Thermal Remediation: Mechanisms, Principles and Case Studies

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Physical Properties of Organic Chemicals that Effect Flow

- Density
- Viscosity
- Vapor Pressure
- Solubility
- Diffusion Rate

Interactions with Other Phases

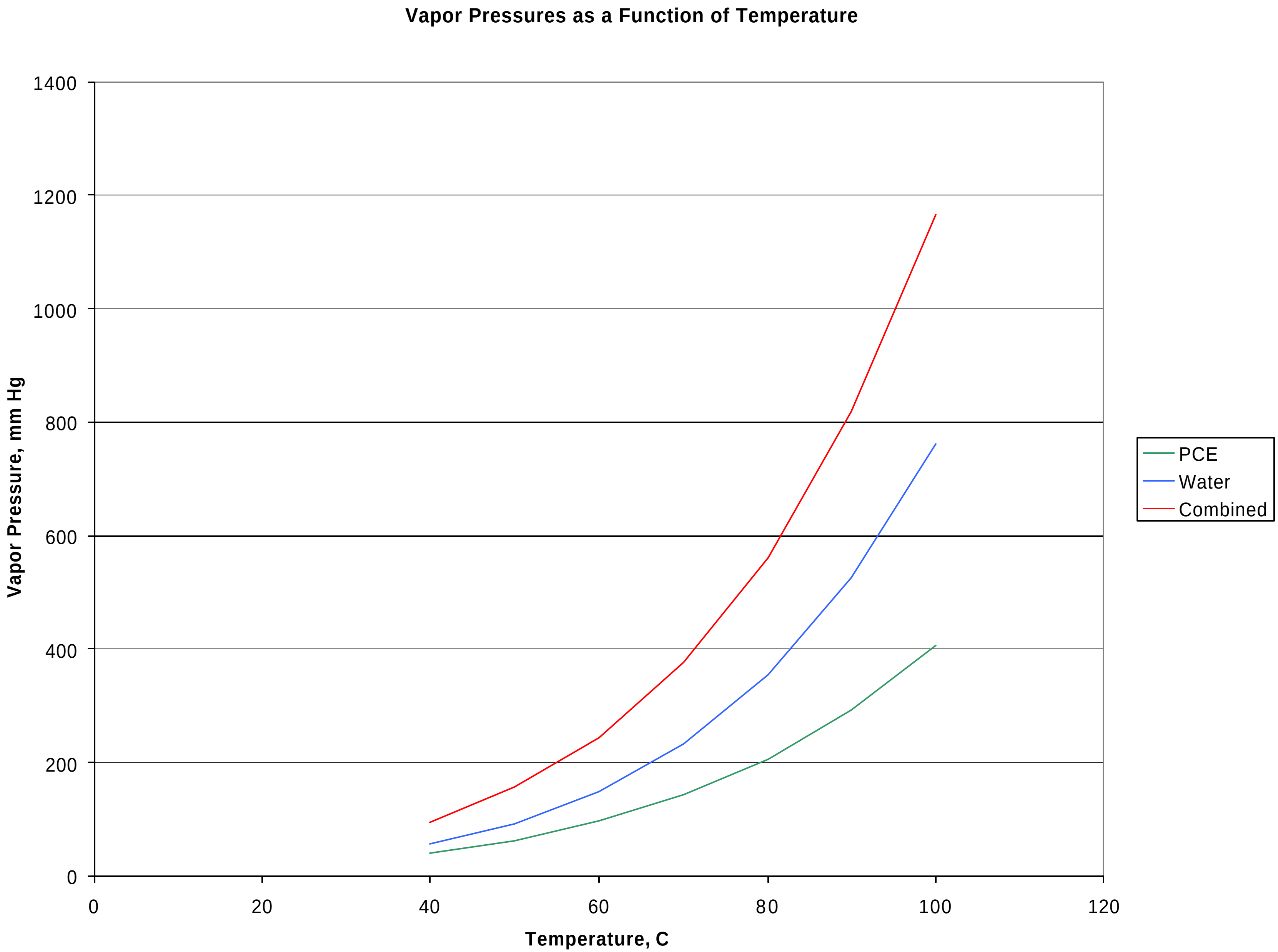
- Adsorption/desorption
- Surface and Interfacial Tension
- Capillary Interactions

Additional Mechanisms to Recover VOCs

- Steam Distillation
- Steam Stripping

Steam Distillation

- Occurs when 2 liquid phases are present
- Liquids boil when their combined vapor pressures equal the local pressure
- Boiling occurs at temperatures less than 100 C



Vapor Pressures as a Function of Temperature
1400
1200
1000
800
600
400
200
0
0
20
40
60
80
100
120
Vapor Pressure, mm Hg
Temperature, C
PCE
Water
Combined

Steam Stripping

- Rapid vaporization of dissolved phase VOC
- Vapor phase concentrations controlled by Henry’s constant
- Boiling off small amount of water will decrease dissolved phase VOC concentrations by orders of magnitude
- Slowed by mass transfer limitations

Mechanisms for the Recovery of Volatile Organic Contaminants

- Vaporization
- Solubilization
- Reduced adsorption
- Increased diffusion from low permeability zones

