Case Studies on Remediation for Soil Contamination Sites

Pro. Vision Environmental Engineering Corporation

Web Site : www.pveec.com.tw

Presenter : Joseph Fan GM

About PVEEC

- PVEEC has many highly experience employees, such as geological technicians, Doctors, contamination investigation and remediation experts.
- We have more than 22 years experience whether foreign or domestic in our region.
- According to our extensive experience, we provide accurate and real subsurface information as well as the best proposal of contamination and remediation about the works of geophysical investigation, geological drilling and prospecting, contamination investigation and remediation, etc.
- For each project, PVEEC treats with professional service and dedicated attitude, and we hope that everyone love and protect our mother-the Earth like us.

Our Vision

Cultivate the Earth’s doctors that love and protect the Earth.

Restore the Earth that would be filled with health and happiness.

Accomplish the blessed mission that manage and restore the Earth.

Core Value

- Integrity
- Authenticity
- Certainty
- Solidity

Our Service

- Soil and Groundwater Contamination Investigation and Restoration
- Environmental Site Assessment
- Aquifer Storage Recovery, ASR, and Water Resource Planning
- Geophysical Prospecting
  - (1) Subsurface Contamination and Waste Investigation
  - (2) Subsurface Structure Survey
  - (3) Hot spring and groundwater resource
  - (4) Sliding hillside, Colluvium or Alluvium
  - (5) Riverbed and Reservoir Sedimentation
  - (6) Subsurface pipelines
- Geological Drilling and Prospecting

Career Information – Joseph Fan

- BS, Civil Engineering, Tamkang University, Taiwan, 1987
- MS, Environmental Engineering, Colorado State University, 1992
- Life Member of Taiwan Association of Soil and Groundwater Environmental Protection
- Over 23 years experience of Soil and groundwater investigation and remediation
- Directed environmental site assessment projects (Phase I & II, and EHS) for multinational companies.
- Managed several remedial projects for soils contaminated with petroleum hydrocarbons and received closure letters from USA government.
- Managed heat-enhanced bioremediation projects for soils containing crude oils, gasoline, diesel and kerosene.
- Developed the electro-kinetic treatment method for soil and groundwater contamination in porous media having low permeability.
- Managed and performed pilot tests to remove heavy metals from contaminated soil and extract selenium, boron and salts from groundwater.
- Directed and performed numerous in-situ soil and groundwater remediation involving LNAPL and DNAPL clean up, using a combination of biodegradation, heat-enhanced soil venting, air sparging, and electro-kinetic techniques.

Content

- Electro-kinetic Enhanced Bioventing
- Advanced Vapor Extraction
- Electro-kinetic Enhanced Soil Washing

Case 1:

Electro-kinetic enhanced bioventing of gasoline in clayey soil

Site Introduction

- A 10,000 gallon of underground storage tank of gasoline was spill, in San Diego, California.
- The soil plume covers an area of about 2,400 (ft^2) and to a depth of about 30 (ft).
- The depth of in surface from 0 to 15(ft) was clay, and the other was conglomerate sandstone.
- The soil was contaminated, but groundwater was not.
- Total gasoline in soil plume is estimate at about 1,000 pounds of gasoline in about 3,500 tone of soil.
- The gasoline concentration in the soil plum range from 100 to 2,200 (ppm) and the target cleanup level was below 100 (ppm).

Problem

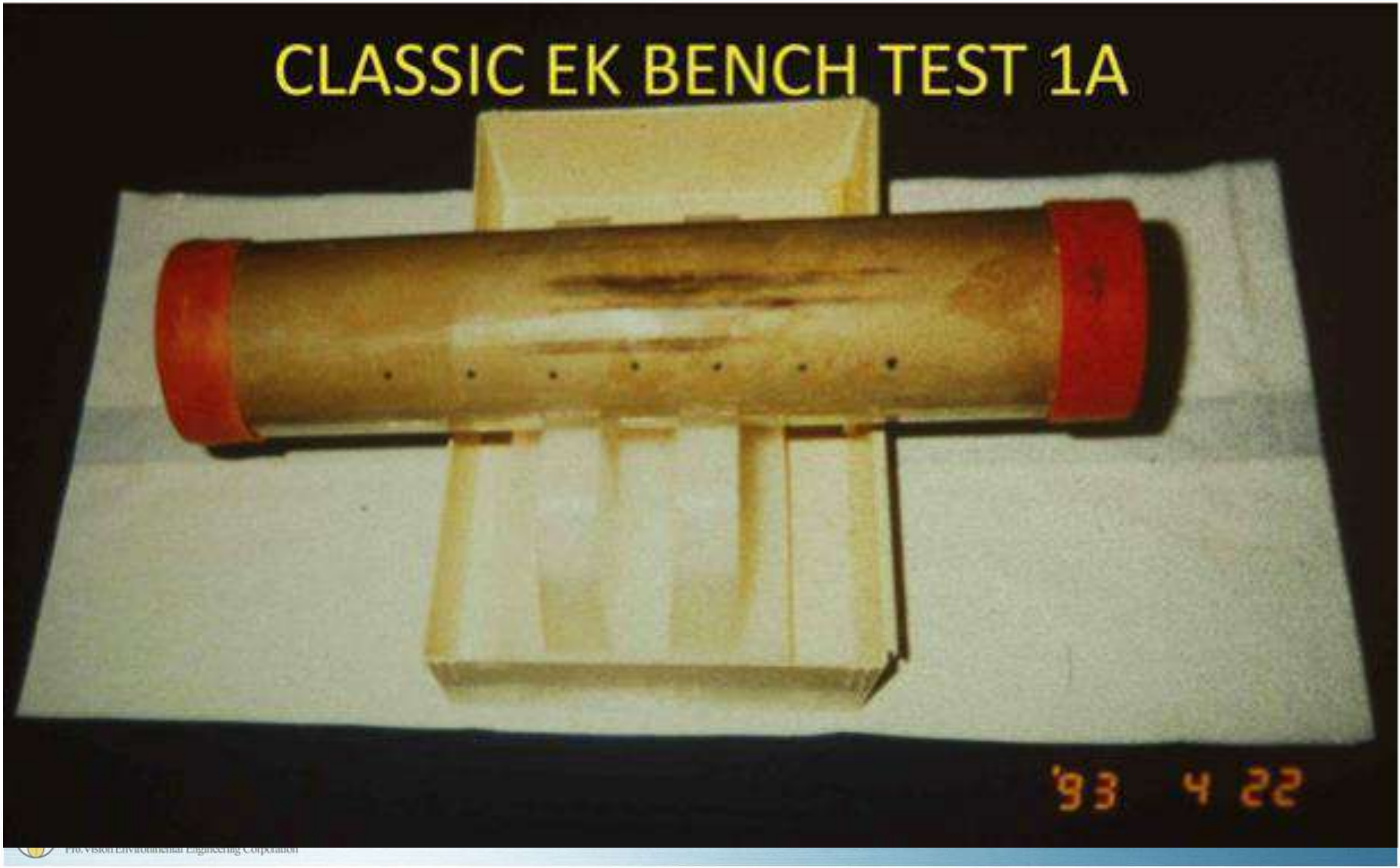
Find problem

- Using open excavation pit was not an economic option.
- The conventional vapor extraction system would not work with the low permeability clay.

Solve problem

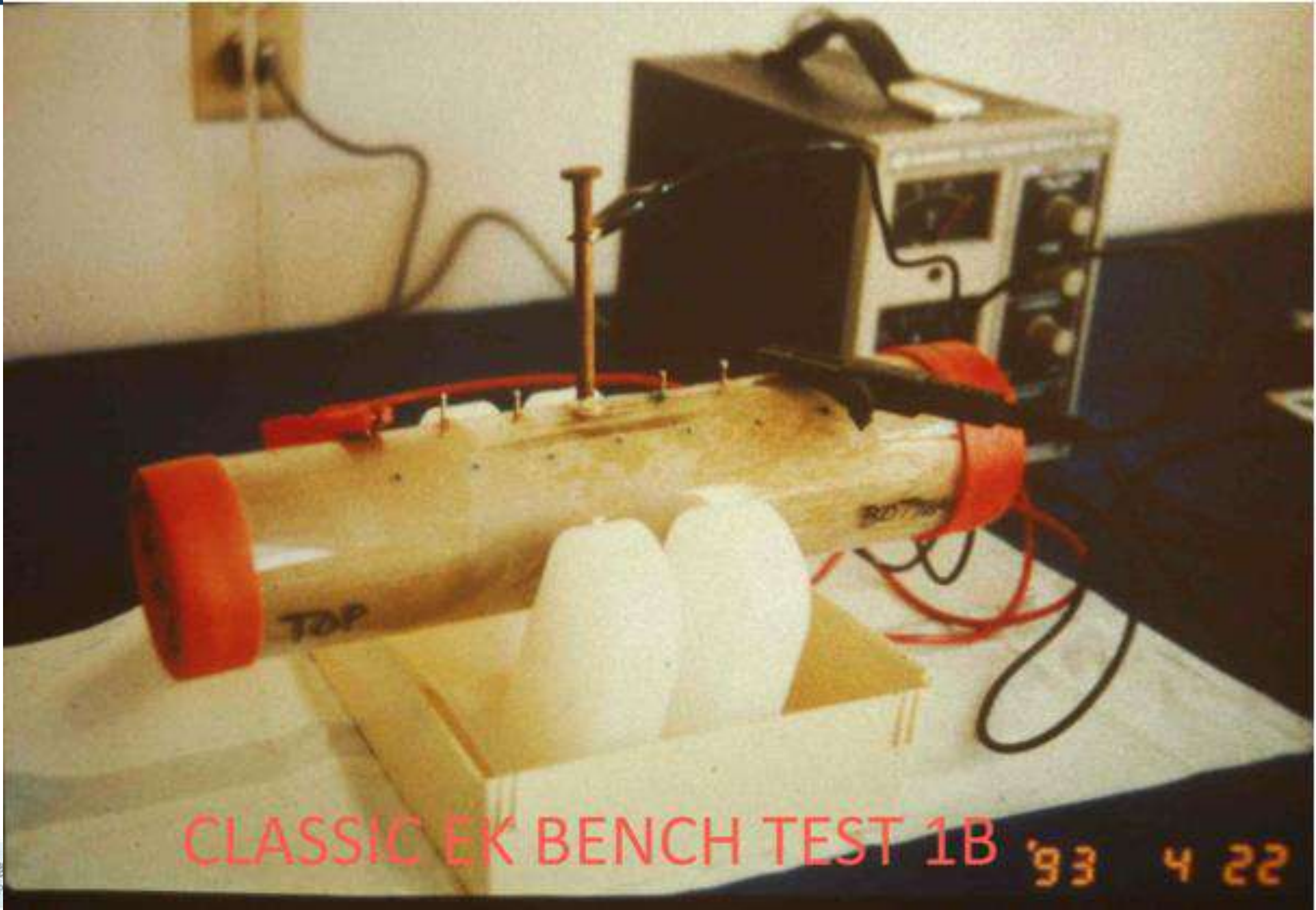
- The electro-kinetic enhanced bioventing method can be applied to treat this clayey soil.
- The electro-kinetic system was operated at electricity flow to dry out the gasoline in clayey soil.
- The technology provides a cost effective and minimum disruption to business operation.

EK Bench Scale Test

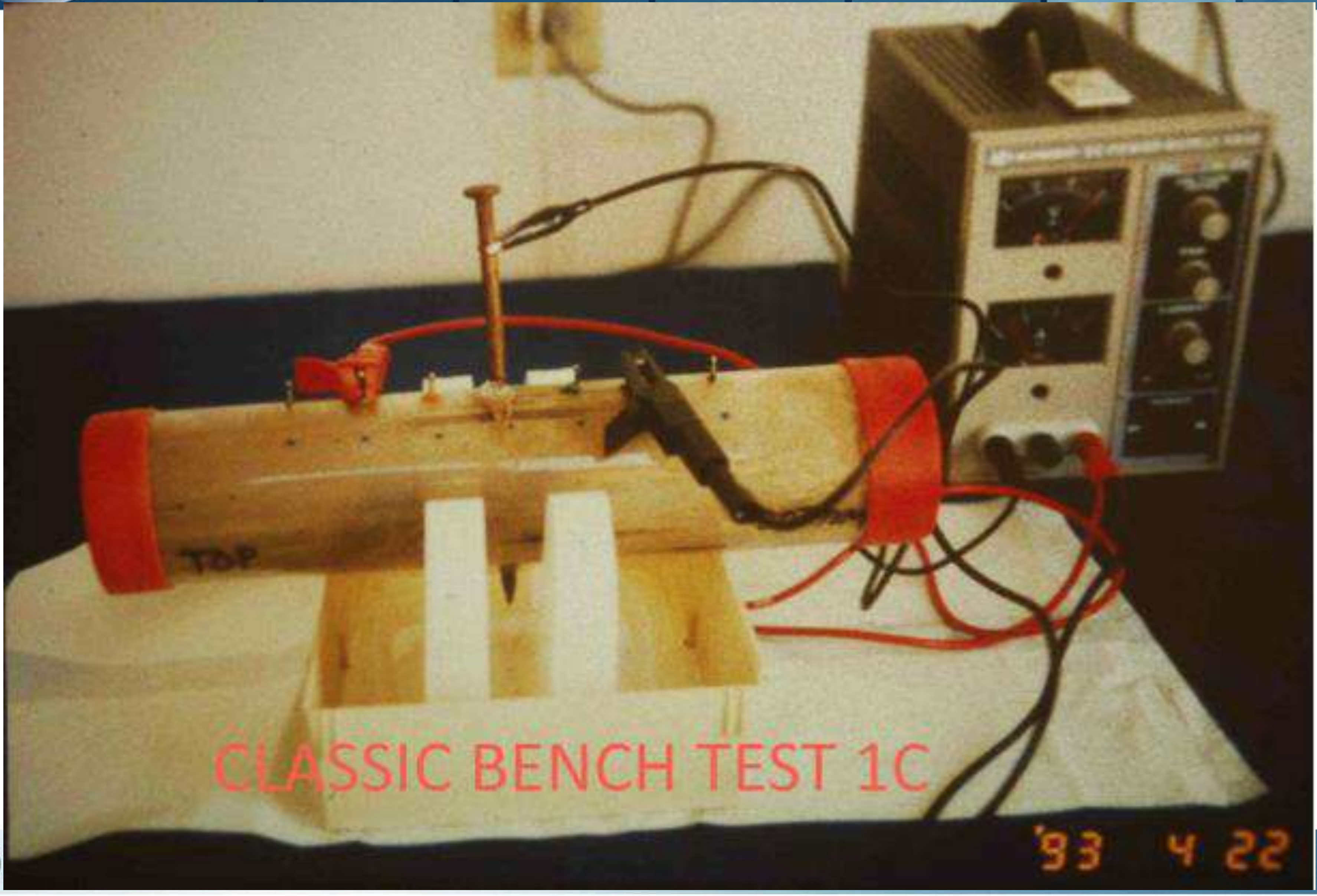


CLASSIC EK BENCH TEST 1A

EK Bench Scale Test – Cont.



EK Bench Scale Test – Cont.



