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In-Situ Chemical Oxidation of TCE in Clay Using Rotating Dual Axis Soil Blending Technology

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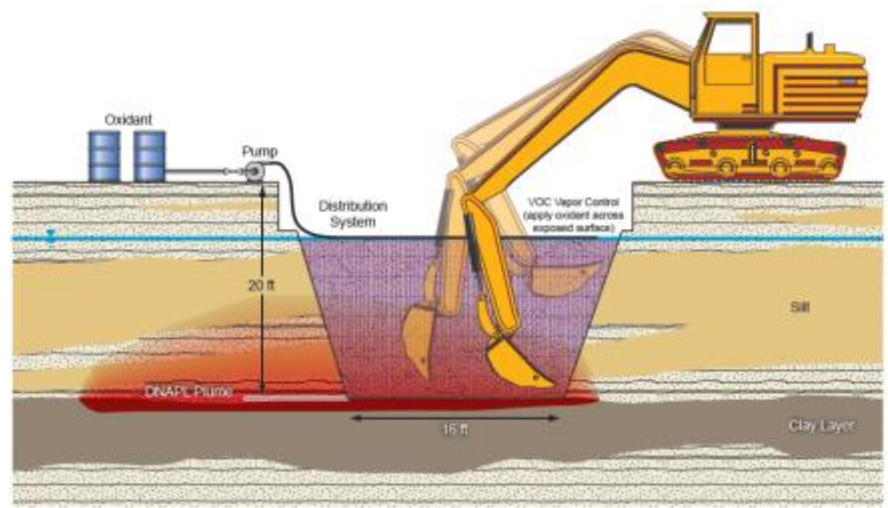
ISCO at High Concentration Source Area Sites

- Generally effective in treating COCs (dissolved phase and lower concentration chemicals)
- Most effective in treating higher permeability soil types
- Limited effectiveness in treating NAPL, viscous products, and coal tar
- Success or failure of ISCO treatment is largely dependent on:
  - Sound conceptual site model
  - Development of site-specific treatment goals
  - Oxidant type
  - Reagent delivery method
  - Contact of chemical reagent with COCs

Traditional Subsurface Delivery Methods

- Direct Injection
  - Temporary injection points (e.g., DPT borings, Geoprobe®)
  - Fixed injection wells (e.g., screened wells)
  - Bedrock injection wells (e.g., inflatable isolation packers)
  - Trenches and horizontal well systems

- Soil Mixing
  - Backhoe methods
  - Auger methods



ISCO Application Challenges in Source Areas

- High concentration sites often require large quantities of reagent:
  - » **HIGH** oxidant demand = **LARGE** oxidant volume
  - » Numerous injection rounds are typically required
- Reagent delivery by injection is limited by soil pore space
  - – Difficult injecting large oxidant volume
- Reagent short-circuiting/ surfacing
- Contaminant displacement
- <u>Reagent contact with COC is critical</u>

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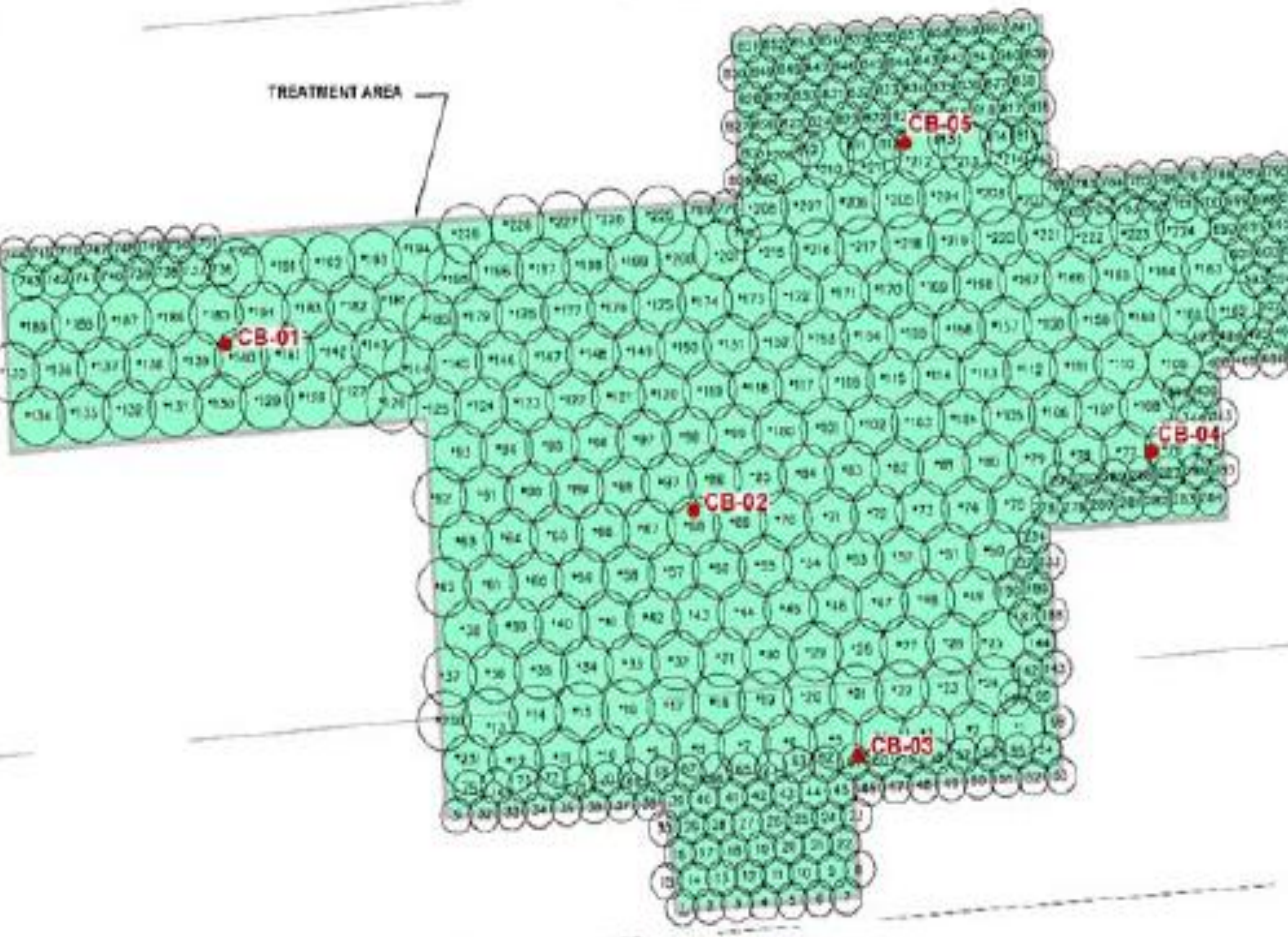
Auger Mixing Unit