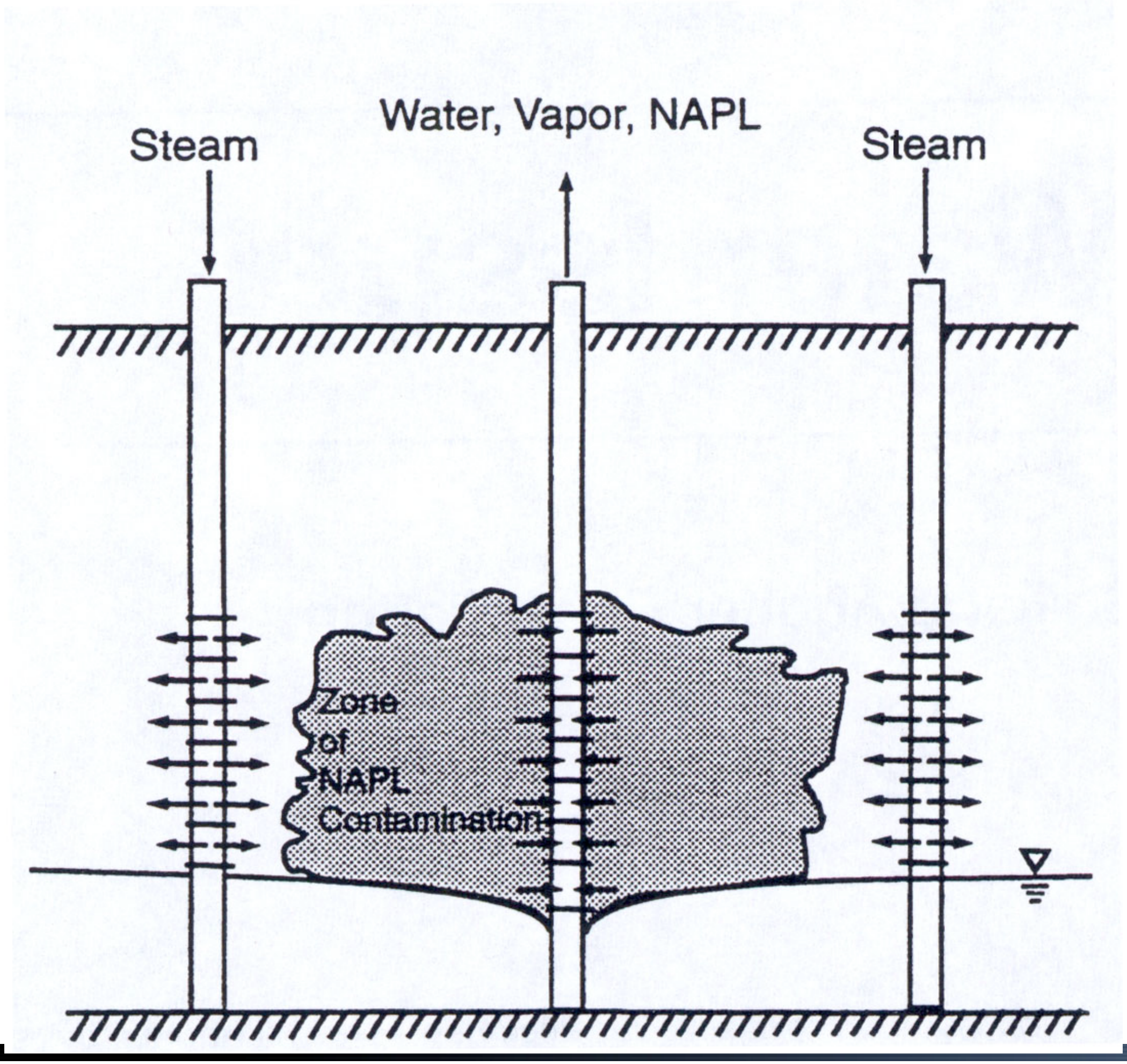
What do physcial properties indicate about downward migration during heating?

- Less density difference driving downward migration
- Minimal effect on capillary pressure, thus on potential to penetrate capillary barrier
- Longer vertical ganglia can be supported at high temperature

Steam Injection for Remediation

- Additional mechanism: displacement
- Recovers contaminants as liquid and vapor
- Targets NAPL contaminated soil and groundwater
- Cyclic steam injection/continuous extraction increases recovery rates

DIAGRAM OF A STEAM INJECTION REMEDIATION SYSTEM



Steam Injection Favored by:

- Bulk soil permeability > 10^{-5} cm/sec
- Low permeability layers less than 2 meters in thickness
- Deeper depths of injection
- Equally effective above and below the water table

Potential of Downward Migration can be Mitigated by:

- Hot floor
  - DNAPL moving downward is vaporized
- Air co-injection
  - Noncondensible gases spread out condensation zone to eliminate DNAPL bank

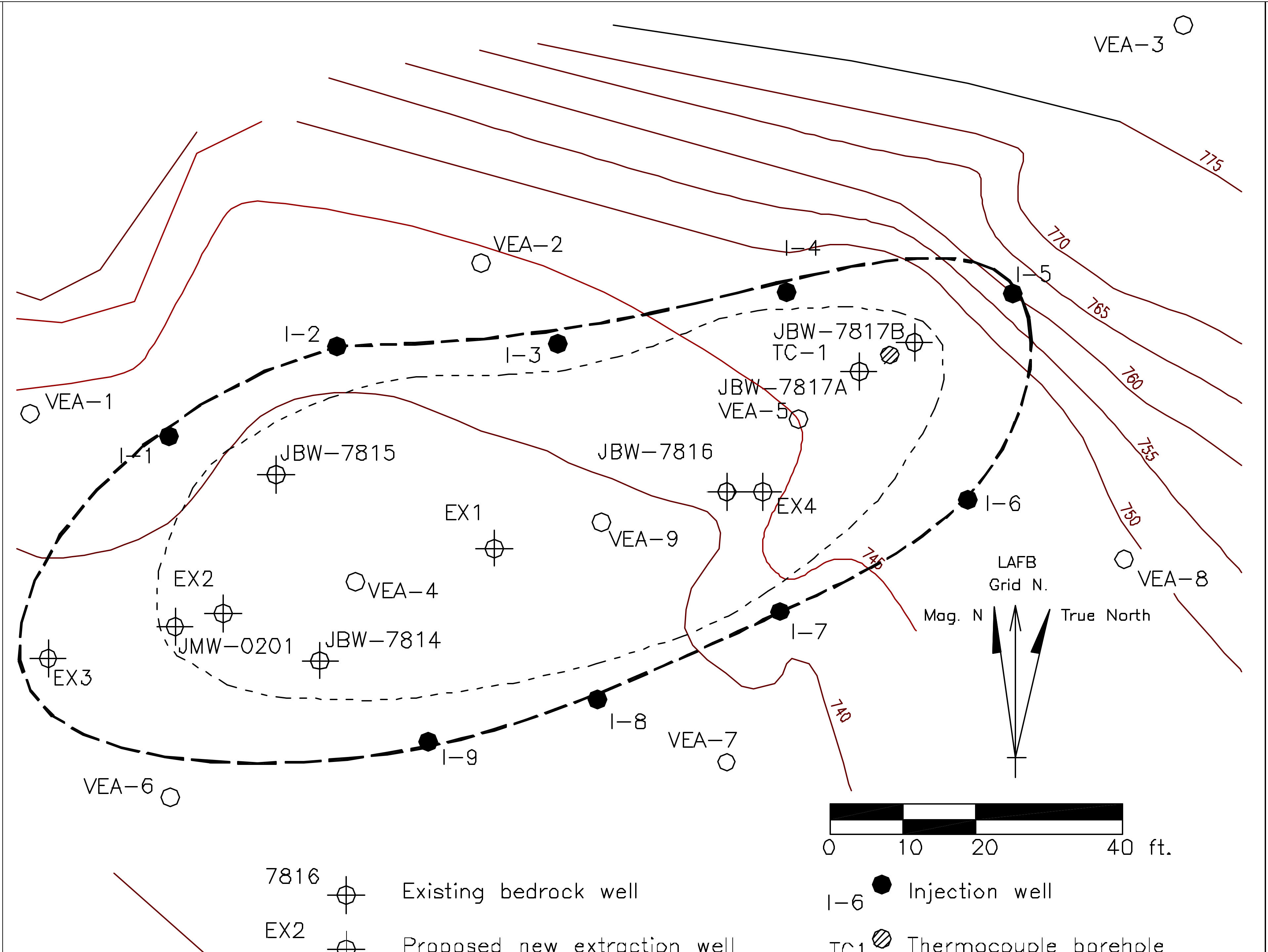
During Steam Injection:

- Mobile NAPL and groundwater is displaced ahead of the steam front
- A steam zone is established
- Residual NAPL with boiling point < 150 C volatilized and transported to NAPL bank
- Adsorbed phase which desorbs slowly is likely to remain

