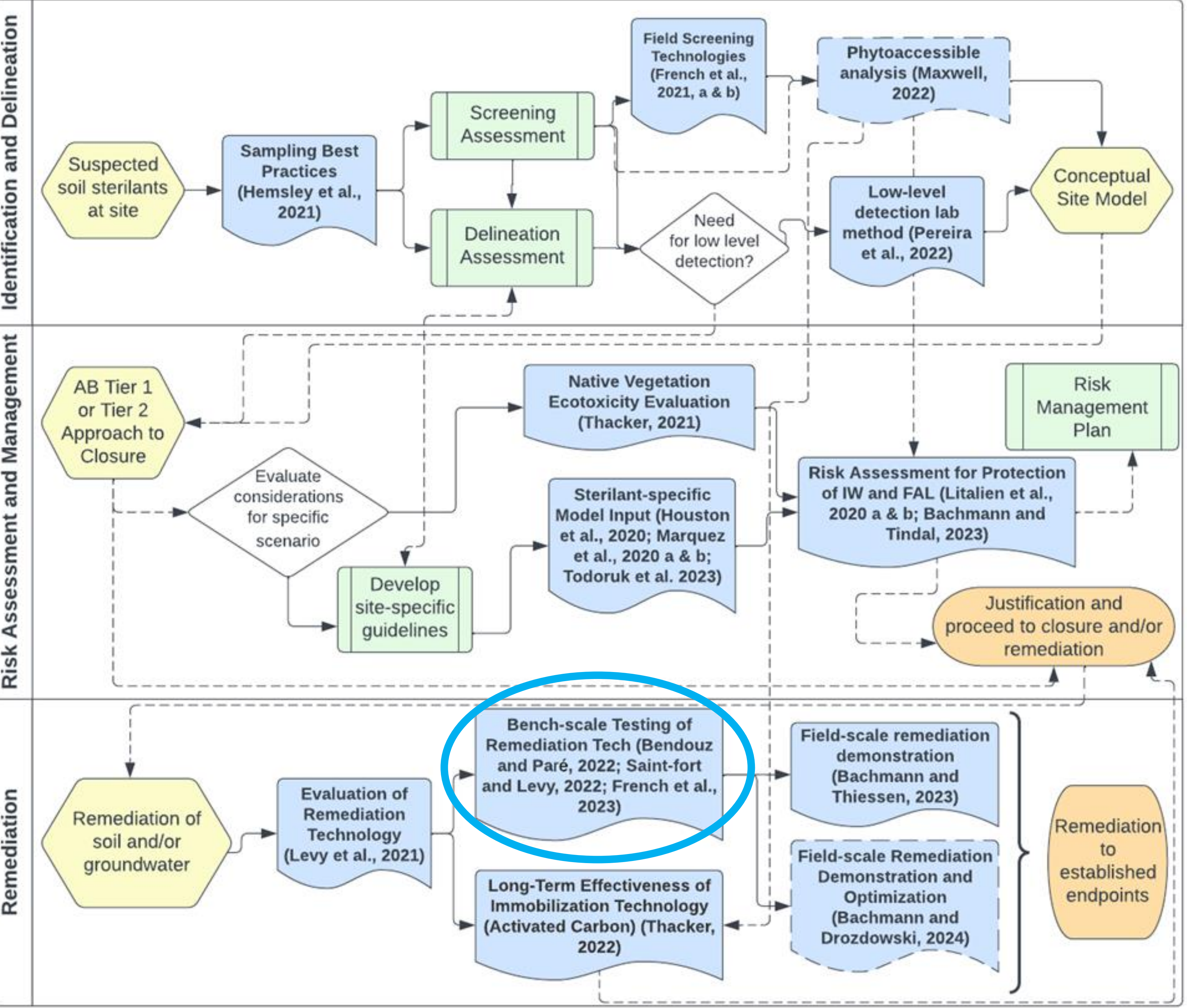
BENCH-SCALE TREATABILITY TESTING FOR BROMACIL AND TEBUTHIURON REMEDIATION

SOIL STERILANTS PROGRAM (SSP)

InnoTech ALBERTA
A SUBSIDIARY OF ALBERTA INNOVATES

CHEMCO ENVIRONMENT

VEI CONTRACTING
Formerly Vertex Environmental Inc.



SSP Soil Sterilants Program

- Objective was to establish **proven, technical** and **cost-effective** strategies and best practices for management of sites impacted by residual soil sterilants, with the goal of supporting regulatory site closure.
- 5 year program
  - Initiated in 2019
- Scope
  - Address challenges specific to AB
  - Applied research
  - Focus on Bromacil and Tebuthiuron
- Executed through a series of projects in:
  - Identification and Delineation
  - Risk Assessment and Management
  - Remediation

SCREENING AND BENCH-SCALE TESTING OF REMEDIATION TECHNOLOGIES

SSP Soil Sterilants Program

Key Challenges
1) Sterilant **destruction** in soil where immobilization is not considered an acceptable option (*in situ* or *ex situ*)
2) Treatment of sterilants at **depths greater than 50 cm bgs** in unsaturated soil, thus inaccessible to treatment at surface (ideally treated *in situ*)
3) *In situ* treatment of **saturated fine-grained till soils and groundwater**
4) **Cost-effective** *ex situ* water remediation

SCREENING AND BENCH-SCALE TESTING OF REMEDIATION TECHNOLOGIES

SSP Soil Sterilants Program

Key Challenge	Bench-Scale Testing
1) Destruction of sterilants (ideally to guideline levels) 2) Treatment of sterilants at depths greater than 50 cm bgs in unsaturated soil, thus inaccessible to treatment at surface (ideally treated *in situ*)	Chemical oxidation and reduction approaches, with and without surfactants CHEMCO ENVIRONMENT
3) Destruction of sterilants (ideally to guideline levels) 4) *In situ* treatment of saturated fine-grained till soils and groundwater at depths greater than 50 cm bgs	In-situ chemical reduction and biostimulation, with and without surfactants VEI CONTRACTING Formerly Vertex Environmental Inc.
5) Cost-effective *ex situ* water remediation (not presented herein)	In-situ biostimulation, with and without surfactants AND Electrocoagulation (*ex situ*) trial MOUNT ROYAL UNIVERSITY 1910

STERILANT CHARACTERISTICS

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Parameter	Sterilant	
	Bromacil	Tebuthiuron
Water Solubility	815 mg/L at 25 °C; increases with higher pH	2,500 mg/L at 25 °C
Soil/organic matter sorption coefficient (K_d/K_{oc}); Octanol-water partition coefficient (log K_{ow})	K_{oc}: 32 g/mL ; K_d/K_{oc}: variable from 2.3 to 289 in soils ranging from sand to peat; Log (Koc): 1.86 (average) for soil; 1.61 (average for sediments) Log K_{ow}: 2.11	K_{oc}: 80 mg/; K_d: 0.2-10.0; Log K_{ow}: 1.79
Mobility	Highly likely to be mobile in soils low in organic matter; Moves horizontally on surface and vertically with water; Moderate mobility in soils high in OM and clay content	Influenced by soil texture and organic matter content (higher mobility in sandy soils and soils low in OM; lower in clay loam soils or highly organic soils)
Leaching Potential	High; important dissipation process; readily leached	Medium; High solubility in water, weak adsorption to soil particles and is highly persistent, therefore has high potential to leach
Adsorption/ Desorption	Lower than other herbicides; sorption to soils increases with clay and OM content; will not partition to suspended particles or sediments in aquatic systems (remains dissolved in water column)	Relatively poor soil sorption; Sorption to soils highest in soils high in OM content followed by clay content; <1% at soil OM of 0.3% and 40% with soil OM of 4.8%
Volatilization	Minor importance	Not volatile
Microbial degradation	Bromacil is slowly debrominated by microflora under anaerobic, methanogenic conditions but is not degraded under denitrifying or sulphate-reducing conditions.	Biodegradation of tebuthiuron in aerobic soil is expected to be slow. It also shows little biodegradation in anaerobic soils. Similarly, tebuthiuron does not degrade appreciably in water.

BENCH SCALE IN-SITU CHEMICAL OXIDATION/REDUCTION – CHEMCO INC.

SSP
Soil Sterilant Program
CANADIAN LEADER IN ENVIRONMENTAL SOLUTIONS

OUR SERVICES

Training & Education

Technical and Design Support

Field-Proven Technologies

Expert Technical Team

CHEMCO ENVIRONMENT

R&D and Treatability Laboratories

Field Support & Logistic

Mixing and Handling Equipment

<u>Specialized Products</u>

- Chemical Oxidation
- Chemical Reduction
- Co solvent-Surfactant soil Washing
- Enhanced Bioremediation
- Permeable Reactive Barrier Amendments
- Metals Stabilization
- Activated Carbon Sorption Technologies

DESTRUCTIVE TECHNOLOGY – IN SITU CHEMICAL OXIDATION

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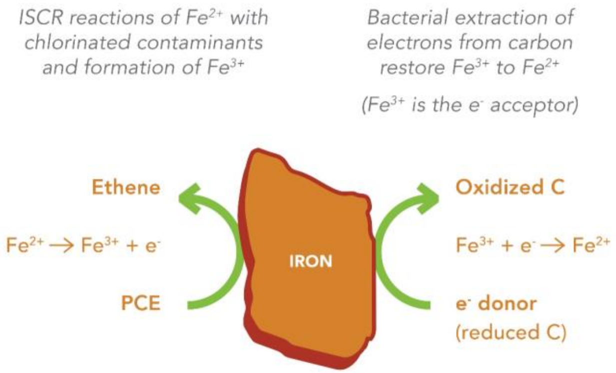
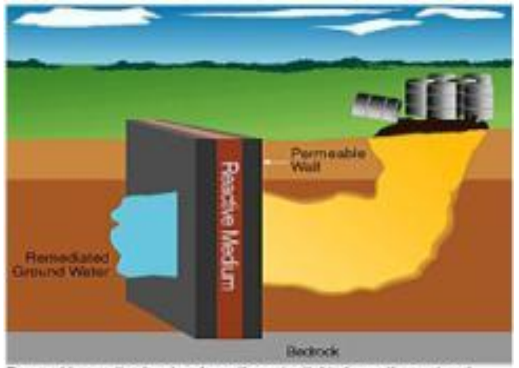
- ✓ Water is the carrier for the oxidants used in chemical oxidation (except for ozone)
- ✓ Surfactant enhanced Chemical Oxidation might be considered Oxidants are non-specific and will react with the targeted contaminants AND with the soil organic and/or mineral soil matrix content Soil Oxidant Demand - SOD).
- ✓ If you have enough oxidant present and sufficient time you will push the destruction toward to FULL mineralization (CO_2, H_2O, Cl^-) of the contaminant of concern
- ✓ Kinetics of the chemical oxidation reaction is thus influence by the contaminant of concern solubility and availability in the groundwater or moisture phase
- ✓ Surfactants can be combined with the oxidant to increase distribution and contaminant availability (S-ISCO)
- ✓ Sorbed phase contamination might be challenging to remediate (less available)
- ✓ Back diffusion of the contamination (rebound) can persist because of high hydrophobic properties or geological consideration
- ✓ Application/Injection technique must induce proper contact between the contaminant and the oxidant for a proper duration for the required reaction to occurs (kinetics)

DESTRUCTIVE TECHNOLOGY – IN SITU CHEMICAL REDUCTION

- ✓ Introduction of a reducing material or generating reducing species to help degrade toxic organic compounds or immobilize metals in the desired area
- ✓ The most commonly used reductant is zero valent iron (ZVI)
- ✓ Possible introduction of organic substrates to produce enhanced conditions to conduct microbial reduction
- ✓ Degradation / Immobilization of contaminants by abiotic or biotic processes
- ✓ Transfer of electrons from reduced metals (ZVI, ferrous iron) or reduced minerals (magnetite, pyrite) to contaminants including chlorinated organics and heavy metals
- ✓ Permeable Reactive Barriers (PRB's) constructed using ZVI = example of simple ISCR
- ✓ Combined ZVI/fermentable carbon reagents are an example of advanced ISCR





Permeable reactive barriers have the potential to lower the cost and increase the effectiveness of groundwater cleanup.

