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Pilot Test of Arsenic Adsorptive Media Treatment Technologies at Socorro Springs, New Mexico

Materials Characterization and Phase I Results Supplemental Appendices

Malcolm Siegel, Alicia Aragon, Hongting Zhao, Randy Everett, Malynda Aragon, Melody Nocon, Brian Dwyer, Justin Marbury, Carolyn Kirby, and Katharine North

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Supplemental Appendices

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Abstract

The Arsenic Water Technology Partnership (AWTP) program is a multi-year program funded by a congressional appropriation through the Department of Energy to develop and test innovative technologies that have the potential to reduce the costs of arsenic removal from drinking water. As a member of the AWTP, Sandia National Laboratories carried out pilot tests of the most promising technologies selected by panels of independent experts. Phase I of the Sandia pilot demonstration at the Socorro Springs site tested arsenic removal performance of five different adsorptive media under constant ambient flow conditions. The media studied included two granular ferric oxides (E33 and ARM 200), a titanium oxide (Metsorb), an ion exchange resin impregnated with iron oxide nanoparticles (ArsenX^{np}) and a zirconium oxide (Isolux). The results of the test are described in Sandia National Laboratories report SAND2007-0161. This report contains appendices describing details of the design and performance of each of columns.

ACKNOWLEDGEMENTS

The contributions of several coworkers to this project are gratefully acknowledged. These include: Charlotte Casaus, Richard Kottenstette, Pamela Puissant, Jerome Wright and Emily Wright, (Sandia National Laboratories), Bruce Bartley (NSF, International), Frederick Partey and Dave Norman (New Mexico Tech) and Judy Campbell (GRAM, Inc). Management support from Tom Hinkebein and John Merson (Sandia National Laboratories) was appreciated. The cooperation and support of members of the Arsenic Water Technology Partnership including Abbas Ghassemi and Rose Thompson (NMSU) and Albert Ilges (AwwaRF) are gratefully acknowledged.

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Note: These appendices are also available at the Sandia National Laboratories Arsenic Water Technology Partnership websites: http://www.sandia.gov/water/arsenic.htm and http://www.sandia.gov/water/pubs1.htm or from the lead author.

Appendix A: Design Calculations for Isolux 302M Cartridge

Isolux 302M is an amorphous inorganic zirconium oxide adsorption media. The adsorptive media is contained in an annulus; flow is perpendicular to the surface. MEI provides the media in pre-packaged radial flow cartridges with following dimensions:

OD of media bed = ID of outer tube = 2.47"
ID of media bed = OD of inner tube = 1.5"
Average bed diameter = 2.018"
Bed depth = 0.574" = 0.0478 ft.
Length of Media Bed = 9.07"

Surface area of annular column@ average bed diameter = 58.2 sq. in. = 0.404 sq. ft.

Volume of Media = $(\pi/4) \times D^2_1 \times L - (\pi/4) \times D^2_2 \times L$
$= (\pi/4) \times (2.47)^2 \times 9.07 - (\pi/4) \times (1.5)^2 \times 9.07$
$= 42.759 - 16.03$
= 27.432 cubic inches = 0.118 gallons/BV = 0.449 L/BV

Actual Flow = 0.5 gpm; (Maximum rated flow = 1 gpm)
Specific flow rate through column = actual flow/surface area
= 0.5/0.404 = 1.24 gpm/sq ft = 0.166 ft/min

Average empty bed contact time = bed depth/specific flow rate
Avg EBCT = bed depth/actual specific FR = 0.0478 ft/0.166 ft/min= 0.29 min = 17.3 sec

Appendix B: Time Line for Pilot

B-1. Events in Pilot Test

Date	Action
10/15/04-11/30/04	Gathered pH, turbidity, conductivity samples weekly
11/30/04	Installed columns
12/7/04	Loaded media into columns
12/9/05	Performed initial backwash of each column Noticed that each of the columns' media height was lower than design height
1/24/05	Added more media to each column – now at design height Backwashed each of the columns
1/26/05	Phase I (no pH adjustment) Two-Week Integrity Verification starts Samples taken daily on columns 4-10, chlorinated and raw water
1/29/05	Totalizing water meters' displays aren't working – they are fixed several times by cleaning out, but continue to show zero total gallons
2/1/05	NSF Visit to site: Inspection of Pilot equipment, training, and question & answer session
2/4/05	Flow meters are moved from influent to effluent side of Columns 4 and 5. Entire pressure drop was taken by the rotameters, which led to no or little pressure to the columns. This solved the problem.
2/9/05	MEI Isolux cartridge has a ΔP of 38 psi – cartridge is depleted.
2/14/05	Socorro Utilities personnel trained
3/11/05	Stopped sampling SA sample point (raw water); all arsenic is present as As(V)
5/3/05	Software glitch on totalizing water meters is fixed; however, problems continue with meters. High water temperature most likely caused their failure.
7/18/05-7/22/05	TOMCO pH Control (CO_2) system installed Field Representative visited and verified settings, trained SNL personnel
7/26/05	Leak on pH adjustment water line to columns – fixed onsite Capacity Extension (Phase IIa) begins Samples taken for analysis three times per day on 7/26, 27, 28
7/28/05	Column 6 (Hydroglobe Metsorb) has high ΔP, is backwashed several times but were unable to get column to flow. Column is isolated and taken offline.
8/6/05	Pump not working; capacity extension cancelled

8/19/05	Pump purchased for Jemez pilot installed Flow Interruption study begins, daily arsenic samples taken
8/23/05	CO_2 system out of calibration (off by more than 0.4 pH units), once system is calibrated, no water flowing
8/24/05	Site visit determines that CO2 had leaked into piping system, once bled off pump worked again
8/30/05-9/30/05	Flow interruption study continues, daily arsenic samples taken. Columns 6 and 8 are removed for mass transfer zone study

B-2. Summary of Column Histories

SC-4: ARM 200

Phase I

On-line: 1/27/2005

2 week Verification daily sampling : 1/27/2005 – 2/11/2005

Capacity verification test with biweekly As sampling and weekly to monthly sampling for other solute

Phase IIa

pH adjusted : 7/27/2005 -12:00AM

48 intense sampling- until 7/29/2005 -11:35 AM

Flow interrupted: about 8/5/2005

Flow interruption experiment – daily sampling 8/21/2005-10/2/2005

Flow continues with some samples taken 10/3 – 10/21

Flow continues with daily samples taken 10/21- 11/8

Column off line 11/9/2005

Pore water samples taken before breakdown.

SC-5 – ArsenX^{np} – same as SC-4

Phase I

On-line: 1/27/2005

2 week Verification daily sampling : 1/27/2005 – 2/11/2005

Capacity verification test with biweekly arsenic sampling and weekly to monthly sampling for other solute

Phase IIa

pH adjusted : 7/27/2005 -12:00AM

48 intense sampling- until 7/29/2005 -11:35 AM

Flow interrupted: about 8/5/2005

Flow interruption experiment – daily sampling 8/21/2005-10/2/2005

Flow continues with some samples taken 10/3 – 10/21

Flow continues with daily samples taken 10/21- 11/8

Column off line 11/9/2005

Pore water samples taken before breakdown.

SC-6 Metsorb
Phase I
On-line: 1/27/2005
2 week Verification daily sampling : 1/27/2005 – 2/11/2005
Capacity verification test with biweekly arsenic sampling and weekly to monthly sampling for other solute

Phase IIa
pH adjusted : 7/27/2005 -12:00AM
48 intense sampling- until 7/28/2005 -4:00 PM
Column off line 7/28/2005
Column returned to Sandia for post-mortem:

SC-7 Isolux
Phase I
On-line: 1/27/2005
2 week Verification daily sampling : 1/27/2005 – 2/09/2005
Column off line 2/9/2005

SC-8 E33- 2 minutes EBCT; later pH adjustment

Phase I
On-line: 1/27/2005
2 week Verification daily sampling : 1/27/2005 – 2/11/2005
Capacity verification test with biweekly arsenic sampling and weekly to monthly sampling for other solute with no pH adjustment until 10/5. We wanted to see complete saturation.

Phase IIa
Flow stops about 8/6/2005
Flow interruption experiment – daily sampling 8/21/2005-10/2/2005
pH adjusted : 10/5/2005 ; first sample taken 10/9
Flow continues with daily samples taken 10/21- 11/8
Column off line 11/10/2005
Pore water sample taken before breakdown.

SC-9 E33- 4 minutes EBCT

Phase I
On-line: 1/27/2005
2 week Verification daily sampling : 1/27/2005 – 2/11/2005
Capacity verification test with biweekly arsenic sampling and weekly to monthly sampling for other solute

Phase IIa
pH adjusted : 7/27/2005 -12:00AM
48 intense sampling- until 7/29/2005 -11:35 PM

No samples until one sample taken 8/11/2005 after flow interruption
Column off line 8/21/2005
About 8/30/2005 -Column returned to Sandia for post-mortem: solid samples taken every 1.5 inches and analyzed for As, Si, Ca

SC-10 E33- 5 minutes EBCT - No pH adjustment

Phase I
On-line: 1/27/2005
2 week Verification daily sampling : 1/27/2005 – 2/11/2005
Capacity verification test with biweekly arsenic sampling and weekly to monthly sampling for other solute
48 intense sampling- until 7/29/2005 -11:35 AM

Phase IIa
Flow interrupted: about 8/5/2005
Flow interruption experiment – daily sampling 8/21/2005-10/2/2005
Flow continues with some samples taken 10/3 – 10/21
Flow continues with daily samples taken 10/21- 10/29
Column off line 11/5/2005
Pore water sampled before column was taken down.

Summary of Column History

	S4	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
pH adjustment (7/27/05)	Y	Y	Y[1]	N	N[2]	Y	N
Flow interruption	Y	Y	N	N	Y	N[3]	Y
Run until exhaustion	N	N	N	Y	Y	N	N
Pore water samples	Y	Y	N	N	Y	N	Y
Core profile sampled	NY	NY	Y	N		Y	
Date removed from service	11/9/05	11/9/05	7/28/05	2/9/05	11/9/05	8/21/05	11/5/05

Notes:

[1]S6 plugged up after pH adjustment 7/28/05.
[2] S8 – pH adjusted 10/5/05 after saturation reached.
[3] S9 – taken off line shortly after flow stopped; only one sample taken and returned to lab for sampling

Appendix C: Media-Specific Results

C-1. Introduction

This appendix presents the testing parameters used in the Socorro, NM Pilot Demonstration for the Sandia National Laboratories Arsenic Water Technology Partnership Pilot Demonstration Project. The results of the testing are also presented as a set of plots for each media.

An objective of the pilot study was to evaluate the accuracy of different methods to predict the performance of adsorptive media from site-specific water chemistry data, batch sorption data, and bench-scale column studies.

Each media was exposed to blended spring water from a local Socorro site (Table C-1). The influent flowed through a three-inch diameter column containing the medium. Prior to reaching the adsorptive media, the water was chlorinated using gaseous chlorine to convert As(III) to As(V). The pH of the water ranged from 7.9 to 8.2. (In Phase II, the pH was reduced to 6.5 to 6.8.) The operating pressure was 38 to 42 psi.

The design parameters and calculations are summarized in subsequent subsections for each media. The design and operating parameters for the pilot columns are compared to the parameters for a full-scale system. Also shown in the subsections are sets of effluent chemistry data plots for each media. (The data in the most of the plots are for results obtained through April 28, 2005 and are indicative of the results obtained through the entire period of data collection at the pilot plant. The data for the arsenic and As(V) in the effluent water represents the testing period through July 29, 2005.) The data plots show the major solutes in the influent to the media column and the effluent from the media column during the tests.

Table C-1. Nominal Socorro Water Quality

Parameter	Unchlorinated Feed Water	Chlorinated Feed Water
Conductivity (µS)	356-360	356-360
Temperature (degrees Celsius)	30.1-30.5	30.1-30.5
Free chlorine (mg/L as Cl_2)	ND	0.5 – 0.8
pH	8.03-8.07	7.89-7.91
Iron (ppb)	43.3	38.2
Total Arsenic (ppb)	42.4	42.9
Speciated Arsenic		
Particulate (ppb)	ND	1.9
As(III) (ppb)	ND (0.53)	2.1
As(V) (ppb)	42.4	40.9
Titanium	ND (0.38)	ND (0.38)
Zirconium (ppb)	0.22	ND (0.22)
Alkalinity (ppm)	123	NA
Nitrate (ppm)	0.48	0.4
Calcium (ppm)	17.5	17.4
Magnesium (ppm)	4.1	4.1
Sodium (ppm)	57.0	57.1
Silica (ppm)	25.0	24.9
Aluminum (ppb)	24.2	23.2
Vanadium (ppb)	11.4	11.3
Gross Alpha/Beta (pCi/L)	NA	Alpha-6.50, Beta-3.52
Chloride (ppm)	11.5	12.1
Fluoride (ppm)	0.62	0.5
Sulfate (ppm)	28.7	28.4
Total Organic Carbon (TOC)	NA	0.5

ppm = parts per million; ppb = parts per billion
NA = not available; ND = not detected above method detection limit (MDL is given)

Appendix C-2 Purolite - ArsenX^{np}

Vendor	Flow Rate (gpm)	Contact Time [EBCT] (minutes)	Bed Volume [BV] (liters)
Purolite	0.4	3	4.74

Pilot	BV to 10 ppb (10 μg/L)	27000
	Capacity at 10 ppb, mg/g	1.38
	BV at C/C_o = 0.8	53000
	Capacity at C/C_o = 0.8	2.10
PD RSSCT	BV to 10 ppb ppb (10 μg/L)	43000
	Capacity at 10 ppb, mg/g	1.33
	BV until $C_e = C_o$	76000
	Capacity at $C_e = C_o$, mg/g	1.38
	BV at C/C_o = 0.8	60000
	Capacity at C/C_o = 0.8	1.37

Notes:

BV to 10 ppb ppb (10 μg/L) is read from breakthrough curve where effluent concentration, C_e, reached and stayed > 10 ppb (10 μg/L).
Capacity at 10 ppb (10 μg/L) is calculated from raw data when C_e reached and stayed > 10 ppb (10 μg/L).
Capacity is integrated from mass balance on arsenic data. (Integration: area above BT curve and below influent concentration represents media capacity.)

Isotherm Results

Capacity 10ppb As [Freundlich] (mg/g)	Capacity 40 ppb As [Freundlich] (mg/g)	Capacity 10 ppb As [Langmuir] (mg/g)	Capacity 40 ppb As [Langmuir] (mg/g)
4.63	9.86	5.77	10.32

Notes: Freundlich isotherm: $Q = K_F C^{nF}$
Langmuir isotherm: $Q = (S_{max} K_L C)/(1+K_L C)$

Where Q = equilibrium mg As/g media; K_F, n, F, K_L = isotherm parameters obtained from curve fits, C = equilibrium concentration in solution , (mg As/L); S_{max} = maximum capacity (mg As/g media).

Purolite - ArsenX^{np} Results:

Arsenic: Arsenic concentrations in the pilot effluent reached 10 ppb (10 μg/L) after 27,000 bed volumes had flowed through the column. This was about 63% (27,000/43,000) of the bed volume capacity predicted by the Proportional Diffusivity (PD) RSSCT experiments. The capacity predicted by mass balance was 1.38 mg As /g media and was 4% greater than that predicted by the PD RSSCT experiments. Capacities at 10 ppb (10 μg/L) calculated from batch sorption data using either the Langmuir or Freundlich isotherms were much higher than those obtained in the flow experiments (RSSCT or pilot). As the effluent arsenic concentration in the pilot column rose above 10 ppb (10 μg/L), the BTC was fairly steep. There was about 52% additional capacity (1.38 to 2.1 mg/g) when the effluent concentration reached 80% of the influent concentration ($C/C_e = 0.8$). The RSSCT columns showed a much smaller additional capacity (BTC was sharper). When the pH was lowered by CO_2 injection in Phase IIA, the effluent arsenic concentration dropped to approximately 12 ppb.

Vanadium: Vanadium (influent approximately 13 ppb) was removed to non-detectable levels (MDL = 0.5 ppb) for the entire Phase I pilot study at ambient pH but increased slightly (about 2 ppb) when the pH was lowered to 6.8 by CO_2 injections in Phase IIA.

Other Solutes: Sulfate was released in the first few bed volumes of effluent but declined to ambient levels by 5000 BV. Silica was adsorbed for the first 2000 BV, and then reached ambient levels by 6000 BV; however, a silica spike was observed at about 5500 BV. Fluoride was adsorbed for the first 5500 BV and then reached ambient levels. Free chlorine was adsorbed quantitatively for the first 20,000 BV; effluent levels slowly rose and reached influent levels after 70,000 BV. The initial pH in the effluent was depressed (pH = 4.3) and rose rapidly to reach ambient pH after about 2000 BV. Other solutes (Ca, Mg, Na, Cl) were not affected by the resin.

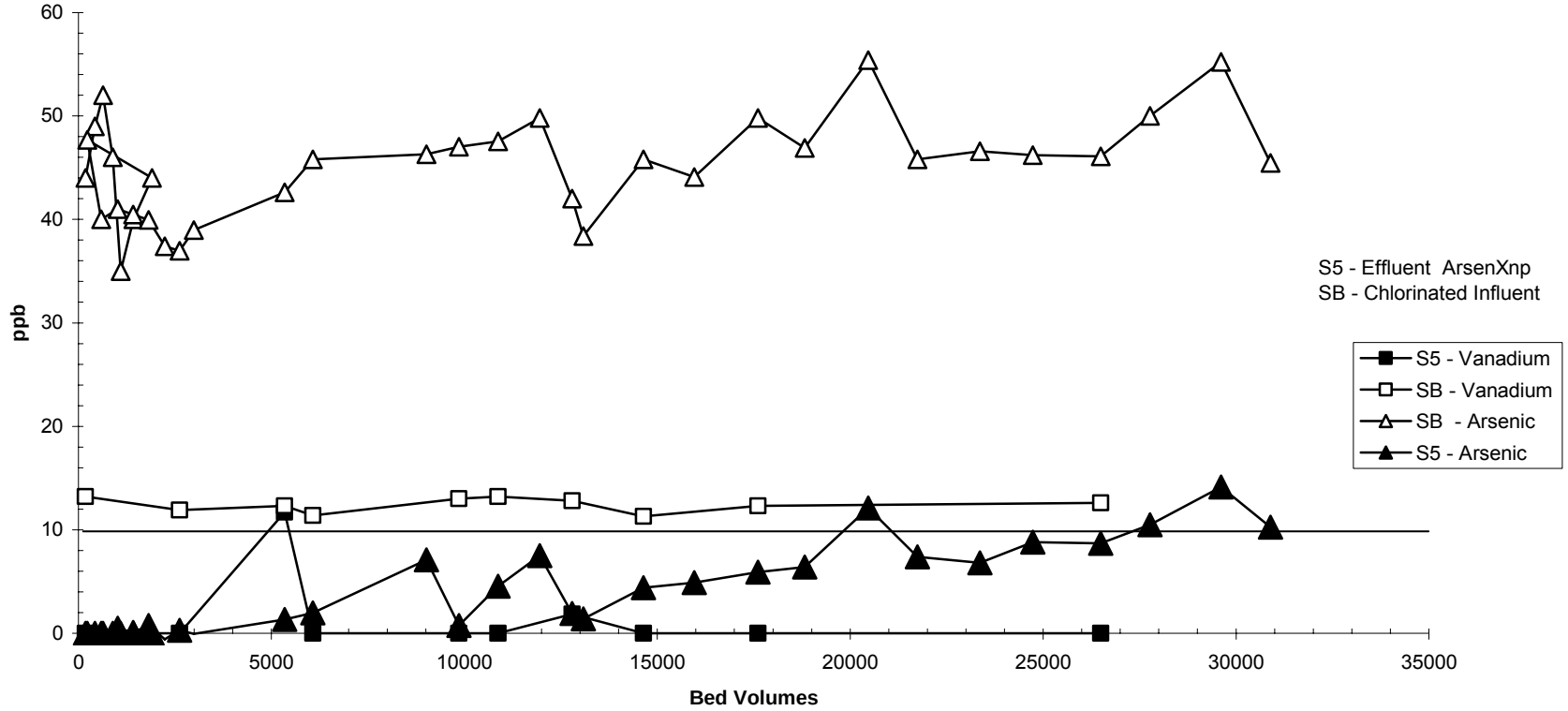
Note: According to the developer of ArsenX^{np} (SolmeteX, Inc.), the material used in this pilot study did not meet the QA/QC requirements for the media due to errors in the production process for this batch. Batch sorption isotherm data provided by the developer (personal communication, Owen Boyd, October 25, 2005) suggest that the arsenic sorption capacity of the material used in this pilot is lower than that of the media currently manufactured by the Purolite company and sold to water utilities.

Table C-2. ArsenX^{np} Treatment Design and Operating Parameters

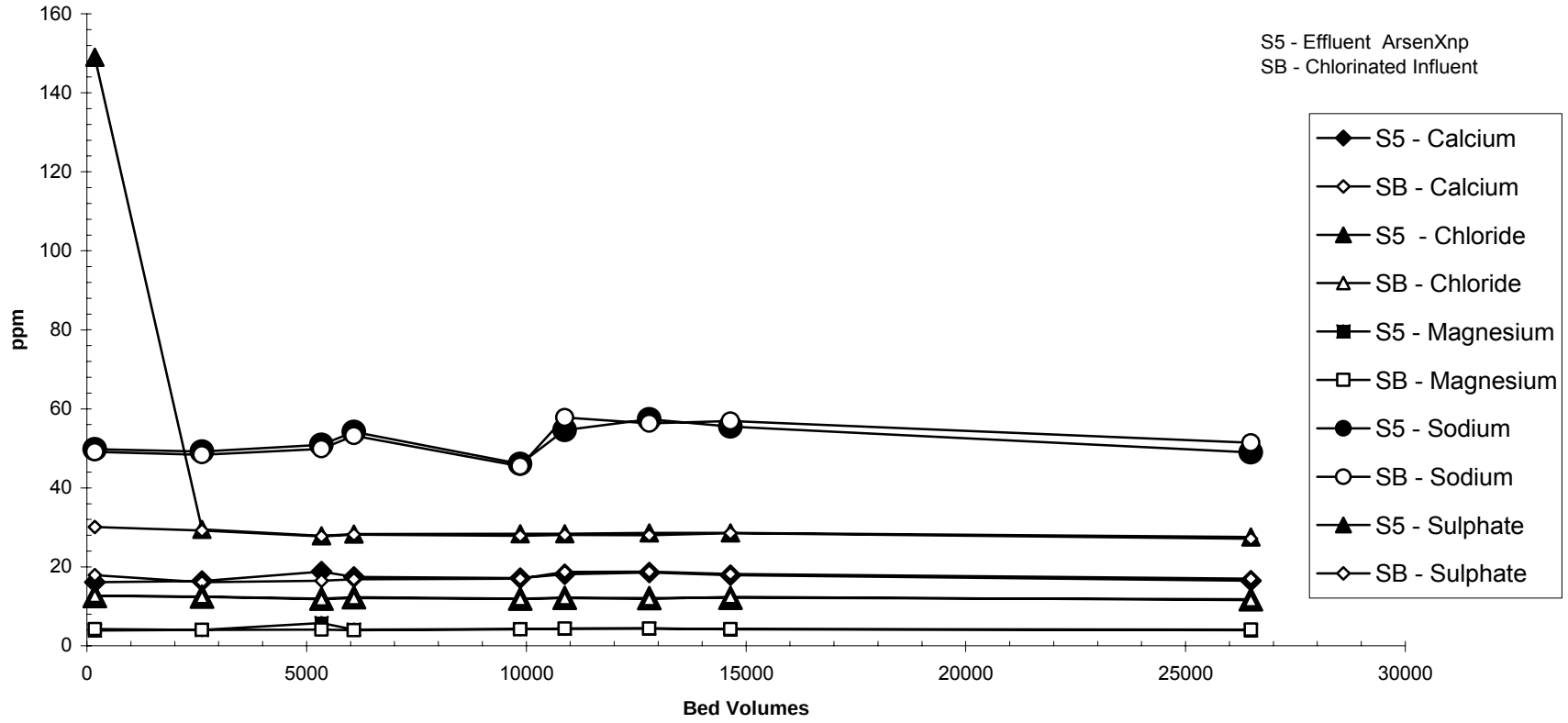
Parameter	RSSCT Columns	ArsenX^{np} Pilot Column	ArsenX^{np} Full Scale Systems
Bulk Density, lb/ft^3	49-52	49-52	49-52
Particle mesh size	100 x 200	US Std Mesh 16 x 50	US Std Mesh 16 x 50
Particle diameter, mm	0.15 x 0.075	1.18 x 0.3	1.18 x 0.3
BET surface area, m^2/g			
Column Layers			
Distributor Configuration	N/A		Hub & Spoke
Underbedding Configuration	N/A	gravel	gravel
Column Number (Drawing SOC-01)		5	
Underbedding Height, inches	N/A	3	
Freeboard, inches		17.8	50% of media height
Media Depth, inches		39.2	30 - 48
Media Volume, Liters		4.74	Function of Q, EBCT
Column Diameter, inches	0.28	3	1-8 ft.
Column Height, inches	19.7	60	
Operating Conditions			
Number of Pilot Columns	1	1	
Hydraulic Loading Rate, gpm/ft^2		8.1487	4 – 16 (typical 8 – 12)
EBCT, minutes		3	3 - 5
pH	7.7	Ambient ~ 7.7	Site specific
Down Flow Pressure Drop, psi	Not meas	6.5 across entire media length	≤ 2 psi/ft.
Maximum Differential Pressure, psi	Not meas		-
Flow Rate, gpm		0.4	Site specific
Face Velocity, ft/s		0.0182	
Backwash Conditions			
Backwash Flux, gpm/ft^2	N/A	4	
Backwash Flow Rate, gpm	N/A	0.2	Function of vessel diameter and HLR
Backwash Duration, minutes	N/A	10 - 15	≤ 15
Backwash Frequency (per month)	N/A		
Unit Cost, $/ft^3			350

