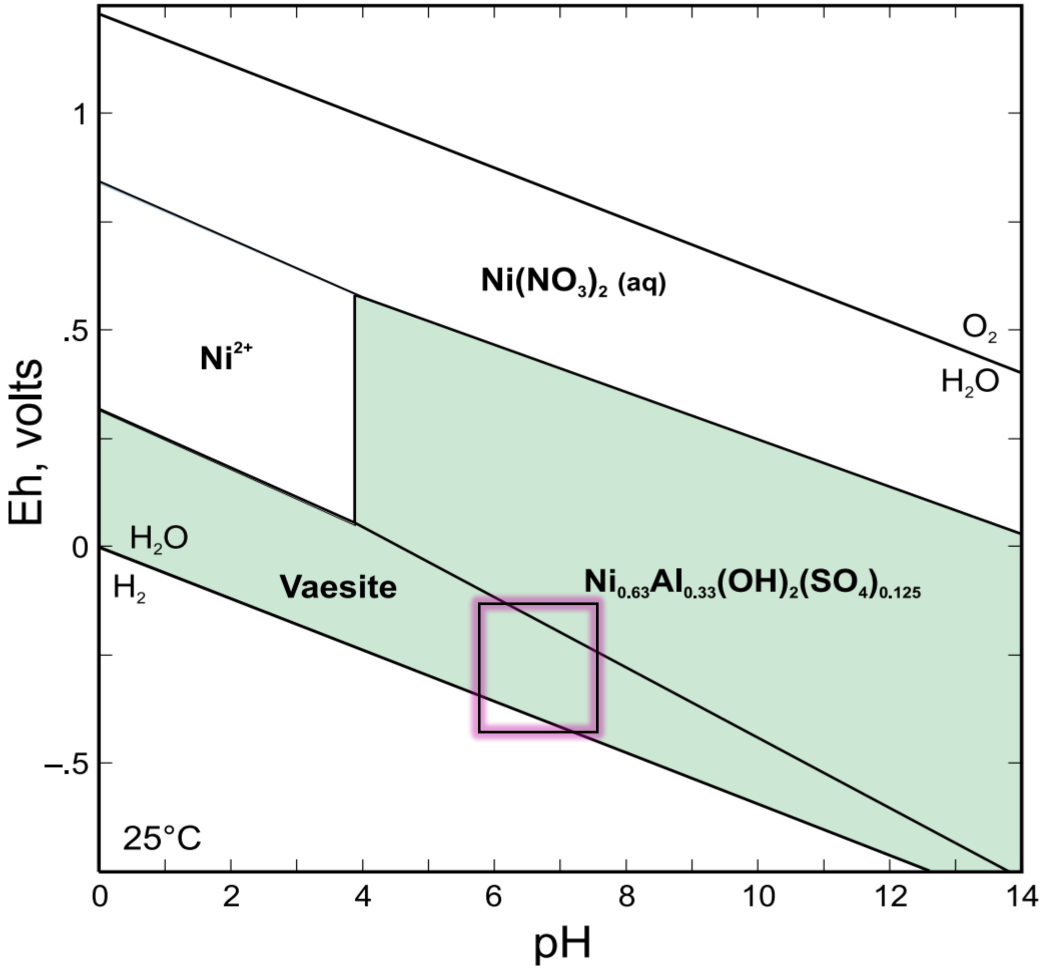
- Divalent cadmium (Cd^{2+}) is the dominant soluble form in most soil and groundwater up to pH of about 9.0 when carbonate and sulfide are not present in substantial concentrations.
- Cadmium carbonate (otavite) has a broad stability field and low solubility above pH = 7.0, but becomes increasingly soluble, even above the MCL, as pH becomes more acidic.
- Cadmium sulfide (greenockite) is stable over the range of pH and Eh conditions typical of groundwater (i.e., pH between 5.5 and 8.5, Eh reducing) and has solubility well below the MCL.
- Cadmium hydroxide has very low solubility but is stable only above pH = 12.
- Substantial dissolved cadmium can be present in organometallic forms where dissolved organic carbon is high.


Otavite, Oshikoto, Namibia


Greenockite, Tyrol Austria

Nickel Stability Regions with Carbonate & Sulfide

Treatment Mechanisms for Metals



Conditions: Total Pb = 10^{-5} molal, Total C = 10^{-3} molal, Total S = 10^{-3} molal, Organo-lead species are not considered. **From: EPA/600/R-07/140**

Notes

- Nickel carbonate is not shown as it is considered to be unstable and has solubility above the MCL.
- Nickel sulfide (vaesite, NiS_2) has very low solubility, well below the MCL, regardless of pH.
- Nickel will coprecipitate with iron hydroxides/oxyhydroxides and iron sulfides.
- Nickel can also be incorporated to layered double hydroxide minerals (garnierite phyllosilicates group) as they are formed.

Vaesite, Italy, credit Gianfranco Ciccolini

Vaesite, DR Congo, credit Rolfe Luetcke

Treatment Approach for Divalent Metals

MetaFix® and GeoForm® Reagents

for Precipitation of Metal Sulfides

Treatment Approach for Divalent Metals

Required Conditions and How to Establish Them

Generate strong, long-lasting reducing conditions:

- Supply readily metabolized organic carbon substrate and nutrients
- Longevity is important (processed plant fiber, lecithin)

Ensure adequate supply of free sulfide:

- Supply both rapidly and slowly soluble sulfate salts
- Ensure adequate supply of phosphorus to support activity of sulfate-reducing bacteria

Ensure adequate supply of ferrous iron:

- Supply soluble ferrous iron salt
- Release ferrous iron from aquifer solids by regulating pH and Eh
- Promote continued release of ferrous iron from ZVI (anaerobic fermentation produces VFAs at ZVI particle surfaces)

Maintain pH in the near-neutral range:

- Use appropriate reagents to increase or decrease pH subject to site conditions
- Prevent acidification by balancing acidity from VFA production with alkalinity from ZVI corrosion

MetaFix® and GeoForm® Reagents

Attribute	MetaFix® I-3	MetaFix® I-6A	MetaFix® I-7A	GeoForm® ER	GeoForm® Soluble
Reactive Minerals	✓	✓	✓	-	-
Microscale ZVI	✓	✓	✓	✓	**Optional (5.0 µm)**
Carbonate	-	✓	-	-	-
Activated Carbon	-	-	✓	-	-
Slow-release, nutrient-rich organic carbon	-	-	-	✓	✓
Quick-release soluble organic carbon	-	-	-	✓	✓
Sulfate	-	-	-	✓	✓
Ferrous Iron	-	-	-	✓	✓
pH Buffer	-	-	-	✓	✓