CLASSIC BENCH TEST 1C

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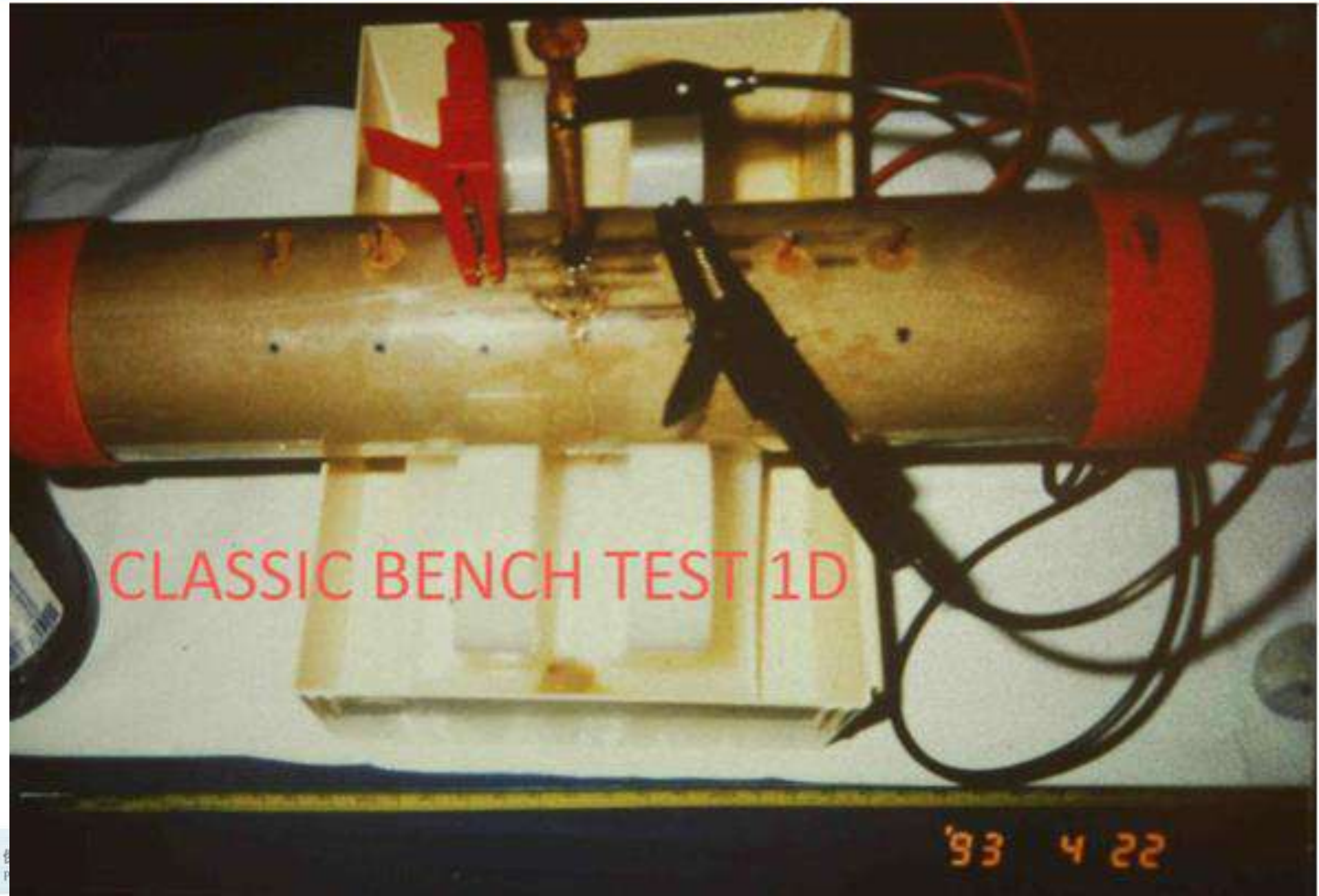
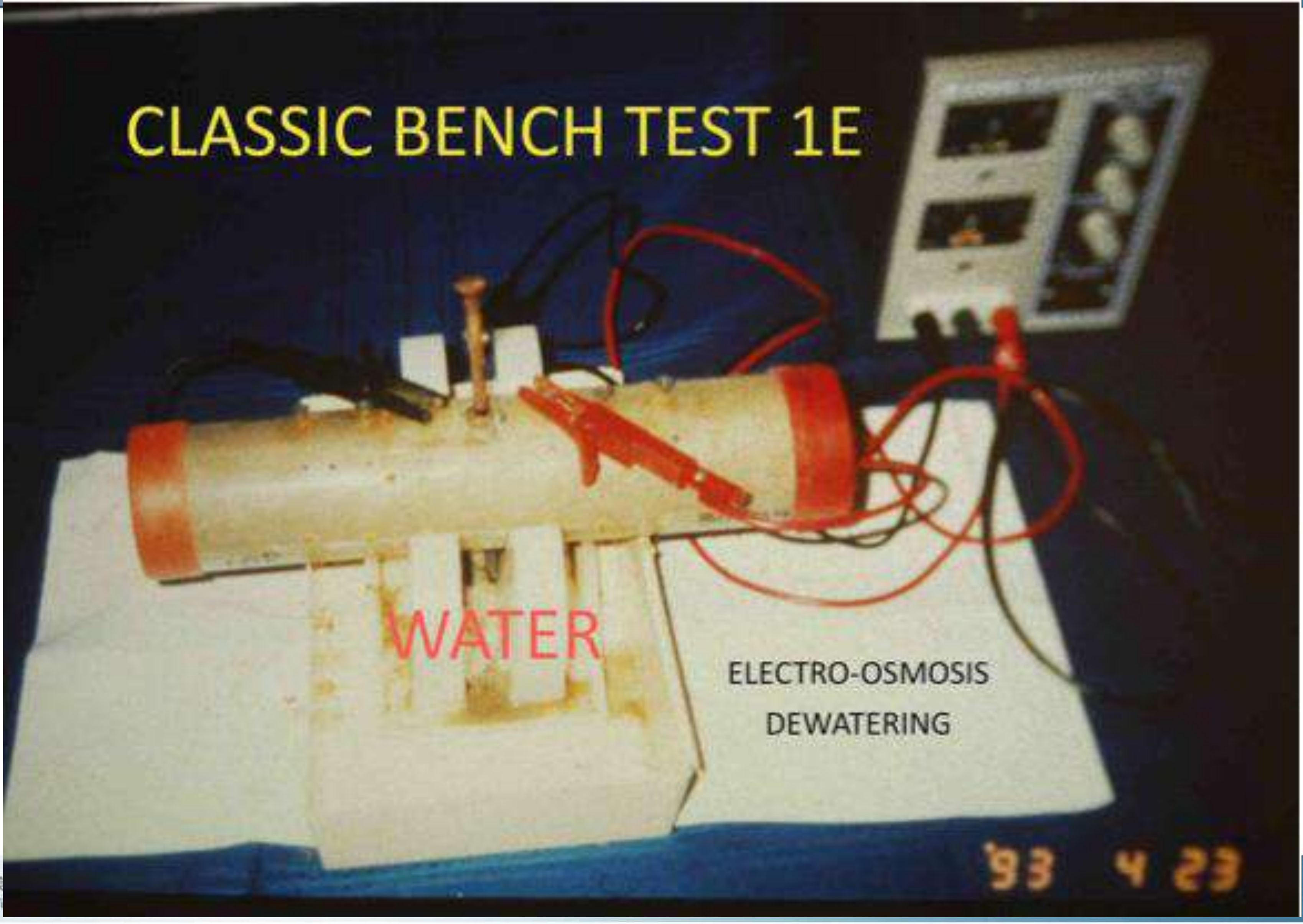
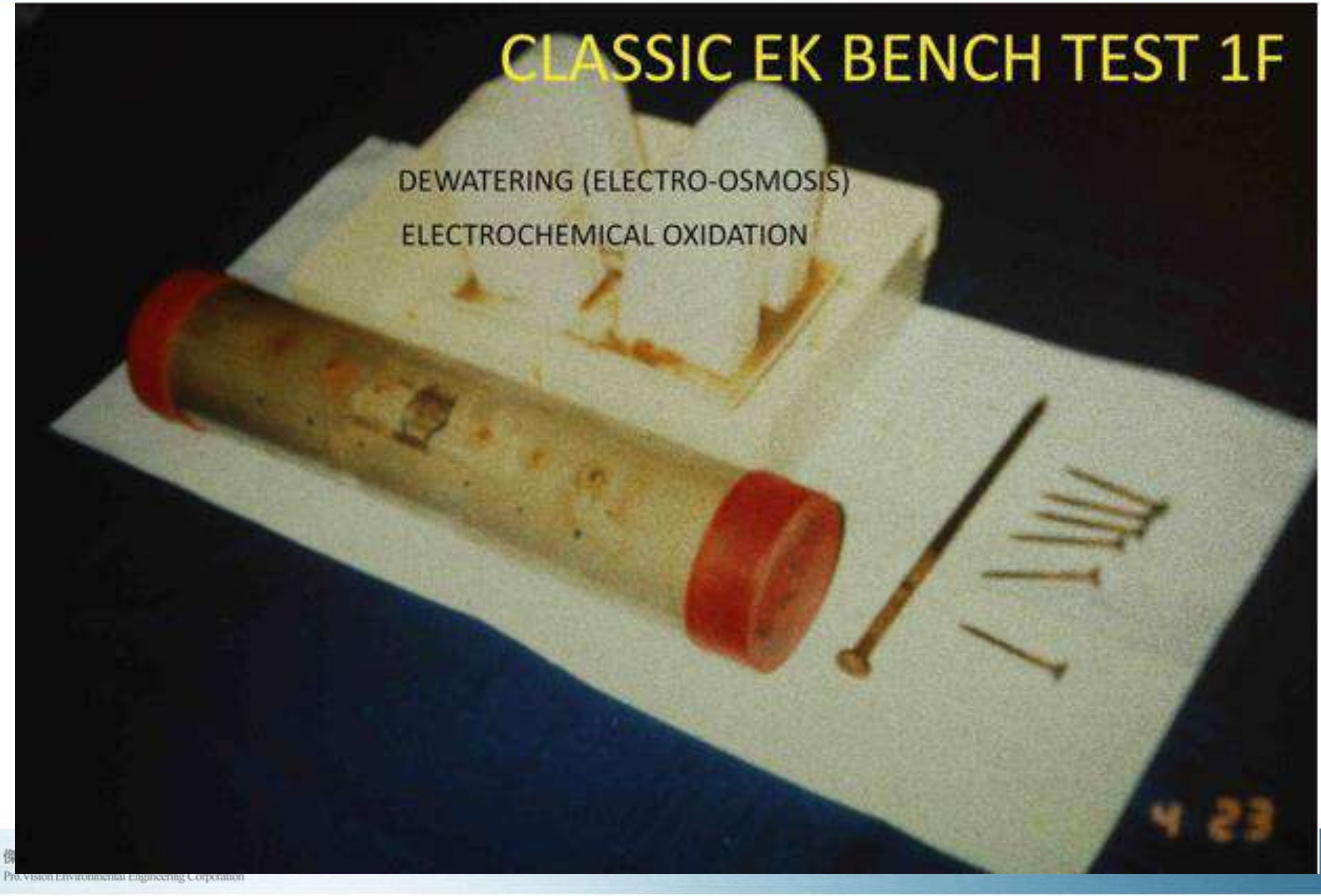
EK Bench Scale Test – Cont.



EK Bench Scale Test – Cont.



EK Bench Scale Test – Cont.



CLASSIC EK BENCH TEST 1F

DEWATERING (ELECTRO-OSMOSIS)

ELECTROCHEMICAL OXIDATION

4 23

EK Bench Scale Test Result

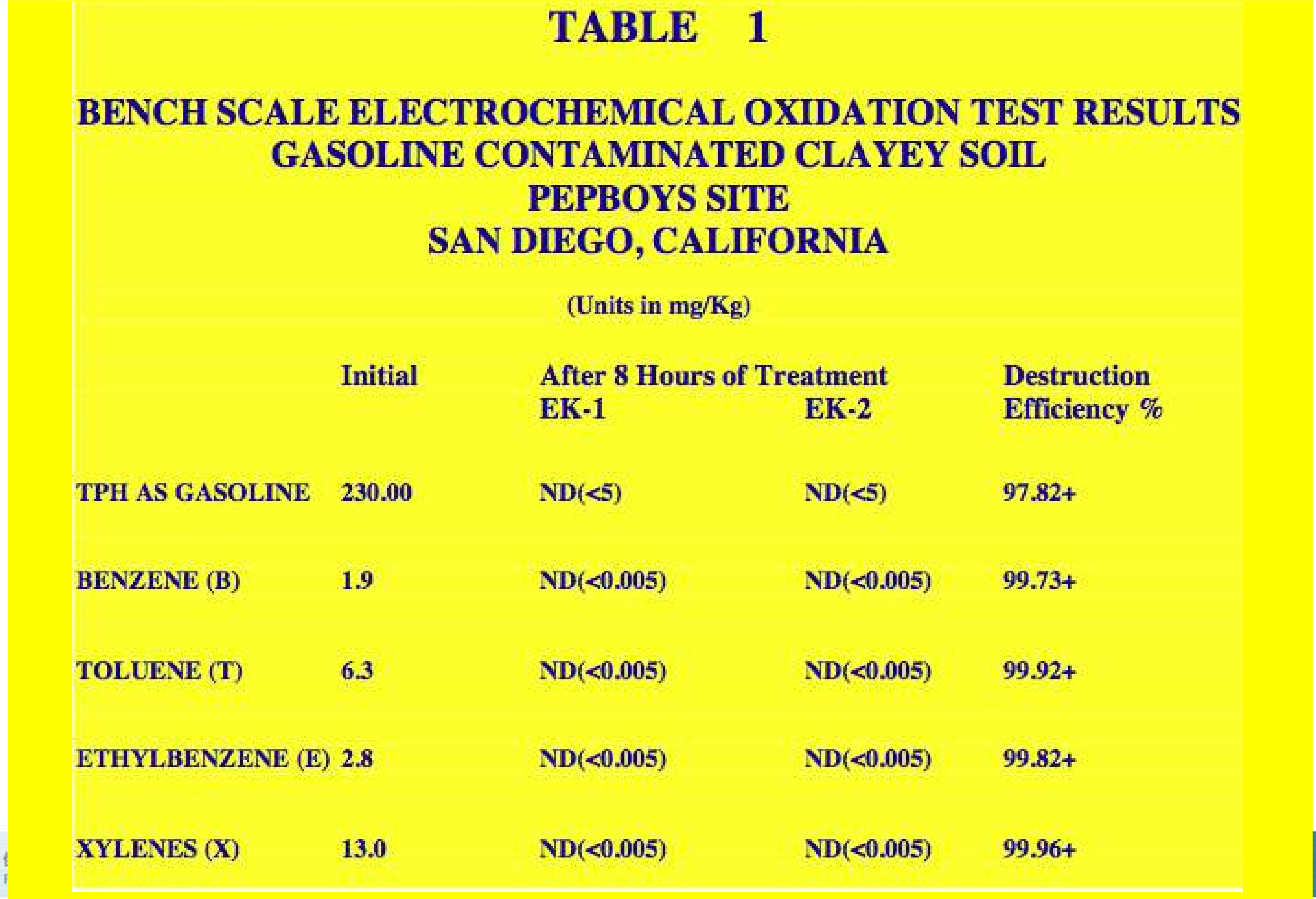


TABLE 1

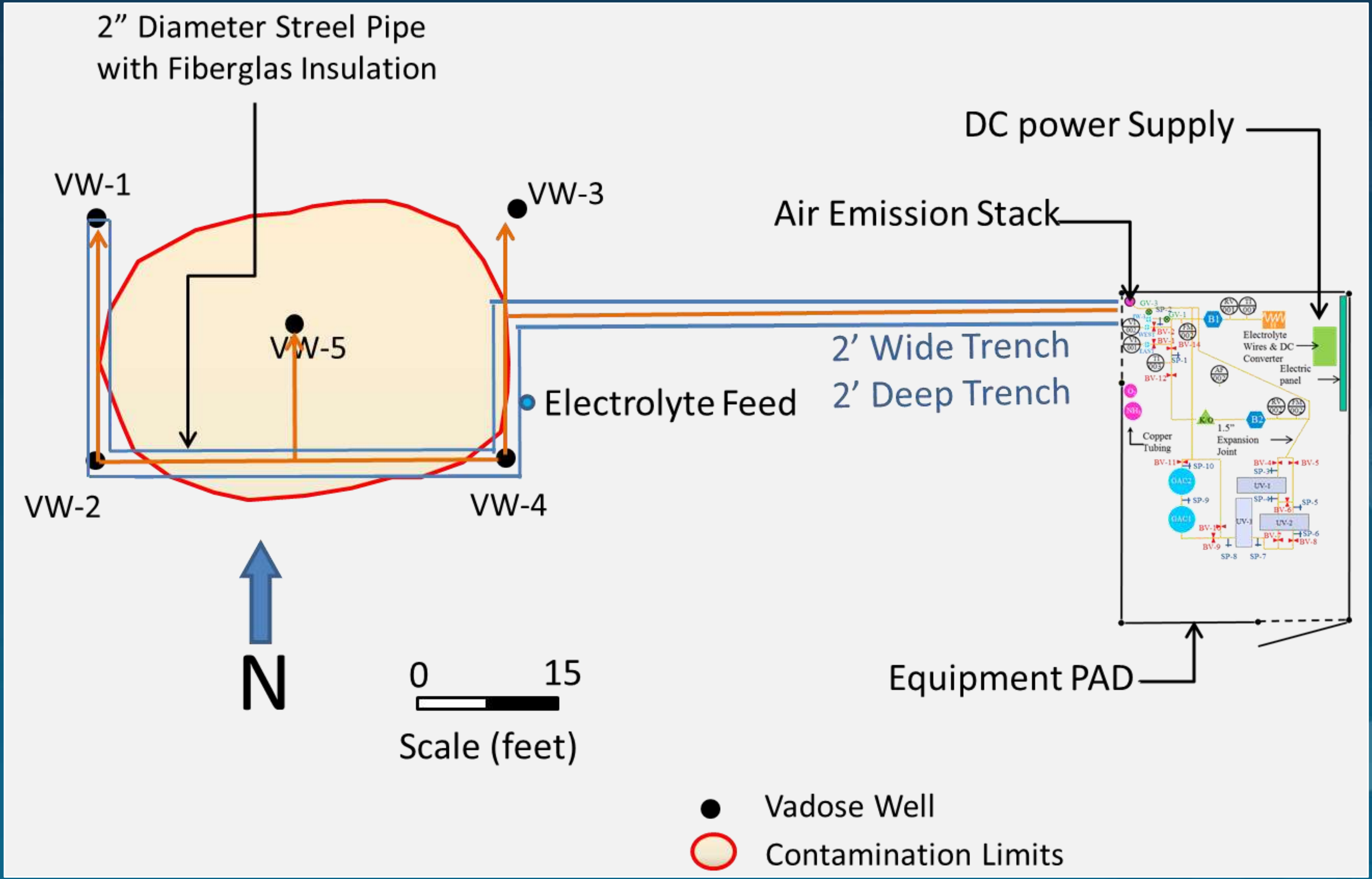
BENCH SCALE ELECTROCHEMICAL OXIDATION TEST RESULTS
GASOLINE CONTAMINATED CLAYEY SOIL
PEPBOYS SITE
SAN DIEGO, CALIFORNIA

(Units in mg/Kg)

	Initial	After 8 Hours of Treatment EK-1	EK-2	Destruction Efficiency %
TPH AS GASOLINE	230.00	ND(<5)	ND(<5)	97.82+
BENZENE (B)	1.9	ND(<0.005)	ND(<0.005)	99.73+
TOLUENE (T)	6.3	ND(<0.005)	ND(<0.005)	99.92+
ETHYLBENZENE (E)	2.8	ND(<0.005)	ND(<0.005)	99.82+
XYLENES (X)	13.0	ND(<0.005)	ND(<0.005)	99.96+

