REGENESIS
Technology-Based Solutions for the Environment

Coupling Sorption and Biodegradation for Rapid and Permanent Groundwater Clean-up

• Field Performance of Dispersive Colloidal Activated Carbon •

Jeremy Birnstingl PhD
Craig Sandefur MS, Kristen Thoreson PhD

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R&D Efforts

2007: Began to focus on use of particulate sorbents to bind dissolved contaminants *in situ*.

- Surfactant-modified zeolites
- Organo-clays
- Activated carbons

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R&D Findings

Activate carbon and other sorbent particulates do not disperse in the aquifer

Granular Activated Carbon particles: > 1,000 µm

Powdered Activated Carbon particles:

- 40 µm diameter
- Agglomerate to >1,000 µm in water

Soil pore-throat diameter for silts/sands ~ 5 – 30 µm

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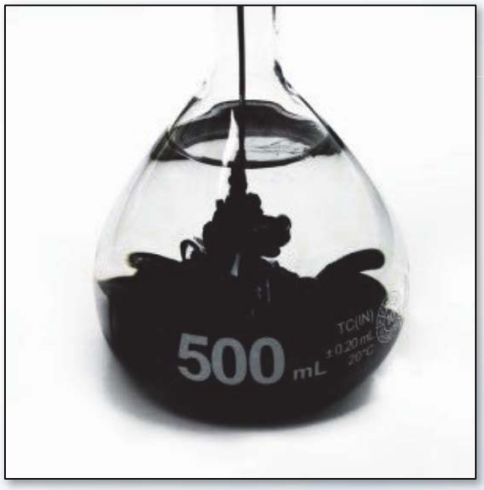
The Reagent – Timeline

- R&D stages 2007 – 2013
  - Ongoing ancillary research
- Field beta tests 2013 – 2014
  - Early tests still running for long term data
- Commercial launch 2014
  - Battelle Monterey
- Commercial applications from 2014
  - Reviewed in this presentation

PLUME STOP™
Liquid Activated Carbon



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The Reagent – what it is

- A highly dispersive, injectable sorbent and microbial growth matrix
- Sorbent
  - Rapid drop in dissolved-phase contaminant concentration
  - Immediate risk-reduction
- Microbial growth matrix
  - Accelerated bio-destruction of sorbed mass
  - Ability to secure clean-up to much lower targets

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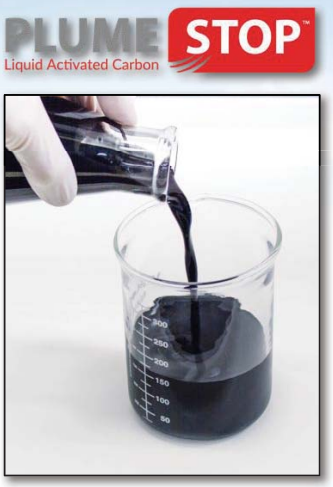
The Reagent – what it is



- Colloidal activated carbon (1 – 2 µm)
  - Size of a bacterium – suspends as 'liquid'
  - Huge surface area – extremely fast sorption
- Proprietary anti-clumping / distribution supporting surface treatment (patent applied for)
  - Core innovation
  - Enables wide-area, low-pressure distribution through the soil matrix without clogging

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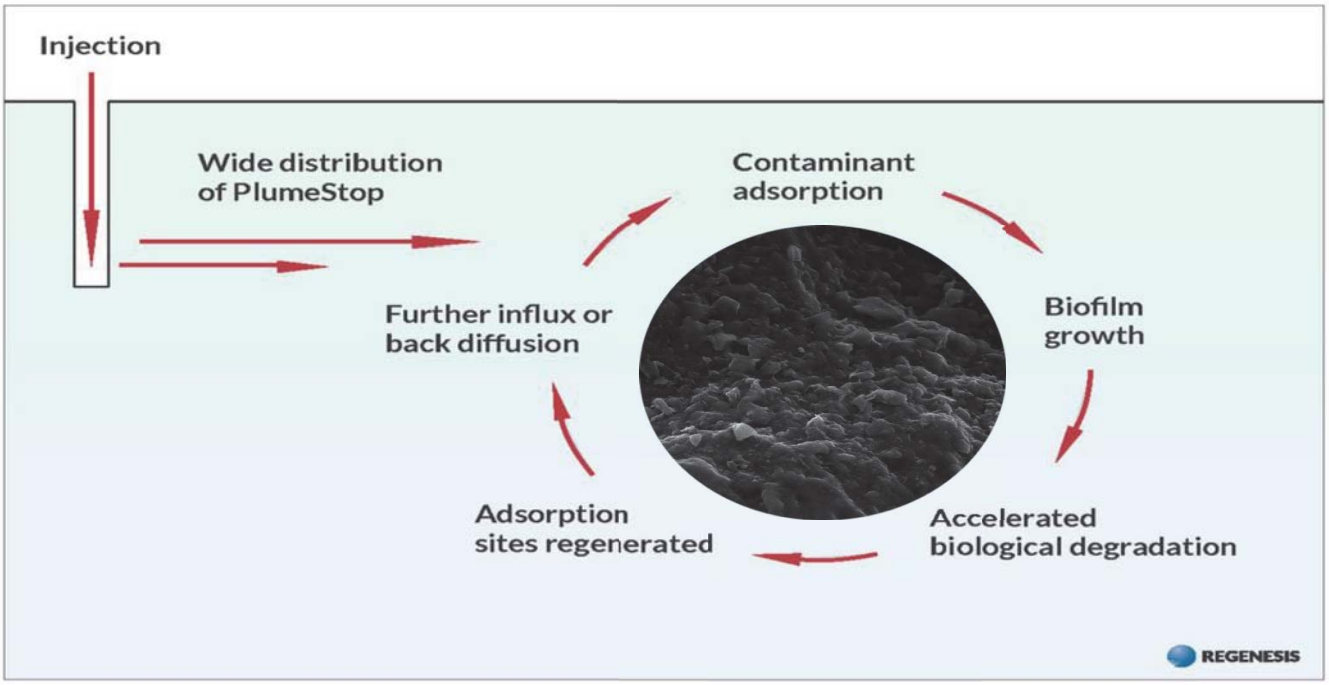
Injection
Wide distribution of PlumeStop
Contaminant adsorption
Biofilm growth
Accelerated biological degradation
Adsorption sites regenerated
Further influx or back diffusion
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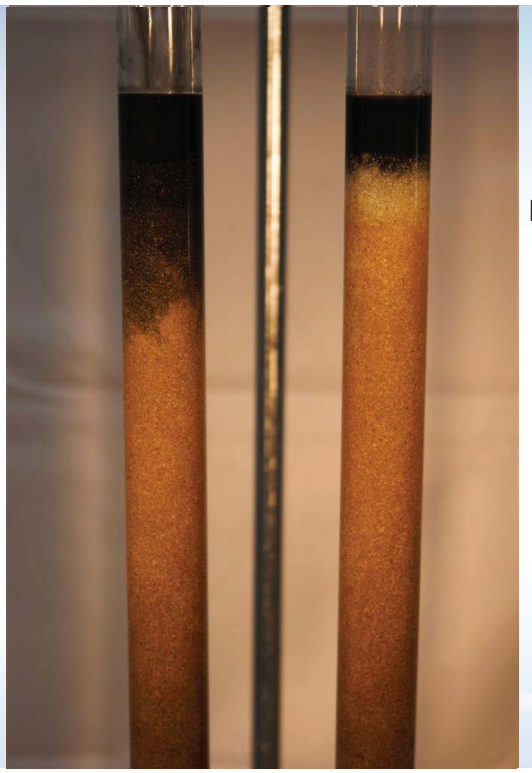
PlumeStop™: reagent distribution

PlumeStop

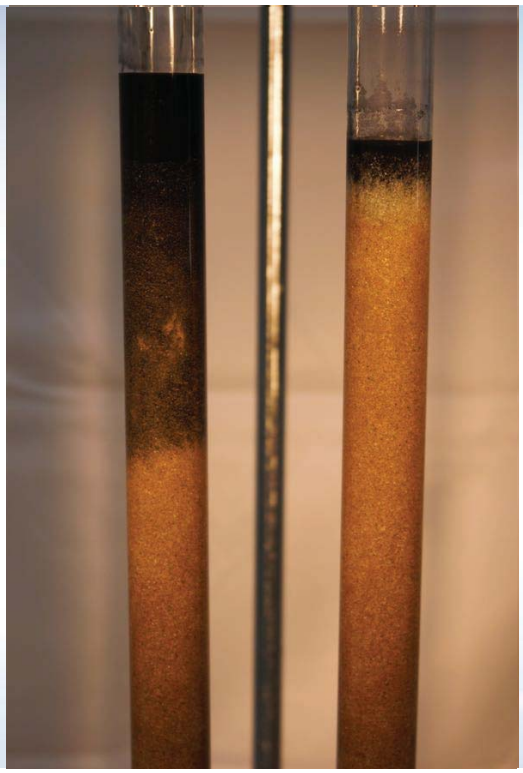
Powdered Activated Carbon

PlumeStop



Powdered Activated Carbon

PlumeStop



Powdered Activated Carbon

PlumeStop

Powdered Activated Carbon

PlumeStop

repeat

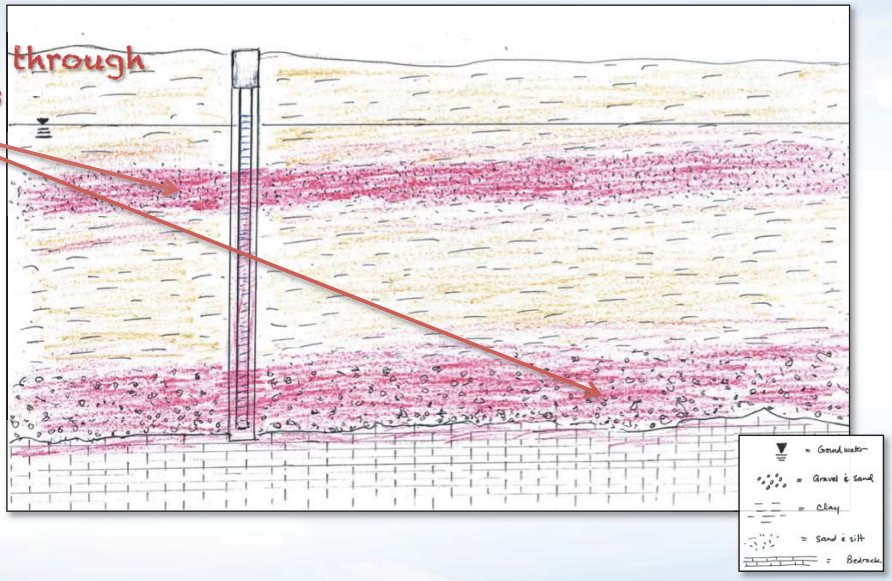
Powdered Activated Carbon

Frequently Asked Questions:

- What about distribution in low permeability zones?
- What about contamination in clays?
- What's your injection radius of influence?

PlumeStop® Liquid Activated Carbon™ Injection

Contamination transports through higher permeability zones – principal flux



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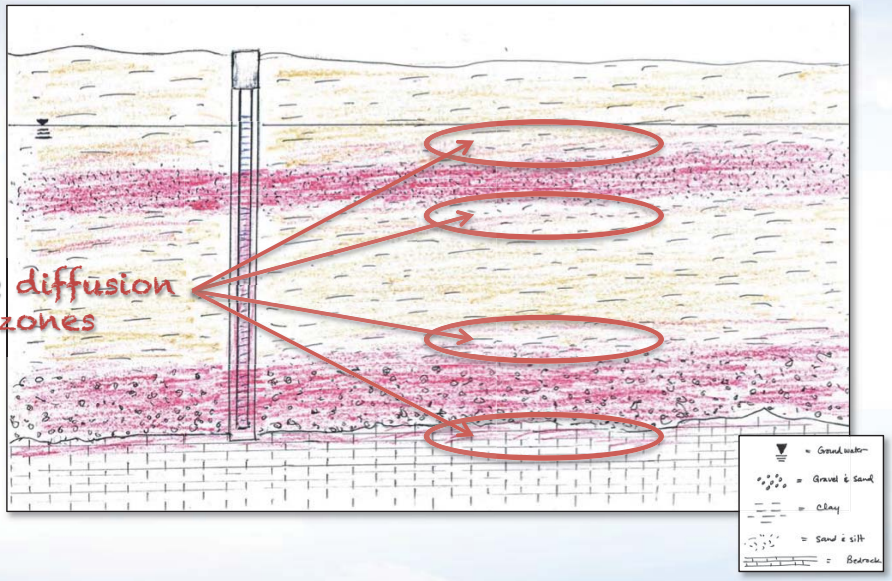
PlumeStop® Liquid Activated Carbon™ Injection

Progressive contaminant diffusion into lower permeability zones – residual storage



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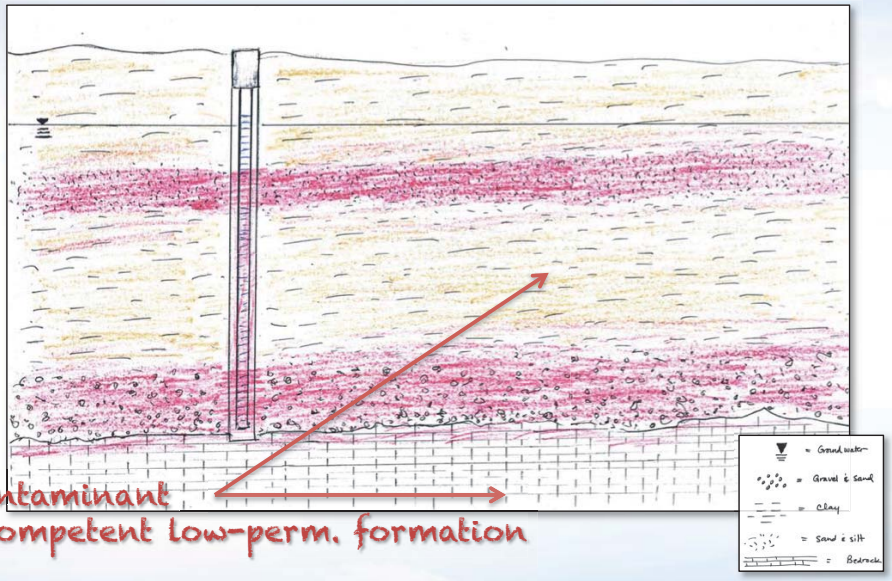
PlumeStop® Liquid Activated Carbon™ Injection



Limited / negligible contaminant penetration deep into competent low-perm. formation

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PlumeStop® Liquid Activated Carbon™ Injection

PLUME STOP

PlumeStop® flows into the subsurface at low pressure - coating the principle flux channels

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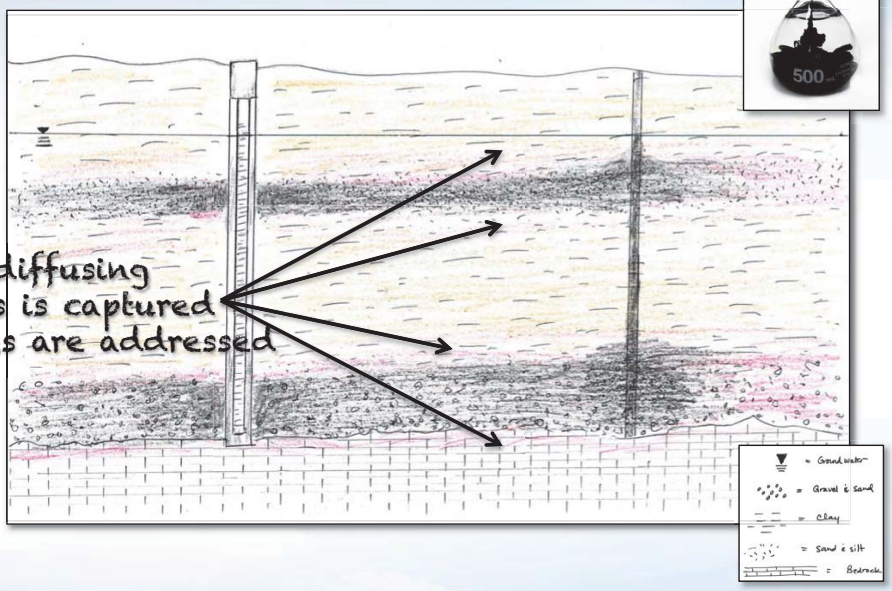
PlumeStop® Liquid Activated Carbon™ Injection