Detail of Auger


TREATMENT AREA
CB-05
CB-01
CB-04
CB-02
CB-03

Dual Axis Soil Blending Technology

Key components and benefits

- Dual–axis rotation (optimal soil mixing performance)
- Reagent application at point of mixing (maximize chemical contact)
- Large amounts of reagent introduced in a single application
- Control of chemical dosing
- Appropriate for most soil, COC, and oxidant types

Dual Axis Soil Blending Technology

- Site conditions favorable for technology
  - Variable soil types
  - Shallow or moderately deep soil and groundwater impacts
  - Dissolved fraction and higher concentration contaminants (COC < C_{sat})
- Less favorable site conditions
  - Limited working space availability
  - Bedrock/ subsurface obstructions
  - Significant NAPL (COC > C_{sat})

Technology Considerations

- Persulfate corrosion testing

Design and Implementation Techniques

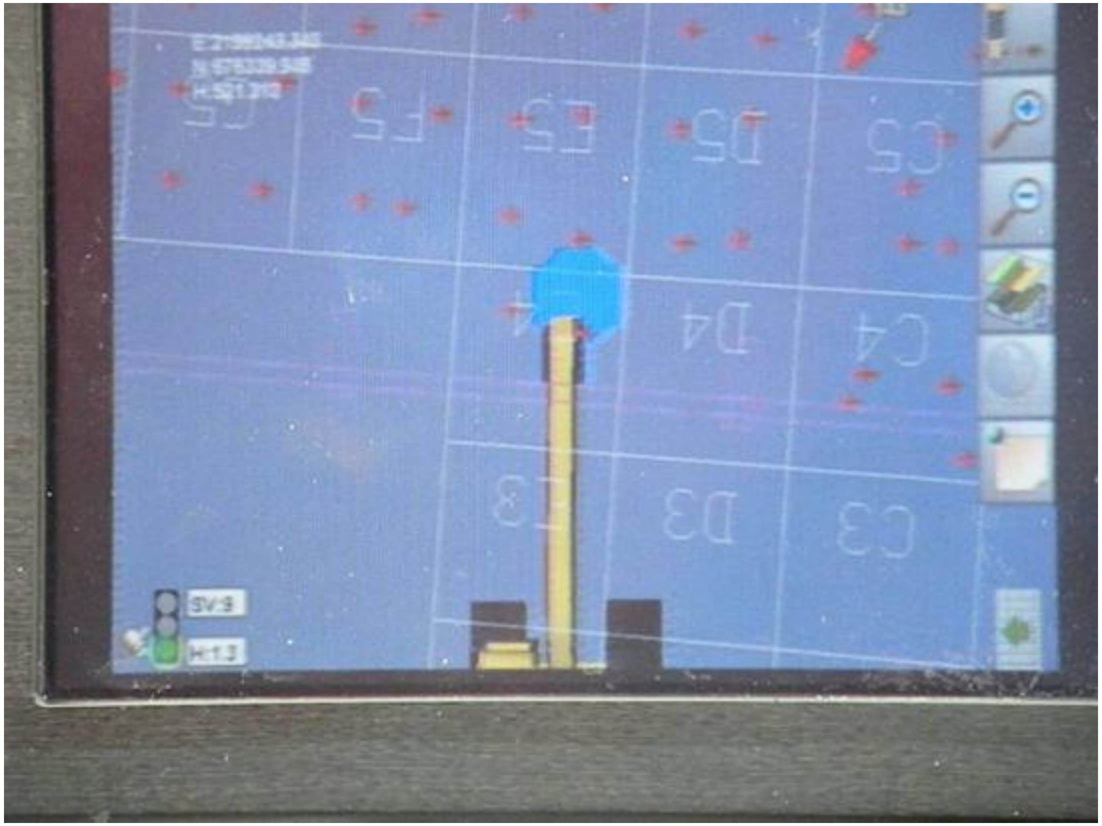
Example of reagent distribution plan and treatment grid