Source: EPA

BENCH-SCALE TESTING APPROACH

1. Surfactant screening – 6 different types (anionic, cationic and non-ionic) to ENHANCE contaminant availability
2. Reductive treatment testing – with and without surfactant (Daramend only tilled)
3. Oxidative treatment testing – without surfactant; two best candidates with surfactant (staged approach)
   - Potassium persulfate activated with calcium-based product (hydrated lime)
   - Sodium persulfate activated with calcium-based product (calcium peroxide FG)
   - Sodium persulfate activated with alkaline base (sodium hydroxide)
   - Hydrogen Peroxide alone or activated using VTX (organic catalyst)

SURFACTANTS SCREENING RESULTS (BROMACIL)

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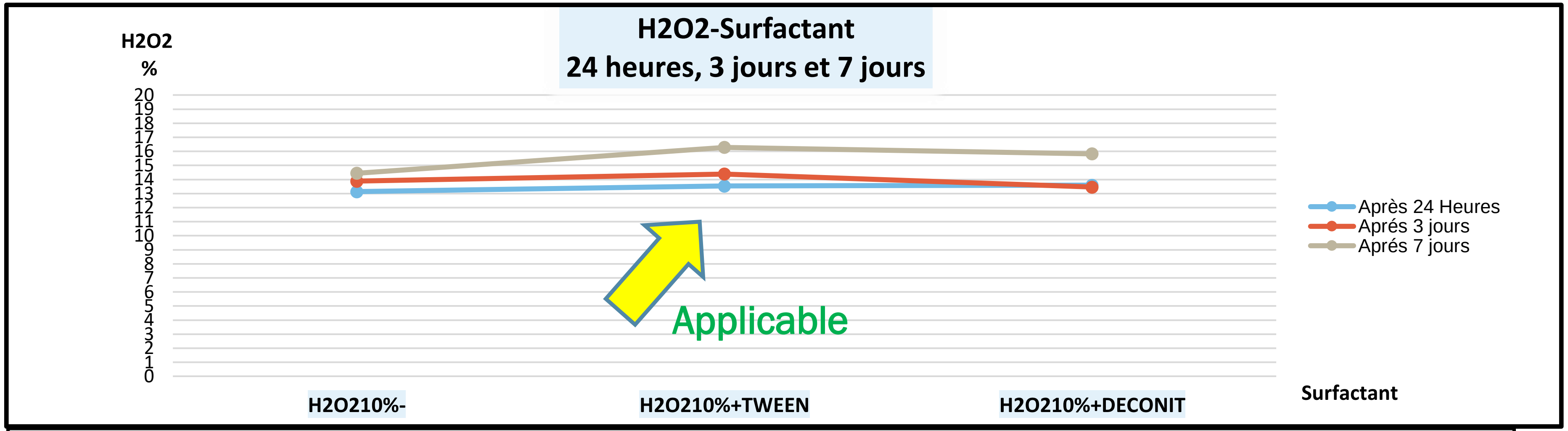
Essay	*Description*	*Type of surfactant*	*Dosage (g/kg)*	***Contaminant Concentration (ppb)***	*% Increase*	*comments*
BROMACIL - TEMOIN 1 - BLANK	**Leachate of Spiked soil with bromacil without surfactant**					
BROMACIL - TEMOIN 2 - BLANK	**Leachate of Spiked soil with bromacil without surfactant**			323		
BROMACIL - TEMOIN 3 - BLANK	**Leachate of Spiked soil with bromacil without surfactant**			258		
BROMACIL - TEMOIN 4 - BLANK	**Leachate of Spiked soil with bromacil without surfactant**			427		
BROMACIL - TWEEN - 1 g/kg	Leachate of Spiked soil with bromacil+Surfactant TWEEN at dosage of 1 g/kg	TWEEN	1	**583**	**74**	**Best results**
BROMACIL - TWEEN - 5 g/kg	Leachate of Spiked soil with bromacil+Surfactant TWEEN at dosage of 5 g/kg	TWEEN	5	483	44	
BROMACIL - TWEEN - 10 g/kg	Leachate of Spiked soil with bromacil+Surfactant TWEEN at dosage of 10 g/kg	TWEEN	10	527	57	
BROMACIL - DECONIT - 1 g/kg	Leachate of Spiked soil with bromacil+Surfactant DECONIT at dosage of 1 g/kg	DECONIT	1	376	12	
BROMACIL - DECONIT - 5 g/kg	Leachate of Spiked soil with bromacil+Surfactant DECONIT at dosage of 5 g/kg	DECONIT	5	264	-21	
BROMACIL - DECONIT - 10 g/kg	Leachate of Spiked soil with bromacil+Surfactant DECONIT at dosage of 10 g/kg	DECONIT	10			
BROMACIL - DL3 - 1 g/kg	Leachate of Spiked soil with bromacil+Surfactant DL3 at dosage of 1 g/kg	DL3	1	413	23	
BROMACIL - DL3 - 5 g/kg	Leachate of Spiked soil with bromacil+Surfactant DL3 at dosage of 5 g/kg	DL3	5	**465**	**38**	**2nd best**
BROMACIL - DL3 - 10 g/kg	Leachate of Spiked soil with bromacil+Surfactant DL3 at dosage of 10 g/kg	DL3	10	395	18	
BROMACIL - DL4 - 1 g/kg	Leachate of Spiked soil with bromacil+Surfactant DL4 at dosage of 1 g/kg	DL4	1	**430**	**28**	**3th best**
BROMACIL - DL4 - 5 g/kg	Leachate of Spiked soil with bromacil+Surfactant DL4 at dosage of 5 g/kg	DL4	5			
BROMACIL - DL4 - 10 g/kg	Leachate of Spiked soil with bromacil+Surfactant DL4 at dosage of 10 g/kg	DL4	10	343	2	
BROMACIL - 106-CL - 1 g/kg	Leachate of Spiked soil with bromacil+Surfactant 106 CL at dosage of 1 g/kg	106 CL	1	280	-17	
BROMACIL - 106-CL - 5 g/kg	Leachate of Spiked soil with bromacil+Surfactant 106 CL at dosage of 5 g/kg	106 CL	5	218	-35	
BROMACIL - 106-CL - 10 g/kg	Leachate of Spiked soil with bromacil+Surfactant 106 CL at dosage of 10 g/kg	106 CL	10	393	17	
BROMACIL - FFT - 1 g/kg	Leachate of Spiked soil with bromacil+Surfactant FFT at dosage of 1 g/kg	FFT	1	393	17	
BROMACIL - FFT - 5 g/kg	Leachate of Spiked soil with bromacil+Surfactant FFT at dosage of 5 g/kg	FFT	5			
BROMACIL - FFT - 10 g/kg	Leachate of Spiked soil with bromacil+Surfactant FFT at dosage of 10 g/kg	FFT	10	424	26	

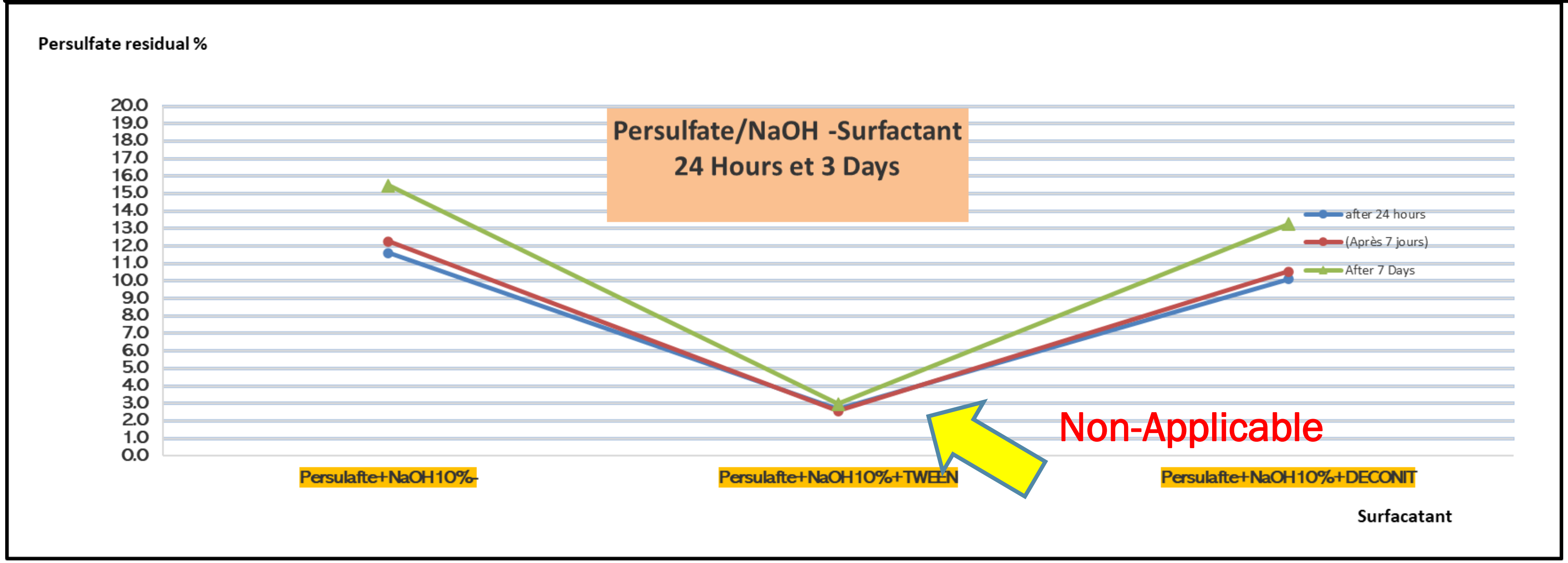
SURFACTANTS SCREENING RESULTS (TEBUTHIURON)