Contaminant mass back-diffusing
from the low-perm zones is captured
∴ Low & high perm zones are addressed

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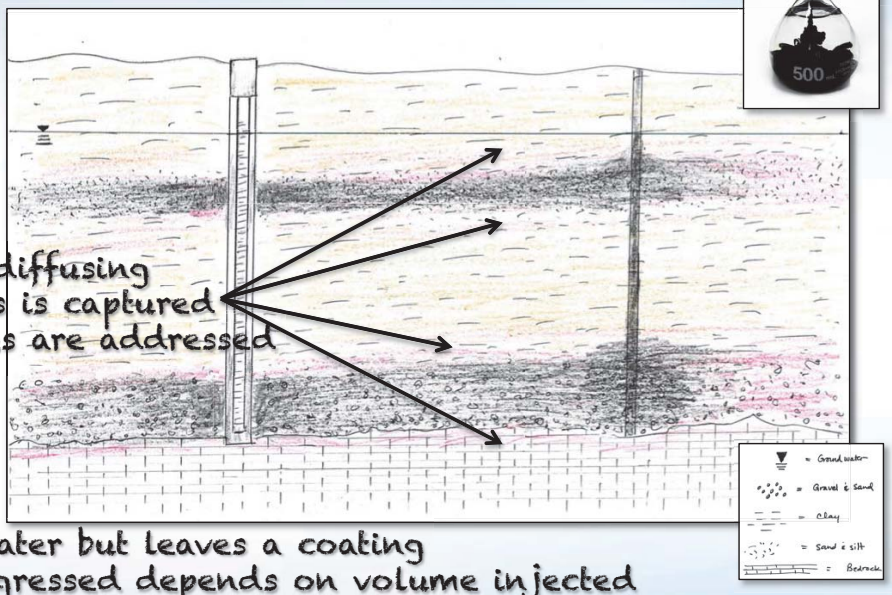
PlumeStop® Liquid Activated Carbon™ Injection



Contaminant mass back-diffusing
from the low-perm zones is captured
∴ Low & high perm zones are addressed

PlumeStop® flows like water but leaves a coating
∴ Distance / radius progressed depends on volume injected

Field application ∴ all about ensuring placement in flow-zones

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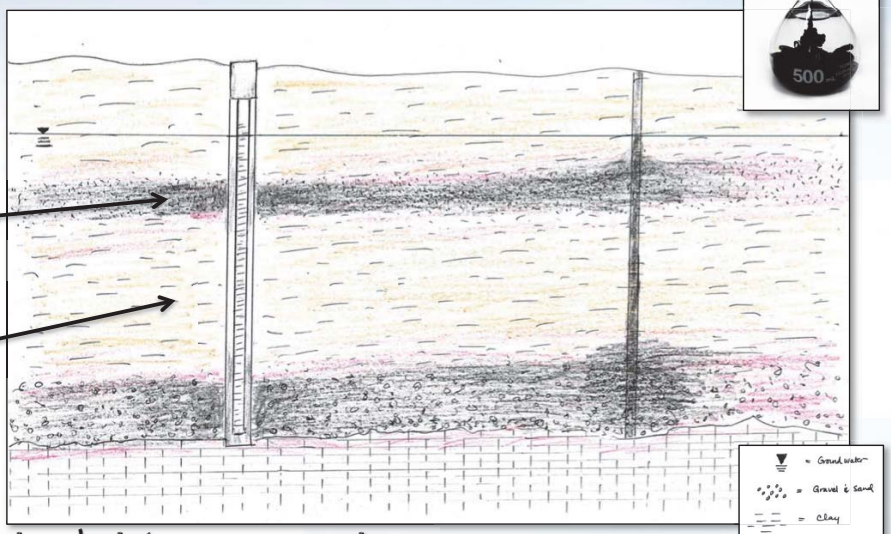
PlumeStop® Liquid Activated Carbon™ Injection



PlumeStop® flows like water but leaves a coating
∴ Distance / radius progressed depends on volume injected

Field application ∴ all about ensuring placement in flow-zones

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PlumeStop Installation into Contaminant Flux Zones - Model

Regenesis-funded Extension of SERDP/ESTCP Back Diffusion Project (Kevin Saller, CDM Smith)

Laboratory of Tom Sale (Colorado State University)

Same Experimental Design (this time with PlumeStop®)


Kevin Saller


Tom Sale

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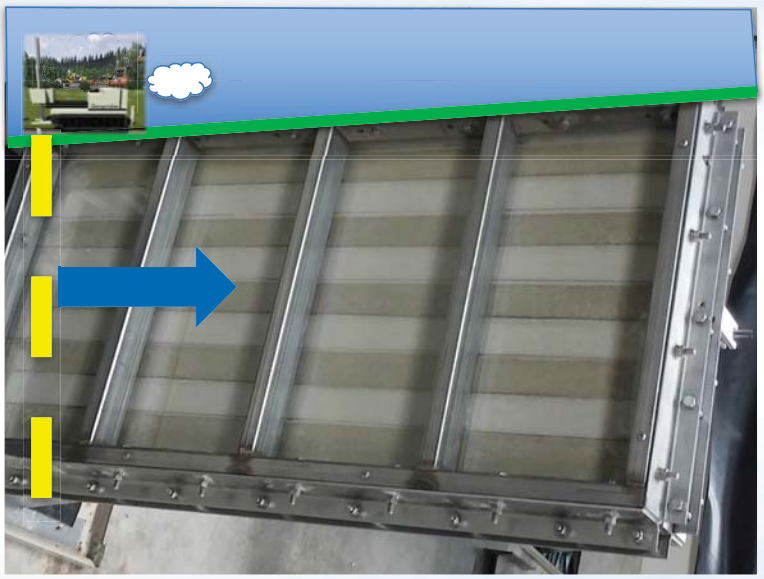
PlumeStop Installation into Contaminant Flux Zones - Model



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PlumeStop Installation into Contaminant Flux Zones - Model

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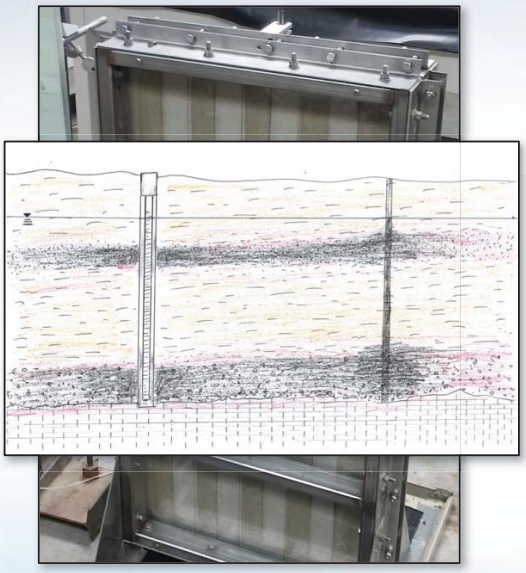

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PlumeStop Installation into Contaminant Flux Zones - Model

no treatment

PLUME STOP

Permanganate

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PLUME STOP™
Liquid Activated Carbon

- usage -

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PlumeStop Applications – October 2016

- Number of sites = 84
- Number of states = 27
- Number of countries = 7

- States
  - AR, CA, CO, FL GA, IA, IL, IN, KY, MA, MI, MO, NC, NE, NJ, NM, OH, PA, PR, RI, SC, TX, UT, VA, WA, WI, WV
- Countries
  - USA, Canada, Italy, Belgium, UK, Sweden, Netherlands
- Scale
  - Pilot 30 (36%)
  - Full 54 (64%)

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PlumeStop Applications – October 2016

- Principally Hydrocarbons (aerobic bio) = 38
- Principally Solvents (anaerobic bio) = 42

- Comingled / no dominant class = 4

- Other contaminants of note
  - PAH, freon-11, MtBE, TBA, chlorobenzene

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- performance analytics -

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Performance Analytics – May 2016

- All available site performance data pooled – 24 sites
- Wells within expected zone of impact highlighted and assessed
  - i.e. those wells within treatment grid and/or advective distance
- Total contaminant reductions monitored over time
- Performance histograms created – **full data set**
  - Initial capture
  - Stability to date

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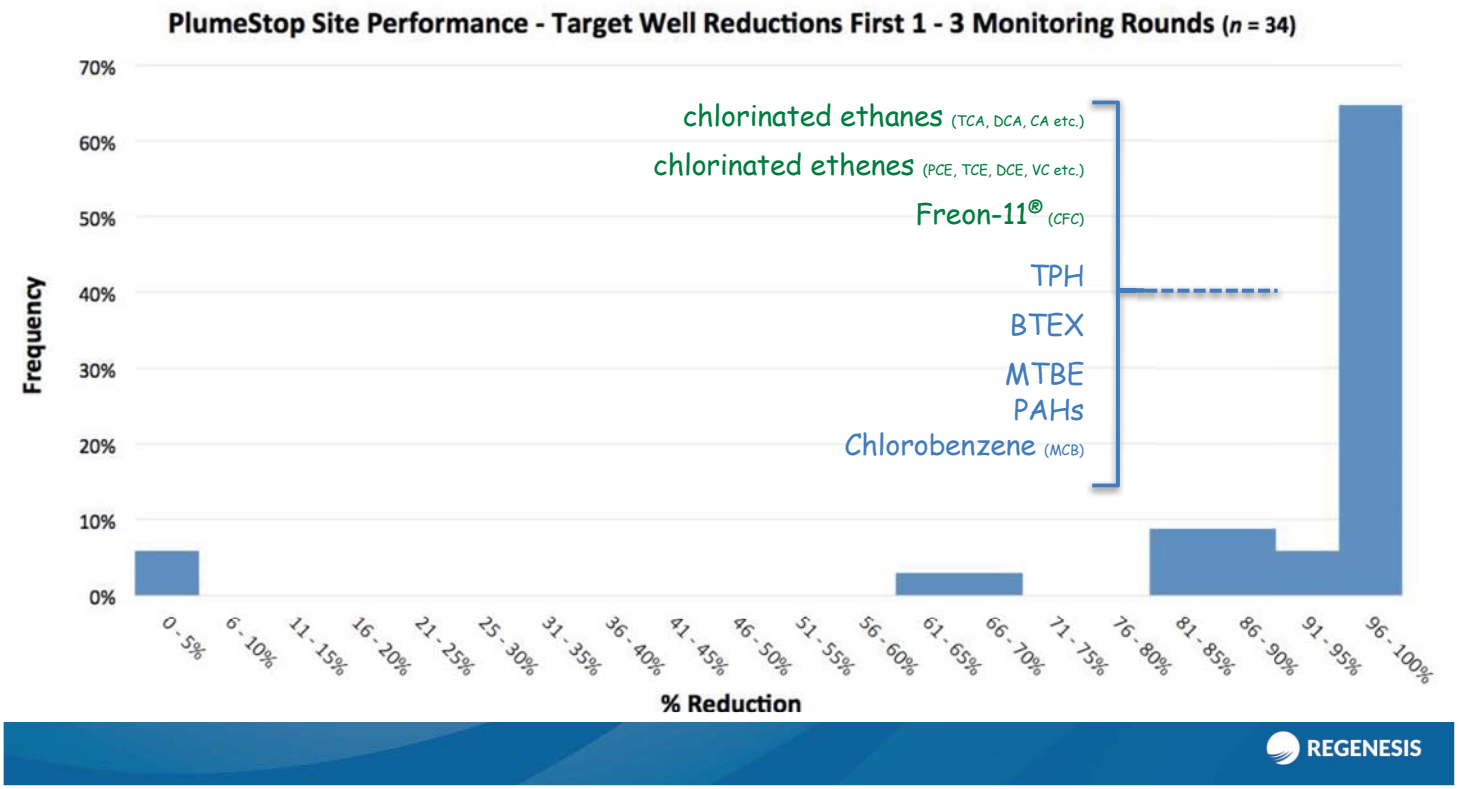
PlumeStop Site Performance - Target Well Reductions First 1 - 3 Monitoring Rounds (n = 34)
chlorinated ethanes (TCA, DCA, CA etc.)
chlorinated ethenes (PCE, TCE, DCE, VC etc.)
Freon-11® (CFC)
TPH
BTEX
MTBE
PAHs
Chlorobenzene (MCB)
Frequency
% Reduction
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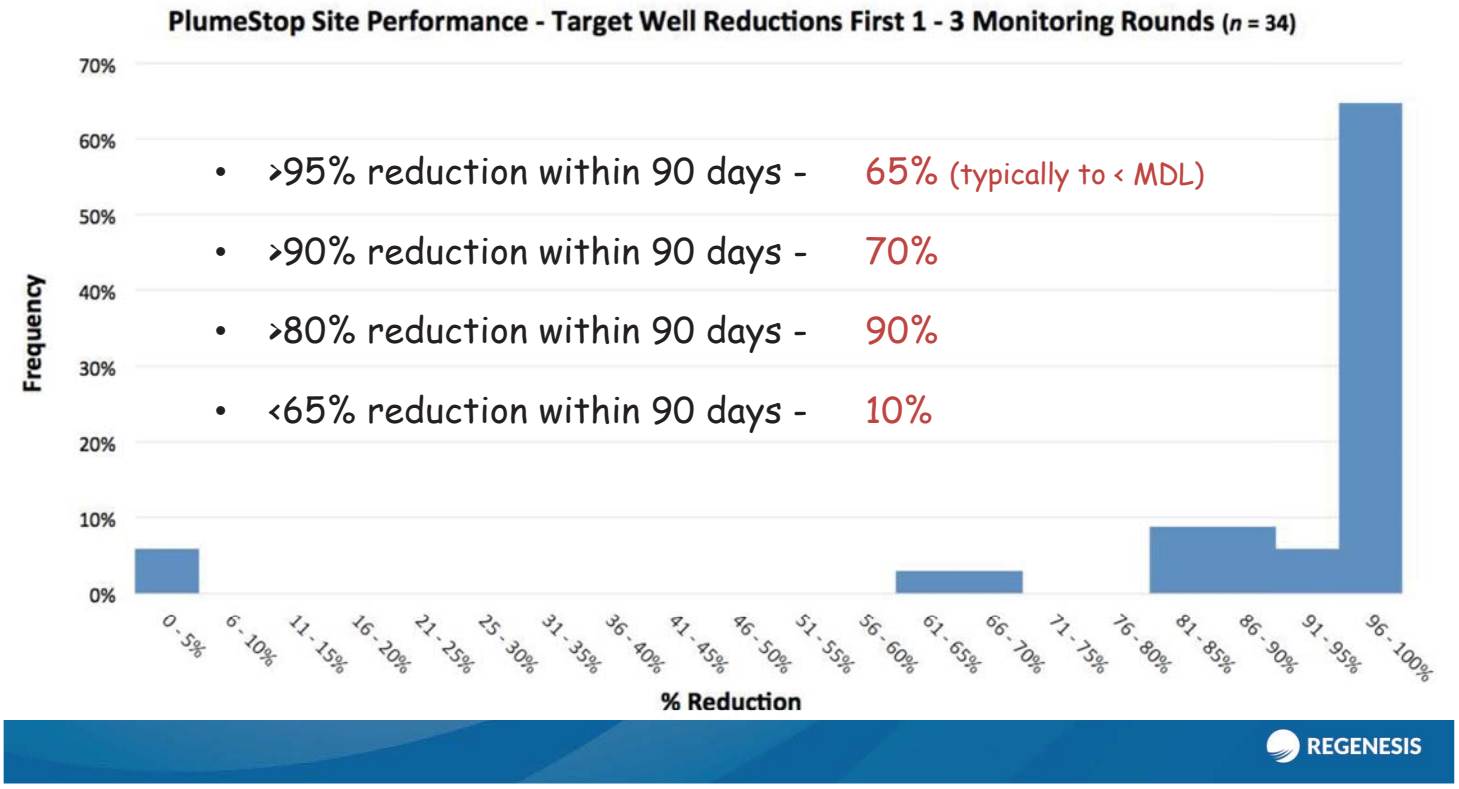
PlumeStop Site Performance - Target Well Reductions First 1 - 3 Monitoring Rounds (n = 34)
• >95% reduction within 90 days - 65% (typically to < MDL)
• >90% reduction within 90 days - 70%
• >80% reduction within 90 days - 90%
• <65% reduction within 90 days - 10%
Frequency
% Reduction
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Stability to date?

