Electrical Resistance Heating
Technology Overview and NASA KSC Case Study
Mississippi Tier II Meeting, July 2017

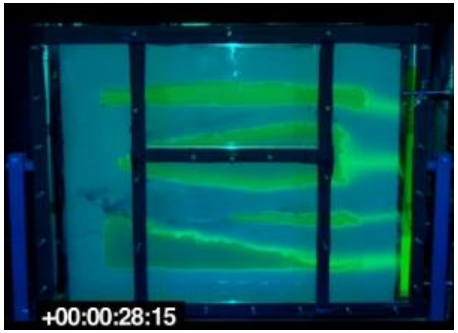
Presentation Content

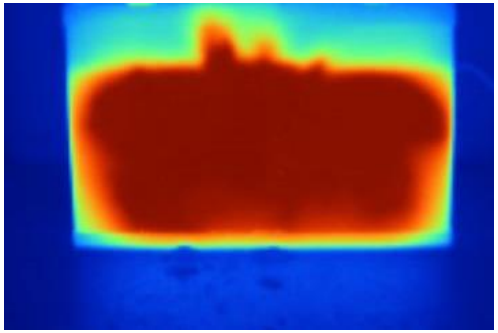
- ERH Technology Overview

- NASA Kennedy Space Center Case Study
  - Site Background
  - ERH Treatment Performance Monitoring
  - Lessons Learned
  - Path Forward

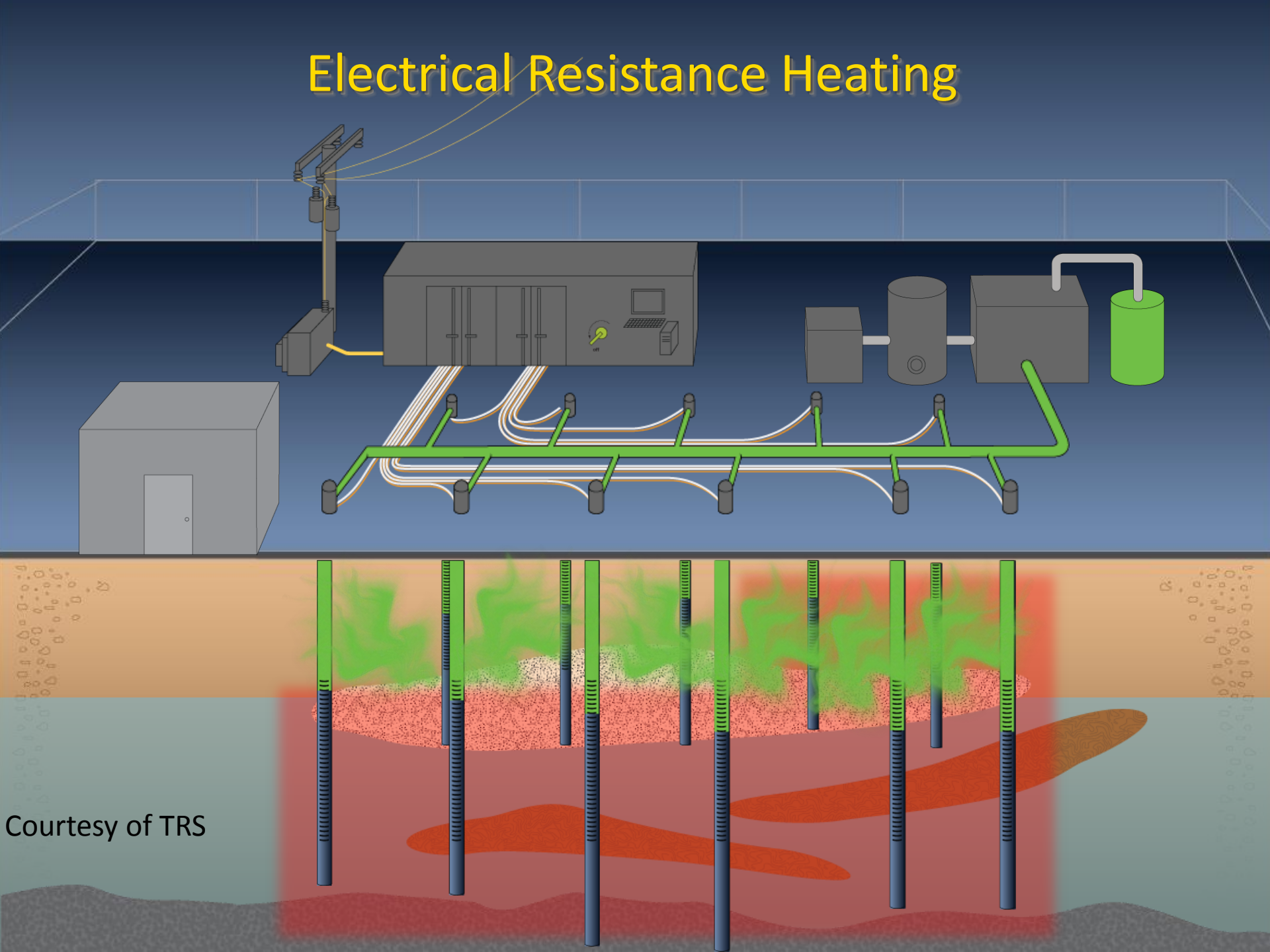
ERH Overview

- How does ERH work?
  - Electrical current passes from electrode to electrode
  - Soil resistance heats subsurface to boiling point of water/VOC mixture
  - Boiled water/VOC mixture captured through vapor recovery in vadose zone
  - Vapors and moisture in steam cooled and separated
  - Vapors treated through activated carbon or catalytic oxidation
- Effective in heterogeneous conditions and bedrock
- Addresses source zone matrix diffusion
- Dissolves natural organic material for post-ERH biotic treatment
- Can be applied at a lower intensity to enhance natural attenuation in dilute plumes or induce thermal hydrolysis