SSP Soil Sterilants Program

Essay	Description	Type of surfactant	Dosage (g/kg)	Contaminant Concentration (ppb)	% Increase	comments
TBT - TEMOIN 1 - BLANK	Leachate of Spiked soil with Tebuthiuron without Surfactant			282		
TBT - TEMOIN 2 - BLANK	Leachate of Spiked soil with Tebuthiuron without Surfactant			316		
TBT - TEMOIN 3 - BLANK	Leachate of Spiked soil with Tebuthiuron without Surfactant					
TBT - TEMOIN 4 - BLANK	Leachate of Spiked soil with Tebuthiuron without Surfactant			347		
TBT - TWEEN - 1 g/kg	Leachate of Spiked soil with Tebuthiuron +Surfactant TWEEN at dosage of 1 g/kg	TWEEN	1	413	31	3 th best
TBT - TWEEN - 5 g/kg	Leachate of Spiked soil with Tebuthiuron +Surfactant TWEEN at dosage of 5 g/kg	TWEEN	5	487	54	Best results
TBT - TWEEN - 10 g/kg	Leachate of Spiked soil with Tebuthiuron +Surfactant TWEEN at dosage of 10 g/kg	TWEEN	10	363	15	
TBT - DECONIT - 1 g/kg	Leachate of Spiked soil with Tebuthiuron +Surfactant DECONIT at dosage of 1 g/kg	DECONIT	1	189	-40	
TBT - DECONIT - 5 g/kg	Leachate of Spiked soil with Tebuthiuron +Surfactant DECONIT at dosage of 5 g/kg	DECONIT	5	462	47	2nd best
TBT - DECONIT - 10 g/kg	Leachate of Spiked soil with Tebuthiuron +Surfactant DECONIT at dosage of 10 g/kg	DECONIT	10	333	6	
TBT - DL3 - 1 g/kg	Leachate of Spiked soil with Tebuthiuron +Surfactant DL3 at dosage of 1 g/kg	DL3	1	323	2	
TBT - DL3 - 5 g/kg	Leachate of Spiked soil with Tebuthiuron +Surfactant DL3 at dosage of 5 g/kg	DL3	5	288	-9	
TBT - DL3 - 10 g/kg	Leachate of Spiked soil with Tebuthiuron +Surfactant DL3 at dosage of 10 g/kg	DL3	10	285	-10	
TBT - DL4 - 1 g/kg	Leachate of Spiked soil with Tebuthiuron +Surfactant DL4 at dosage of 1 g/kg	DL4	1	267	-15	
TBT - DL4 - 5 g/kg	Leachate of Spiked soil with Tebuthiuron +Surfactant DL4 at dosage of 5 g/kg	DL4	5	304	-3	
TBT - DL4 - 10 g/kg	Leachate Spiked soil with Tebuthiuron +Surfactant DL4 at dosage of 10 g/kg	DL4	10	202	-36	
TBT - 106-Ckg - 1 g/kg	Leachate of Spiked soil with Tebuthiuron +Surfactant 106 CL at dosage of 1 g/kg	106 CL	1	158	-50	
TBT - 106-Ckg - 5 g/kg	Leachate of Spiked soil with Tebuthiuron +Surfactant 106 CL at dosage of 5 g/kg	106 CL	5	181	-42	
TBT - 106-Ckg - 10 g/kg	Leachate of Spiked soil with Tebuthiuron +Surfactant 106 CL at dosage of 10 g/kg	106 CL	10	128	-59	
TBT - FFT - 1 g/kg	Leachate of Spiked soil with Tebuthiuron +Surfactant FFT at dosage of 1 g/kg	FFT	1			
TBT - FFT - 5 g/kg	Leachate of Spiked soil with Tebuthiuron +Surfactant FFT at dosage of 5 g/kg	FFT	5			
TBT - FFT - 10 g/kg	Leachate of Spiked soil with Tebuthiuron +Surfactant FFT at dosage of 10 g/kg	FFT	10	256	-19	

SURFACTANT REACTIVITY TESTING VERSUS OXIDANT





OXIDATIVE TESTING NO SURFACTANT (BROMACIL)

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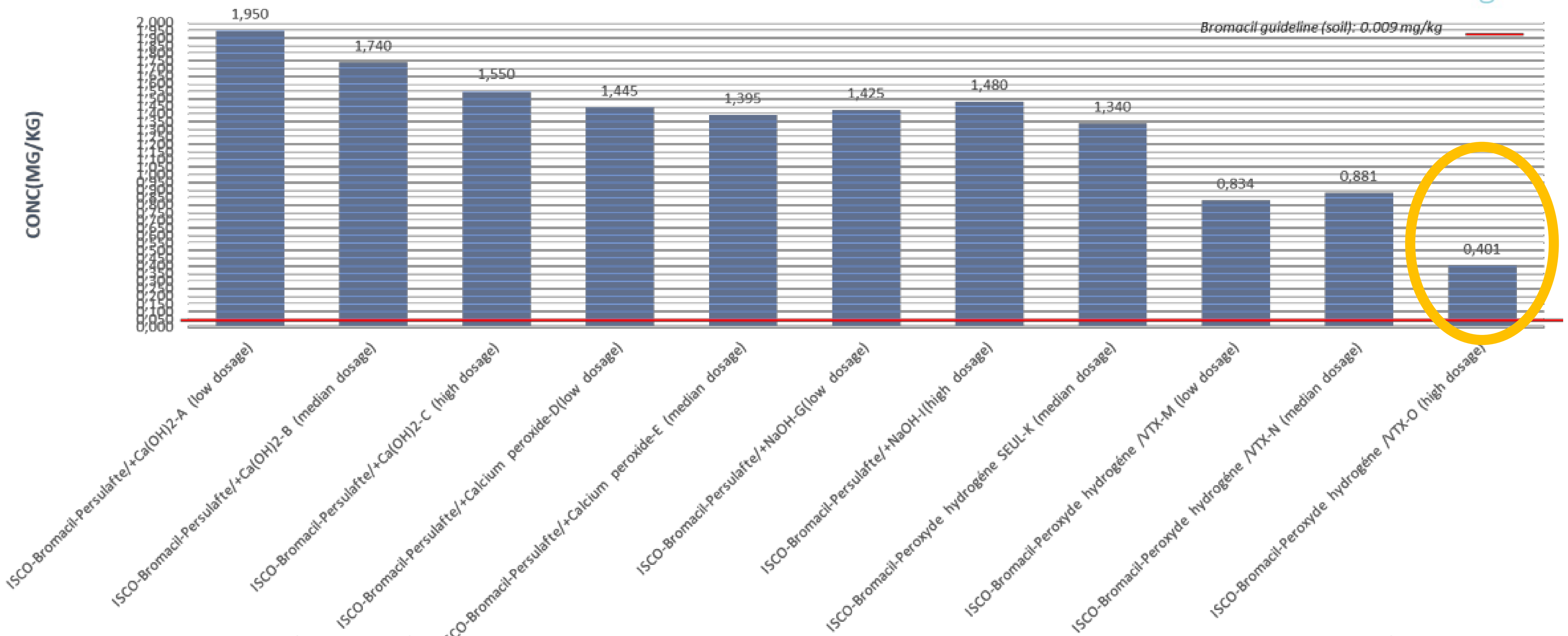
average concentration blank sample= 1.36 mg/kg (n=3)

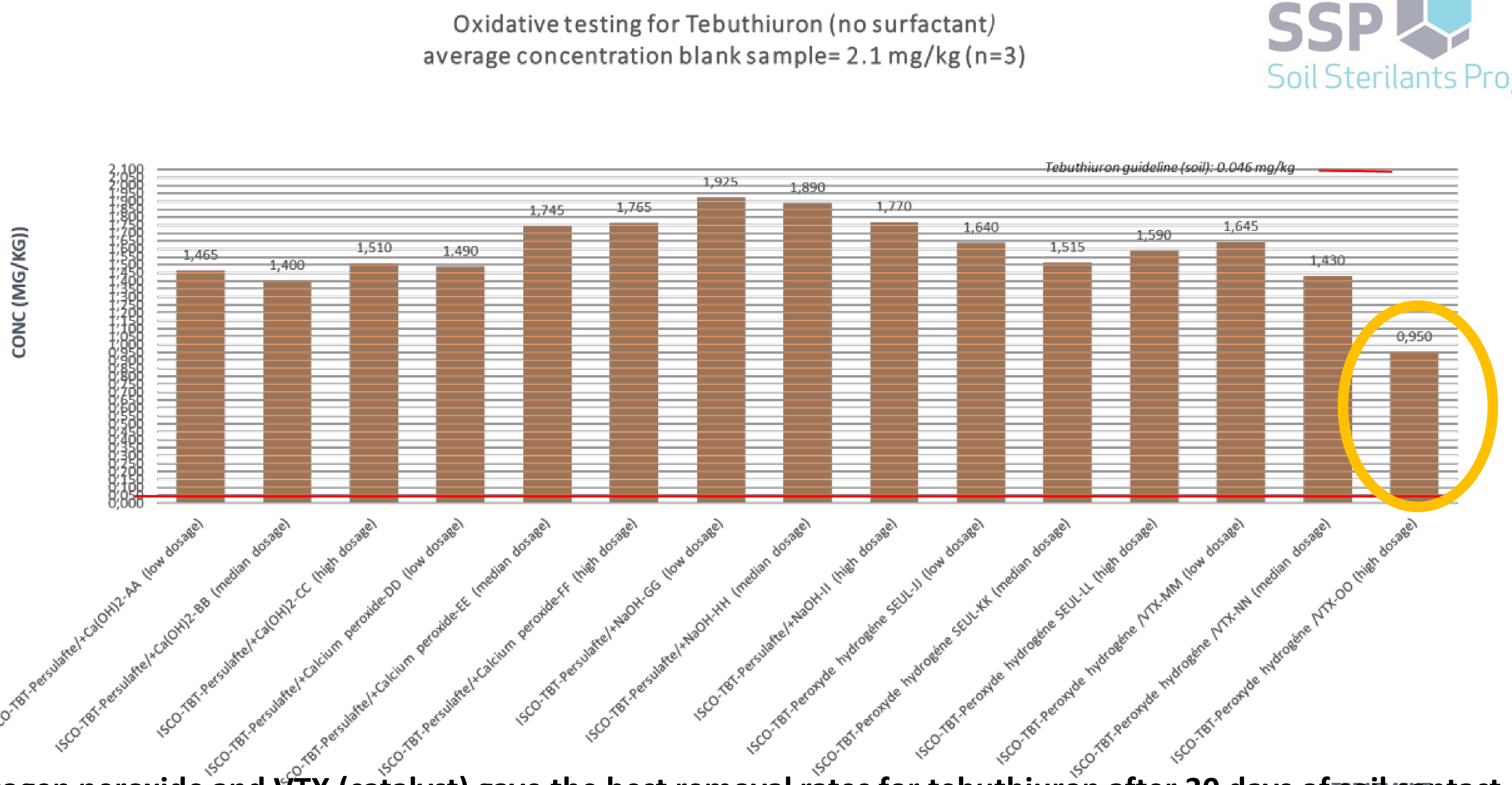


Hydrogen peroxide and VTX (catalyst) gave the best removal rates for bromacil after 30 days of soil contact. (40:1 oxidant to contaminant dosage: 40,2 g of hydrogen peroxide 50% + 4 g/kg VTX per kg of dry soil)

- **70% of Bromacil destruction obtained @ final concentration of 0,401 mg/kg after 30 days of reaction**

OXIDATIVE TESTING NO SURFACTANT (TEBUTHIURON)