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1	10 ft x 10 ft Treatment Cells						SP 255 Na 180		SP 278 Na 196	SP 278 Na 196	SP 278 Na 196					Upper Clay Unit Reagent Quantities					
2					SP 268 Na 180	SP 537 Na 361	SP 510 Na 359	SP 510 Na 359	SP 510 Na 359	SP 510 Na 359	SP 557 Na 392		SP 586 Na 394	SP 586 Na 394							
3				SP 537 Na 361	SP 537 Na 361	SP 537 Na 361	SP 537 Na 361	SP 537 Na 361	SP 537 Na 361	SP 537 Na 361	SP 586 Na 394	SP 586 Na 394	SP 586 Na 394	SP 586 Na 394	SP 586 Na 394	SP 388 Na 200	SP 776 Na 399	SP 776 Na 399	SP 841 Na 432		
4	SP 278 Na 196	SP 510 Na 359	SP 510 Na 359	SP 510 Na 359	SP 712 Na 365	SP 537 Na 361	SP 537 Na 361	SP 537 Na 361	SP 510 Na 359	SP 712 Na 365	SP 712 Na 365	SP 586 Na 394	SP 586 Na 394	SP 586 Na 394	SP 586 Na 394	SP 776 Na 399	SP 776 Na 399	SP 776 Na 399	SP 841 Na 432	SP 933 Na 442	SP 933 Na 442
5	SP 557 Na 392	SP 510 Na 359	SP 510 Na 359	SP 510 Na 359	SP 712 Na 365	SP 537 Na 361	SP 510 Na 359	SP 510 Na 359	SP 510 Na 359	SP 712 Na 365	SP 712 Na 365	SP 586 Na 394	SP 586 Na 394	SP 586 Na 394	SP 586 Na 394	SP 776 Na 399	SP 776 Na 399	SP 776 Na 399	SP 841 Na 432	SP 933 Na 442	SP 933 Na 442
6	SP 557 Na 392	SP 557 Na 392	SP 510 Na 359	SP 537 Na 361	SP 712 Na 365	SP 510 Na 359	SP 510 Na 359	SP 510 Na 359	SP 510 Na 359	SP 790 Na 374	SP 862 Na 408	SP 586 Na 394	SP 586 Na 394	SP 586 Na 394	SP 586 Na 394	SP 776 Na 399	SP 776 Na 399	SP 776 Na 399	SP 841 Na 432	SP 933 Na 442	SP 933 Na 442
7	SP 557 Na 392	SP 557 Na 392	SP 586 Na 394	SP 586 Na 394	SP 586 Na 394	SP 586 Na 394	SP 557 Na 392	SP 557 Na 392	SP 557 Na 392	SP 586 Na 394	SP 862 Na 408	SP 862 Na 408	SP 586 Na 394	SP 586 Na 394	SP 586 Na 394	SP 841 Na 432	SP 841 Na 432	SP 1294 Na 432	SP 841 Na 432	SP 933 Na 442	SP 933 Na 442
8	SP 557 Na 392	SP 557 Na 392	SP 557 Na 392	SP 586 Na 394	SP 586 Na 394	SP 586 Na 394	SP 557 Na 392	SP 557 Na 392	SP 586 Na 394	SP 586 Na 394	SP 776 Na 399	SP 776 Na 399	SP 586 Na 394	SP 586 Na 394	SP 603 Na 424	SP 841 Na 432	SP 841 Na 432	SP 841 Na 432	SP 841 Na 432	SP 933 Na 442	SP 1005 Na 476
9	SP 557 Na 392	SP 557 Na 392	SP 557 Na 392	SP 557 Na 392	SP 586 Na 394	SP 634 Na 426	SP 975 Na 457	SP 650 Na 457	SP 634 Na 426	SP 862 Na 408	SP 862 Na 408	SP 776 Na 399				SP 420 Na 216	SP 1262 Na 432	SP 841 Na 432	SP 906 Na 465	SP 1005 Na 476	
10	SP 557 Na 392	SP 557 Na 392	SP 557 Na 392	SP 557 Na 392	SP 650 Na 457	SP 650 Na 457	SP 603 Na 424	SP 603 Na 424	SP 683 Na 459	SP 862 Na 408	SP 933 Na 442	SP 933 Na 442									
11	SP 325 Na 228	SP 650 Na 457	SP 603 Na 424	SP 603 Na 424	SP 603 Na 424	SP 603 Na 424	SP 732 Na 492	SP 732 Na 492	SP 1005 Na 476	SP 1005 Na 476	SP 503 Na 238										
12			SP 650 Na 457	SP 650 Na 456	SP 634 Na 426	SP 634 Na 426	SP 732 Na 492	SP 684 Na 460	SP 906 Na 464	SP 453 Na 232											
13				SP 650 Na 457	SP 603 Na 424	SP 603 Na 424	SP 634 Na 426	SP 906 Na 465	SP 453 Na 232												