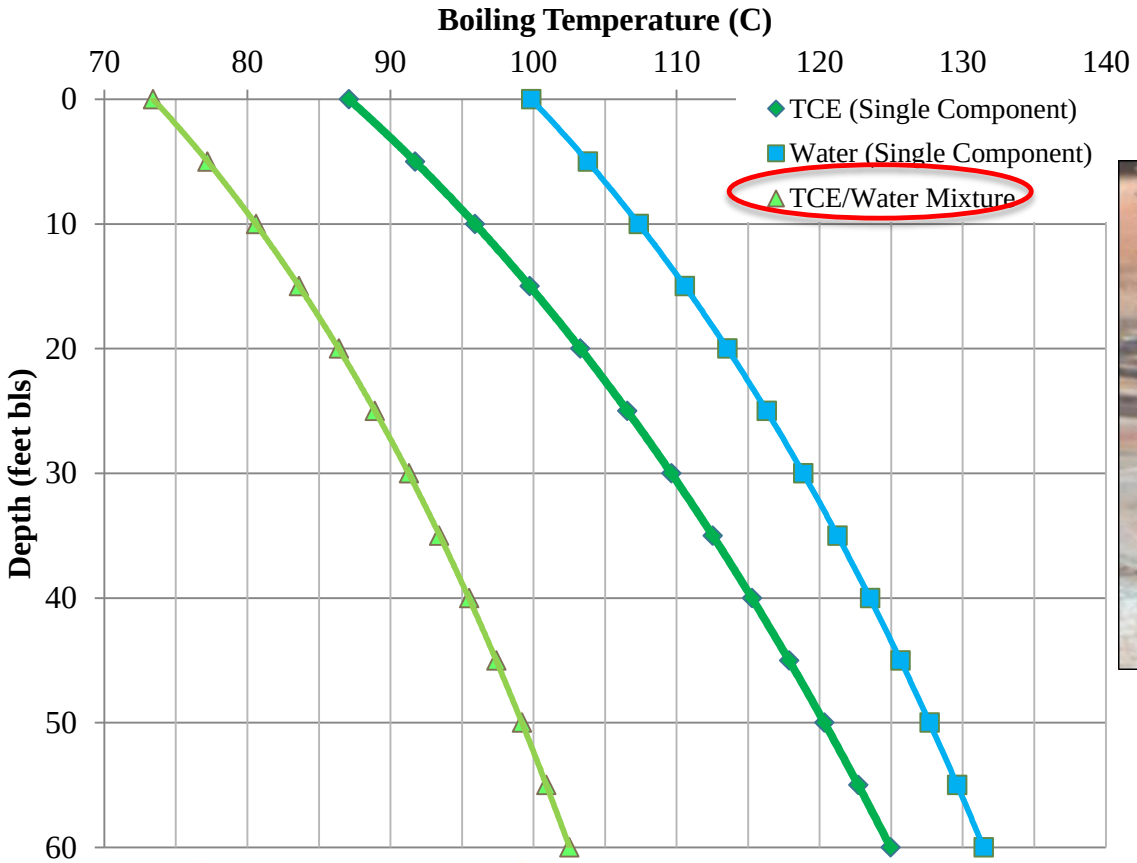


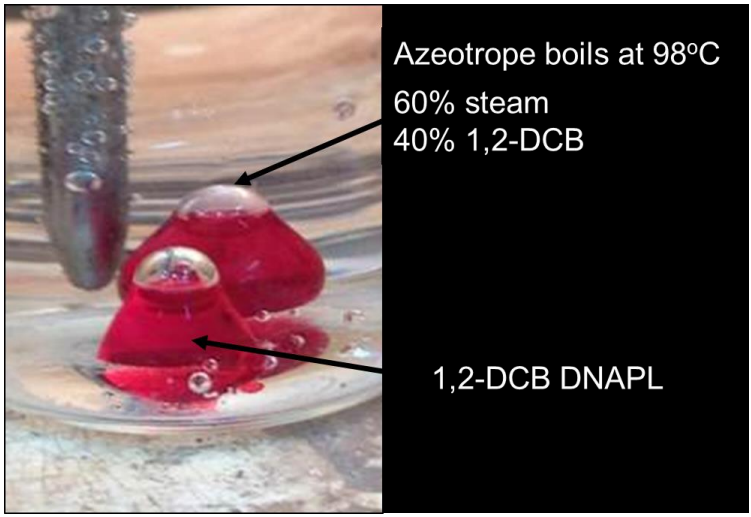
Electrical Resistance Heating



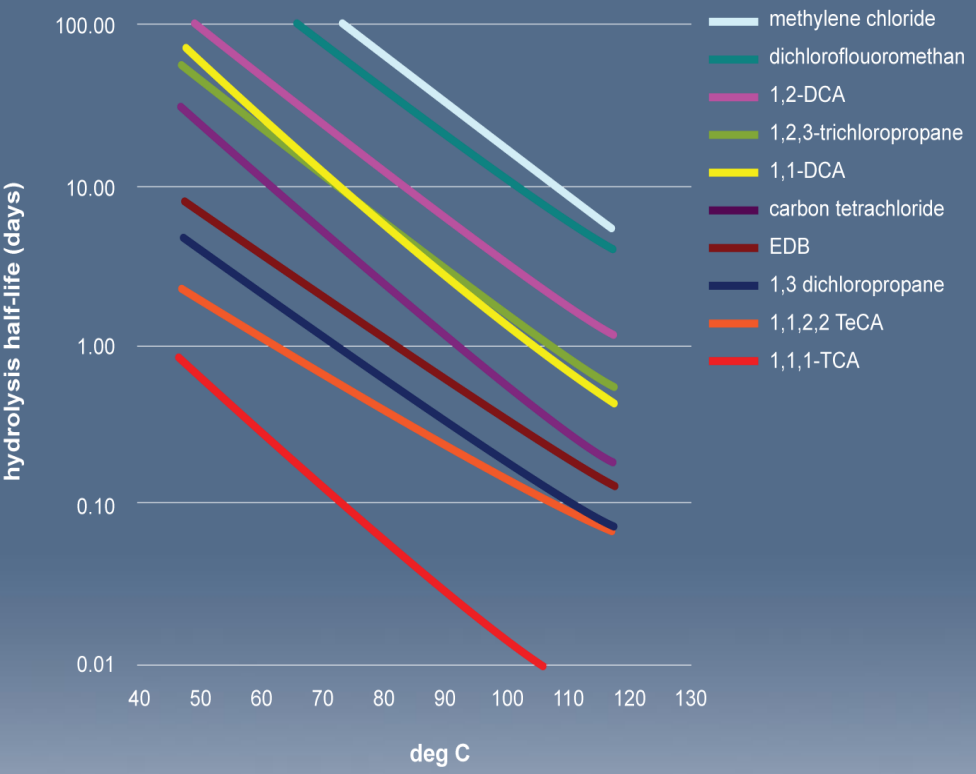
Courtesy of TRS

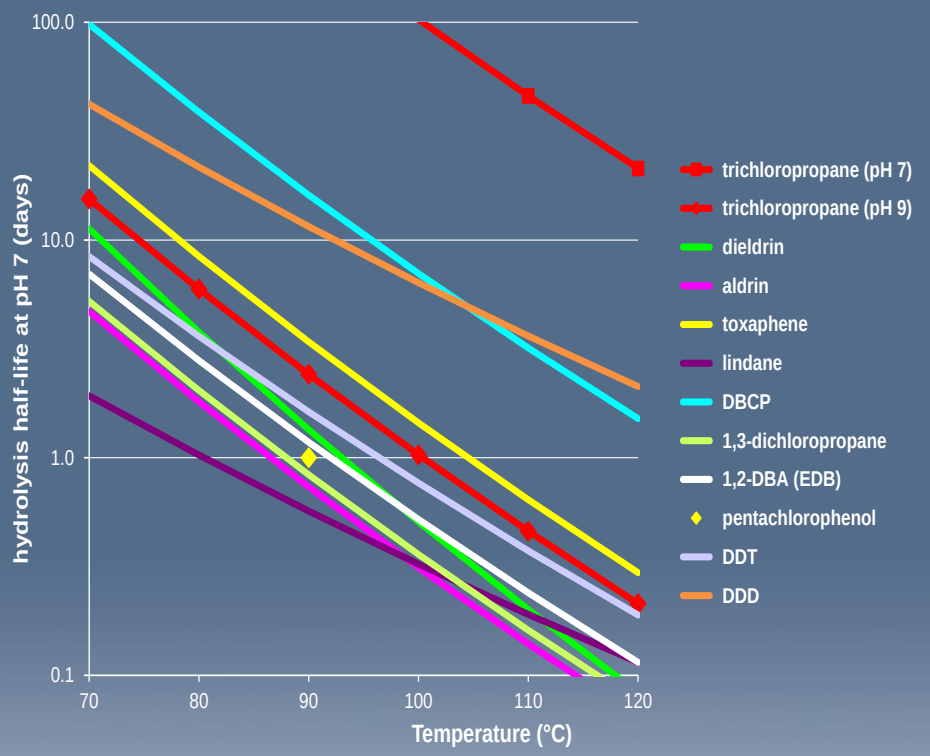
- Many VOCs form a positive heteroazeotropic mixture with water
- What is a positive heteroazeotrope?
  - a mixture where the equilibrium vapor and liquid compositions are equal at a given pressure and temperature
  - the vapor has the same composition as the liquid and the mixture boils at a temperature other than that of the pure components' boiling points (positive azeotrope = lower boiling point)





Hydrolysis of Halogenated Alkanes and Pesticides





Common ERH Misnomers

- Expensive
  - In certain settings, competitive to less costly than other source removal technologies
  - Selection of technology based on site specific evaluation
  - Cost is generally a function of volume and geometry
  - Temporal benefit of 6-9 month treatment durations
- Temperature is the goal
  - Steam production is the goal
  - Reducing mass concentrations is the goal

- Electrical conductivity of matrix matters
  - ERH equipment has large dynamic range across many conductivities
- Water is problematic
  - Water (or moisture) conducts electricity
- Vadose zone is challenging
  - Originally developed for the vadose zone
- Only for VOCs
  - Can treat compounds such as chlorinated compounds, pesticides, and energetic compounds

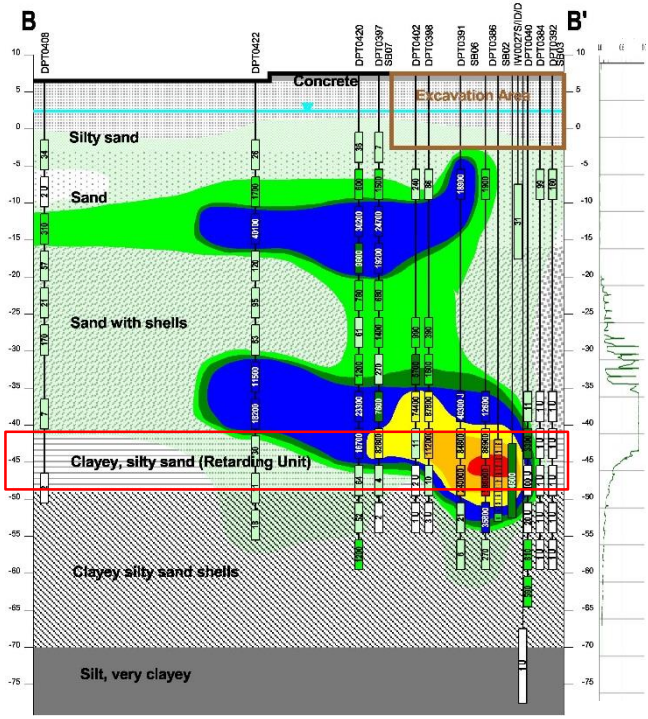
Site Background

- Site: NASA Kennedy Space Center, Components Cleaning Facility
- Area developed in 1962 for cleaning and refurbishment of hardware and an associated analytical laboratory
- Designated Solid Waste Management Unit 030
- Currently site is vacant (buildings demolished ~2006)
- Groundwater plume co-mingled with Area South of K7-0526, SMWU 100
- Located northeast of intersection of Crawler Parkway and Fluid Servicing Road

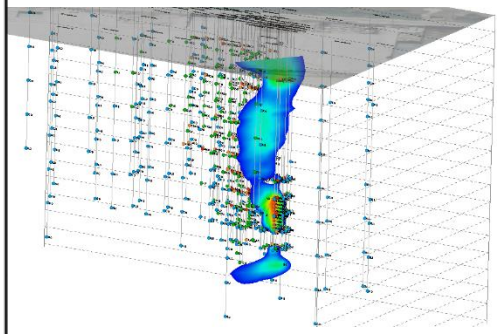
Components Cleaning Facility (1990)

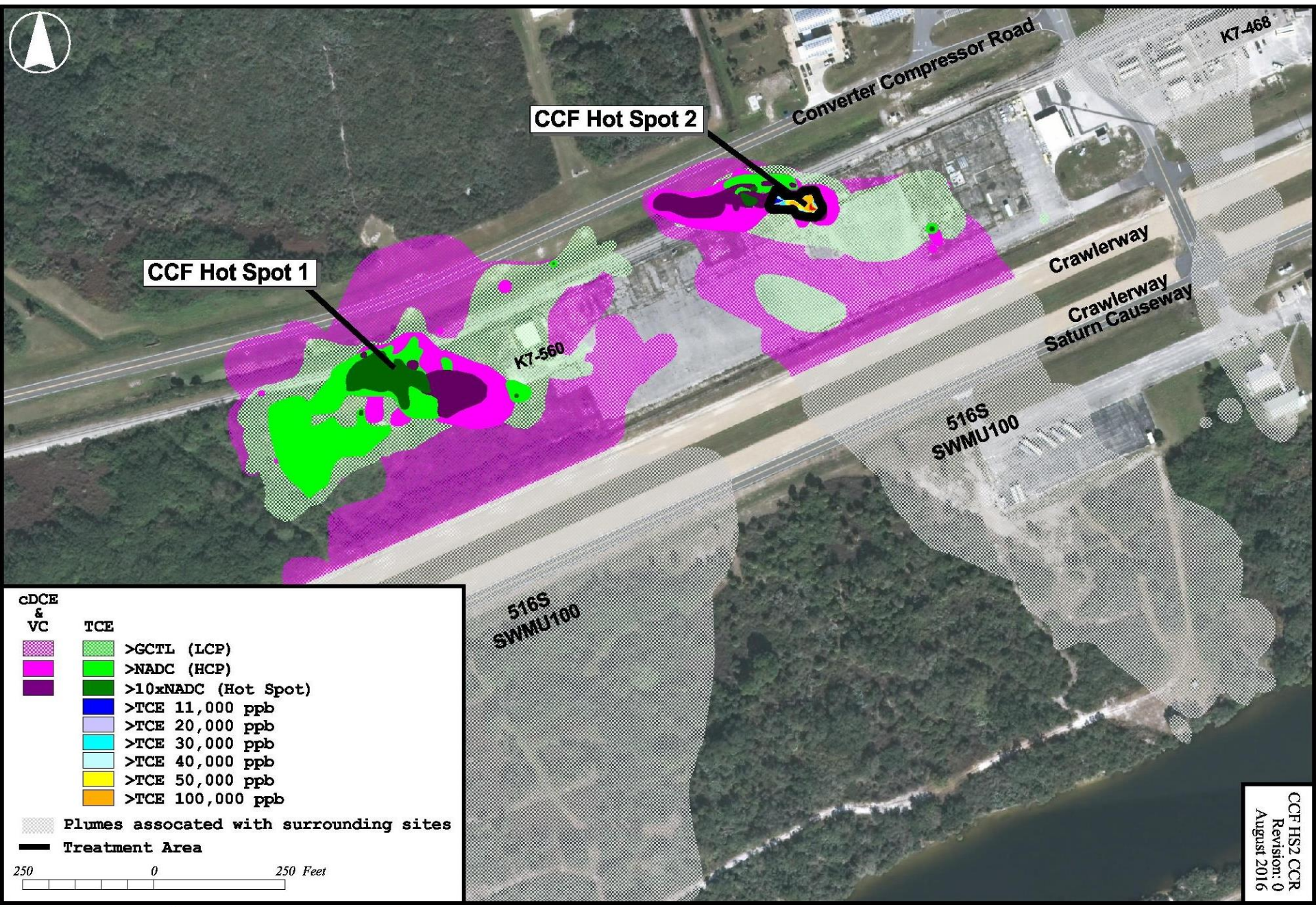
HS2 Site Characterization

- Source zone site characterization:
  - Source zone definition of ~1% TCE solubility (11 mg/L)
  - Investigated by DPT sampling with on-site mobile lab
  - General 10’ source zone DPT spacing
  - 5’ vertical spacing
    - Selective 1’ intervals in semi-confining unit
  - Membrane interface probe borings
- Semi-confining, fine-grained unit from 49 to 61 feet bls
  - 76% of TCE HS mass within fine-grained unit
    - Conceptual model “Storage” or back-diffusion layer
  - 23% of TCE HS mass 10’ above fine-grained unit
    - Conceptual model advective layer