SSP
Soil Sterilants Program

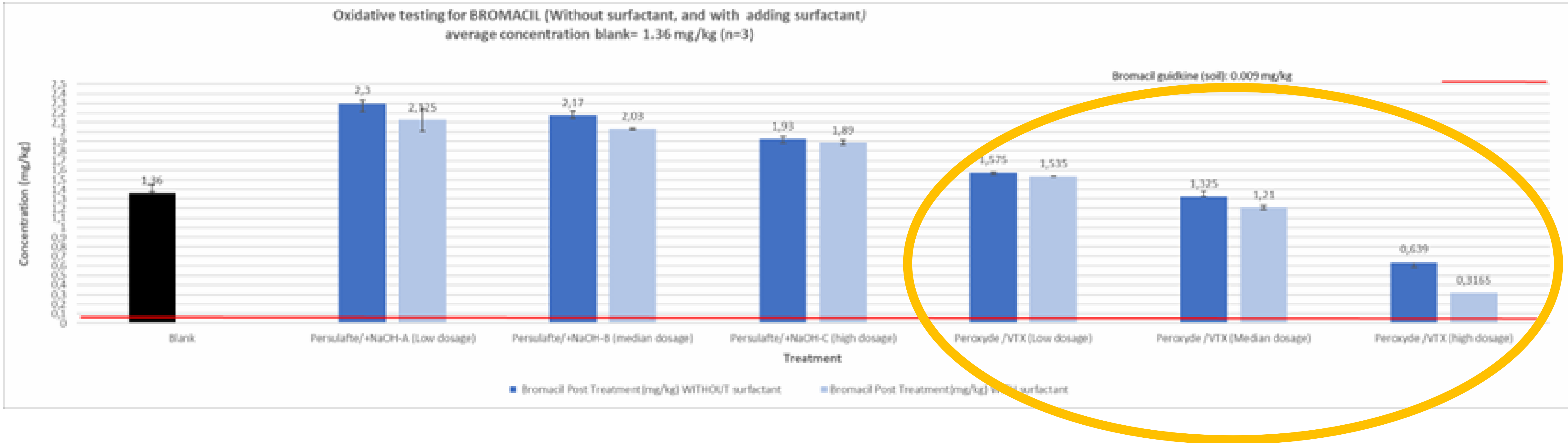


Hydrogen peroxide and VTX (catalyst) gave the best removal rates for tebuthiuron after 30 days of soil contact. (40:1 oxidant to contaminant dosage: 40,2 g of hydrogen peroxide 50% + 4 g/kg VTX per kg of dry soil)

- **55% of Tebuthiuron destruction @ final concentration of 0,95 mg/kg after 30 days of reaction**

OXIDATIVE TREATMENT ON BROMACIL WITH AND WITHOUT THE ADDITION OF SURFACTANT

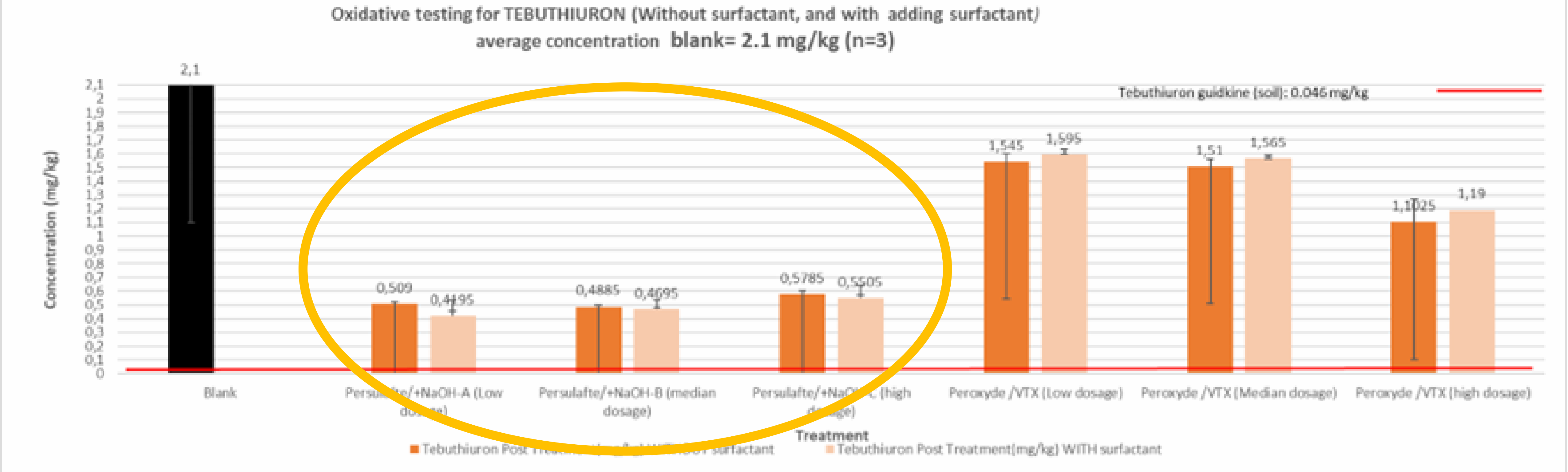
SSP Soil Sterilants Program



- ✓ Very good contaminant removal with the use of Hydrogen peroxide activated with VTX at high dosage combined with the addition of the surfactant (TWEEN®).: high dosage of Hydrogen peroxide (40: 1 oxidant to contaminant dosage) by using 40,2 g of hydrogen peroxide 50% plus 4 g/kg VTX, + surfactant TWEEN (1 g per kg of soil)
- ✓ The Bromacil destruction = 76 %.

OXIDATIVE TREATMENT ON TEBUTHIURON WITH AND WITHOUT THE ADDITION OF SURFACTANT

SSP Soil Sterilants Program



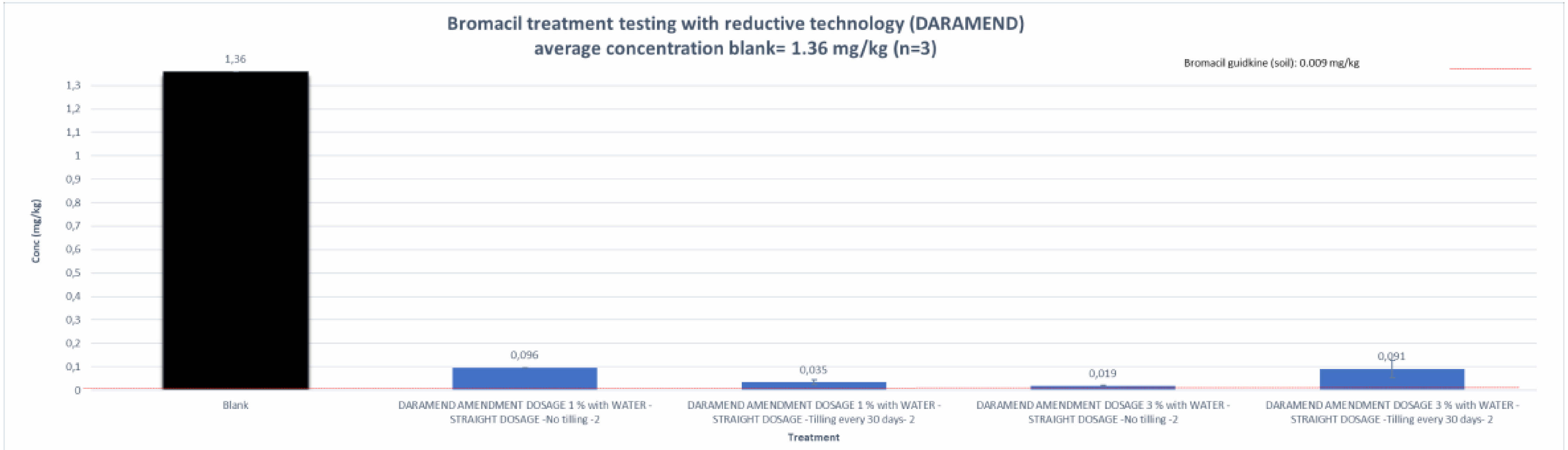
- ✓ The use of Alkaline activated Sodium persulfate without surfactant was successful.
- ✓ Tebuthiuron destruction = 76 %(without the surfactant) AND 80 %(with the surfactant)

- the use of a surfactant will not be recommended for this treatment

The high SOD value obtained (41 g of sodium persulfate per kg of soil) for the submitted soil might have limited contaminant destruction by this oxidant in the submitted soil samples

EFFECT OF DARAMEND® TREATMENT CONCENTRATIONS IN SOIL ON BROMACIL

SSP Soil Sterilants Program



Removal rates for bromacil :

- Daramend®@ 3 % (wt/wt basis) with no tilling : **98 %**
- Daramend®@ 1 % (wt/wt basis) with a tilling every 30 days: **97%**

Note: 1 % (wt/wt basis) = 10 g of Daramend® per kg of dry soil and using water to increase moisture content to 90% WHC