Yellow	**Pre-Treatment VOC Concentration <7,000 ppb**
Green	**Pre-Treatment VOC Concentration 7,000-20,000 ppb**
Blue	**Pre-Treatment VOC Concentration 20,000-25,000 ppb**
Magenta	**Pre-Treatment VOC Concentration >25,000 ppb**

Dual Axis Soil Blending Technology

- Control of blending location with GPS
- On-board GPS with 3-D visualization



Health and Safety

- Operator communication – overcoming equipment noise
- Hazardous chemicals – handling and management of chemicals and daily residuals

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Site Preparation – Overburden Removed & Stockpiled

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Site Preparation – Dike Construction

Example of Clay Soil

Dual-Axis Mixer

LTC Chemical Mixing Truck

Mixing Unit Treating in Deep Zone

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Mixing Unit Treating in Deep Zone, cont.

Mixing Unit Treating in Deep Zone, cont.

Mixing Unit Treating in Deep Zone, cont.

Design and Implementation Techniques

- Soil treatment verification sampling

Decision Factors Affecting Performance

- Real-time soil treatment verification sampling
- Adjusting mixing duration and/or reagent dosage

- Soil management
- Chemical supply logistics
- Chemical mixing quality control

Backfilling Stockpiled Overburden

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Technology Considerations

- Re-blending limitations
- Large rocks or boulders

- Poor drainage in fine-grained soil (ponding of water and chemical reagents)
- Soil expansion
- Post-blending soil structure – site redevelopment considerations