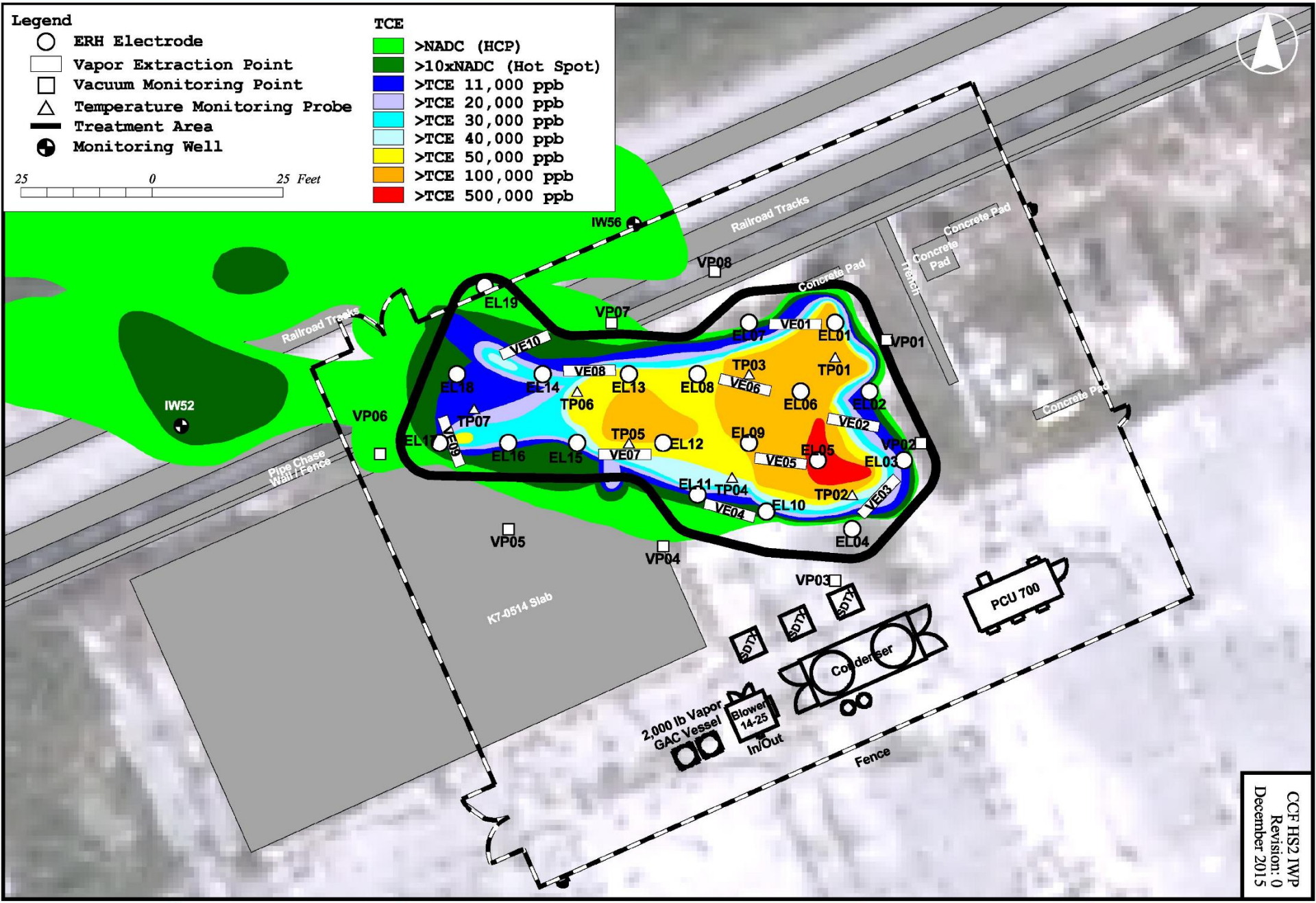


Interval (ft bls)	TCE Dissolved (lb)	TCE Sorbed (lb)	TCE Total (lb)		cDCE Dissolved (lb)	cDCE Sorbed (lb)	cDCE Total (lb)		VC Dissolved (lb)	VC Sorbed (lb)	VC Total (lb)	
0 - 10	0.6	1.1	1.8	0%	1.0	0.8	1.8	3%	0.2	0.1	0.3	2%
10 - 20	2.3	4.2	6.5	0%	4.4	3.4	7.7	12%	1.8	0.5	2.3	11%
20 - 30	0.6	1.1	1.7	0%	3.7	2.8	6.5	10%	2.7	0.8	3.5	17%
30 - 40	1.7	3.1	4.7	0%	5.7	4.4	10.1	16%	2.9	0.9	3.8	19%
40 - 50	97.7	282.8	380.5	23%	9.8	11.9	21.7	35%	3.9	1.8	5.7	28%
50 - 60	129.0	1106.3	1235.2	76%	3.2	11.4	14.5	23%	2.1	2.8	4.9	24%
>60	0.0	0.1	0.2	0%	0.0	0.0	0.1	0%	0.0	0.0	0.0	0%
Totals:	232	1399	1631		28	35	62		14	7	20	





CCF Plume Overview (Pre-IM, 2015)


Legend
ERH Electrode
Vapor Extraction Point
Vacuum Monitoring Point
Temperature Monitoring Probe
Treatment Area
Monitoring Well
25 0 25 Feet
TCE
>NADC (HCP)
>10xNADC (Hot Spot)
>TCE 11,000 ppb
>TCE 20,000 ppb
>TCE 30,000 ppb
>TCE 40,000 ppb
>TCE 50,000 ppb
>TCE 100,000 ppb
>TCE 500,000 ppb
IW56
IW52
VP01
VP02
VP03
VP04
VP05
VP06
VP07
VP08
EL01
EL02
EL03
EL04
EL05
EL06
EL07
EL08
EL09
EL10
EL11
EL12
EL13
EL14
EL15
EL16
EL17
EL18
EL19
VE01
VE02
VE03
VE04
VE05
VE06
VE07
VE08
VE09
VE10
TP01
TP02
TP03
TP04
TP05
TP06
TP07
Railroad Tracks
Railroad Tracks
Concrete Pad
Concrete Pad
Concrete Pad
Trench
Concrete Pad
Pipe Chase Wall / Fence
K7-0514 Slab
PCU 700
Condenser
2,000 lb Vapor GAC Vessel
Blower 14-25 In/Out
SDTV
SDTV
SDTV
Fence
CCF HS2 IWP
Revision: 0
December 2015

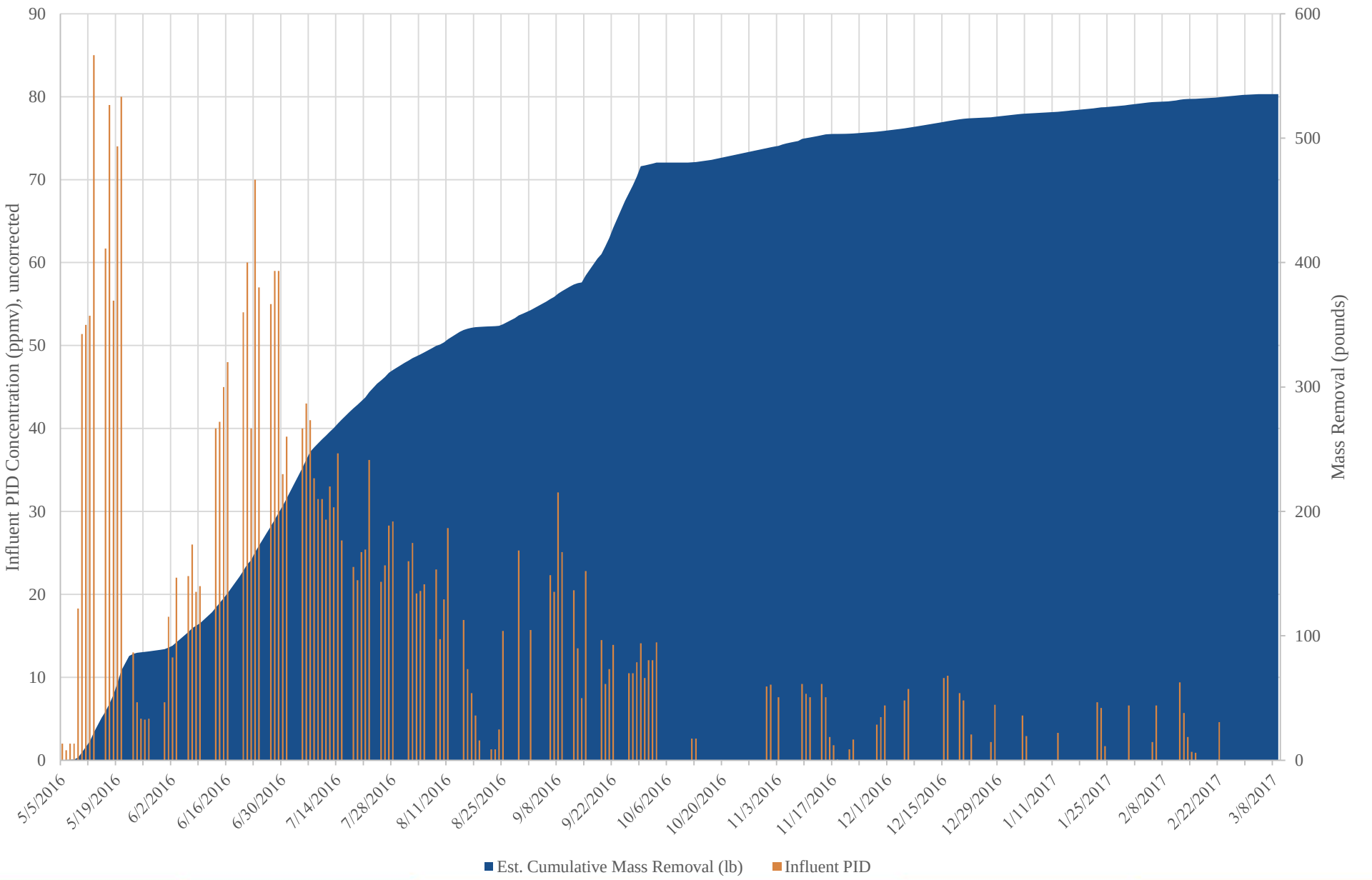
ERH Layout

IM Components

Quantity	Component
19	Vertically-bored electrodes (3 elements per electrode)
10	Horizontal vapor extraction (VE) points
7	Temperature monitoring points (TMPs)
8	Vapor monitoring probes (VMPs)
1	700-kW power control unit (PCU)
1	Condenser and cooling tower skid
1	Vapor recovery blower skid
3	2,000 lb. Vapor-phase granular activated carbon (VPGAC) units
2	400 lb. Liquid-phase granular activated carbon (LPGAC) units
	Electrode field vapor cover
	Motion sensing and security camera system
	Vinyl coated perimeter fencing
	Electrical and potable water utilities