Remedial System Description

Vapor Extraction Injection System Piping Diagram

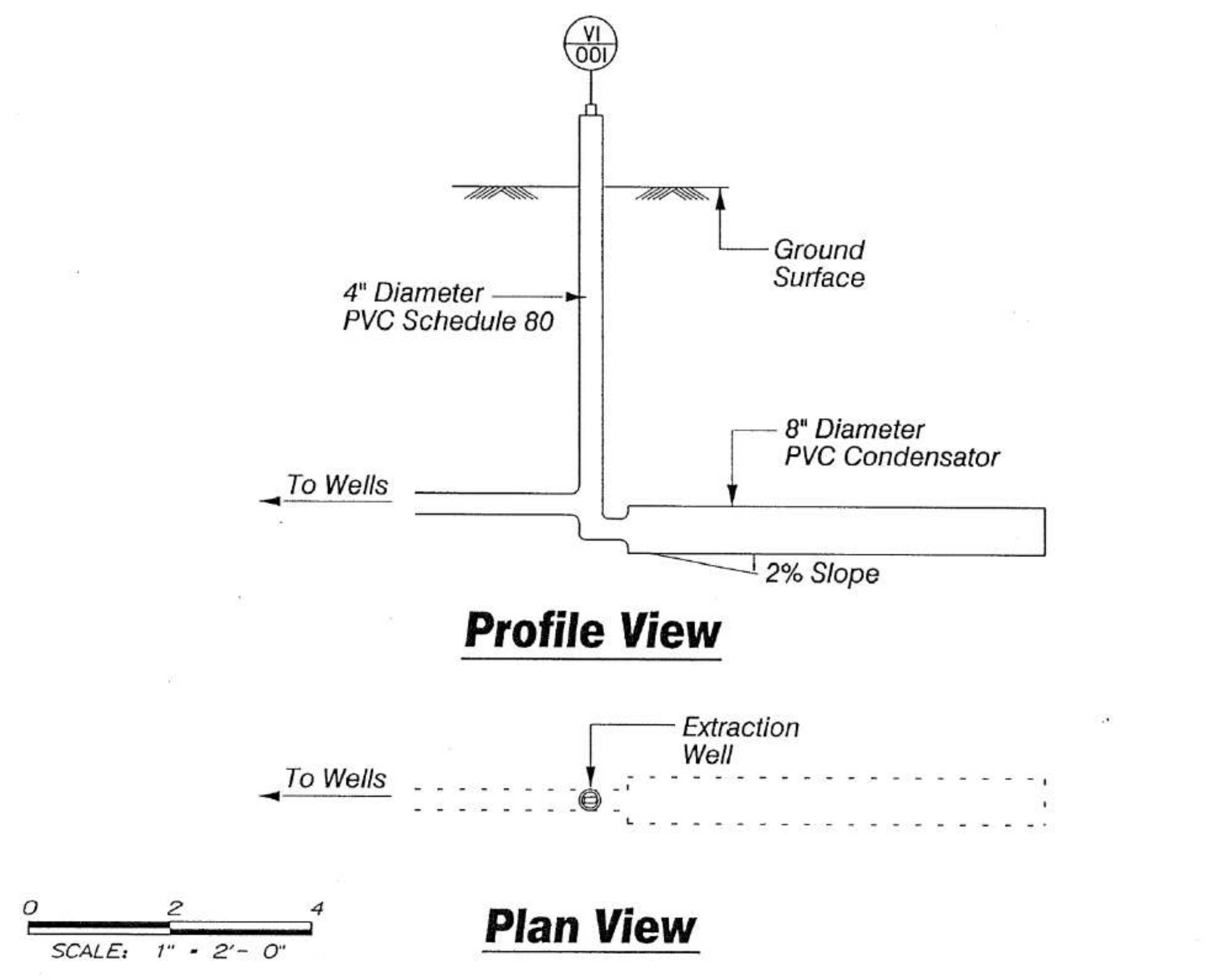


● Vadose Well

⬭ Contamination Limits

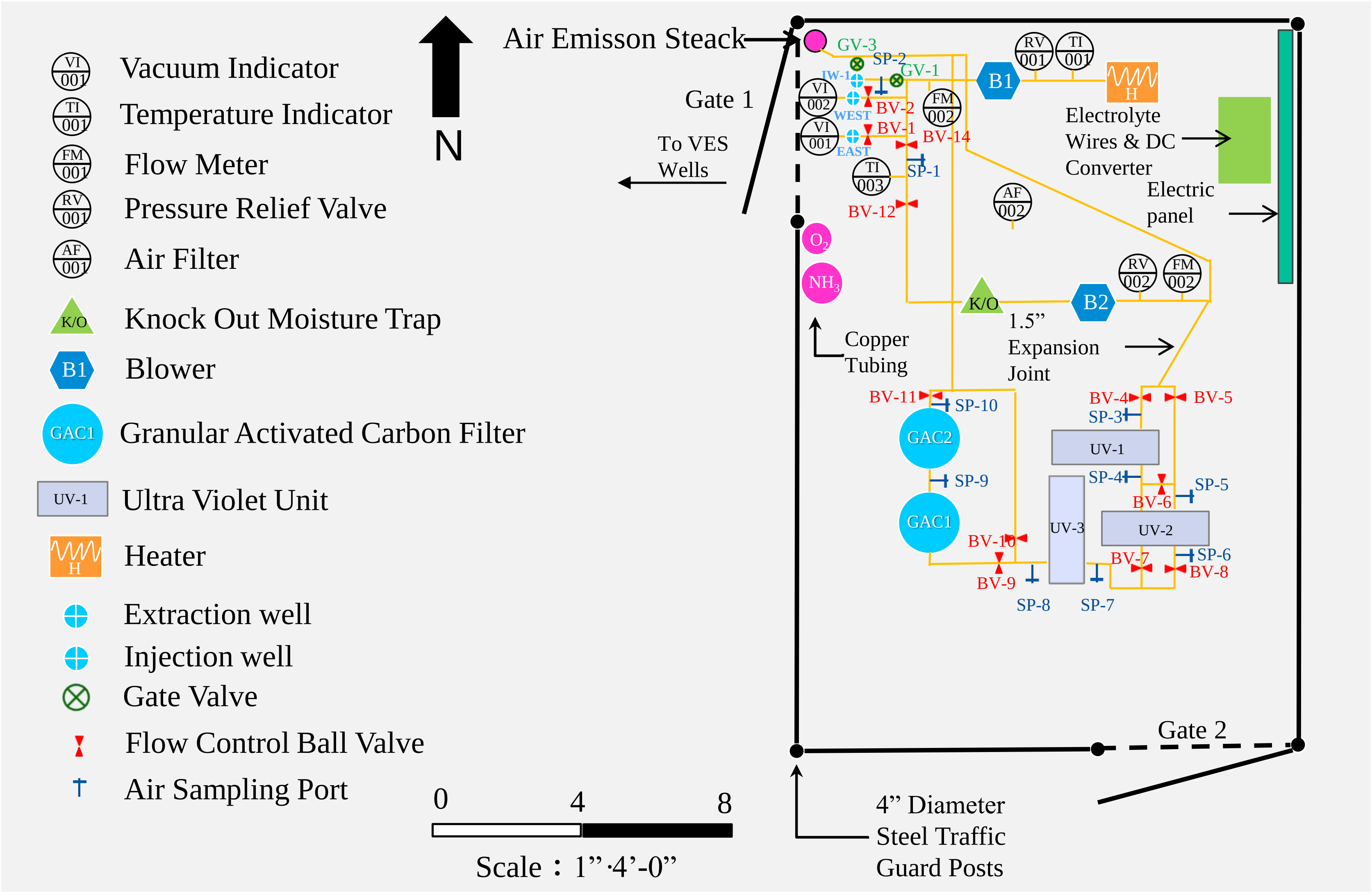
Remedial System Description

Vapor Extraction System - Condensator



Remedial System Description

Piping and Equipment Layout

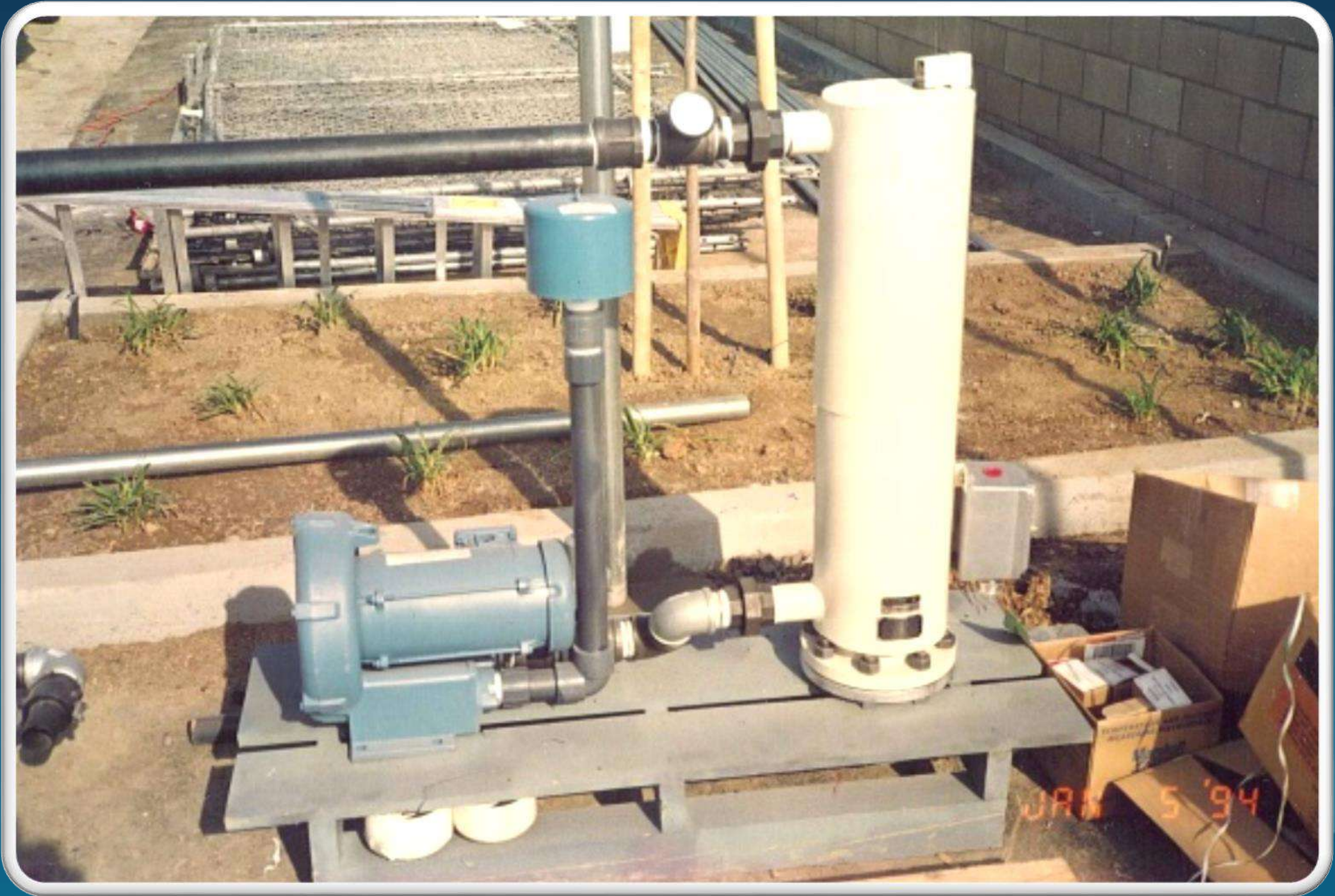


Remedial System Description

Pipe and Equipment Layout

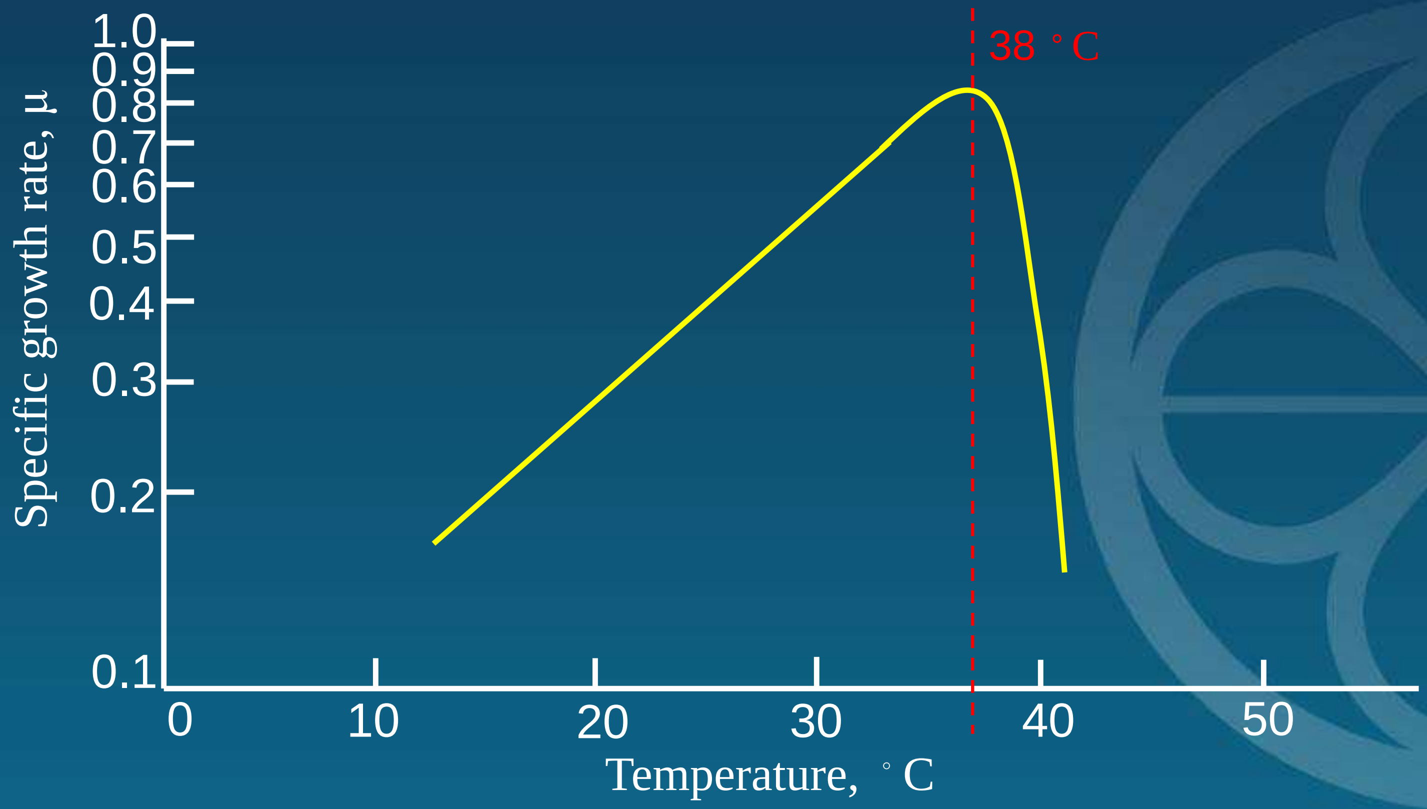
Remedial System Description

Heat Enhanced Biovention System



Remedial System Description

Temperature Effects Microbe Growth Rate



Remedial System Description

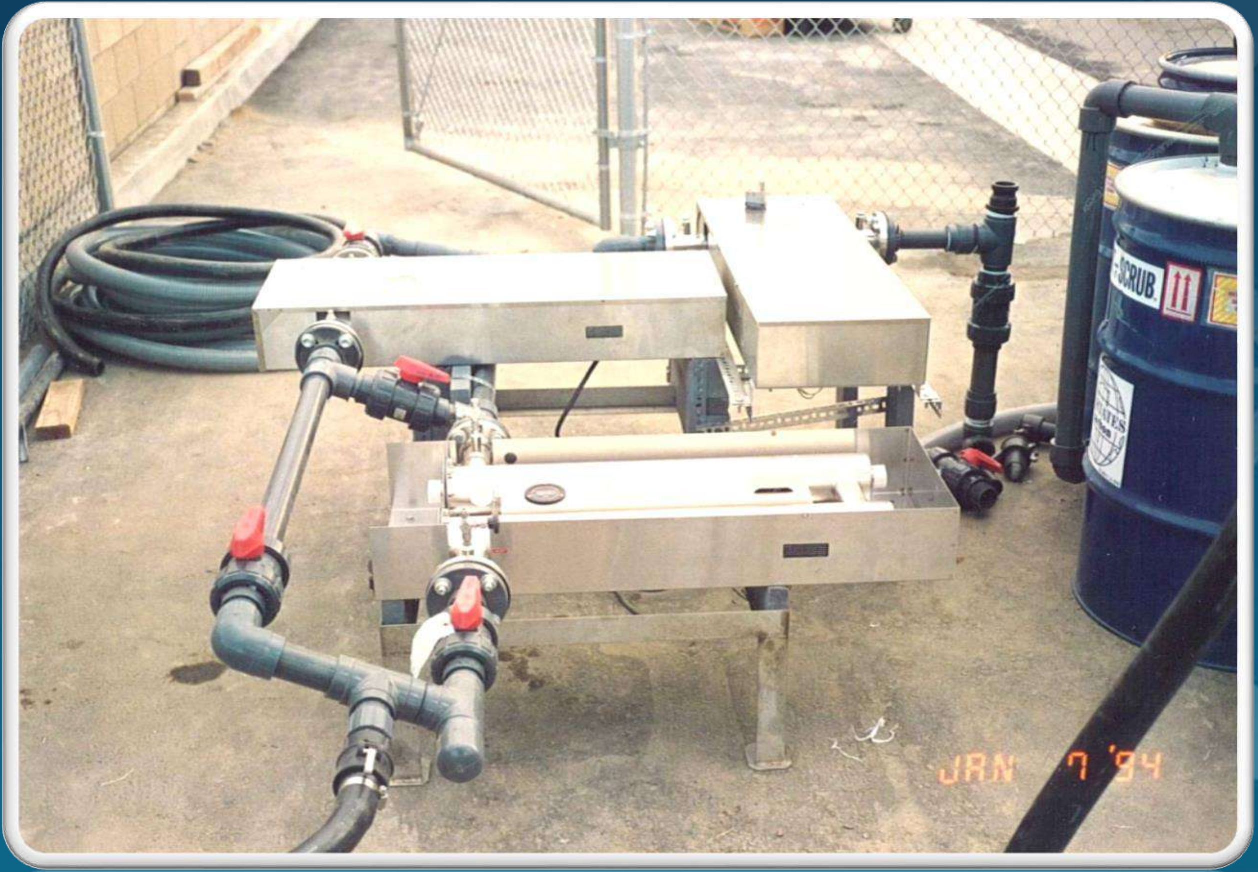
Knock Out Moisture Trap

- Removed moisture in the extracted air, Avoid condensation to block piping.

Remedial System Description

Ultraviolet (UV) Light Disinfection System

- The UV system was to eliminate bacteria in the extracted air form contaminated plume.