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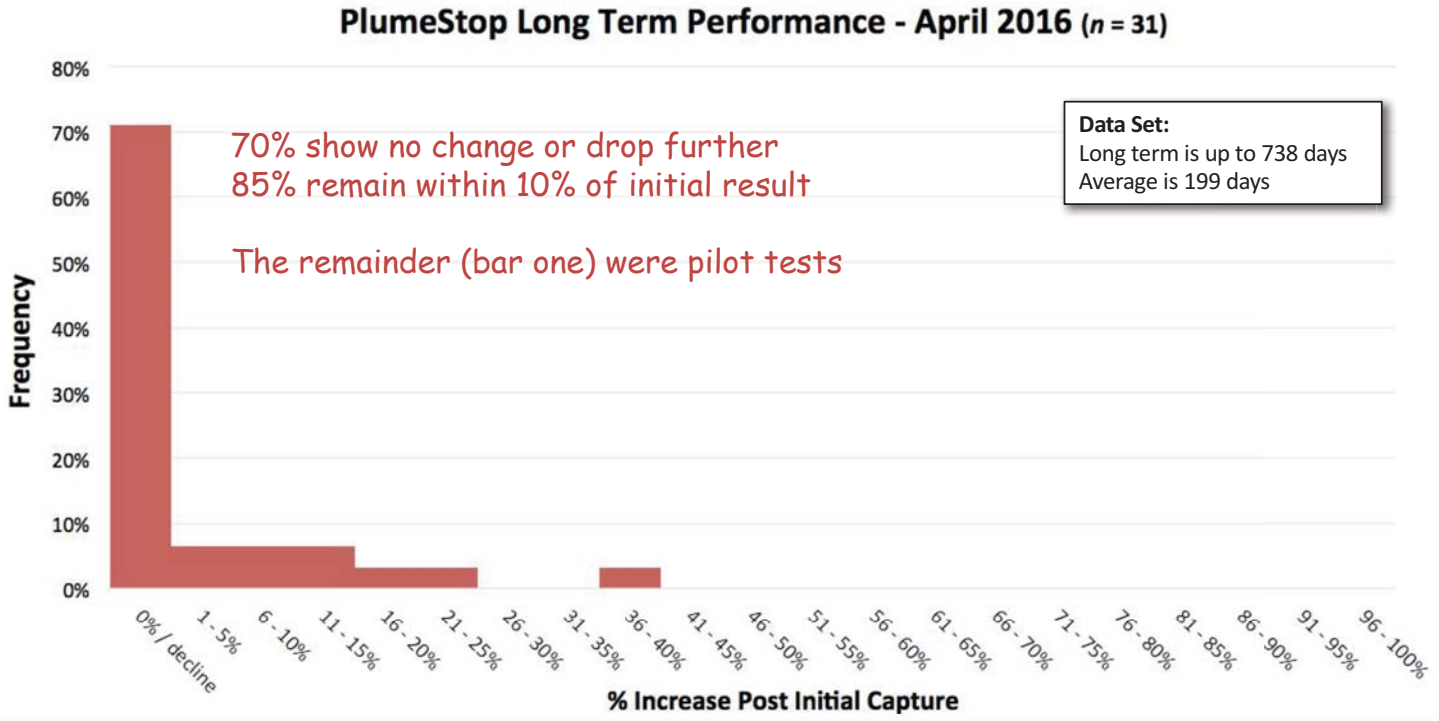

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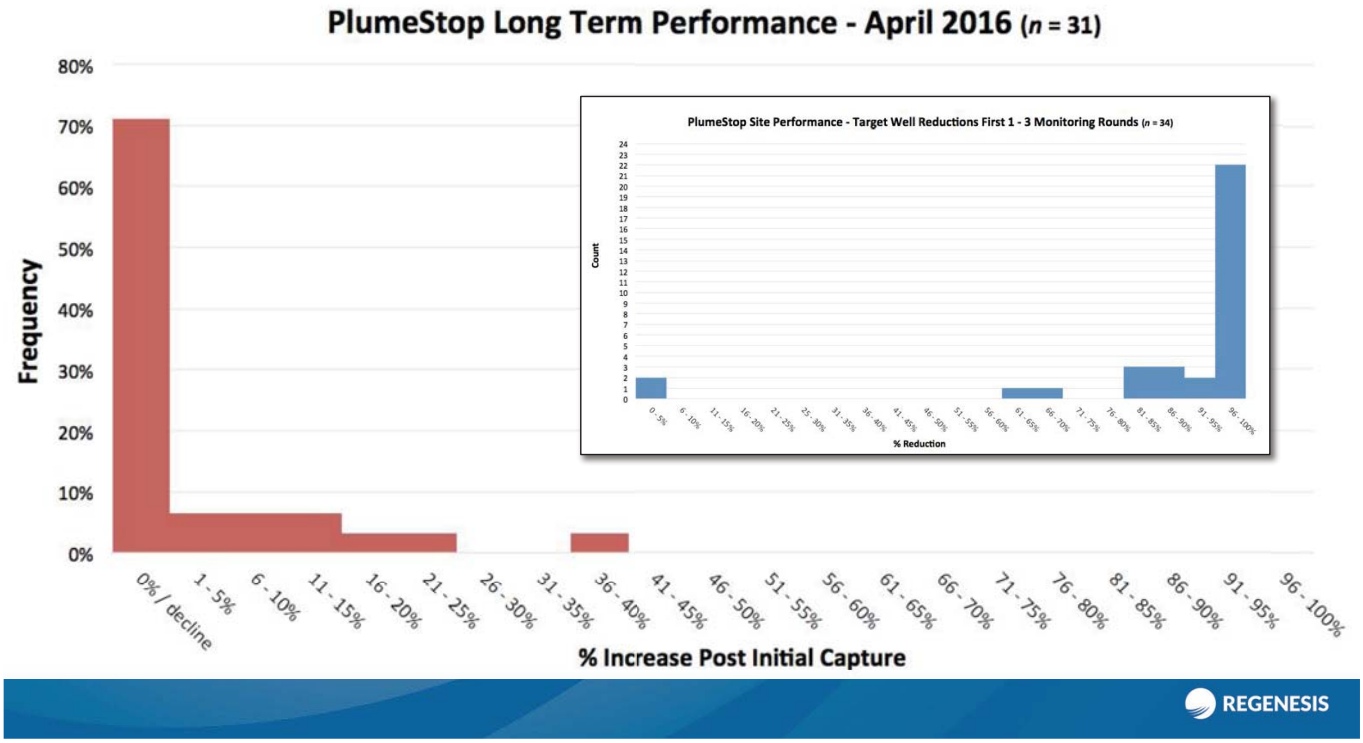

PLUME STOP™
Liquid Activated Carbon

–performance –

chlorinated solvents – post-sorption degradation – lines of evidence

(skip to next)

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California Site

- 'Dune Sand' formation
- 10 m/year groundwater flow
- High redox conditions (aerobic)
- No attenuation evident

- PCE 550 µg/L
- No daughter products
- PlumeStop™
- Electron donor and bacteria

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MW-3 (ppb)

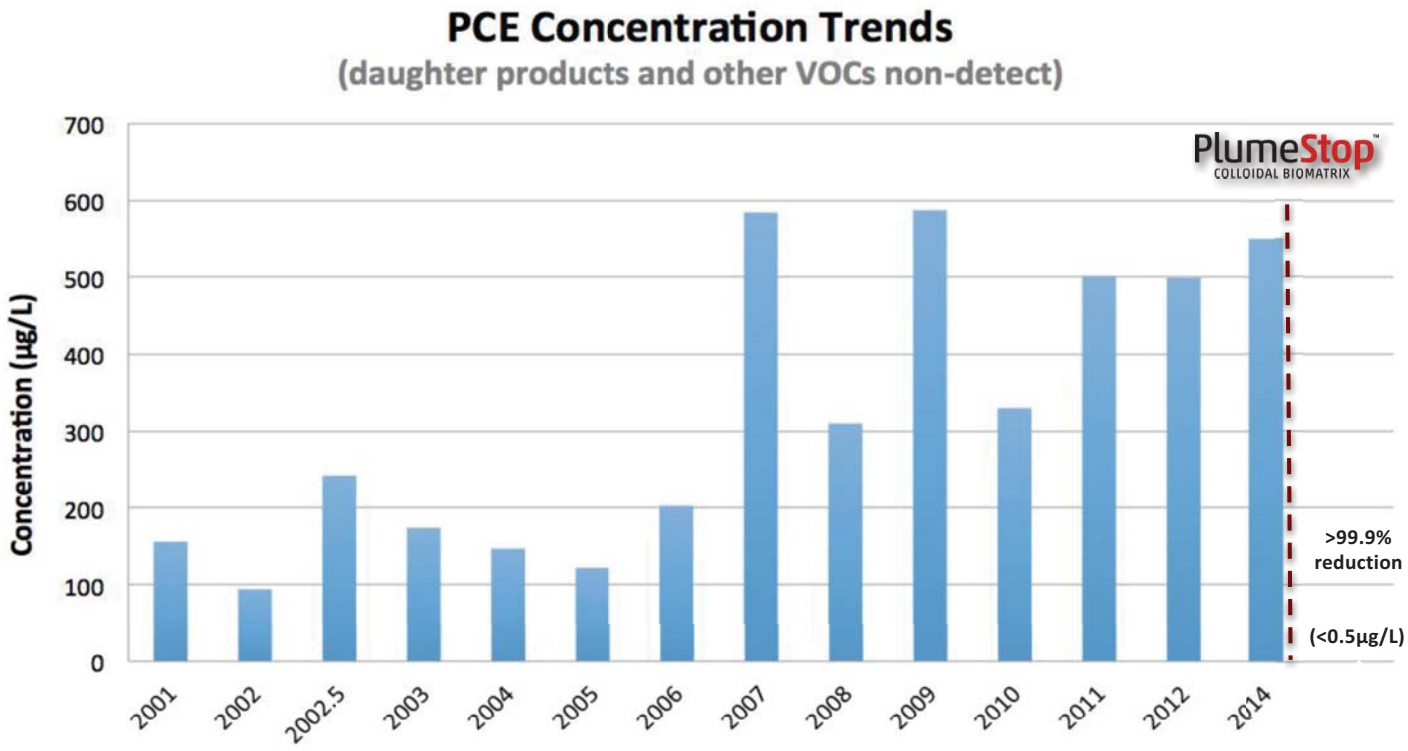
Historic Data

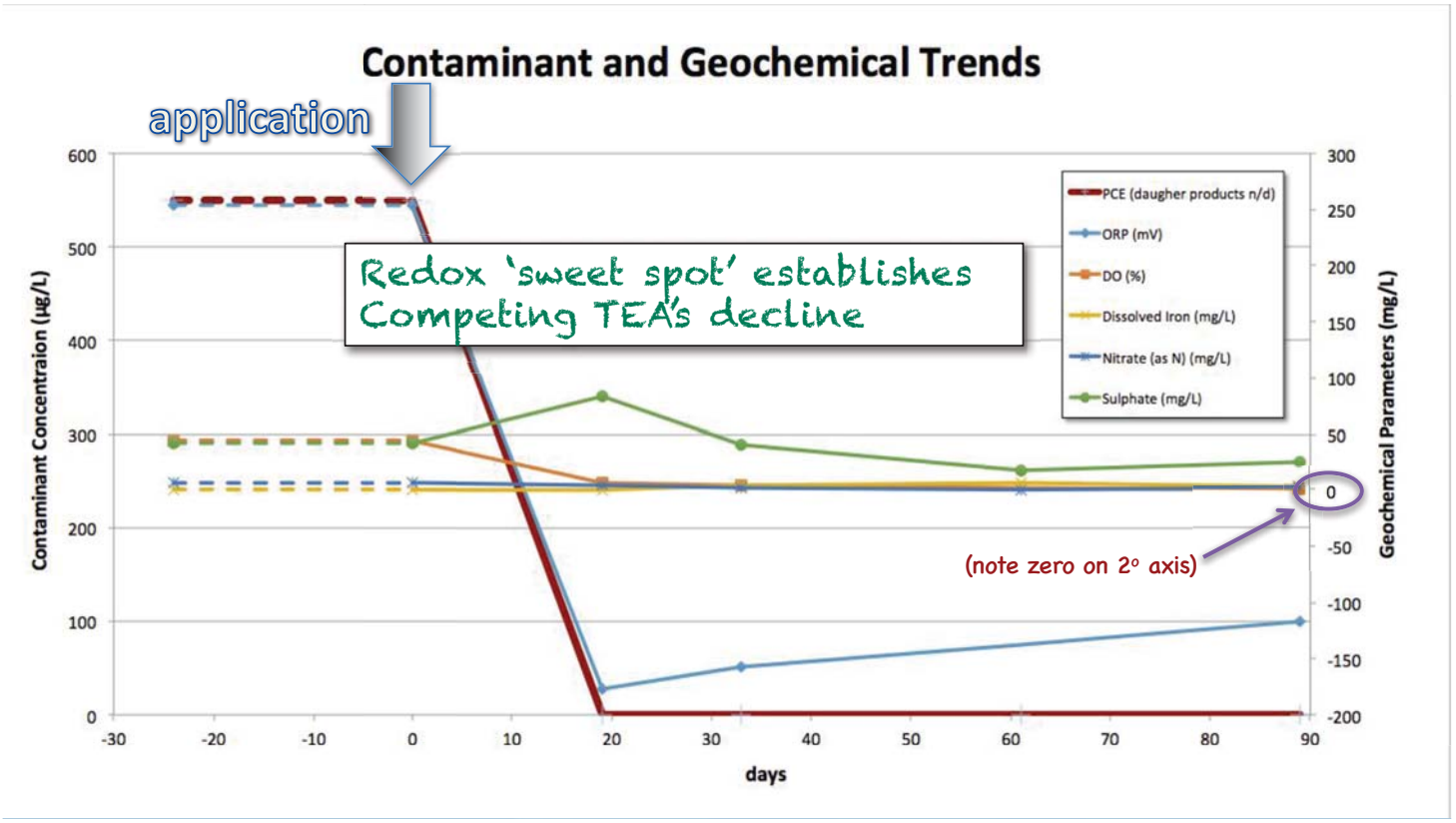
Year	PCE	TCE	VC	1,2 Cis	VC
2001	156	0	0	0	0
2002	94	0	0	0	0
2002.5	242	0	0	0	0
2003	174				0
2004	147				0
2005	122				0
2006	203				0
2007	584				0
2008	310				0
2009	587				0
2010	330	0	0	0	0
2011	501	0	0	0	0
2012	499	0	0	0	0