IM Timeline

- November 2015: Pre-mobilization Activities
- December 2015: Mobilization Activities
- January to April 2016: IM Installation
- May 2016: Commissioning and Startup
- May 2016 to February 2017: OM&M
- March to April 2017: Demobilization



Influent Concentrations and Mass Removal

KSC77

Field Temperatures

B3		C3		D4		E3		F3		F4		G4	
5 ft	99.1 °C	5 ft	102.7 °C	5 ft	99.0 °C	5 ft	98.5 °C	5 ft	99.7 °C	5 ft	98.2 °C	5 ft	99.9 °C
10 ft	102.9 °C	10 ft	106.6 °C	10 ft	105.8 °C	10 ft	103.1 °C	10 ft	106.5 °C	10 ft	102.7 °C	10 ft	104.0 °C
15 ft	107.8 °C	15 ft	109.2 °C	15 ft	110.5 °C	15 ft	108.9 °C	15 ft	109.2 °C	15 ft	104.5 °C	15 ft	106.6 °C
20 ft	110.0 °C	20 ft	110.2 °C	20 ft	110.7 °C	20 ft	112.9 °C	20 ft	112.2 °C	20 ft	114.0 °C	20 ft	111.1 °C
25 ft	112.3 °C	25 ft	111.6 °C	25 ft	114.3 °C	25 ft	115.1 °C	25 ft	116.4 °C	25 ft	114.5 °C	25 ft	113.7 °C
30 ft	115.5 °C	30 ft	115.5 °C	30 ft	114.9 °C	30 ft	117.7 °C	30 ft	118.4 °C	30 ft	118.3 °C	30 ft	107.2 °C
35 ft	112.0 °C	35 ft	119.0 °C	35 ft	115.5 °C	35 ft	119.4 °C	35 ft	118.8 °C	35 ft	117.2 °C	35 ft	117.6 °C
40 ft	118.9 °C	40 ft	121.0 °C	40 ft	101.3 °C	40 ft	122.3 °C	40 ft	122.8 °C	40 ft	122.1 °C	40 ft	111.6 °C
45 ft	122.7 °C	45 ft	124.0 °C	45 ft	119.8 °C	45 ft	123.0 °C	45 ft	125.6 °C	45 ft	122.7 °C	45 ft	120.7 °C
50 ft	125.7 °C	50 ft	126.6 °C	50 ft	126.8 °C	50 ft	125.1 °C	50 ft	127.5 °C	50 ft	126.8 °C	50 ft	126.7 °C
55 ft	128.2 °C	55 ft	128.5 °C	55 ft	122.0 °C	55 ft	128.7 °C	55 ft	129.7 °C	55 ft	126.8 °C	55 ft	124.5 °C
60 ft	130.5 °C	60 ft	129.3 °C	60 ft	125.4 °C	60 ft	119.1 °C	60 ft	122.7 °C	60 ft	128.2 °C	60 ft	128.9 °C

PCU

Main Contactor
(Green = Open) (Red = Closed)

Total Uptime: 1445 Hours

Electrode Voltage: 127 VAC

Electrode Total Power: 780 kW

Field Data:

Field Vacuum: -2.00 PSIa

Manifold Temp "Condenser IN": 80.6°C

Manifold Temp "Condenser OUT": 36.6°C

Blower OUT Data:

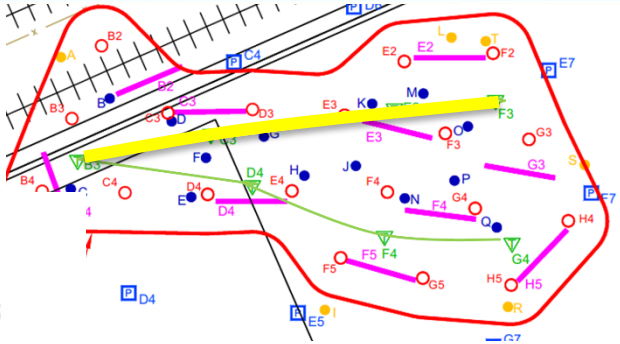
Manifold Temp: 64.6°C

Manifold Pressure: 2.756 "WC

Humidity: 34.6 %R.H.

Air Flow: 336. SCFM

Temperature Monitoring Data



5/5/2016

B3 C3 E3 F3

Temperature Data Video

-5 -10 -15 -20 -25 -30 -35 -40 -45 -50 -55 -60

Depth (feet bls)

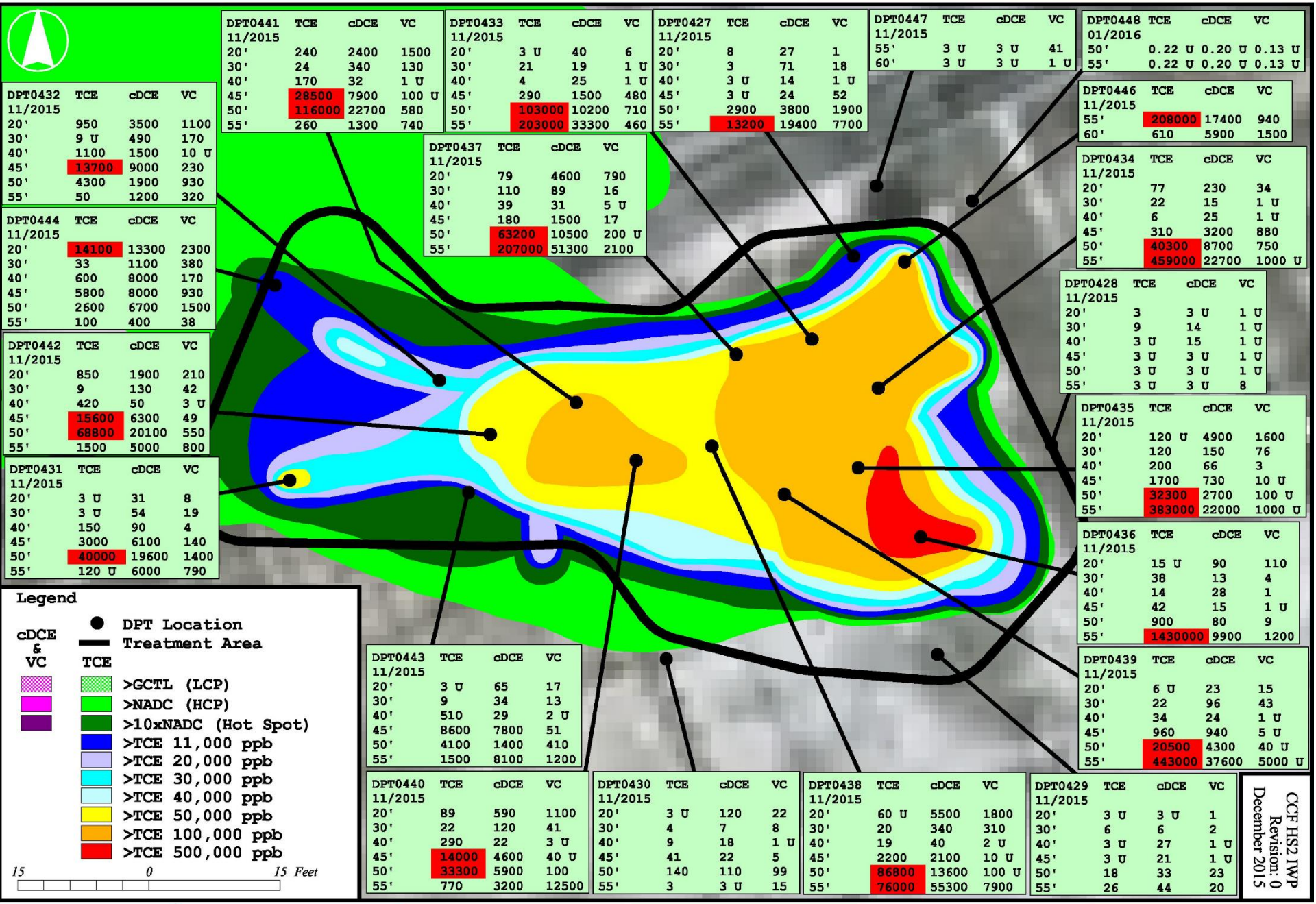
Temperature (C):

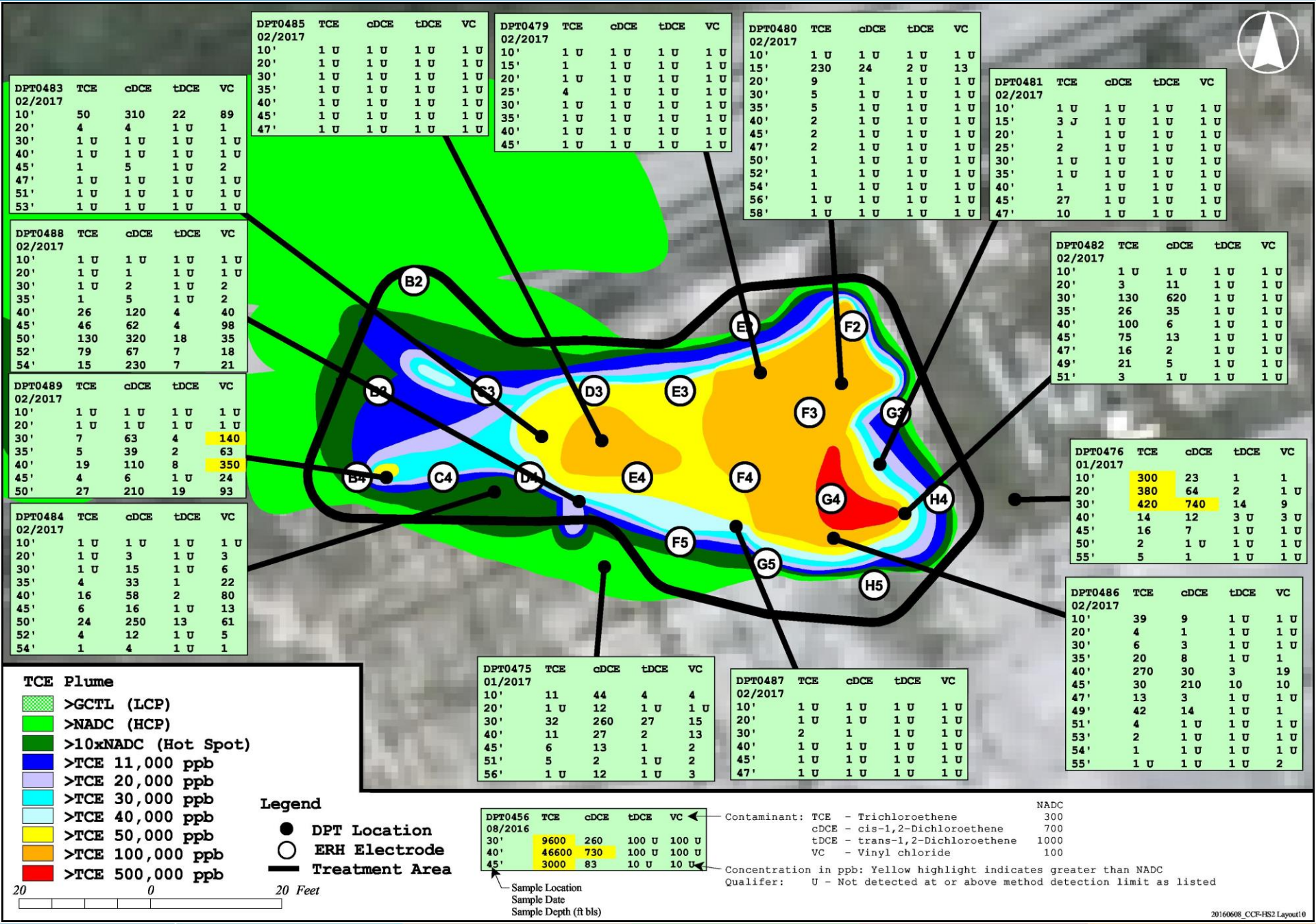
20-30 30-40 40-50 50-60 60-70 70-80 80-90 90-100 100-110 110-120 120-130 130-140

Note: Horizontal TMP distances not scaled.