COMPARING THE EFFECT OF REDUCTIVE TREATMENT ON BROMACIL WITH AND WITHOUT ADDITION OF SURFACTANT

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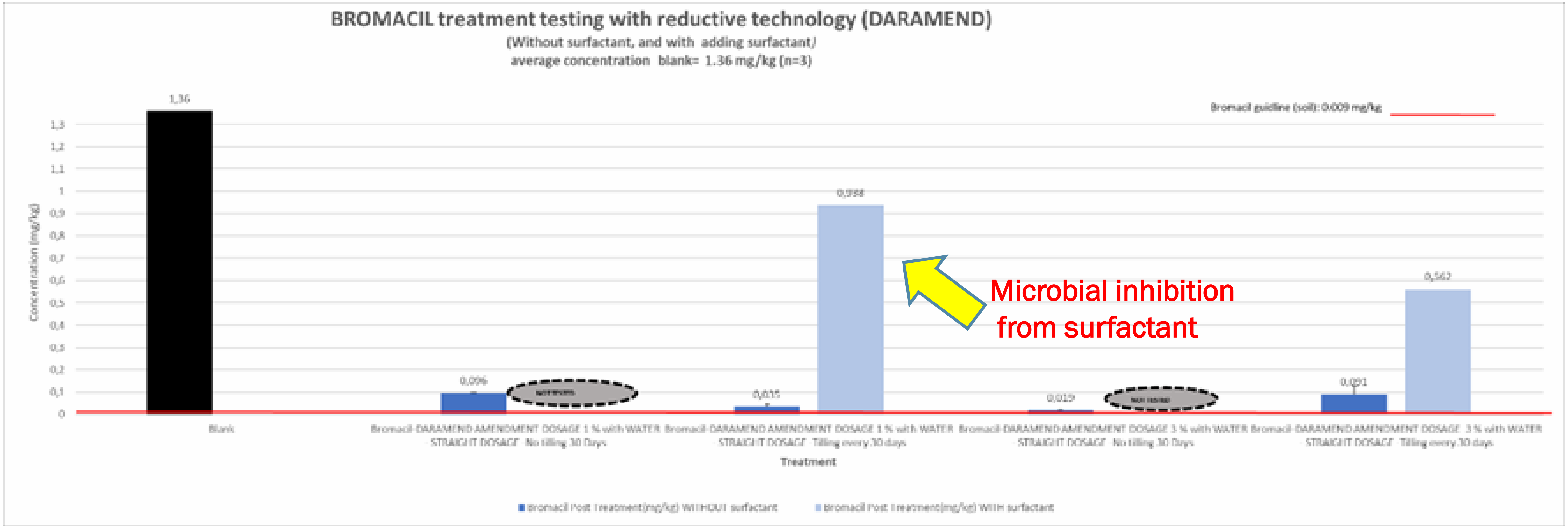
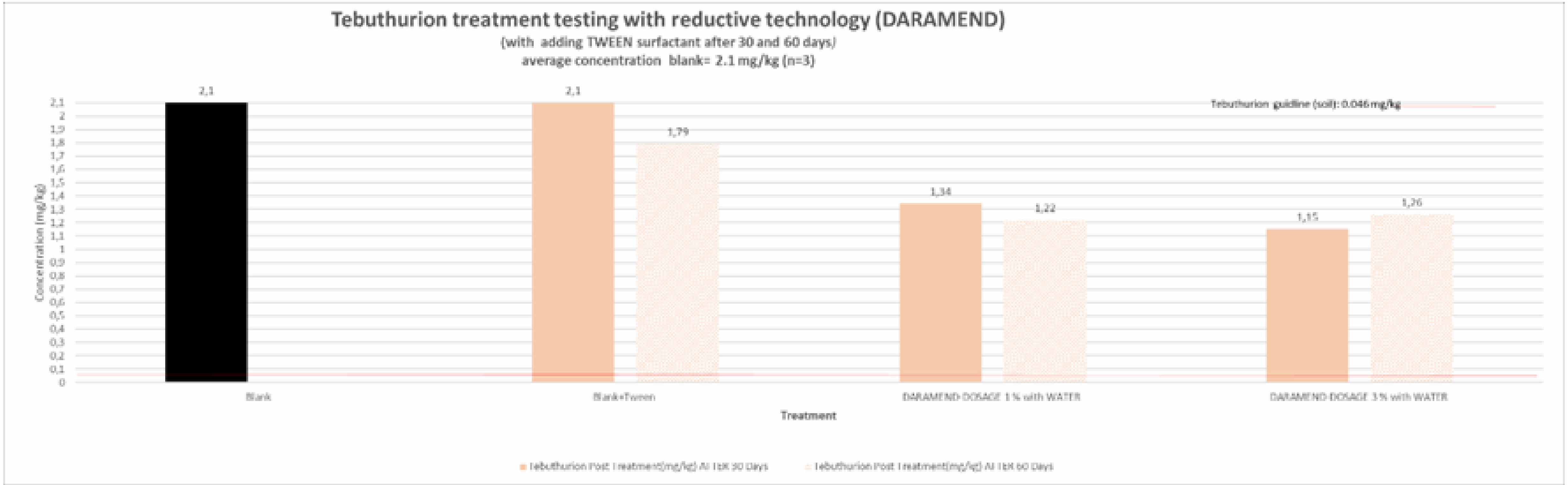


COMPARING THE EFFECT OF REDUCTIVE TREATMENT ON TEBUTHIURON WITH AND WITHOUT ADDITION OF SURFACTANT

SSP Soil Sterilants Program



Bromacil:

- ✓ Average percentage removal ranged from 31% to 59% after 30 days, although it was reduced by 98% after a treatment cycle of 60 days by tilling 1 % of DARAMEND amendment with the addition of surfactant TWEEN into the soil and using water to increase soil moisture content to 60% of the soil's water holding capacity (WHC). The tilling process served to aerate and homogenize the soil. **The Bromacil concentrations were reduced from 1,36 mg/kg to 0,016 mg/kg showing a significant reduction of 99%**.

- ➢ **The surfactant was detrimental to successful treatment with DARAMEND after 30 days, due to microbial cell wall interference.**

Tebuthiuron

- ✓ Average percentage removal was between 36 % and 45% after a treatment cycle of 30 days, and it was reduced by an average of 40 and 42% after a treatment cycle of 60 days using DARAMEND at a dosage of 1 and 3 % (wt/wt basis) respectively.

SUMMARY & LESSONS LEARNED

- **Destructive Technology targeting Bromacil:**

  - ✓ Daramend approach was highly effective in the treatment of Bromacil in the tested soil samples. Overall treatment product cost was approximately $55 / MT (product only) of soil using a 1 % w/w loading rate.
  - ✓ DARAMEND would only work in saturated conditions (or high-water content soil) as the contaminant destruction pathway would not be efficient if the water content is insufficient.
  - ✓ The hydrogen peroxide oxidation process using the VTX catalyst and surfactant more costly than the DARAMEND technology at 99 $\MT (product only) for the destruction of 1.0 mg/kg contaminant concentration. This product combination would be an alternative treatment method for a combined soil and groundwater issue.
  - ✓ These approaches enabled a rapid, cost- effective, and long-lasting treatment., very sustainable

SSP Soil Sterilants Program

SUMMARY & LESSONS LEARNED

- **Destructive Technology Targeting Tebuthiuron**

✓ ISCO approach with alkaline activated Klozur® persulfate study has been successful allow a reduction of 76 % of the Tebuthiuron without adding the surfactant using a low dosage of Klozur® persulfate.

✓ The stability of persulfate, can last weeks to months in the soil, provides a large radius of influence, and maximizes contact time with contaminants

✓ Treatment cost of $ 5/TM (product only) per 1 mg/kg removal of Tebuthiuron (without surfactant)

✓ This reactivity between the alkaline activated persulfate and the Tebuthiuron could also be an alternative treatment method in the case of a combined soil and groundwater issue.

Notes:

- The use of a surfactant will not be recommended for this treatment.
- No residual sodium persulfate was measured in the sacrificial samples
- The high SOD value obtained for the submitted soil might have limited contaminant destruction by this oxidant in the submitted soil samples.

NEXT STEPS AND TAKEAWAY

SSP Soil Sterilants Program

In Situ / Ex situ Destructive Technologies

- ✓ Soil Oxidant Demand (SOD) validation for any oxidation destructive is HIGHLY RECOMMENDED
- ✓ Potassium persulfate vs. Sodium Persulfate for additional persistency and face
- ✓ DARAMEND dosage optimization to obtain lower treatment cost needto be evaluated
- ✓ EHC could be applicable In situ as a Permeable reactive barrier setting for the saturated zone
- ✓ Mixing optimization and Water integration and maintenance for better reductive processes ex situ

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BENCH SCALE IN-SITU CHEMICAL REDUCTION & BIOSTIMULATION – VEI CONTRACTING

VEI Contracting Inc.

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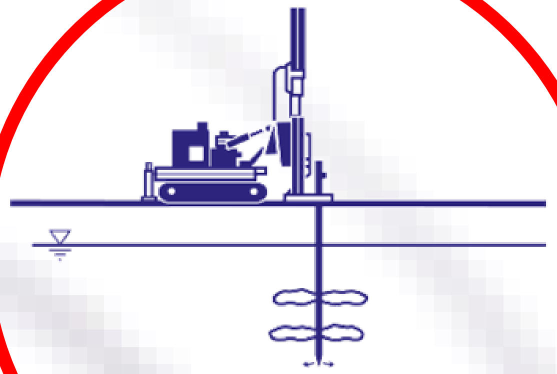
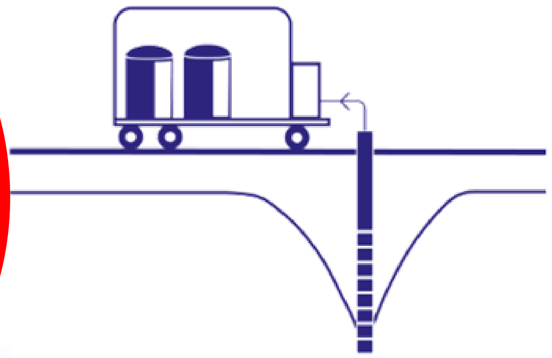
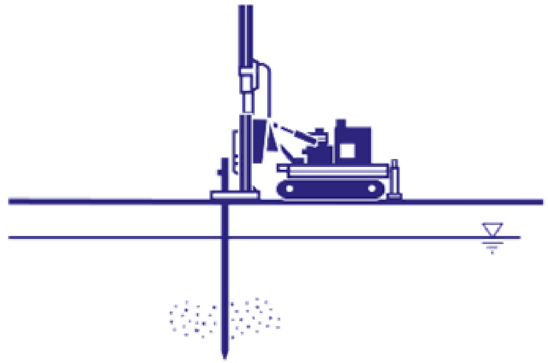

In-Situ Remediation


WTS & Dewatering

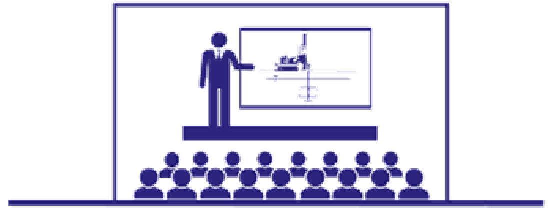

Ex-Situ Remediation


HRSC & RDC


Vapour Intrusion


Bench-Scale Testing


Remedial Design


Outreach

METHODS & RESULTS – TECHNOLOGIES ASSESSED

- Remedial technologies assessed:
  - Trap & Treat® BOS 200+®
  - Trap & Treat® CAT 100
  - Simulated Trap & Treat® BOS 200+® (i.e., no AC)
  - Simulated Trap & Treat® CAT 100 (i.e., no AC)
  - Zero-valent iron (ZVI)
  - ZVI with aluminum sulphate
  - Trap & Treat® BOS 200+® with surfactant
  - Trap & Treat® CAT 100 with surfactant
  - Simulated Trap & Treat® BOS 200+® with surfactant
  - Simulated Trap & Treat® CAT 100 with surfactant

SSP Soil Sterilants Program

METHODS & RESULTS – COMPOUNDS/MEDIA

Hyvar® X-L – commercial, 20% bromacil, liquid

Spike® 80DF – commercial, 80% tebuthiuron, solid

- Compounds/media tested:
  - Actual samples of sterilant impacted soils from Alberta provided by InnoTech
  - Samples had detectable concentrations of sterilants above the standards:
    - Bromacil: baseline = 0.210 mg/kg
    - Tebuthiuron: baseline = 0.136 mg/kg
  - Soils were impacted with Hyvar® or Spike®
  - Samples were not previously augmented with AC
  - **Required degree of treatment to meet standards from baseline concentrations:**
    - **Bromacil: 95.7%**
    - **Tebuthiuron: 93.4%**

METHODS & RESULTS – TESTING PROCEDURE

- Approx. 2.5 kg of impacted soil was mixed with remedial amendments, saturated with distilled water and placed into a 3 L glass jar for each of the reactors and configurations.
- Reactors were equipped with an inlet valve and a water-sealed check valve to allow nitrogen gas to be injected into the headspace of the reactor to maintain anaerobic conditions.
- Reactors were covered with a black cloth to prevent any photochemistry from occurring.
- The soils in each reactor was thoroughly mixed on a daily basis for the first 2 weeks to ensure good contact between the remedial amendments and the sterilants. Following this, the reactors were mixed weekly until the 2-month sampling event, and then left without mixing for the final 2 months of the testing program.