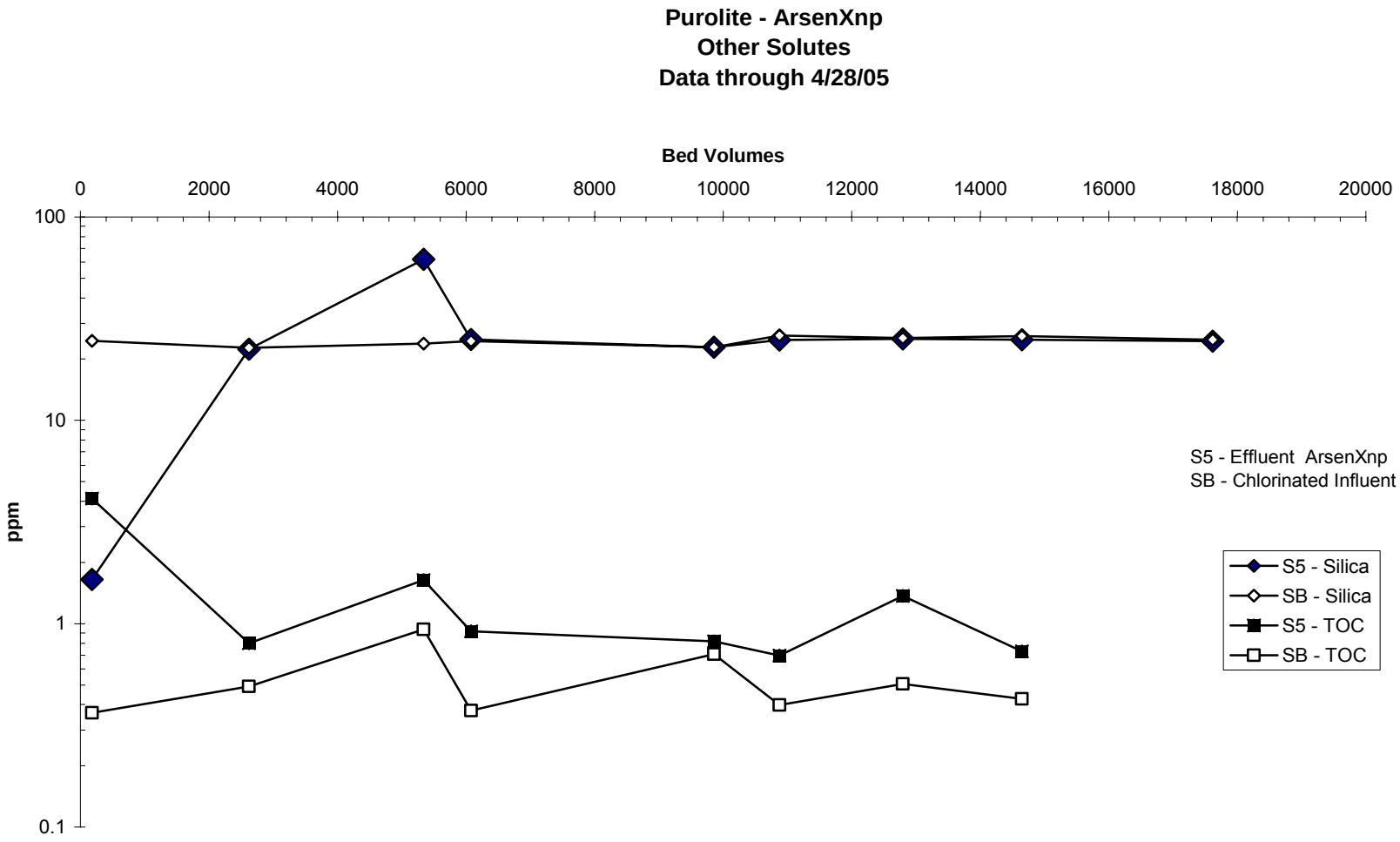
N/A = not applicable

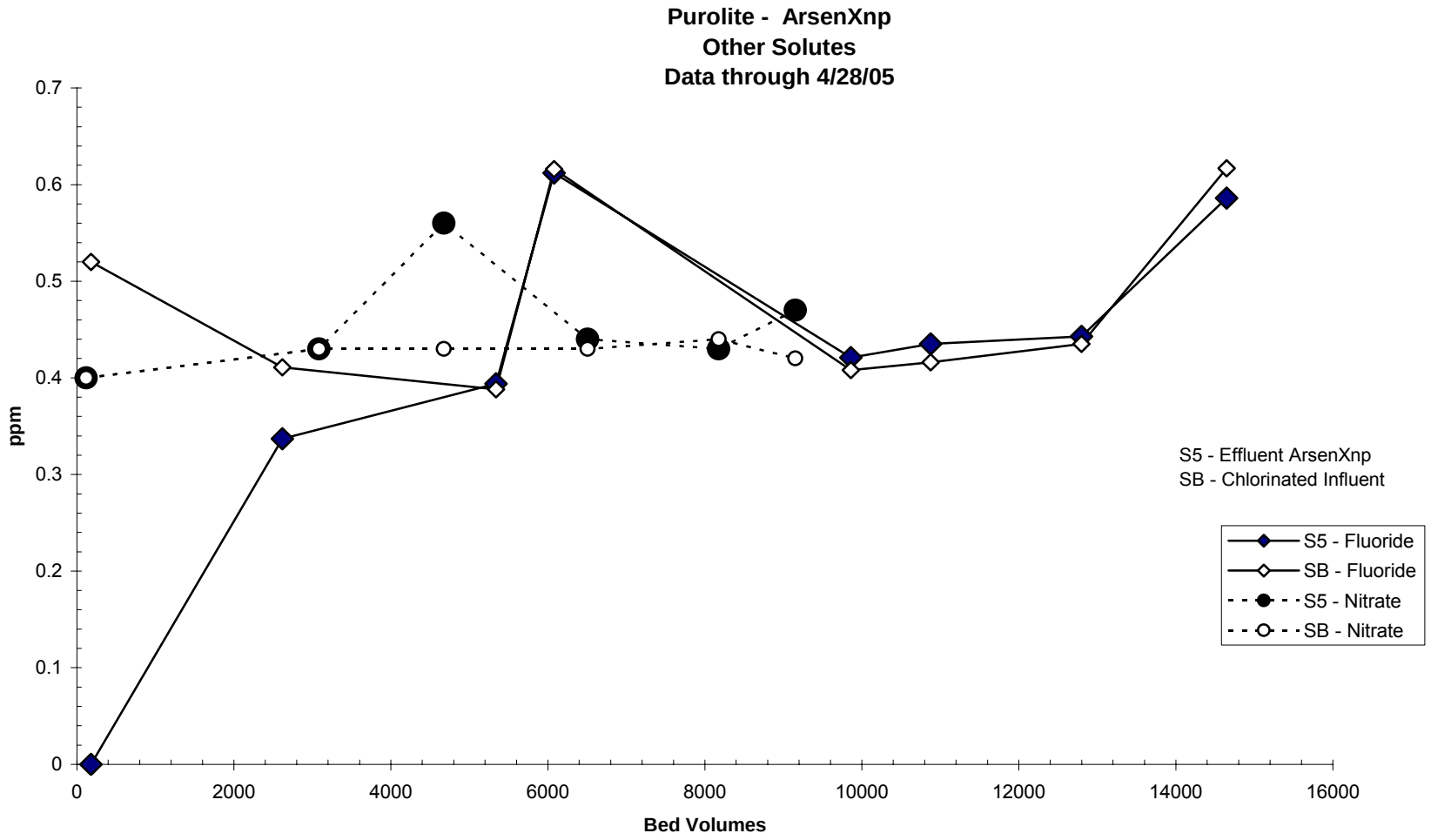
Purolite - ArsenXnp
Vanadium and Arsenic Data
through 4/28/05

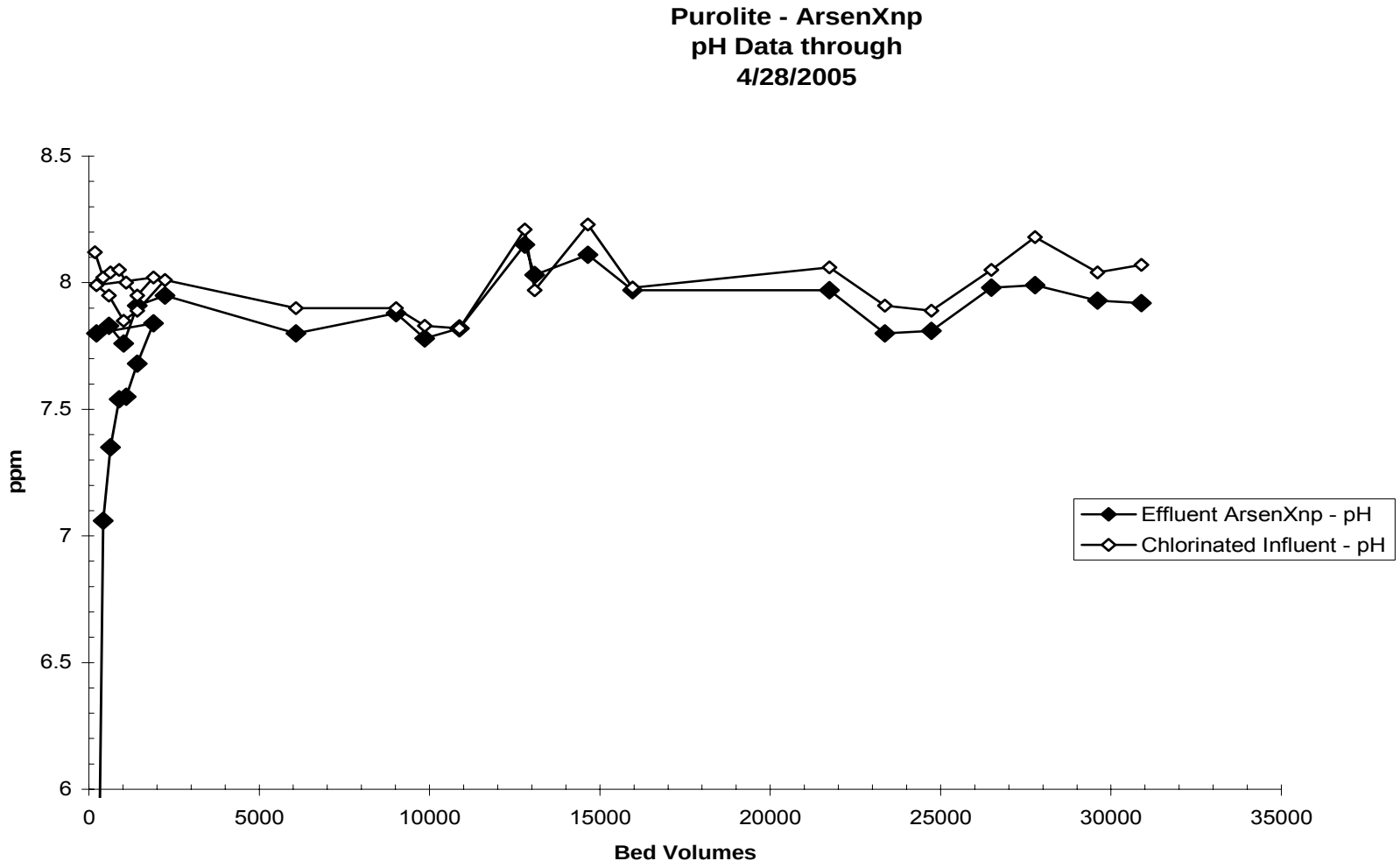


Purolite - ArsenXnp
Major Solutes
Data through 4/28/05

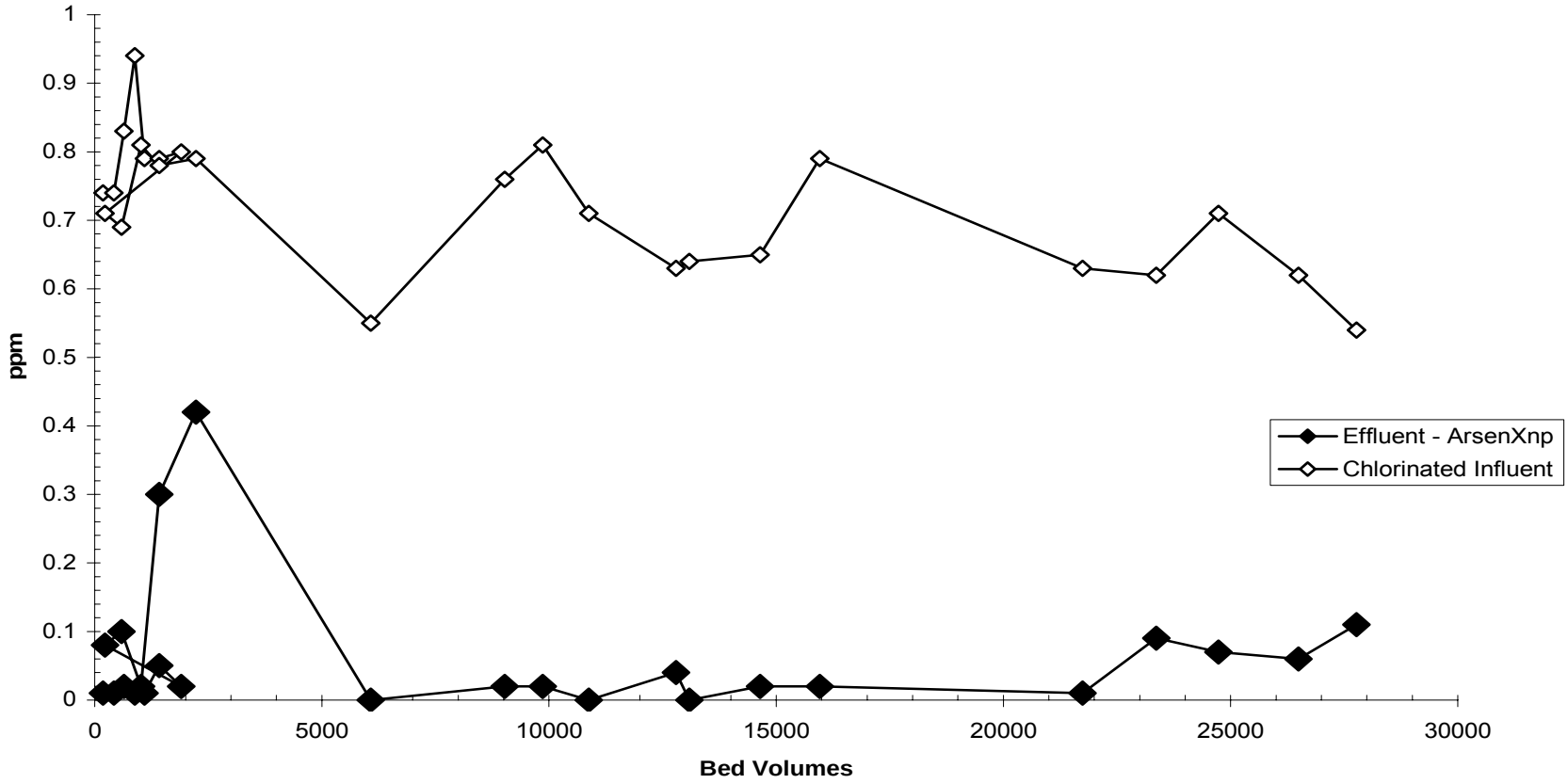



Purolite - ArsenXnp
Other Solutes
Data through 4/28/05
Bed Volumes
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
100
10
1
0.1
ppm
S5 - Effluent ArsenXnp
SB - Chlorinated Influent
S5 - Silica
SB - Silica
S5 - TOC
SB - TOC

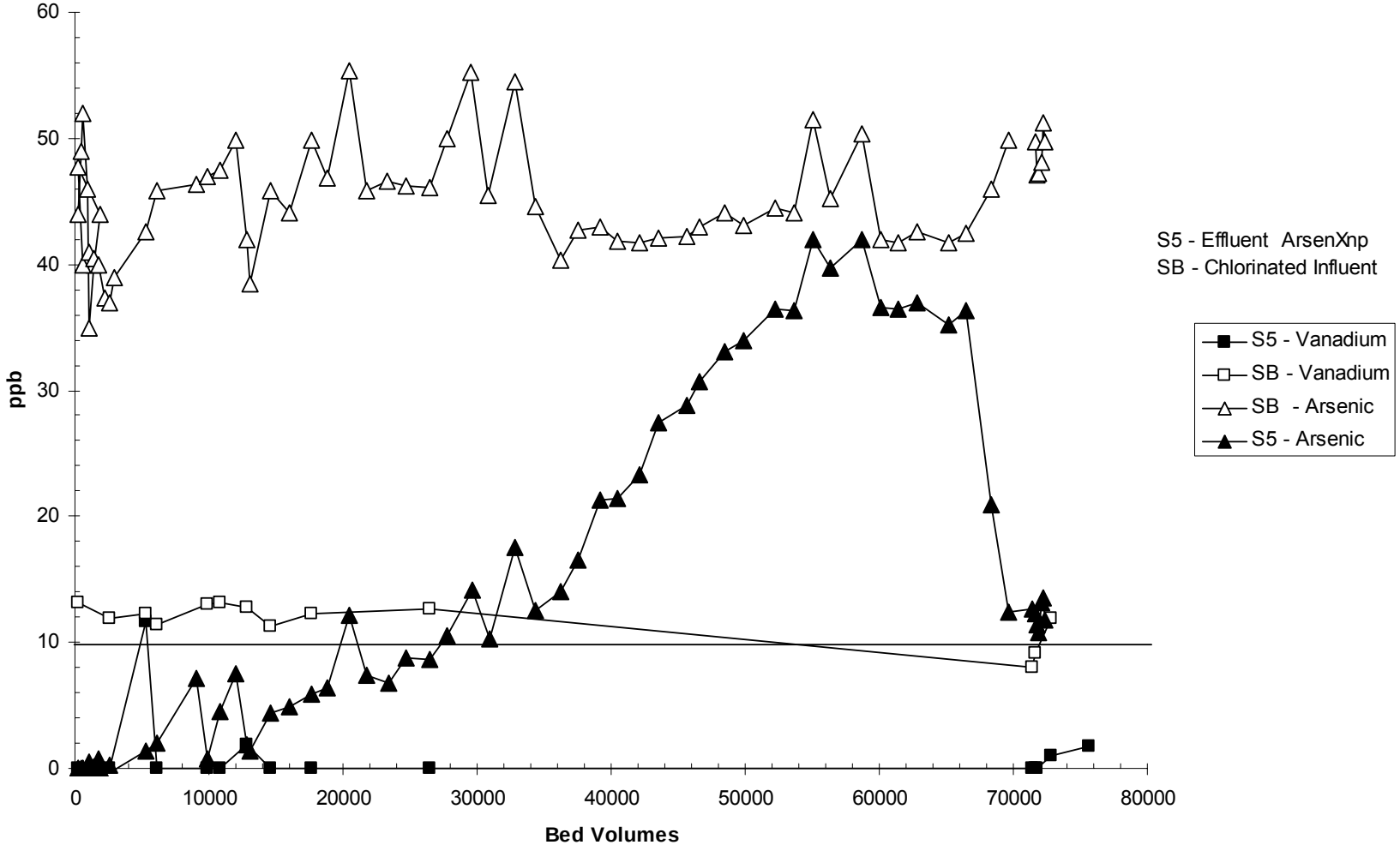

Purolite - ArsenXnp
Other Solutes
Data through 4/28/05
ppm
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2000
4000
6000
8000
10000
12000
14000
16000
Bed Volumes
S5 - Effluent ArsenXnp
SB - Chlorinated Influent
S5 - Fluoride
SB - Fluoride
S5 - Nitrate
SB - Nitrate


Purolite - ArsenXnp
pH Data through
4/28/2005
8.5
8
7.5
7
6.5
6
ppm
0
5000
10000
15000
20000
25000
30000
35000
Bed Volumes
Effluent ArsenXnp - pH
Chlorinated Influent - pH

Purolite - ArsenXnp
Free Chlorine (ml/L as CL_2)
Data through 4/28/05



Purolite - ArsenXnp
Vanadium and Influent Arsenic Data
through 7/29/05



Appendix C-3 AdEdge – E33

Vendor	Flow Rate (gpm)	Contact Time [EBCT] (minutes)	Bed Volume [BV] (liters)
AdEdge	0.3	2, 4, 5	2.23, 4.5, 5.57

		E33		
		2 min	4 min	5 min
Pilot	BV to 10 ppb (10 μg/L)	24000	43000	52000
	Capacity at 10 ppb, mg/g	1.95	3.56	4.21
	BV at C/C_o = 0.8	84000	NA	NA
	Capacity at C/C_o = 0.8	4.03	NA	NA
CD RSSCT	BV to 10 ppb (10 μg/L)	9000	7700	11700
	Capacity at 10 ppb, mg/g	1.25	0.72	1.18
	BV until $C_e = C_o$	> 370000	> 190000	> 150000
	Capacity at $C_e = C_o$, mg/g	> 9.60	> 4.94	> 4.63
	BV at C/C_o = 0.8	>370000	80000	97000
	Capacity at C/C_o = 0.8	> 9.6	>3.06	3.83
PD RSSCT	BV to 10 ppb (10 μg/L)	15400	43000	41000
	Capacity at 10 ppb, mg/g	1.95	3.39	3.07
	BV until $C_e = C_o$	225000	180000	113000
	Capacity at $C_e = C_o$, mg/g	5.08	5.61	5.02
	BV at C/C_o = 0.8	94000	82000	83000
	Capacity at C/C_o = 0.8	4.26	4.68	4.71

Notes:

BV to 10 ppb (10 μg/L) is read from breakthrough curve where effluent concentration, C_e, reached and stayed > 10 ppb (10 μg/L).
Capacity at 10 ppb (10 μg/L) is calculated from raw data when C_e reached and stayed > 10 ppb (10 μg/L).
Capacity is integrated from mass balance on arsenic data. (Integration: area above BT curve and below influent concentration represents media capacity.)
Product is referred to as AD33 in following figures; actual product name is E33.

Isotherm Results

Capacity 10 ppb As [Freundlich] (mg/g)	Capacity 40 ppb As [Freundlich] (mg/g)	Capacity 10 ppb As [Langmuir] (mg/g)	Capacity 40 ppb As [Langmuir] (mg/g)
4.97	7.67	7.50	9.23

Notes: Freundlich isotherm: $Q = K_F C^{nF}$

Langmuir isotherm: $Q = (S_{max} K_L C)/(1+K_L C)$

where Q = equilibrium mg As/g media; K_F, n, F, K_L = isotherm parameters obtained from curve fits; C = equilibrium concentration in solution (mg As/L); S_{max} = maximum capacity (mg As/g media).

AdEdge – E33 Results:

The AdEdge E33 media was subjected to three different empty bed contact times, 2, 4, and 5 minutes.

Arsenic: Arsenic concentrations in the pilot effluent reached 10 ppb (10 μg/L) after 24000 bed volumes had flowed through the column for the 2-minute EBCT, but the number of BVs to 10 ppb (10 μg/L) arsenic break-though increased to 43000 BV for the 4-minute EBCT. This was about 156% of the bed volume capacity predicted by the Proportional Diffusivity (PD) RSSCT experiments for the 2-minute EBCT and about 100% of the bed volume capacity predicted by the PD RSSCT experiments for the 4- and 5-minute EBCTs. The capacity predicted by mass balance was up to 13% greater than that predicted by the PD RSSCT experiments for the 5-minute EBCT. Capacities at 10 ppb (10 μg/L) calculated from batch sorption data using either the Langmuir or Freundlich isotherms were higher than those obtained in the flow experiments (RSSCT or pilot). As the effluent arsenic concentration in the pilot column rose above 10 ppb (10 μg/L), the BTC was fairly steep. There was from 30% to over 100% additional capacity when the effluent concentration reached 80% of the influent concentration ($C/C_e = 0.8$), depending upon the EBCT. The RSSCT columns showed a much smaller additional capacity (BTC was sharper). When the pH was lowered by CO_2 injection in Phase IIA, the effluent arsenic concentration dropped to approximately 12 ppb.

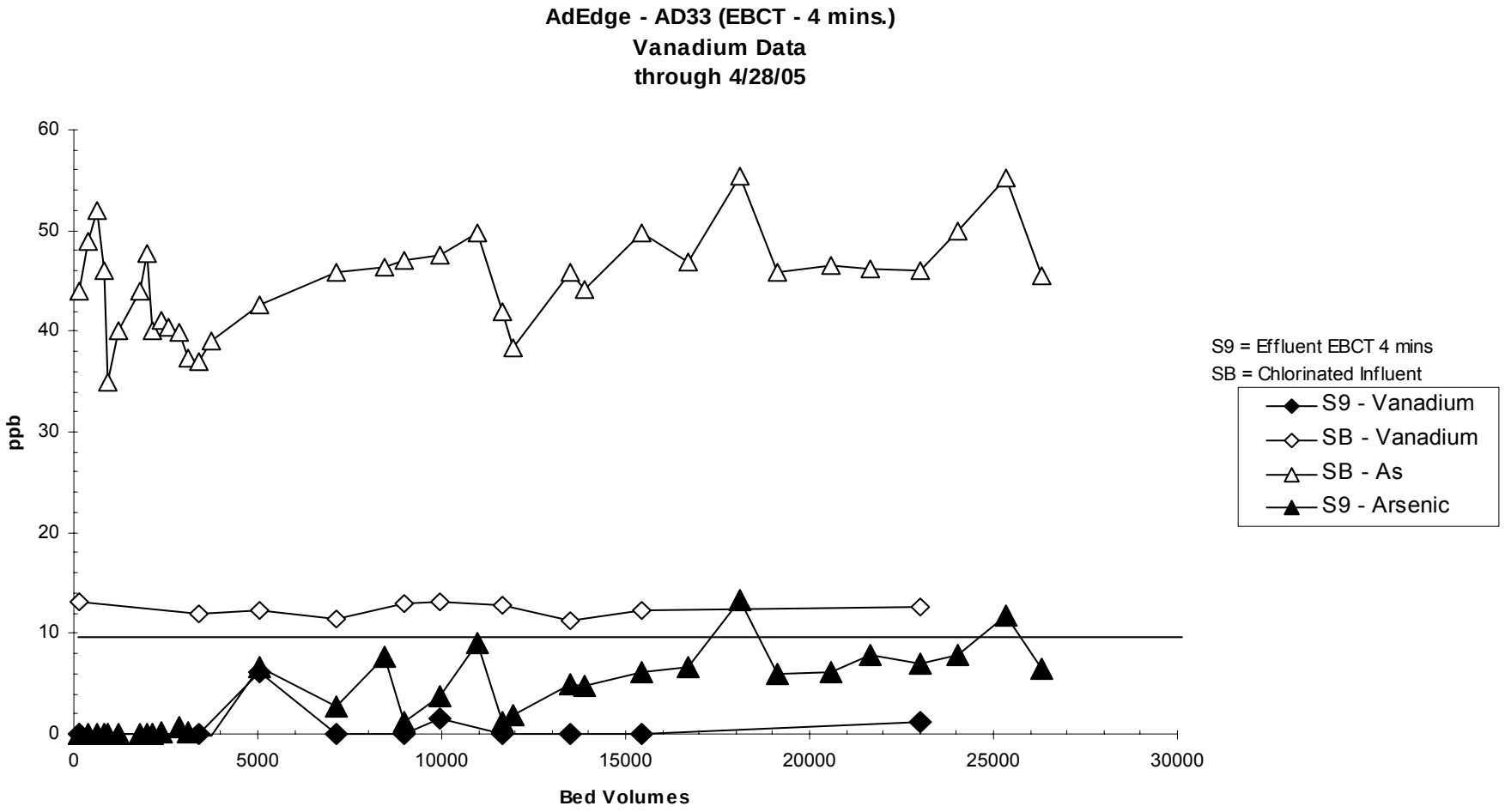
Vanadium: Vanadium (influent approximately 13 ppb) was removed to non-detectable levels (MDL = 0.5 ppb) for the entire Phase I pilot study at ambient pH but increased steadily for the 2-minute EBCT condition after about 7000 BV to nearly influent levels at 35000 BV. When the pH was lowered to 6.8 by CO_2 injections in Phase IIa, the V increased for all EBCT conditions--slightly for the 4- and 5-minute EBCTs and to ambient levels for the 2-minute EBCT at about 40000 BV.