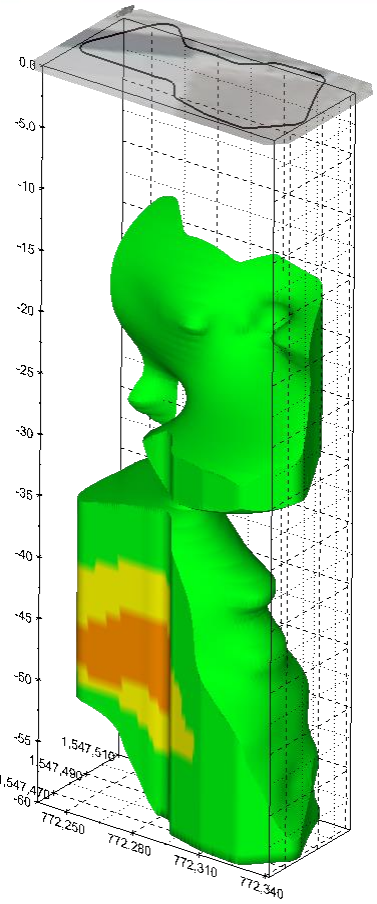
Performance Monitoring

- Hot sampling techniques utilized
  - Stainless steel cooling coil in ice bath for sample cooling
  - Artesian conditions due to the difference in formation pressure/temperature at depth; traditional DPT methods were not used
  - Waterloo profiler with adaptive sample approach (focused sampling in 1’ increments)
- 3-man drill crew allowed resting and engineering controls to manage heat stress
- Sampling intervals and optimized based on data from round to round

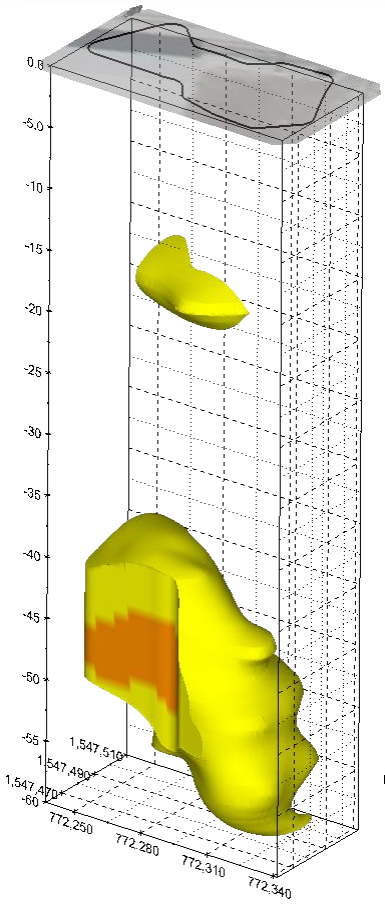

DPT0441 TCE cDCE VC
11/2015
20' 240 2400 1500
30' 24 340 130
40' 170 32 1 U
45' 28500 7900 100 U
50' 116000 22700 580
55' 260 1300 740
DPT0433 TCE cDCE VC
11/2015
20' 3 U 40 6
30' 21 19 1 U
40' 4 25 1 U
45' 290 1500 480
50' 103000 10200 710
55' 203000 33300 460
DPT0427 TCE cDCE VC
11/2015
20' 8 27 1
30' 3 71 18
40' 3 U 14 1 U
45' 3 U 24 52
50' 2900 3800 1900
55' 13200 19400 7700
DPT0447 TCE cDCE VC
11/2015
55' 3 U 3 U 41
60' 3 U 3 U 1 U
DPT0448 TCE cDCE VC
01/2016
50' 0.22 U 0.20 U 0.13 U
55' 0.22 U 0.20 U 0.13 U
DPT0432 TCE cDCE VC
11/2015
20' 950 3500 1100
30' 9 U 490 170
40' 1100 1500 10 U
45' 13700 9000 230
50' 4300 1900 930
55' 50 1200 320
DPT0437 TCE cDCE VC
11/2015
20' 79 4600 790
30' 110 89 16
40' 39 31 5 U
45' 180 1500 17
50' 63200 10500 200 U
55' 207000 51300 2100
DPT0446 TCE cDCE VC
11/2015
55' 208000 17400 940
60' 610 5900 1500
DPT0434 TCE cDCE VC
11/2015
20' 77 230 34
30' 22 15 1 U
40' 6 25 1 U
45' 310 3200 880
50' 40300 8700 750
55' 459000 22700 1000 U
DPT0444 TCE cDCE VC
11/2015
20' 14100 13300 2300
30' 33 1100 380
40' 600 8000 170
45' 5800 8000 930
50' 2600 6700 1500
55' 100 400 38
DPT0428 TCE cDCE VC
11/2015
20' 3 3 U 1 U
30' 9 14 1 U
40' 3 U 15 1 U
45' 3 U 3 U 1 U
50' 3 U 3 U 1 U
55' 3 U 3 U 8
DPT0442 TCE cDCE VC
11/2015
20' 850 1900 210
30' 9 130 42
40' 420 50 3 U
45' 15600 6300 49
50' 68800 20100 550
55' 1500 5000 800
DPT0435 TCE cDCE VC
11/2015
20' 120 U 4900 1600
30' 120 150 76
40' 200 66 3
45' 1700 730 10 U
50' 32300 2700 100 U
55' 383000 22000 1000 U
DPT0431 TCE cDCE VC
11/2015
20' 3 U 31 8
30' 3 U 54 19
40' 150 90 4
45' 3000 6100 140
50' 40000 19600 1400
55' 120 U 6000 790
DPT0436 TCE cDCE VC
11/2015
20' 15 U 90 110
30' 38 13 4
40' 14 28 1
45' 42 15 1 U
50' 900 80 9
55' 1430000 9900 1200
Legend
cDCE & VC
TCE
DPT Location
Treatment Area
>GCTL (LCP)
>NADC (HCP)
>10xNADC (Hot Spot)
>TCE 11,000 ppb
>TCE 20,000 ppb
>TCE 30,000 ppb
>TCE 40,000 ppb
>TCE 50,000 ppb
>TCE 100,000 ppb
>TCE 500,000 ppb
15 0 15 Feet
DPT0443 TCE cDCE VC
11/2015
20' 3 U 65 17
30' 9 34 13
40' 510 29 2 U
45' 8600 7800 51
50' 4100 1400 410
55' 1500 8100 1200
DPT0439 TCE cDCE VC
11/2015
20' 6 U 23 15
30' 22 96 43
40' 34 24 1 U
45' 960 940 5 U
50' 20500 4300 40 U
55' 443000 37600 5000 U
DPT0440 TCE cDCE VC
11/2015
20' 89 590 1100
30' 22 120 41
40' 290 22 3 U
45' 14000 4600 40 U
50' 33300 5900 100
55' 770 3200 12500
DPT0430 TCE cDCE VC
11/2015
20' 3 U 120 22
30' 4 7 8
40' 9 18 1 U
45' 41 22 5
50' 140 110 99
55' 3 3 U 15
DPT0438 TCE cDCE VC
11/2015
20' 60 U 5500 1800
30' 20 340 310
40' 19 40 2 U
45' 2200 2100 10 U
50' 86800 13600 100 U
55' 76000 55300 7900
DPT0429 TCE cDCE VC
11/2015
20' 3 U 3 U 1
30' 6 6 2
40' 3 U 27 1 U
45' 3 U 21 1 U
50' 18 33 23
55' 26 44 20
CCF HS2 IWP
Revision: 0
December 2015