METHODS & RESULTS – REACTOR CONFIGURATION

- #1 – Control reactor; only the contaminated soil with no added reagents or amendments
- #2 - 1.2% wt. Trap & Treat® BOS 200+®
- #3 - 0.7% wt. Trap & Treat® CAT 100
- #4 - Same components and weight percentages as #2 but without any AC component
- #5 - Same components and weight percentages as reactor #3 but without any AC component
- #6 - 5% wt. ZVI (ISCR)
- #7 - 5% wt. ZVI with 3.5% wt. aluminum sulphate (ISCR+)
- #8 - Same as reactor #2 with 0.2% wt. Tween 80 surfactant
- #9 - Same as reactor #3 with 0.2% wt. Tween 80 surfactant
- #10 - Same as reactor #4 with 0.2% wt. Tween 80 surfactant
- #11 - Same as reactor #5 with 0.2% wt. Tween 80 surfactant

METHODS & RESULTS – BROMACIL RESULTS

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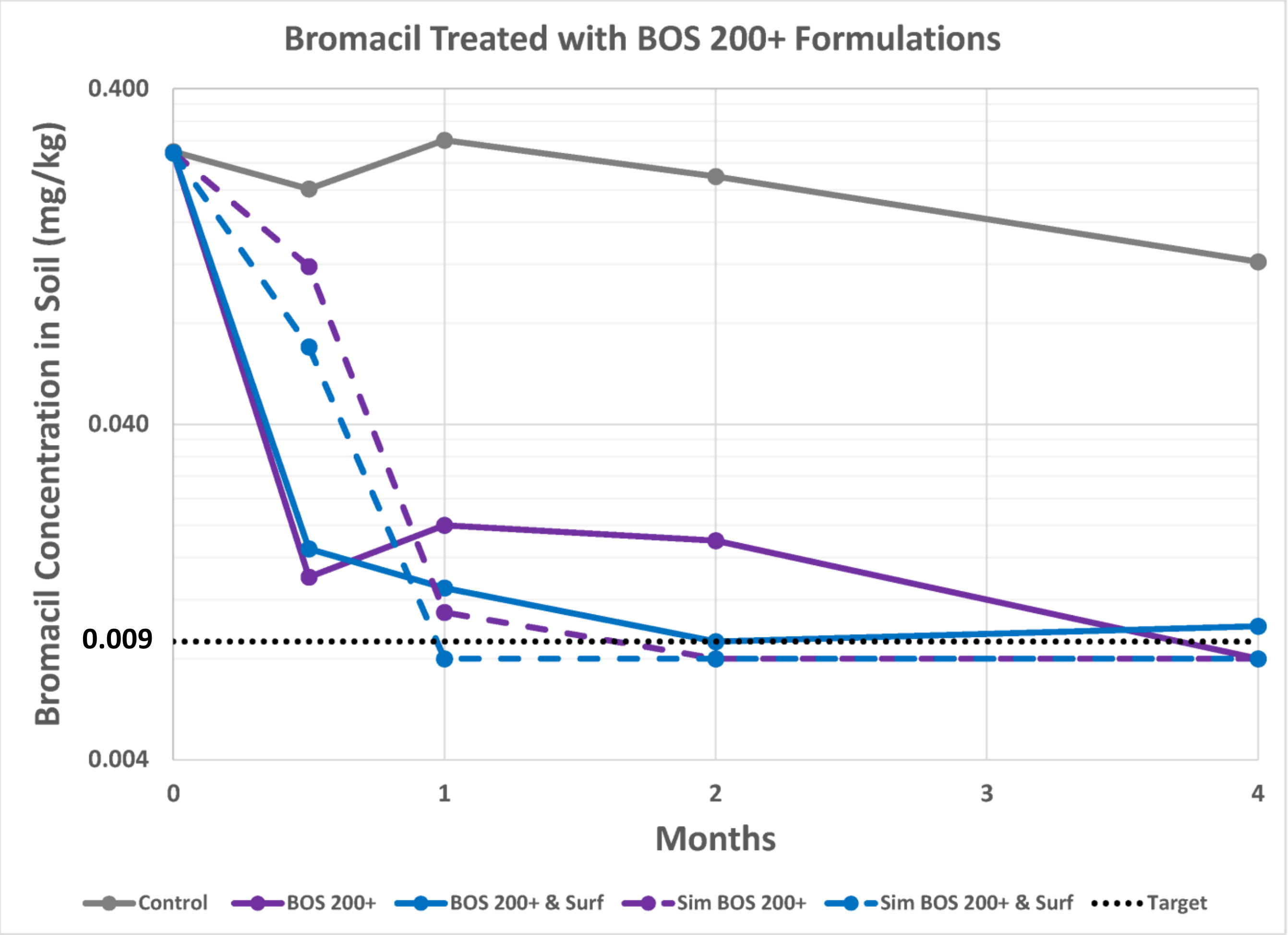
Reactor ID	Bromacil Concentrations in Soil (mg/kg)							Final Net Percent Reduction vs Control (%)
	Sampling Dates							
	Mixed Soil Baseline 2022-04-27	Starting Baseline 2022-06-08	Adjusted Starting Baseline 2022-06-08	2 Weeks 2022-07-18	1 Month 2022-08-04	2 Months 2022-09-06	4 Months 2022-11-04	
Control	0.210	0.260	0.260	0.202	0.281	0.219	0.122	0.0%
BOS 200+	0.210	0.260	0.257	0.014	0.020	0.018	**<0.008**	**>44.9%**
BOS 200+ & Surf	0.210	0.260	0.257	0.017	0.013	0.009	0.010	44.1%
Sim BOS 200+	0.210	0.260	0.258	0.118	0.011	**<0.008**	**<0.008**	**>44.6%**
Sim BOS 200+ & Surf	0.210	0.260	0.258	0.068	**<0.008**	**<0.008**	**<0.008**	**>44.6%**
CAT 100	0.210	0.260	0.258	0.051	0.081	0.038	0.034	34.3%
CAT 100 & Surf	0.210	0.260	0.258	0.066	0.042	0.024	0.014	42.1%
Sim CAT 100	0.210	0.260	0.257	0.050	**<0.008**	**<0.008**	**<0.008**	**>45.0%**
Sim CAT 100 & Surf	0.210	0.260	0.257	0.027	**<0.008**	**<0.008**	**<0.008**	**>45.0%**
ISCR	0.210	0.260	0.248	0.198	0.086	**<0.008**	**<0.008**	**>48.5%**
ISCR +	0.210	0.260	0.239	0.106	0.101	0.073	0.076	21.2%
Target Standard	**0.009**							

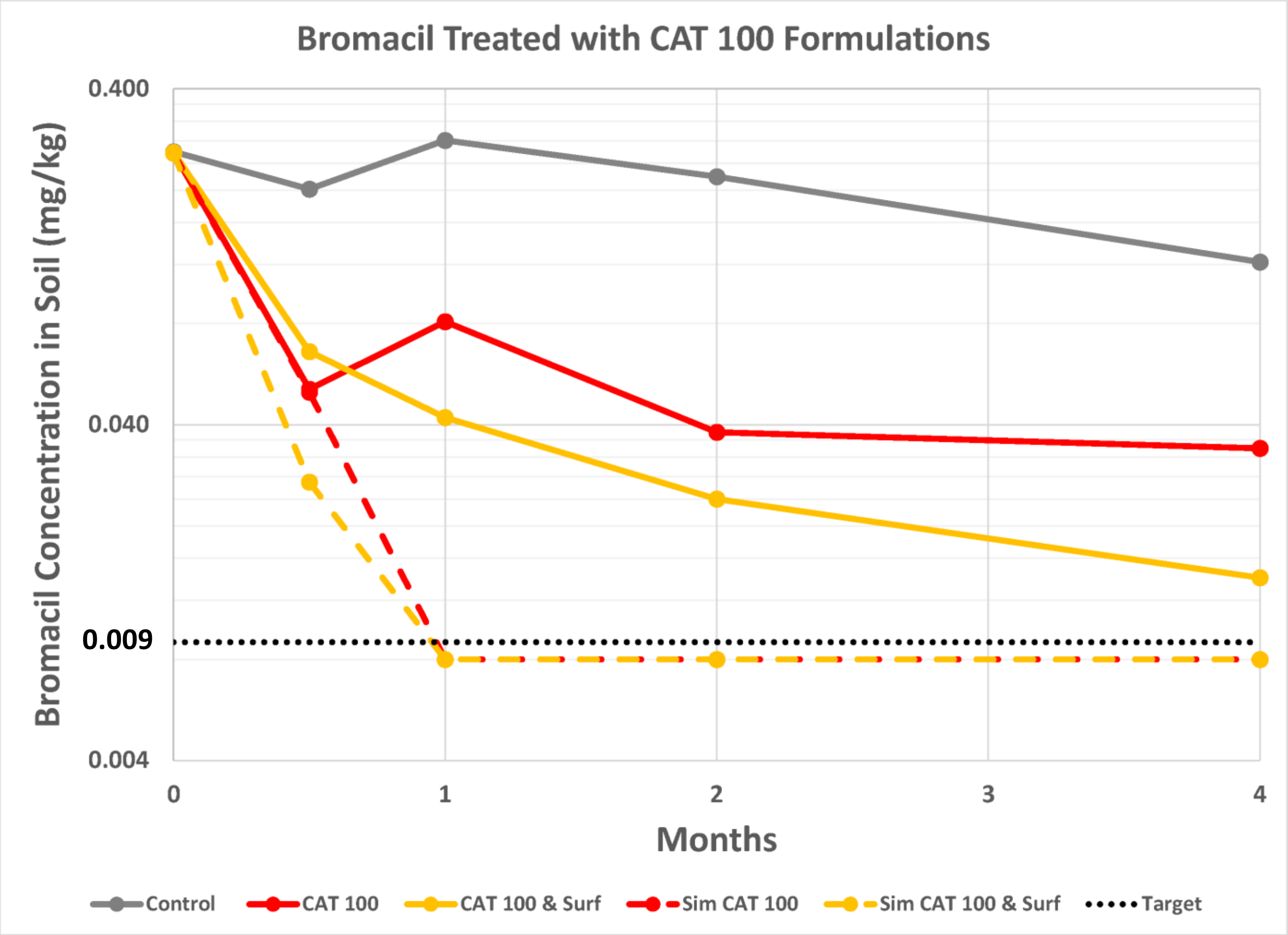
METHODS & RESULTS – BROMACIL RESULTS

- Technology: Bromacil-impacted soils treated with BOS 200+ formulations:
  - All treatment reactors reduced bromacil concentrations more than in the control
  - **Bromide was detected** in all treatment reactors indicating **bromacil destruction** (not just adsorption)
  - Surfactant slightly improved treatment performance
  - **All BOS 200+ formulations can reduce bromacil in soil to below the target concentration within a few months**