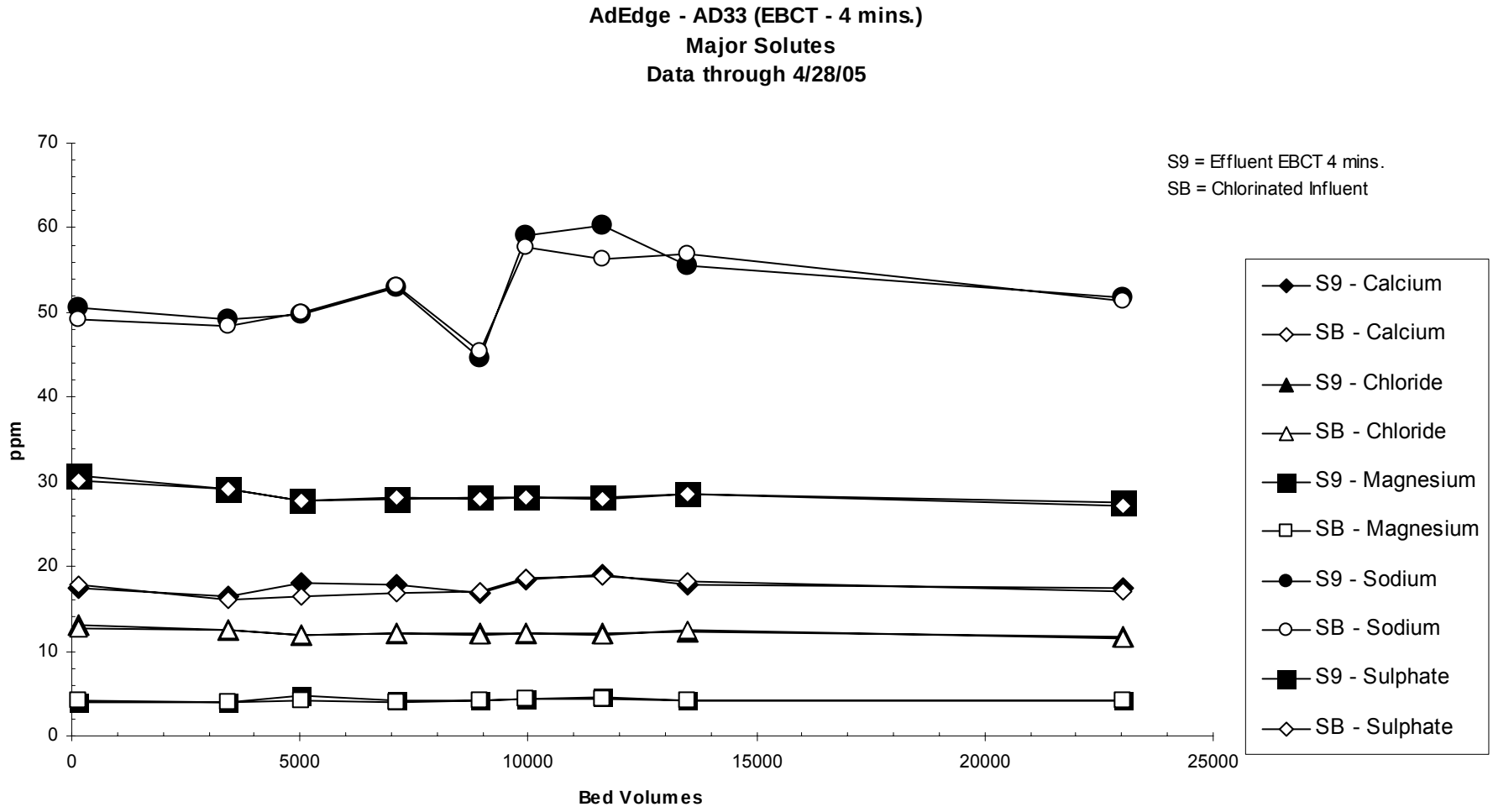
Other Solutes:
Sulfate was released at ambient levels for all the EBCT conditions. Silica was adsorbed for the first 3000 - 5000 BV and then reached ambient levels after a small silica spike was observed. Fluoride was adsorbed slightly for about the first 4000 BV and then reached ambient levels. The initial pH in the effluent was depressed but rose rapidly to reach ambient pH after about 1000 BV. Other solutes (Ca, Mg, Na, Cl) were not affected by the media.

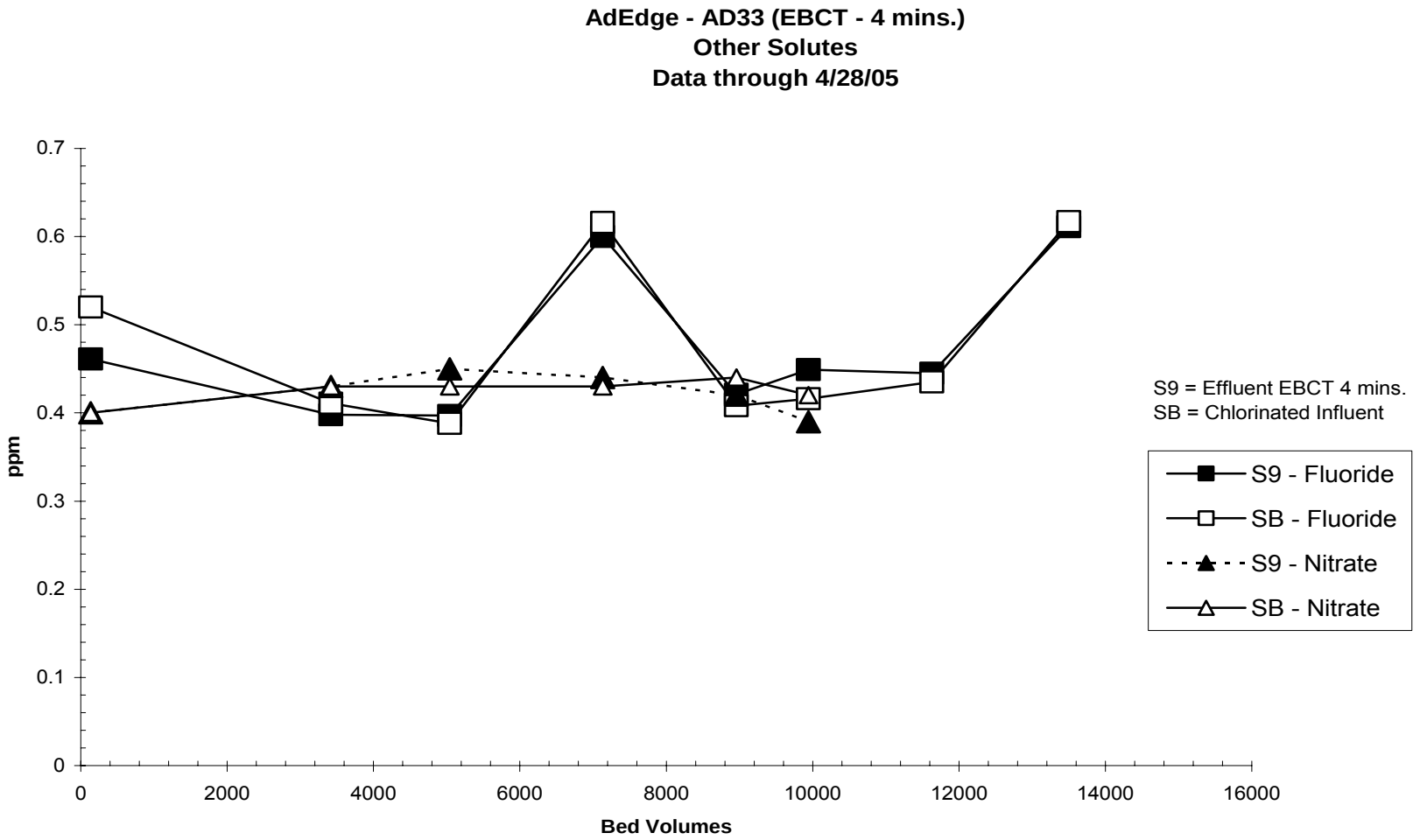
Table C-3. E33 Treatment Design and Operating Parameters.

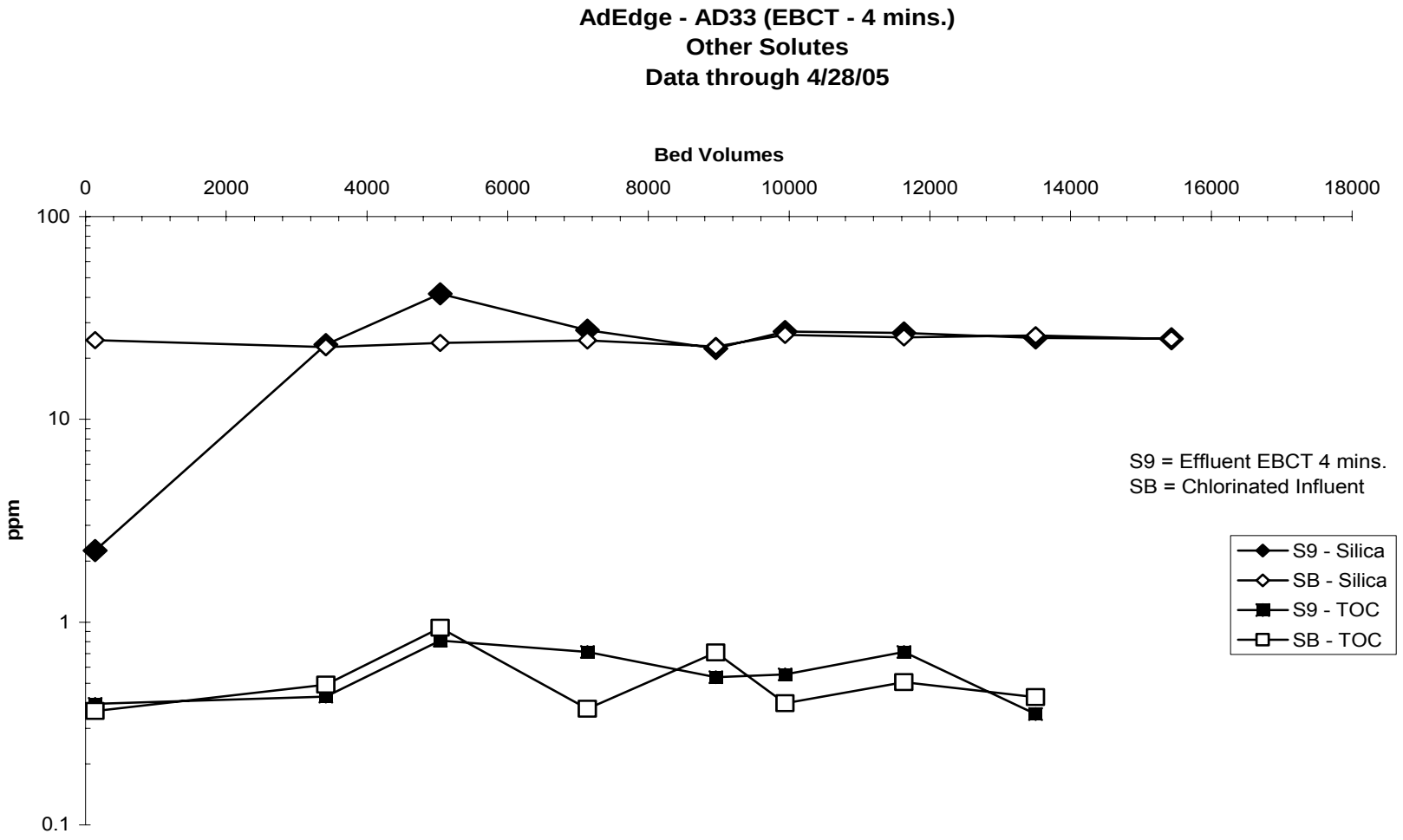
Parameter	RSSCT Columns			ED33 Pilot Columns				E33 Full Scale Systems
Bulk Density, lb/ft^3	30			30				30
Particle mesh size	US Std Mesh 100 x 200			US Std Mesh 10 x 35				US Std Mesh 10 x 35
Particle diameter, mm	0.15 x 0.075			2 x 0.5				2 x 0.5
BET surface area, m^2/g	NA			140				140
Column Layers								
Distributor Configuration	NA			Fritted disc				Hub & Spoke
Underbedding Configuration	NA			gravel				1/8" x 1/16" gravel
Column Number (Drawing SOC-01)				8	9	10	1	NA
Underbedding Height, inches	N/A			3	3	3	3	NA
Freeboard, inches	17.65	15.57	14.54	16.75	18.5	8.9	18.5	40-50% of Hm
Media Depth (Hm), inches	2.05	4.13	5.16	19.25	38.5	48.12	38.5	24 - 48
Media Volume, Liters	0.002	0.004	0.005	2.23	4.5	5.57	4.5	Function of Q, EBCT
Column Diameter, inches	0.28			3	3	3	3	1-12 ft.
Column Height, inches	19.7			39	60	60	60	NA
Operating Conditions								
Number of Pilot Columns	3			4				NA
Hydraulic Loading Rate, gpm/ft^2	6.18			6	6	6	6	6 - 10
EBCT, minutes	0.21	0.42	0.53	2	4	5	4	3 - 5
pH	7.7			~7.7	~7.7	~7.7	6.8	Site specific
Down Flow Pressure Drop, psi	NA			1.6	3.2	4.0	3.2	< 5
Maximum Differential Pressure, psi	NA			NA	NA	NA	NA	NA
Flow Rate, gpm	0.0025			0.3	0.3	0.3	0.3	Site specific
Face Velocity, ft/s	0.0135			0.134	0.134	0.134	0.134	NA
Backwash Conditions								
Backwash Flux, gpm/ft^2	N/A			6				10-12
Backwash Flow Rate, gpm	N/A			0.3				Function of vessel diameter and HLR
Backwash Duration, minutes	N/A			≤15				15
Backwash Frequency (per month)	N/A			Backwash only if Δ p > 1.5 x initial pressure drop across media bed				1 x (dependent on raw water quality)

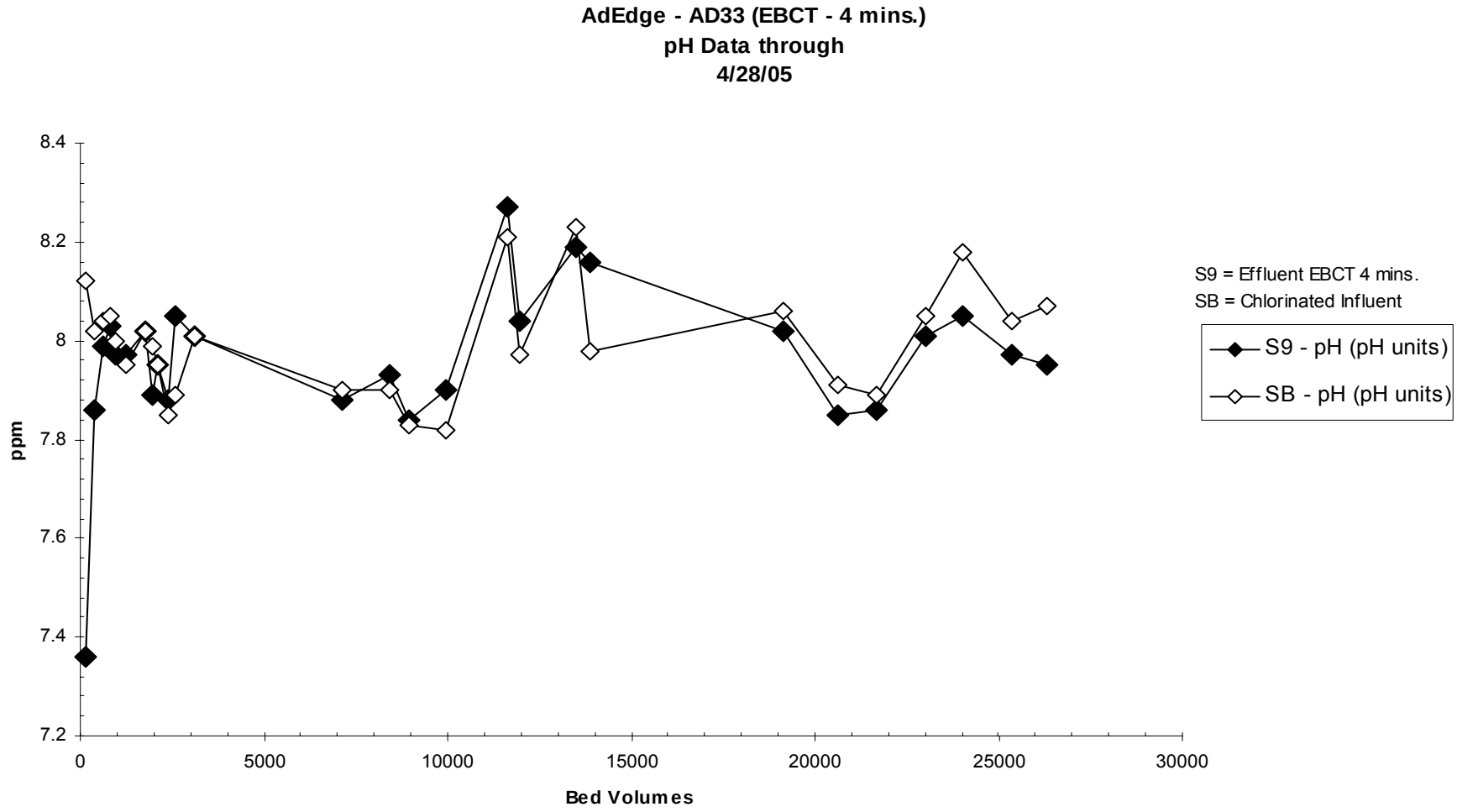
N/A = not applicable; NA = not analyzed or available.


AdEdge - AD33 (EBCT - 4 mins.)
Vanadium Data
through 4/28/05
ppb
60
50
40
30
20
10
0
0
5000
10000
15000
20000
25000
30000
Bed Volumes
S9 = Effluent EBCT 4 mins
SB = Chlorinated Influent
S9 - Vanadium
SB - Vanadium
SB - As
S9 - Arsenic

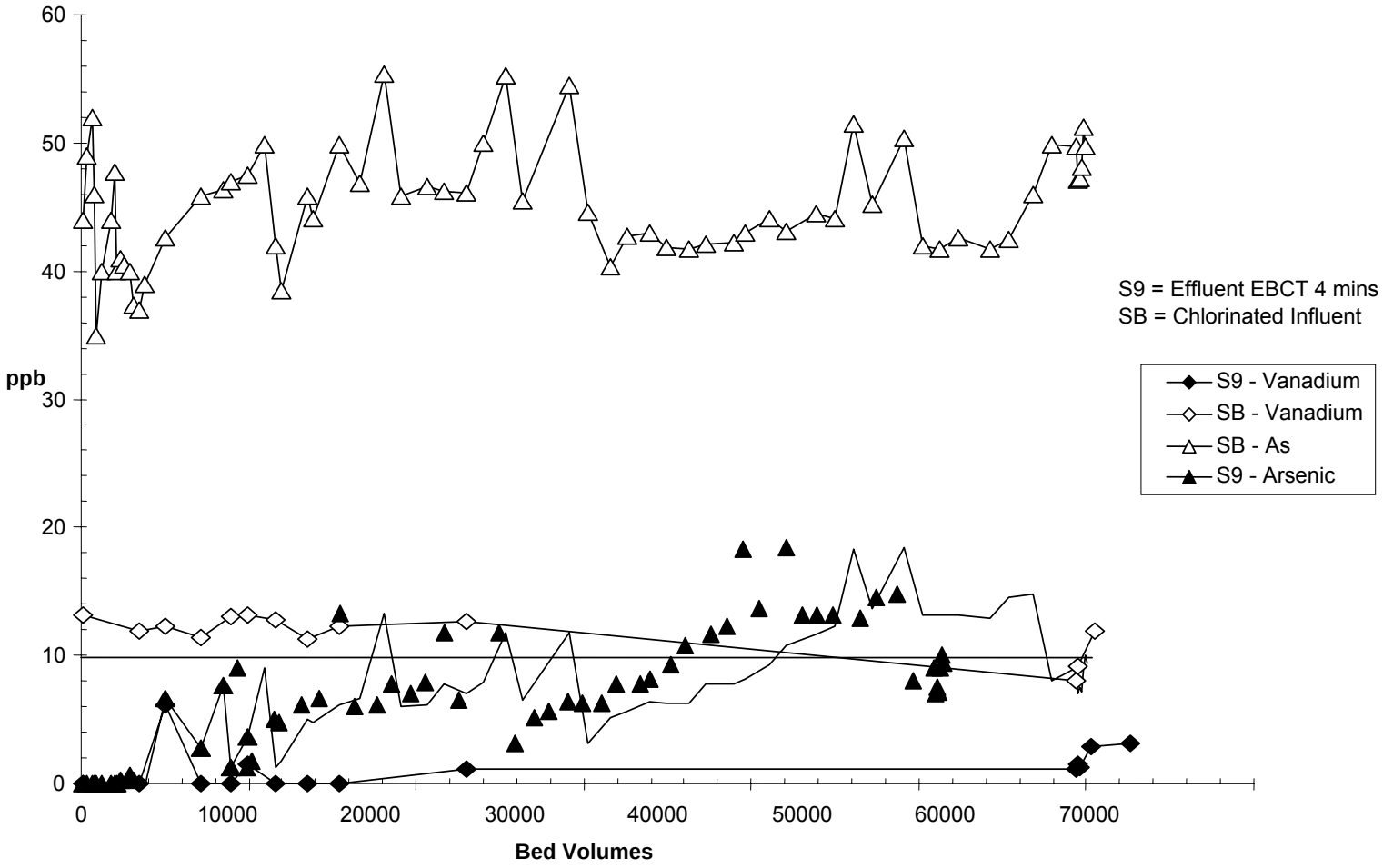

AdEdge - AD33 (EBCT - 4 mins.)
Major Solutes
Data through 4/28/05
S9 = Effluent EBCT 4 mins.
SB = Chlorinated Influent
ppm
Bed Volumes
0
10
20
30
40
50
60
70
0
5000
10000
15000
20000
25000
S9 - Calcium
SB - Calcium
S9 - Chloride
SB - Chloride
S9 - Magnesium
SB - Magnesium
S9 - Sodium
SB - Sodium
S9 - Sulphate
SB - Sulphate

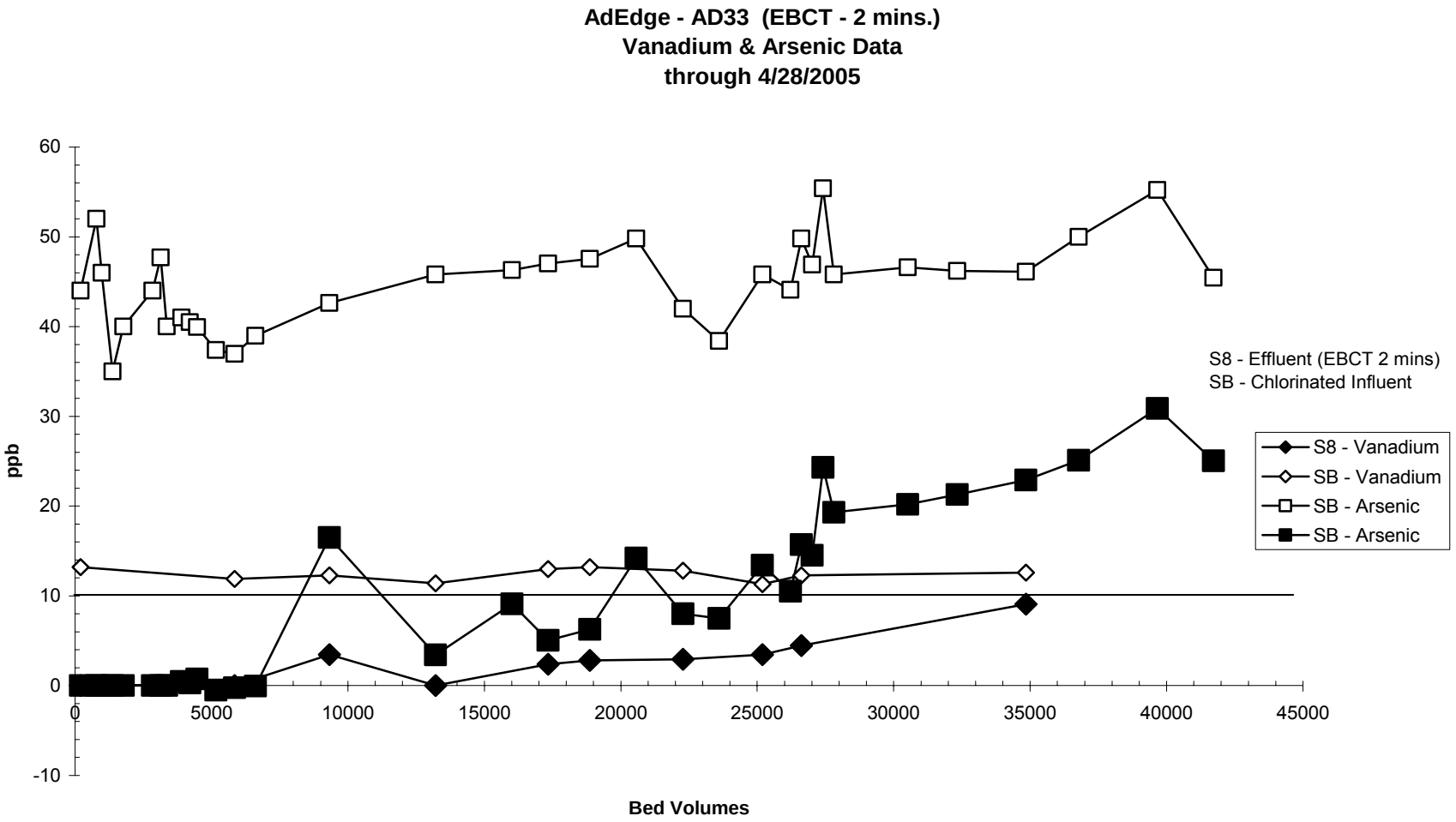

AdEdge - AD33 (EBCT - 4 mins.)
Other Solutes
Data through 4/28/05
ppm
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2000
4000
6000
8000
10000
12000
14000
16000
Bed Volumes
S9 = Effluent EBCT 4 mins.
SB = Chlorinated Influent
S9 - Fluoride
SB - Fluoride
S9 - Nitrate
SB - Nitrate