Loring Quarry Steam Injection

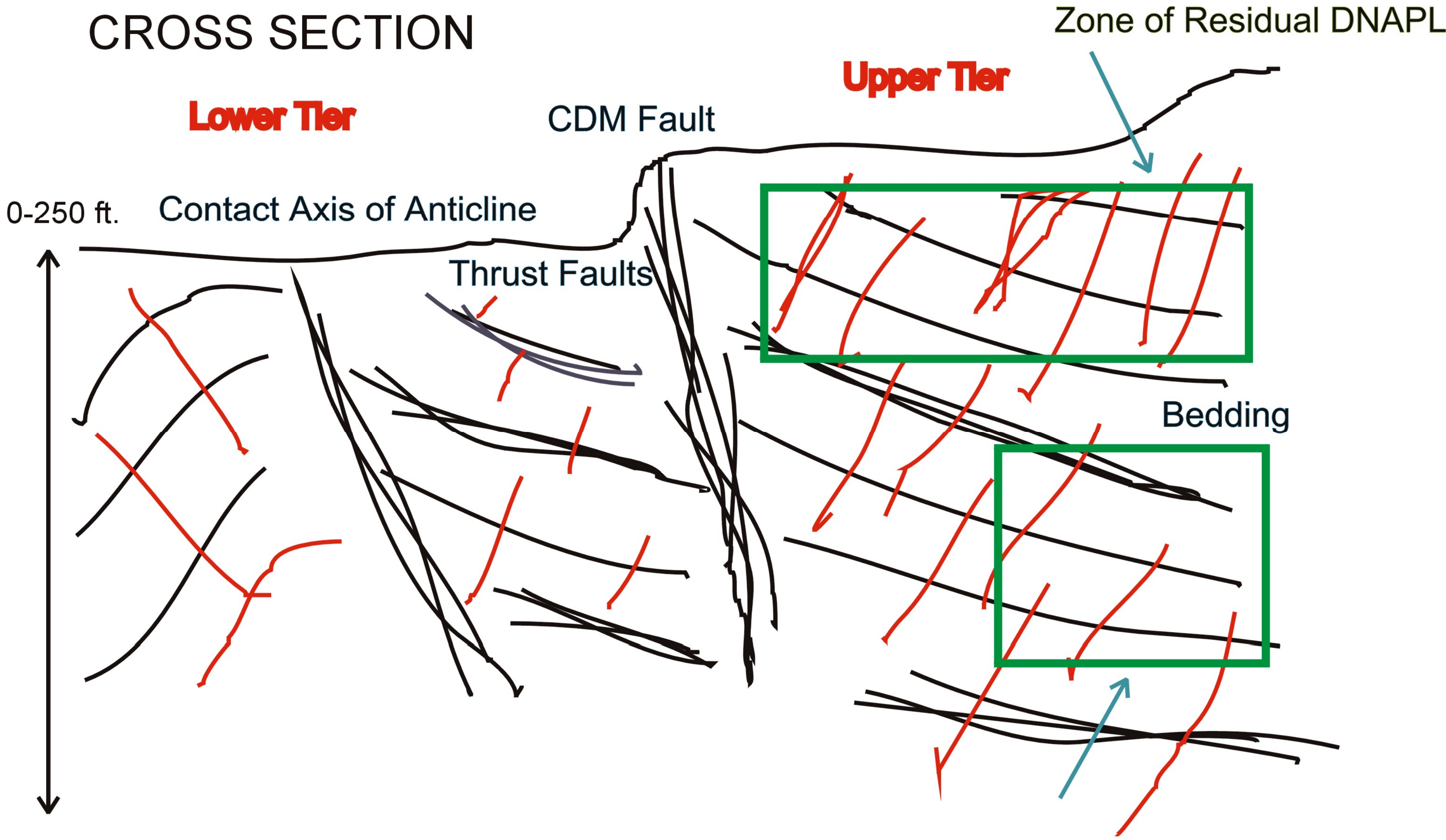
Loring Quarry Site

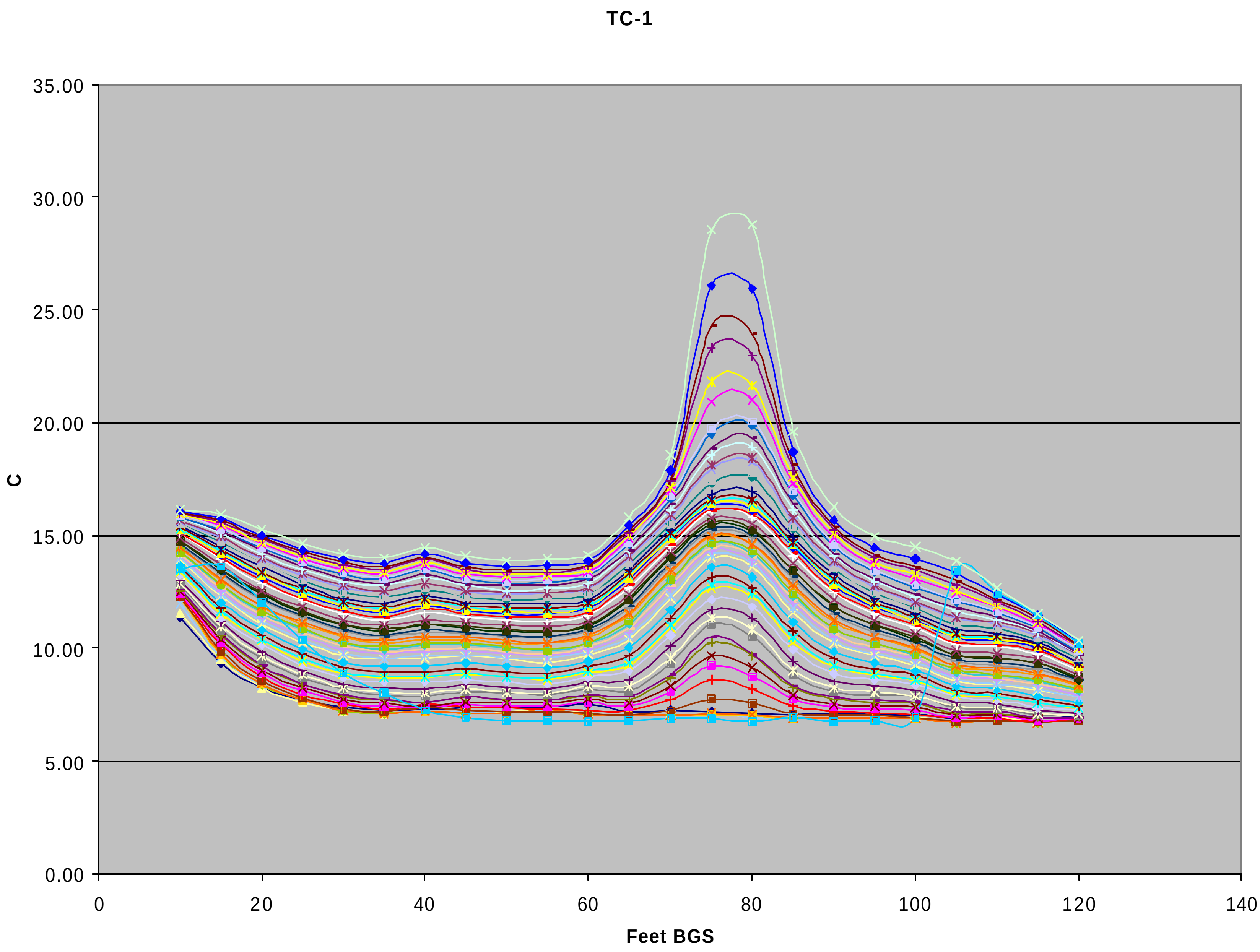
- Quarry used for drum burial
- PCE DNAPL found in fractured bedrock
- TI waiver granted
- Research project on DNAPL removal from fractured bedrock
- Steam injection chosen over oxidation