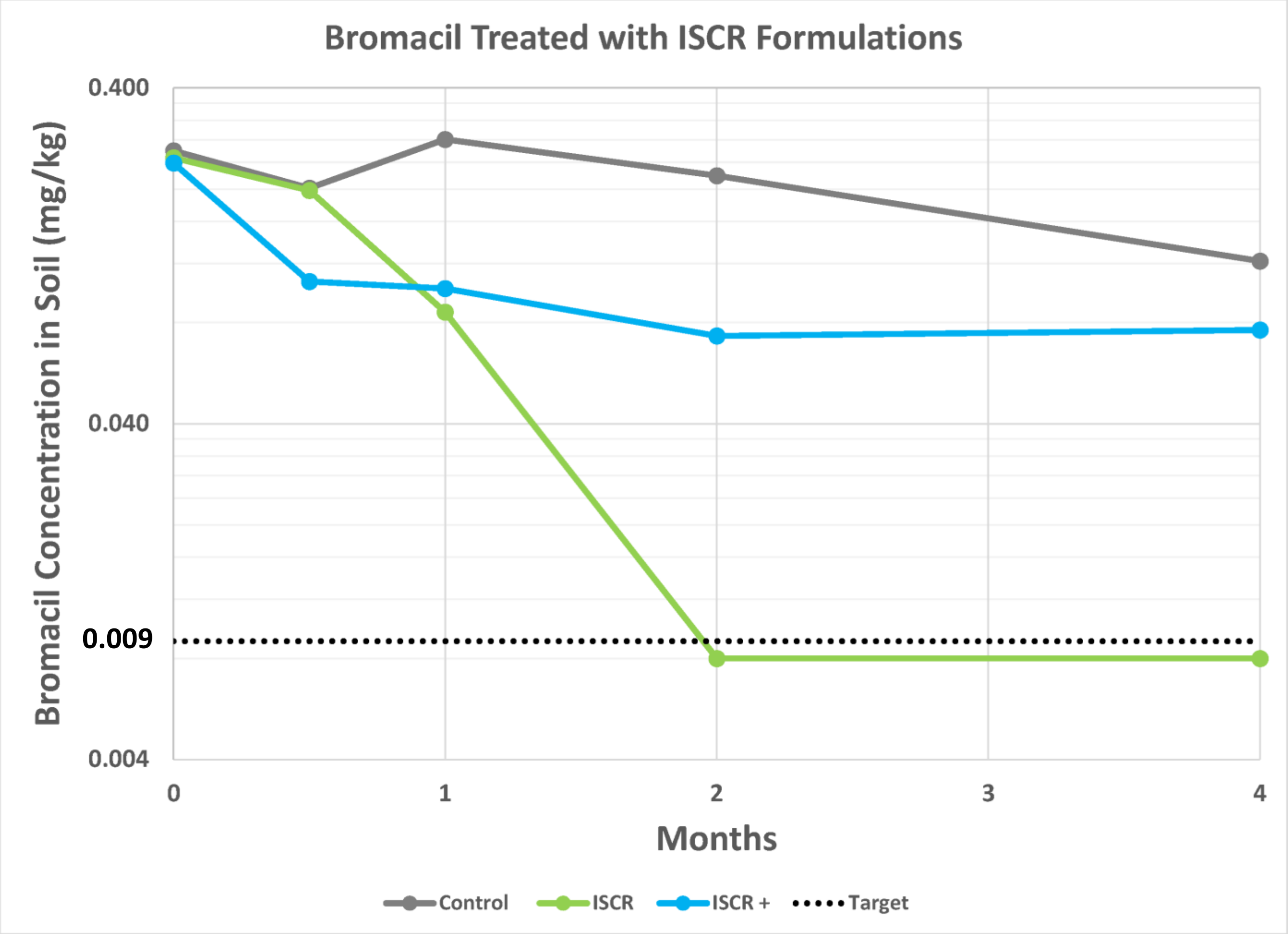
METHODS & RESULTS – BROMACIL RESULTS

- Technology: Bromacil-impacted soils treated with CAT 100 formulations:
  - All treatment reactors reduced bromacil concentrations more than in the control
  - **Bromide was detected** in all treatment reactors indicating **bromacil destruction** (not just adsorption)
  - AC reduced treatment performance
  - Surfactant slightly improved treatment performance
  - **All CAT 100 formulations can reduce bromacil in soil, but only the reactors without AC met the target concentrations within a few months**



METHODS & RESULTS – BROMACIL RESULTS

- Technology: Bromacil-impacted soils treated with ISCR formulations:
  - Both treatment reactors reduced bromacil concentrations more than in the control
  - **Bromide was detected** in both treatment reactors indicating **bromacil destruction**
  - pH adjustment reduced treatment performance
  - **ISCR (ZVI) can reduce bromacil in soil to below the target concentration within a few months**



METHODS & RESULTS – BROMACIL RESULTS SUMMARY

- Technology Summary: Treatment of bromacil-impacted soils
  - **All treatment approaches**, BOS 200+, CAT 100 and ISCR formulations, **reduced bromacil concentrations in soil**
  - **Bromide generation** in reactors containing no AC **confirm bromacil destruction**, not just adsorption.
  - The presence of surfactant slightly improved performance for CAT 100 and BOS 200+ formulations
  - **Simulated BOS 200+ and simulated CAT 100 (both without their AC component), with and without surfactant,** were the best performing and would be **applicable for general plume treatment**
  - **ISCR (ZVI)** was slightly slower but would also be **applicable for general plume treatment**
  - For a potential permeable reactive barrier (PRB) application the AC component is desirable for longevity and the absence of surfactant is desirable for adsorptive strength
  - Therefore, for a **PRB application** to treat migrating plumes of bromacil in groundwater, **the preferred amendment is the full formulation of BOS 100 (AC and elemental iron; less expensive than CAT 100)**

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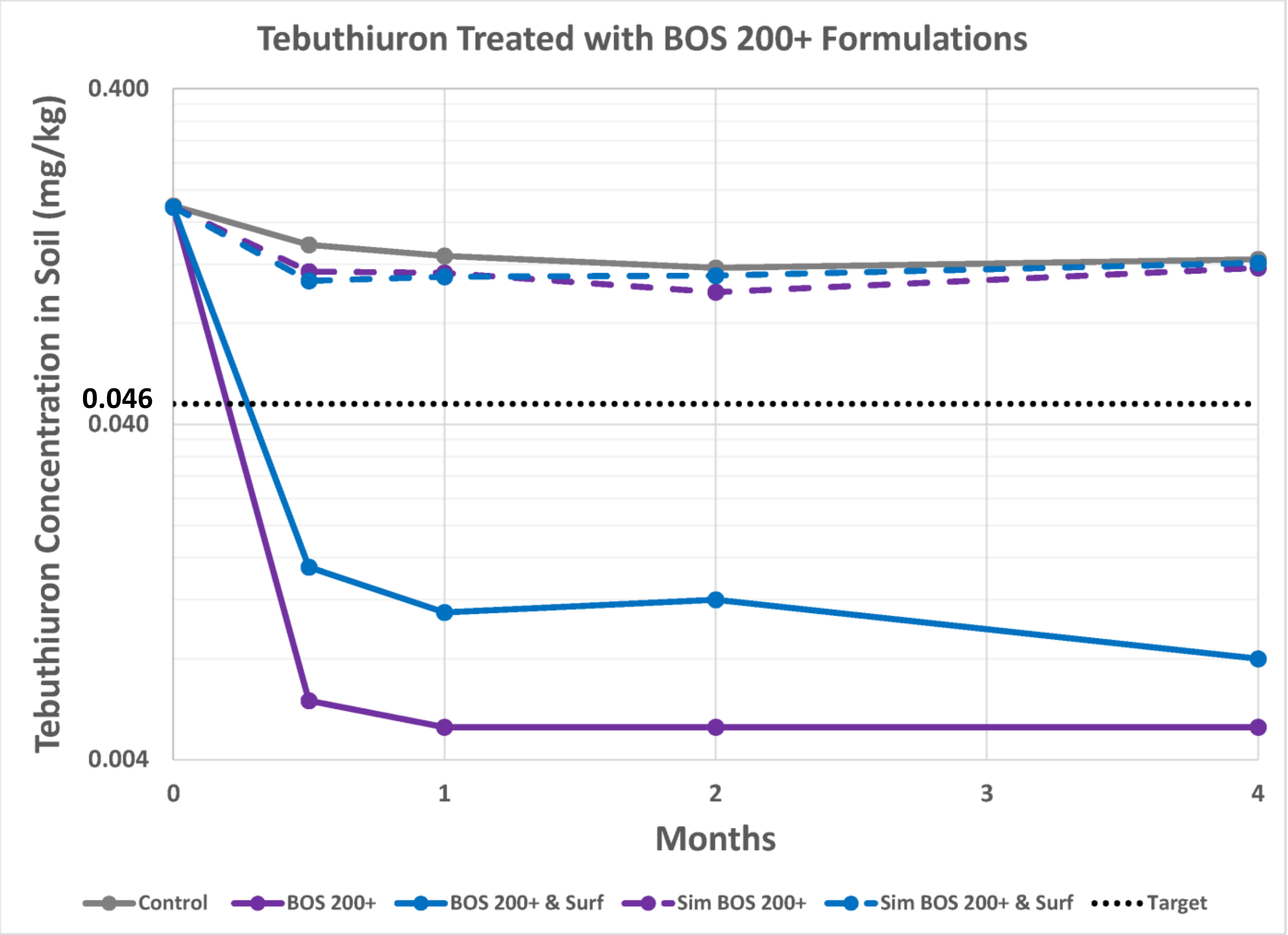
METHODS & RESULTS – TEBUTHIURON RESULTS

Reactor ID	Tebuthiuron Concentrations in Soil (mg/kg) – Sampling Dates: Mixed Soil Baseline 2022-04-27	Starting Baseline 2022-06-08	Adjusted Starting Baseline 2022-06-08	2 Weeks 2022-07-18	1 Month 2022-08-04	2 Months 2022-09-06	4 Months 2022-11-04	Final Net Percent Reduction vs Control (%)
Control	0.136	0.179	0.179	0.137	0.127	0.117	0.124	0.0%
BOS 200+	0.136	0.179	0.177	**0.006**	**<0.005**	**<0.005**	**<0.005**	**>67.5%**
BOS 200+ & Surf	0.136	0.179	0.177	**0.015**	**0.011**	**0.012**	**0.008**	65.8%
Sim BOS 200+	0.136	0.179	0.178	0.114	0.113	0.099	0.117	3.7%
Sim BOS 200+ & Surf	0.136	0.179	0.178	0.107	0.110	0.111	0.121	1.4%
CAT 100	0.136	0.179	0.178	**0.039**	**0.020**	**0.022**	**0.035**	50.1%
CAT 100 & Surf	0.136	0.179	0.178	0.076	0.072	0.065	**0.036**	49.5%
Sim CAT 100	0.136	0.179	0.177	0.095	0.111	0.118	0.094	16.7%
Sim CAT 100 & Surf	0.136	0.179	0.177	0.106	0.101	0.096	0.112	6.4%
ISCR	0.136	0.179	0.170	0.111	0.121	0.105	0.088	20.1%
ISCR +	0.136	0.179	0.164	0.079	0.080	0.066	0.067	33.8%
Target Standard	0.046							