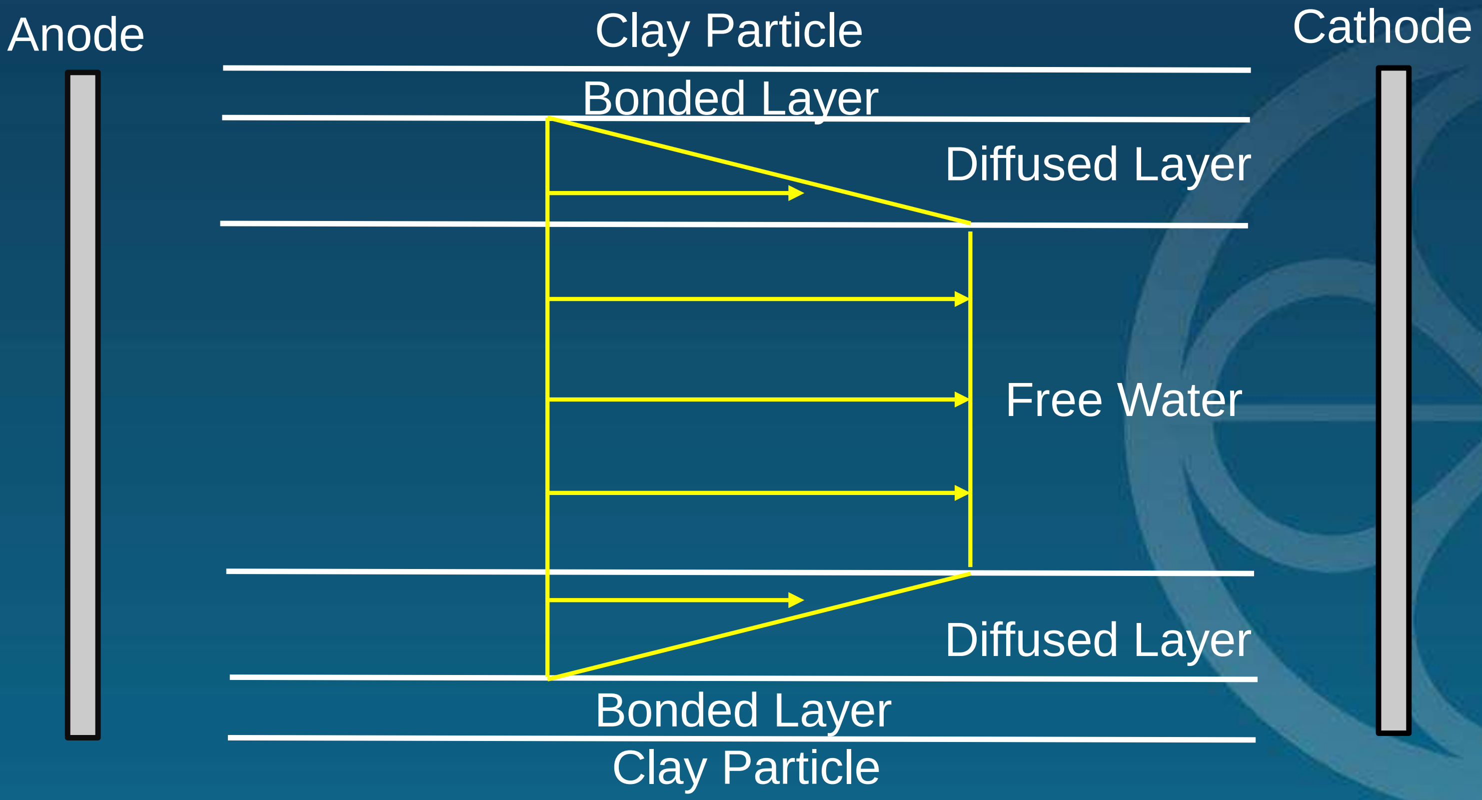
Remedial System Description

Granular Activated Carbon (GAC) Adsorption

- Two 55 gallon drums of GAC were serially installed after UV light disinfection system.
- The closed loop recirculation setup could bypass GAC or through it to injection well.

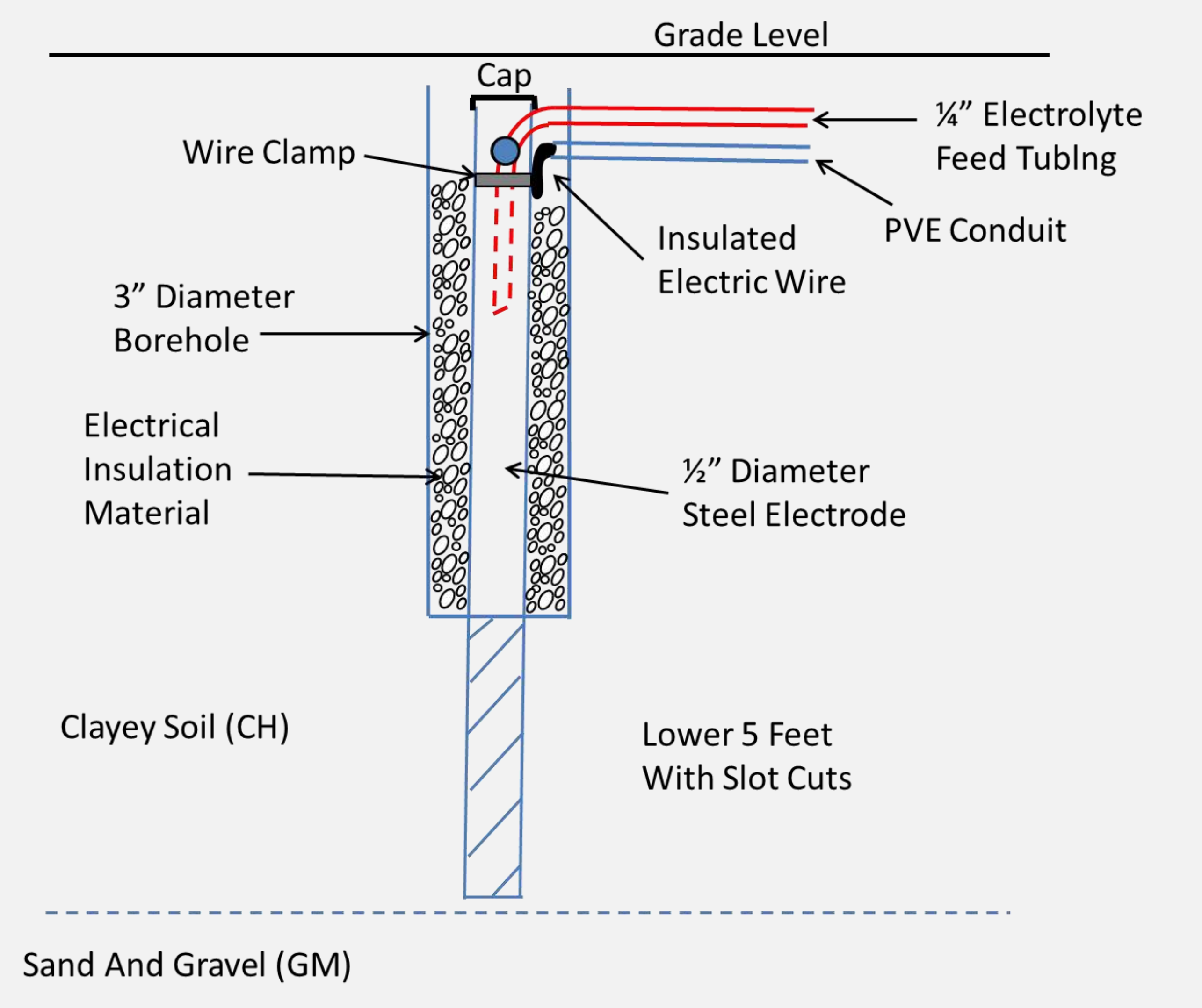
Remedial System Description

Electro-kinetic Methodology – Electro-Osmotic Flow in Capillaries



Remedial System Description

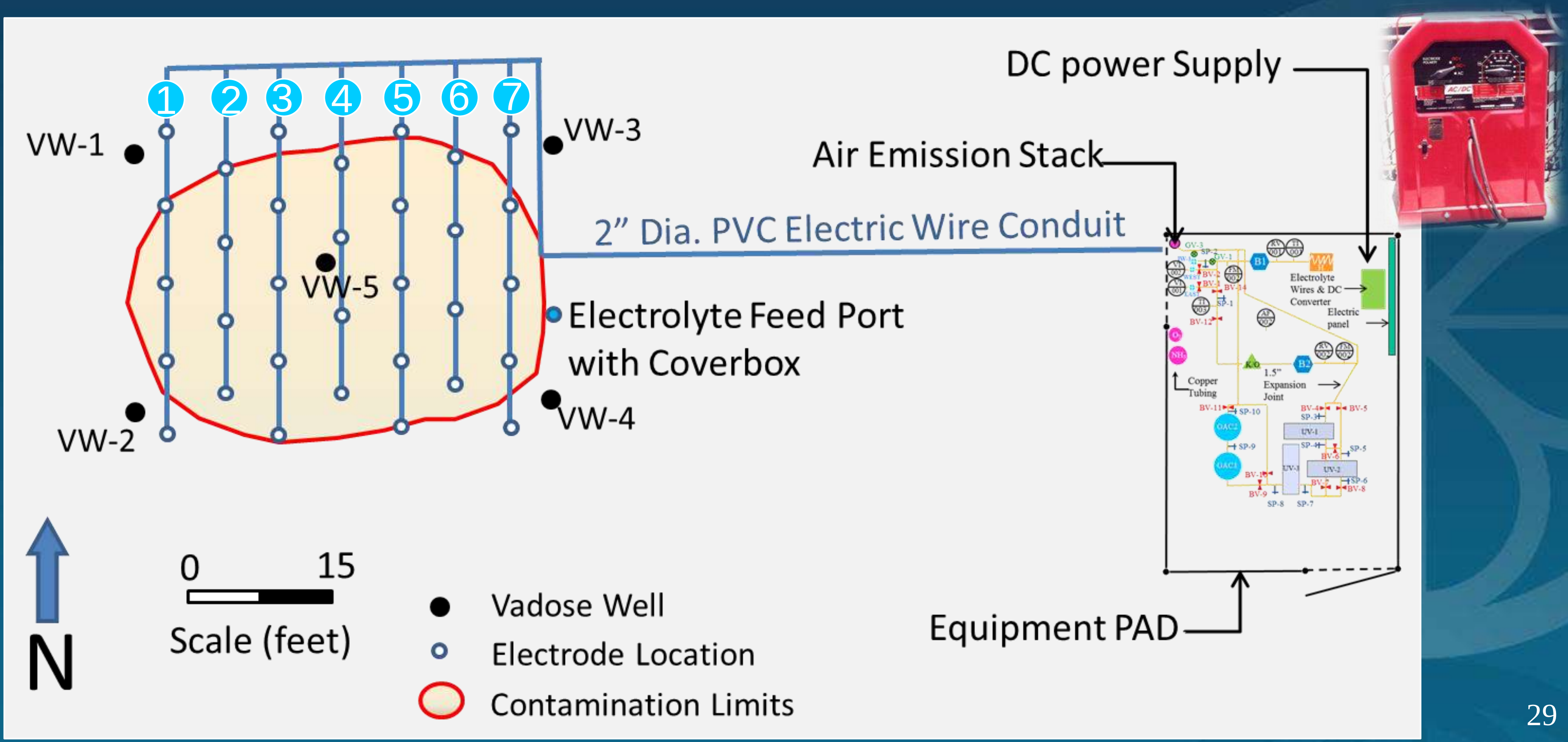
Electro Installation Diagram



Remedial System Description

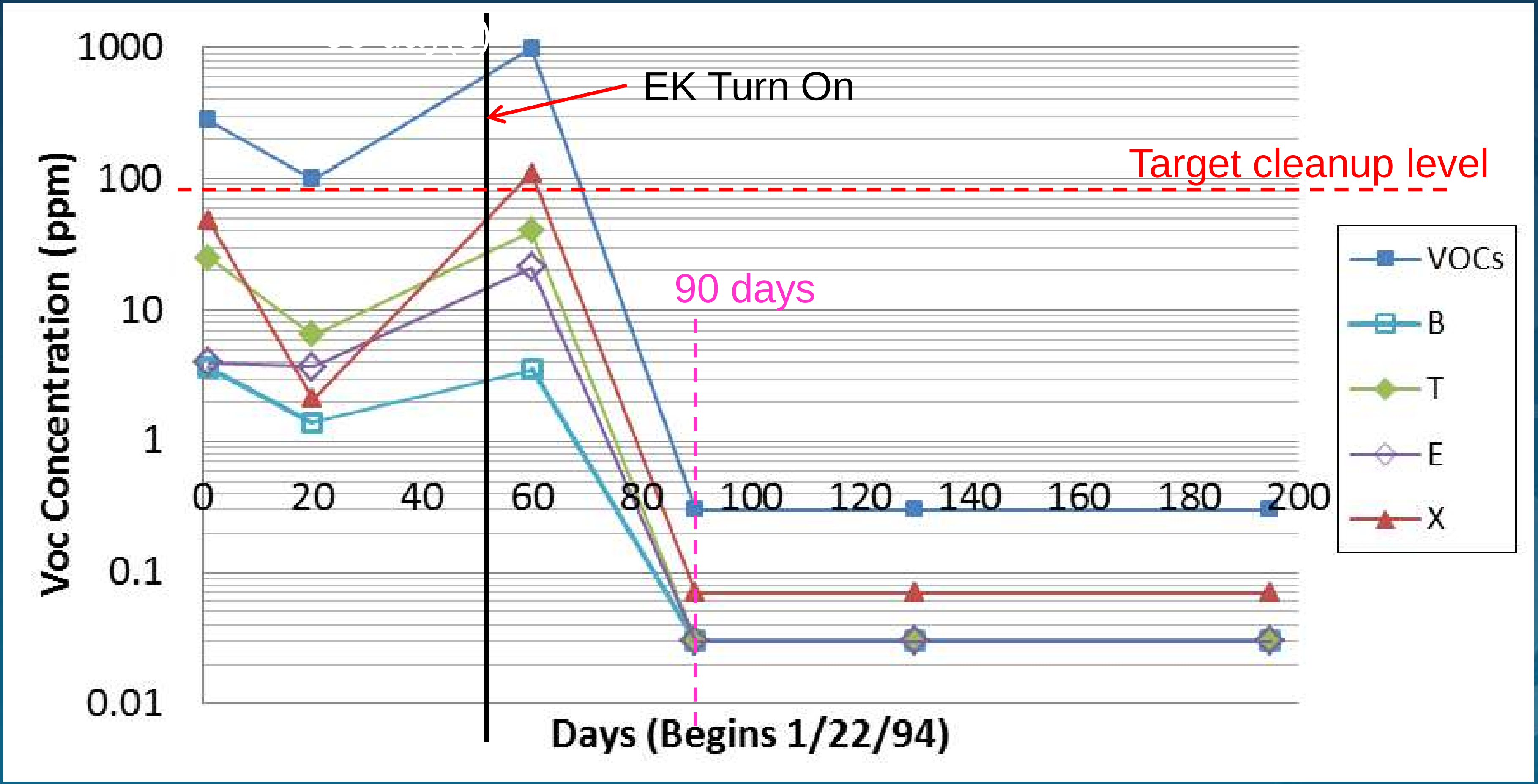
Electro-kinetic Treatment System

- The 39 electrodes was connected to DC power supply.
- Electricity flow was operated at about 10 to 15 ampere.



Field Analysis Data

VOCs Concentration



EK Turn On

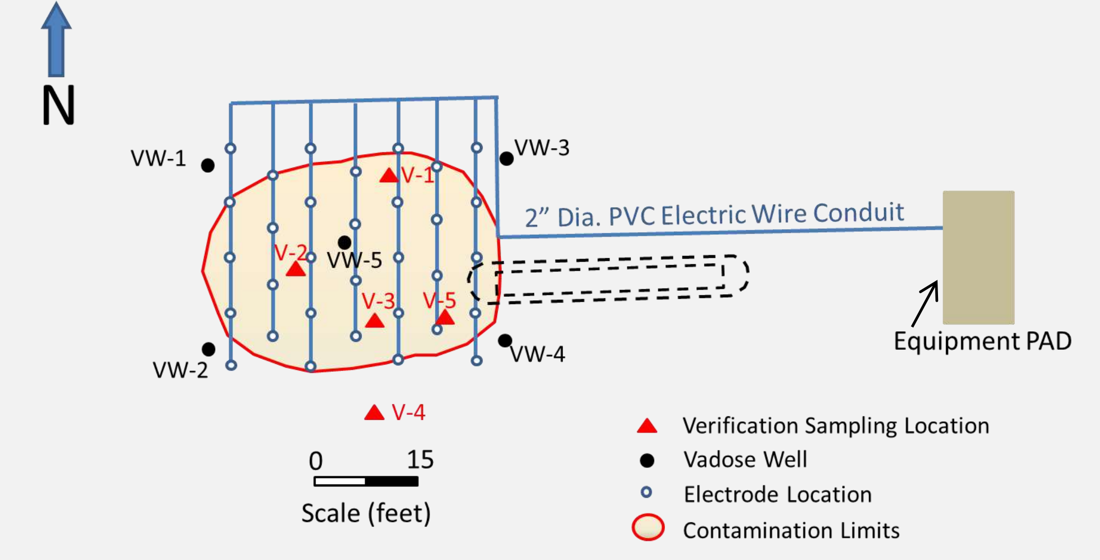
Target cleanup level

90 days

Confirmation Result

Confirmation Drilling

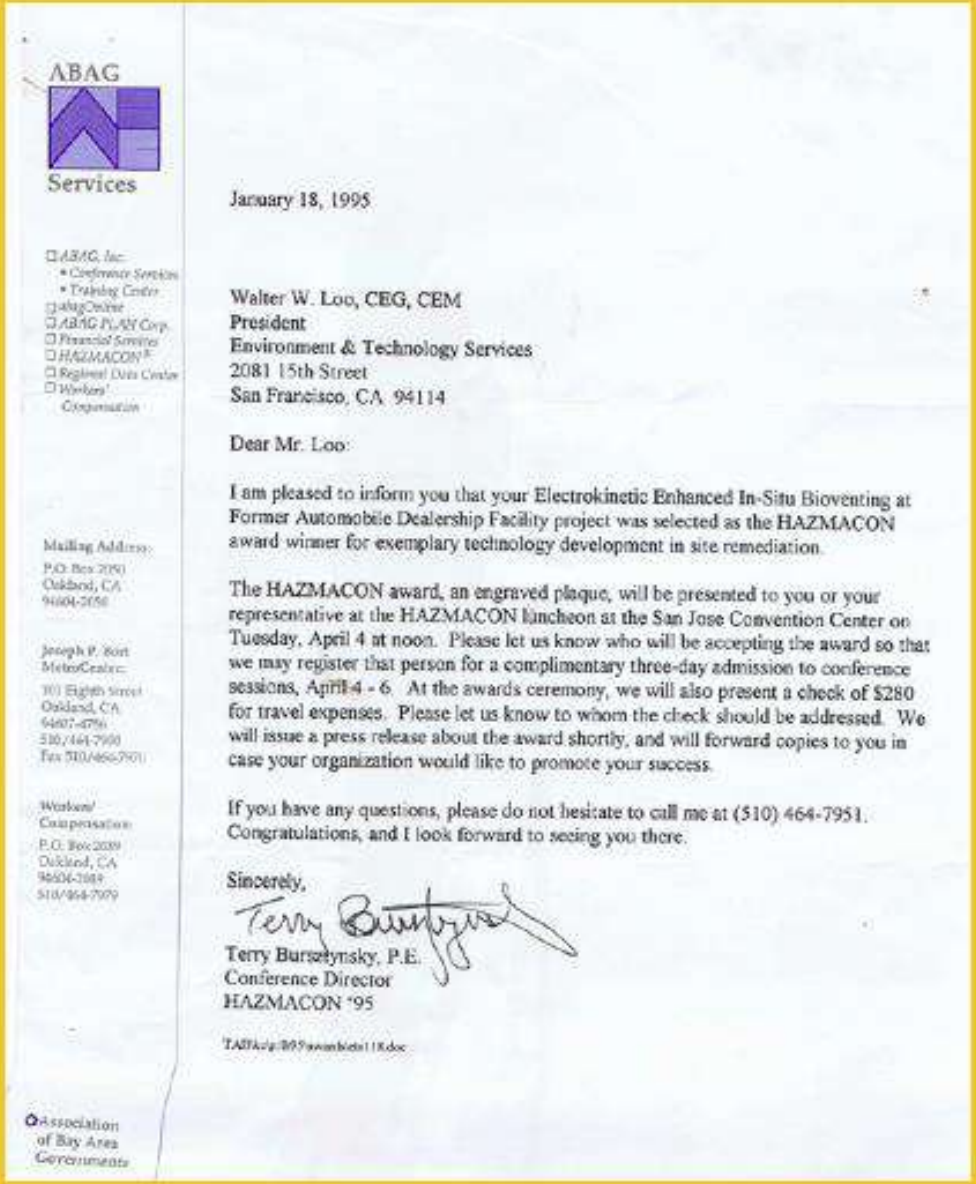
Sampling depth intervals：10, 15, 20, 25, and 30 (ft)