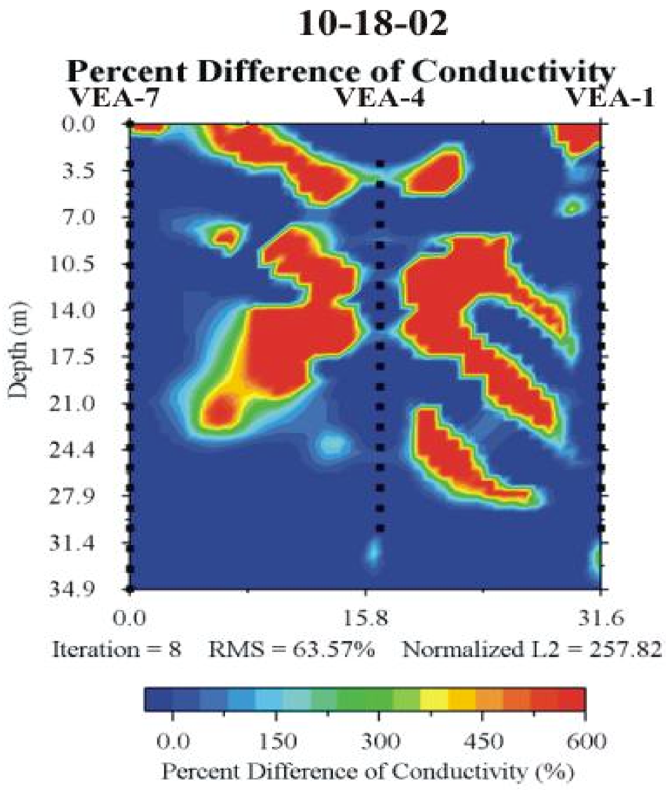
VEA-3
775
770
765
760
755
750
745
740
VEA-2
I-4
I-5
I-2
I-3
JBW-7817B
TC-1
JBW-7817A
VEA-5
VEA-1
I-1
JBW-7815
JBW-7816
EX4
EX1
VEA-9
I-6
LAFB
Grid N.
Mag. N
True North
VEA-8
EX2
VEA-4
I-7
JMW-0201
JBW-7814
EX3
I-8
VEA-7
I-9
VEA-6
0
10
20
40 ft.
7816
Existing bedrock well
I-6
Injection well
EX2
Proposed new extraction well
TC1
Thermocouple borehole

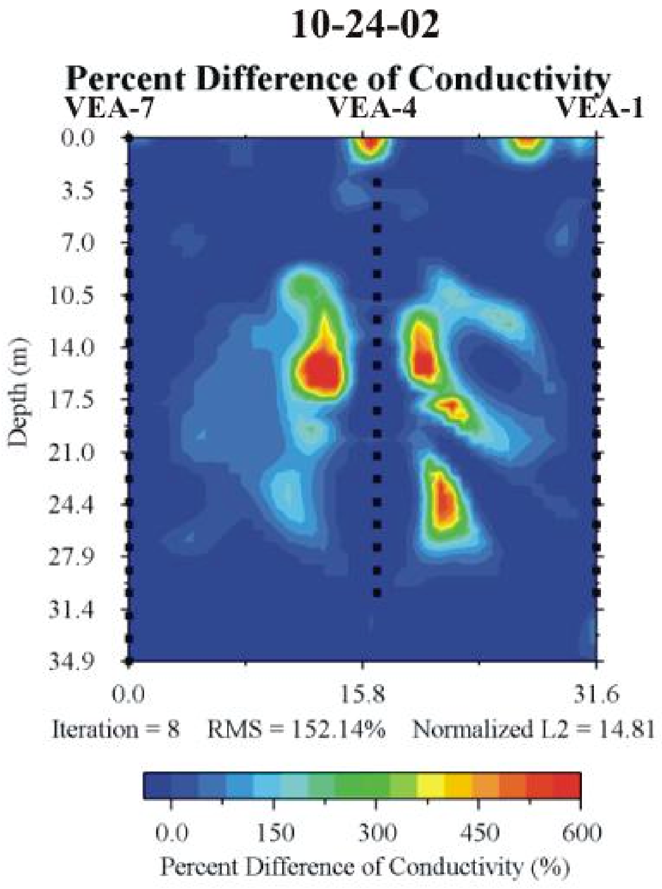
CROSS SECTION



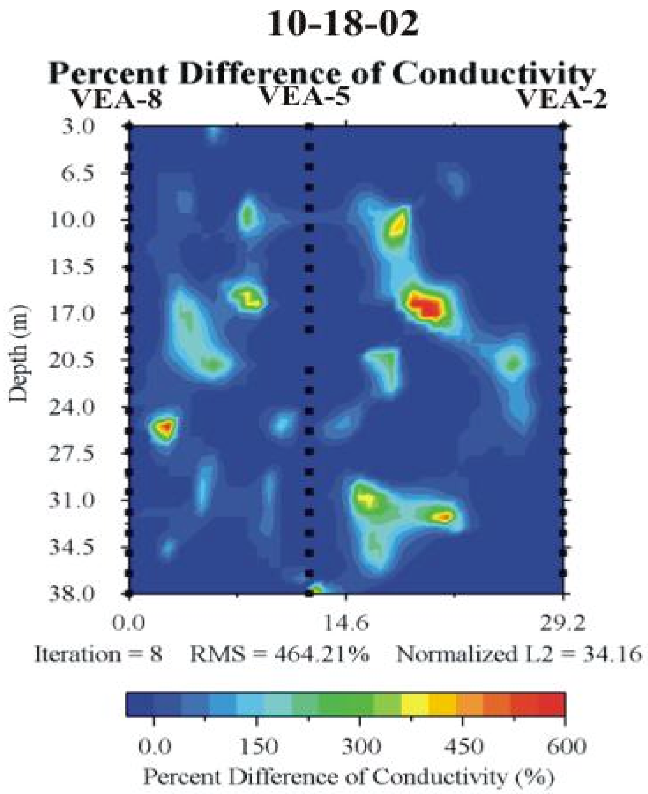

TC-1
C
Feet BGS
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
0
20
40
60
80
100
120
140