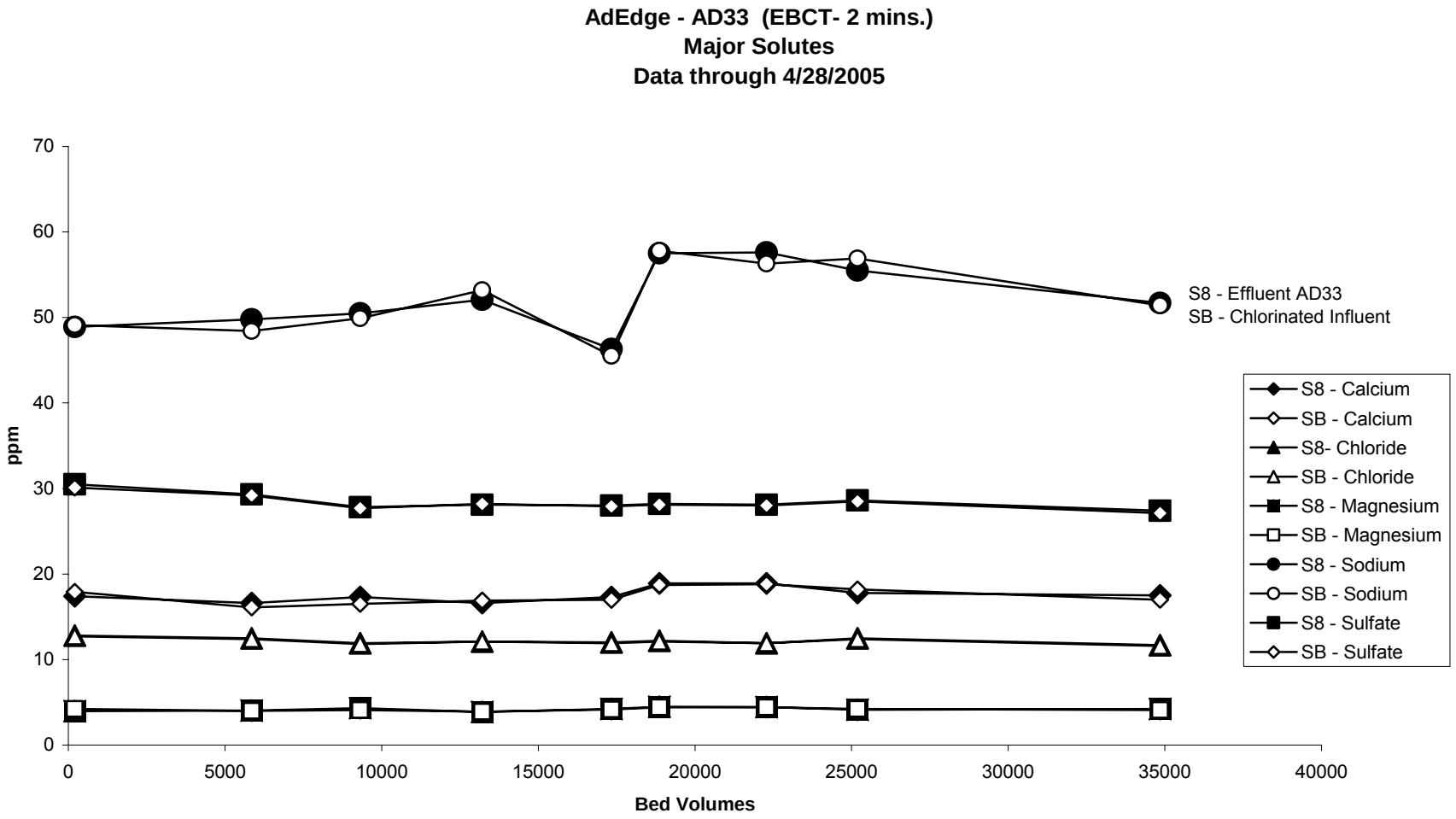

AdEdge - AD33 (EBCT - 4 mins.)
Other Solutes
Data through 4/28/05
Bed Volumes
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
100
10
1
0.1
ppm
S9 = Effluent EBCT 4 mins.
SB = Chlorinated Influent
S9 - Silica
SB - Silica
S9 - TOC
SB - TOC

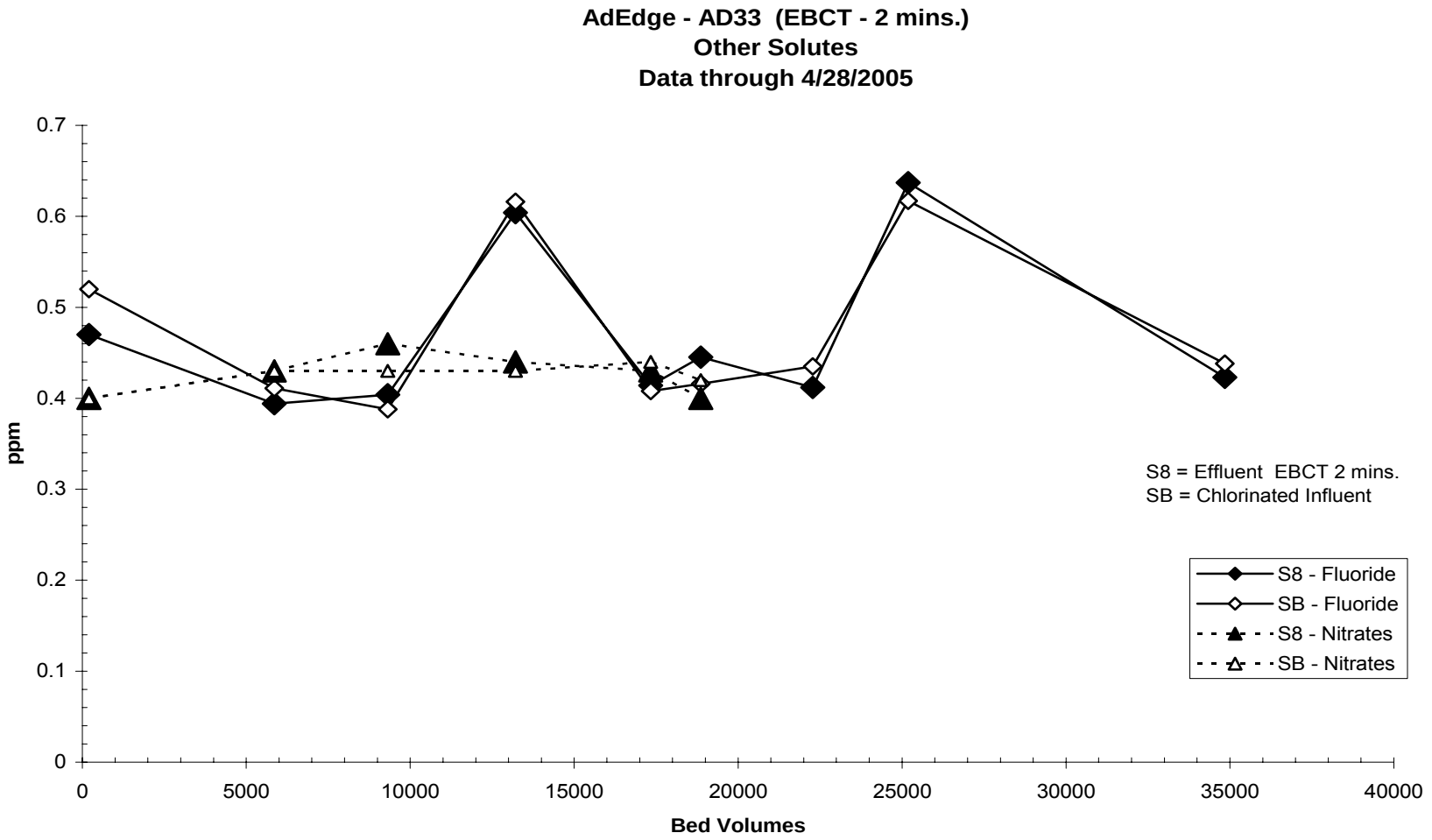

AdEdge - AD33 (EBCT - 4 mins.)
pH Data through
4/28/05
8.4
8.2
8
7.8
7.6
7.4
7.2
ppm
0
5000
10000
15000
20000
25000
30000
Bed Volumes
S9 = Effluent EBCT 4 mins.
SB = Chlorinated Influent
S9 - pH (pH units)
SB - pH (pH units)

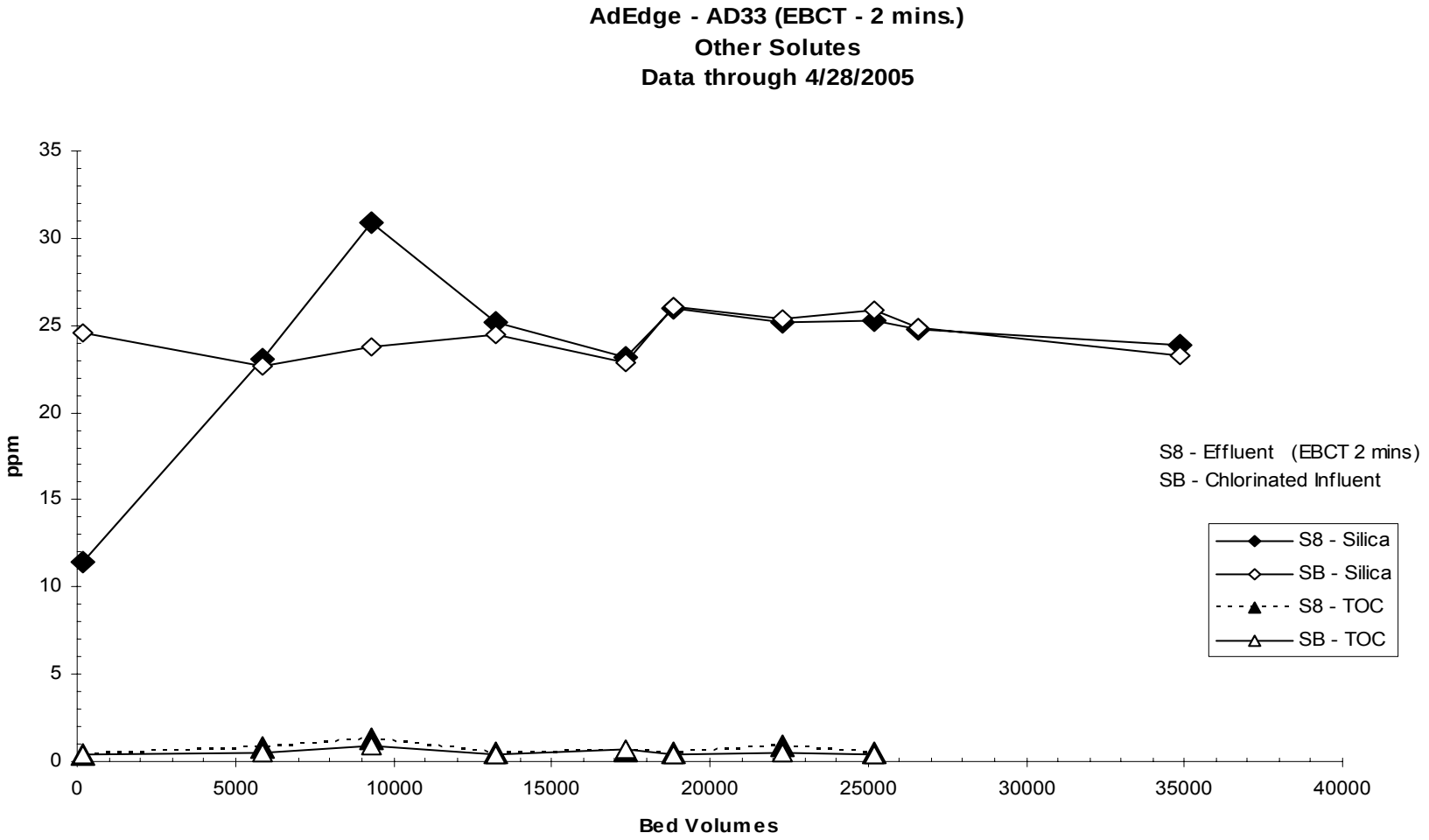
AdEdge - AD33 (EBCT - 4 mins.)
Vanadium Data
through 7/29/05

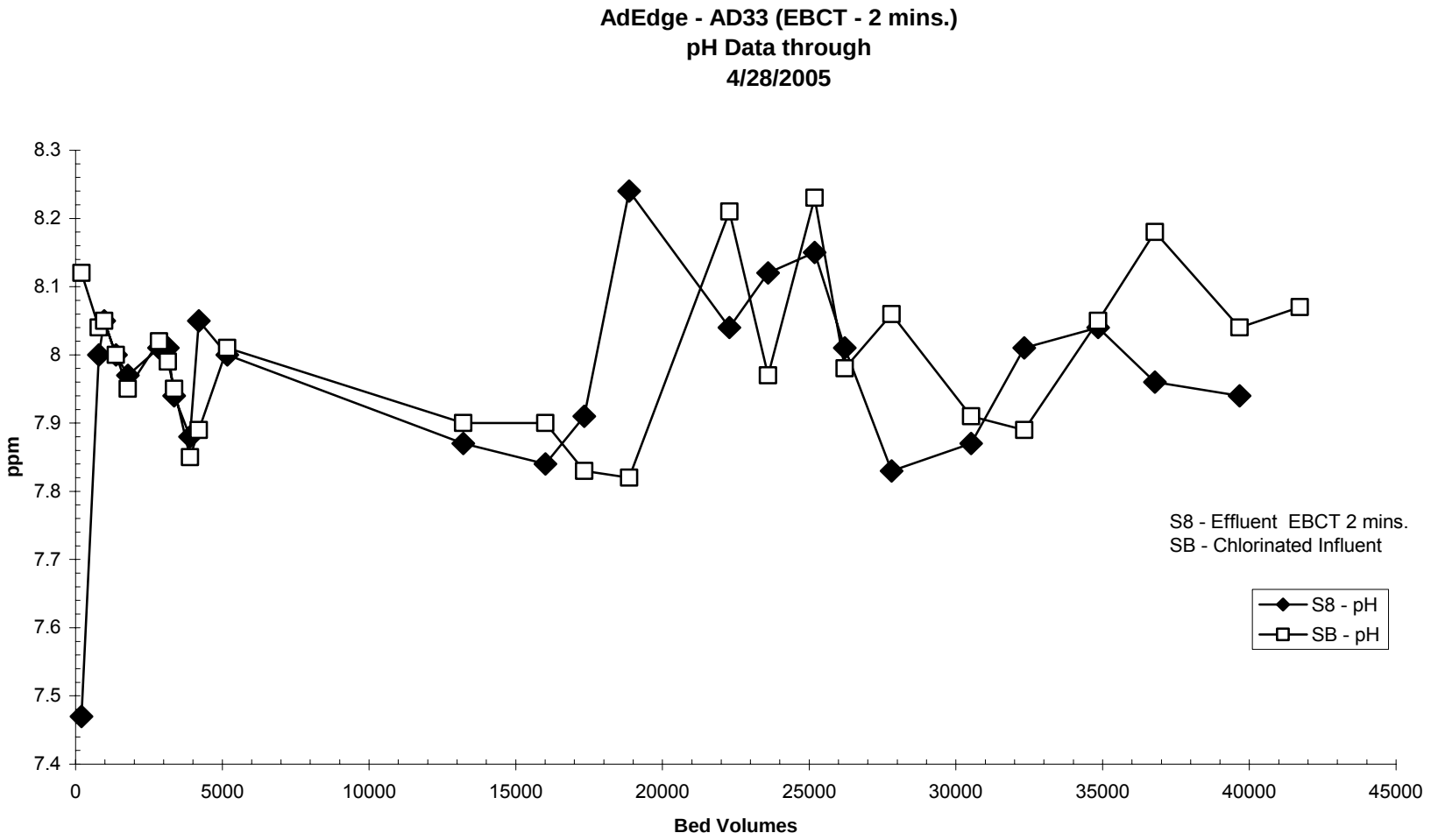



AdEdge - AD33 (EBCT - 2 mins.)
Vanadium & Arsenic Data
through 4/28/2005
60
50
40
30
20
10
0
-10
ppb
0
5000
10000
15000
20000
25000
30000
35000
40000
45000
Bed Volumes
S8 - Effluent (EBCT 2 mins)
SB - Chlorinated Influent
S8 - Vanadium
SB - Vanadium
SB - Arsenic
SB - Arsenic

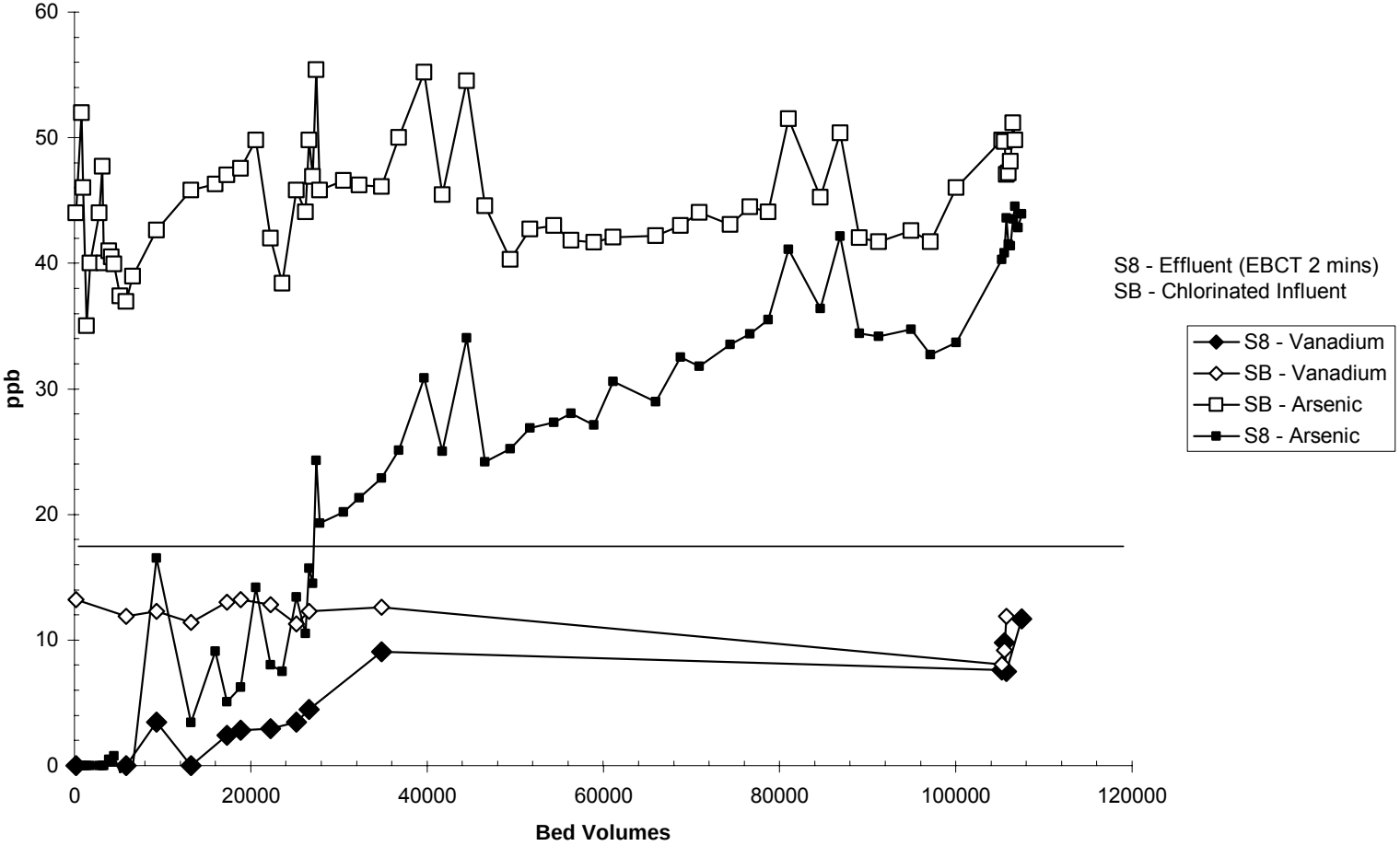

AdEdge - AD33 (EBCT- 2 mins.)
Major Solutes
Data through 4/28/2005
ppm
Bed Volumes
0
10
20
30
40
50
60
70
0
5000
10000
15000
20000
25000
30000
35000
40000
S8 - Effluent AD33
SB - Chlorinated Influent
S8 - Calcium
SB - Calcium
S8- Chloride
SB - Chloride
S8 - Magnesium
SB - Magnesium
S8 - Sodium
SB - Sodium
S8 - Sulfate
SB - Sulfate

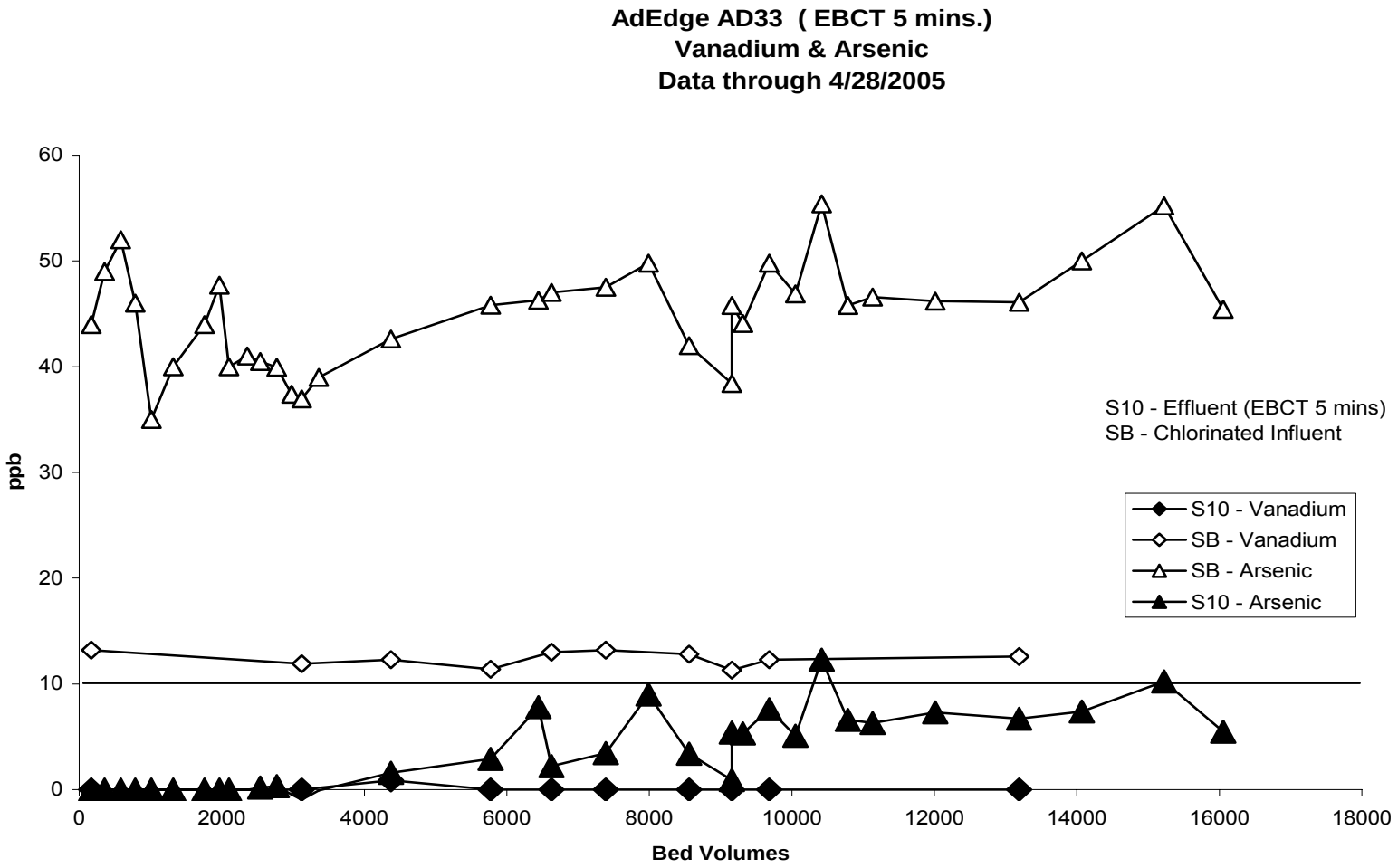

AdEdge - AD33 (EBCT - 2 mins.)
Other Solutes
Data through 4/28/2005
ppm
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5000
10000
15000
20000
25000
30000
35000
40000
Bed Volumes
S8 = Effluent EBCT 2 mins.
SB = Chlorinated Influent
S8 - Fluoride
SB - Fluoride
S8 - Nitrates
SB - Nitrates