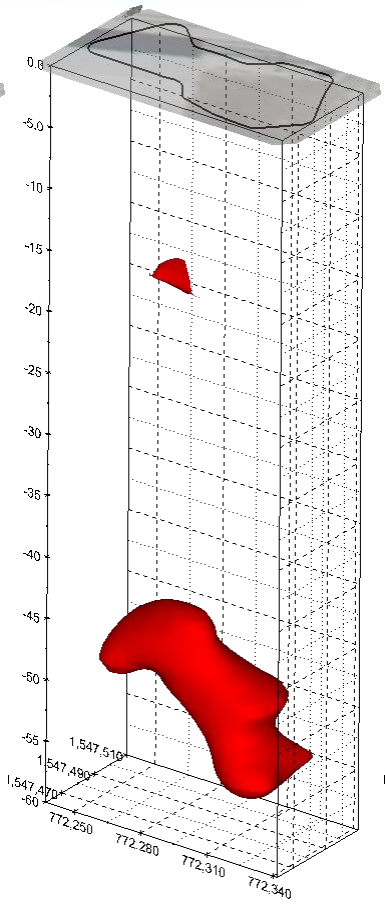
Treatment Confirmation Results



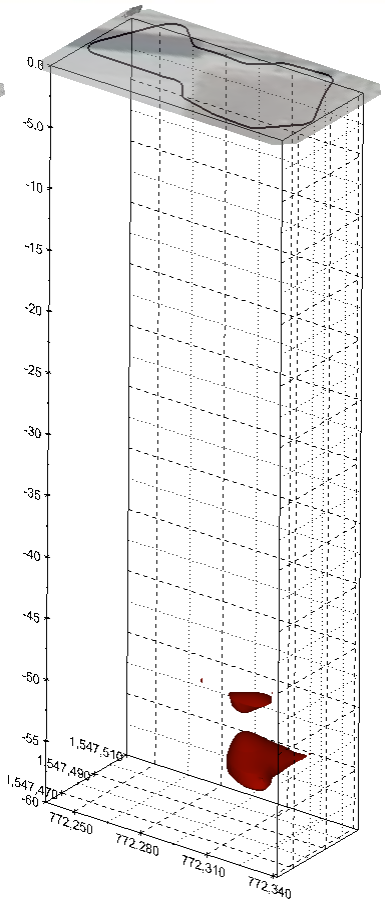
TCE (11/2015): 3 ug/L



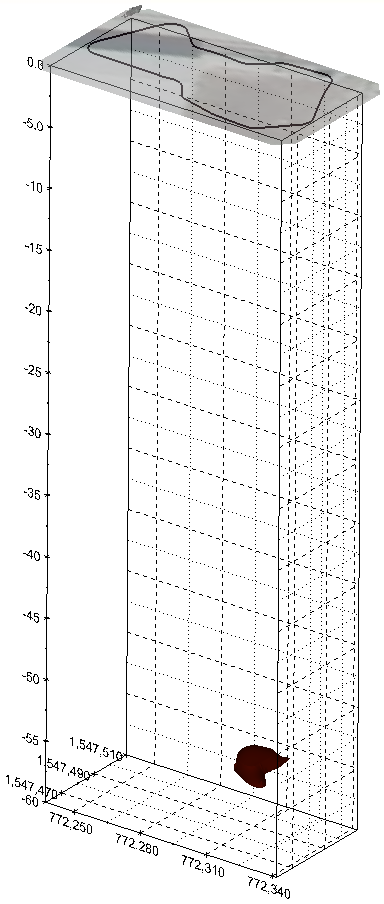
TCE (11/2015): 300 ug/L



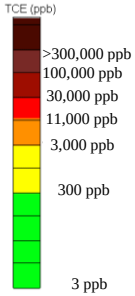
TCE (11/2015): 11,000 ug/L



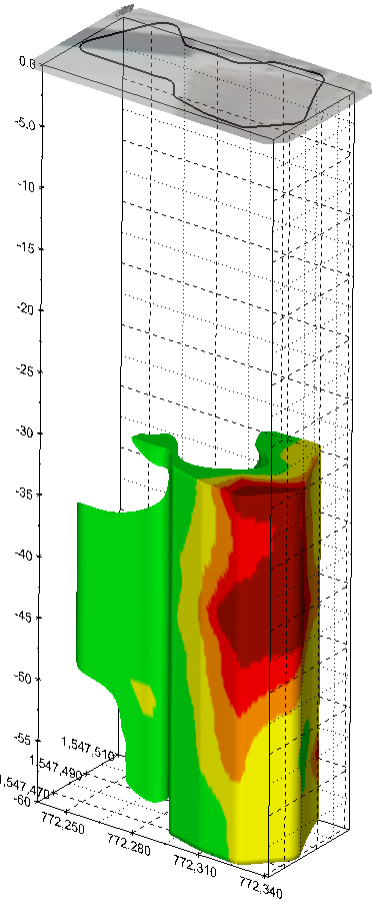
TCE (11/2015): 100,000 ug/L



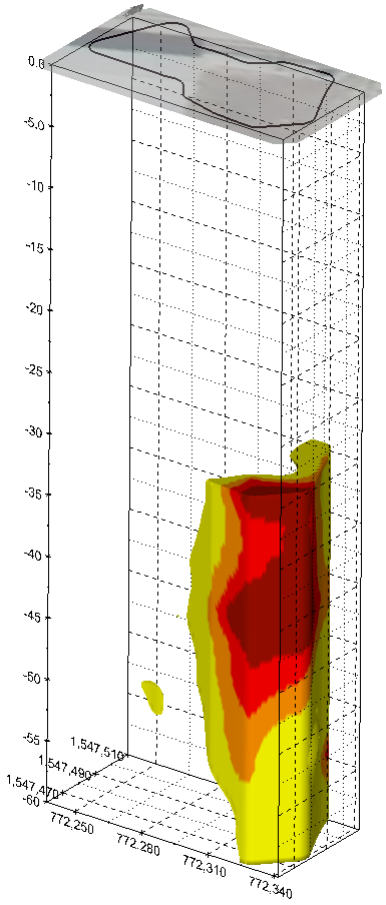
TCE (11/2015): 300,000 ug/L



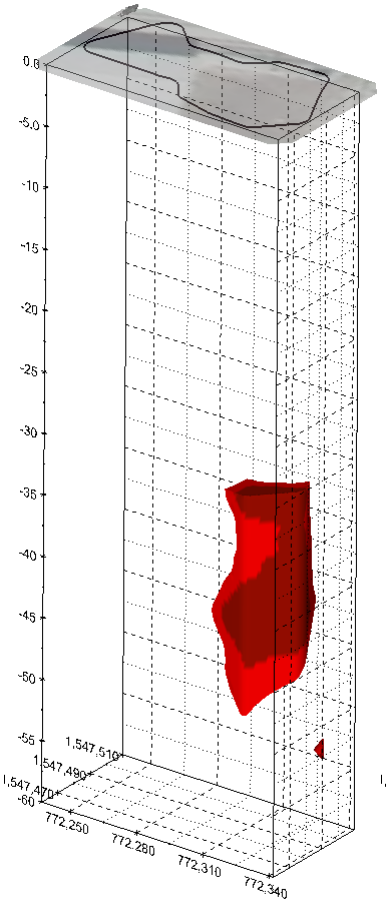
TCE EVS Plumes, Baseline



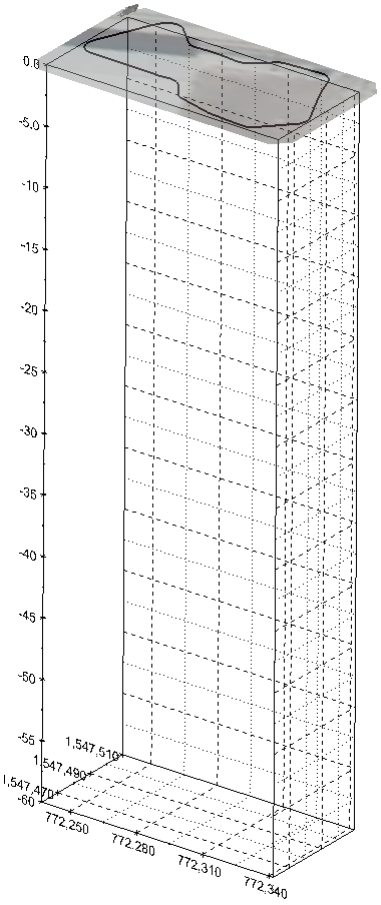
TCE (08/2016): 3 ug/L



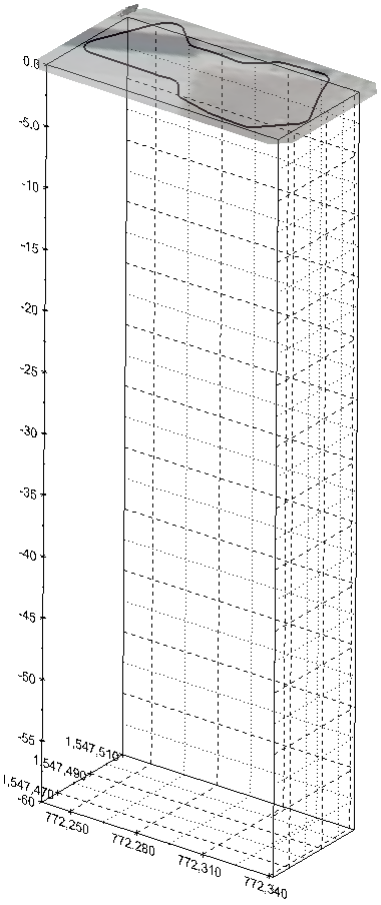
TCE (08/2016): 300 ug/L



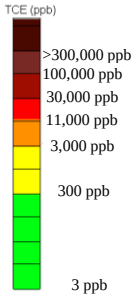
TCE (08/2016): 11,000 ug/L



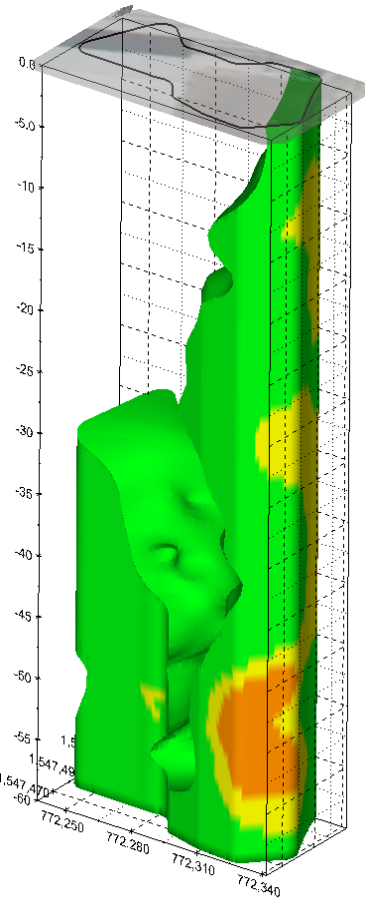
TCE (08/2016): 100,000 ug/L



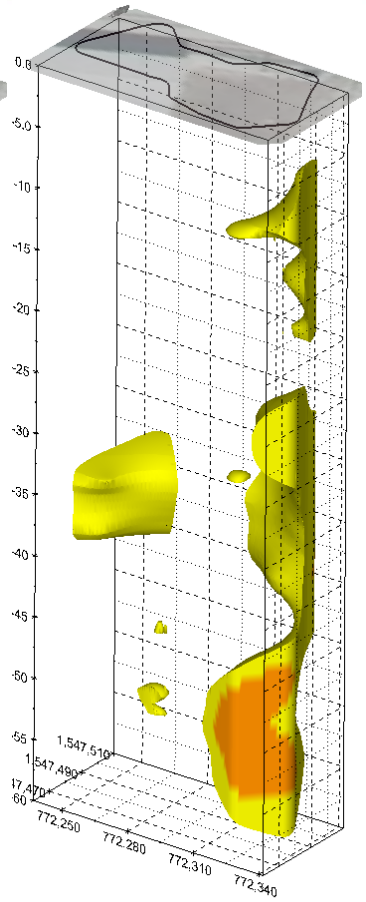
TCE (08/2016): 300,000 ug/L



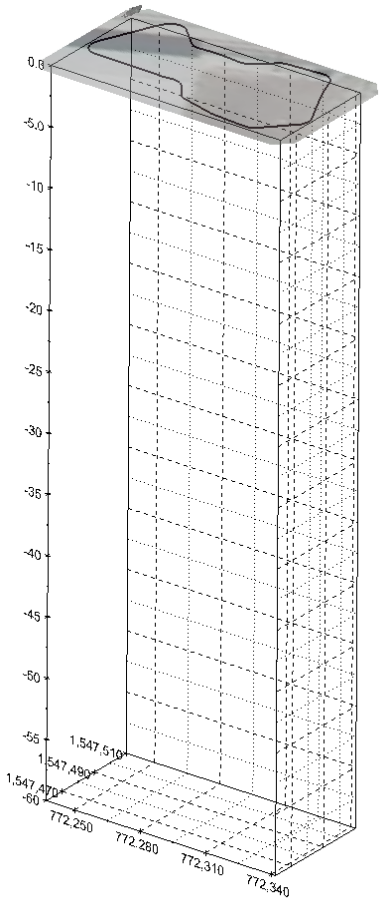
TCE EVS Plumes, August 2016



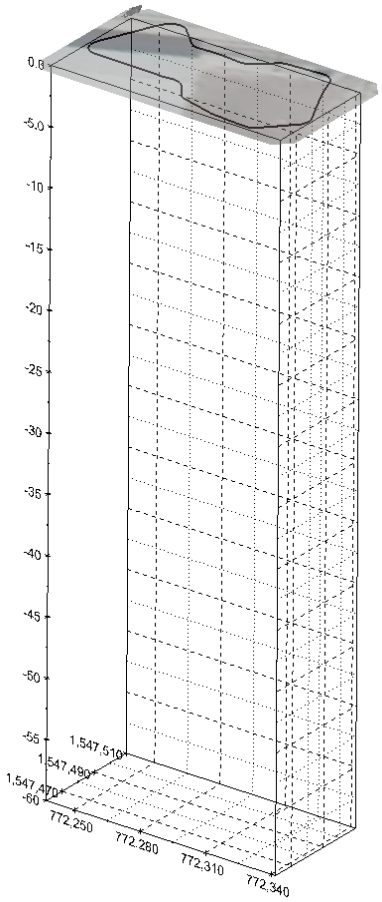
TCE (11/2016): 3 ug/L



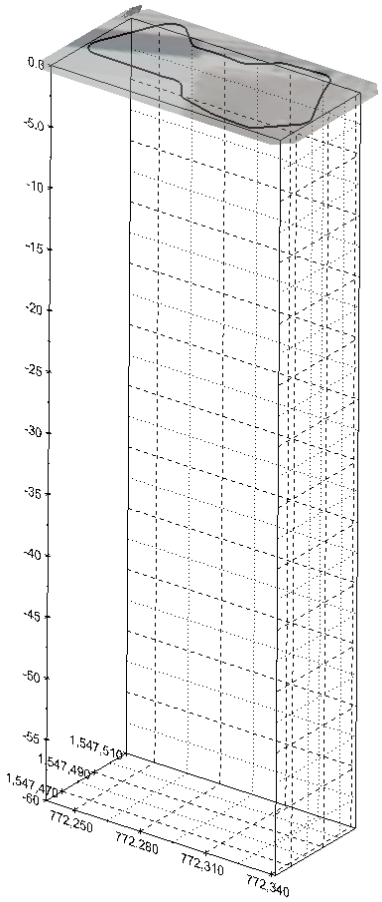
TCE (11/2016): 300 ug/L



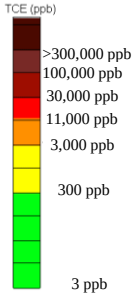
TCE (11/2016): 11,000 ug/L



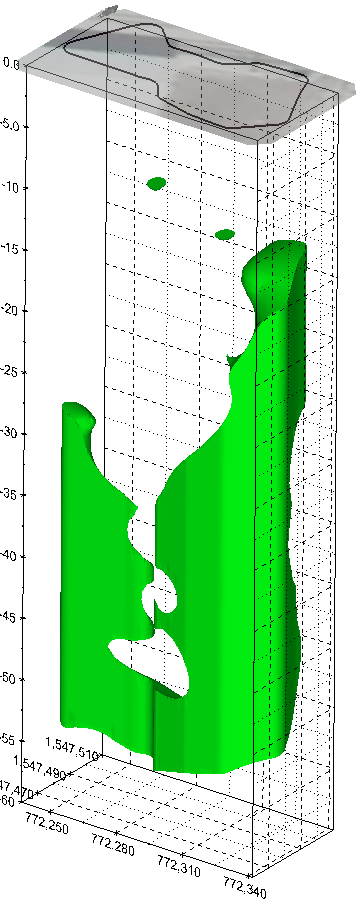
TCE (11/2016): 100,000 ug/L



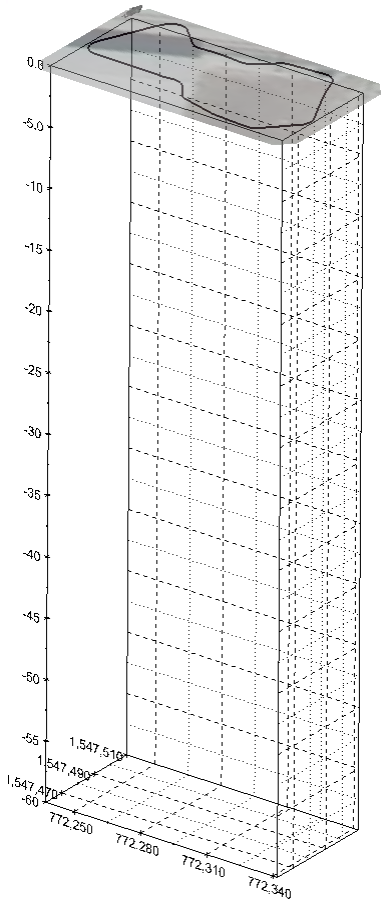
TCE (11/2016): 300,000 ug/L



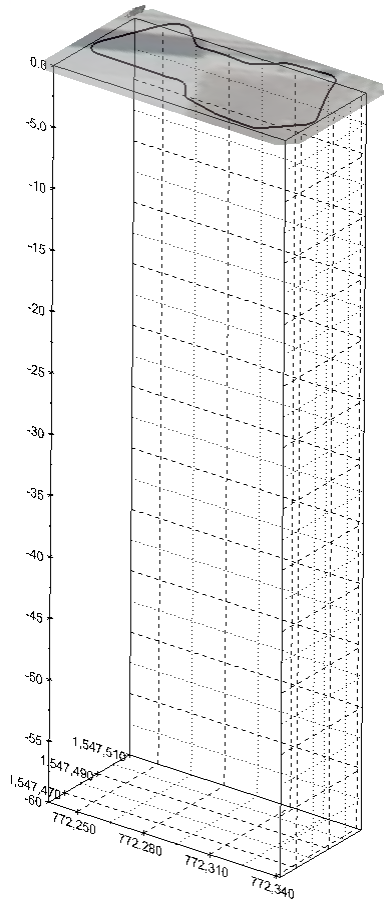
TCE EVS Plumes, November 2016



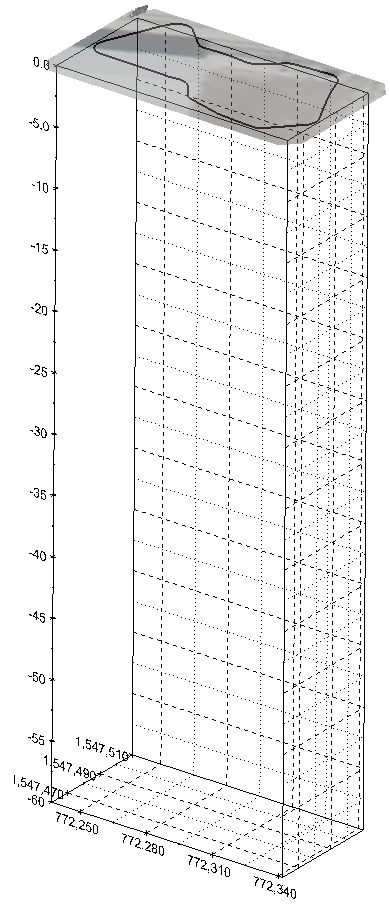
TCE (02/2017): 3 ug/L



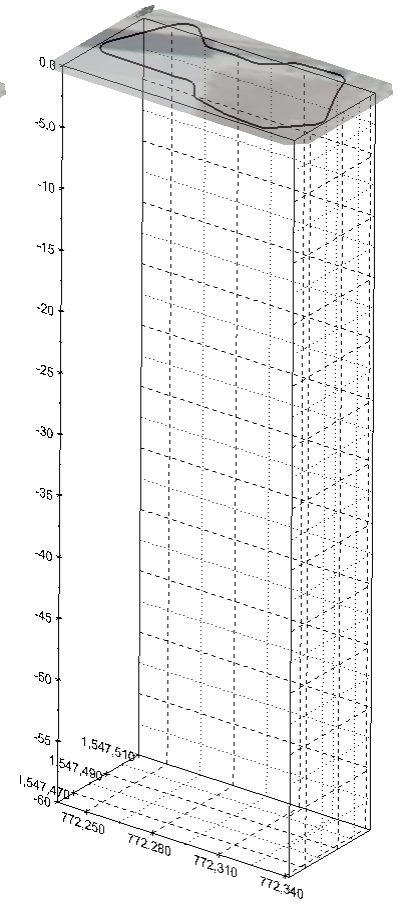
TCE (02/2017): 300 ug/L