VEA 7-4-1

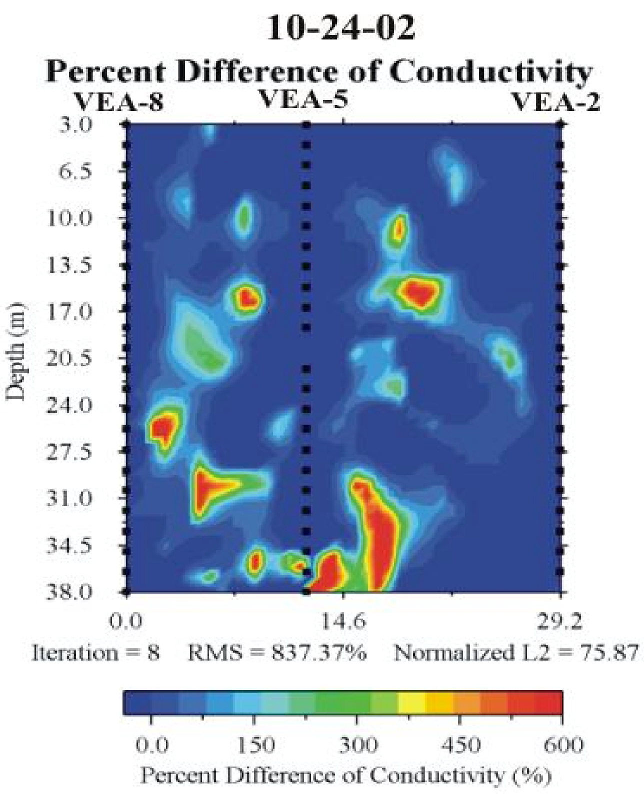

10-18-02
Percent Difference of Conductivity
VEA-7
VEA-4
VEA-1
Depth (m)
0.0
3.5
7.0
10.5
14.0
17.5
21.0
24.4
27.9
31.4
34.9
0.0
15.8
31.6
Iteration = 8 RMS = 63.57% Normalized L2 = 257.82
0.0 150 300 450 600
Percent Difference of Conductivity (%)


10-24-02
Percent Difference of Conductivity
VEA-7
VEA-4
VEA-1
Depth (m)
0.0
3.5
7.0
10.5
14.0
17.5
21.0
24.4
27.9
31.4
34.9
0.0
15.8
31.6
Iteration = 8 RMS = 152.14% Normalized L2 = 14.81
0.0 150 300 450 600
Percent Difference of Conductivity (%)

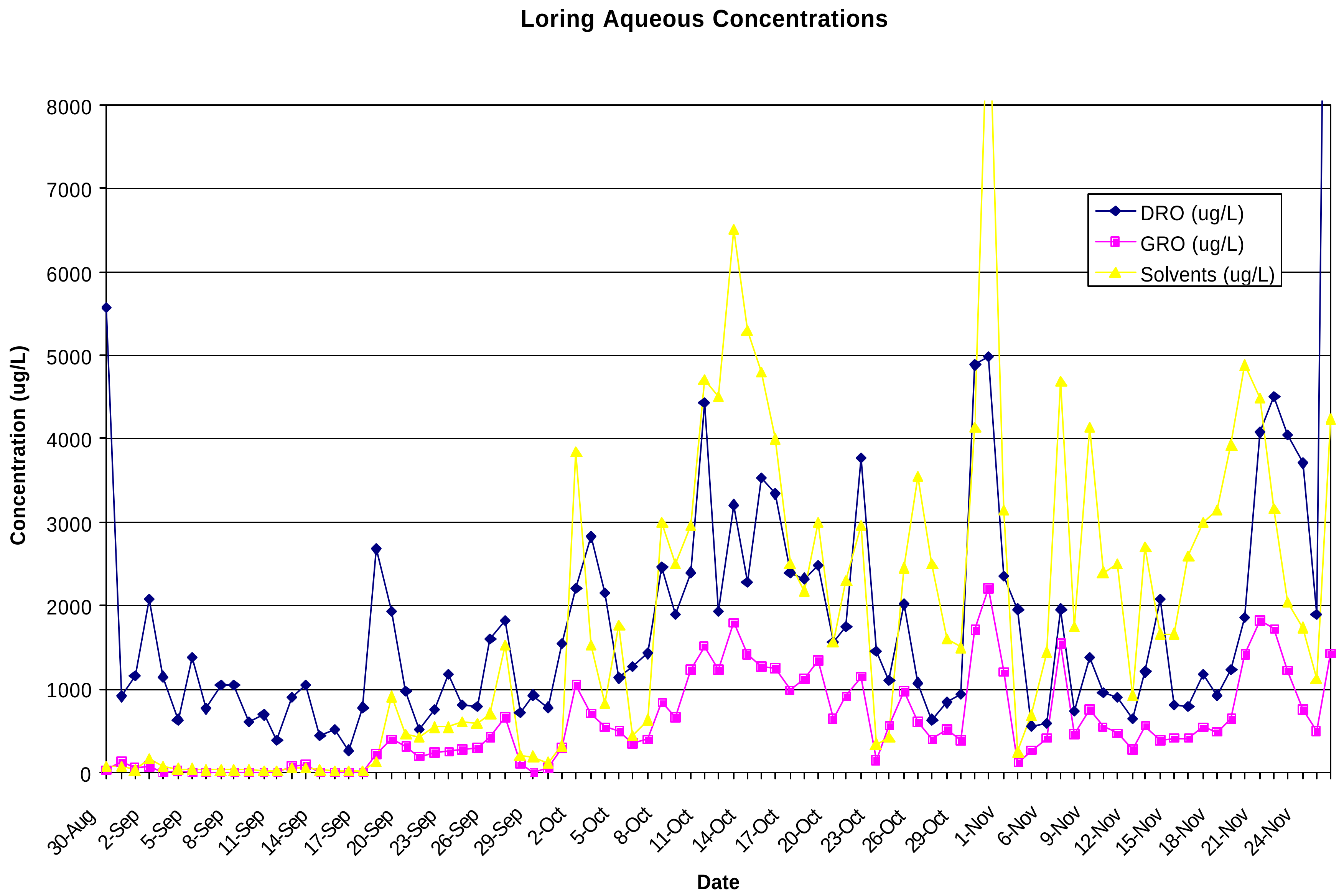
VEA 8-5-2



10-18-02
Percent Difference of Conductivity
VEA-8
VEA-5
VEA-2
Depth (m)
3.0
6.5
10.0
13.5
17.0
20.5
24.0
27.5
31.0
34.5
38.0
0.0
14.6
29.2
Iteration = 8 RMS = 464.21% Normalized L2 = 34.16
0.0
150
300
450
600
Percent Difference of Conductivity (%)



10-24-02
Percent Difference of Conductivity
VEA-8
VEA-5
VEA-2
Depth (m)
3.0
6.5
10.0
13.5
17.0
20.5
24.0
27.5
31.0
34.5
38.0
0.0
14.6
29.2
Iteration = 8 RMS = 837.37% Normalized L2 = 75.87
0.0
150
300
450
600
Percent Difference of Conductivity (%)