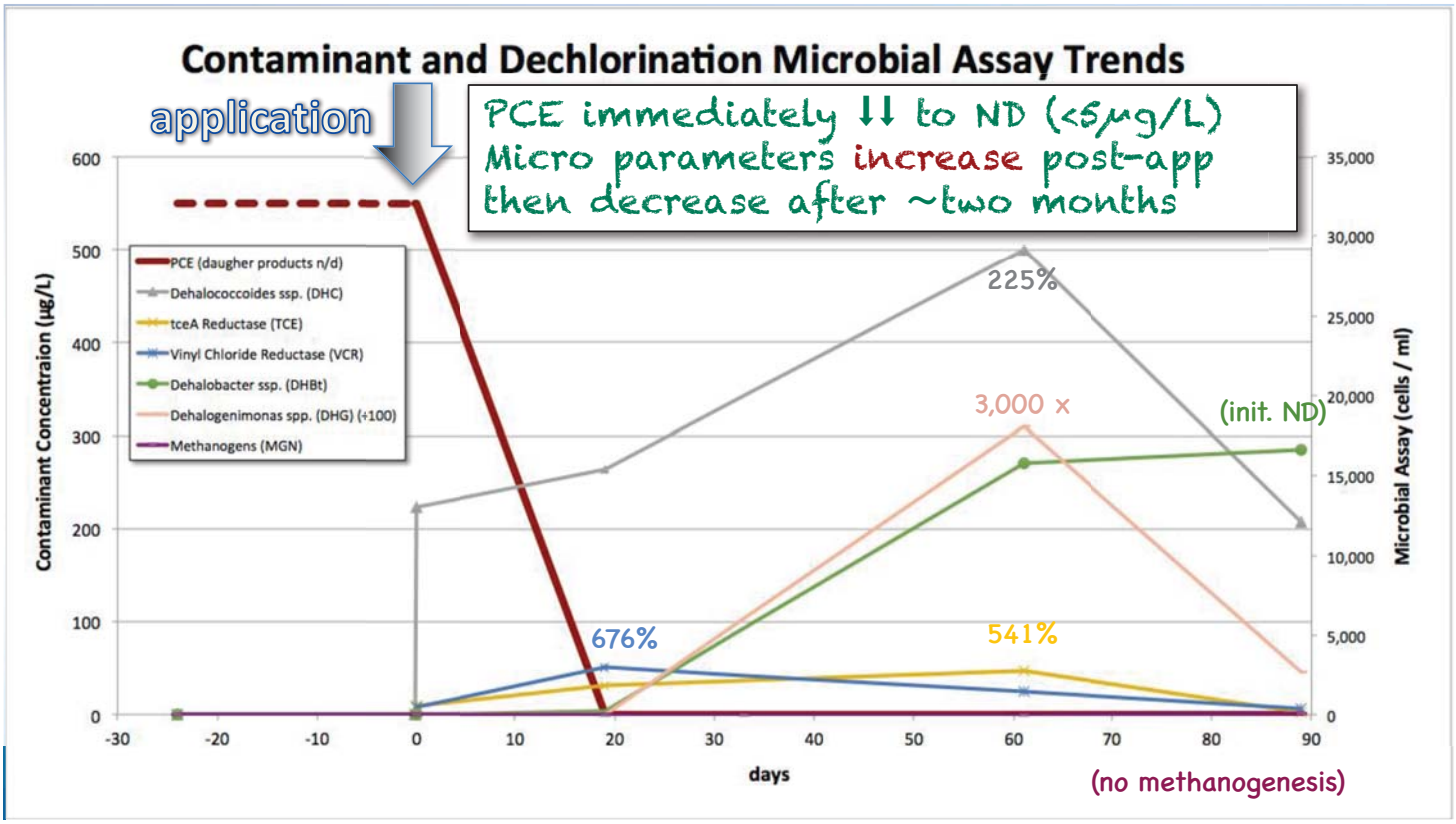
Steadily increasing PCE

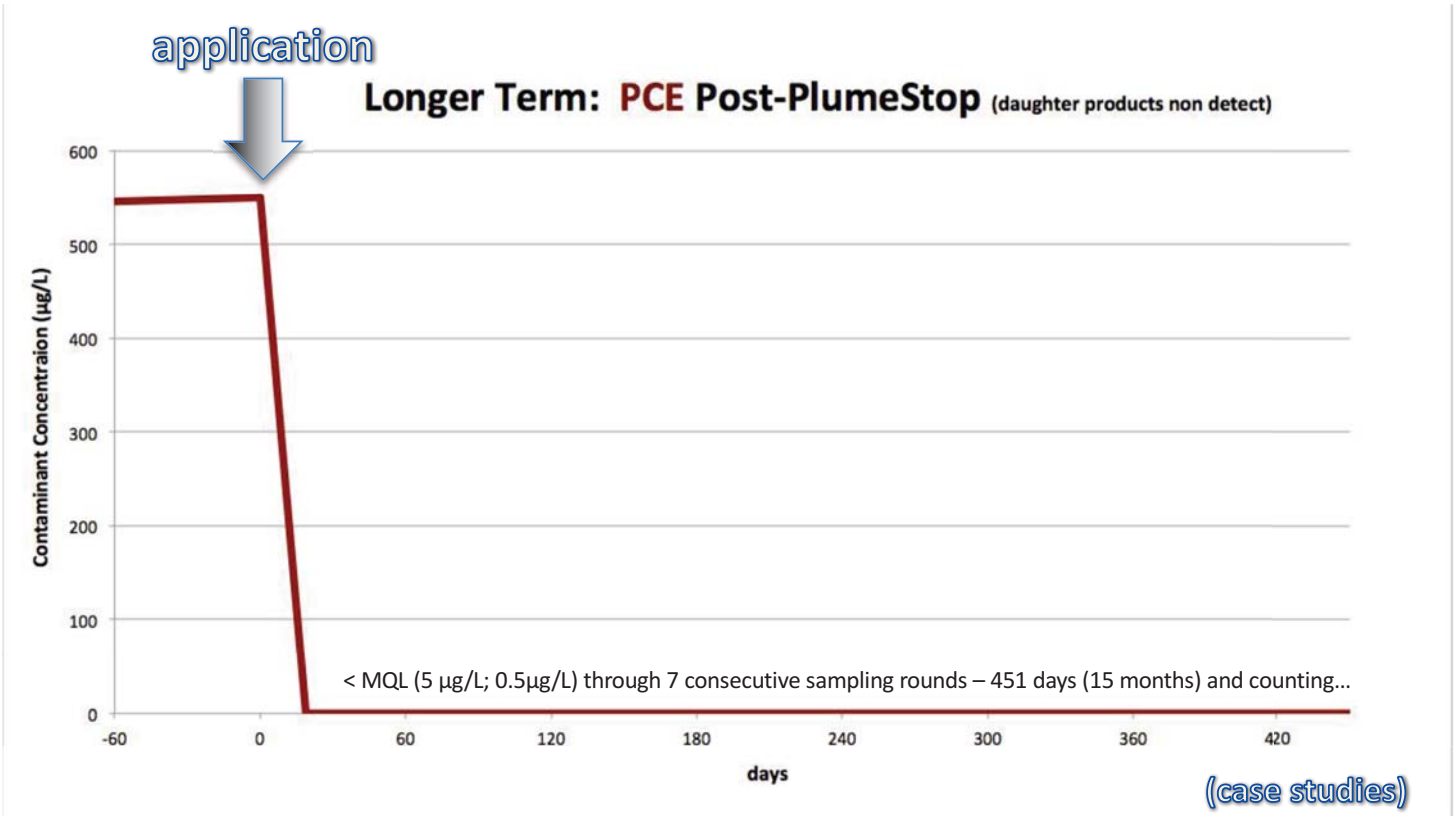
No daughter products

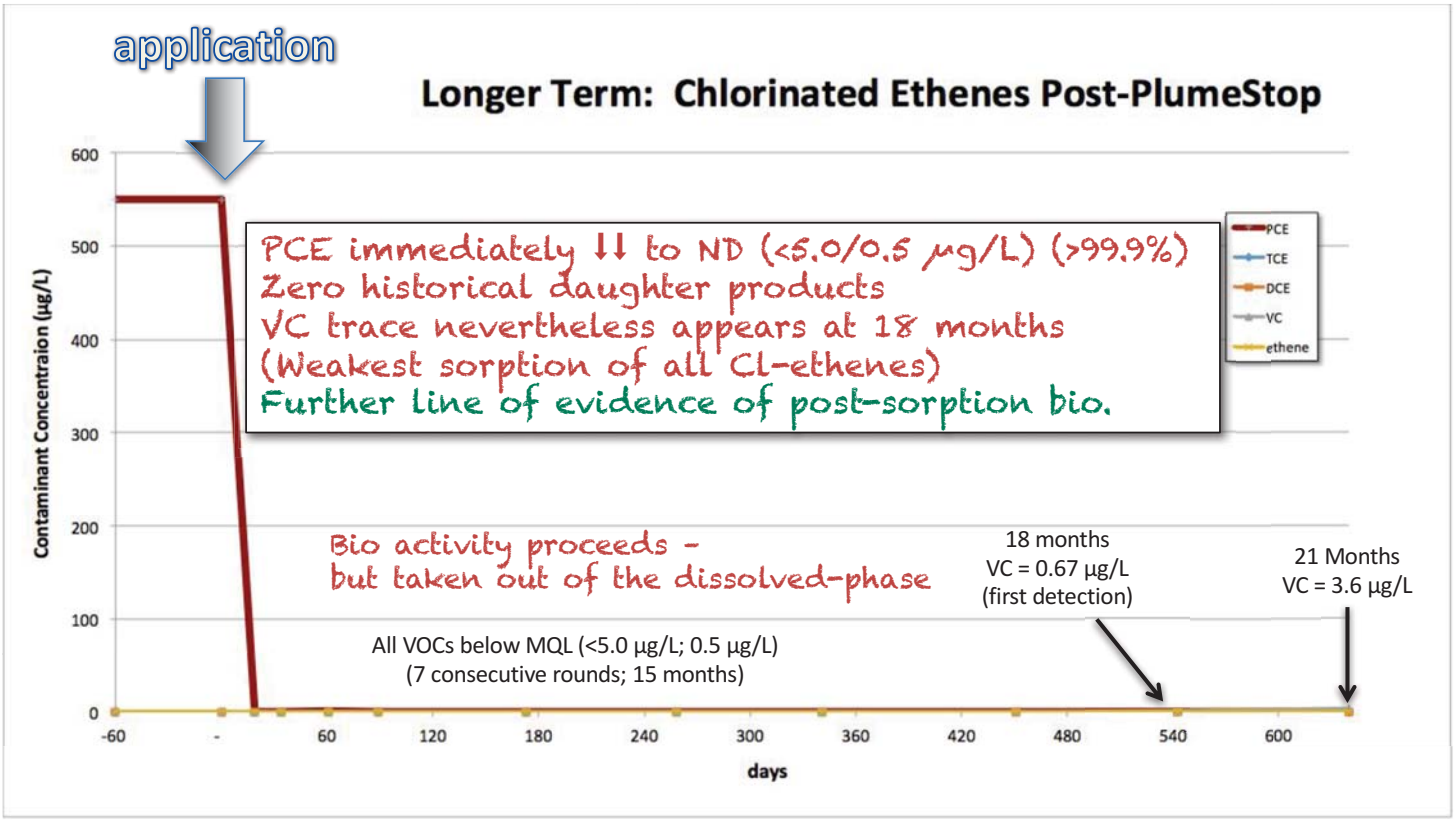
(aerobic conditions)

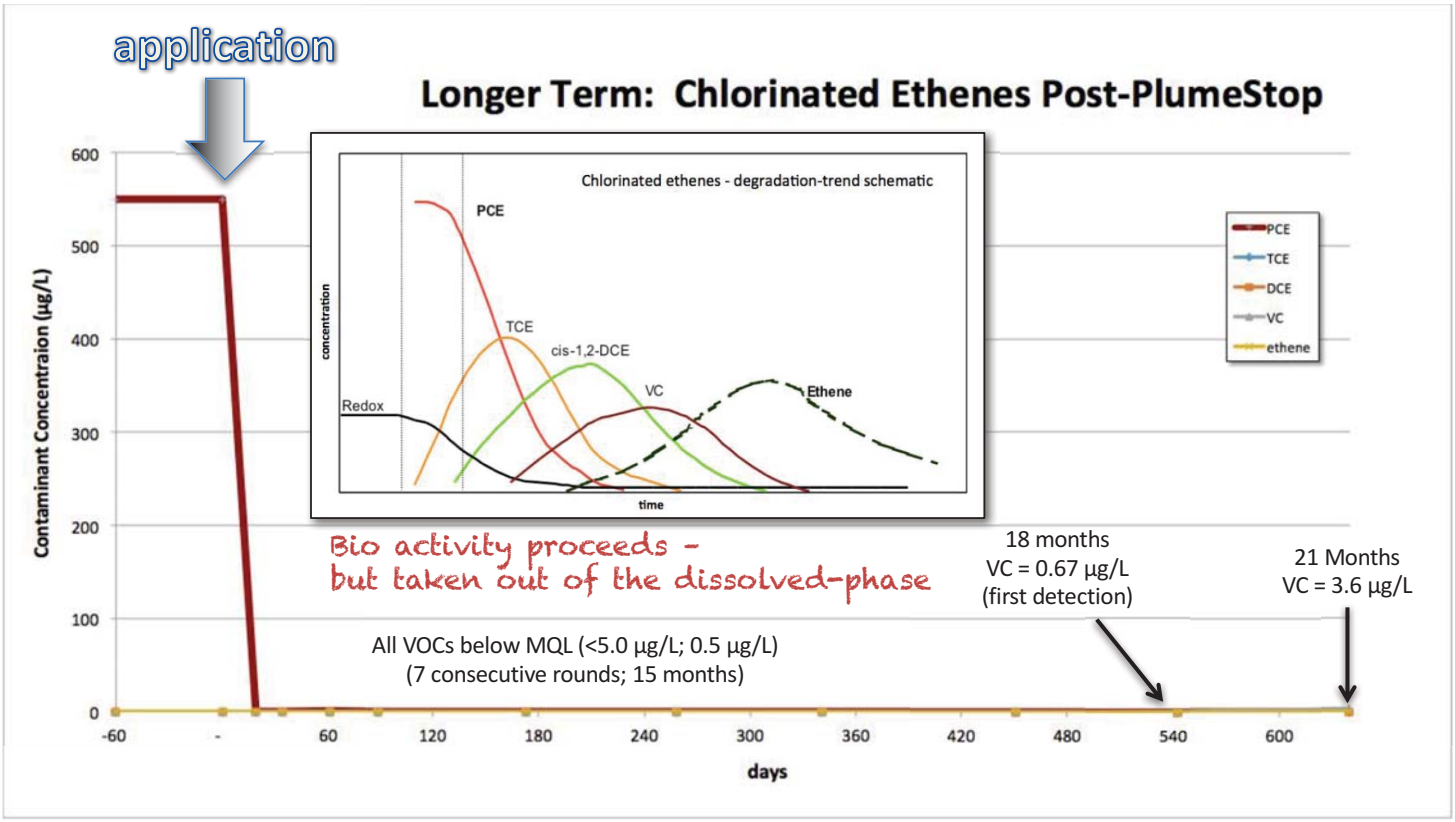

PCE Concentration Trends
(daughter products and other VOCs non-detect)
PlumeStop
COLLOIDAL BIOMATRIX
Concentration (µg/L)
700
600
500
400
300
200
100
0
2001
2002
2002.5
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2014
>99.9% reduction
(<0.5µg/L)