MetaFix® and GeoForm® Reagents

Treatment Mechanism for Divalent Metals

- ✓ Slowly-metabolized fibrous organic carbon and lecithin in GeoForm® reagents ensure long-lasting microbial growth and development of a large biomass to generate reduced conditions
- ✓ ZVI as a chemical reducing agent and long-lasting supply of ferrous iron
- ✓ Blend of soluble sulfate salts ensures a long-lasting supply of dissolved sulfate to be reduced to the free sulfide needed in reduction and precipitation reactions and formation of low solubility metal sulfides.
- ✓ High surface area reactive minerals (sulfides, oxides) in MetaFix® provide very slowly released sulfide and ferrous ion
- ✓ Activated carbon in MetaFix® I-7A enables removal of organometallic compounds (methyl mercury, tetraethyl lead).
- ✓ VFAs produced during anaerobic fermentation of processed plant fiber and phospholipids will (a) balance alkalinity from ZVI to prevent passivation of ZVI surfaces, (b) increase flow of ferrous iron by increasing ZVI corrosion rate, and (c) ensure adequate supply of simple carbon compounds for SRB.
- ✓ Phosphate essential for SRB is a structural component of GeoForm® reagents.
- ✓ The strong, long-lasting, treatment conditions created by combining MetaFix® + GeoForm® reagents to promote occlusion of newly-precipitated metals and minimize rebound.

Bacterial Sulfate Reduction

In Situ Generation of Sulfide for Precipitation of Dissolved Metals

- Anaerobic bacteria that use inorganic sulfur compounds (i.e., sulfate, sulfite, thiosulfate) as their terminal electron acceptor during anaerobic respiration and produce sulfide (S^{2-}, HS^-, H_2S).
- This is a large, diverse, almost ubiquitous group of bacteria (40 genera, >120 species).
- Free sulfide promotes corrosion of iron and steel (bad for life of cast iron piping, but good for flow of Fe^{2+} from ZVI).
- Require *simple organic electron donors* (VFAs, ethanol, glucose).
- Steady flow of fermentation products and phosphate from metabolism of plant fiber supports growth and stability of SRB population
- It is important that sulfate must be activated by the enzyme ATP sulfurylase before reduction to sulfide can begin (*n.b., importance of bioavailable phosphate, reagent considerations*).

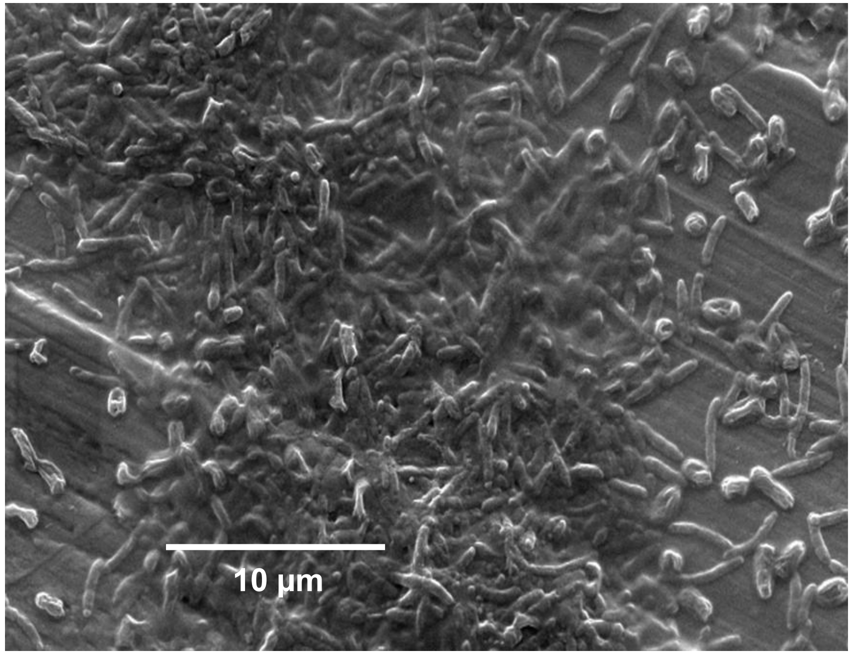
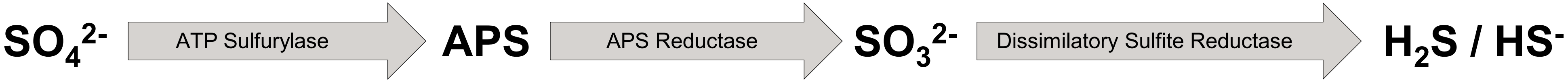


Figure 1. Mixed bacterial biofilm on iron particle.

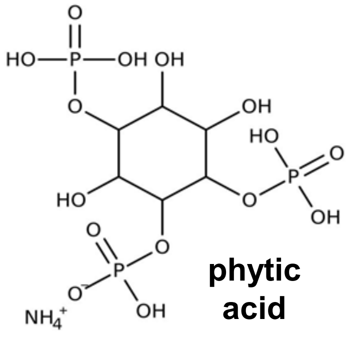


SO_4^{2-} → ATP Sulfurylase → APS → APS Reductase → SO_3^{2-} → Dissimilatory Sulfite Reductase → H_2S / HS^-