Loring Aqueous Concentrations
Concentration (ug/L)
8000
7000
6000
5000
4000
3000
2000
1000
0
DRO (ug/L)
GRO (ug/L)
Solvents (ug/L)
30-Aug
2-Sep
5-Sep
8-Sep
11-Sep
14-Sep
17-Sep
20-Sep
23-Sep
26-Sep
29-Sep
2-Oct
5-Oct
8-Oct
11-Oct
14-Oct
17-Oct
20-Oct
23-Oct
26-Oct
29-Oct
1-Nov
6-Nov
9-Nov
12-Nov
15-Nov
18-Nov
21-Nov
24-Nov
Date

Electrical Heating for Remediation

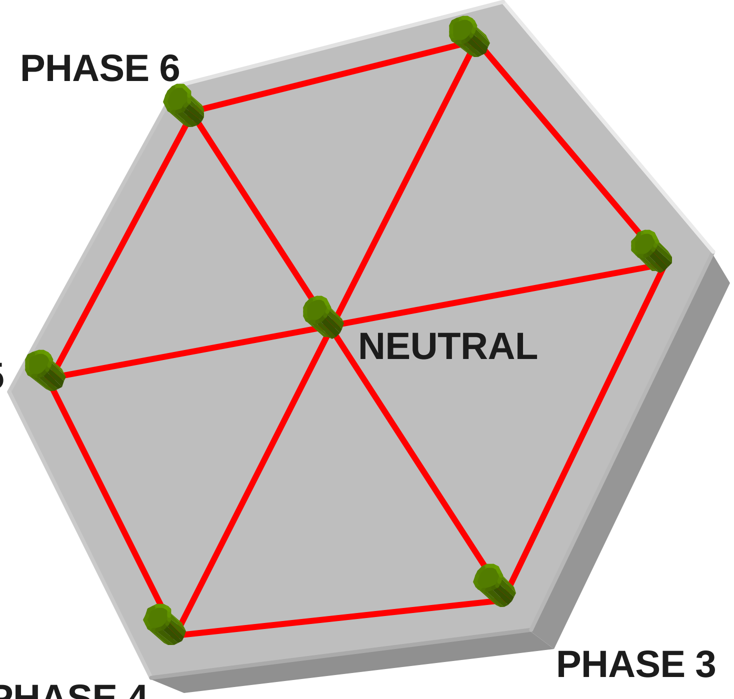
- Called Six Phase Soil Heating, Electrical Resistance Heating
- Relies on electrical resistance of soils to produce heat
- Heating dependent on soil type: low permeability zones often heated first
- Works above and below water table
- Contaminants collected as vapors: vapor bubbles rise to vadose zone or move laterally to deep vents

How Does Six-Phase Heating Work ?

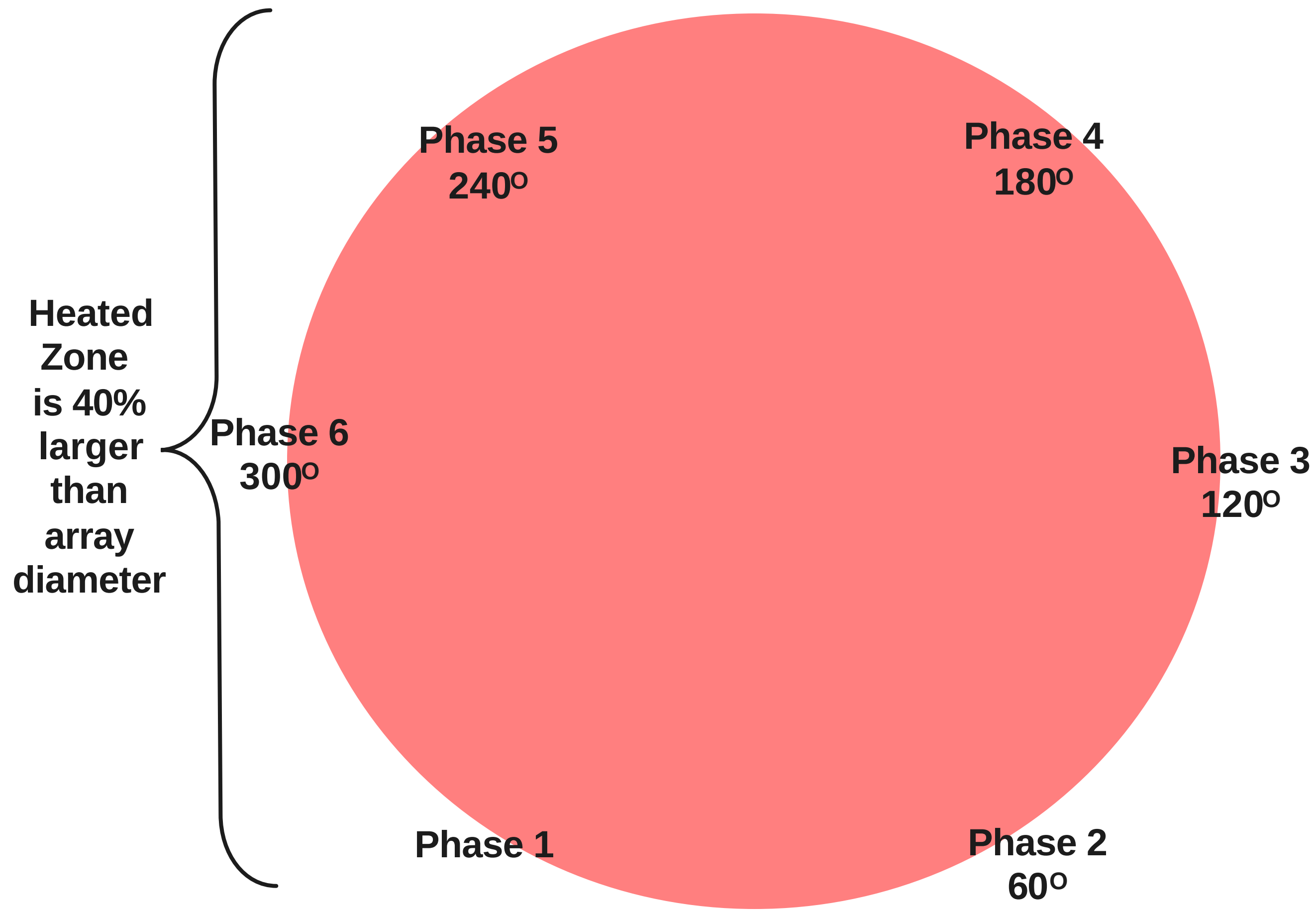
- The Six-Phase Array (SPA™) is made up of 6 electrodes

A 7th "Neutral" electrode in the center can serve as a vent

A typical array diameter is 30' - 80' (up from 20' - 40')