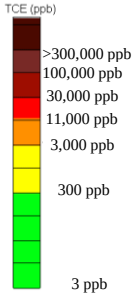
TCE (02/2017): 11,000 ug/L



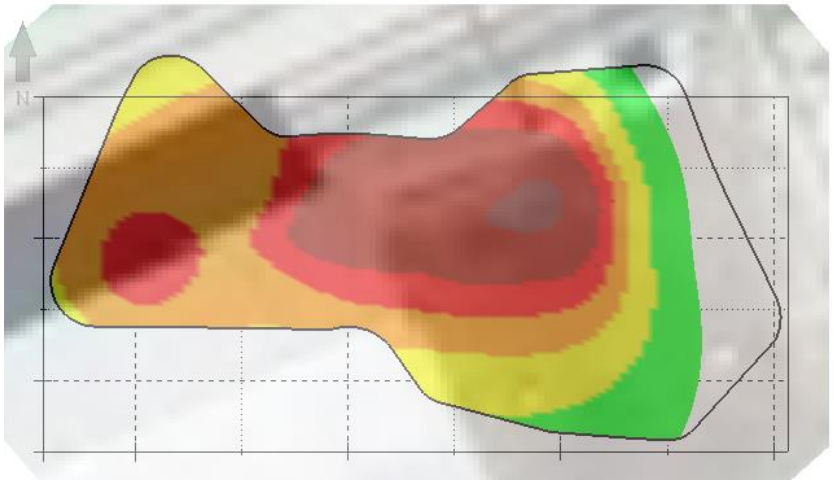
TCE (02/2017): 100,000 ug/L



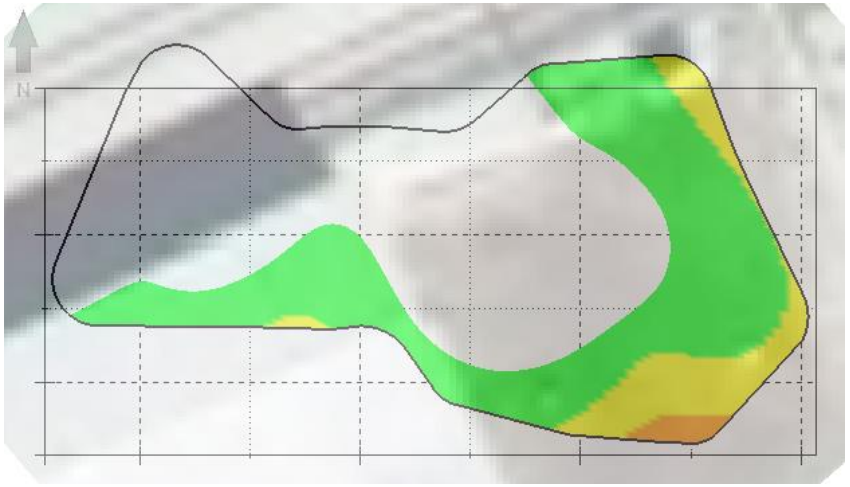
TCE (02/2017): 300,000 ug/L



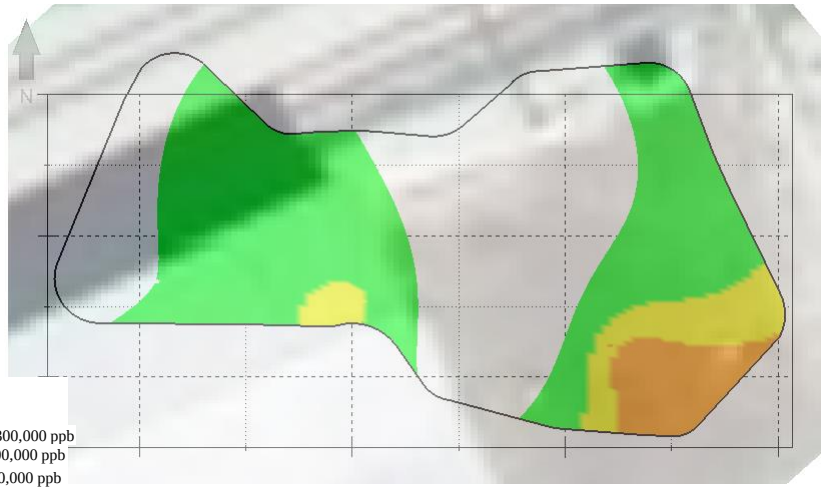
TCE EVS Plumes, February 2017



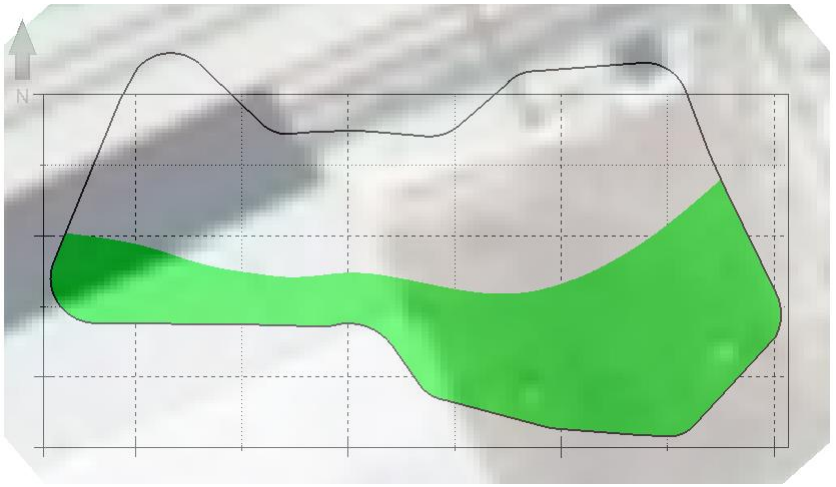
Baseline, November 2015



August 2016

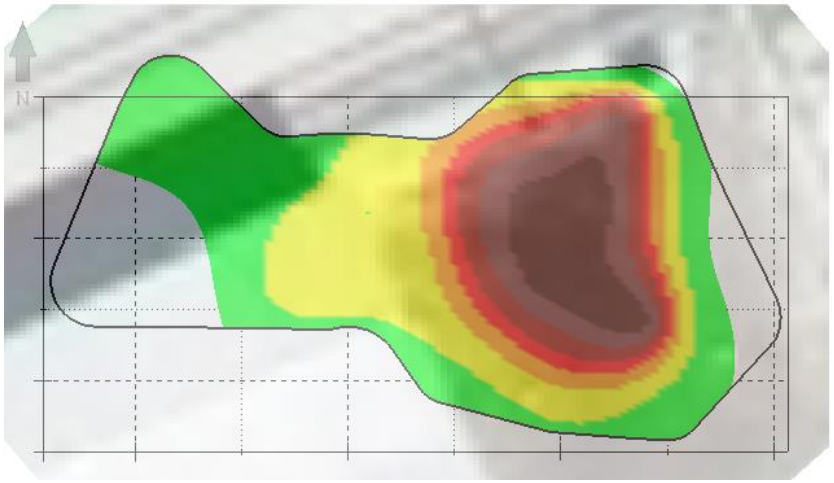


November 2016

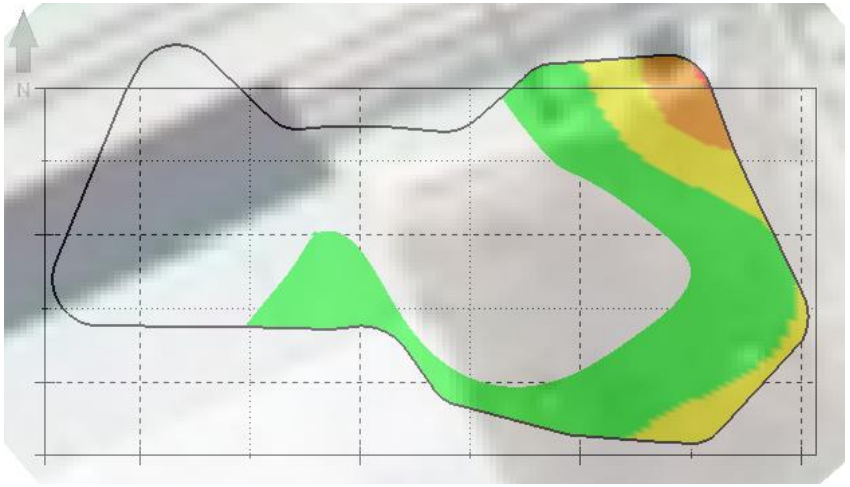


February 2017

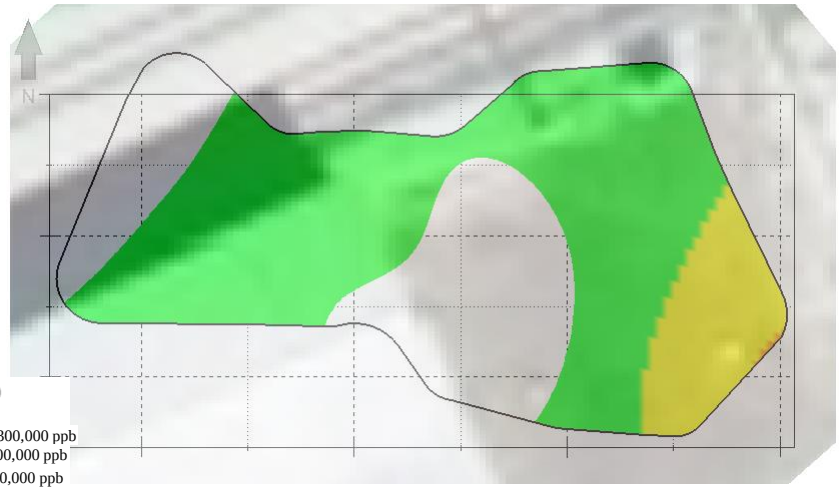
EVS Depth Layers – 50 feet bls



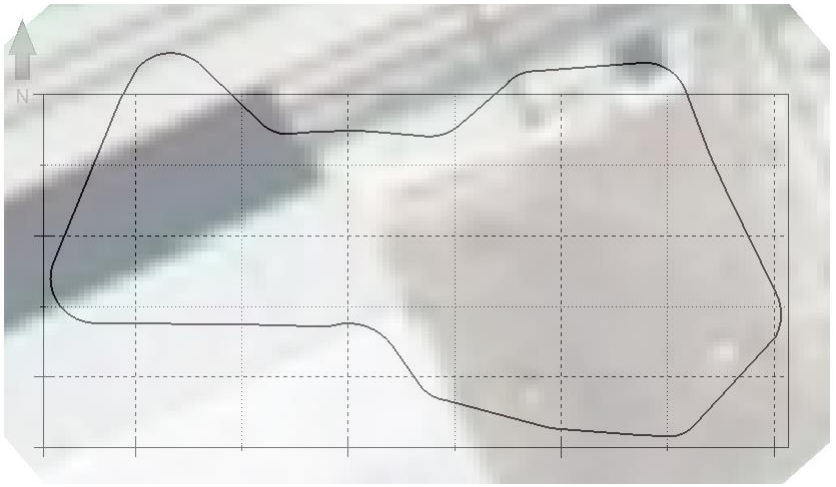
Baseline, November 2015



August 2016



November 2016



February 2017

EVS Depth Layers – 55 feet bls

PM DPT # (DPT-0)	Max TCE PM Result (µg/L)	Baseline DPT # (DPT-0)	Baseline TCE Result (µg/L)	% TCE Concentration Reduction	Orders of Magnitude Reduction
479	4	433	203,000	99.998%	4.7
480	230	434	459,000	99.950%	3.3
481	27	435	383,000	99.993%	4.2
482	130	436	1,430,000	99.991%	4.0
486	270	439	443,000	99.939%	3.2
487	2	393	241,000	99.999%	5.1
485	1	441	116,000	99.999%	5.1
483	50	442	68,800	99.927%	3.1
488	130	396	37,200	99.651%	2.5
484	24	443	8,600	99.721%	2.6
489	27	431	40,000	99.933%	3.2

Average % Reduction (of >100 ppm baseline locations): 99.981%

Average % Reduction (of <100 ppm baseline locations): 99.808%

Average % Reduction (overall): 99.918%

TCE Concentration Reduction

Lessons Learned

- Site conditions can change from investigation to design
  - Ensure the installation is appropriate for site conditions
  - DPT baseline sampling resulted in revision of treatment area and +2 electrodes
- Advocate f_{oc} soil data in source area
  - orders of magnitude sensitivity in mass estimates
- Sonic electrode installation significantly reduced waste
  - Minimal drilling spoils; soil displaced outward in boring
  - Liquid IDW treated and discharged onsite with mobile air stripper
- Effective communication with facility and project stakeholders is paramount
- Continuous data review and subcontractor interaction an important aspect of efficiently optimizing ERH performance
- High resolution site monitoring provided effective optimization tools
- Performance based contract an effective risk management resource to secure key subcontractors to objectives
  - Without performance guarantee to ERH subcontractor, typical ERH contracts are based on subsurface energy delivery or temperature targets. In those cases, site objectives to <NADC levels (e.g., <300 ppb TCE) may not be accomplished.

Conclusions and Path Forward

- IM successfully removed TCE source zone and contaminant mass in fine grained and overlying units
- Operations terminated based on confirmation DPT sampling results and secondary lines of evidence such as temperature, mass removal trends, etc.
- Source zone transitioning to MNA
- Air sparging treatment planned for surrounding dilute plume

Thank you! Questions?

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