Tran, T.T.T. et al., 2021. Appl. Sci. 11, 2021

Essential Components of Effective Metal Sulfide Precipitation

Simple Organic Electron Donors, Phosphate, Sulfide, Ferrous Iron

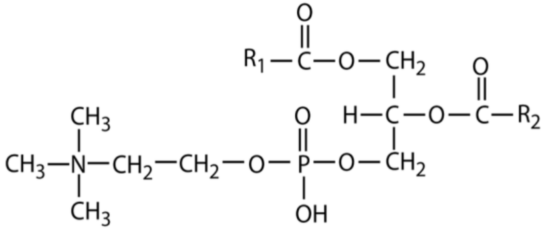


phytic acid

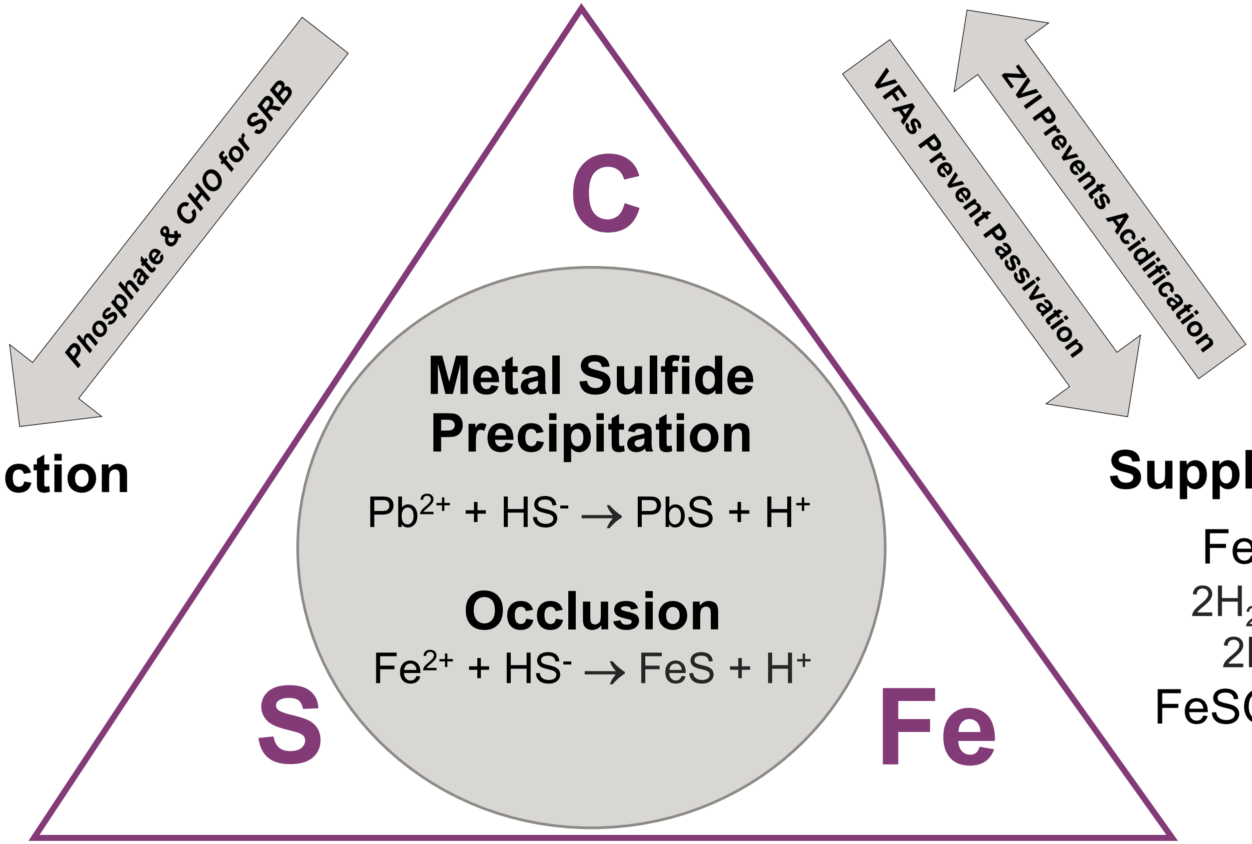
Microbial Metabolism of Organic Carbon and Phosphorus