Underground Obstructions Result in Maintenance

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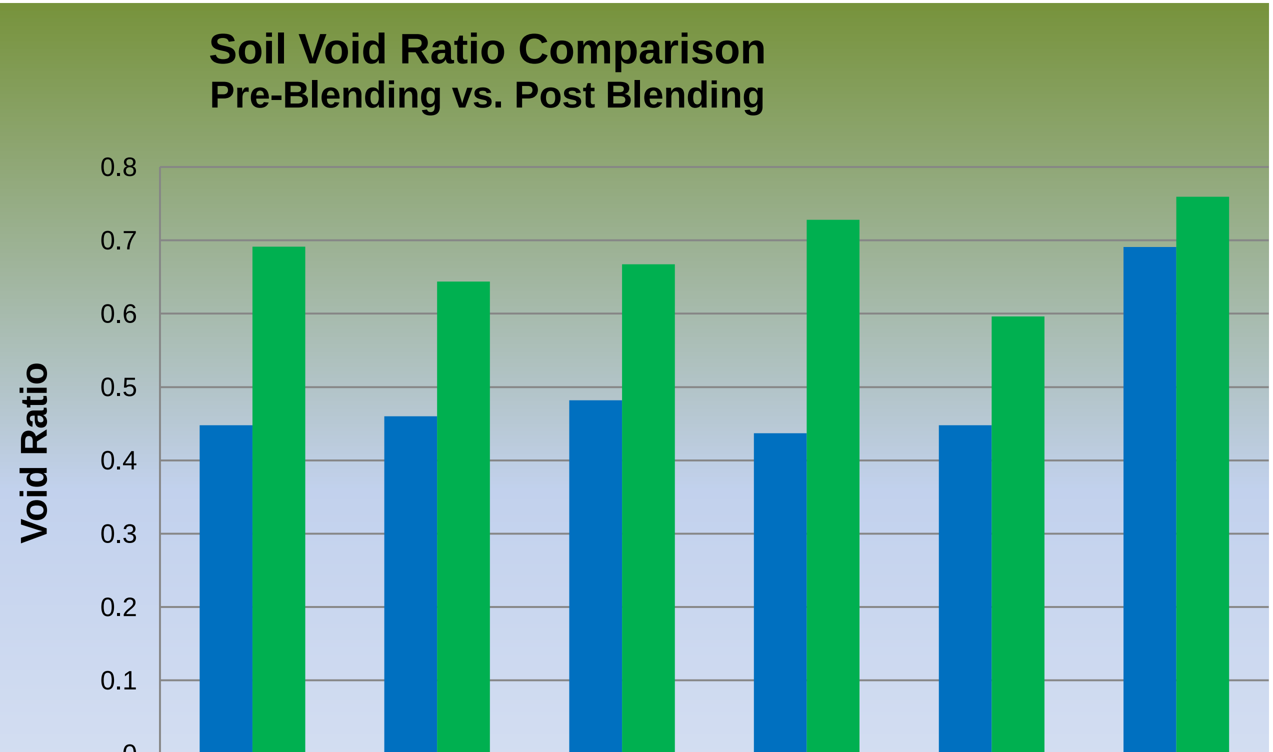
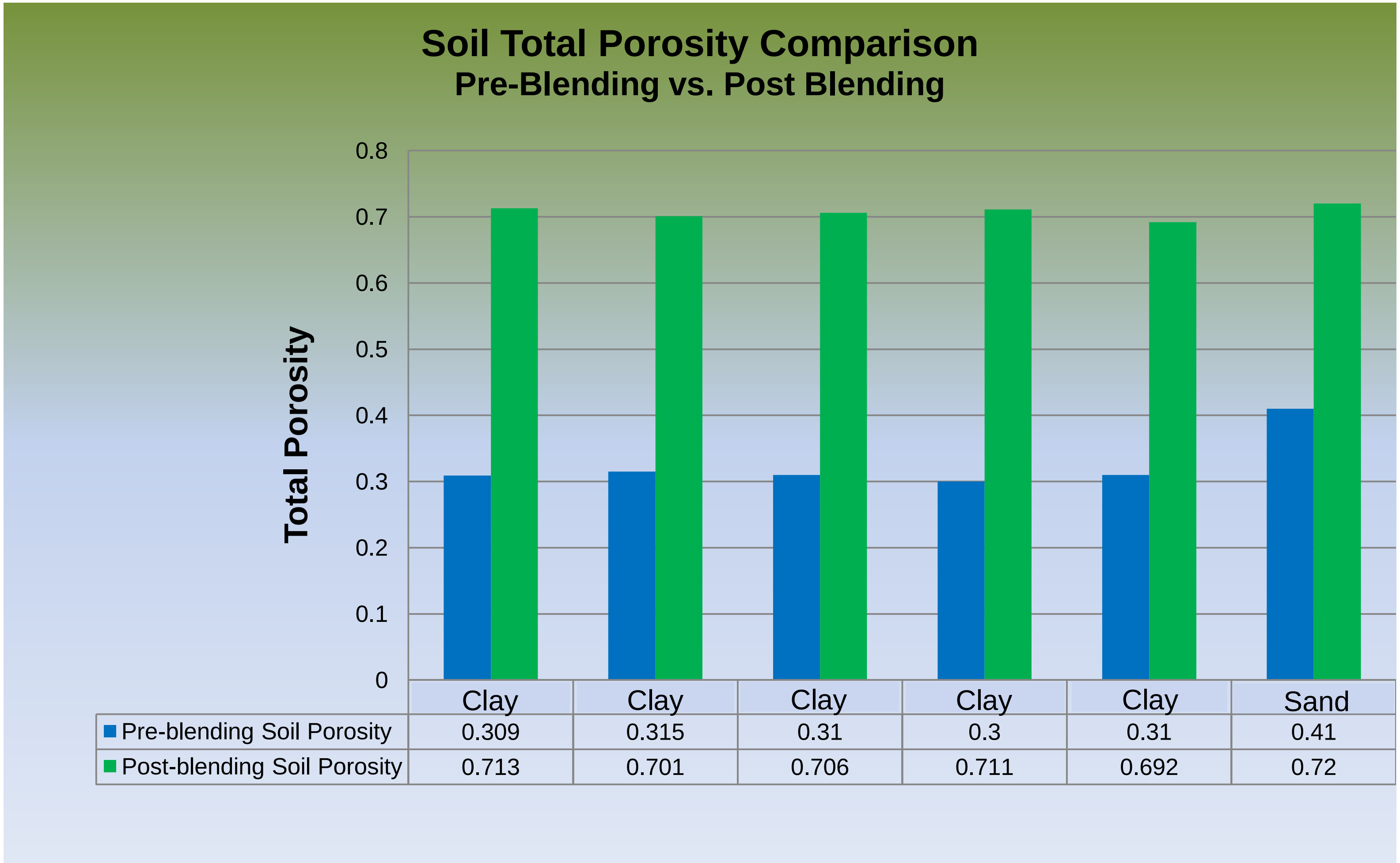
Underground Obstructions Result in Lost Time

Soil Blending/Mixing Effectiveness



	Clay	Clay	Clay	Clay	Clay	Sand
Pre-Blending Soil Void Ratio	0.448	0.46	0.482	0.437	0.448	0.691
Post Blending Soil Void Ratio	0.691	0.644	0.668	0.728	0.596	0.760