Sample ID	TPH as Gasoline (ppm)	B (ppm)	T (ppm)	E (ppm)	X (ppm)
V1-10'	ND	ND	ND	ND	ND
V1-15'	1.2	0.0079	0.039	0.0098	0.073
V1-20'	ND	ND	ND	ND	ND
V1-25'	ND	ND	ND	ND	ND
V1-26'	ND	ND	ND	ND	ND
V2-1-10'	0.1	0.017	0.013	ND	ND
V2-2-15'	1.7	0.048	0.062	0.015	0.069
V2-3A-20'	ND	ND	ND	ND	ND
V2-3B-20'	ND	ND	ND	ND	ND
V2-4-26'	ND	ND	ND	ND	ND
V2-5-30'	ND	ND	ND	ND	ND
V3-1-10'	ND	ND	ND	ND	ND
V3-2-15'	170	1	9	3.5	19
V3-3-20'	220	ND	1	2.5	18
V3-4-31'	290	0.22	1.8	2.7	15
V4-1-10'	ND	ND	ND	ND	ND
V4-2-15'	1.3	0.033	0.15	0.03	0.22
V4-3-20'	4.4	0.047	0.3	0.099	0.72
V4-4A-25.5'	12	ND	ND	ND	ND
V4-4B-25.5'	11	ND	0.0087	0.05	0.42
V5-1A-10'	ND	ND	ND	ND	ND
V5-1B-10'	0.28	ND	ND	ND	ND
V5-2A-15'	126	3.6	11	1.2	6.6
V5-2B-15'	3.4	ND	0.09	0.046	0.27
V5-3-20'	14	ND	0.14	0.1	0.69
V5-4-26	98	0.0085	1.4	1.6	12
Average	36.707	0.156	0.964	0.458	2.815

Conclusion

- Two 120 cfm explosion proof blowers were operated with 35~70 cfm
- The remediation effort was completed about 90 days.
- The average concentration was below the proposed cleanup level 100 ppm.
- The cost of treatment is about $50 per ton.
- The technology provides a cost effective and minimum disruption to business to operation.



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Association
of Bay Area
Governments

January 18, 1995

Walter W. Loo, CEG, CEM
President
Environment & Technology Services
2081 15th Street
San Francisco, CA 94114

Dear Mr. Loo:

I am pleased to inform you that your Electrokinetic Enhanced In-Situ Bioventing at Former Automobile Dealership Facility project was selected as the HAZMACON award winner for exemplary technology development in site remediation.

The HAZMACON award, an engraved plaque, will be presented to you or your representative at the HAZMACON luncheon at the San Jose Convention Center on Tuesday, April 4 at noon. Please let us know who will be accepting the award so that we may register that person for a complimentary three-day admission to conference sessions, April 4 - 6. At the awards ceremony, we will also present a check of $280 for travel expenses. Please let us know to whom the check should be addressed. We will issue a press release about the award shortly, and will forward copies to you in case your organization would like to promote your success.

If you have any questions, please do not hesitate to call me at (510) 464-7951. Congratulations, and I look forward to seeing you there.

Sincerely,

Terry Bursztynsky, P.E.
Conference Director
HAZMACON '95

HAZMACON
AWARD
1995

For exemplary technology development
in site remediation,

HAZMACON honors

Environment and Technology Services,
for Electrokinetic Enhanced In-Situ Bioventing
at a Former Automobile Dealership Facility

Presented at HAZMACON '95
San José, California
April 4, 1995

Case 2：

Advanced vapor extraction system enhanced biodegradation of gasoline

Site Introduction

- A 1,000 gallon of underground storage tank of waste oil was spill, in Anaheim, California.
- The soil plume covered an area of about 900 (ft^2) and to a depth of about 15 (ft).
- The site was underlain by alluvial soils which were composed of loose sands.
- The soil was contaminated, but groundwater was not.
- Total waste oil in the plume was estimated at about 12,000 pounds in about 700 tons of soil.

Site Introduction

- The TPH concentration in the soil plum was range from 7,100 to 15,000 (ppm).
- The target cleanup level: TPH as gasoline and TPH as diesel were 100(ppm), TPH as waste oil was 1,000(ppm).

Problem

Find problem

- Using open excavation pit was not an economic option.
- Operating Equipment Rental Site

Solve problem

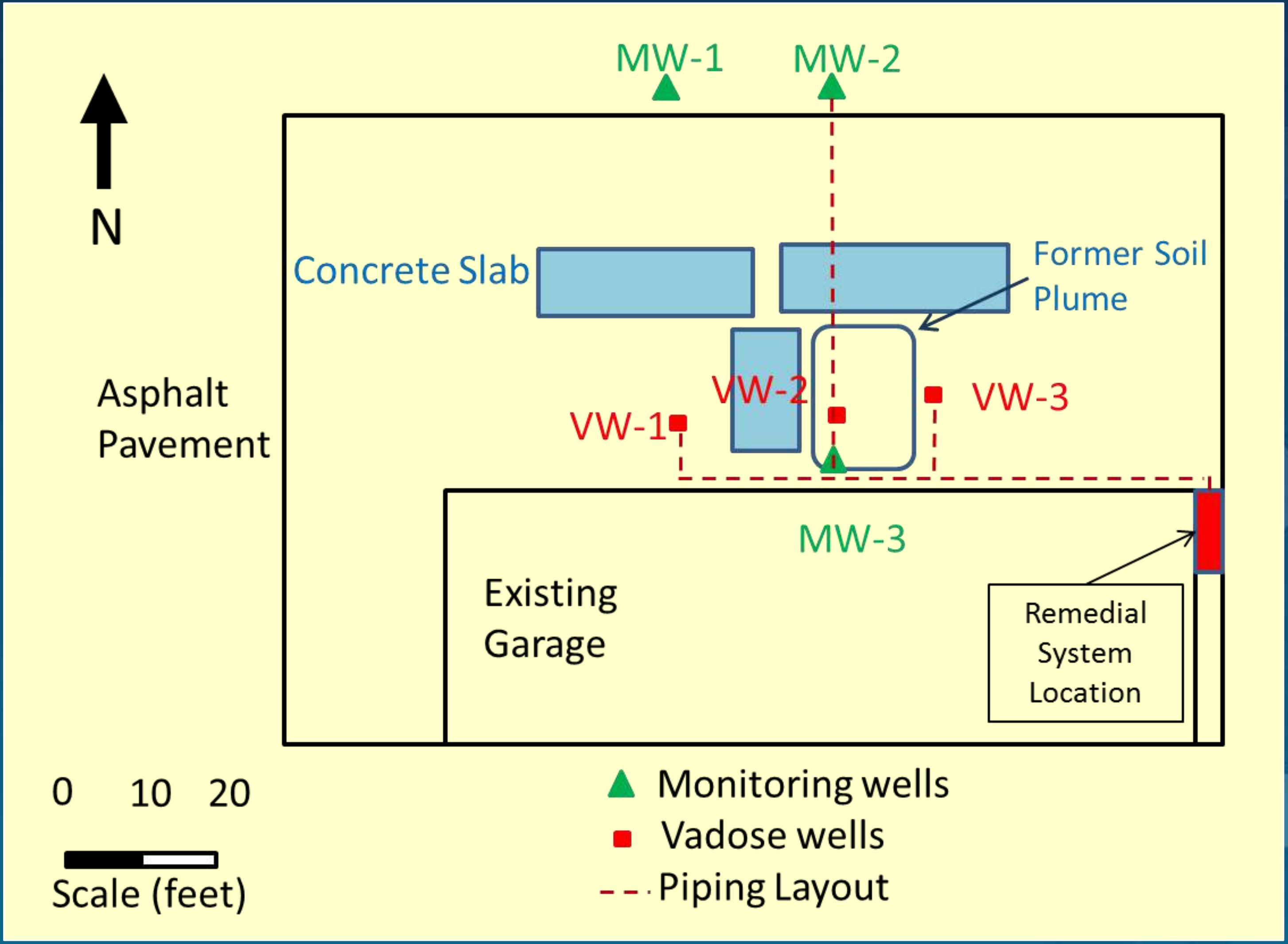
- The advanced vapor extraction could mediate the TPH concentration in the soil.
- The technology provided a cost effective and minimum disruption of business operation.

Field Construction

Monitoring Well Installation

Field Construction

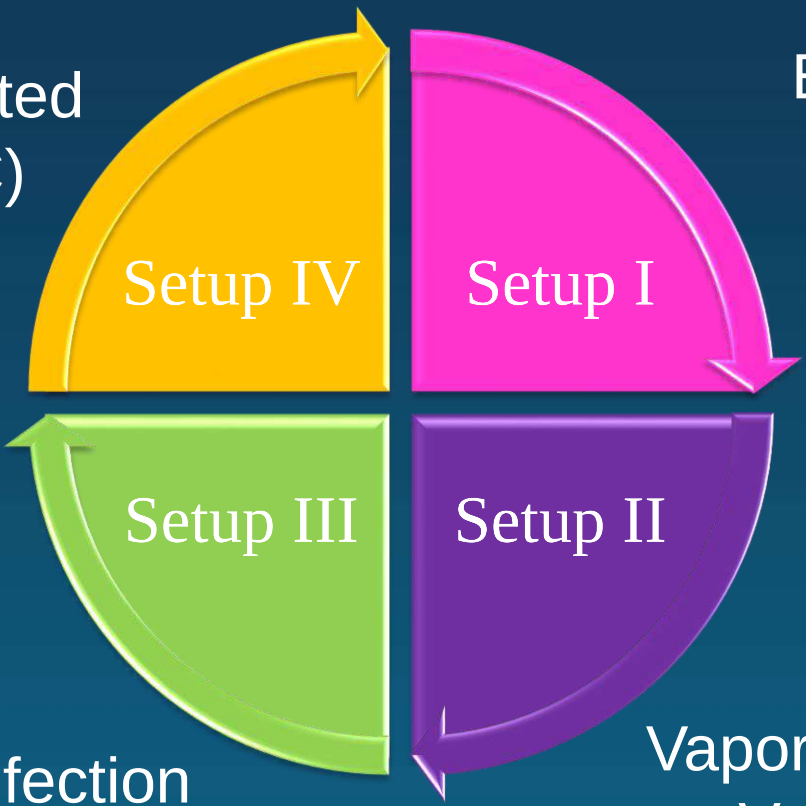
Well & Remedial System Layout



Field Construction

Piping and Vapor Extraction System

Remedial System Description



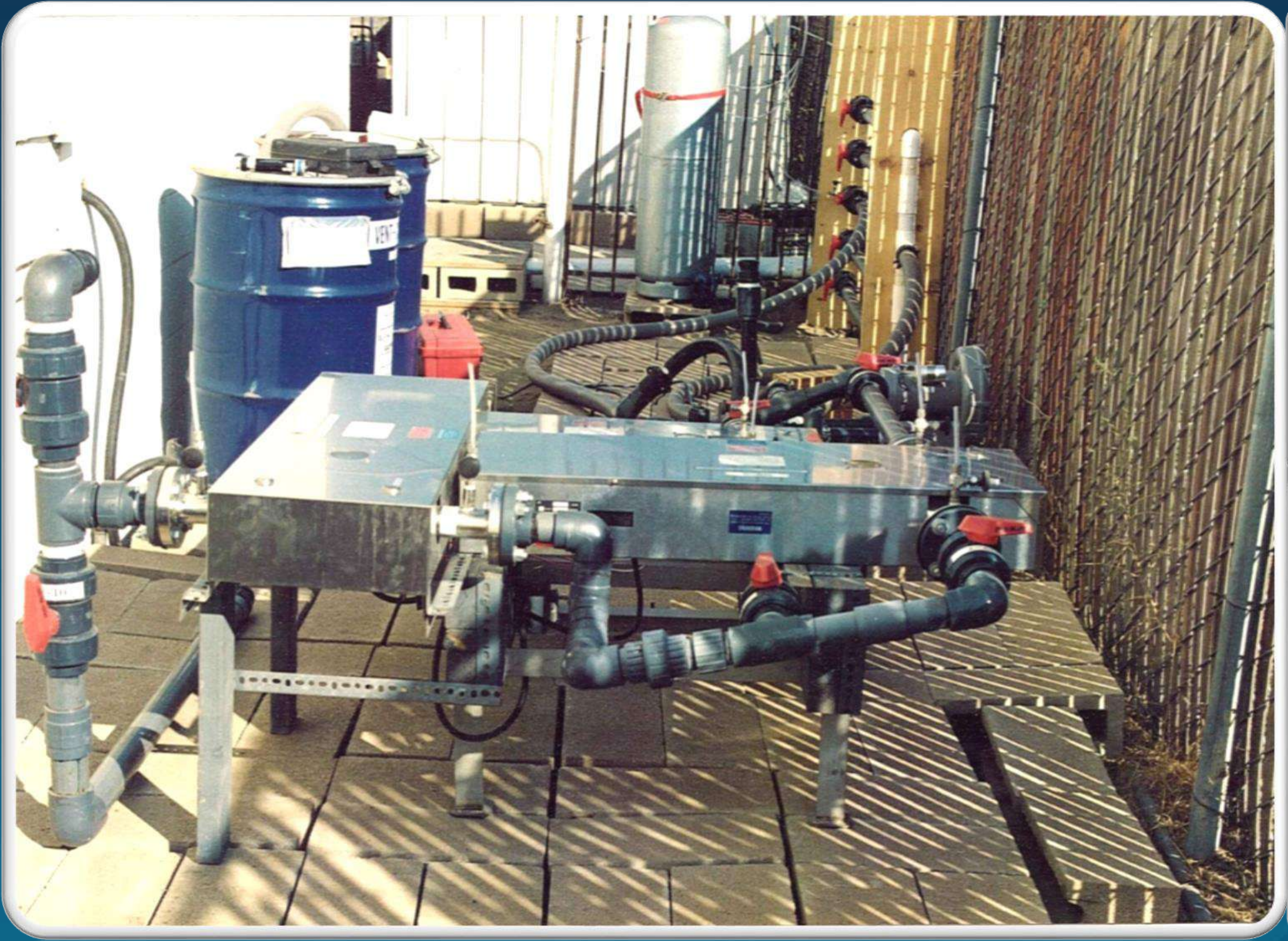
Granular Activated
Carbon (GAC)
adsorption

Existing Wells
-injected
-extracted

UV Light Disinfection
Bacteria System

Vapor Extraction system
-Vacuum blowers
-moisture condensation

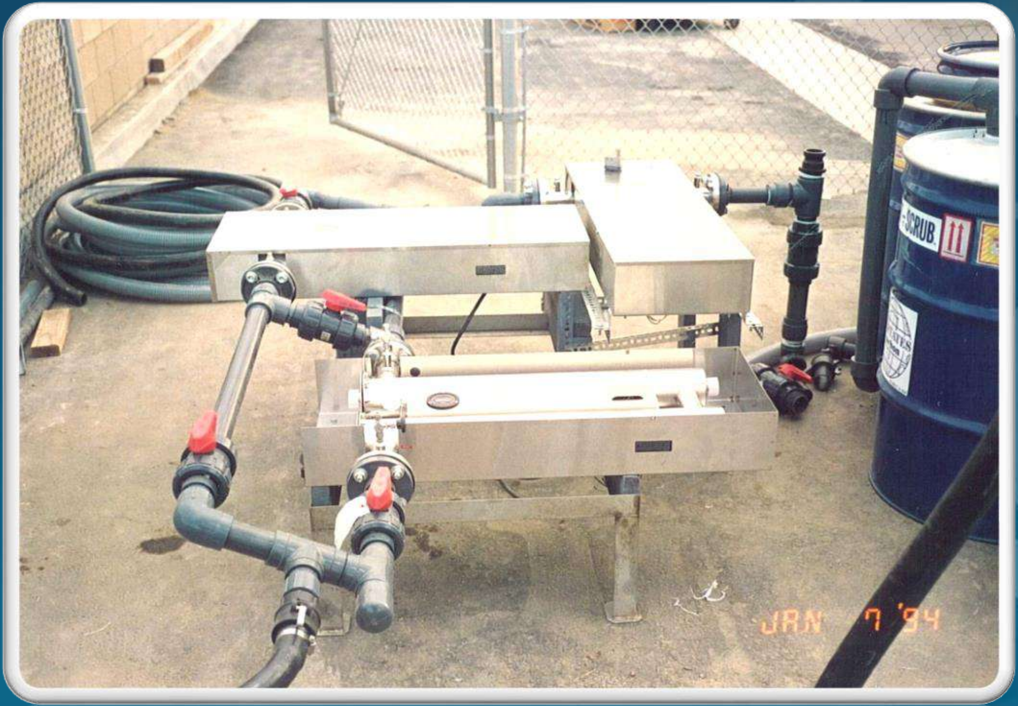
Remedial System Description



Remedial System Description

Ultraviolet (UV) Light Disinfection System

- Three UV light units were connected in series or parallel by switched control ball valves.
- The UV system was to eliminate bacteria in the extracted air from contaminated plume.