$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2$

Phytic Acid & Phospholipids $\rightarrow H_2PO_4^- + HPO_4^{2-}$



phosphatidylcholine



Phosphate & CHO for SRB

VFAs Prevent Passivation

ZVI Prevents Acidification

C

S

Fe

Metal Sulfide Precipitation

$Pb^{2+} + HS^- \rightarrow PbS + H^+$

Occlusion

$Fe^{2+} + HS^- \rightarrow FeS + H^+$

Microbial Sulfate Reduction

$2CH_2O + SO_4^{2-} + H^+$

$\downarrow$

$HS^- + CO_2 + H_2O$

Supply of Ferrous Iron

$Fe^0 \rightarrow Fe^{2+} + 2e^-$

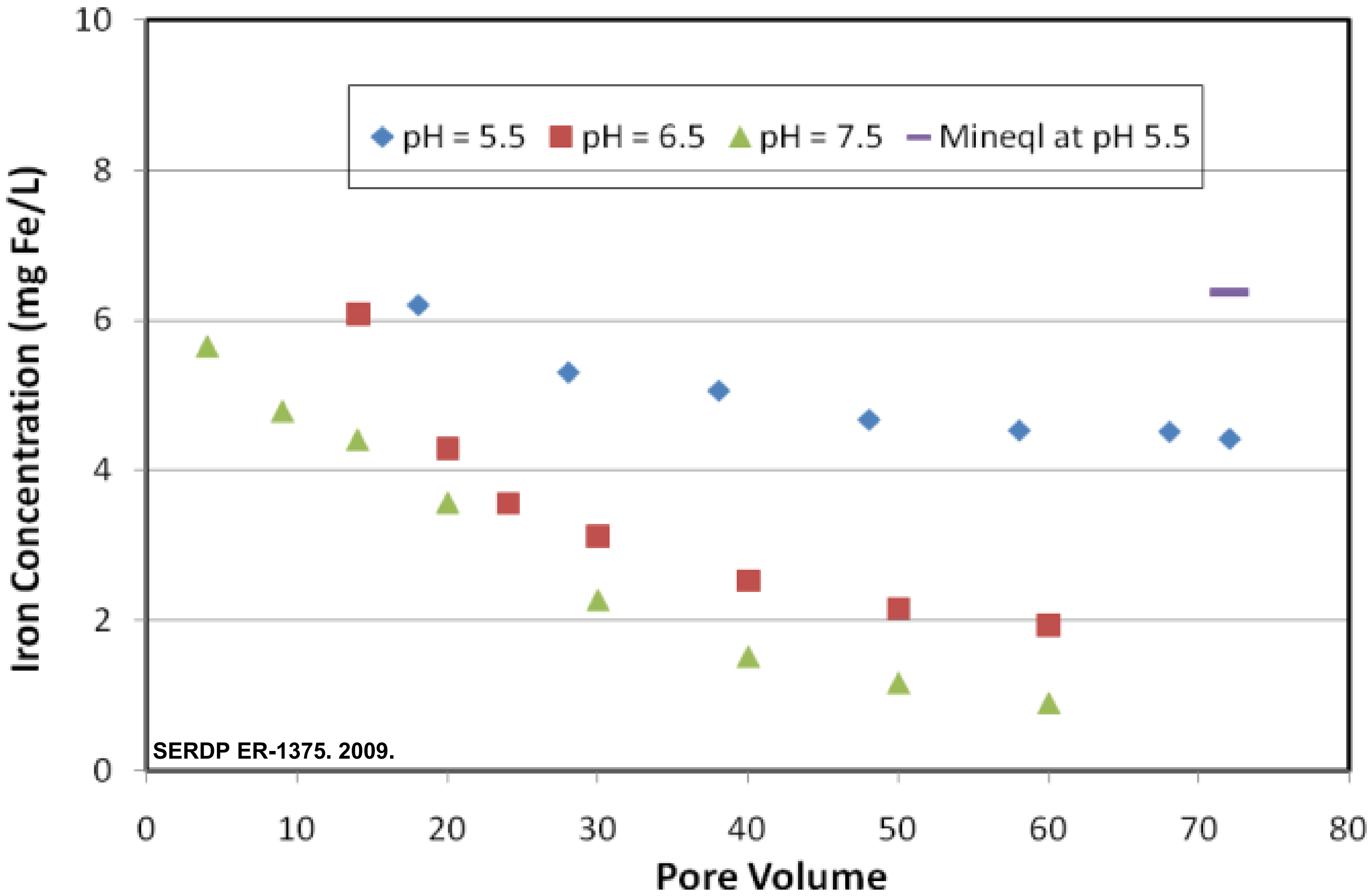
$2H_2O \rightarrow 2H^+ + 2OH^-$

$2H^+ + 2e^- \rightarrow H_{2\,(g)}$

$FeSO_4 \rightarrow Fe^{2+} + SO_4^{2-}$

Longevity of FeS Precipitates

Influence of pH on Fe^{2+} release from FeS



SERDP ER-1375. 2009.

- Up-flow columns packed with FeS coated sand (FeS = 122 mg/kg).
- Very thin layer of FeS on the sand
- Effluent Fe^{+2} between approximately 1.0 µg/L and 5.0 µg/L
- Indicates that thin layers of FeS will last for 19 years under the pH 6.5 condition and 15 cm/day GW velocity.
- About 2.4% Fe released over 60 PV.
- Provides an indication of ferrous iron and sulfide release from biogenic FeS created with GeoForm® treatment.
- Longevity of Fe^{2+} and HS^- release from iron sulfide in MetaFix® reagents should be greater than this, based on particle size.

Divalent Metals Treatment

Reducing Susceptibility to Rebound

Reducing Susceptibility to Rebound

The Importance of Redox Longevity

Observations

- Long-lasting reagents allow time for chemical and microbiological processes to work their way through many oxidized compounds present in the soil/groundwater matrix.
- During an extended reductive phase, a reservoir of redox buffers is created which enable to treatment zone to resist movement back to an oxidized state (think of this as “treatment capacity”).
- These redox buffers include (a) reduced iron phases (i.e., Fe(II) minerals), (b) biogenic iron sulfides, and (c) dead microbial cells and associated extracellular polysaccharides (“microbial necromass”).
- As layers of these redox-buffering materials are laid down on the soil or aquifer solids they protect/occlude heavy metal precipitates (i.e., divalent metal sulfides) from exposure to oxidizing conditions or acidity that could promote dissolution.
- This may be particularly important for treatment of metals in aquifers that have substantial dissolved oxygen, positive Eh conditions, or tend to drift into the acidic range.

Practical Application

- Reagents that provide long-lasting reducing conditions can reduce the probability of re-solubilization of metals/metalloids that have been removed by adsorption or precipitation.
- Reagents that promote long-lasting formation of iron sulfides can add another degree of resistance to re-solubilization (rebound).