Soil Blending/Mixing Effectiveness



	Clay	Clay	Clay	Clay	Clay	Sand
Pre-blending Soil Porosity	0.309	0.315	0.31	0.3	0.31	0.41
Post-blending Soil Porosity	0.713	0.701	0.706	0.711	0.692	0.72

Treatment Design Matrix & Introduced Reagent Volumes

Unit	Date	Klozur (lbs.)	Persulfate (Gallons)	Activator (Gallons)	Cell Locations
Lower Sand (LS) Unit	8/15/11	3,535	2,584	2,893	Q9, R9, S9, T9, U6, U7, U8
	8/16/11	4,379	3,201	3,233	Q9, S8, T4, T5, T6, T7, T8, U4, U5
	8/17/11	3,327	2,432	3,254	R8, S3, S4, S5, S6, S7, S8
	8/18/11	6,365	4,653	5,302	R3, R4, R5, R6, R7, Q3, Q4, Q5, Q6, Q7, Q8
	8/20/11	7,958	5,817	3,256	P3, P4, P5, P6, P7, P8, O6, O7, O8
	8/21/11	8,516	6,225	3,248	N3, N4, N5, N6, N7, N8, O3, O4, O5
	8/22/11	5,631	4,116	2,166	M3, M4, M5, M6, M7, M8
	8/23/11	6,070	4,437	2,385	I3, J3, K3, L3, L4, L5, L6, L7, L8
	8/24/11	7,573	5,536	2,888	F4, F5, G4, G5, H4, H5, I4, J4, K4
	8/25/11	8,341	6,097	3,026	F6, G6, H6, I5, I6, J5, J6, K5, K6
	8/26/11	10,255	7,496	4,048	F7, F8, G7, G8, H7, H8, I7, I8, J7, J8, K7, K8
	8/27/11	9,555	6,985	3,982	F9, F10, F11, G9, G10, H9, H10, I9, I10, I11, J9
	8/29/11	8,802	6,434	3,620	E12, E13, F12, F13, G11, G12, G13, H11, H12, H13
	8/30/11	8,487	6,204	2,534	E14, E15, F14, F15, G14, G15, H14, L8
	LS Totals	*98,793*	*72,217*	*45,835*	-
Upper Clay (UC) Unit	9/7/11	14,237	10,407	4,930	U4, U5, U6, U7, U8, T4, T5, T6, T7, T8, T9
	9/8/11	6,224	4,550	2,805	F11, G11, H11, I11, F12, G12, H12, I12
	9/9/11	6,401	4,679	3,281	A7, A8, A9, 10, C11, D11, E11, D12, E12
	9/10/11	10,197	7,454	5,228	A4, A5, A6, B4, B5, B6, B7, B8, B9, B10, C7, C8, C9, C10
	9/12/11	6,653	4,863	3,369	C4, C5, C6, D5, D6, D7, D8, D9, D10
	9/13/11	10,487	7,666	4,967	C12, D3, D4, D13, E13, F13, G13, H13, I13, D12, E12, F12, G12, H12, I12
	9/14/11	12,103	8,847	5,256	A11, B11, E2, E3, E4, E5, E6, E7, E8, E9, E10, S3, S4, S5
	9/15/11	10,798	7,893	4,778	F2, F3, F4, F5, F6, F7, F8, F9, F10, S6, S7, S8, S9
	9/16/11	11,490	8,399	5,397	F10, G1, G2, G3, G4, G5, G6, G7, G8, G9, G10, R7, R8, R9
	9/17/11	12,111	8,853	5,060	H2, H3, H4, H5, H6, H7, H8, H9, H10, R3, R4, R5, R6, G9, R7
	9/18/11	13,156	9,617	5,640	I4, I5, I6, I7, I8, I9, 10, Q3, Q4, Q5, Q6, Q7, Q8, Q9
	9/20/11	11,200	8,187	4,536	I1, I2, I3, J1, J2, K1, K2, P3, P4, P5, P6, P7, P8, P9, Q9
	9/21/11	10,156	7,235	4,637	J3, J4, K3, K4, L3, M2, M3, N2, N3, N4, O3, O4
	9/22/11	10,620	7,178	4,270	J5, J6, K5, K6, L4, L5, L6, M4, M5, N5, O5
	9/23/11	11,695	7,964	4,766	J7, J8, K7, K8, L7, L8, M6, M7, N6, N7, O6, O7
	9/24/11	14,280	8,964	4,665	J9, J10, J11, J12, K9, K10, K11, L9, L10, M8, N8, O8
	UC Totals	*171,807*	*122,756*	*73,585*	-
	Totals	**270,600**	**194,973**	**119,420**	-

Note:

Klozur lbs. = Pounds of FMC Klozur (sodium persulfate powder) utilized per day within 15% liquid sodium persulfate mixture.

Persulfate = Volume of liquid sodium persulfate solution (~15%) consisting of water, FMC Klozur (dry powder) and sodium hydroxide activator (~20-25% concentration), that was mixed/blended into the treatment cells.