Contaminant and Geochemical Trends
application
Redox 'sweet spot' establishes
Competing TEA's decline
PCE (daugher products n/d)
ORP (mV)
DO (%)
Dissolved Iron (mg/L)
Nitrate (as N) (mg/L)
Sulphate (mg/L)
Contaminant Concentraion (µg/L)
Geochemical Parameters (mg/L)
(note zero on 2° axis)
days


Contaminant and Dechlorination Microbial Assay Trends
application
PCE immediately ↓↓ to ND (<5µg/L)
Micro parameters increase post-app
then decrease after ~two months
PCE (daugher products n/d)
Dehalococcoides ssp. (DHC)
tceA Reductase (TCE)
Vinyl Chloride Reductase (VCR)
Dehalobacter ssp. (DHBt)
Dehalogenimonas spp. (DHG) (+100)
Methanogens (MGN)
225%
3,000 x
(init. ND)
676%
541%
Contaminant Concentraion (µg/L)
Microbial Assay (cells / ml)
days
(no methanogenesis)


application
Longer Term: PCE Post-PlumeStop (daughter products non detect)
Contaminant Concentraion (µg/L)
< MQL (5 µg/L; 0.5µg/L) through 7 consecutive sampling rounds – 451 days (15 months) and counting…
days
(case studies)


application
Longer Term: Chlorinated Ethenes Post-PlumeStop
PCE immediately ↓↓ to ND (<5.0/0.5 µg/L) (>99.9%)
Zero historical daughter products
VC trace nevertheless appears at 18 months
(Weakest sorption of all Cl-ethenes)
Further line of evidence of post-sorption bio.
Bio activity proceeds –
but taken out of the dissolved-phase
18 months
VC = 0.67 µg/L
(first detection)
21 Months
VC = 3.6 µg/L
All VOCs below MQL (<5.0 µg/L; 0.5 µg/L)
(7 consecutive rounds; 15 months)
Contaminant Concentraion (µg/L)
days
PCE
TCE
DCE
VC
ethene


application
Longer Term: Chlorinated Ethenes Post-PlumeStop
Chlorinated ethenes - degradation-trend schematic
PCE
TCE
cis-1,2-DCE
VC
Ethene
Redox
concentration
time
Bio activity proceeds –
but taken out of the dissolved-phase
18 months
VC = 0.67 µg/L
(first detection)
21 Months
VC = 3.6 µg/L
All VOCs below MQL (<5.0 µg/L; 0.5 µg/L)
(7 consecutive rounds; 15 months)
Contaminant Concentraion (µg/L)
days
PCE
TCE
DCE
VC
ethene

PLUME STOP™
Liquid Activated Carbon

- commercial projects -

(close)

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PLUME STOP™
Liquid Activated Carbon

Case Study
- Manufactured Gas Plant / PAHs -

Richmond IN

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(skip to next)

PlumeStop™ MGP

- Silty clay loam transitioning to sand and gravel
- Globules of oil-like material in pore space
- Injection 4.0 – 6.7 mbgl

- PlumeStop™
- ORC-Advanced®

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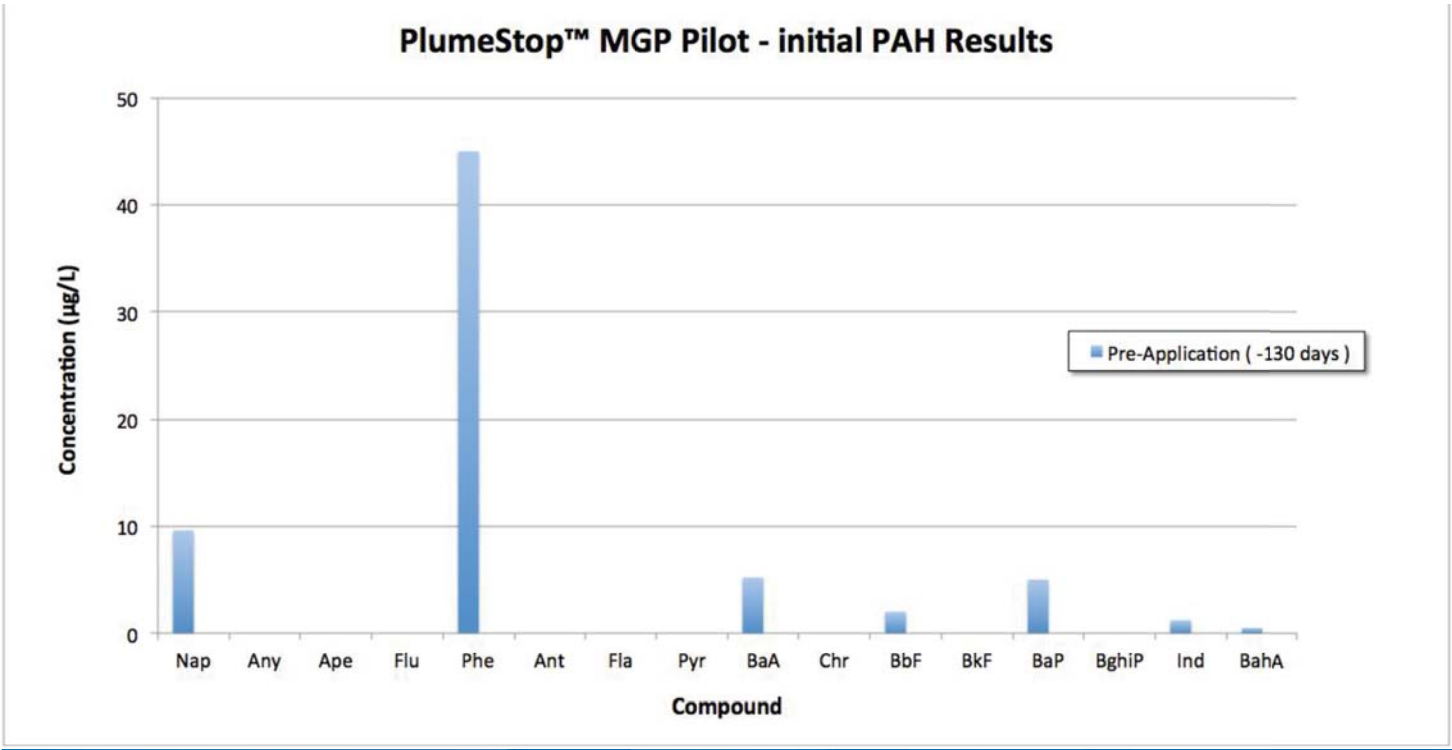

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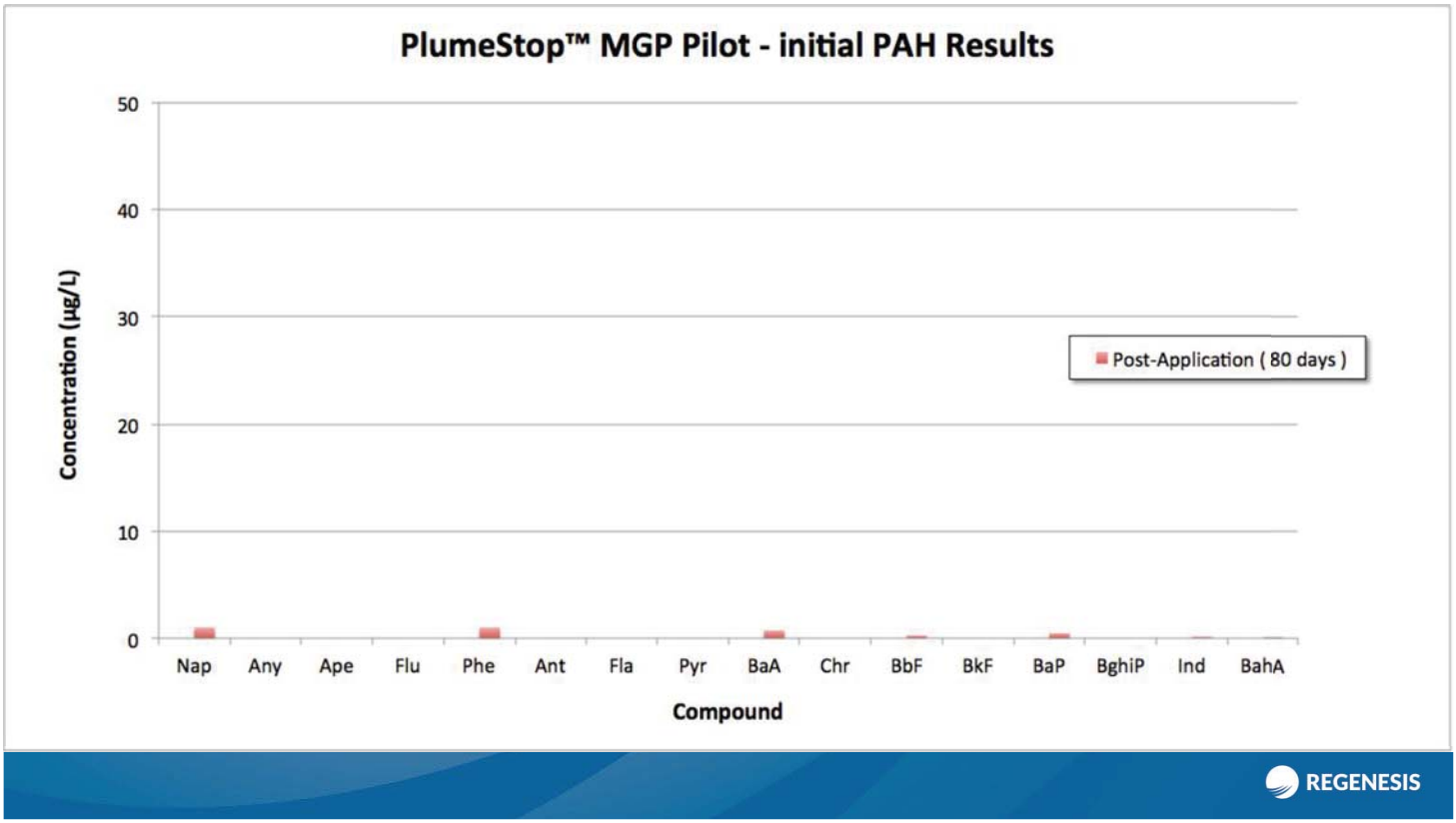
PlumeStop™ MGP Pilot - initial PAH Results
Concentration (µg/L)
50
40
30
20
10
0
Post-Application (80 days)
Nap Any Ape Flu Phe Ant Fla Pyr BaA Chr BbF BkF BaP BghiP Ind BahA
Compound
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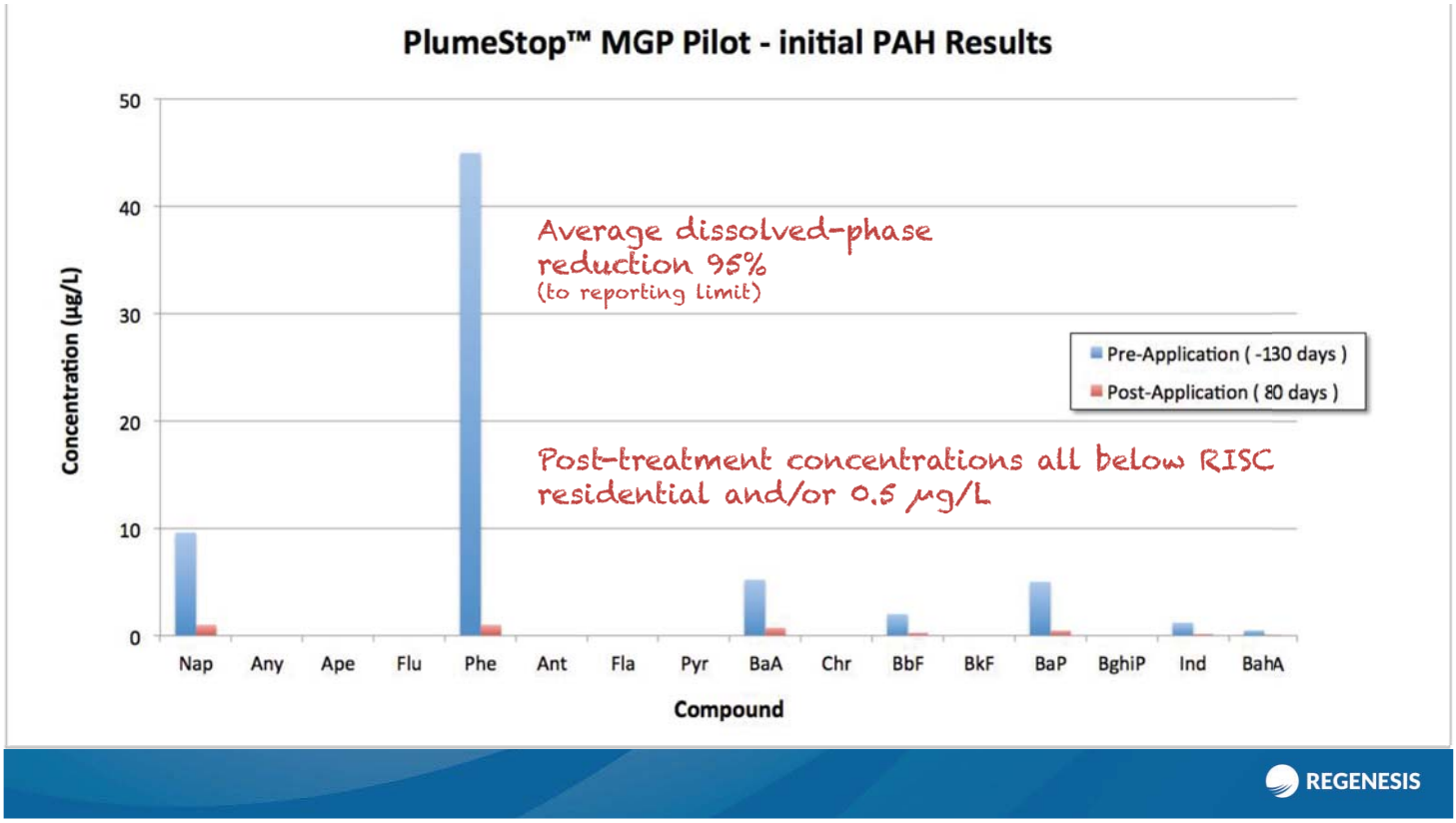
PlumeStop™ MGP Pilot - initial PAH Results
Concentration (µg/L)
50
40
30
20
10
0
Average dissolved-phase reduction 95%
(to reporting limit)
Pre-Application (-130 days)
Post-Application (80 days)
Post-treatment concentrations all below RISC residential and/or 0.5 µg/L
Nap Any Ape Flu Phe Ant Fla Pyr BaA Chr BbF BkF BaP BghiP Ind BahA
Compound
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PLUME STOP Liquid Activated Carbon

Case Study
- Migrating Plume – Barrier Application -

North Carolina

(skip) REGENESIS (close)

PlumeStop™ - Migration Cut-off Barrier

- Former Industrial Dry Cleaner
- PCE residues
- Pilot Barrier

- Multiple targeted formations
- 2.75 – 12.5 mbgl

- Silty Sand (*ca*. 1.4 to 5.3x10^{-4} cm/sec)
- Seepage Velocity *ca*. 22 m/year