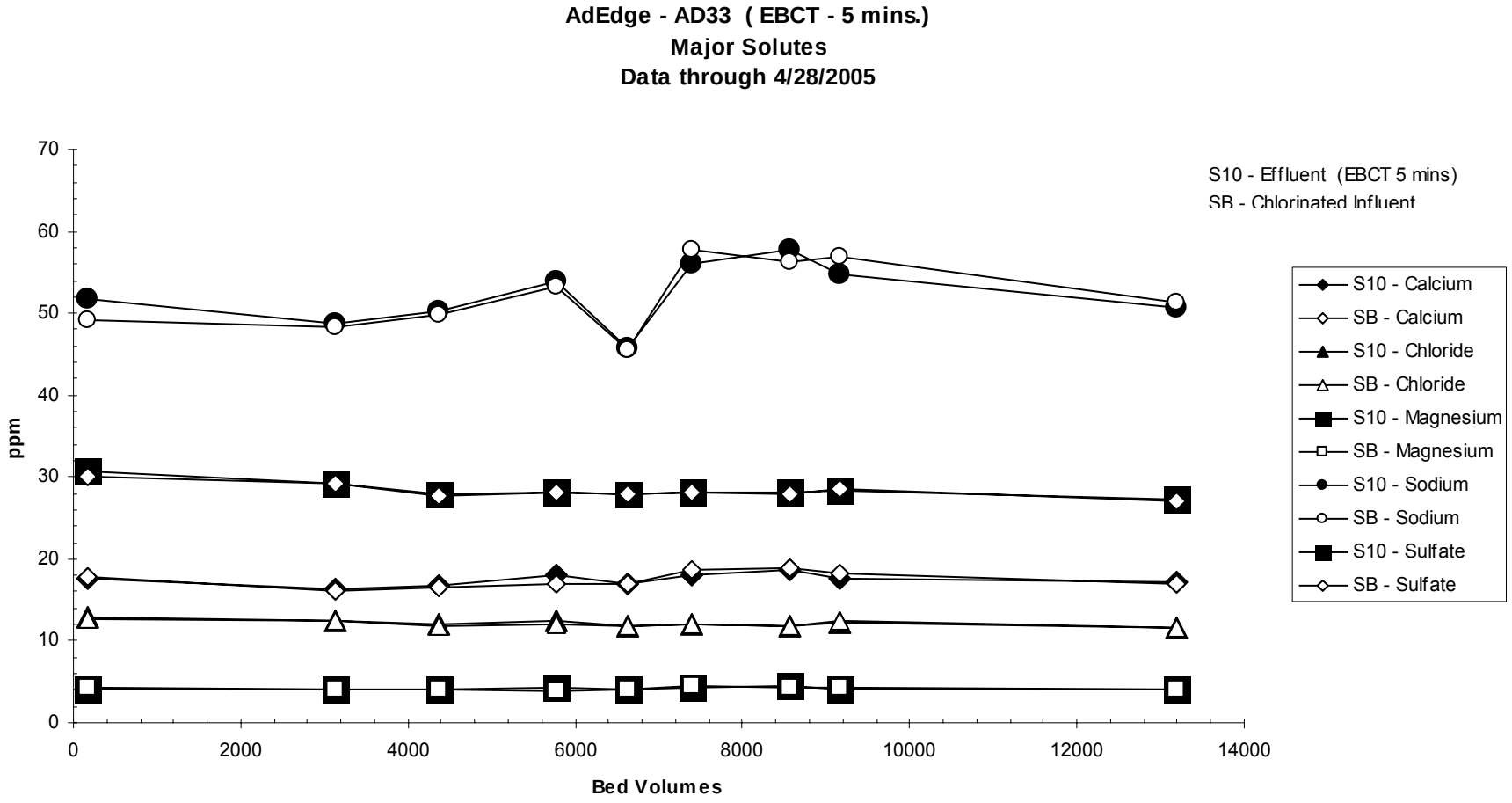

AdEdge - AD33 (EBCT - 2 mins.)
Other Solutes
Data through 4/28/2005
ppm
Bed Volumes
0
5
10
15
20
25
30
35
0
5000
10000
15000
20000
25000
30000
35000
40000
S8 - Effluent (EBCT 2 mins)
SB - Chlorinated Influent
S8 - Silica
SB - Silica
S8 - TOC
SB - TOC

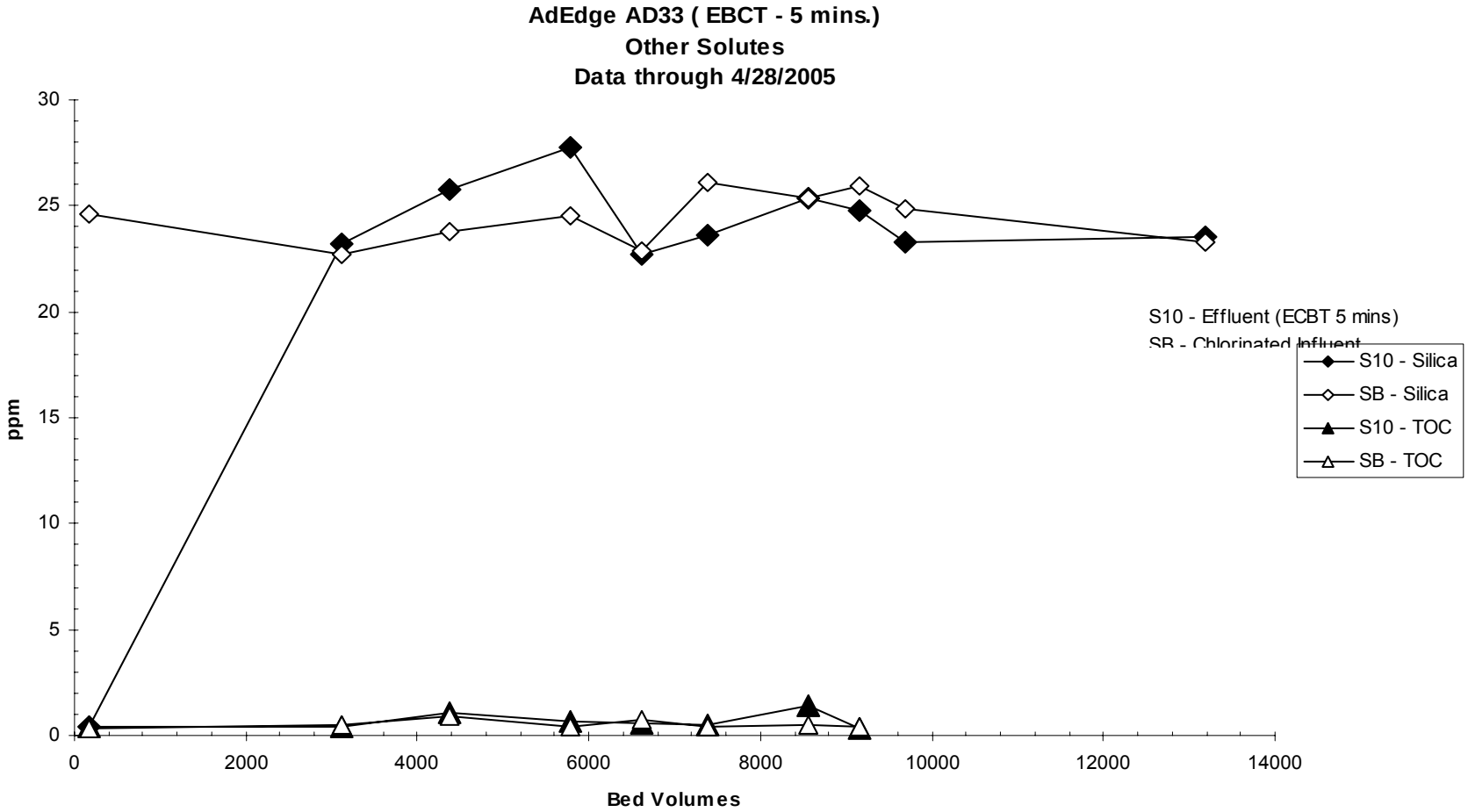

AdEdge - AD33 (EBCT - 2 mins.)
pH Data through
4/28/2005
ppm
8.3
8.2
8.1
8
7.9
7.8
7.7
7.6
7.5
7.4
0
5000
10000
15000
20000
25000
30000
35000
40000
45000
Bed Volumes
S8 - Effluent EBCT 2 mins.
SB - Chlorinated Influent
S8 - pH
SB - pH

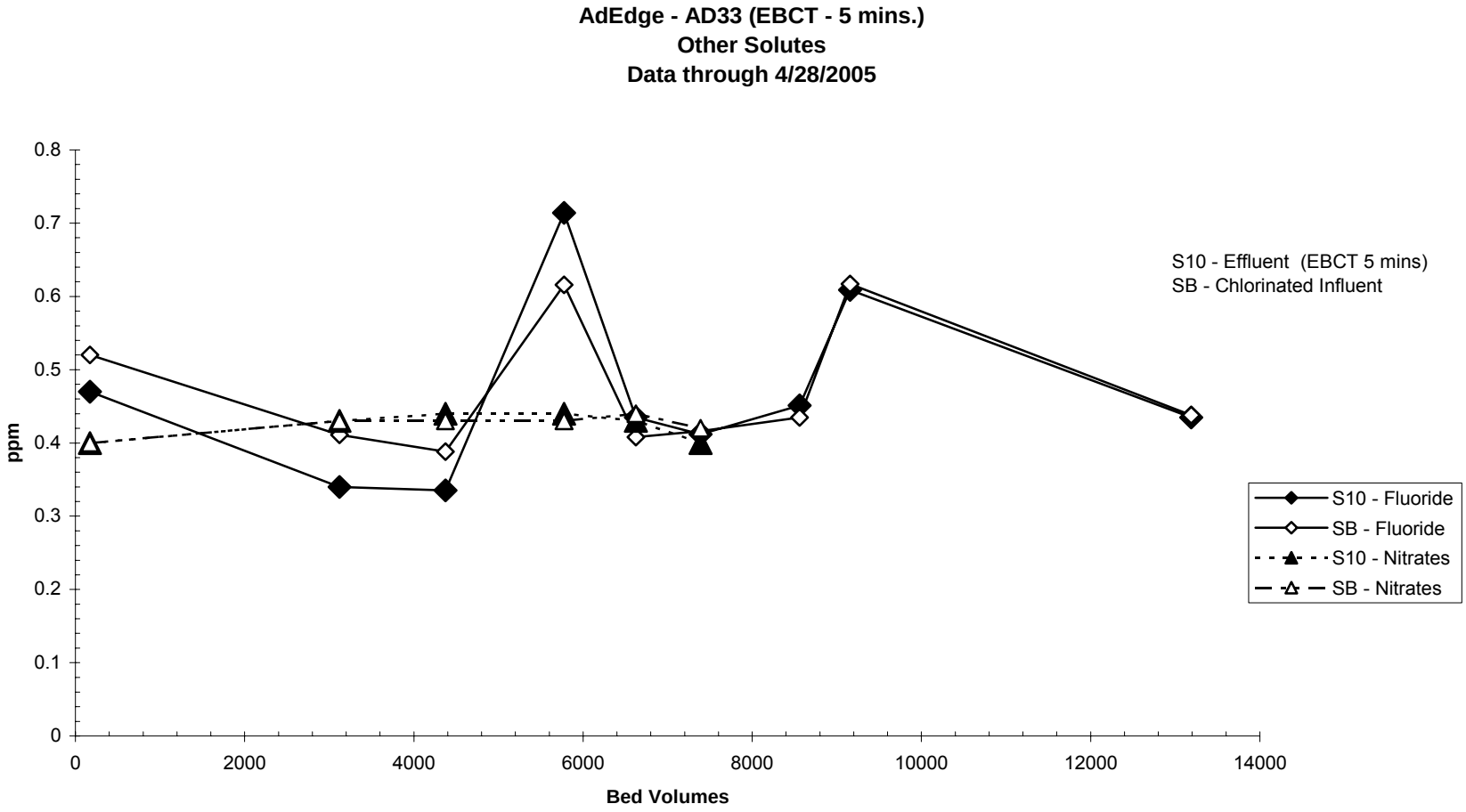
AdEdge - AD33 (EBCT - 2 mins.)
Vanadium & Arsenic Data
through 7/29/2005

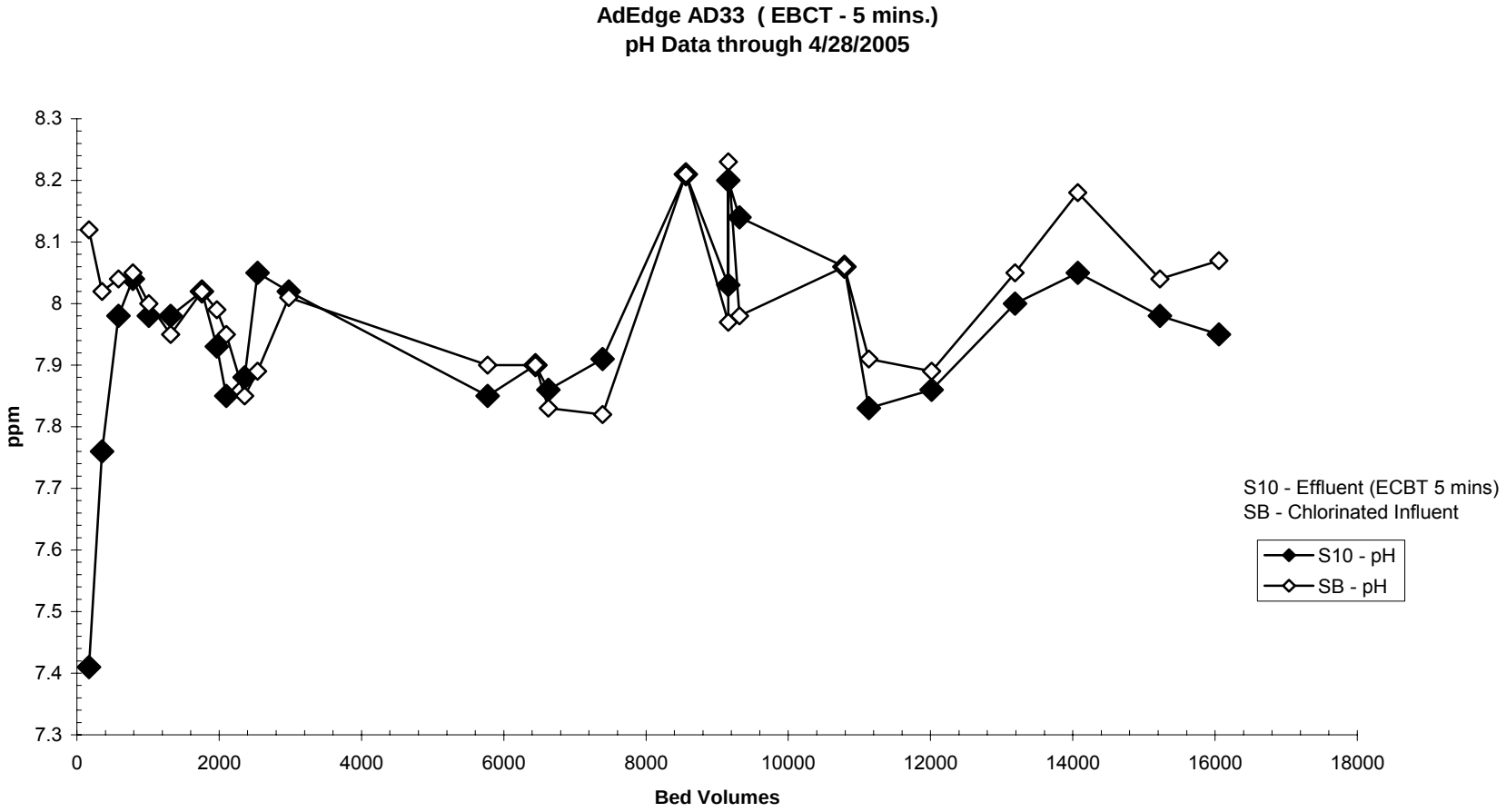



AdEdge AD33 (EBCT 5 mins.)
Vanadium & Arsenic
Data through 4/28/2005
ppb
Bed Volumes
S10 - Effluent (EBCT 5 mins)
SB - Chlorinated Influent
S10 - Vanadium
SB - Vanadium
SB - Arsenic
S10 - Arsenic
0
10
20
30
40
50
60
0
2000
4000
6000
8000
10000
12000
14000
16000
18000

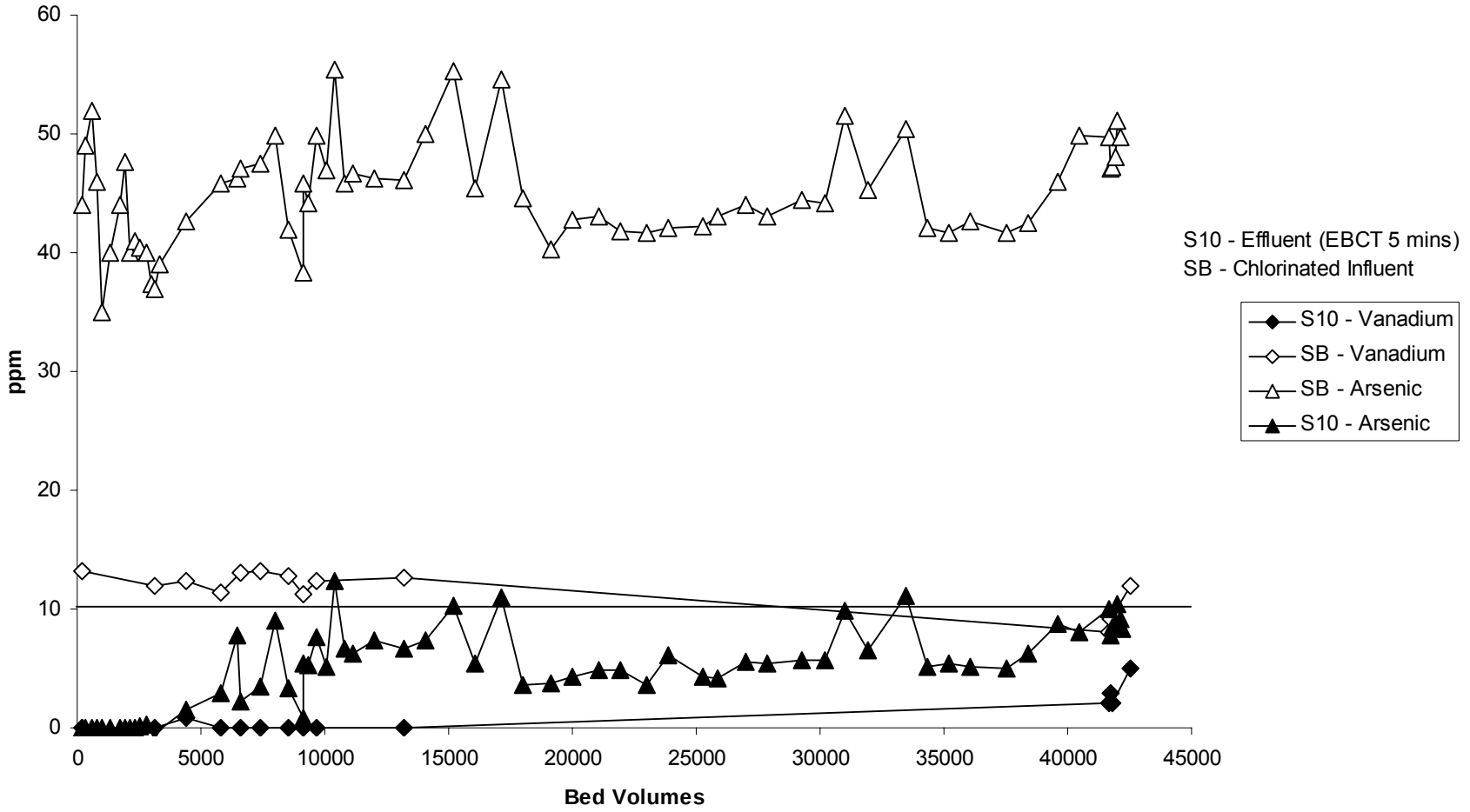

AdEdge - AD33 (EBCT - 5 mins.)
Major Solutes
Data through 4/28/2005
S10 - Effluent (EBCT 5 mins)
SB - Chlorinated Influent
S10 - Calcium
SB - Calcium
S10 - Chloride
SB - Chloride
S10 - Magnesium
SB - Magnesium
S10 - Sodium
SB - Sodium
S10 - Sulfate
SB - Sulfate
ppm
Bed Volumes
0
10
20
30
40
50
60
70
0
2000
4000
6000
8000
10000
12000
14000


AdEdge AD33 (EBCT - 5 mins.)
Other Solutes
Data through 4/28/2005
ppm
Bed Volumes
0
5
10
15
20
25
30
0
2000
4000
6000
8000
10000
12000
14000
S10 - Effluent (ECBT 5 mins)
SB - Chlorinated Influent
S10 - Silica
SB - Silica
S10 - TOC
SB - TOC


AdEdge - AD33 (EBCT - 5 mins.)
Other Solutes
Data through 4/28/2005
S10 - Effluent (EBCT 5 mins)
SB - Chlorinated Influent
S10 - Fluoride
SB - Fluoride
S10 - Nitrates
SB - Nitrates
ppm
Bed Volumes
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
2000
4000
6000
8000
10000
12000
14000


AdEdge AD33 (EBCT - 5 mins.)
pH Data through 4/28/2005
ppm
8.3
8.2
8.1
8
7.9
7.8
7.7
7.6
7.5
7.4
7.3
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
Bed Volumes
S10 - Effluent (ECBT 5 mins)
SB - Chlorinated Influent
S10 - pH
SB - pH

AdEdge AD33 (EBCT 5 mins.)
Vanadium & Arsenic
Data through 7/29/2005



Appendix C-4 Engelhard – ARM 200

Vendor	Flow Rate (gpm)	Contact Time [EBCT] (minutes)	Bed Volume [BV] (liters)
Engelhard	0.3	4	4.46

Pilot	BV to 10 ppb (10 μg/L)	8600
	Capacity at 10 ppb, mg/g	0.60
	BV at C/C_o = 0.8	33000
	Capacity at C/C_o = 0.8	1.15
CD RSSCT	BV to 10 ppb (10 μg/L)	6000
	Capacity at 10 ppb, mg/g	0.42
	BV until $C_e = C_o$	>140000
	Capacity at $C_e = C_o$, mg/g	>2.08
	BV at C/C_o = 0.8	44000
	Capacity at C/C_o = 0.8	1.35
PD RSSCT	BV to 10 ppb (10 μg/L)	16300
	Capacity at 10 ppb, mg/g	3.82
	BV until $C_e = C_o$	39000
	Capacity at $C_e = C_o$, mg/g	5.45
	BV at C/C_o = 0.8	27000
	Capacity at C/C_o = 0.8	5.07

Notes:

BV to 10 ppb (10 μg/L) is read from breakthrough curve where effluent concentration, C_e, reached and stayed > 10 ppb (10 μg/L).
Capacity at 10 ppb (10 μg/L) is calculated from raw data when C_e reached and stayed > 10 ppb (10 μg/L).
Capacity is integrated from mass balance on arsenic data. (Integration: area above BT curve and below influent concentration represents media capacity.)

Isotherm Results

Capacity 10ppb As [Freundlich] (mg/g)	Capacity 40ppb As [Freundlich] (mg/g)	Capacity 10ppb As [Langmuir] (mg/g)	Capacity 40ppb As [Langmuir] (mg/g)
3.58	7.91	5.00	8.00

Notes: Freundlich isotherm: $Q = K_F C^{nF}$
Langmuir isotherm: $Q = (S_{max} K_L C)/(1+K_L C)$
Where Q = equilibrium mg As/g media; K_F, n, F, K_L = isotherm parameters obtained from curve fits, C = equilibrium concentration in solution , (mg As/L); S_{max} = maximum capacity (mg As/g media).

Engelhard – ARM 200 Results

Arsenic: Arsenic concentrations in the pilot effluent reached 10 ppb (10 μg/L) after 8600 bed volumes had flowed through the column. This was about 53% (8600/16300) of the bed volume capacity predicted by the PD RSSCT experiments. The capacity predicted by mass balance was 0.60 mg As/g media and was 43% greater than that predicted by the PD RSSCT experiments. Capacities at 10 ppb (10 μg/L) calculated from batch sorption data using either the Langmuir or Freundlich isotherms were higher than those obtained in the flow experiments (RSSCT or pilot). As the effluent arsenic concentration in the pilot column rose above 10 ppb (10 μg/L), the BTC was fairly steep. There was about 92% additional capacity (0.60 to 1.15 mg/g) when the effluent concentration reached 80% of the influent concentration ($C/C_e = 0.8$). The RSSCT columns showed a smaller additional capacity (BTC was sharper). When the pH was lowered by CO_2 injection in Phase IIA, the effluent arsenic concentration dropped to approximately 12 ppb.

Vanadium: Vanadium (influent approximately 13 ppb) was removed to non-detectable levels (MDL = 0.5 ppb) for the entire Phase I pilot study at ambient pH but increased slightly (about 2 ppb) when the pH was lowered to 6.8 by CO_2 injections in Phase IIA.