Activator = Volume of sodium hydroxide (~20-25% concentration) solution that was mixed/blended into the treatment cells after sodium persulfate solution was mixed/blended into the treatment cells.

Cell Locations = ID locations of the treatment cells that were mixed/blended on that given day.

TCE Remediation Results Using Dual Axis Soil Blending Technology

Boring Location	Sample ID	Sample Collection Date	Sample Depth Interval (feet bgs)		TCE (ug/kg)
VS1	VS1A	2/21/2012	2	4	<32
	VS1B	2/21/2012	10	12	240
	VS1D	2/21/2012	24	26	470
VS2	VS2A	2/21/2012	2	4	130 J
	VS2B	2/21/2012	10	12	<30
	VS2C	2/21/2012	24	26	**2800**
VS3	VS3A	2/21/2012	2	4	<32
	VS3B	2/21/2012	11	13	<29
	VS3E	2/21/2012	25	27	<31
VS4	VS4A	2/21/2012	2	4	<35
	VS4B	2/21/2012	10	12	<29
	VS4C	2/21/2012	24	26	<30
VS5	VS5A	2/21/2012	2	4	<30
	VS5B	2/21/2012	11	13	260
	VS5E	2/21/2012	25	27	<29
VS6	VS6A	2/21/2012	2	4	<31
	VS6B	2/21/2012	11	13	520
	VS6C	2/21/2012	25	27	<28
VS7	VS7A	2/21/2012	2	4	<31
	VS7B	2/21/2012	9	11	<30
	VS7D	2/21/2012	23	25	<28
VS8	VS8A	2/21/2012	2	4	<30
	VS8B	2/21/2012	10	12	85 J
	VS8C	2/21/2012	24	26	<25
VS9	VS9A	2/21/2012	2	4	<34
	VS9B	2/21/2012	11	13	34 J
	VS9D	2/21/2012	25	27	<29
VS10	VS10A	2/21/2012	2	4	63 J
	VS10B	2/21/2012	10	12	280
	VS10D	2/21/2012	24	26	<29
VS11	VS11A	2/21/2012	2	4	<30
	VS11B	2/21/2012	8	10	<29
VS12	VS12A	2/21/2012	2	4	<30
	VS12B	2/21/2012	8	10	<32
MW-3PR	MW-3PRA	2/20/2012	2	4	<30
	MW-3PRB	2/20/2012	11	13	43 J
	MW-3PRC	2/20/2012	25	27	<29

Notes:

TCE trichloroethylene
ug/kg micrograms per kilogram
J Results reported between the Method Detection Limit and Limit of Quantitat
bgs Below ground surface (post remediation elevations).
Clay unit depth is 0 to 15 ft bgs and lower sand unit is greater than 15 ft

Concentration in bold exceeds the cleanup goal of 1,500 ug/kg established based on direct contact criteria.

All samples were analyzed for the full VOC suite.
Only TCE was detected above laboratory detection limits.

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TCE Remediation Results Using Dual Axis Soil Blending Technology

Pre-Remediation TCE Soil Concentrations					Post-Remediation TCE Soil Concentrations					Change in TCE Concentration (%)
Boring Location	Sample Collection Date	Sample Depth Interval (Elevation in ft msl)		TCE (ug/kg)	Boring Location	Sample Collection Date	Sample Depth Interval (Elevation in ft msl)		TCE (ug/kg)	
None	-	-	-	-	VS1	2/21/2012	840	838	<32	NA
	-	-	-	-		2/21/2012	832	830	240	NA
	-	-	-	-		2/21/2012	818	816	470	NA
None	-	-	-	-	VS2	2/21/2012	840	838	130 J	NA
B-26	10/16/2007	829.3	827.3	<28		2/21/2012	832	830	<30	NC
TB2P	11/13/2000	820.31	818.31	**1680**		2/21/2012	818	816	**2800**	66.7%
None	-	-	-	-	VS3	2/21/2012	841	839	<32	NA
	-	-	-	-		2/21/2012	832	830	<29	NA
	-	-	-	-		2/21/2012	818	816	<31	NA
B-34	10/17/2007	837.24	835.24	280	VS4	2/21/2012	840	838	<35	-87.5%
GP-7	1/25/2000	833.23	831.23	**6880**		2/21/2012	832	830	<29	-99.6%
	1/25/2000	821.23	819.23	1130		2/21/2012	818	816	<30	-97.3%
None	-	-	-	-	VS5	2/21/2012	841	839	<30	NA
B-22	7/27/2007	831.128	829.128	**140000**		2/21/2012	832	830	260	-99.8%
GP-6	1/25/2000	821.26	819.26	**6890**		2/21/2012	818	816	<29	-99.6%
None	-	-	-	-	VS6	2/21/2012	841	839	<31	NA
B-48	7/16/2010	830.16	829.16	**73000**		2/21/2012	832	830	520	-99%
None	-	-	-	-		2/21/2012	818	816	<28	NA
B-63	8/20/2010	836.16	835.16	790	VS7	2/21/2012	839	837	<31	-96.1%
	8/20/2010	830.16	829.16	**7900**		2/21/2012	832	830	<30	-99.6%
B-62	8/20/2010	820.16	819.16	**4800**		2/21/2012	818	816	<28	-99.4%
None	-	-	-	-	VS8	2/21/2012	840	838	<30	NA
B-5	7/26/2007	831.438	829.438	**2400**		2/21/2012	832	830	85 J	-96.5%
None	-	-	-	-		2/21/2012	818	816	<25	NA
None	-	-	-	-	VS9	2/21/2012	841	839	<34	NA
B-68	7/16/2010	830.16	829.16	**12000**		2/21/2012	832	830	34 J	-99.7%
None	-	-	-	-		2/21/2012	818	816	<29	NA
GP-1	1/25/2000	837.16	835.16	**24500**	VS10	2/21/2012	840	838	63 J	-99.7%
B-73	7/16/2010	830.16	829.16	**3600**		2/21/2012	832	830	280	-92.2%
GP-1	1/25/2000	821.16	819.16	**18500**		2/21/2012	818	816	<29	-99.8%
B-67	8/20/2010	836.16	835.16	1500	VS11	2/21/2012	838	836	<30	-98.0%
	8/20/2010	830.16	829.16	1200		2/21/2012	832	830	<29	-97.6%
B-72	8/19/2010	836.16	835.16	850	VS12	2/21/2012	838	836	<30	-96.5%
	8/19/2010	830.16	829.16	**4000**		2/21/2012	832	830	<32	-99.2%
None	-	-	-	-	MW-3PR	2/20/2012	841	839	<30	NA
B-31	10/16/2007	831.18	829.18	1100		2/20/2012	832	830	43 J	-96.1%
MW-3P	4/25/2000	816.32	814.32	**27500**		2/20/2012	818	816	<29	-99.9%