Representative Performance

Bench-scale Treatability Results

Up-flow Columns

Packed with Site Soil

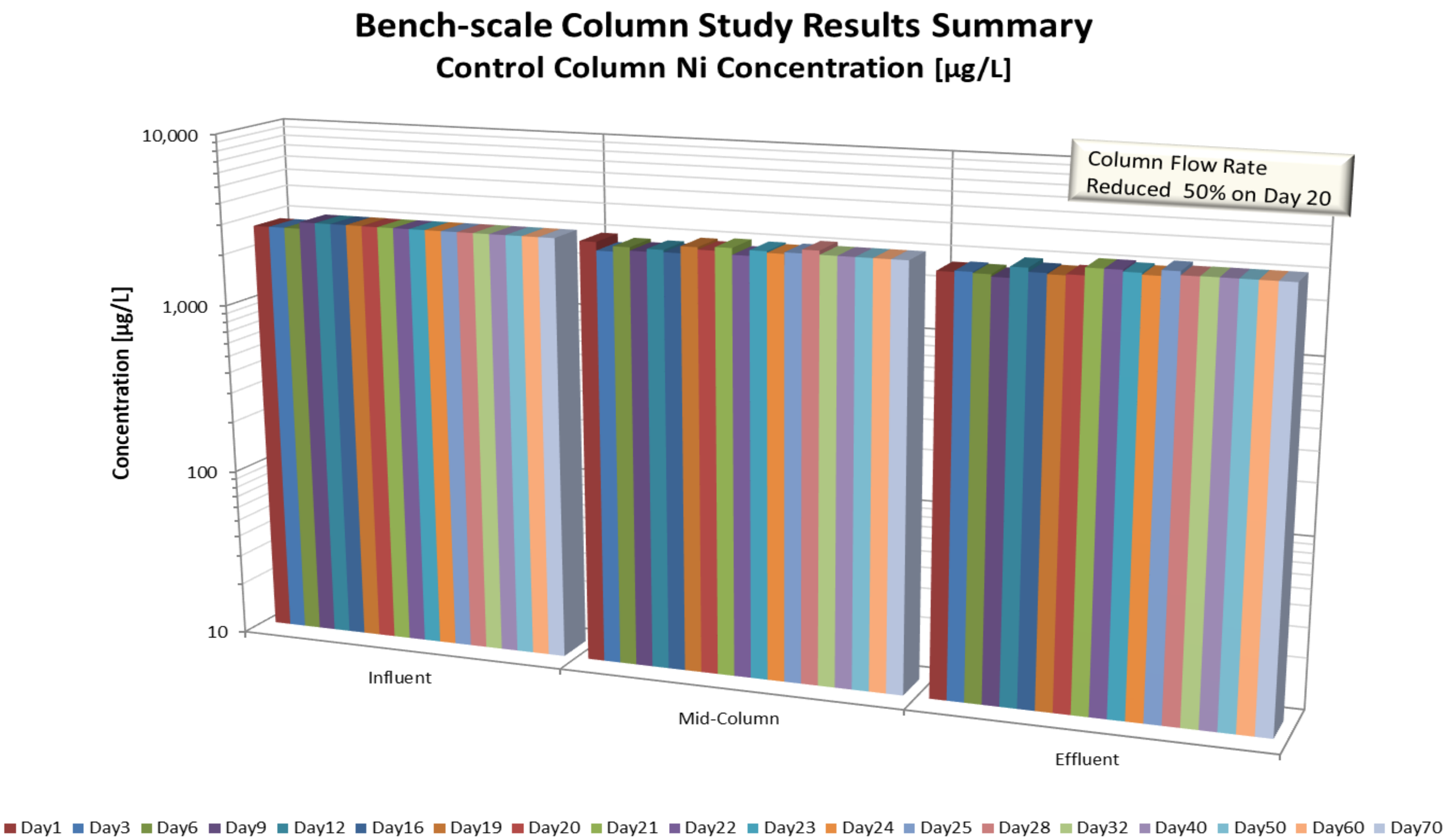
Notes

- Columns packed with Site soil
- Up-flow pumping Site groundwater
- Soil Ni: 1,963 mg/kg
- Soil SPLP Ni: 33,384 µg/L
- Soil pH: 6.5
- Groundwater Ni: 2,753 µg/L
- Groundwater flow velocity was set to 1.2 feet/day until day 50 and then reduced by 50%.

4 February 2026 | Remediation of Soil & Groundwater Contaminated with Divalent Metals

Independent Evaluation of MetaFix® Reagent

Removal of Dissolved Nickel in Up-flow Columns



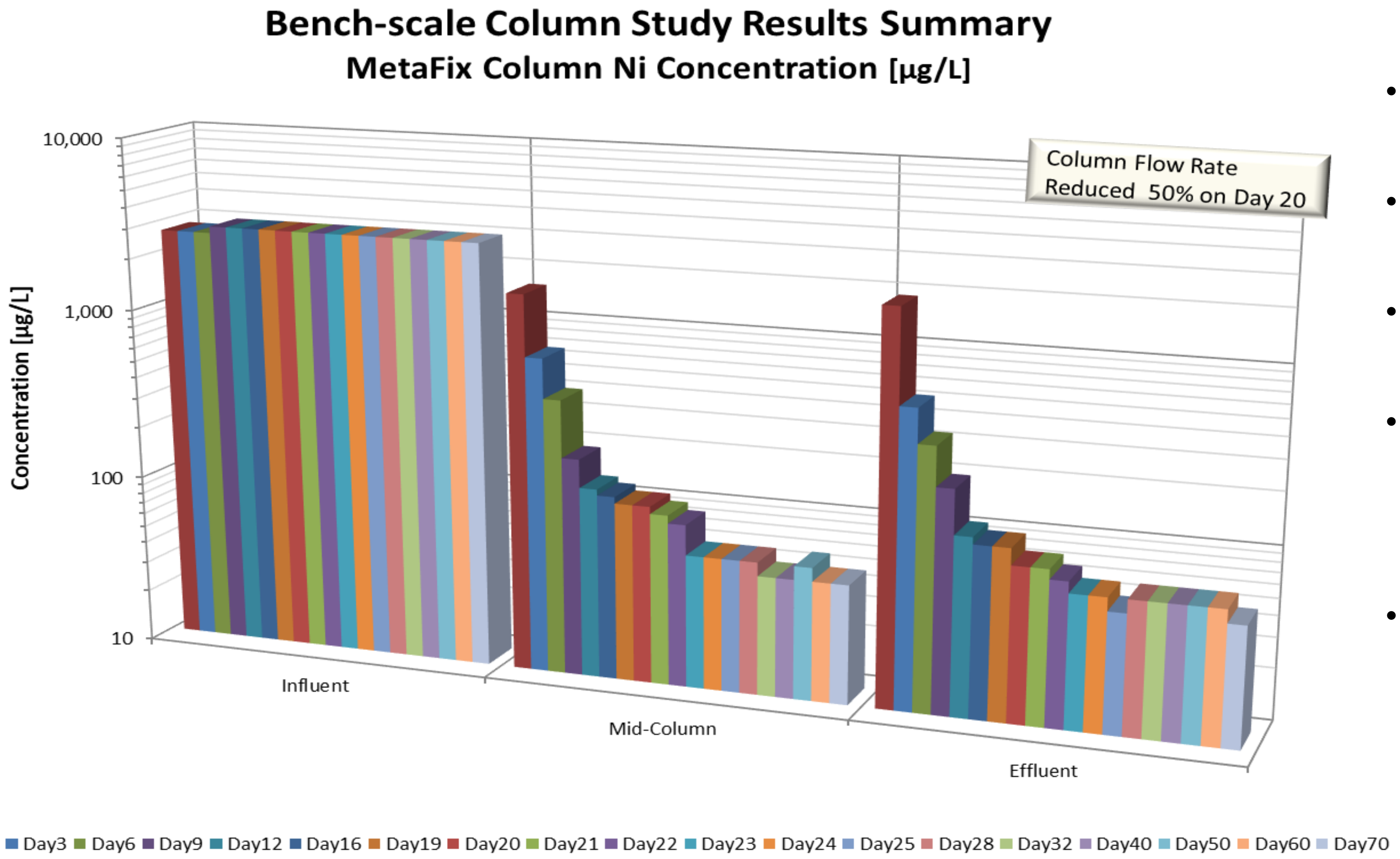
Column Flow Rate Reduced 50% on Day 20

Notes

- Dissolved nickel in µg/L (log scale)
- Influent dissolved nickel at approximately 3,000 µg/L.
- Groundwater flow velocity approximately 1.2 ft/day.
- Little or no reduction in dissolved nickel as groundwater pumped through column filled with untreated site soil.
- Dissolved nickel in mid-columns and effluent ranged from *ca*. 2,600 µg/L to 3,000 µg/L.