- HRC® BDI® PlumeStop™

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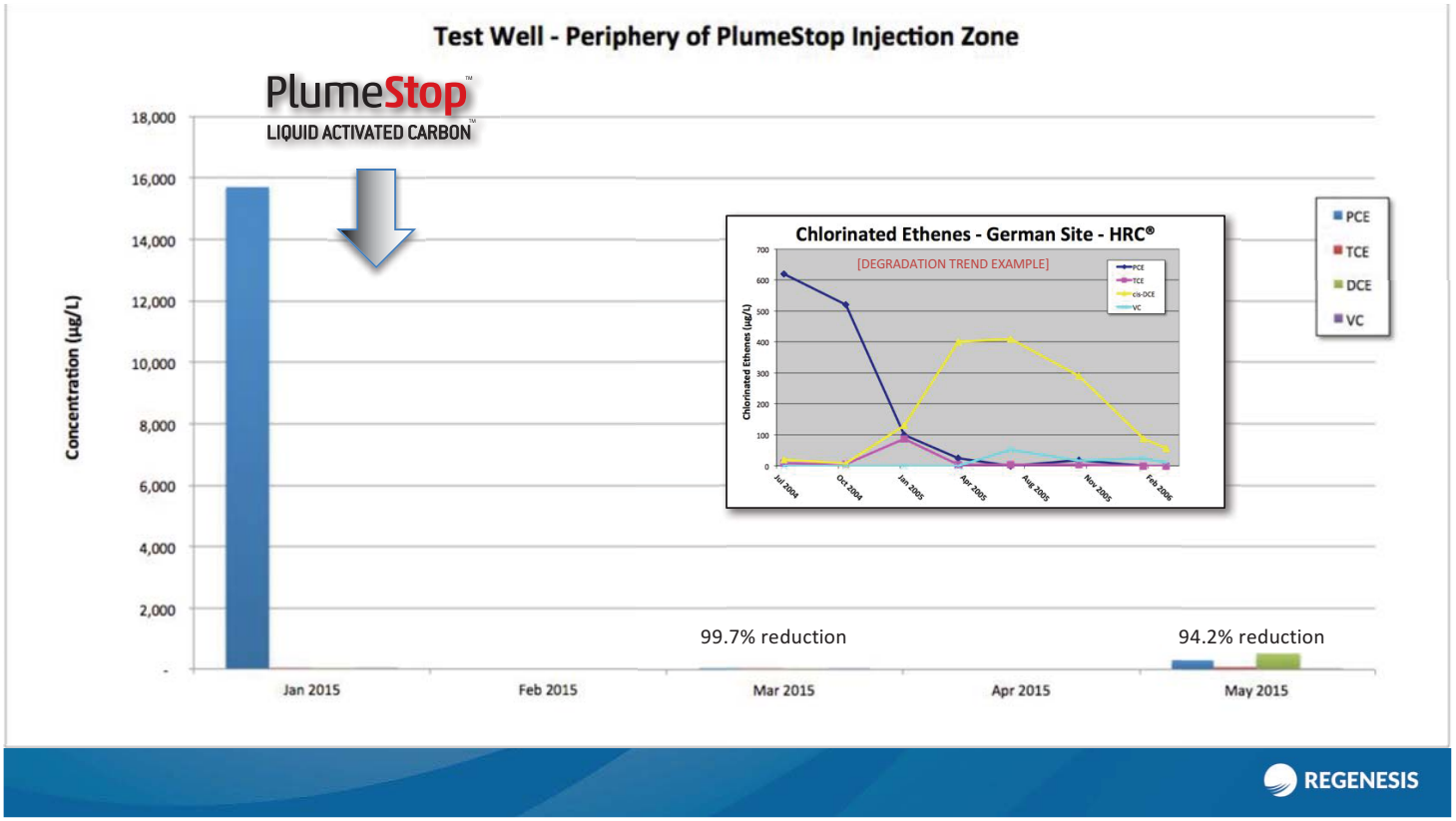
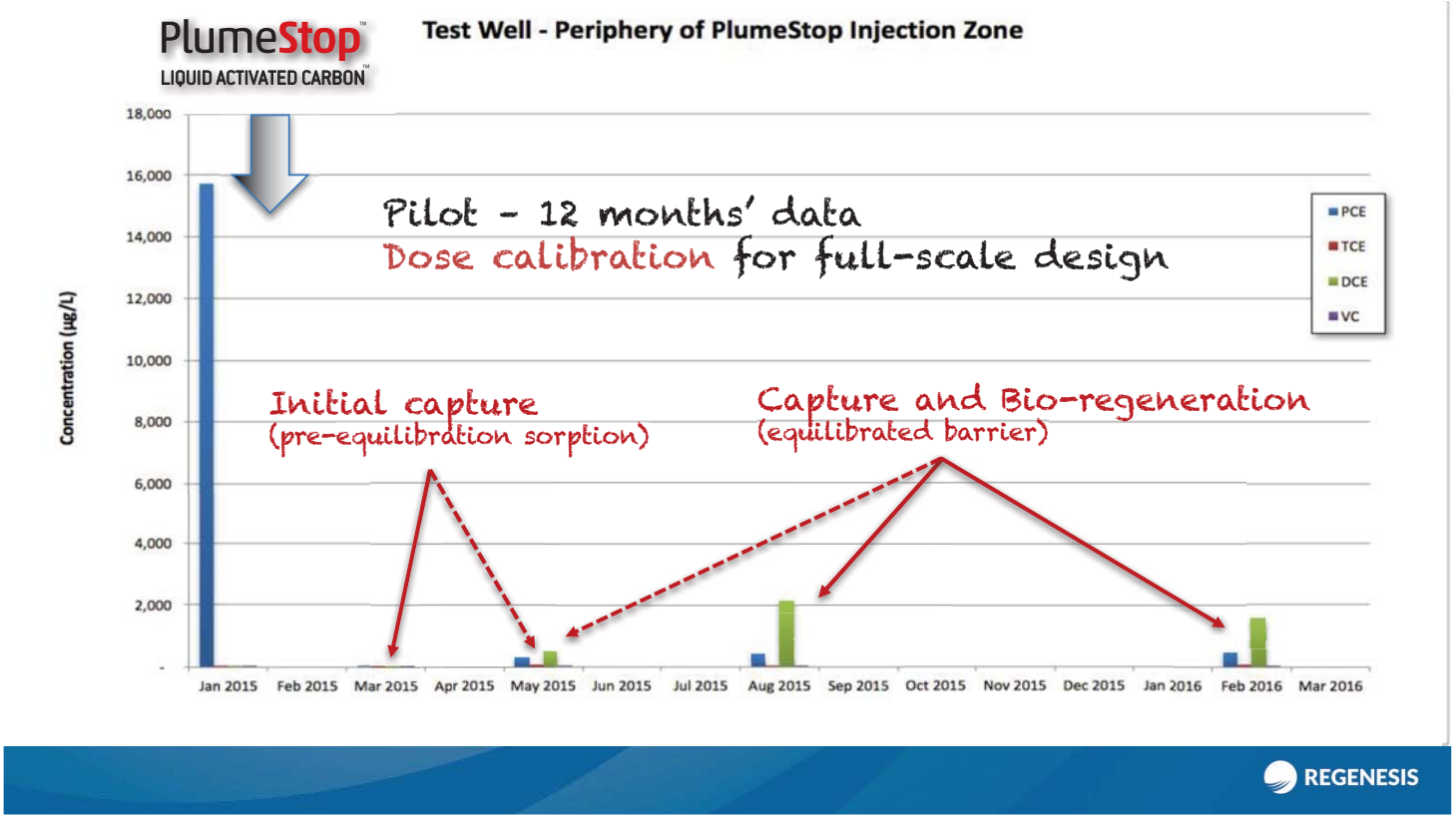

Test Well - Periphery of PlumeStop Injection Zone
PlumeStop
LIQUID ACTIVATED CARBON
Concentration (µg/L)
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
-
Jan 2015
Feb 2015
Mar 2015
Apr 2015
May 2015
99.7% reduction
94.2% reduction
PCE
TCE
DCE
VC
Chlorinated Ethenes - German Site - HRC®
[DEGRADATION TREND EXAMPLE]
Chlorinated Ethenes (µg/L)
PCE
TCE
cis-DCE
VC
Jul 2004
Oct 2004
Jan 2005
Apr 2005
Aug 2005
Nov 2005
Feb 2006
REGENESIS


PlumeStop
LIQUID ACTIVATED CARBON
Test Well - Periphery of PlumeStop Injection Zone
Concentration (µg/L)
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
-
Pilot – 12 months' data
Dose calibration for full-scale design
PCE
TCE
DCE
VC
Initial capture
(pre-equilibration sorption)
Capture and Bio-regeneration
(equilibrated barrier)
Jan 2015
Feb 2015
Mar 2015
Apr 2015
May 2015
Jun 2015
Jul 2015
Aug 2015
Sep 2015
Oct 2015
Nov 2015
Dec 2015
Jan 2016
Feb 2016
Mar 2016
REGENESIS

PLUME STOP Liquid Activated Carbon

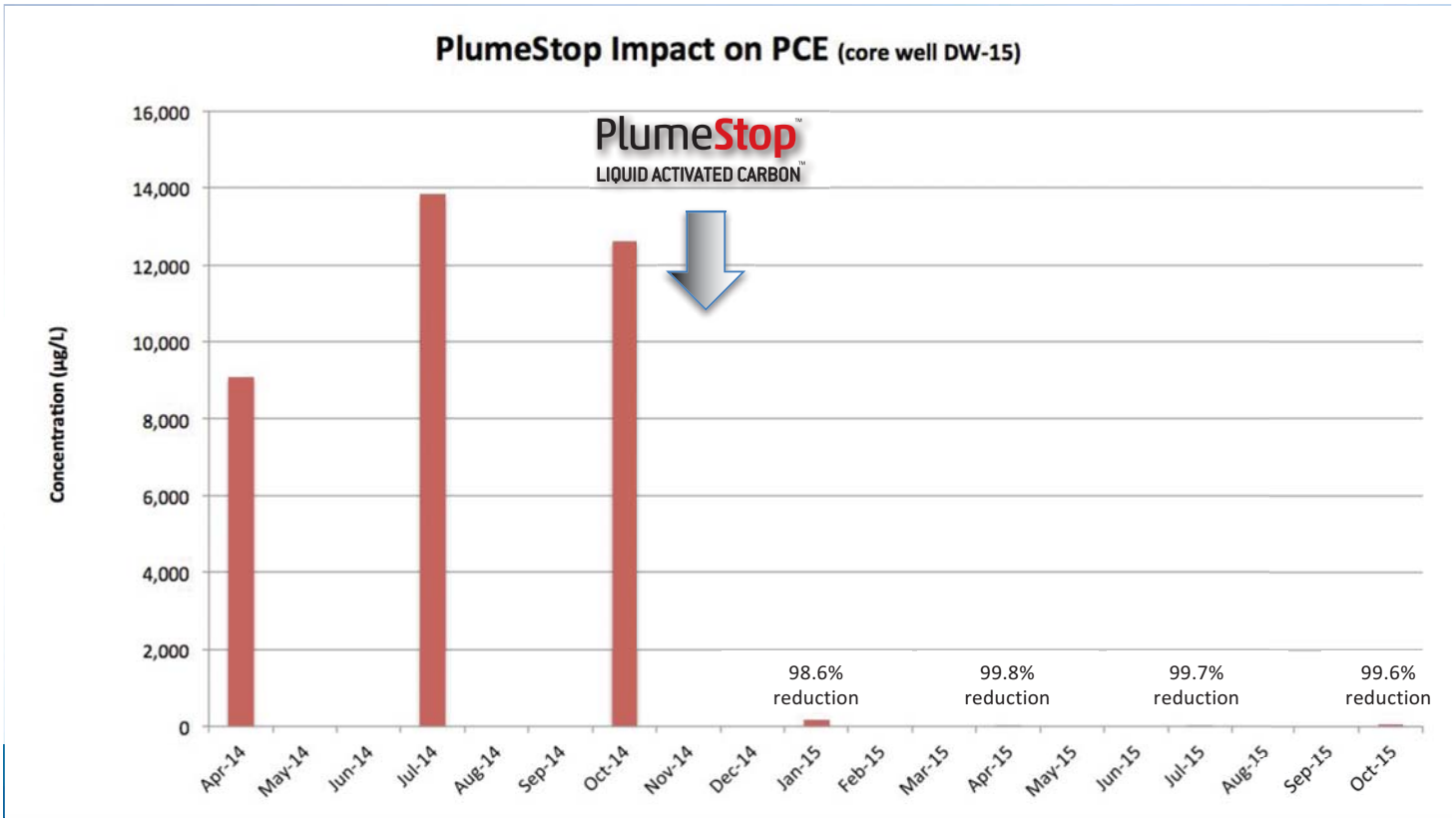
Case Study
- Deep Plume Treatment -

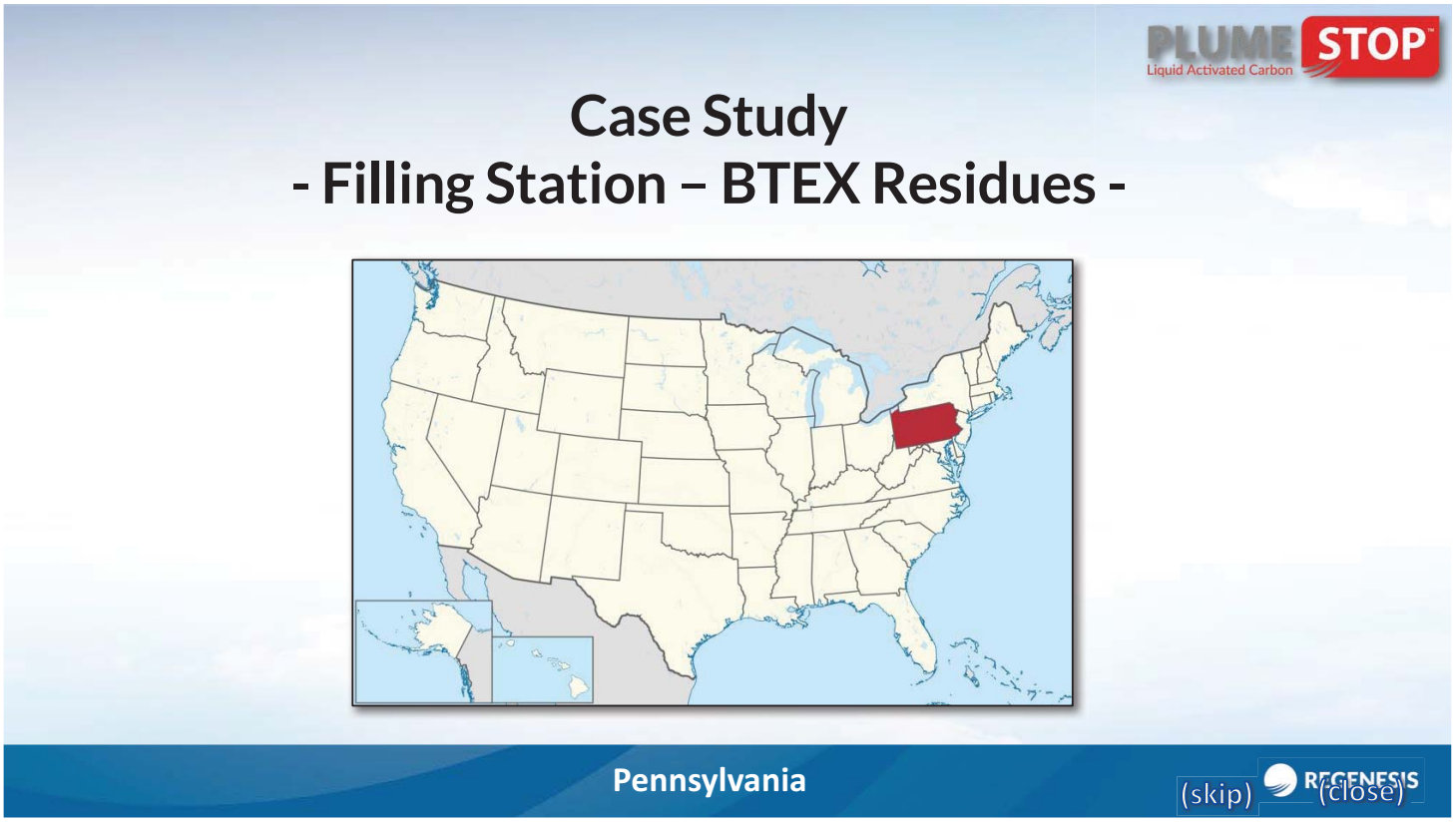
West Allis, WI (skip) (close) REGENESIS

PlumeStop™ - Deep Plume Treatment

- Former Dry Cleaner
- PCE residues
- Vadose soil mixing
- RegenOx® ISCO
- Deep plume treatment
- 24 – 27 mbgl
- HRC® BDI® PlumeStop™