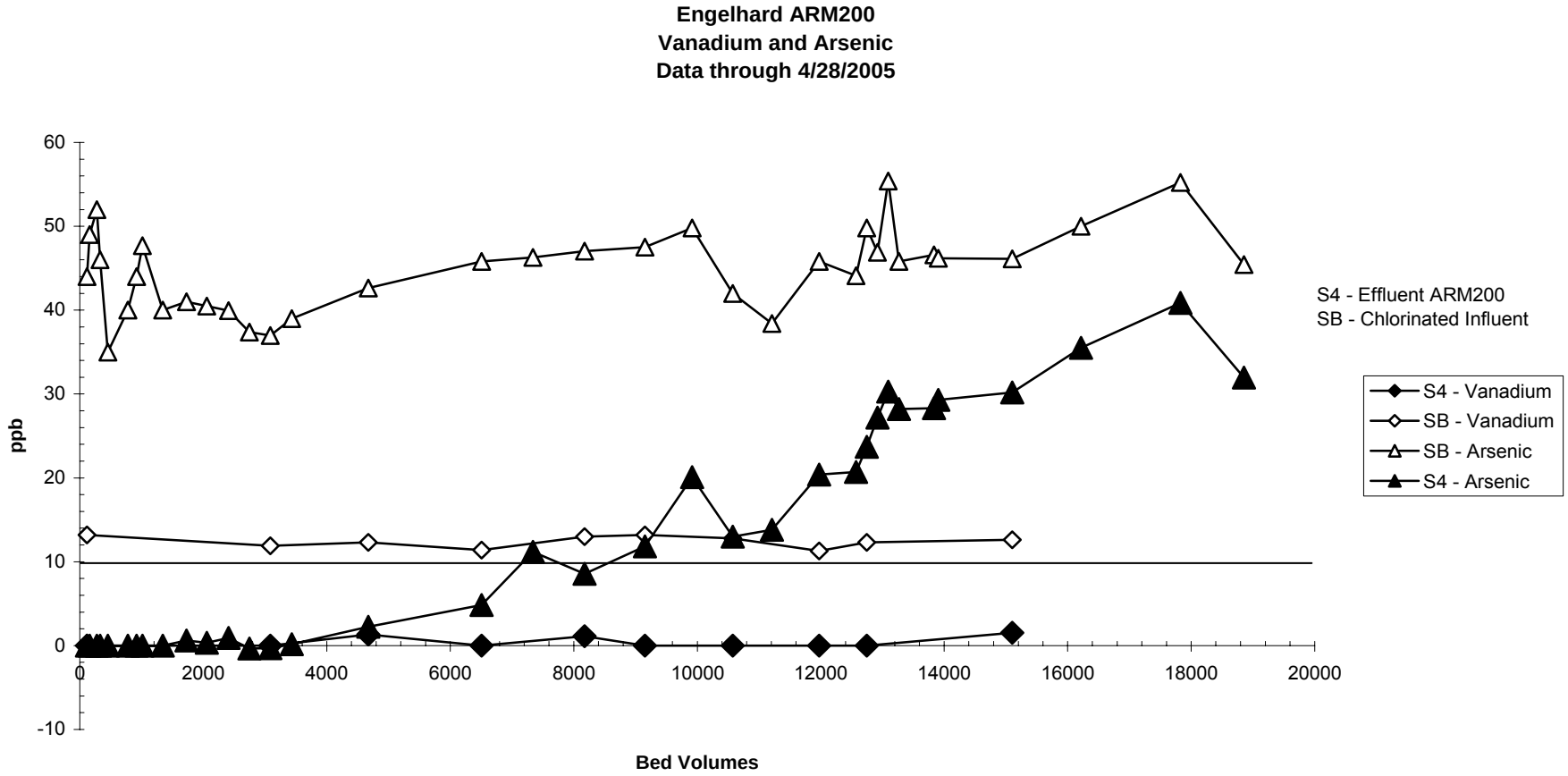
Other Solutes: Sulfate was released in the first few bed volumes of effluent but declined to ambient levels by 3000 BV. Silica reached ambient levels by 6250 BV. Fluoride was released at ambient levels. Free chlorine was released at influent levels. The initial pH in the effluent was initially depressed (7.1) and rose rapidly to reach ambient pH after about 2000 BV. Other solutes (Ca, Mg, Na, Cl) were not affected by the media.

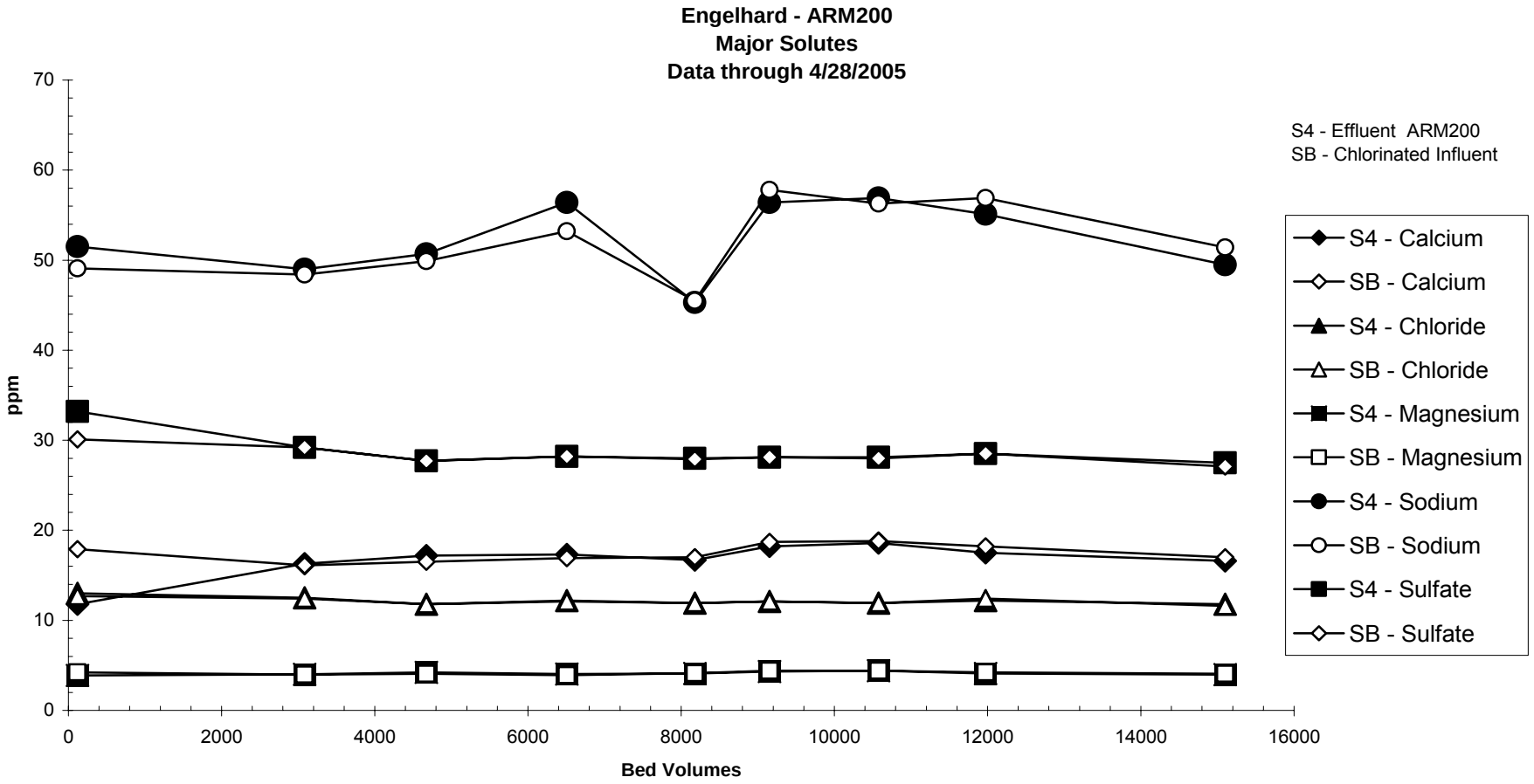
Note: According to a company spokesperson, the arsenic sorption capacity of the material used in this pilot is lower than that of the media currently manufactured by the Engelhard company and sold to water utilities. "Engelhard Corporation supplied Sandia National Laboratories product in late 2004 that was prepared in a laboratory/pilot plant facility. In 2005 a fully devoted production facility was constructed and received NSF approval in April 2005. During the production scale up process, significant improvements in the arsenic capacity were made with the media." (L. Muroski, personal communication, January 27, 2006).

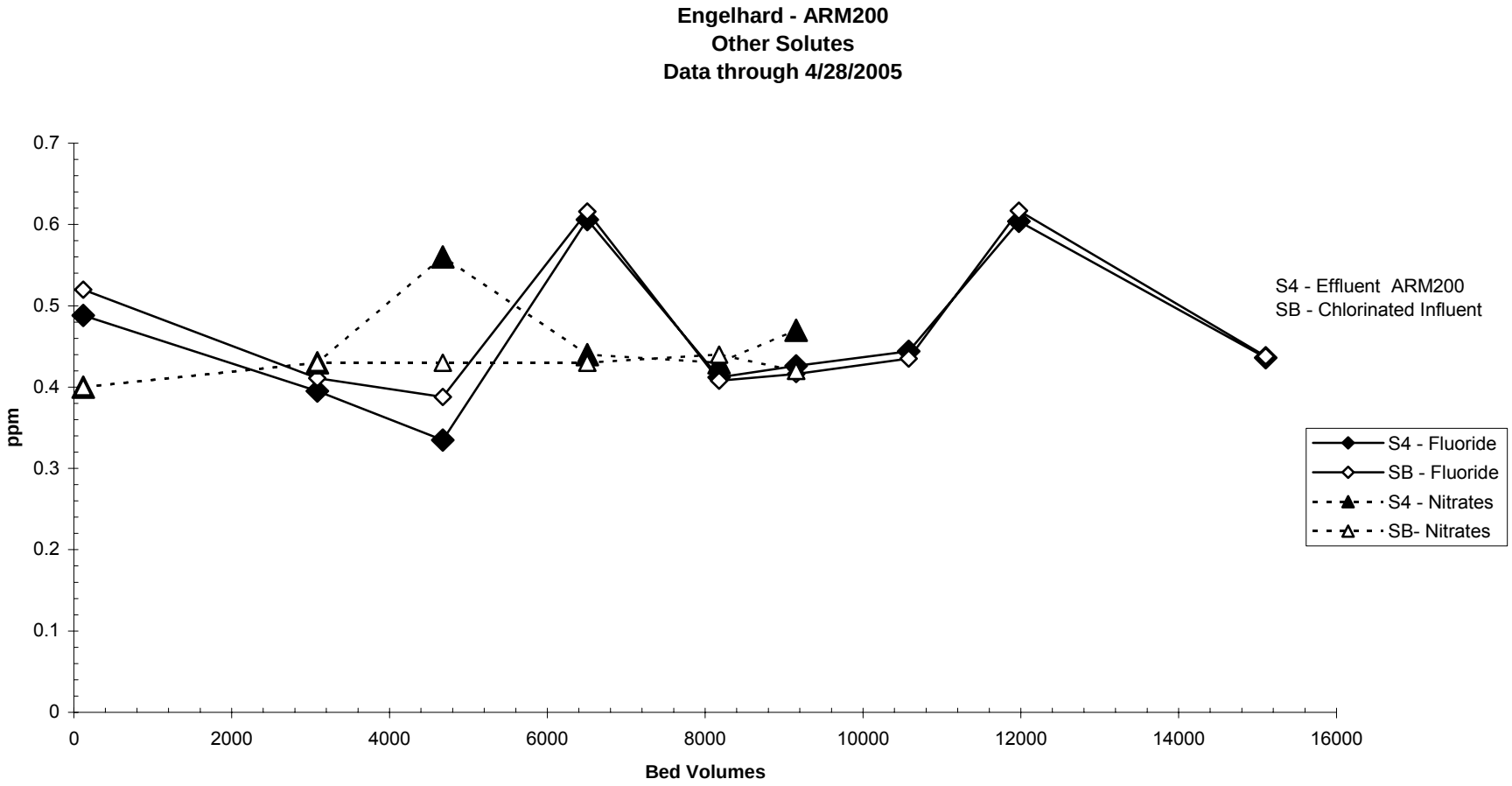
Table C-4. ARM 200 Treatment Design and Operating Parameters.

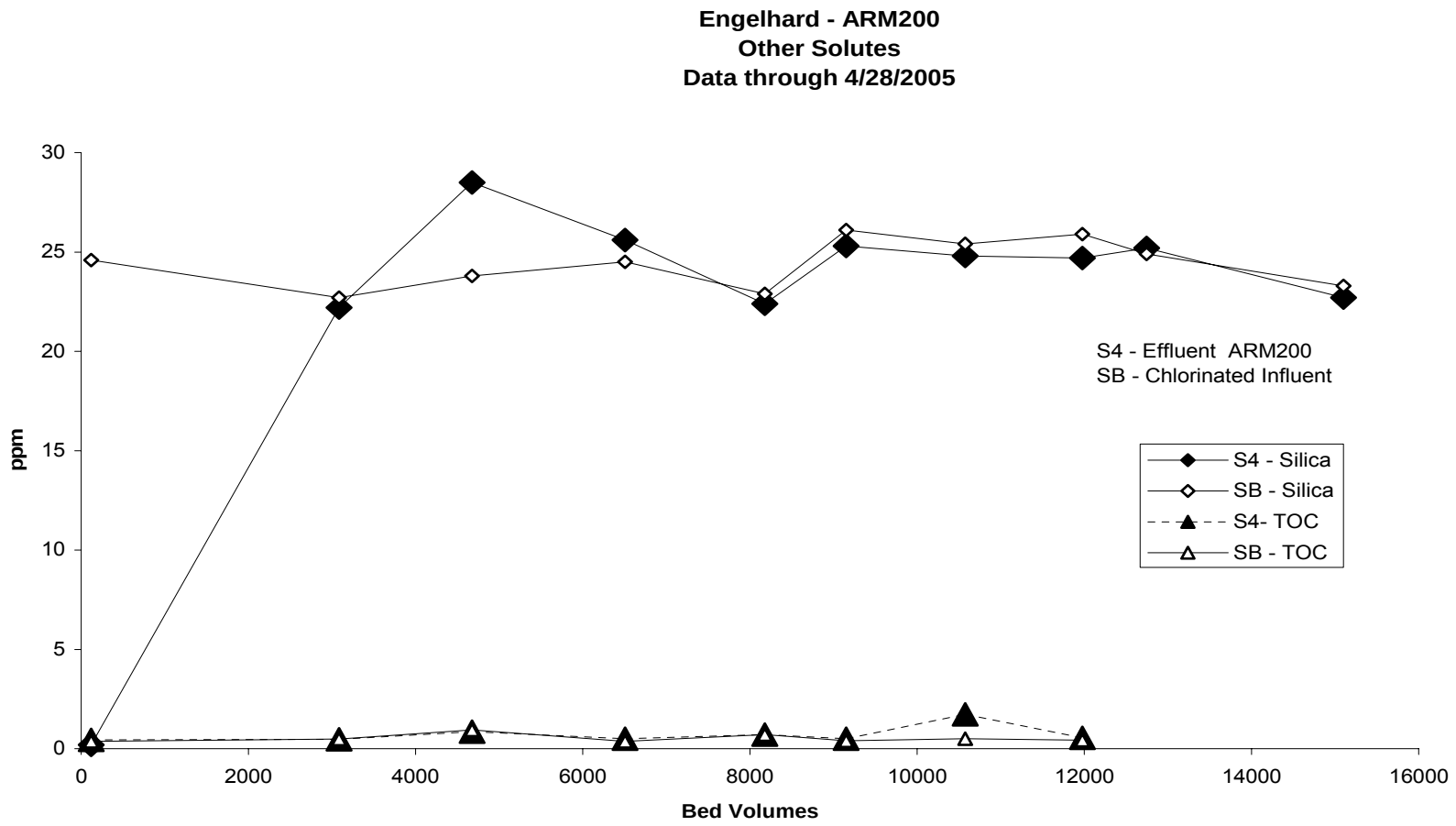
Parameter	RSSCT Columns	ARM 200 Pilot Column	ARM 200 Full Scale Systems
Bulk Density, lb/ft^3	30-45	30 - 45	30 - 45
Particle mesh size	100 x 200	12 x 40	Any US Std Mesh size
Particle diameter, mm	0.15 x 0.075	1.40 x 0.425	Any size
BET surface area, m^2/g	NA		
Column Layers			
Distributor Configuration	N/A		Hub & Spoke
Underbedding Configuration	N/A	gravel	gravel
Column Number (Drawing SOC-01)		4	N/A
Underbedding Height, inches	N/A	3	NA
Freeboard, inches	14.35	18.5	40-50% of Hm
Media Depth (Hm), inches	5.35	38.5	24 - 48
Media Volume, Liters	0.0052	4.46	Function of Q, EBCT
Column Diameter, inches	0.28	3	1-12 ft.
Column Height, inches	19.7	60	NA
Operating Conditions			
Number of Pilot Columns	1	1	
Hydraulic Loading Rate, gpm/ft^2	6.18	6	6 - 10
EBCT, minutes	0.55	4	3 - 5
pH	7.7	Ambient ~ 7.7	Site specific
Down Flow Pressure Drop, psi	NA	1/ft.	1/ft.
Maximum Differential Pressure, psi	NA	3.3	NA
Flow Rate, gpm	0.0025	0.3	Site specific
Face Velocity, ft/s	0.0135	0.0134	NA
Backwash Conditions			
Backwash Flux, gpm/ft^2	N/A	6	10 - 12
Backwash Flow Rate, gpm	N/A	0.3	Function of vessel diameter and HLR
Backwash Duration, minutes	N/A	TBD	15
Backwash Frequency (per month)	N/A	TBD	Site specific

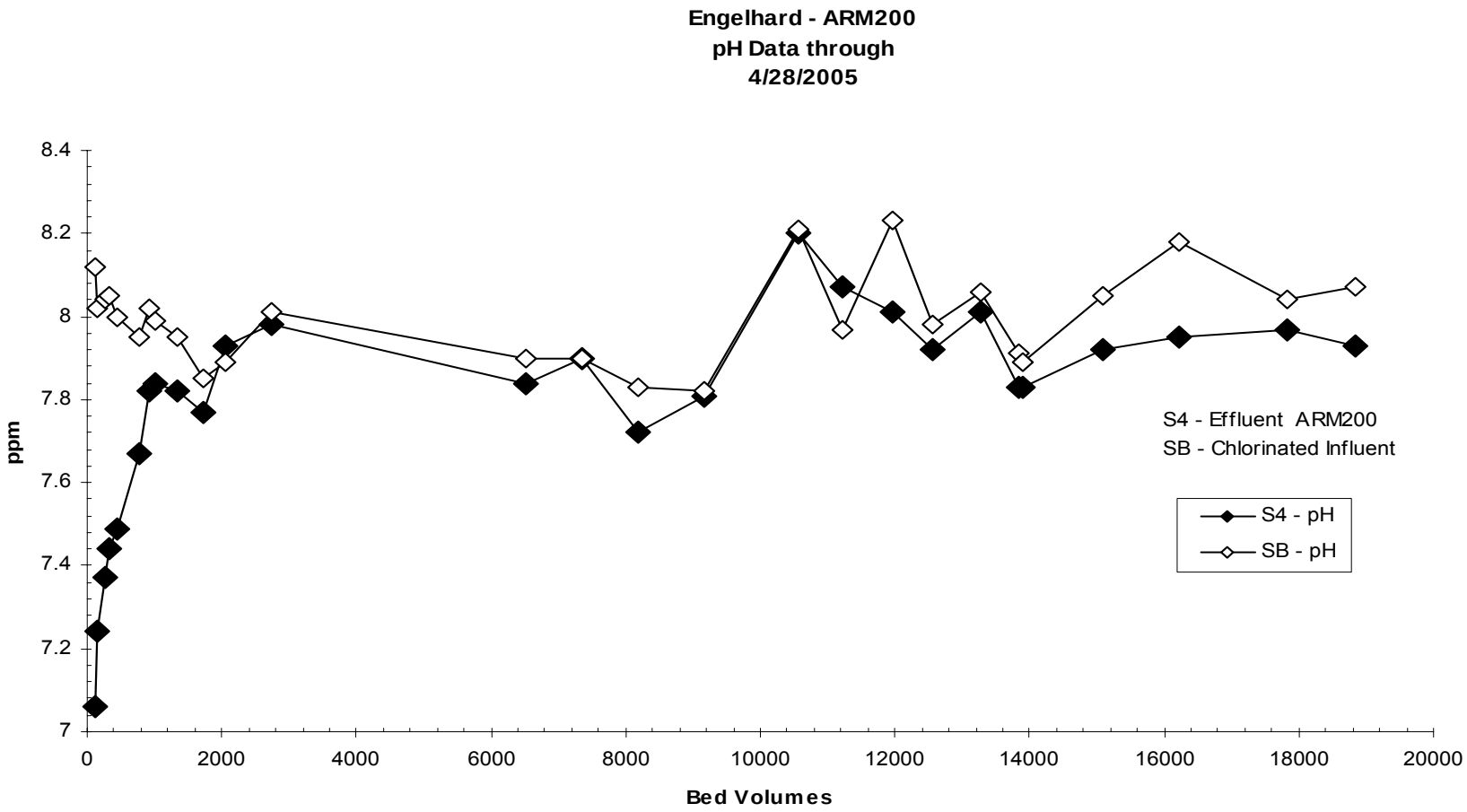
N/A = not applicable; NA = not analyzed or available


Engelhard ARM200
Vanadium and Arsenic
Data through 4/28/2005
ppb
60
50
40
30
20
10
0
-10
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Bed Volumes
S4 - Effluent ARM200
SB - Chlorinated Influent
S4 - Vanadium
SB - Vanadium
SB - Arsenic
S4 - Arsenic

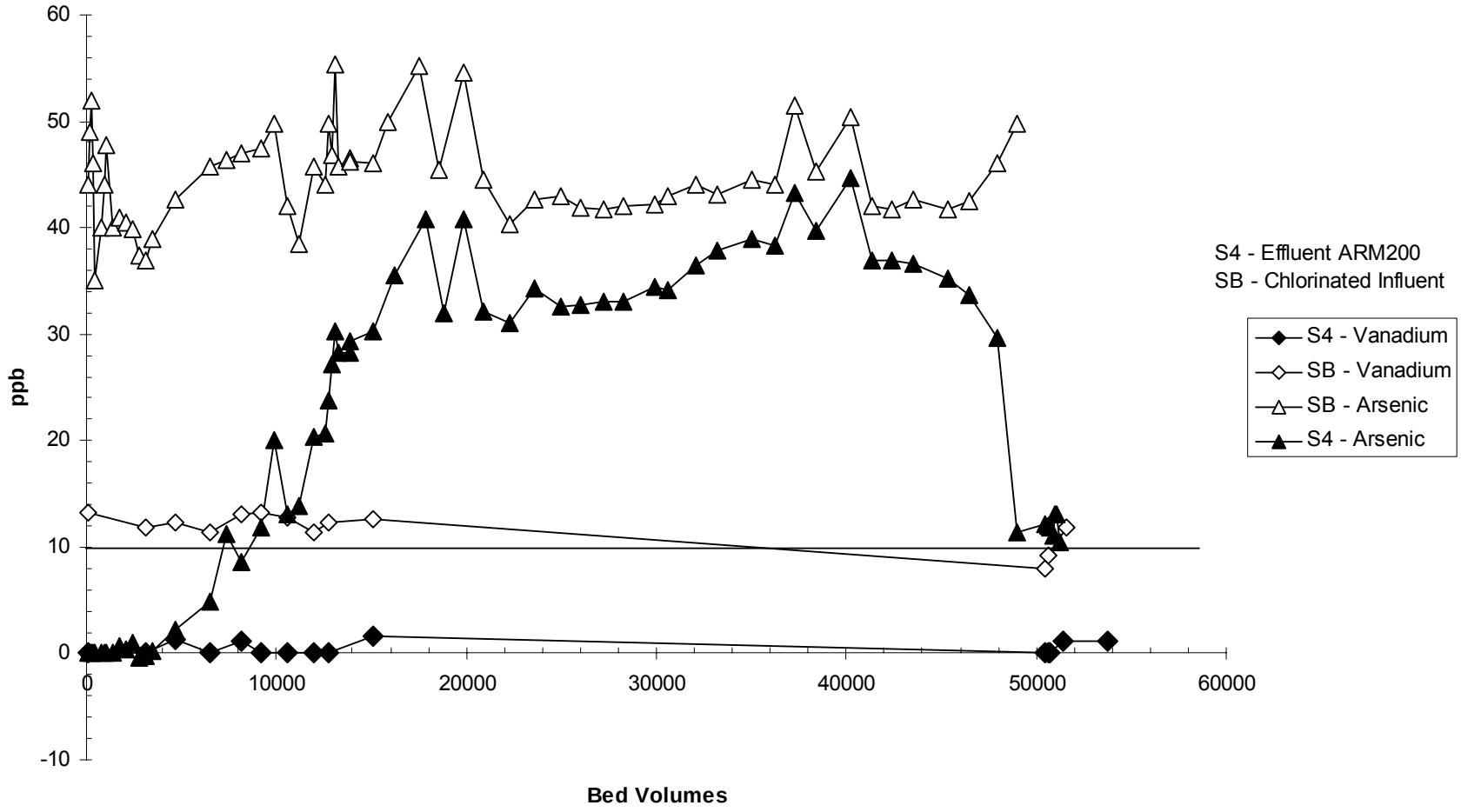

Engelhard - ARM200
Major Solutes
Data through 4/28/2005
S4 - Effluent ARM200
SB - Chlorinated Influent
S4 - Calcium
SB - Calcium
S4 - Chloride
SB - Chloride
S4 - Magnesium
SB - Magnesium
S4 - Sodium
SB - Sodium
S4 - Sulfate
SB - Sulfate
ppm
Bed Volumes
0
10
20
30
40
50
60
70
0
2000
4000
6000
8000
10000
12000
14000
16000


Engelhard - ARM200
Other Solutes
Data through 4/28/2005
ppm
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2000
4000
6000
8000
10000
12000
14000
16000
Bed Volumes
S4 - Effluent ARM200
SB - Chlorinated Influent
S4 - Fluoride
SB - Fluoride
S4 - Nitrates
SB- Nitrates


Engelhard - ARM200
Other Solutes
Data through 4/28/2005
ppm
Bed Volumes
0
5
10
15
20
25
30
0
2000
4000
6000
8000
10000
12000
14000
16000
S4 - Effluent ARM200
SB - Chlorinated Influent
S4 - Silica
SB - Silica
S4- TOC
SB - TOC


Engelhard - ARM200
pH Data through
4/28/2005
8.4
8.2
8
7.8
7.6
7.4
7.2
7
ppm
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Bed Volumes
S4 - Effluent ARM200
SB - Chlorinated Influent
S4 - pH
SB - pH

Engelhard ARM200
Vanadium and Arsenic
Data through 7/29/2005



Appendix C-5 HyroGlobe - MetSorb

Vendor	Flow Rate (gpm)	Contact Time [EBCT] (minutes)	Bed Volume [BV] (liters)
HydroGlobe	0.4	2	2.97

Pilot	BV to 10 ppb (10 μg/L)	13000
	Capacity at 10 ppb, mg/g	0.70
	BV at C/C_o = 0.8	87000
	Capacity at C/C_o = 0.8	2.26
CD RSSCT	BV to 10 ppb (10 μg/L)	11500
	Capacity at 10 ppb, mg/g	0.66
	BV until $C_e = C_o$	>65000
	Capacity at $C_e = C_o$, mg/g	>1.72
	BV at C/C_o = 0.8	>65000
	Capacity at C/C_o = 0.8	>1.72
PD RSSCT	BV to 10 ppb (10 μg/L)	12800
	Capacity at 10 ppb, mg/g	0.69
	BV until $C_e = C_o$	68000
	Capacity at $C_e = C_o$, mg/g	1.31
	BV at C/C_o = 0.8	40000
	Capacity at C/C_o = 0.8	1.24

Notes:

BV to 10 ppb (10 μg/L) is read from breakthrough curve where effluent concentration, C_e, reached and stayed > 10 ppb (10 μg/L).
Capacity at 10 ppb (10 μg/L) is calculated from raw data when C_e reached and stayed > 10 ppb (10 μg/L).
Capacity is integrated from mass balance on arsenic data. (Integration: area above BT curve and below influent concentration represents media capacity.)