Independent Evaluation of MetaFix® Reagent

Removal of Dissolved Nickel in Up-flow Columns



Notes

- Dissolved nickel in µg/L (log scale)
- Influent dissolved nickel at approximately 3,000 µg/L.
- Groundwater flow velocity approximately 1.2 ft/day.
- Dissolved nickel in both mid-column and effluent was rapidly and substantially reduced.
- Dissolved nickel in the mid-column port and the effluent was continuously reduced until stable at about 50 µ/L was achieved.

Representative Performance

Field-Scale Project Snapshots

CASE STUDY | METAFIX® REAGENT

METAFIX® REAGENT

PRB TREATMENT OF MIXED HEAVY METALS

PACIFIC NORTHWEST, UNITED STATES

Leading Beyond Chemistry

Site Information

Site: Manufacturing facility in Pacific Northwest

Consultant: Maul Foster & Alongi

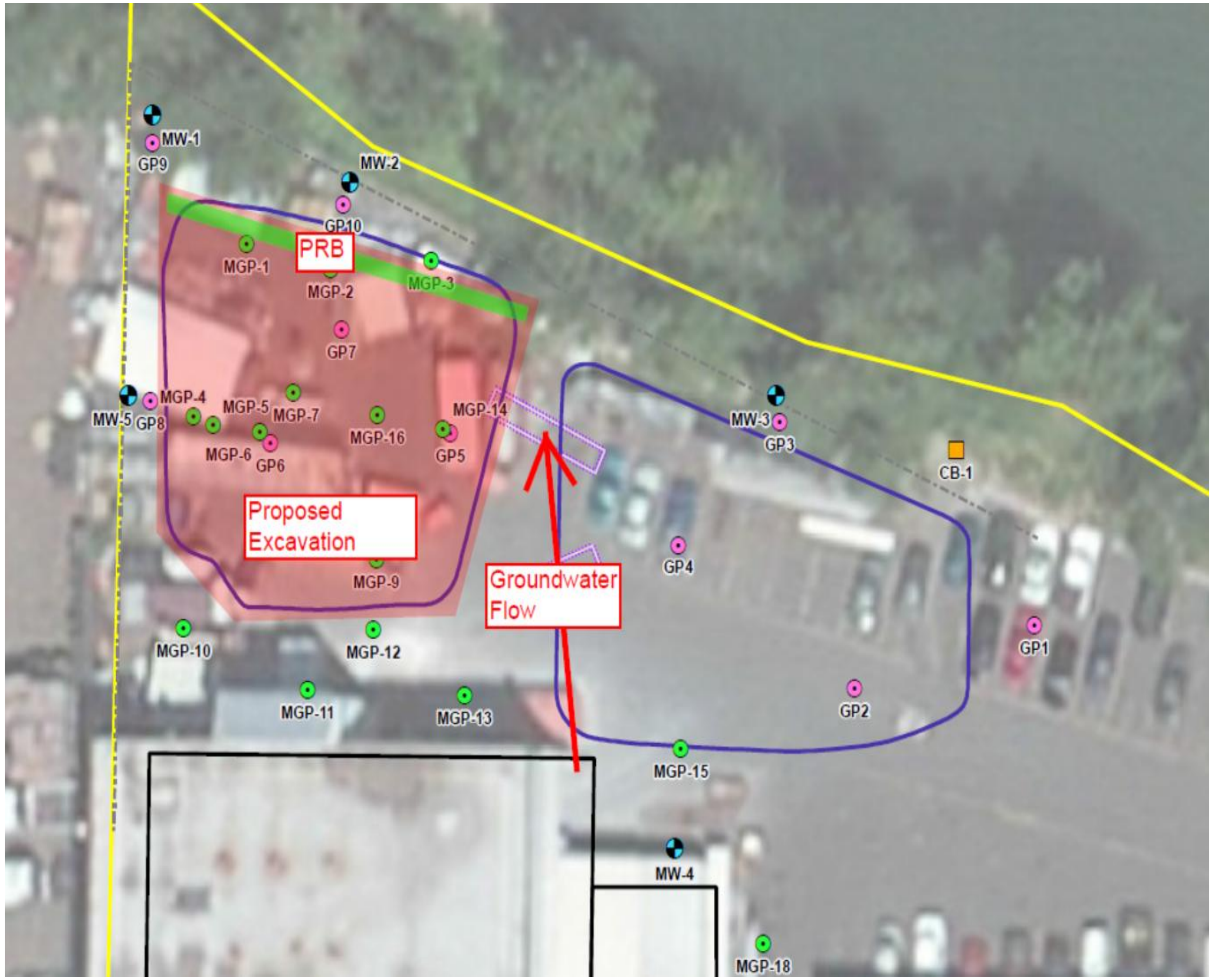
COCs: Mixed heavy metals (aluminum, arsenic, copper) and high alkalinity

Treatment: Excavation of source area soil combined with MetaFix® Reagent permeable reactive barrier (PRB) designed to prevent migration of residual metals into adjacent river

Application: MetaFix® mixed into to backfill to cover downgradient wall of excavation to form PRB