REGENESIS


PlumeStop Impact on PCE (core well DW-15)
PlumeStop
LIQUID ACTIVATED CARBON
Concentration (µg/L)
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
98.6% reduction
99.8% reduction
99.7% reduction
99.6% reduction
Apr-14
May-14
Jun-14
Jul-14
Aug-14
Sep-14
Oct-14
Nov-14
Dec-14
Jan-15
Feb-15
Mar-15
Apr-15
May-15
Jun-15
Jul-15
Aug-15
Sep-15
Oct-15


PLUME STOP
Liquid Activated Carbon
Case Study
- Filling Station – BTEX Residues -
Pennsylvania
(skip)
REGENESIS
(close)

PlumeStop™ - Filling Station

- Former Filling Station
- **BTEX residues**
- Pilot Application

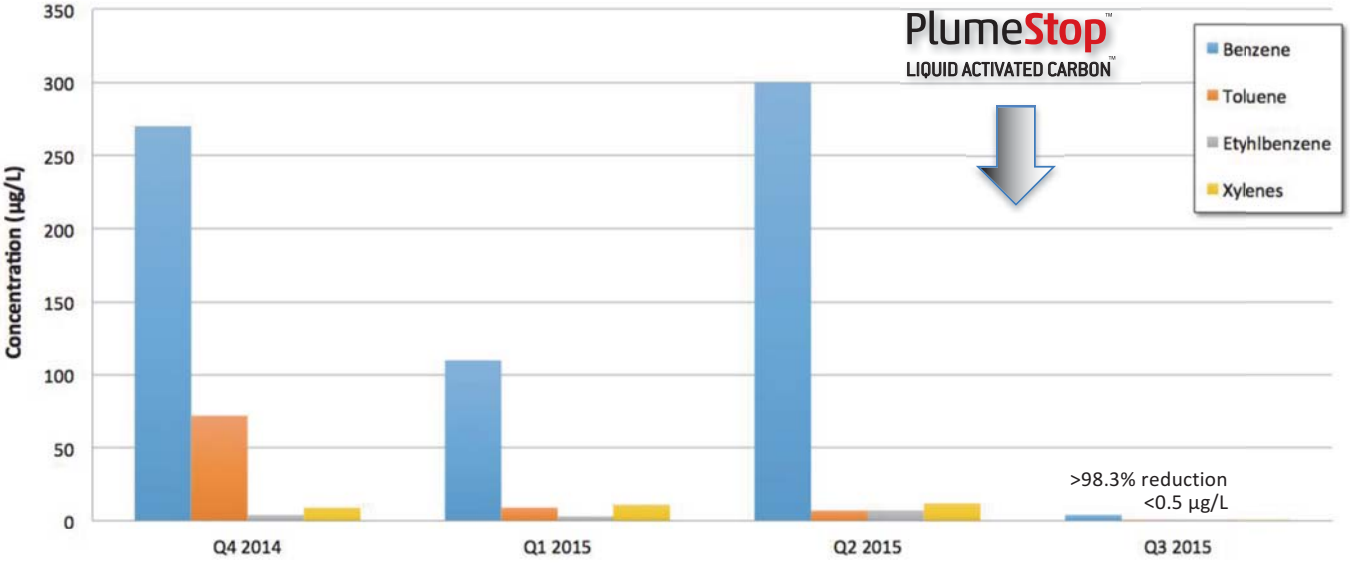
- **Tight formation**
- 2.75 – 4.5 mbgl

- Clay with Sand (*ca.* 3.53x10^{-7} cm/sec)
- Seepage Velocity Zero

- ORC-Advanced®, PlumeStop™

REGENESIS

BTEX - Well MW-6R



REGENESIS

PLUME STOP Liquid Activated Carbon

Case Study
- Filling Station – BTEX and MTBE -

Nebraska

(skip) (close) REGENESIS

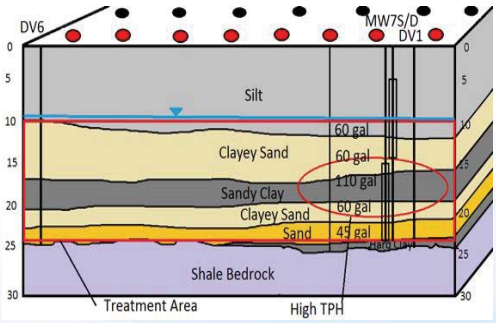
PlumeStop™ - Filling Station

- Filling Station
- **Gasoline BTEX and MTBE**
- Full Scale Application

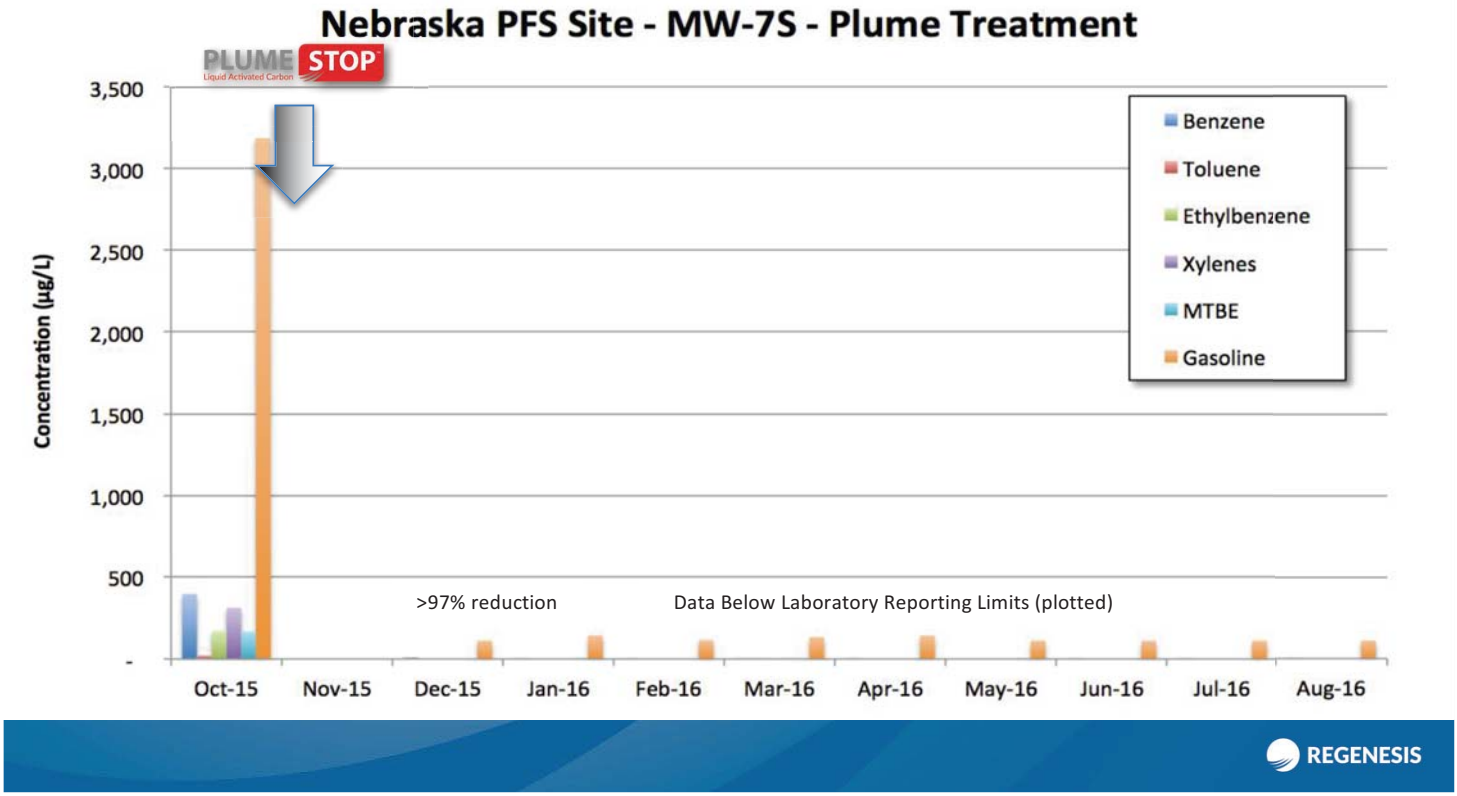
- Mixed-permeability formation
- 3.0 – 7.5 mbgl

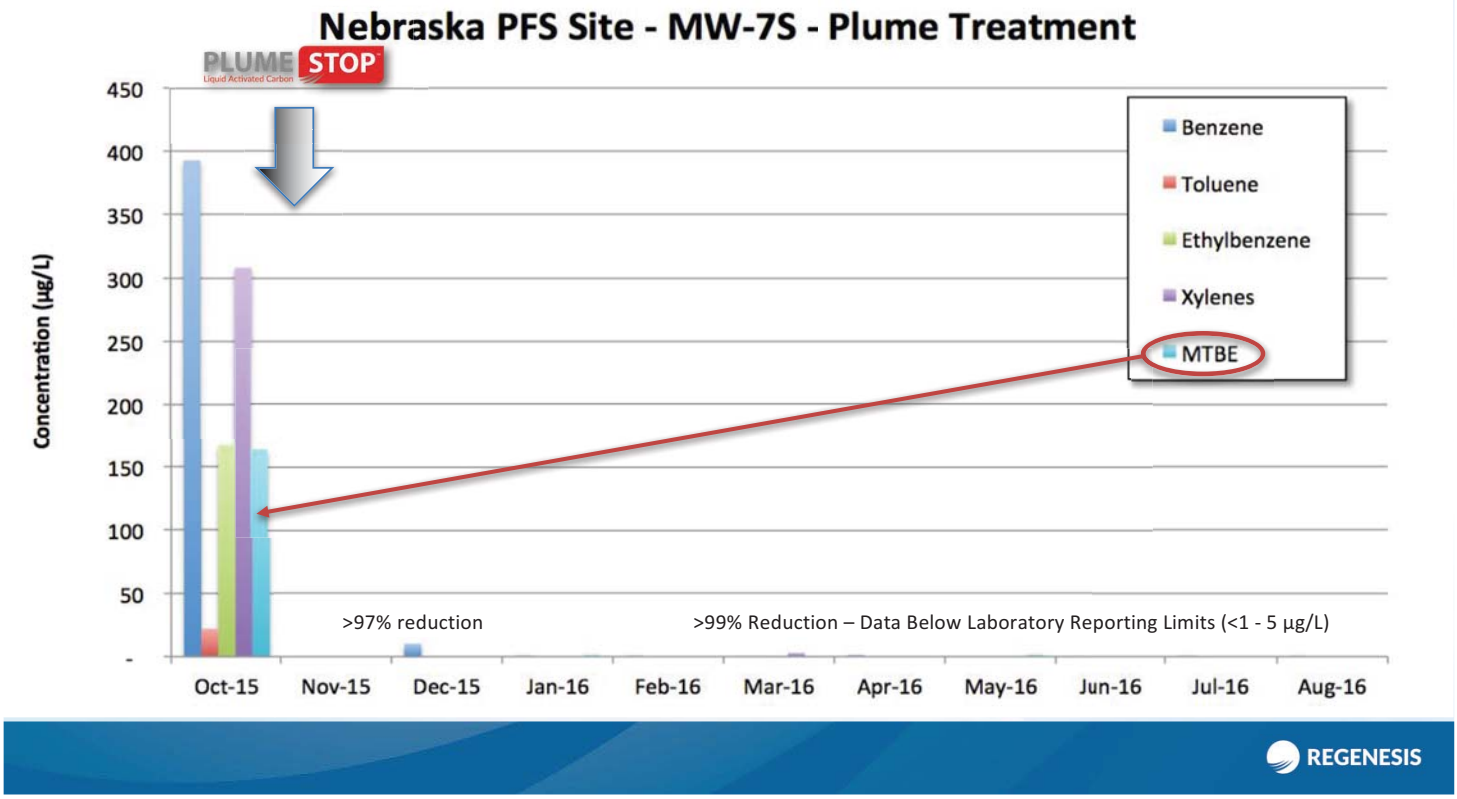
- Clay with Sand (*ca.* 10^{-2} to 10^{-7} cm/sec)
- Seepage Velocity ≤28 m/year

- ORC-Advanced®, PlumeStop™
  - Plume treatment
  - PersulfOx® ISCO in source area



REGENESIS


Nebraska PFS Site - MW-7S - Plume Treatment
PLUME STOP
Liquid Activated Carbon
Concentration (µg/L)
3,500
3,000
2,500
2,000
1,500
1,000
500
-
Benzene
Toluene
Ethylbenzene
Xylenes
MTBE
Gasoline
>97% reduction
Data Below Laboratory Reporting Limits (plotted)
Oct-15
Nov-15
Dec-15
Jan-16
Feb-16
Mar-16
Apr-16
May-16
Jun-16
Jul-16
Aug-16
REGENESIS


Nebraska PFS Site - MW-7S - Plume Treatment
PLUME STOP
Liquid Activated Carbon
Concentration (µg/L)
450
400
350
300
250
200
150
100
50
-
Benzene
Toluene
Ethylbenzene
Xylenes
MTBE
>97% reduction
>99% Reduction – Data Below Laboratory Reporting Limits (<1 - 5 µg/L)
Oct-15
Nov-15
Dec-15
Jan-16
Feb-16
Mar-16
Apr-16
May-16
Jun-16
Jul-16
Aug-16
REGENESIS

PLUME STOP Liquid Activated Carbon

Case Study
- Inner-City Development / Time Pressure -

Downtown Chicago

(skip) (close)

REGENESIS

Case Study: Inner City Development – Time Pressure

- Neighborhood of McCormick Place – Central Chicago
  - New Sports Stadium
  - New Hotel Complex

- Solvent residues
- Tight time window
- High cost implications of delay
- Key remediation requirement: **FAST**

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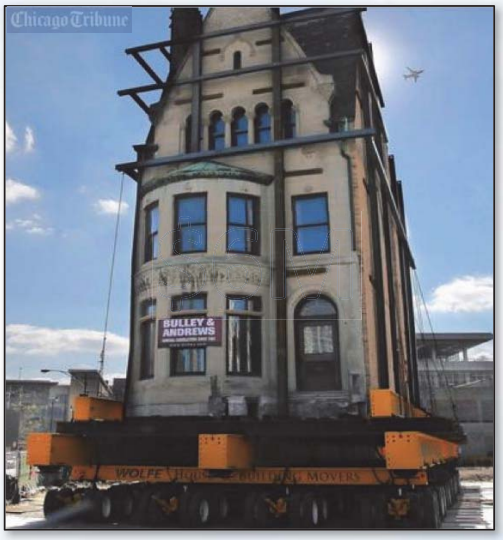
Case Study: Inner City Development – Time Pressure