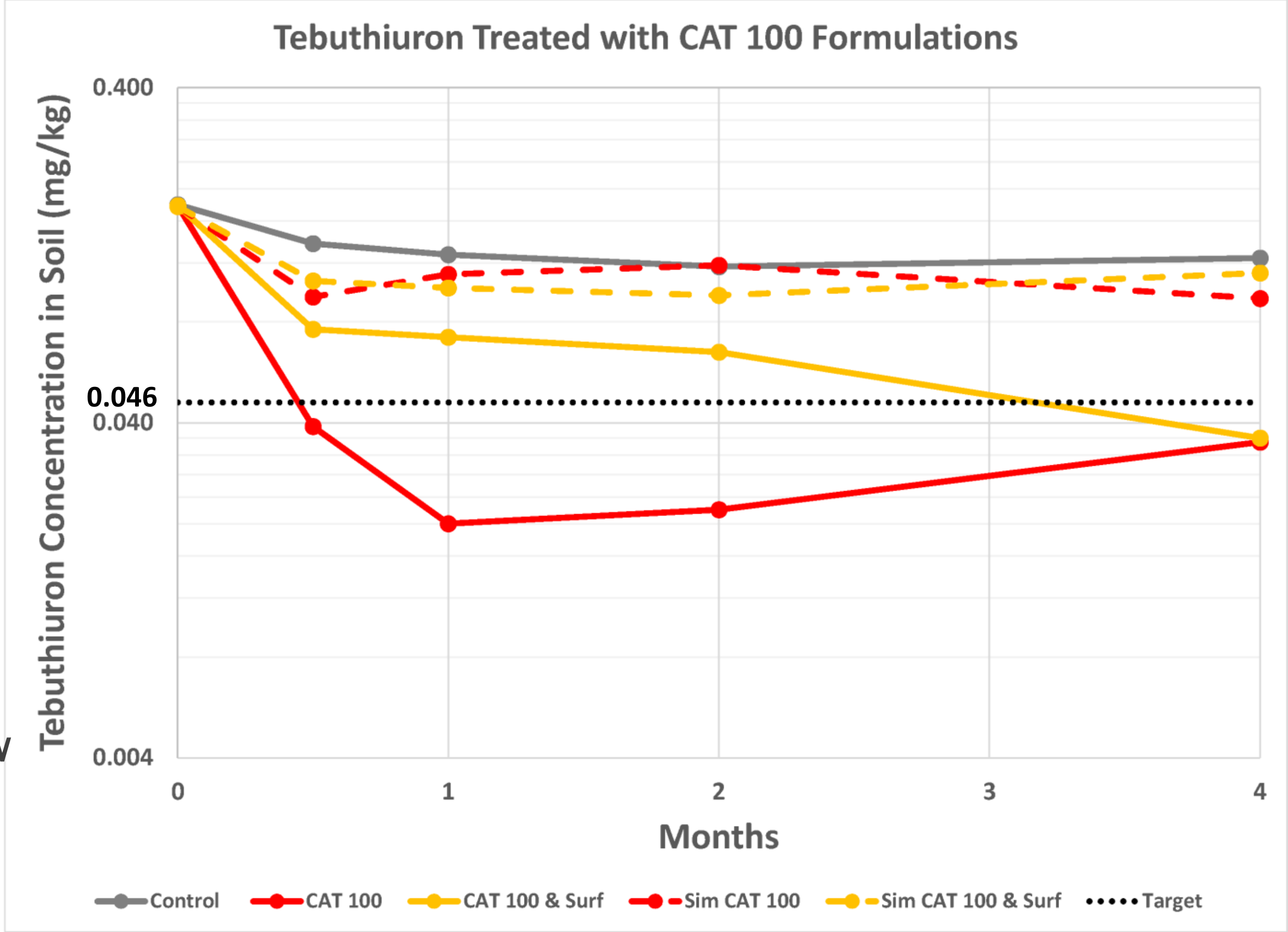
METHODS & RESULTS – TEBUTHIURON RESULTS

- Technology: Tebuthiuron-impacted soils treated with BOS 200+ formulations:
  - Only the full BOS 200+ treatment reactors reduced tebuthiuron concentrations more than in the control
  - **No evidence of tebuthiuron destruction** (adsorption only)
  - Surfactant reduced treatment performance
  - **Both full formulations BOS 200+ (with AC) can reduce tebuthiuron in soil to below the target concentration within a few weeks**



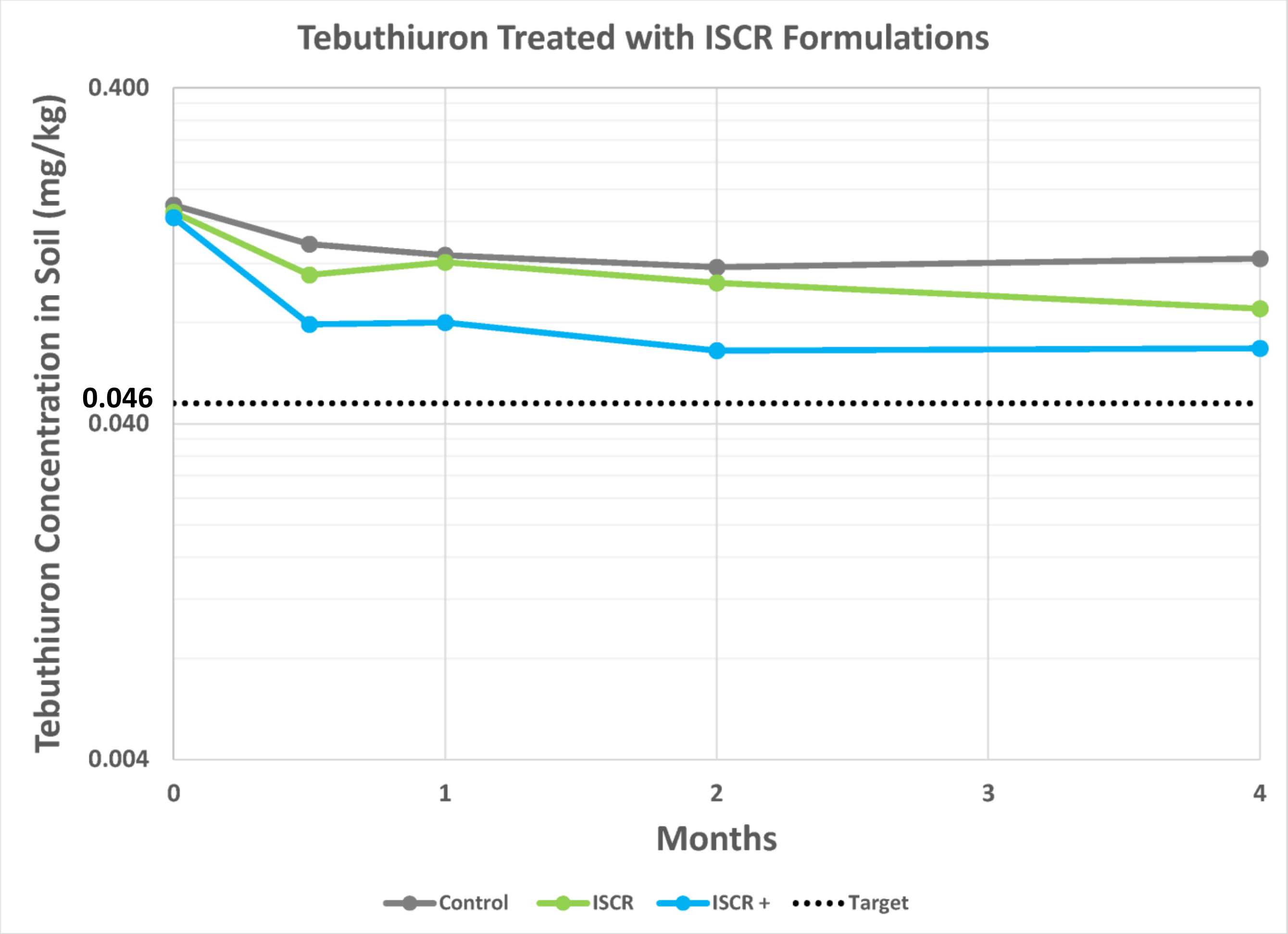
METHODS & RESULTS – TEBUTHIURON RESULTS

- Technology: Tebuthiuron-impacted soils treated with CAT 100 formulations:
  - All treatment reactors reduced tebuthiuron concentrations more than in the control
  - Simulated versions of CAT 100 (no AC) performed slightly better than the control – **possibly indicating some tebuthiuron destruction**
  - Surfactant reduced treatment performance
  - **All CAT 100 formulations can reduce tebuthiuron in soil, but only the reactors with AC met the target concentrations within a few weeks**



METHODS & RESULTS – TEBUTHIURON RESULTS

- Technology: Tebuthiuron-impacted soils treated with ISCR formulations:
  - Both treatment reactors reduced tebuthiuron concentrations to greater extents than in the control **likely indicating tebuthiuron destruction**
  - pH adjustment increased treatment performance
  - Neither of the ISCR configurations reduced tebuthiuron to below the target concentration
  - **ISCR formulations can degrade tebuthiuron in soil** but did not meet the target concentration within 4 months



METHODS & RESULTS – TEBUTHIURON RESULTS SUMMARY

- Technology Summary: Treatment of tebuthiuron-impacted soils
  - **All treatment approaches**, BOS 200+, CAT 100 and ISCR formulations, **reduced tebuthiuron concentrations in soil**
  - BOS 200+ reduced concentrations more than CAT 100 (both with and without surfactant)
  - However, **evidence of destruction** (i.e., reductions in the absence of AC) was only **observed for the ISCR and possibly the CAT 100 reactors**
  - **The full formulations of BOS 200+ (with their AC component), with and without surfactant,** were the best performing and would be **applicable for general plume treatment, but would not provide permanent destruction of the tebuthiuron**
  - For a potential PRB application destruction is preferable, the AC component is desirable for longevity and the absence of surfactant is desirable for adsorptive strength
  - Therefore, **for permanent plume treatment or a PRB application** to treat migrating plumes of tebuthiuron in groundwater, **the preferred amendment is the full formulation of CAT 100 (or possibly BOS 100)**

SUMMARY & LESSONS LEARNED

- **Permanent destructive technologies were demonstrated for both bromacil and (to a lesser extent) tebuthiuron**
- **For sites with bromacil impacts:**
  - **Simulated BOS 200+ and simulated CAT 100** (both without their AC component), **with and without surfactant,** were the best performing and would be **applicable for general plume treatment**
  - The **full formulation of BOS 100 (AC and elemental iron), without surfactant,** is the preferred formulation for a PRB application to treat **migrating plumes of bromacil in groundwater**
- **For sites with tebuthiuron impacts:**
  - The **full formulations of BOS 200+, with and without surfactant,** were the best performing and would be **applicable for general plume treatment, but would not provide permanent destruction**
  - The **full formulation of CAT 100 (or possibly BOS 100), without surfactant,** is the preferred formulation for a PRB application to treat **migrating plumes of tebuthiuron in groundwater and for permanent plume treatment**

TAKEAWAYS & NEXT STEPS

- **Several remedial amendments** were assessed and **shown to be effective in reducing bromacil and tebuthiuron concentrations** in Alberta soils to below target concentrations
- **Permanent destruction of bromacil was demonstrated** through the generation of bromide in the samples
- **Permanent destruction of tebuthiuron was inferred** based on measured reductions in the absence of AC
- The treatment reactors were dosed with standard remedial amendment loading rates commonly used at other types of impacted sites, confirming financial viability of treatment
- The **preferred remedial amendments can be applied under field conditions** via soil mixing or injection approaches
- The preferred remedial amendments are **all applicable to subsurface applications (at or below the water table)** as they work under anaerobic conditions
- **Approaches for general plume treatment and for permeable reactive barrier (PRB) applications are feasible**
- Further pilot- or field-scale trials are recommended to confirm the suitability for treating bromacil and tebuthiuron in soil and/or groundwater under real-world conditions

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QUESTIONS?

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