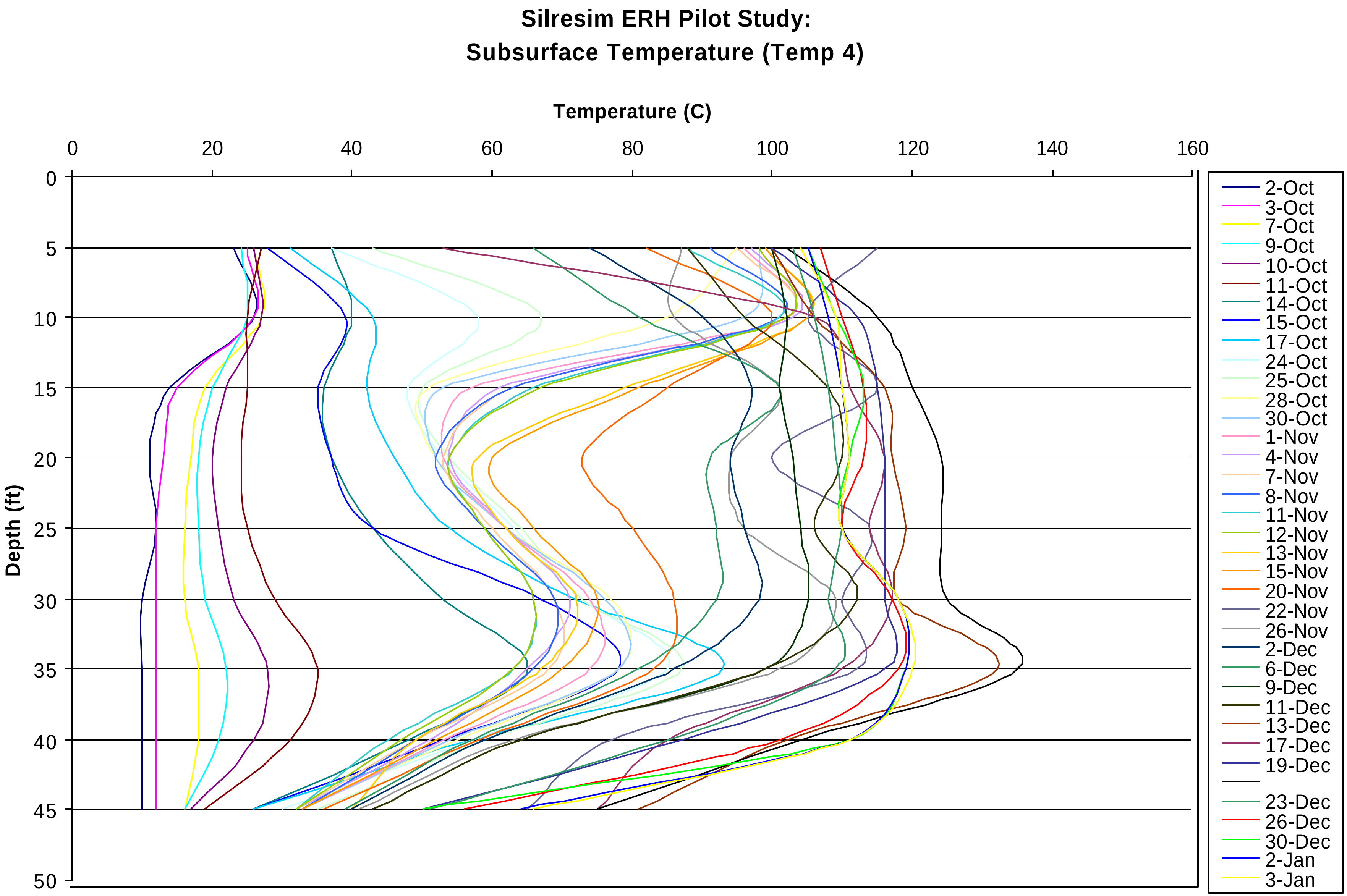


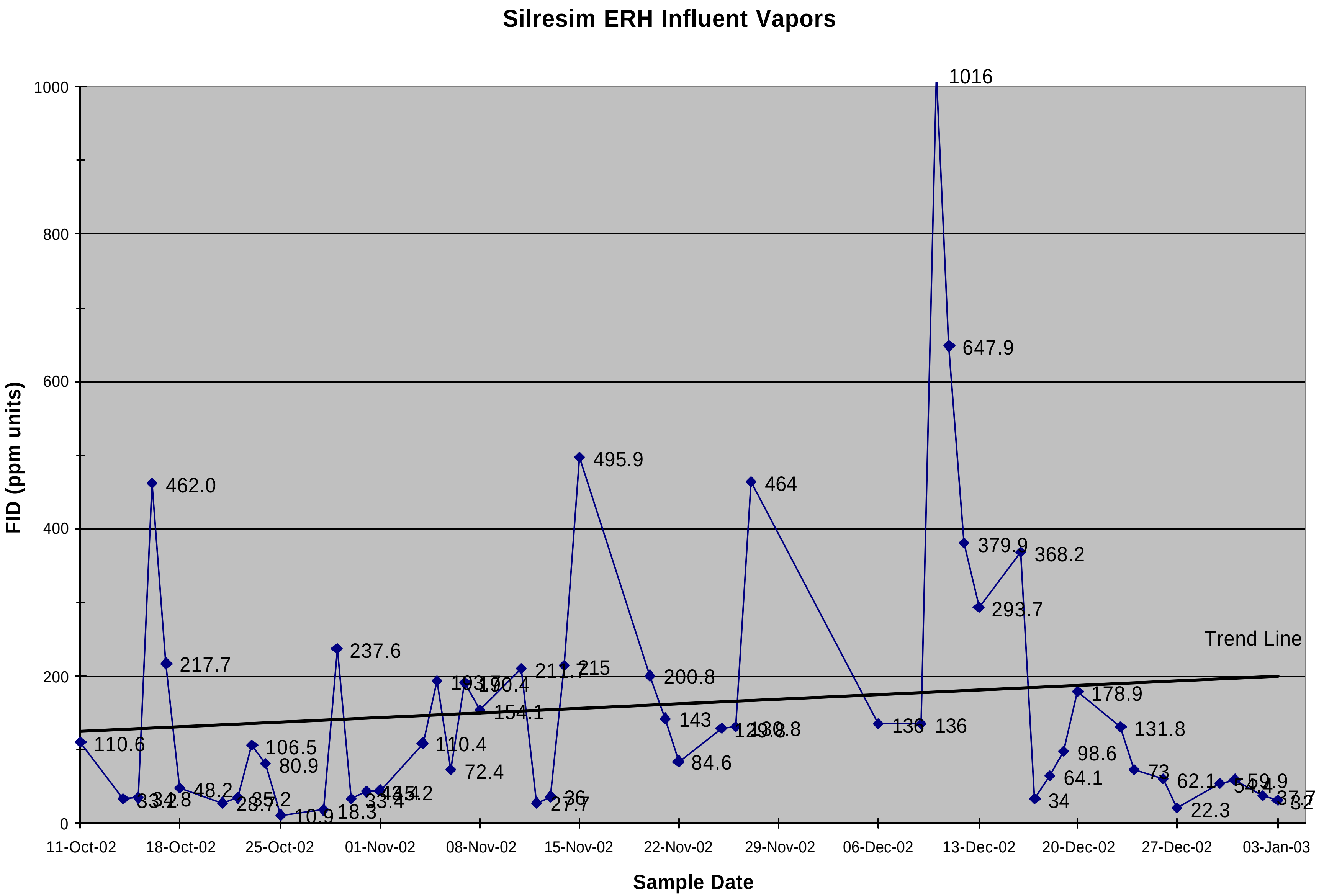
Self Correcting Heat Distribution & Uniform Heating