- **Why the tight time window?**
  - **Weren't the solvent residues known?**
- **Access restrictions – historic buildings**
  - **Precluded early start**
- **Problem was moved aside**



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Case Study: Inner City Development – Time Pressure

- PCE and TCE residues – up to 7,440 µg/L
- Sand formation over clay
  - Treatment area 300 m x 500 m – (1,000' x 1,600')
  - Treatment Zone 3 – 7 mbgl - (10' – 22')
- Enhanced bio: HRC®, BDI®
  - Sufficient to address the contamination
- PlumeStop™
  - Rapid risk reduction and bio process acceleration
  - Take the bio process out of the groundwater phase
- 19 days' fieldwork on site (Chicago winter)
  - 138 direct-push injections – no resident equipment

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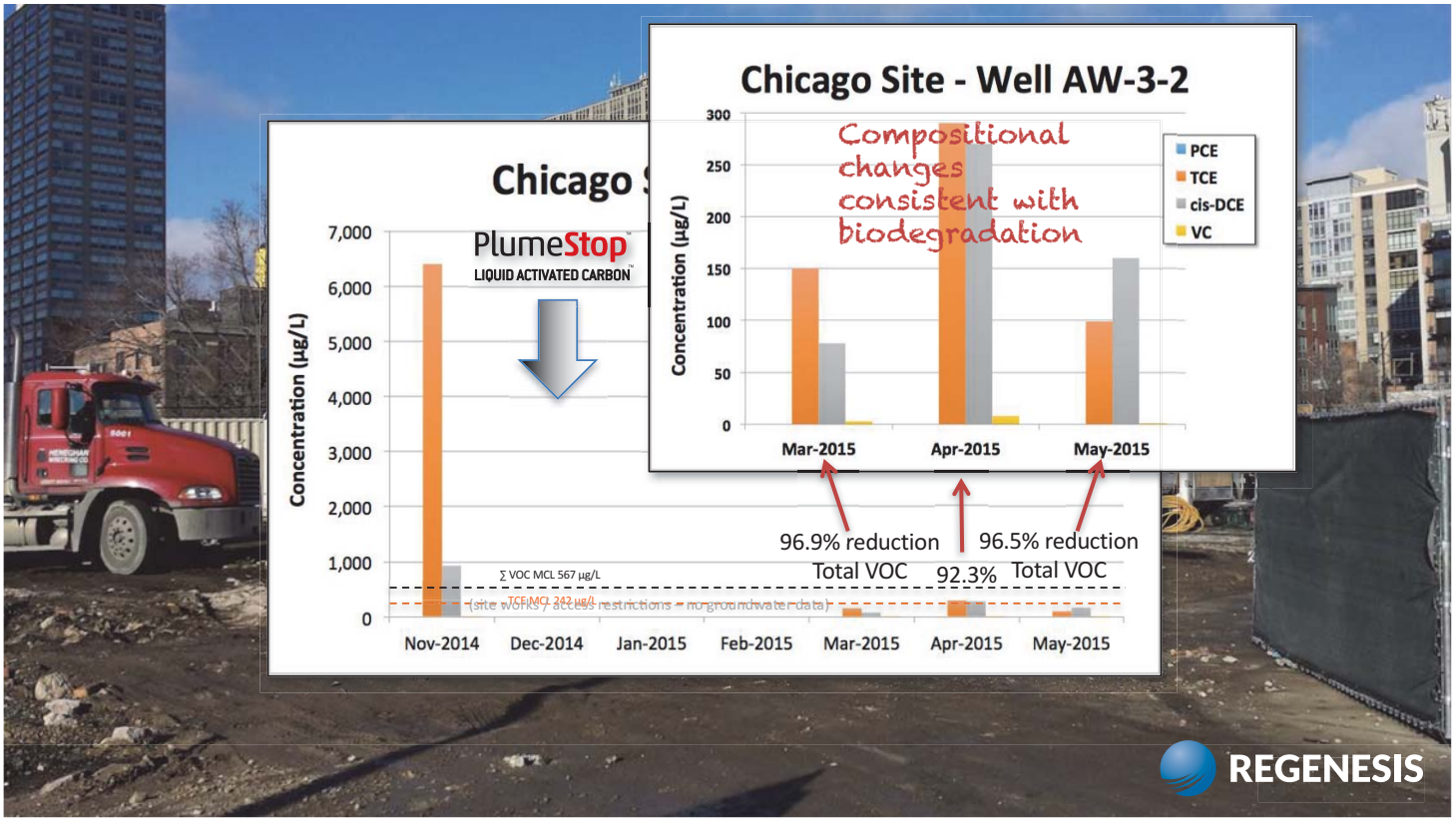
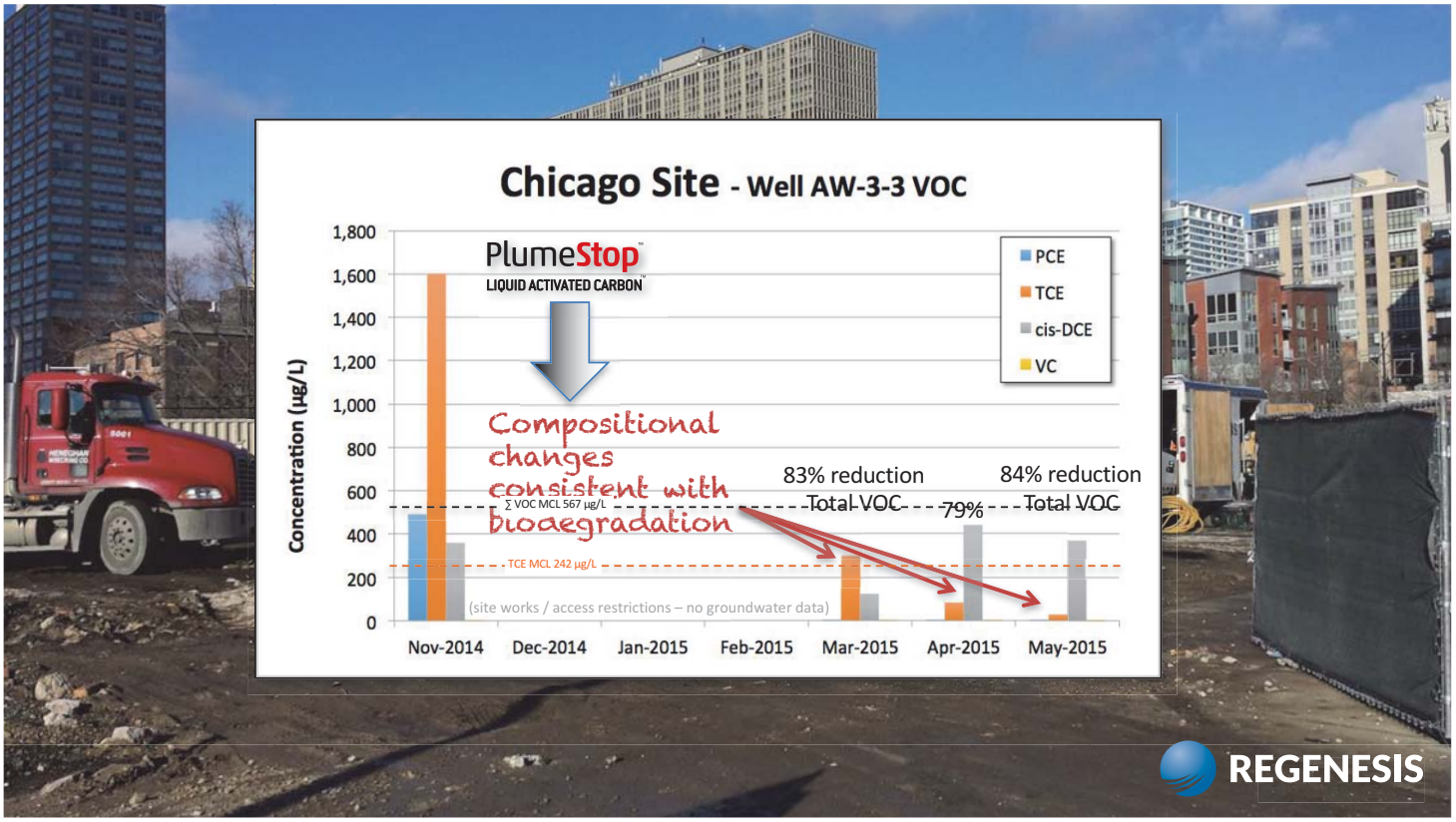

Chicago Site - Well AW-3-2
Compositional changes consistent with biodegradation
PCE
TCE
cis-DCE
VC
Concentration (µg/L)
Mar-2015
Apr-2015
May-2015
Chicago S
PlumeStop
LIQUID ACTIVATED CARBON
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
∑ VOC MCL 567 µg/L
TCE MCL 242 µg/L
(site works / access restrictions – no groundwater data)
Nov-2014
Dec-2014
Jan-2015
Feb-2015
Mar-2015
Apr-2015
May-2015
96.9% reduction Total VOC
92.3%
96.5% reduction Total VOC
REGENESIS


Chicago Site - Well AW-3-3 VOC
PlumeStop
LIQUID ACTIVATED CARBON
PCE
TCE
cis-DCE
VC
Concentration (µg/L)
Compositional changes consistent with biodegradation
83% reduction Total VOC
79%
84% reduction Total VOC
∑ VOC MCL 567 µg/L
TCE MCL 242 µg/L
(site works / access restrictions – no groundwater data)
Nov-2014
Dec-2014
Jan-2015
Feb-2015
Mar-2015
Apr-2015
May-2015
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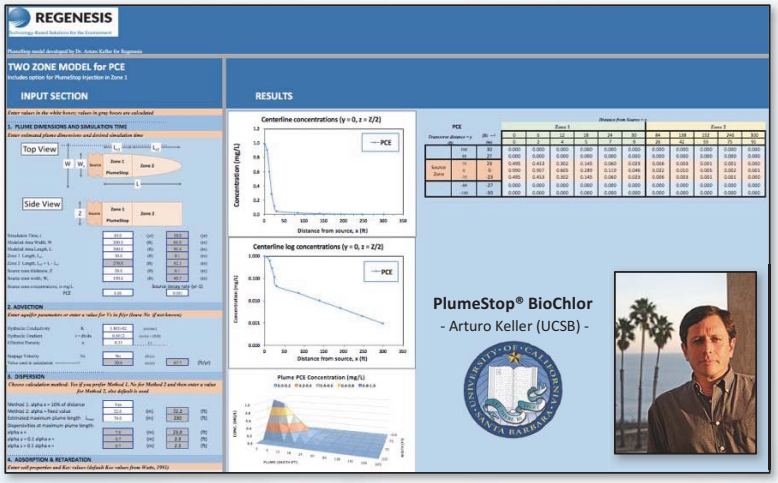
Chicago Site - Status

- Rapid reduction in groundwater contamination
  - 80 – 97% from first sampling interval (total solvents)
- Bio conditions established (redox, TOC, microbial numbers)
  - Parent/daughter compound ratio shifts (dissolved phase)
  - (consistent with biodegradation)
- ∑VOC targets met – from first sampling round (through all rounds)
- TCE targets met – from second sampling round (and degrading fast)
- Completion report submitted (June 2015)
- No further action required

- The Road Ahead -

PlumeStop® Integration with Fate & Transport Models



PlumeStop® BioChlor
- Arturo Keller (UCSB) -

We now have the engineering ability to emplace the desired retardation factor into the transport zones

- Dial-in the desired outcome
- Explore design options

Then turn it into reality

PLUME STOP
Liquid Activated Carbon

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Which brings us to....

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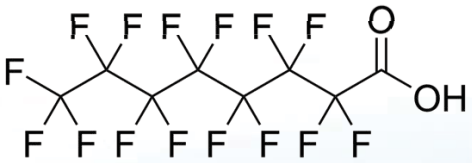
PLUME STOP™
Liquid Activated Carbon

- Perfluorinated Compounds -



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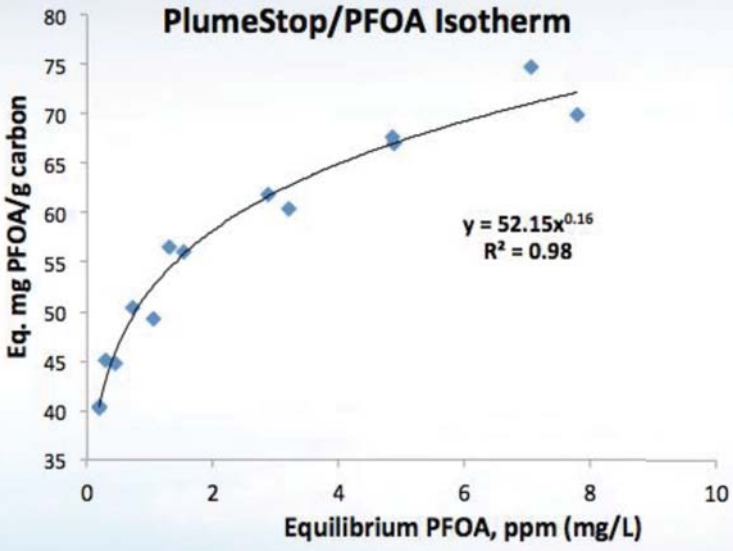
PlumeStop + PFOA/PFOS



	Kf	1/n	PS dose, mg/L: 5 ppm -> .005 ppm
PFOA	52	0.16	224
PFOS	135	0.28	163
PCE	105	0.42	445

Sorption only
(currently no validated destruction methods are available)

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PlumeStop + PFOA/PFOS: retardation factor

For a PlumeStop® barrier at a mid-range dose:

- PFOA
  - The *R* of a 1,000 µg/L plume is 80
  - The *R* of a 100 µg/L plume is 570
  - The *R* of a 10 µg/L plume is 4,000
- PFOS
  - The *R* of a 1,000 µg/L plume is 375
  - The *R* of a 100 µg/L plume is 2,000
  - The *R* of a 10 µg/L plume is 10,000

based on individual components

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PlumeStop + PFOA/PFOS: retardation factor

Example:

- PlumeStop® barrier width 5 m (single application at mid-range dose)
- 50 m per year seepage velocity
- 100 µg/L influent concentration

This is at 100 µg/L
At lower influent concentrations, the retardation quickly becomes much greater.

- Groundwater transit time 36.5 days
- PFOA transit time* = 20,800 days (57 years)
- PFOS transit time* = 73,000 days (200 years)

* transit time peak based on individual components

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PlumeStop + PFOA/PFOS

Does not eliminate the problem

But it stops it spreading

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- Take Home -

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Take Home

We can now turn the subsurface into an activated carbon filter

- **To capture contaminants and focus bioremediation**
  - Secure stringent targets faster – manage back-diffusion
- **To passively engineer plume dynamics**
  - Long term migration control without pumping
  - Groundwater flow remains uninterrupted

The retardation factor is now an engineering variable

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Vice President
Environmental Technology

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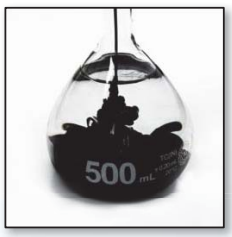
jbirnstingl@regenesis.com

REGENESIS®
Technology-Based Solutions for the Environment

Thank You



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