Isotherm Results

Capacity 10 ppb As [Freundlich] (mg/g)	Capacity 40 ppb As [Freundlich] (mg/g)
1.18	4.13

Notes: Freundlich isotherm: $Q = K_F C^{nF}$
where Q = mg As/g media; K, n, F = isotherm parameters obtained form curve fits; C = equilibrium concentration in solution (mg As/L).

Hydroglobe MetSorb Results:

Arsenic: Arsenic concentrations in the pilot effluent reached 10 ppb (10 μg/L) after 13000 bed volumes had flowed through the column. This was about 2% greater (13000/12800) than the bed volume capacity predicted by the Proportional Diffusivity (PD) RSSCT experiments. The capacity predicted by mass balance was 0.70 mg As /g media and was 6% greater than that predicted by the PD RSSCT experiments. Capacities at 10 ppb (10 μg/L) calculated from batch sorption data using either the Langmuir or Freundlich isotherms were higher than those obtained in the flow experiments (RSSCT or pilot). As the effluent arsenic concentration in the pilot column rose above 10 ppb (10 μg/L), the BTC was fairly steep. There was about 322% additional capacity (0.70 to 2.26 mg/g) when the effluent concentration reached 80% of the influent concentration ($C/C_e = 0.8$). The RSSCT columns showed a much smaller additional capacity (BTC was sharper). When the pH was lowered by CO_2 injection in Phase IIA, the effluent arsenic concentration dropped to approximately 12 ppb.

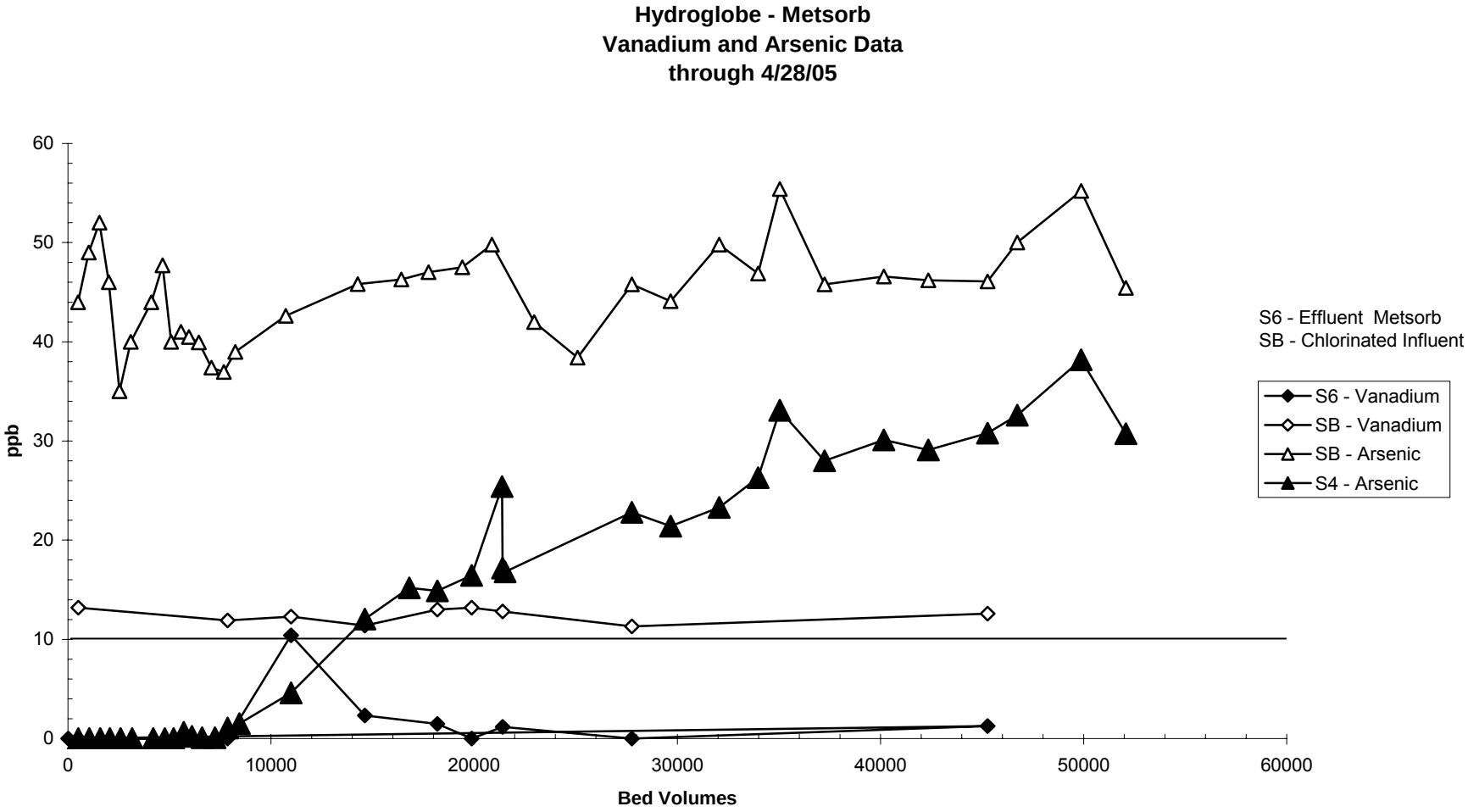
Vanadium: Vanadium (influent approximately 13 ppb) was removed to non-detectable levels (MDL = 0.5 ppb) for the entire Phase I pilot study at ambient pH except for a spike in V in the effluent at about 10000 BV. The V increased slightly (about 2 ppb) when the pH was lowered to 6.8 by CO_2 injections in Phase IIA.

Other Solutes: Sulfate was released at ambient levels. Silica reached ambient levels by 8000 BV; however, a silica spike was observed at about 11000 BV. Fluoride was released at ambient levels. Free chlorine was released at ambient levels. The initial pH in the effluent was depressed and rose rapidly to reach ambient pH after about 5000 BV. Calcium was adsorbed during the initial 7000 BV of flow. Other solutes (Cl, Mg, Na) were not affected by the media.

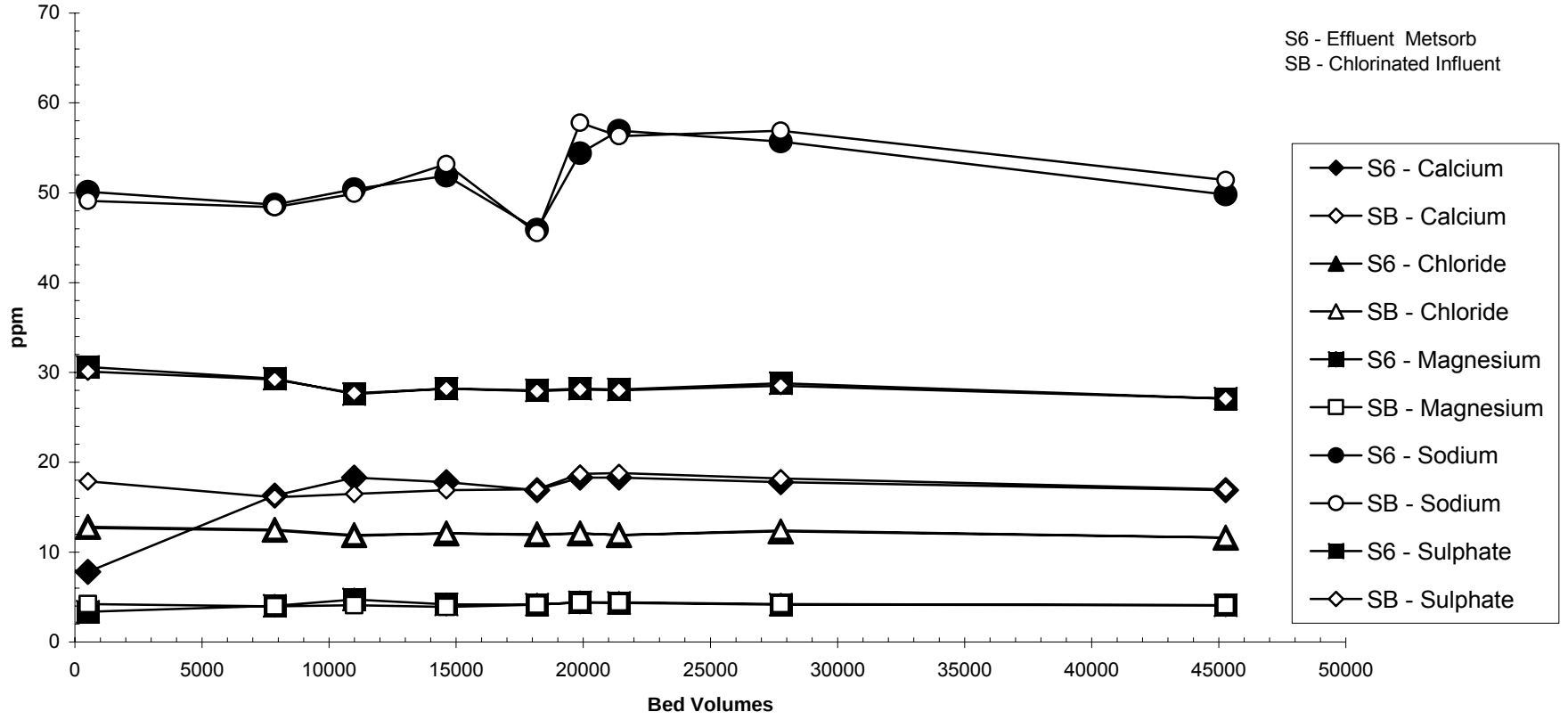
Table CB-5. MetSorb Treatment Design and Operating Parameters

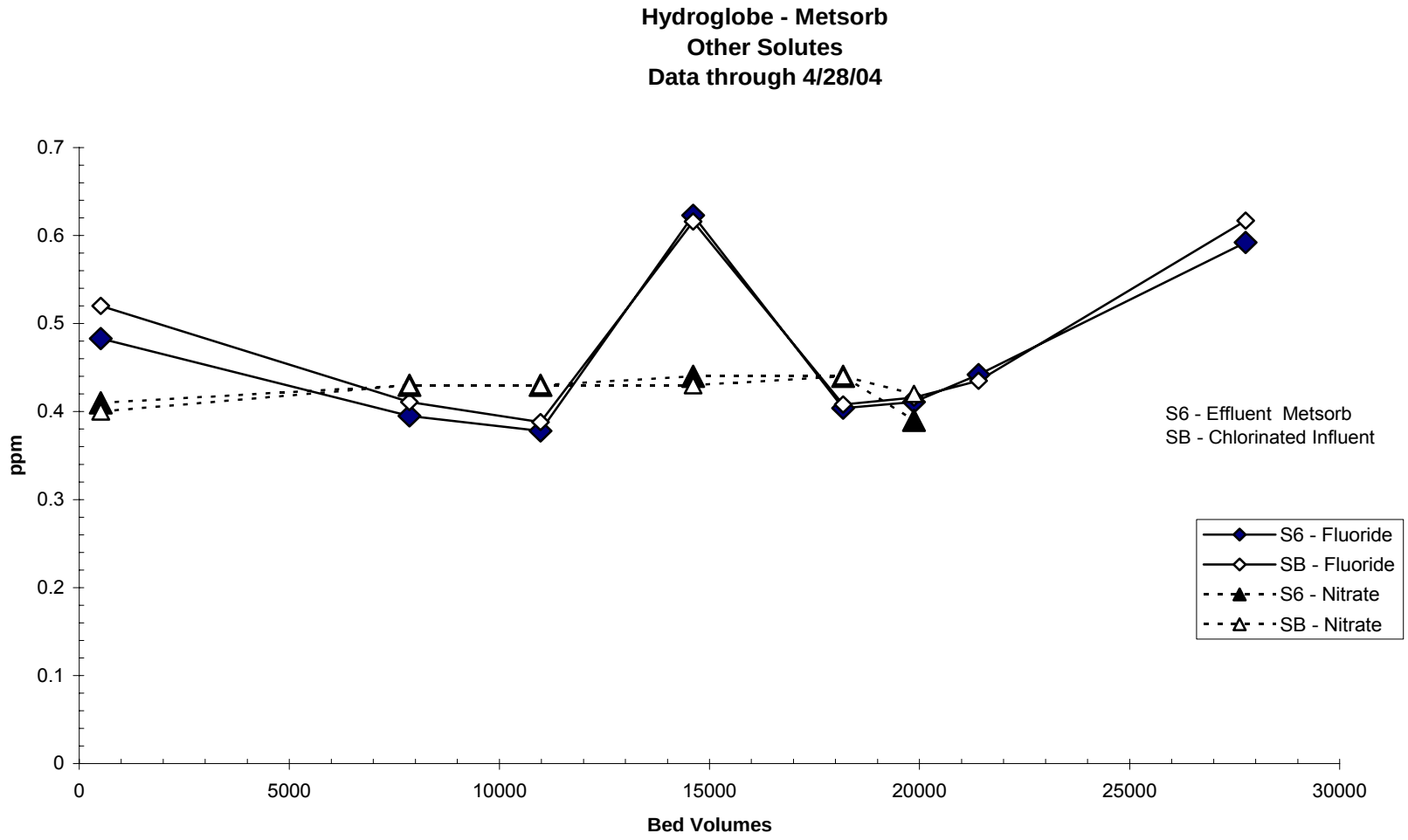
Parameter	RSSCT Columns (PD)	MetSorb Pilot Columns		MetSorb Full Scale Systems
Bulk Density, lb/ft^3	50	50		50
Particle mesh size	100 x 200	US Std Mesh 16 x 60		US Std Mesh 16 x 60
Particle diameter, mm	0.15 x 0.075	1.18 x 0.25		1.18 x 0.25
BET surface area, m^2/g	NA	220		220
Column Layers				
Distributor Configuration	N/A	Fritted disc		Hub & Spoke
Underbedding Configuration	N/A	1/16" gravel		1/16" gravel
Column Number (Drawing SOC-01)		6	2	N/A
Underbedding Height, inches	N/A	3	3	NA
Freeboard, inches	14.6	10.3	10.3	40-50% of Hm
Media Depth (Hm), inches	5.1	25.7	25.7	24 -48
Media Volume, Liters	0.005	2.97	2.97	Function of Q, EBCT
Column Diameter, inches	0.28	3	3	1-12 ft.
Column Height, inches	19.7	39	39	24 - 60
Operating Conditions				
Number of Pilot Columns	1	4		
Hydraulic Loading Rate, gpm/ft^2	8.28	8	8	8 - 10
EBCT, minuntes	0.39	2	2	1.6-2.5
pH	7.7	7.7	6.8	Site specific
Down Flow Pressure Drop, psi	NA	1.7	1.7	< 5
Maximum Differential Pressure, psi	NA	NA	NA	NA
Flow Rate, gpm	0.00337	0.4	0.4	Site specific
Face Velocity, ft/s	0.018	0.178	0.178	NA
Backwash Conditions				
Backwash Flux, gpm/ft^2	N/A	6		10-12
Backwash Flow Rate, gpm	N/A	0.3		Function of vessel diameter and HLR
Backwash Duration, minutes	N/A	≤15		15
Backwash Frequency (per month)	N/A	Backwash only if Δ p > 2 x initial pressure drop across media bed		1 x (dependent on raw water quality)

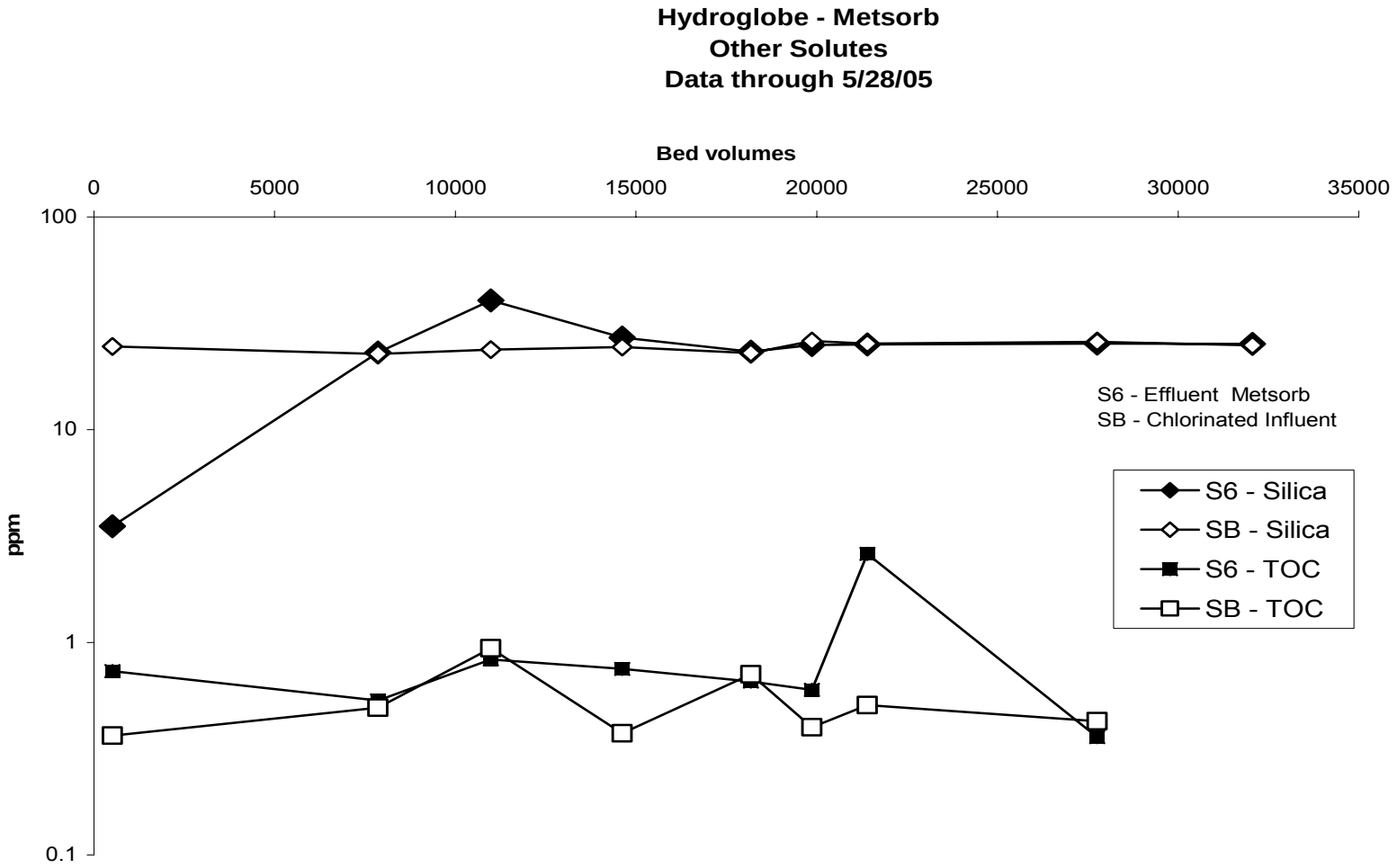
N/A = not applicable; NA = not analyzed or available

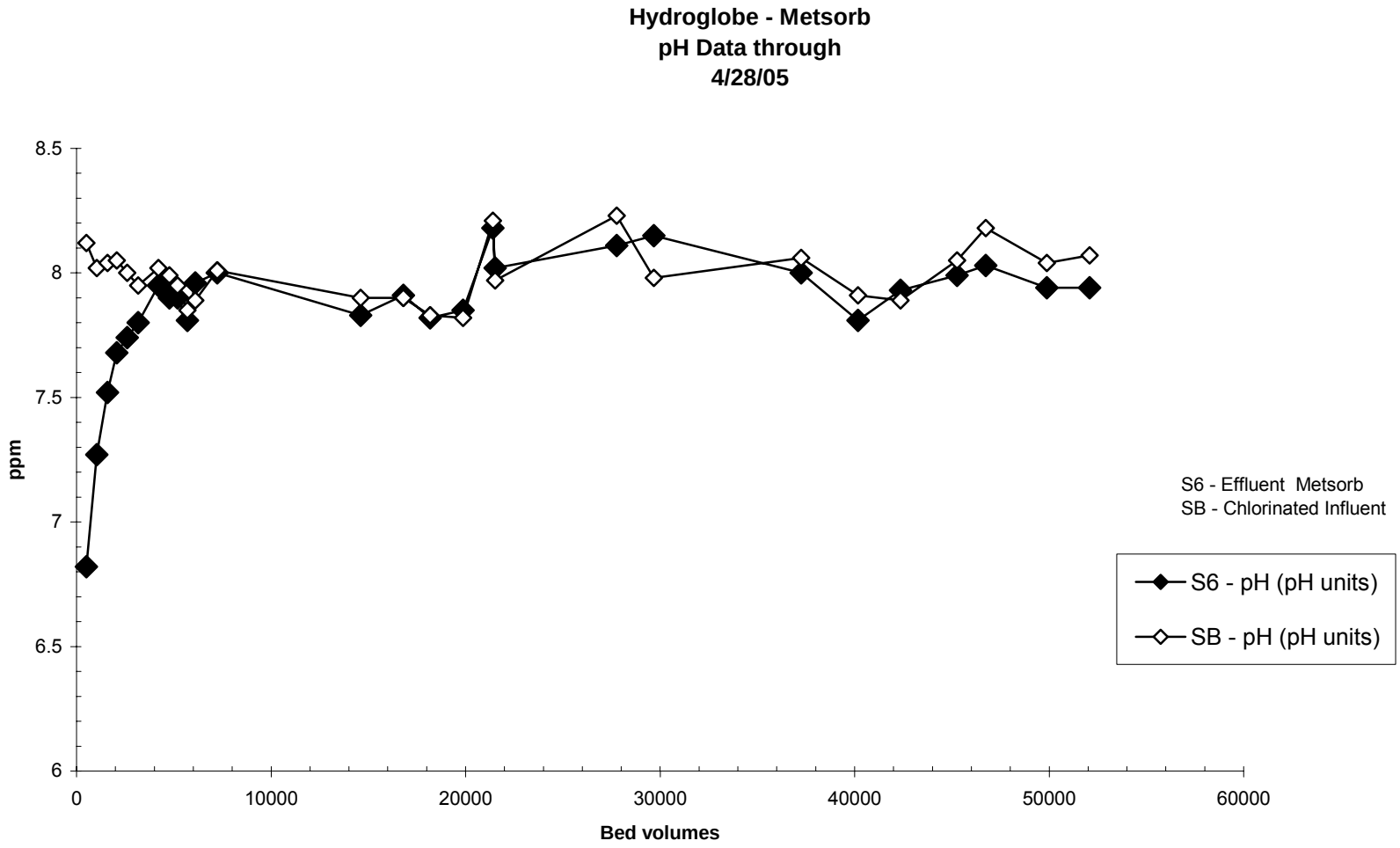

Hydroglobe - Metsorb
Vanadium and Arsenic Data
through 4/28/05
ppb
Bed Volumes
0
10
20
30
40
50
60
0
10000
20000
30000
40000
50000
60000
S6 - Effluent Metsorb
SB - Chlorinated Influent
S6 - Vanadium
SB - Vanadium
SB - Arsenic
S4 - Arsenic

Hydroglobe - Metsorb
Major Solutes
Data through 4/28/05

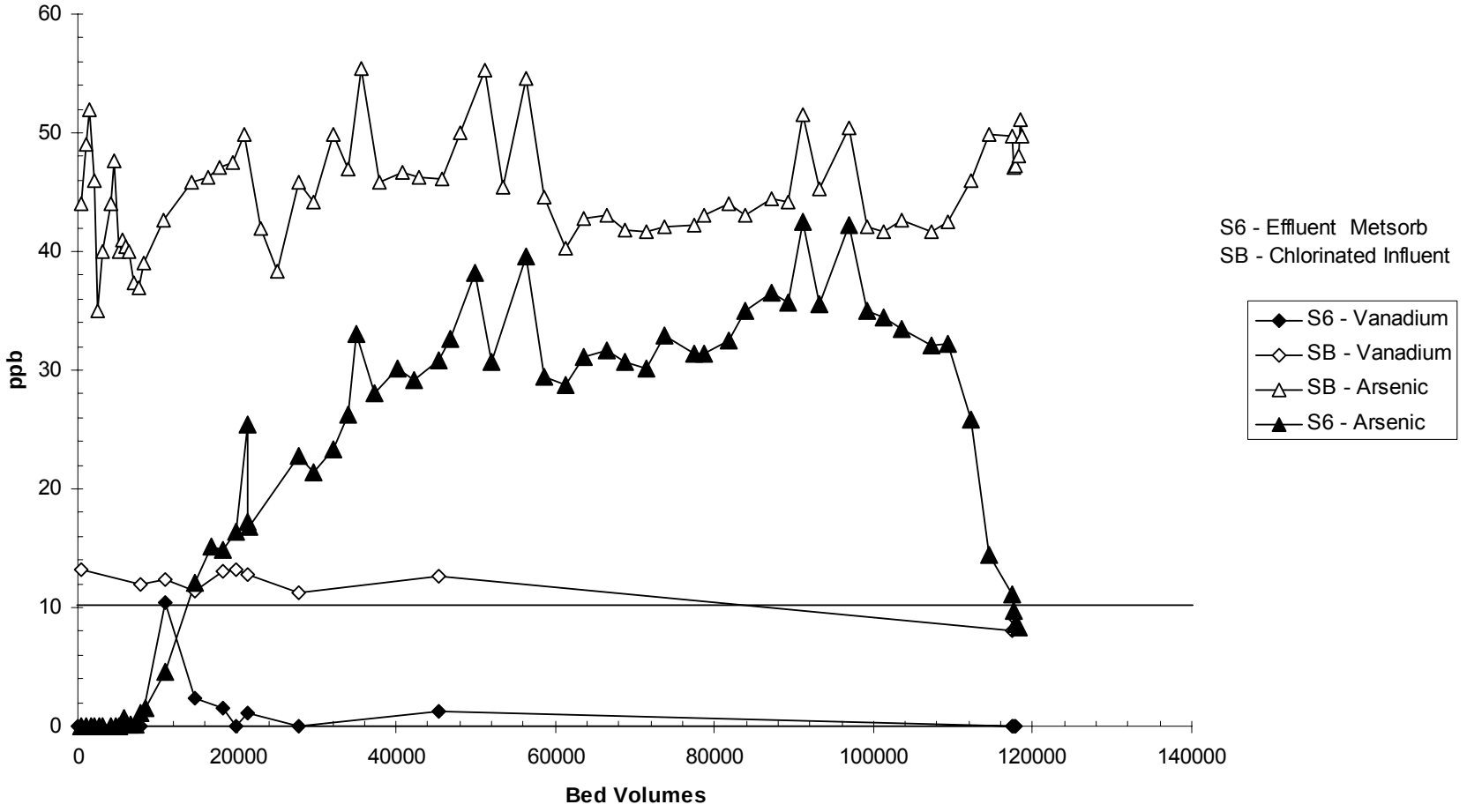



Hydroglobe - Metsorb
Other Solutes
Data through 4/28/04
ppm
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5000
10000
15000
20000
25000
30000
Bed Volumes
S6 - Effluent Metsorb
SB - Chlorinated Influent
S6 - Fluoride
SB - Fluoride
S6 - Nitrate
SB - Nitrate


Hydroglobe - Metsorb
Other Solutes
Data through 5/28/05
Bed volumes
0
5000
10000
15000
20000
25000
30000
35000
100
10
1
0.1
ppm
S6 - Effluent Metsorb
SB - Chlorinated Influent
S6 - Silica
SB - Silica
S6 - TOC
SB - TOC


Hydroglobe - Metsorb
pH Data through
4/28/05
8.5
8
7.5
7
6.5
6
ppm
0
10000
20000
30000
40000
50000
60000
Bed volumes
S6 - Effluent Metsorb
SB - Chlorinated Influent
S6 - pH (pH units)
SB - pH (pH units)

Hydroglobe - Metsorb
Vanadium and Arsenic Data
through 7/28/05



Appendix C-6 MEI - Isolux

Vendor	Flow Rate (gpm)	Contact Time [EBCT] (minutes)	Bed Volume [BV] (liters)
MEI	0.5	0.25	NA

Pilot	BV to 10 ppb (10 μg/L)	32000
	Capacity at 10 ppb, mg/g	1.67
	BV at C/C_o = 0.8	63000
	Capacity at C/C_o = 0.8	2.23

Notes:
BV to 10 ppb (10 μg/L) is read from breakthrough curve where effluent concentration, C_e, reached and stayed > 10 ppb (10 μg/L).
Capacity at 10 ppb (10 μg/L) is calculated from raw data when C_e reached and stayed > 10 ppb (10 μg/L).
Capacity is integrated from mass balance on arsenic data. (Integration: area above BT curve and below influent concentration represents media capacity.)