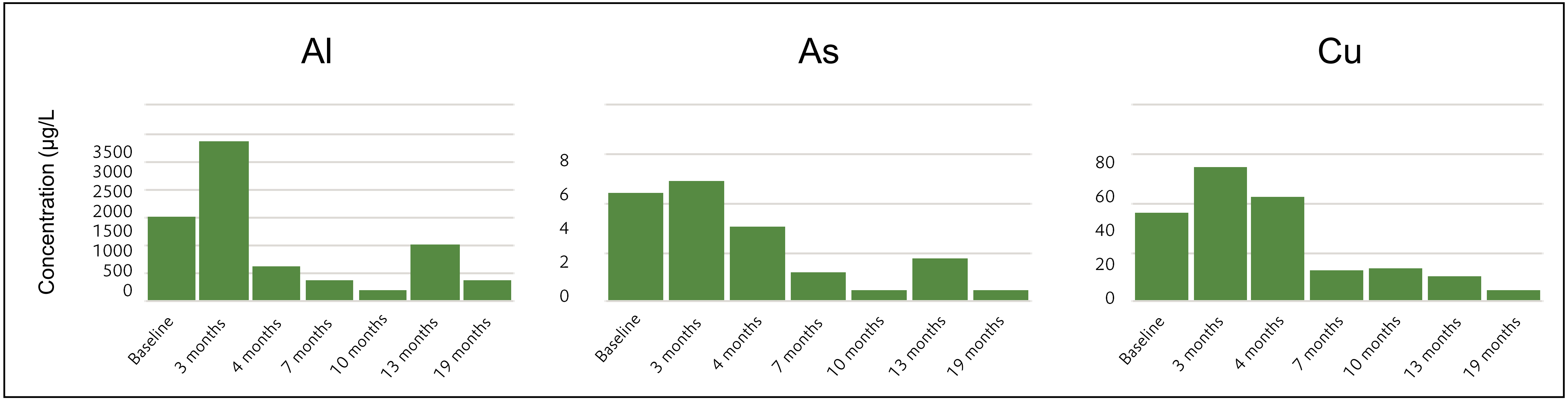
PRB Design and Implementation

- Most heavily-impacted soil was excavated down to 18 ft below ground surface (bgs) and removed
- Custom MetaFix® formulation emplaced as a PRB along sheet piling at the downgradient wall of excavation in conjunction with backfilling the excavation with clean soil
- PRB Dimensions: 80 ft long x 3 ft wide x 15 ft thick
- 5 to 20 ft bgs
- Target Dosage in Soil: 6% by soil mass
- Mass: 24,000 lb (12 x 2,000 lb supersacks)



MetaFix® Performance

- Monitoring data at 3, 4, 7, 13, and 19 months, post-installation
- Transient post-installation increase presumably due to physical mobilization of metals
- All RGs achieved: Al (750 µg/L), As (2.1 µg/L), and Cu (12 µg/L)

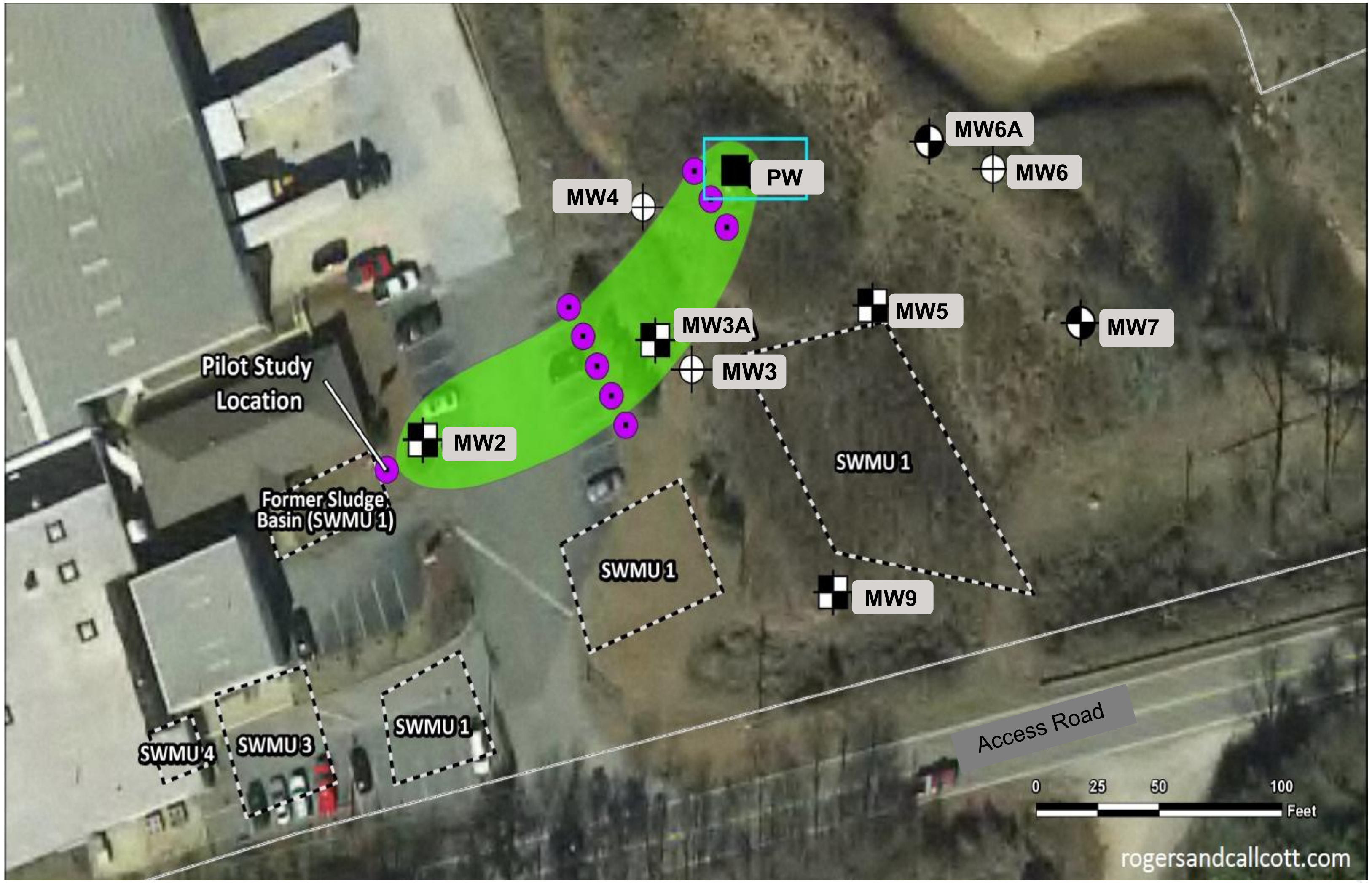


Project Snapshot
MetaFix® I-7A + GeoForm® ER

Removal of Dissolved Cd, Ni, and Zn
In Situ BioGeoChemical Reduction of cVOCs
Industrial Metal Plating Facility
SE, USA

MetaFix® I-7A + GeoForm® ER Project Snapshot

Full-scale Treatment of Metals and cVOCs (Confidential Industrial Site, USA)



Application Process

- Temporary boring
- Sonic drilling
- Pneumatic fracture enhancement
- Bottom-up injection
- Abandon borings
- 65 discrete intervals
- 11,500 lb. MetaFix® I-7A
- 11,500 lb. GeoForm® ER
- 5,600 lb. Flow K™
- 30 L SDC-9™
- 44,000 lb. water

MetaFix® I-7A + GeoForm® ER Project Snapshot

Field-scale Treatment of Metals and cVOCs

Table 1. Chlorinated VOC and divalent metals concentrations at MW3.