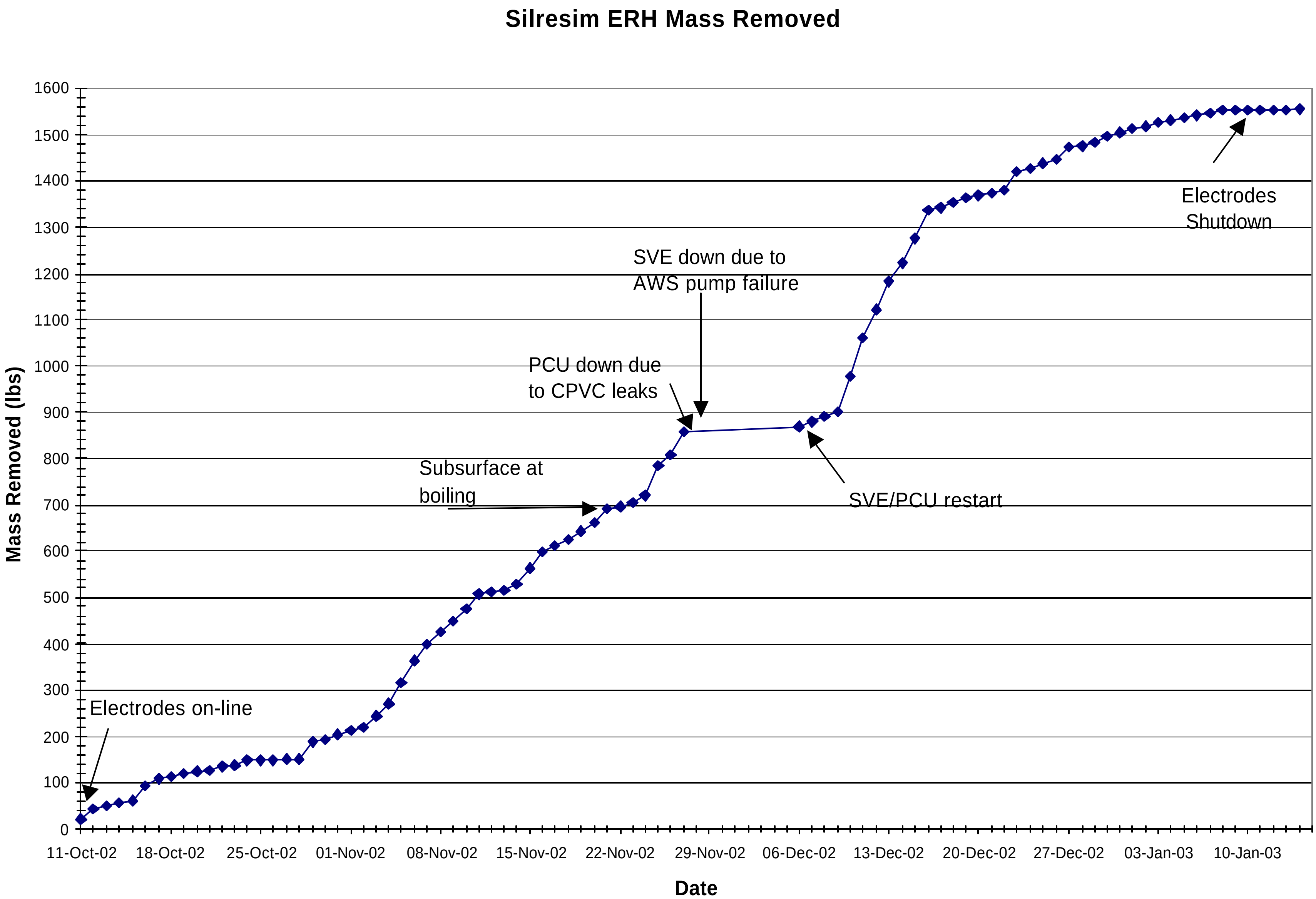
Silresim Superfund Site

- Former fuel depot and waste reclamation facility
- Volatile contaminants migrating off site
- SVE pilot test removed 12 tons in 2 years
- ERH pilot initiated in September 2002


Silresim ERH Pilot Study:
Subsurface Temperature (Temp 4)
Temperature (C)
0
20
40
60
80
100
120
140
160
Depth (ft)
0
5
10
15
20
25
30
35
40
45
50
2-Oct
3-Oct
7-Oct
9-Oct
10-Oct
11-Oct
14-Oct
15-Oct
17-Oct
24-Oct
25-Oct
28-Oct
30-Oct
1-Nov
4-Nov
7-Nov
8-Nov
11-Nov
12-Nov
13-Nov
15-Nov
20-Nov
22-Nov
26-Nov
2-Dec
6-Dec
9-Dec
11-Dec
13-Dec
17-Dec
19-Dec
23-Dec
26-Dec
30-Dec
2-Jan
3-Jan



Silresim ERH Influent Vapors
FID (ppm units)
Sample Date
Trend Line
0
200
400
600
800
1000
11-Oct-02
18-Oct-02
25-Oct-02
01-Nov-02
08-Nov-02
15-Nov-02
22-Nov-02
29-Nov-02
06-Dec-02
13-Dec-02
20-Dec-02
27-Dec-02
03-Jan-03
110.6
462.0
217.7
48.2
106.5
80.9
10.9
18.3
237.6
110.4
72.4
154.1
495.9
215
200.8
143
84.6
464
136
136
1016
647.9
379.9
368.2
293.7
178.9
131.8
98.6
64.1
34
62.1
22.3
59.9



Silresim ERH Mass Removed
Mass Removed (lbs)
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
11-Oct-02
18-Oct-02
25-Oct-02
01-Nov-02
08-Nov-02
15-Nov-02
22-Nov-02
29-Nov-02
06-Dec-02
13-Dec-02
20-Dec-02
27-Dec-02
03-Jan-03
10-Jan-03
Date
Electrodes on-line
Subsurface at boiling
PCU down due to CPVC leaks
SVE down due to AWS pump failure
SVE/PCU restart
Electrodes Shutdown

Groundwater concentrations of VOCs reduced by >94%

- Shallow groundwater
  - TCE: 320 ppm to <0.1 ppm
  - 1,1,1-TCA: 240 ppm to <0.1 ppm
  - BTEX: 17 ppm to <0.1 ppm

- Groundwater to 40 ft depth
  - TCE: 260 ppm to <10 ppm
  - 1,1,1-TCA: 200 ppm to 6.2 ppm
  - PCE: 21 ppm to 2.2 ppm

In Situ Thermal Remediation

- Aggressive technologies:
  - Recover NAPL
  - Reduce dissolved phase concentrations by orders of magnitude
- Applicable in wide variety of settings
  - Highly heterogeneous lithologies
  - Waste pit with buried metal
  - Sites with surface structures
  - Fractured bedrock