Isotherm Results

Capacity 10 ppb As [Freundlich] (mg/g)	Capacity 40 ppb As [Freundlich] (mg/g)
2.67	7.77

Notes: Freundlich isotherm: $Q = K_F C^{nF}$
where Q = mg As/g media; K, n, F = isotherm parameters obtained form curve fits; C = equilibrium concentration in solution (mg As/L).

MEI - Isolux Results:

Arsenic: Arsenic concentrations in the pilot effluent reached 10 ppb (10 μg/L) after 32000 bed volumes had flowed through the column. Capacities at 10 ppb (10 μg/L) calculated from batch sorption data using either the Langmuir or Freundlich isotherms were much higher than those obtained in the flow experiments. As the effluent arsenic concentration in the pilot column rose above 10 ppb (10 μg/L), the BTC was fairly steep. There was about 34% additional capacity (1.67 to 2.23 mg/g) when the effluent concentration reached 80% of the influent concentration

($C/C_e = 0.8$). When the pH was lowered by CO_2 injection in Phase IIA, the effluent arsenic concentration dropped to approximately 12 ppb.

Other Solutes: Free chlorine was adsorbed quantitatively for the first 28000 BV when effluent levels reached influent levels. (There was a free chlorine adsorption spike at about 58000 BV.) The initial pH in the effluent was depressed and rose to reach ambient pH after about 22000 BV.

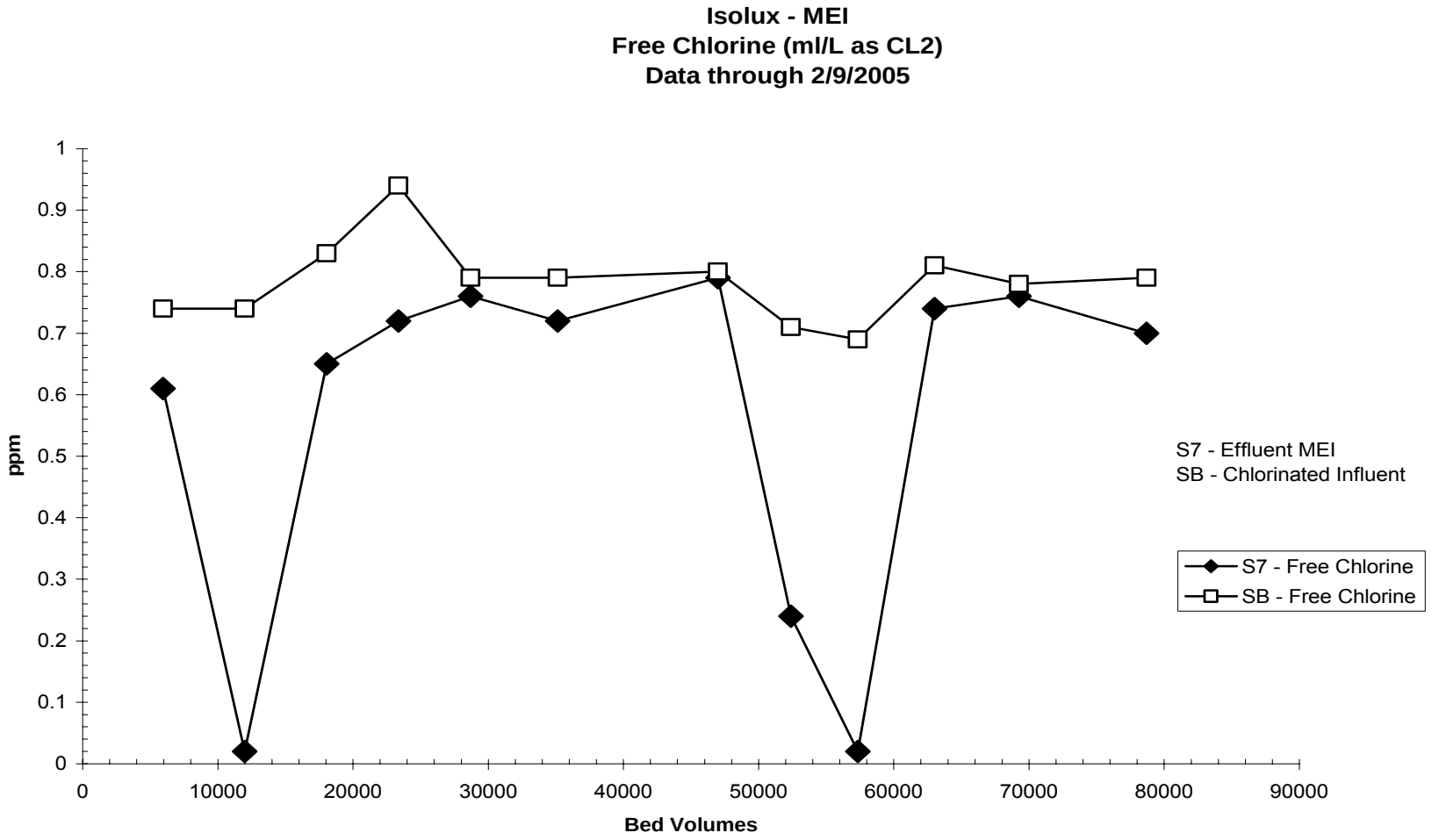
MEI Treatment Design and Operating Parameters

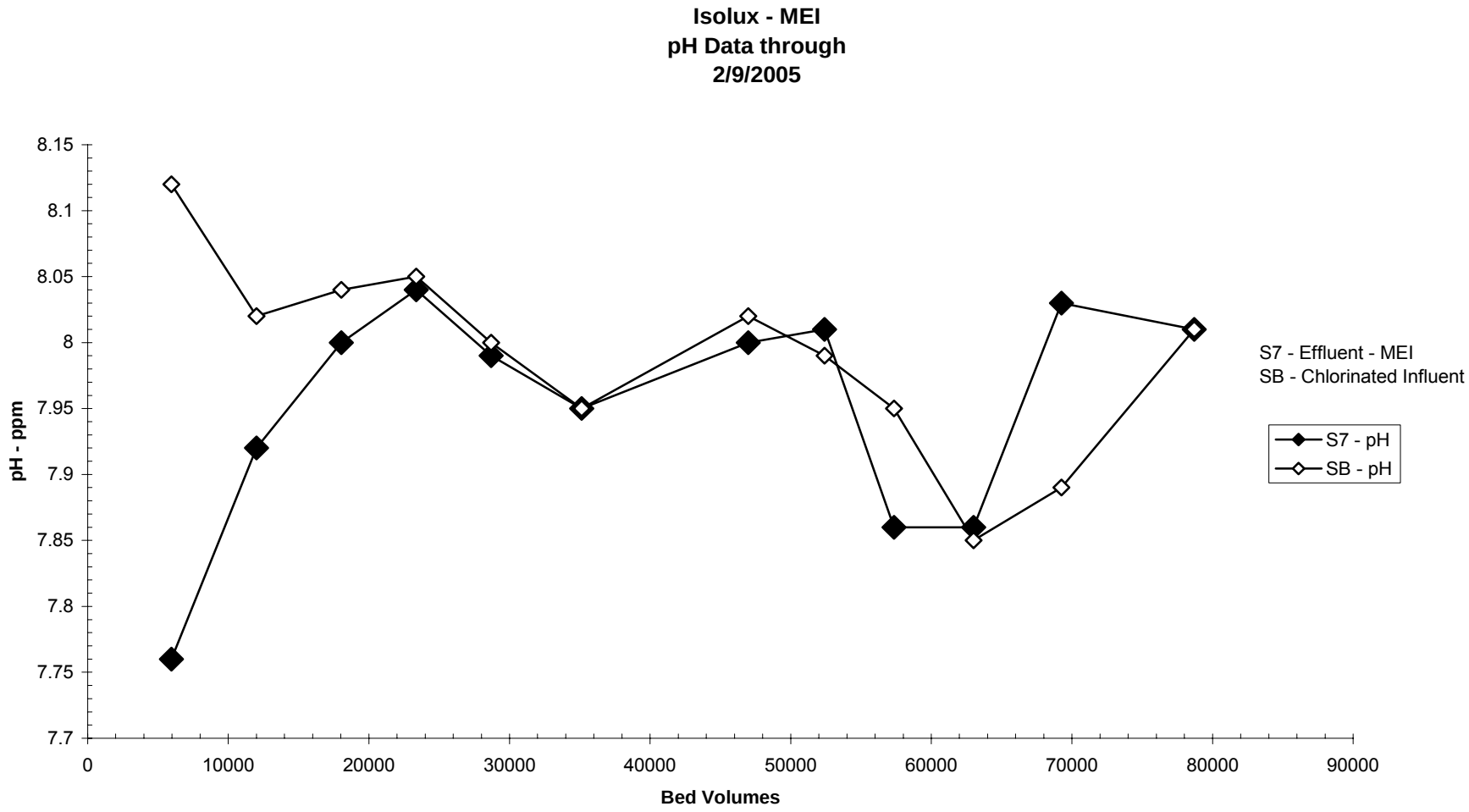
Isolux 302M is an amorphous inorganic zirconium oxide adsorption media. MEI provides the media in pre-packaged radial flow cartridges. Cartridges in series are used for higher flow rates. The table below contains specific design basis information for the Isolux columns.

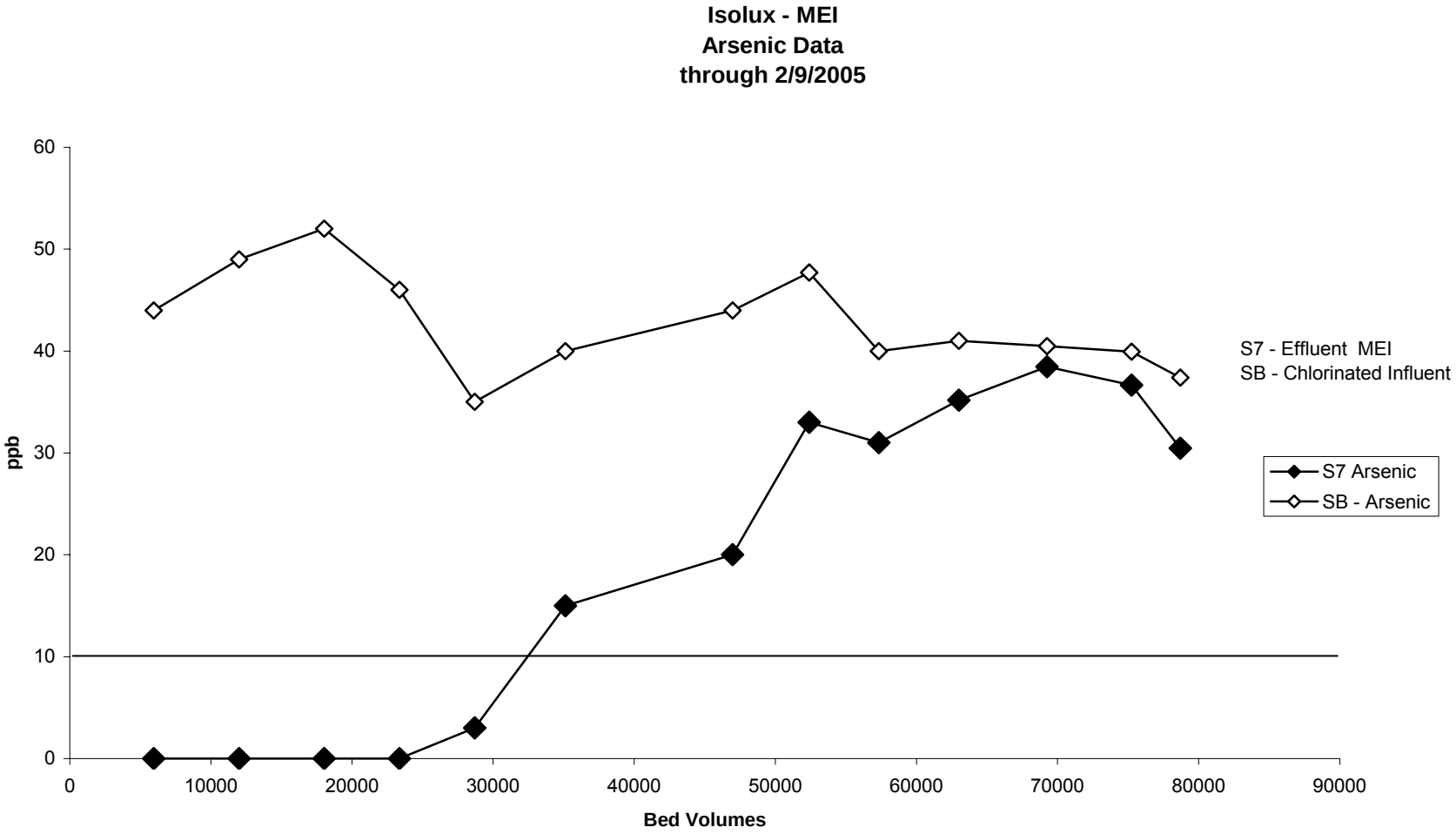
Table C-6. Isolux 302M Treatment Design and Operating Parameters

Parameter	Isolux Pilot Columns	Isolux Full Scale Systems
Bulk Density, lb/ft^3	54	54
Particle mesh size	< 400	< 400
Particle diameter, mm	0.02	0.02
Column Layers		
Distributor Configuration	Radial flow cartridge with 5 μm pre-filter	Radial flow cartridges in series with 5 μm pre-filter
Under bedding Configuration	N/A	N/A
Underbedding Height, inches	N/A	N/A
Freeboard, inches	N/A	N/A
Media Depth, inches	0.57	N/A
Media Volume, Liters	0.45	Based on cartridge dimensions
Column Diameter, inches	2.47 OD 1.5 ID	Based on cartridge dimensions
Column Height, inches	10	42
Operating Conditions		
Hydraulic Loading Rate, gpm/ft^2	1.2	Based on cartridge dimensions
EBCT, minutes	0.29	Based on cartridge dimensions
pH	7.7	Site specific
Down Flow Pressure Drop, psi	NA	NA
Maximum Differential Pressure, psi	0.3	Site specific
Flow Rate, gpm	0.5	Based on cartridge dimensions
Backwash Conditions		
Backwash Flux, gpm/ft^2	N/A	N/A
Backwash Flow Rate, gpm	N/A	N/A
Backwash Duration, minutes	N/A	N/A
Backwash Frequency (per month)	N/A	N/A

N/A = not applicable; NA = not analyzed or available


Isolux - MEI
Free Chlorine (ml/L as CL2)
Data through 2/9/2005
ppm
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
Bed Volumes
S7 - Effluent MEI
SB - Chlorinated Influent
S7 - Free Chlorine
SB - Free Chlorine


Isolux - MEI
pH Data through
2/9/2005
8.15
8.1
8.05
8
7.95
7.9
7.85
7.8
7.75
7.7
pH - ppm
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
Bed Volumes
S7 - Effluent - MEI
SB - Chlorinated Influent
S7 - pH
SB - pH


Isolux - MEI
Arsenic Data
through 2/9/2005
60
50
40
30
20
10
0
ppb
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
Bed Volumes
S7 - Effluent MEI
SB - Chlorinated Influent
S7 Arsenic
SB - Arsenic

Appendix D: Interlaboratory Comparison of Arsenic Analyses

An interlaboratory study comparing arsenic concentrations in 227 check samples measured by WQL and GEL (General Engineering Laboratories, LLC; Charleston, SC 29407) was carried out. Figure D-1 shows the correlation between the WQL and GEL analyses. The maximum difference observed was 10.2 ppb (WQL-GEL); the minimum difference was -6.5 ppb (WQL-GEL); the average difference was 1.1 ± 3.4 ppb. Evaluation of the possible effect of this bias on the shape of the breakthrough curves suggested that the uncertainty in estimates of number of BVs required to reach breakthrough at 10 ppb in the column effluents was less than 15%. This is similar to the uncertainty in the method used to estimate the breakthrough point (visual examination of the curves).

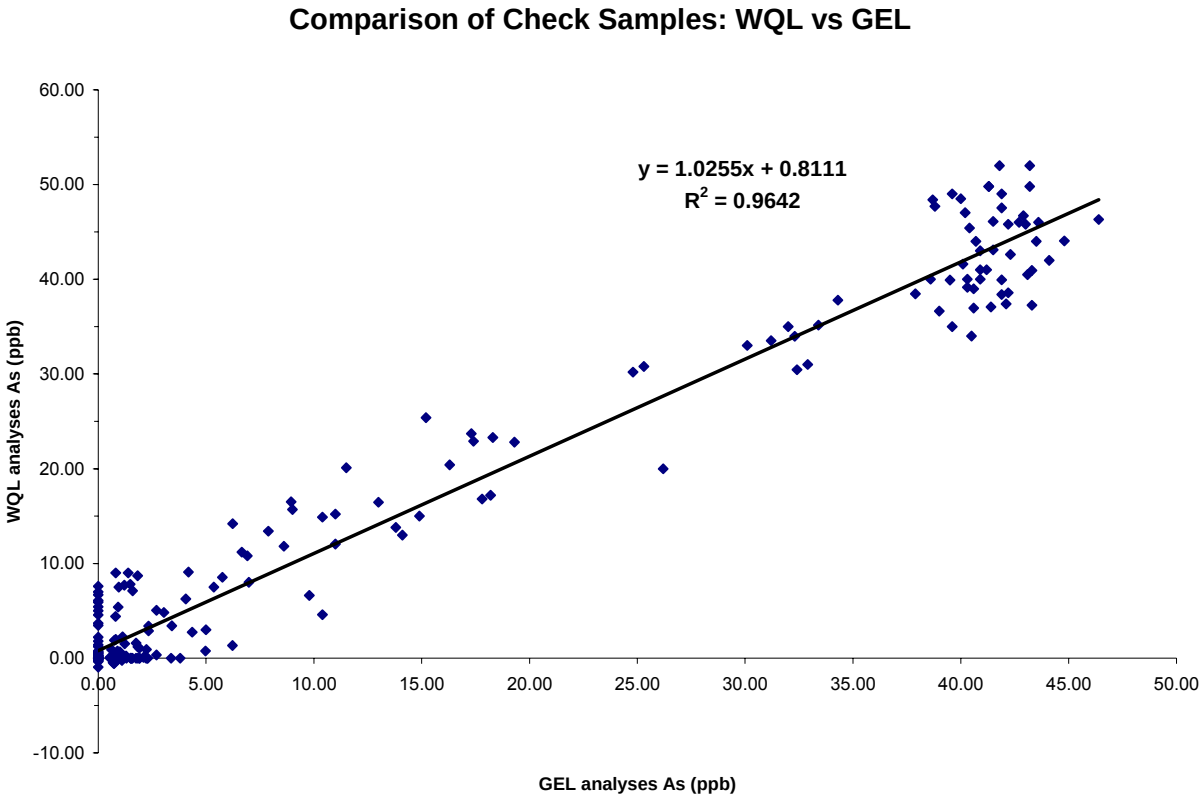


Figure D-1. Comparison of arsenic analysis results for 227 check samples by WQL and GEL.

Appendix E: Results of TCLP and CA WET tests on Spent Media

TCLP leachate results from Assaigai Laboratories, Albuquerque, NM.

instrument detection limit mg/L	IDL=.125			IDL=.125		
Maximum allowable in ppm	5.00	100.00	N/R	5.00	N/R	
Sample ID	**Arsenic**	**Barium**	**Copper**	**Lead**	**Zinc**	**PASS**
SS-ARM 200	<0.125	6.140	0.690	<0.125	0.239	**Y**
SS-AD33-1	<0.125	1.180	0.428	<0.125	0.197	**Y**
SS-AD33-2	<0.125	0.696	0.050	<0.125	0.250	**Y**
SS-AD33-3	<0.125	1.700	0.060	<0.125	0.250	**Y**
SS-Metsorb	<0.125	30.600	0.198	<0.125	0.102	**Y**
SS-ArsenX^{np}	0.146	1.730	0.319	<0.125	0.117	**Y**

TCLP results for other metals were below the TCLP limits: Cr <0.05, Hg < 0.2, Cd < 0.125, Se < 0.25, Ag < 0.125. Note: concentrations in diluted samples run in ICP-MS were below the instrumental detection limits

N/R = not regulated in TCLP

Toxicity Characteristic Leaching Procedure, leachable in mg/L (ppm); SW846 1311/3010A/6010B ICP TCLP

California WET results from Assaigai Laboratories, Albuquerque, NM

totals metals analysis results (mg/kg)
Acid digestion

Element	As mg/kg	Ba mg/kg	Cd mg/kg	Cr mg/kg	Cu mg/kg	Pb mg/kg
Sample ID						
SS-ARM 200	1660.0	592.0	35.0	51.6	525.0	27.5
SS-AD33-1	3640.0	55.6	76.0	43.7	464.0	52.0
SS-AD33-2	5590.0	33.9	33.5	37.6	10.0	10.4
SS-AD33-3	2950.0	69.5	50.8	42.3	26.6	10.6
SS-Metsorb	1.17	2260.0	2.5	3.45	44.3	4.48
SS-ArsenX^{np}	2060.0	76.6	78.8	4.65	217.0	18.3
Limit	50,000		10,000			

	Hg μg/kg	Ni mg/kg	Se mg/kg	Ag mg/kg	Zn mg/kg
SS-ARM 200	82.4	68.9	250.0	12.5	59.1
SS-AD33-1	44.5	52.6	<15000.0[a]	2.5	76
SS-AD33-2	36.0	46.1	50.0	2.5	47.4
SS-AD33-3	67.8	51.7	25.0	25.0	15.3
SS-Metsorb	14.8	8.78	5.00	2.5	11.4
SS-ArsenX^{np}	9.54	0.264	25.0	12.5	24.6
Limit	2,000		10,000		

CA Wet, solids in mg/kg; SW846 3050B/6010B ICP

[a] – below detection limit of 0.5 mg/kg with dilution of 30,000x

leachable metals analysis results (ppm)

Element	As ppm	Ba ppm	Cd ppm	Cr ppm	Cu ppm	Pb ppm
Sample ID						
SS-ARM 200	**33.600**[a]	18.600	0.647	0.792	33.800	0.574
SS-AD33-1	4.770	2.120	0.131	0.024	37.200	0.220
SS-AD33-2	1.790	1.130	0.044	0.043	0.290	0.410
SS-AD33-3	2.240	2.870	0.058	0.050	1.680	0.060
SS-Metsorb	0.694	28.800	0.019	0.050	3.690	0.051
SS-ArsenX^{np}	2.820	2.340	0.074	0.087	9.970	0.125
Limit	5.0	100	1.0	5.0	N/R	5.0

	Hg ppm	Ni ppm	Se ppm	Ag ppm	Zn ppm
SS-ARM 200	0.00106	1.440	0.500	0.250	3.190
SS-AD33-1	0.00037	0.136	0.250	0.125	4.630
SS-AD33-2	0.00092	0.285	0.250	0.125	0.233
SS-AD33-3	0.00035	0.157	0.250	0.125	0.807
SS-Metsorb	0.00012	0.234	0.250	0.125	0.996
SS-ArsenX^{np}	0.00064	0.050	0.250	0.125	0.972
Limit	0.02	N/R	1.0	5.0	N/R

CA Wet, leachable in mg/L (ppm); SW846 1311/3010A/6010B ICP TCLP

[a]- pre-production media may not reflect performance of commercial media

Distribution:

1	MS 1002	S. Roehrig, 06300
1	MS 0735	J. Merson, 06310
1	MS-0754	A. Sun, 06316
1	MS 0754	M. Aragon, 06316
1	MS 0754	A. Aragon, 06316
1	MS 0754	P. Brady, 06316
1	MS 0754	B. Dwyer, 06316
1	MS 0754	R. Everett, 06316
1	MS 0754	W. Holub, 06316
1	MS 0750	C. Kirby, 06314
1	MS 0754	R. Kottenstette, 06316
1	MS 0754	J. Krumhansl, 06316
1	MS 0754	T. Meyer, 06316
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