Remedial System Description

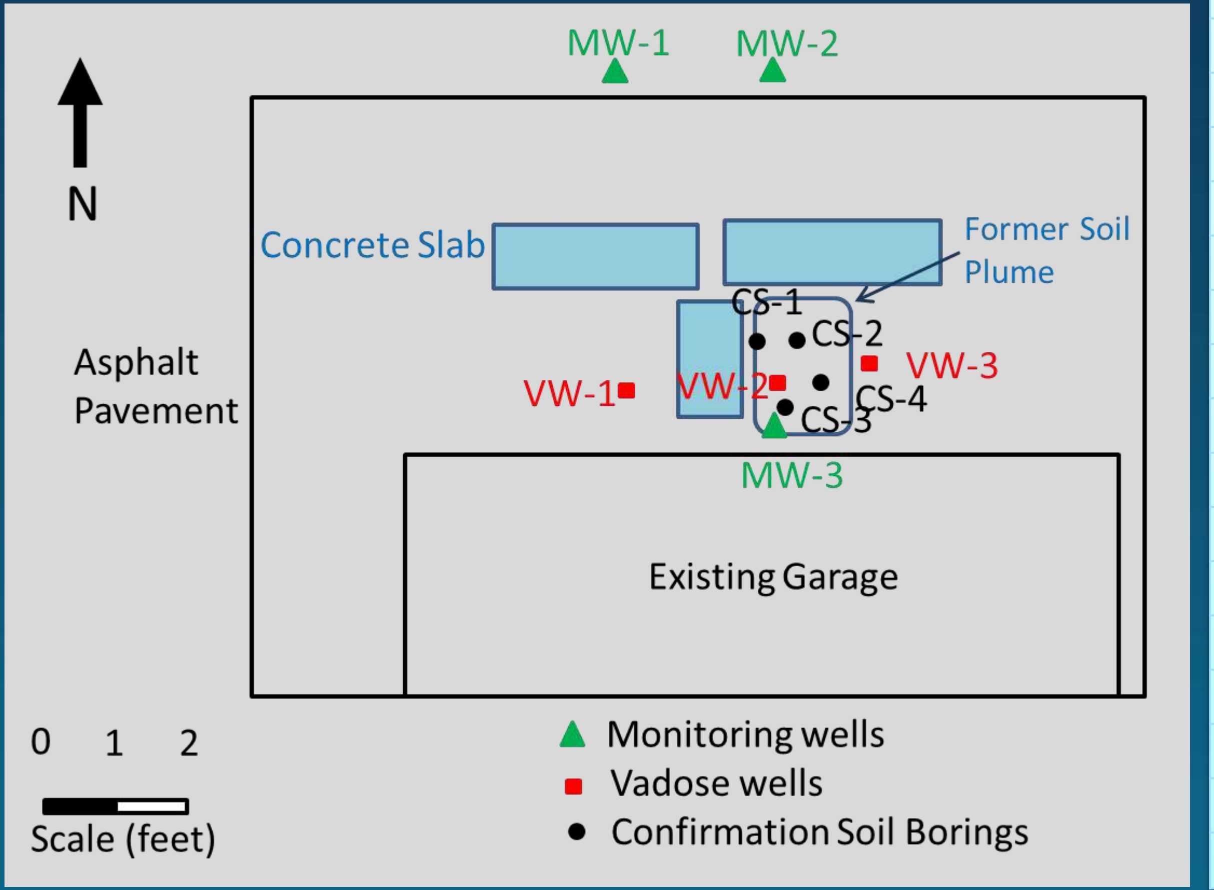
Granular Activated Carbon (GAC) Adsorption

- Two 55 gallon drums of GAC were serially installed after UV light disinfection system.
- The closed loop recirculation setup could bypass GAC or through it to injection well.

Confirmation Result

Confirmation Drilling

Sampling depth intervals：5, 10, and 15 (ft)



Sample ID	TPH (ppm)			Tox (ppm)
	Gasoline	Diesel	Oil	
CS-1-05	ND	ND	ND	ND
CS-1-10	ND	ND	ND	ND
CS-1-15	ND	ND	210	ND
CS-2-05	ND	ND	ND	ND
CS-2-10	ND	ND	ND	ND
CS-2-15	ND	ND	ND	ND
CS-3-05	ND	200	ND	ND
CS-3-10	ND	24	160	ND
CS-3-15	ND	160	420	ND
CS-4-05	ND	ND	ND	ND
CS-4-10	ND	ND	ND	ND
CS-4-15	ND	ND	ND	ND
A.C.L	100	100	1,000	1
Min. Ave.	ND	36.9	65.8	ND
Max. Ave.	ND	43.6	140.8	ND

Conclusion

- The remediation effort was completed about 90 days.
- The concentration was way below the proposed cleanup.
- The cost of treatment is about $50 per ton.
- The technology provides a cost effective and minimum disruption to business to operation.

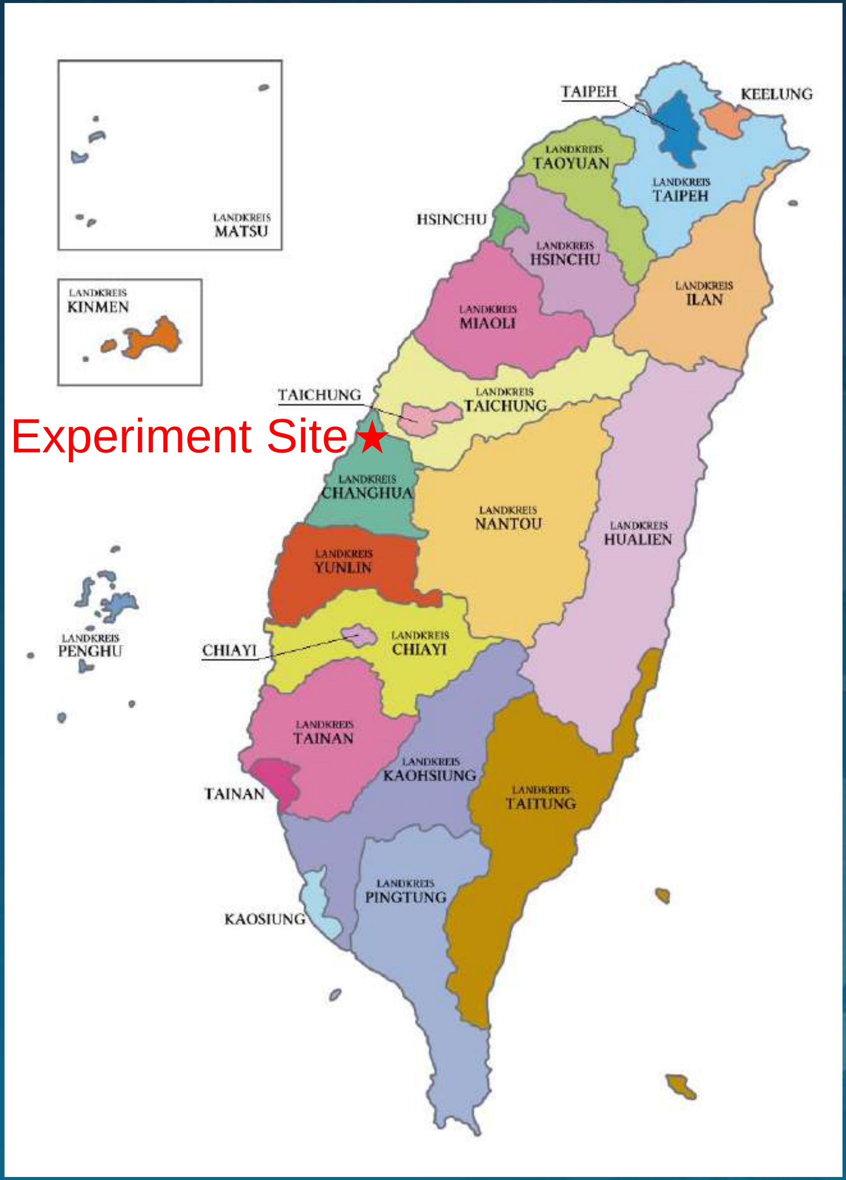
Case 3：

Electro-kinetic Enhanced Soil Washing For Heavy Metals Contaminated Soil

Soil Washing and EK for Heavy Metals – Vandenberg Air Force Base, CA

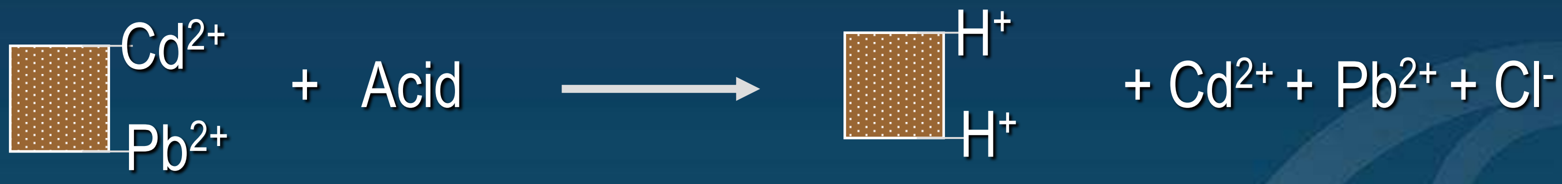
Site Introduction

- The experiment site was in Changhua county, Taiwan.
- The site was heavy metal contaminated farmland.
- The contaminants were Cd, Cr and Pb.



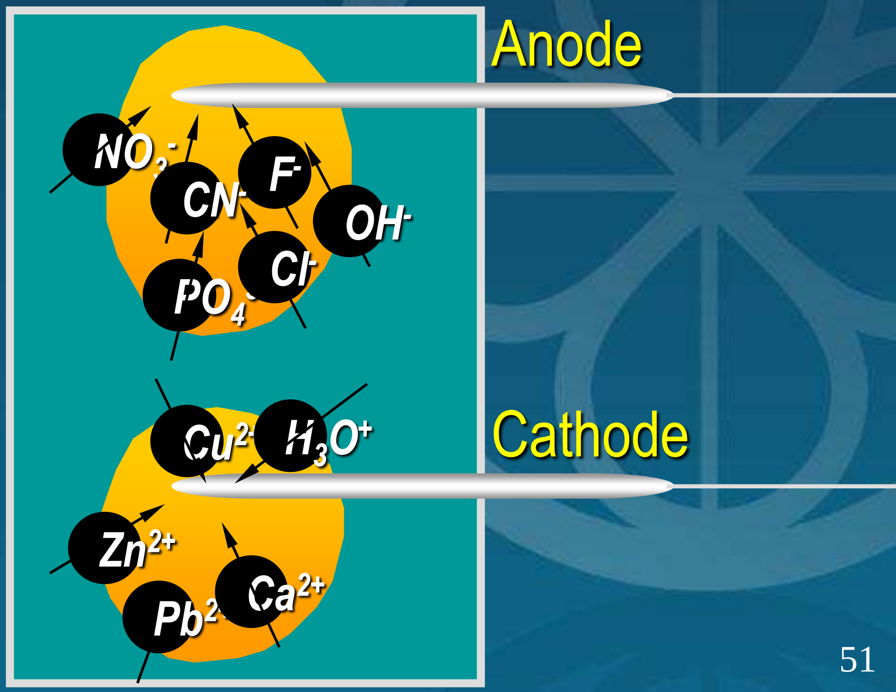
Electro-kinetic Methodology

- Desorption of Heavy Metals ：



$$\text{Cd}^{2+}\ \text{Pb}^{2+} + \text{Acid} \longrightarrow \text{H}^{+}\ \text{H}^{+} + \text{Cd}^{2+} + \text{Pb}^{2+} + \text{Cl}^{-}$$

- Electro-kinetic ：
  - Electrophoresis
  - Electro-osmosis
  - Electrolysis
  - Ion Exchange

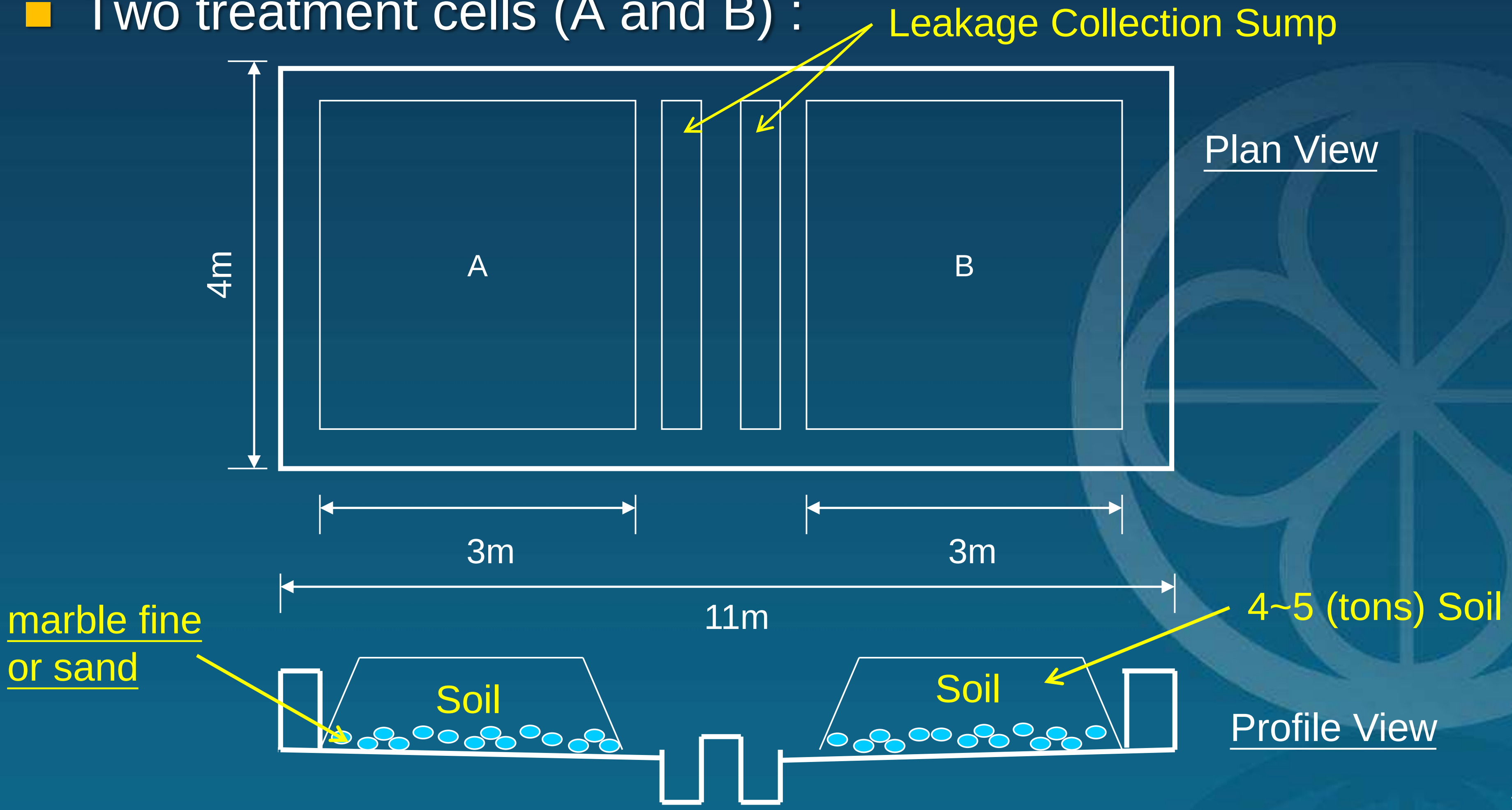


Electro-kinetic Methodology

- Electrophoresis is the motion of dispersed particles relative to a fluid under the influence of a spatially uniform electric field.
- Electro-osmosis is the motion of liquid induced by an applied potential across a porous material, capillary tube, membrane, microchannel, or any other fluid conduit.
- Electrolysis is a technique that uses a DC current to drive an otherwise non-spontaneous chemical reaction.
- Ion Exchange is an exchange of ions between two electrolytes or between an electrolyte solution and a complex.

Experimental Layout

- Study of electro-kinetic Enhanced Soil Washing for heavy metals contaminated soil
- Two treatment cells (A and B) :