Notes:

ug/kg micrograms per kilogram

J Results reported between the Method Detection Limit and Limit of Quantitation

ft msl Feet above mean sea level.

Concentration in bold exceeds the cleanup goal of 1,500 ug/kg established based on direct contact criteria.

NA = Not applicable; no pre-remediation soil samples collected at similar location and/or depth.

NC = No change; both pre- and post-remediation samples were below laboratory detection limits.

Average pre-remediation ground surface elevation was approximately 840 ft msl.

For the purposes of this comparison, a elevation variation of less than 4 feet was used for comparing pre- and post-remediation TCE concentrations.

Negative % change reflects a reduction in concentrations when comparing pre- and post-remediation TCE concentrations.

Where the TCE concentration was less than the detection limit, the detection limit was used to calculate the reduction.

TCE Remediation Results Using Dual Axis Soil Blending Technology

- Average TCE concentration in upper clay reduced from 13,300 ug/kg to 84 ug/kg
- Up to 99.4% mass reduction in TCE from pre-remedial estimates in upper clay soil
- Average TCE concentration in lower sand reduced from 10,200 ug/kg to 321 ug/kg
- Up to 96.3% mass reduction in TCE in lower sand unit
- Met TCE mass reduction goal established for site (>95%)
- 36 out of 37 post-remediation soil verification samples were below the treatment goal of 1,500 ug/kg TCE

Cost of Dual-Axis Blending Technology

Example for ~15,000 CY soil treatment volume using alkaline activated sodium persulfate (2011)

Item	Unit Cost Range
Soil Blending	
< 15 feet depth (no soil excavation)	$ 38 to $ 40/ yd^3
> 15 feet and < 30 ft depth (with soil excavation)	$ 43 to $ 46/ yd^3
Chemical Reagents (Alkaline activated sodium persulfate)	
Klozur ® Sodium Persulfate	$ 1.90 to $ 2.10/ lb
50% Sodium Hydroxide Solution	$ 3.00 to $ 4.00/ gallon
Municipal Water	$ 0.35 to $ 0.45/ yd^3 of soil treated
Equipment Mobilization and Demobilization	
~400 mi radius	$30,000 to $ 40,000
Ancillary Project Costs	
Sediment and Erosion Controls	$ 1,500 to $ 2,000/ acre
Temporary facilities, perimeter fencing, decon pad	$ 1.00 to $ 1.25/ sq. ft of treatment area
Site grading, topsoil placement, seeding and mulch	$ 10,000 to $ 12,000/ acre

Observations/Lessons Learned

- Site planning is critical
- Requires application flexibility
  - Adjust dosing rates based on field/laboratory test results
  - Soil management
- May require significant mixing water to be added – delays site restoration
- Resulting soil structure will make redevelopment efforts more complex
- Schedule should allow for downtime (e.g. large boulders break teeth on rotating mixer head)
- Customized sampling equipment/ techniques are beneficial
- Odor controls must be considered at some sites
- Reagent contact with COCs is maximized!

Site Conditions Post Treatment

Thank You

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