Sampling Event	PCE	TCE	cDCE	tDCE	VC	Cadmium	Nickel	Zinc
	µg/L							
Q-1	13.9	43.3	14.6	<1.0	<1.0	16	161	2,950
Q-3	7.7	31.7	8.5	<1.0	<1.0	17	199	3,260
Q-4	7.0	33.0	12.0	<1.0	<1.0	9.0	248	2,560
Q-5	<1.0	1.6	29.7	<1.0	5.0	<4.0	39	250
GWPS	5.0	5.0	70	100	2.0	5.0	700	5,000

***Notes**: 1. Gradual pH increase from 5.6 to 6.5. 2. Both DO and ORP dropped moderately.*

MetaFix® Project Snapshot

On-Site Treatment of Mercury: Bench-scale Treatability Test

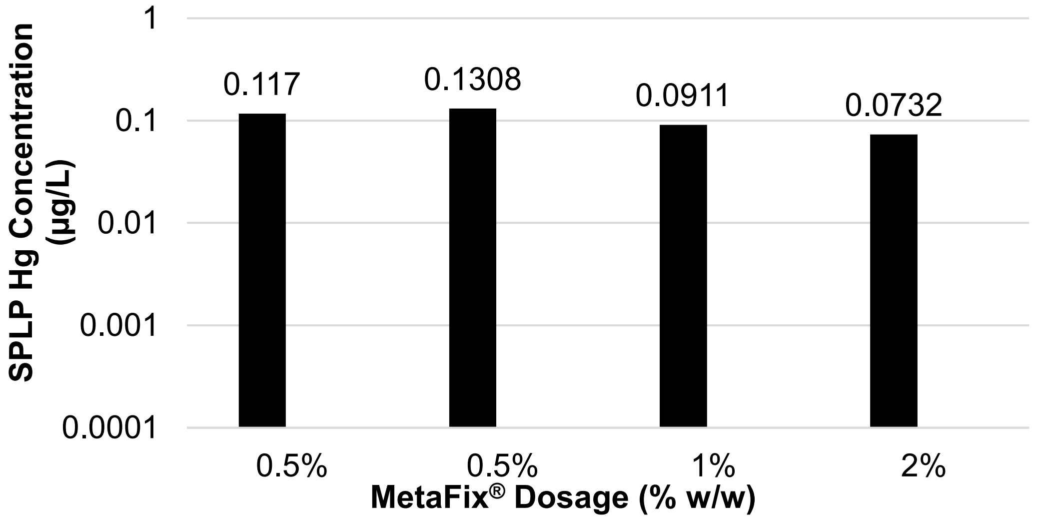
- Mercuric chloride was used as a catalyst in chemical synthesis at this former chemical plant

- Soil mercury concentrations ranged from 300 to 420 mg/kg.
- The remedial goal was to stabilize the soil and to then dispose of the treated soil at an offsite landfill and the land will be developed for residential use.
- Results from bench-scale testing indicated that a MetaFix® dosage of 0.5% (w/w) would achieve the remedial objective for mercury (i.e., 1.0 µg/L SPLP).

Parameter	**Control** (untreated)	**MetaFix®** 0.5% (w/w)	**MetaFix®** 1.0% (w/w)
Soil Moisture (%)	18.3	18.5	20.0
pH	8.6	8.0	7.9
Total Hg (mg/kg)	315	293	314
SPLP Hg (µg/L)	35.1	<1.0	<1.0

MetaFix® Project Snapshot

On-Site Treatment of Mercury: Pilot-scale Demonstration



Pilot-Scale Demonstration

- Four treatment cells, each with 50 m3 soil
- A range of MetaFix® dosages compared including 0.5% 1.0%, and 2.0% (w/w)
- MetaFix reagent mixed into the soil with an excavator bucket and a screening bucket
- Sufficient water added to increase soil moisture content to near but below the point of saturation (ca. 90% WHC)
- Soil was covered with HDPE to prevent drying and support creation of anaerobic conditions
- Reaction period was 7 days
- Even the lowest dosage achieve the remedial objective of 1.0 µg Hg/L in SPLP testing
- Decision was to use 0.5% w/w reagent dosage for full-scale application

MetaFix® Project Snapshot

On-Site Soil Mixing Treatment of Mercury to Achieve SPLP Goal

Allu Screening Bucket

2,000 kg Bulk Bags

Full-Scale Application

- The MetaFix® dosage of 0.5% w/w selected for the full-scale treatment.
- Full scale implementation utilizes an integrated soil mixing system where soil crushing/screening and reagent dosing/mixing are completed in a single process.
- Water addition to approximately 80% of soil water holding capacity (i.e., soil quite wet but no free water).
- Reaction period was the same as in the pilot-scale demonstration (7 days).
- Several thousand tons successfully treated.
- Remedial goal of 1.0 µg/L SPLP achieved for all batches.

Review & Conclusions

- Divalent metals can be removed from solution by precipitation as metal sulfides, metal carbonates, or metal hydroxides.

- The metal sulfide precipitation approach has important advantages including lower solubility and much wider pH range stability.

- These important characteristics of metal sulfide precipitates provide greater assurance that remedial goals will be achieved including MCLs, SPLP, and TCLP.

- The metal sulfide precipitation approach is broadly applicable to treatment of groundwater since it is best practiced under pH and Eh conditions that can be readily achieved using combined chemical/biological treatment (i.e., ZVI + organic electron donors).

Review & Conclusions

- **An effective approach to removal of dissolved divalent heavy metals in soil or groundwater should be based on reagents that will:**
  - ✓ Generate reducing conditions
  - ✓ Provide adequate free sulfide
  - ✓ Provide adequate ferrous iron
  - ✓ Maintain pH in the near-neutral range
- **Use of long-lasting reagents provide the additional benefit of reduced potential for rebound because they support occlusion of newly precipitated divalent metal sulfides through continuous formation of iron sulfides (i.e., FeS, FeS_2).**
- **MetaFix® and GeoForm® reagents are designed to generate effective and long-lasting conditions for removal of divalent heavy metals via sulfide precipitation while minimizing the potential for rebound.**

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Questions are Welcome!

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