Field Construction

Site Preparation

Removed Weeds

Collected Contaminated Soil

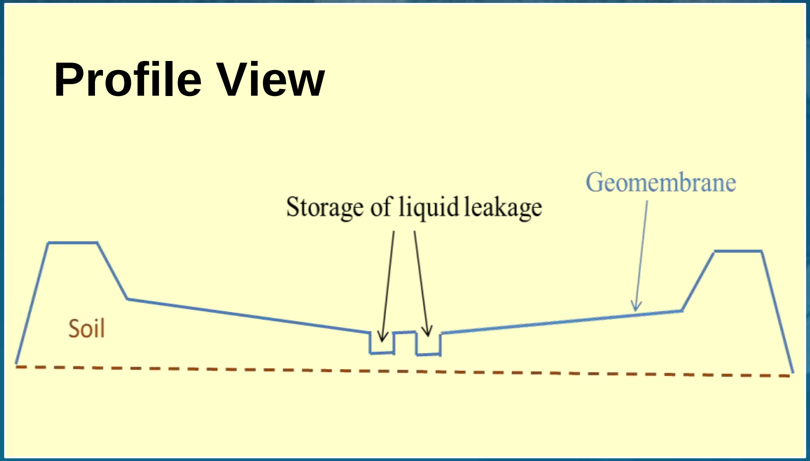
Field Construction

Treatment Cell Construction


Treatment Cells


liquid leakage Sumps

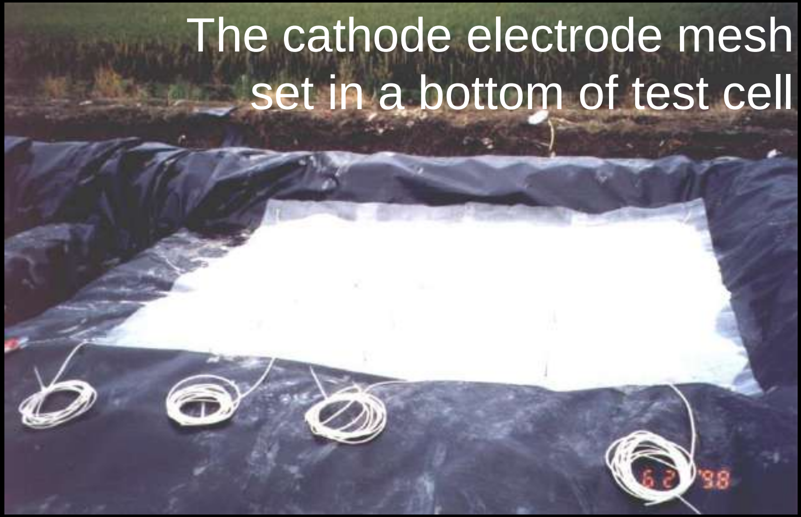

PE Geomembrane


Profile View

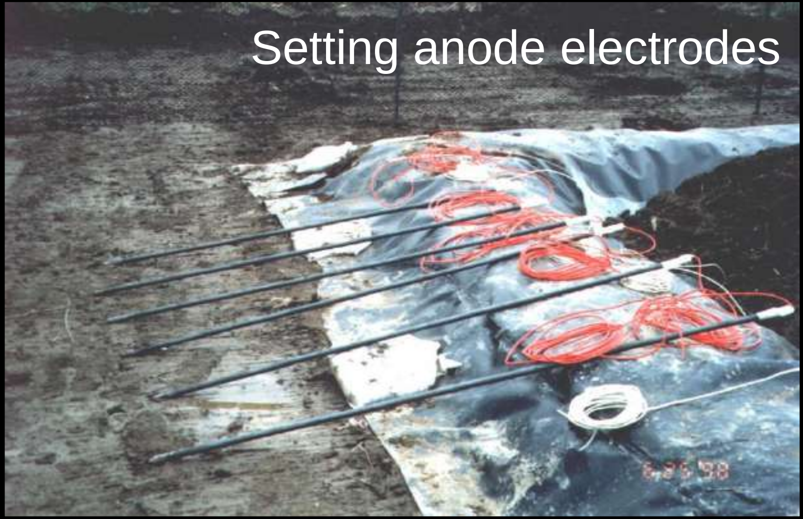
Field Construction

Treatment Cell Construction


The marble fines paving

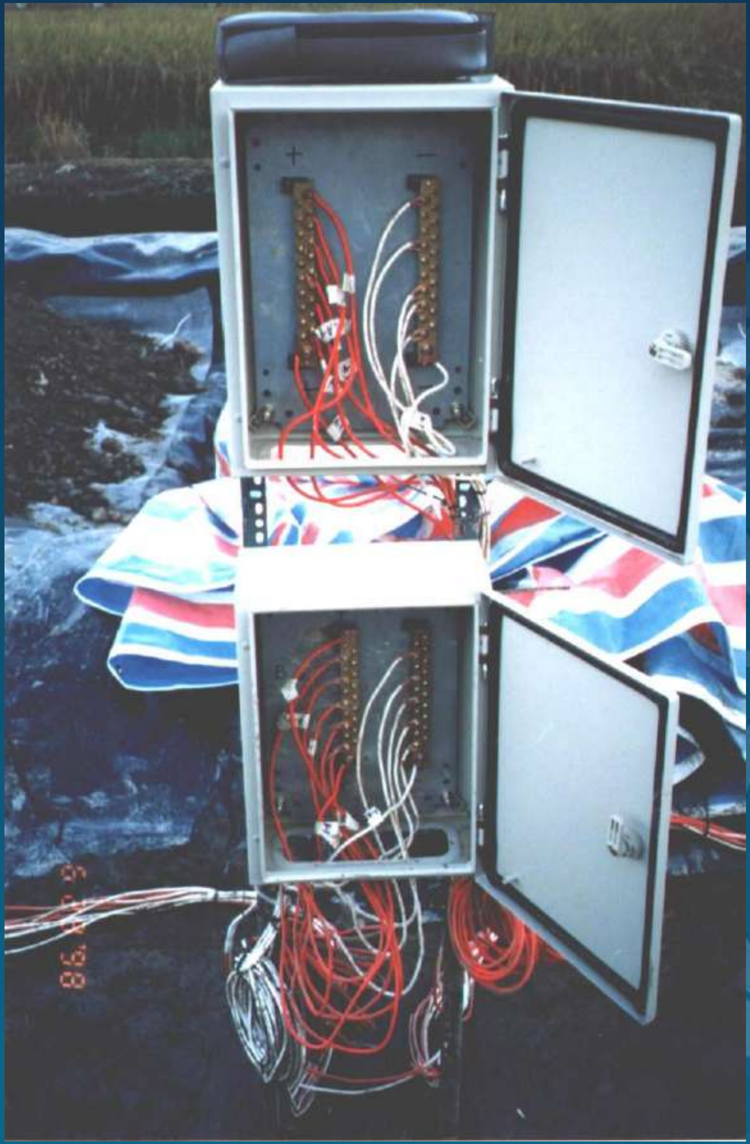

The cathode electrode mesh set in a bottom of test cell


Adding electrolyte and soil sampling


Setting anode electrodes

Field Construction

Electrode Control Box



Field Construction

Safety Fence

Experimental Process

Phase I (40 days)

6/29
Begin

6/29
Current::10A→5A

8/11
Finish

- Material:

  -A&B: Marble fines
- Electric: A&B

  -Current:10A

  -Voltage:30V
- Electrolyte:

  -A: citric acid

  -B: citric acid & desorbent

Experimental Process

Phase II (90 days)

8/25 Begin

9/15 Design Conductivity Water Hole

9/18 Anode & Cathode Exchange

9/30 Anode & Cathode Exchange

10/2 Current:: 5A→8A

10/19 Electrolyte: Double Concentration

11/25 Finish

- Material:
  - -A&B: Sand
- Electric: A&B
  - -Current:5A
  - -Voltage:30V
- Electrolyte:
  - -A: citric acid, amino acid
  - -B: citric acid amino acid & desorbent

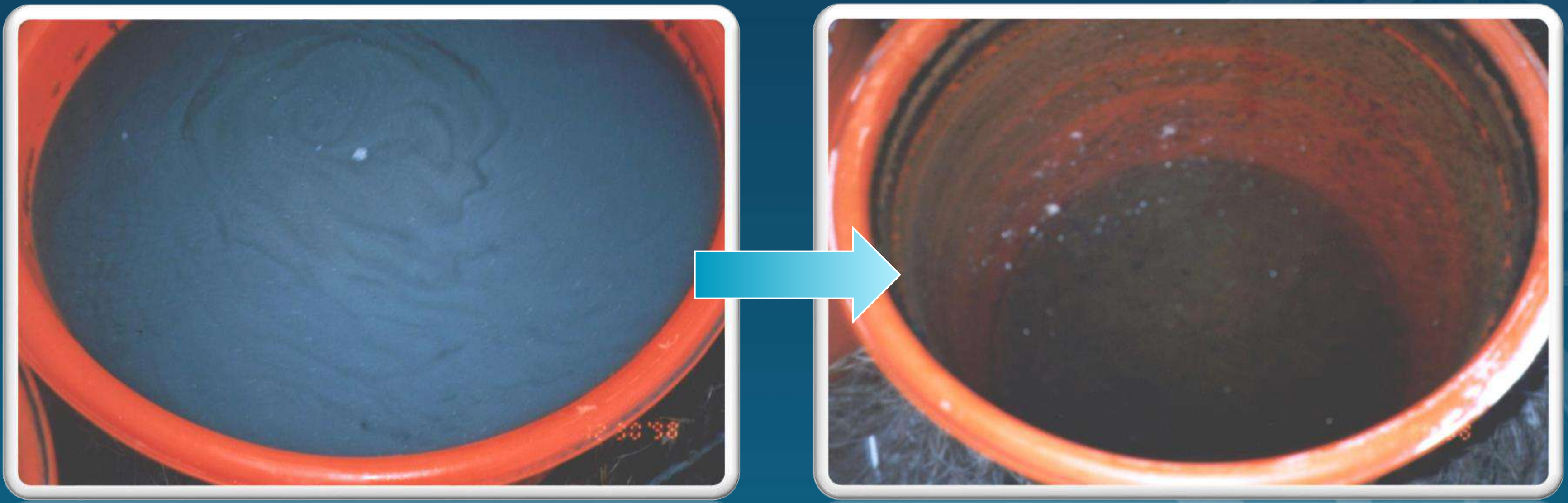
Electrolyte Leakage

Covered with Plastic Sheet

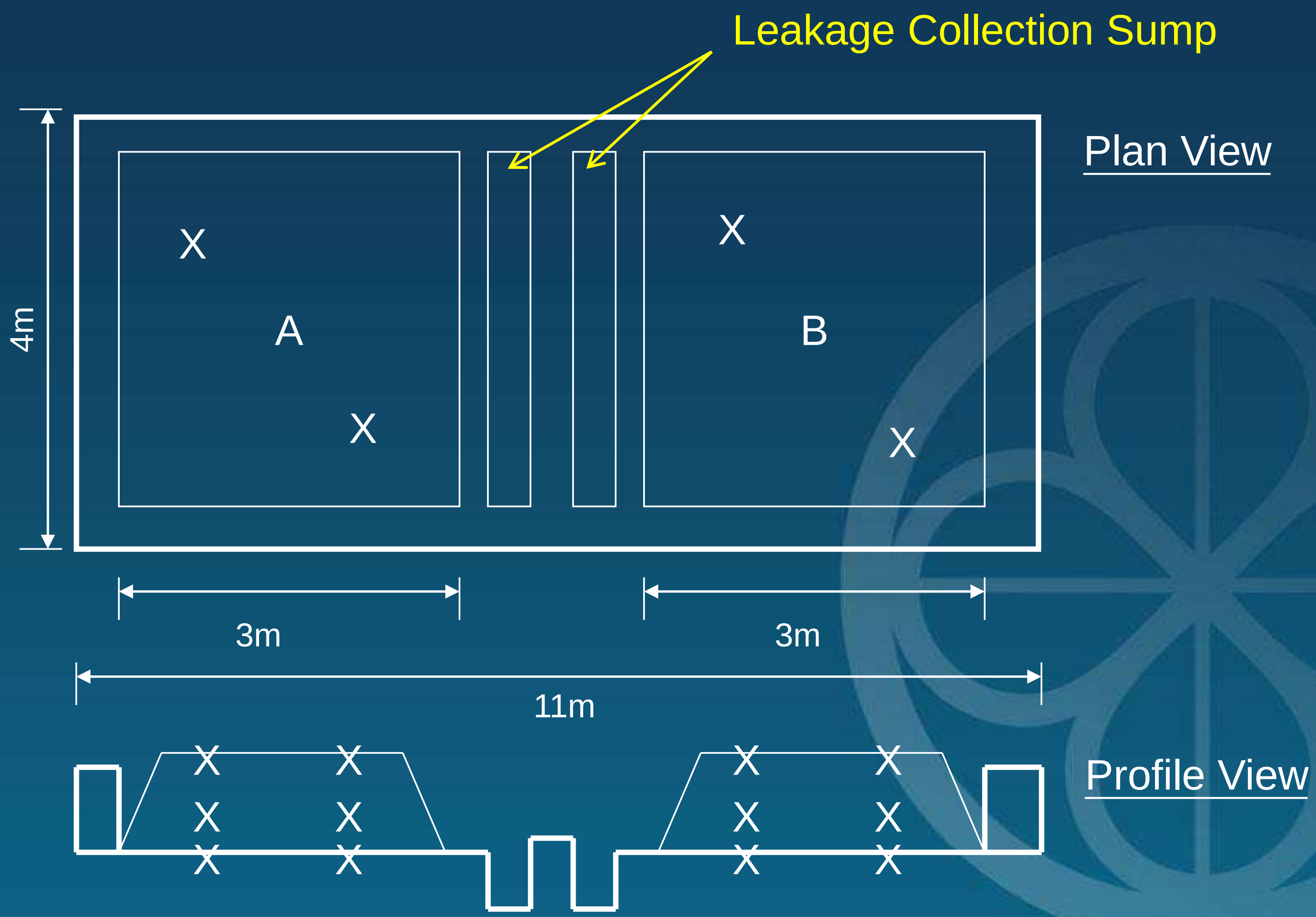
Leakage Collection Sump

Result of Experiment

Leakage Liquid



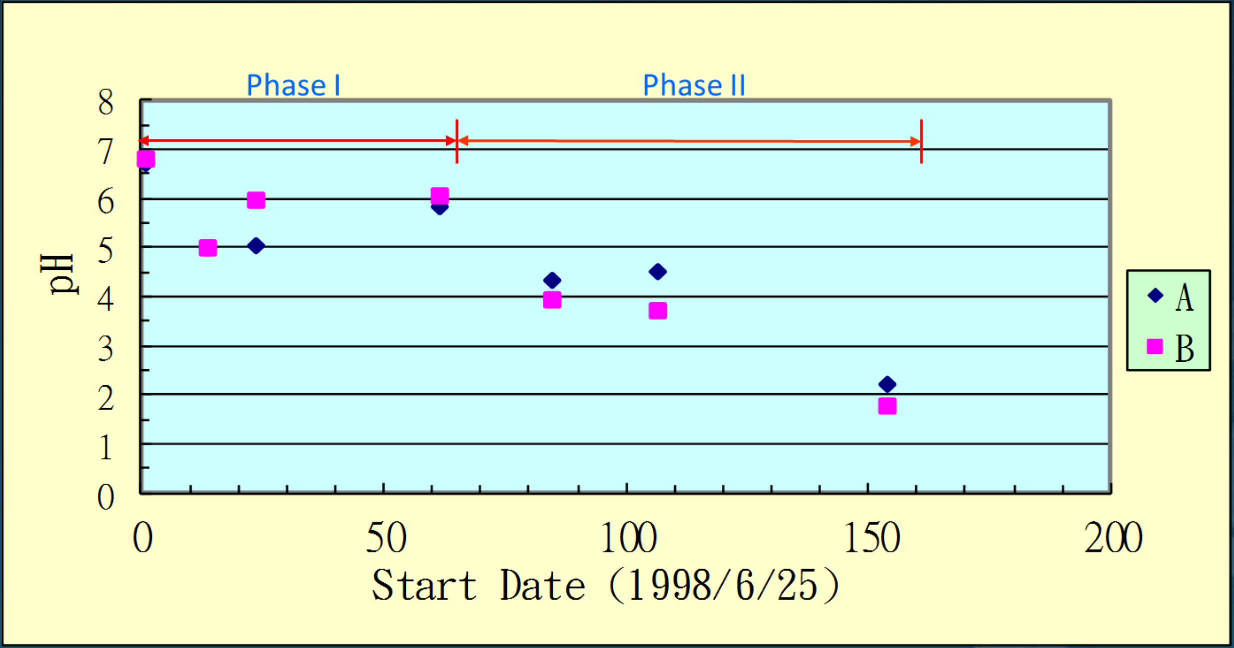
Confirmation Sampling



X : Soil Confirmation Sampling Location

Result of Experiment

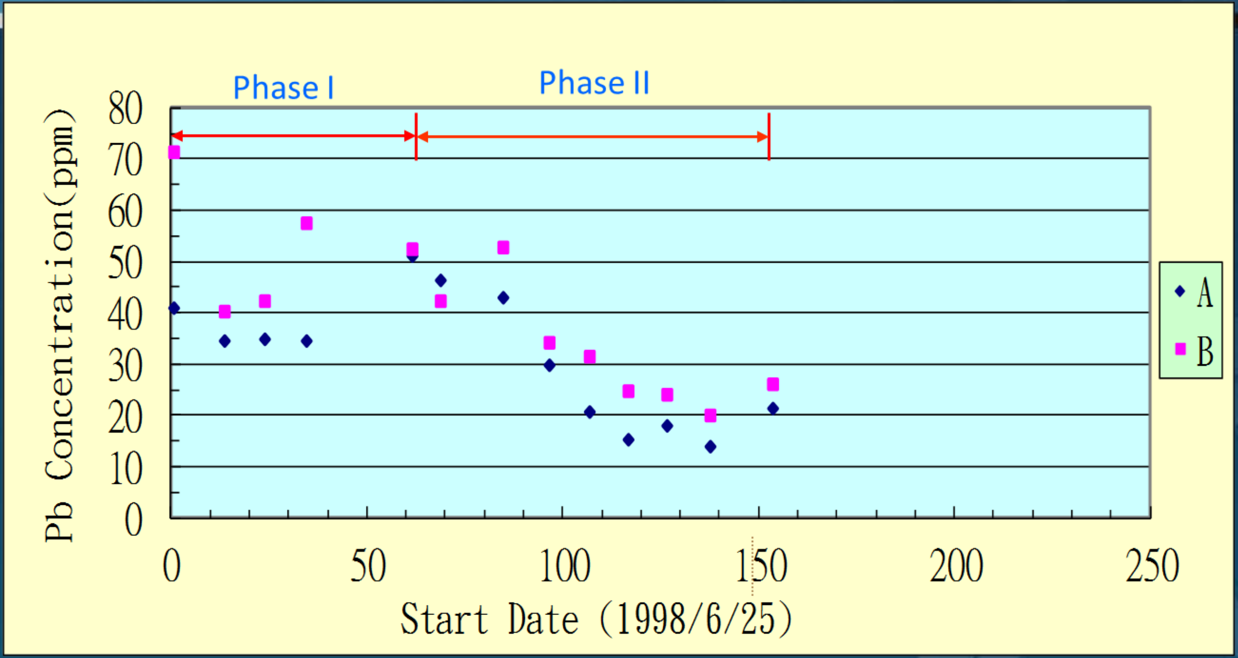
pH



Pb	Phase I			Phase II			
Date	6/26	7/8	7/18	8/25	9/17	10/9	11/25
AC-1	6.80	3.82	3.80	5.89	3.57	4.51	1.48
AC-2	6.70	4.96	2.00	5.75	4.83	4.78	2.56
AC-3	6.60	6.16	6.20	5.72	4.55	4.22	2.56
Ave.	6.70	4.98	4.00	5.79	4.32	4.50	2.20
BC-1	6.70	3.18	6.10	5.67	2.74	3.02	1.19
BC-2	6.70	5.77	5.80	6.27	3.91	3.72	1.77
BC-3	6.90	6.01	5.90	6.16	5.14	4.29	2.33
Ave.	6.77	4.99	5.93	6.03	3.93	3.68	1.76

Result of Experiment

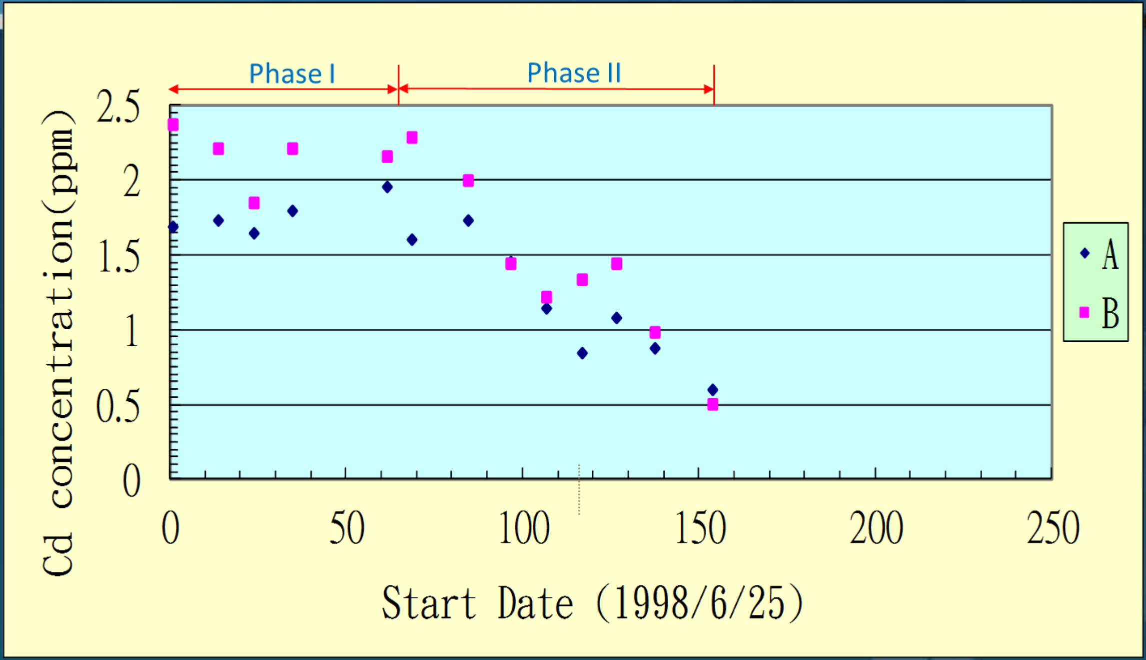
HCL→Pb



Pb	Phase I					Phase II									Removal (%)	Total Removal(%)
Date	6/26	7/8	7/18	7/29	Removal(%)	8/25	9/1	9/17	9/29	10/9	10/19	10/29	11/9	11/25		
AC-1	22.36	13.76	10.70	13.78	38.36	17.62	15.93	13.17	12.95	9.14	9.09	11.92	8.25	6.18	64.93	72.36
AC-2	19.48	15.13	9.62	14.07	27.80	18.94	16.89	16.93	26.34	11.96	11.66	16.38	11.07	7.99	57.81	58.98
AC-3	20.22	14.61	9.71	17.21	14.90	17.54	16.34	18.20	17.33	13.13	11.49	15.46	13.04	8.54	51.32	57.76
Ave.	20.69	14.50	10.01	15.02	27.40	18.03	16.39	16.10	18.87	11.41	10.75	14.59	10.79	7.57	58.02	63.41
BC-1	25.45	8.95	9.08	10.75	57.78	12.98	13.4	12.34	16.79	10.23	9.19	11.83	5.33	4.09	68.49	83.93
BC-2	23.30	14.40	10.40	11.69	49.85	17.88	13.46	13.12	17.75	12.66	12.09	14.89	11.48	6.26	64.98	73.13
BC-3	27.66	15.96	13.80	13.02	52.95	15.66	15.02	14.19	18.25	18.52	12.40	15.46	10.79	7.21	53.97	73.93
Ave.	25.47	13.10	11.09	11.82	53.61	15.51	13.96	13.22	17.60	13.8	11.14	14.06	9.20	5.85	62.25	77.02

Result of Experiment

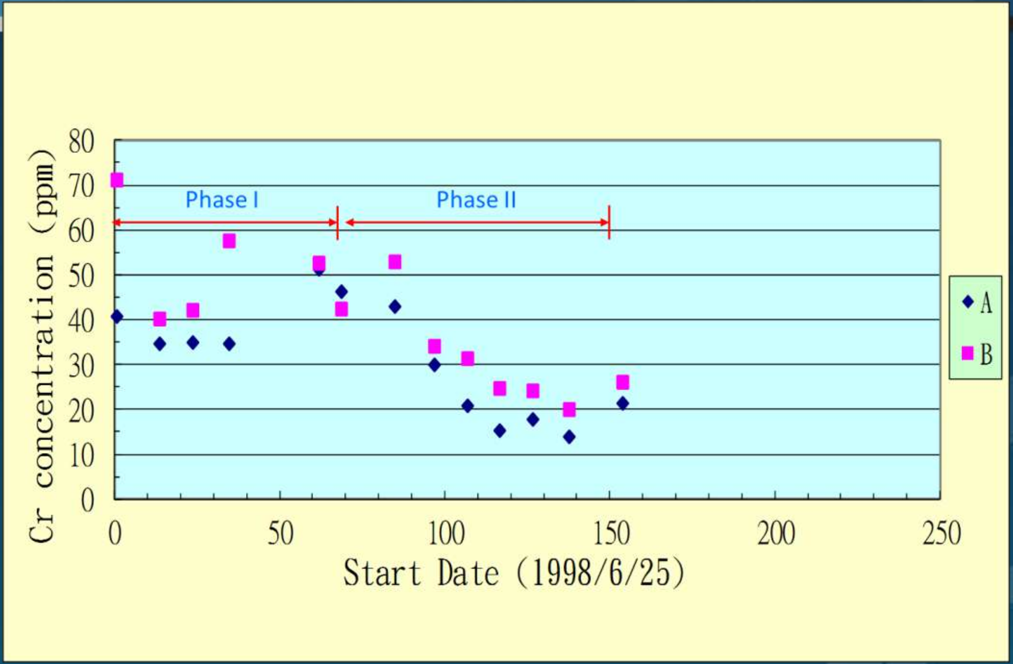
HCL→Cd



Cd	Phase I					Phase II									Removal (%)	Total Removal(%)
Date	6/26	7/8	7/18	7/29	Removal(%)	8/25	9/1	9/17	9/29	10/9	10/19	10/29	11/9	11/25		
AC-1	1.84	1.56	1.44	1.11	39.84	1.85	1.33	1.40	0.83	0.77	0.64	0.27	0.42	0.26	85.91	85.87
AC-2	1.56	1.90	1.61	2.09	0.00	2.14	1.48	1.94	1.67	1.36	1.02	1.38	1.27	0.72	66.37	53.85
AC-3	1.65	1.69	1.87	2.18	0.00	1.86	1.95	1.82	1.85	1.29	0.87	1.56	0.93	0.79	57.55	52.12
Ave.	1.68	1.72	1.64	1.79	0.00	1.95	1.59	1.72	1.45	1.14	0.84	1.07	0.87	0.59	69.73	64.95
BC-1	2.28	1.73	1.24	1.11	51.18	1.91	1.61	1.49	0.67	0.45	0.41	0.64	0.27	0.12	93.72	94.74
BC-2	2.06	2.41	1.75	2.41	0.00	2.37	2.46	1.89	1.66	1.46	1.65	2.02	1.08	0.50	78.91	75.73
BC-3	2.74	2.47	2.54	3.08	0.00	2.17	2.75	2.58	1.97	1.73	1.93	1.65	1.55	0.89	58.99	67.52
Ave.	2.36	2.20	1.84	2.20	6.84	2.15	2.28	1.99	1.43	1.21	1.33	1.44	0.97	0.50	76.6	78.67

Result of Experiment

HCL→Cr



Cr	Phase I					Phase II									Removal (%)	Total Removal(%)
Date	6/26	7/8	7/18	7/29	Removal(%)	8/25	9/1	9/17	9/29	10/9	10/19	10/29	11/9	11/25		
AC-1	51.46	44.02	47.10	52.76	0.00	48.80	43.52	30.33	22.67	16.97	11.08	11.29	11.57	27.23	44.20	47.09
AC-2	32.74	30.70	29.90	26.09	20.31	55.29	45.19	49.73	32.65	17.58	16.75	15.14	13.41	16.02	71.02	51.07
AC-3	37.62	28.40	27.20	24.57	34.69	48.98	49.34	48.32	33.99	27.44	17.55	26.75	16.43	19.99	59.16	46.86
Ave.	40.61	34.37	34.73	34.47	15.1	51.01	46.02	42.79	29.77	20.66	15.13	17.73	13.80	21.08	58.68	48.09
BC-1	69.60	46.38	43.80	64.63	7.14	37.04	41.81	52.03	30.69	23.75	18.62	28.77	20.43	20.72	44.05	70.23
BC-2	57.49	34.38	31.50	41.48	27.85	65.75	41.22	53.80	30.75	28.40	27.49	21.56	18.75	28.35	56.88	50.69
BC-3	86.20	39.19	50.70	66.27	23.12	54.26	43.23	52.15	40.60	41.64	27.75	21.61	19.9	28.82	46.89	66.57
Ave.	71.1	39.98	42.00	57.46	19.18	52.35	42.09	52.66	34.01	31.27	24.62	23.98	19.69	25.96	50.40	63.48

Result of Experiment

Soil Fertility Analysis

Analysis	Experimental			
	A		B	
	Before	After	Before	After
pH	6.7	2.2	6.77	1.76
EC (dS/m)	0.48	NA	0.57	NA
Organic(%)	4.4	4.1	5	5.1
Nitrogen(%)	0.24	0.42	0.25	0.75
Bray-1 P(mg/Kg)	42.3	10.6	49.77	66.2
CEC (C mol/kg)	17.97	NA	19.4	NA
Exchangeable Potassium (mg/kg)	51.47	61.5	61.9	63.2

NA: Not Available

Result of Experiment

Heavy metals contaminated in liquid leakage

Analysis	A		B		Sewage Standard
	Experimental		Experimental		
	Before	After	Before	After	
pH	3.5	7.89	3.58	8.02	6.0~9.0
Cr	0.206	0.025	0.30	0.022	0.03
Pb	1.524	0.082	2.19	0.052	1
Cd	1.646	0.016	2.034	0.029	2

Unit: ppm

Conclusion

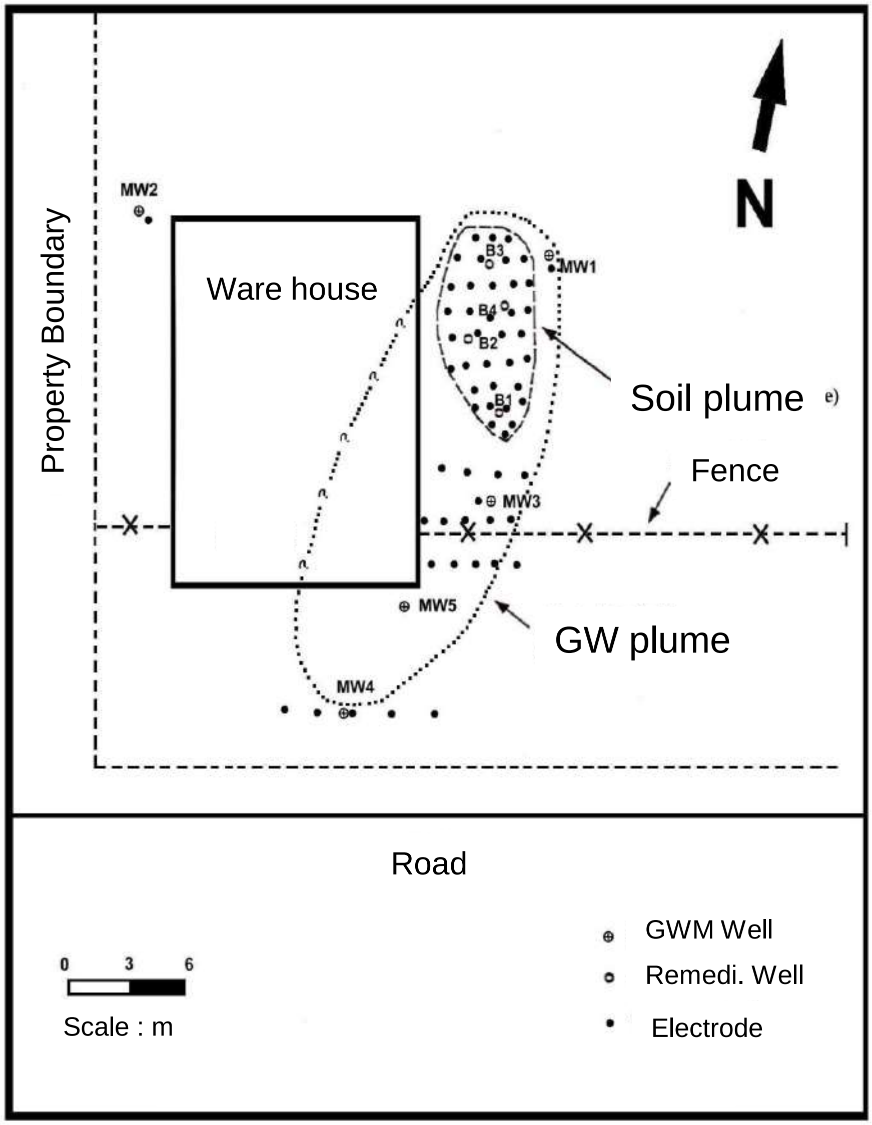
- The lower pH 2~3 in soil could be more effective desorption of heavy metals.
- Adding the desorbent could increase desorption heavy metal contaminants in soil and improved soil fertility.
- Exchanging the cathode and anode could increase desorption Cr elements in soil.
- The remediation experiment was completed about 140 days.

EK Remediation Case 4 -

In-Situ Bioremediation with EK for TPH

- Bay Area, San Francisco, CA
- TPH-G and TPH-D
- Soil plume covered an area of 45m^2 with a depth of 3~3.5m
- GW plume covered an area of 240 m^2 with bsg 3.5~4.5m
- Clayey bay mud
- Soil TPH within 1.5 month from 3,900 ppm to 40 ppm
- After 9 months work, GW BTEX Concentration was lower than CA cleanup standards
- Installed total 59 electrodes with 5m longs

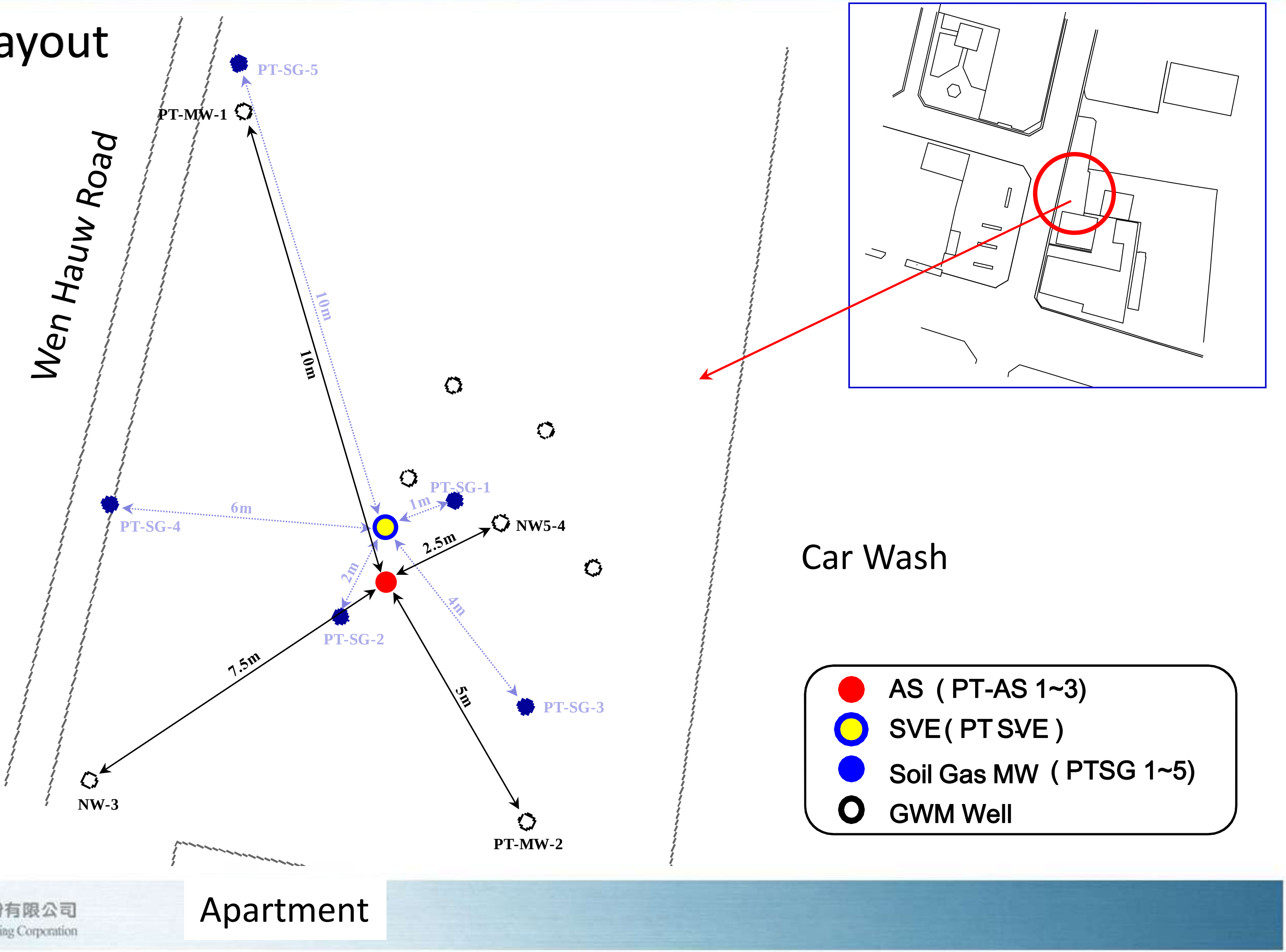
Site Layout


Property Boundary
MW2
Ware house
B3
MW1
B4
B2
B1
N
Soil plume
Fence
MW3
MW5
GW plume
MW4
Road
0
3
6
Scale : m
⊕ GWM Well
○ Remedi. Well
• Electrode

EK Remediation Case 5 -

In-Situ Bioremediation with EK for TPH

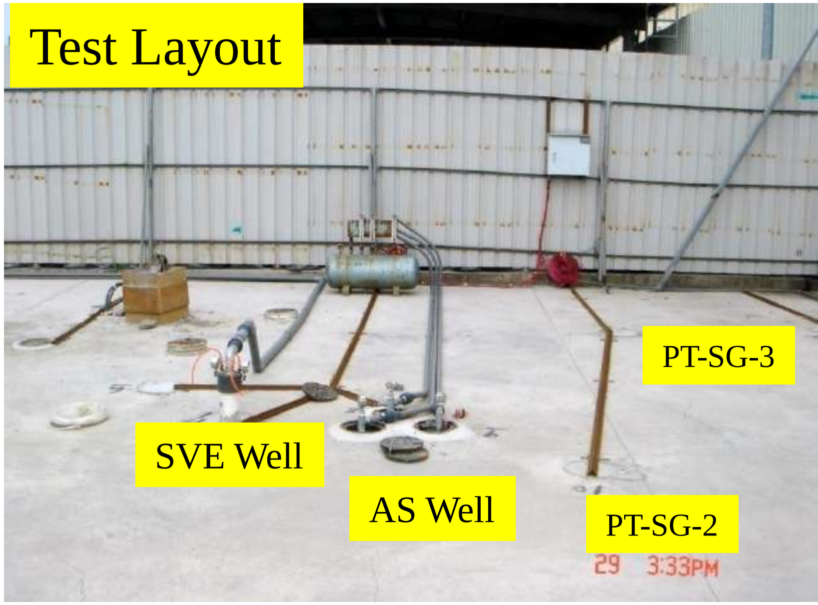
Pilot Test Layout



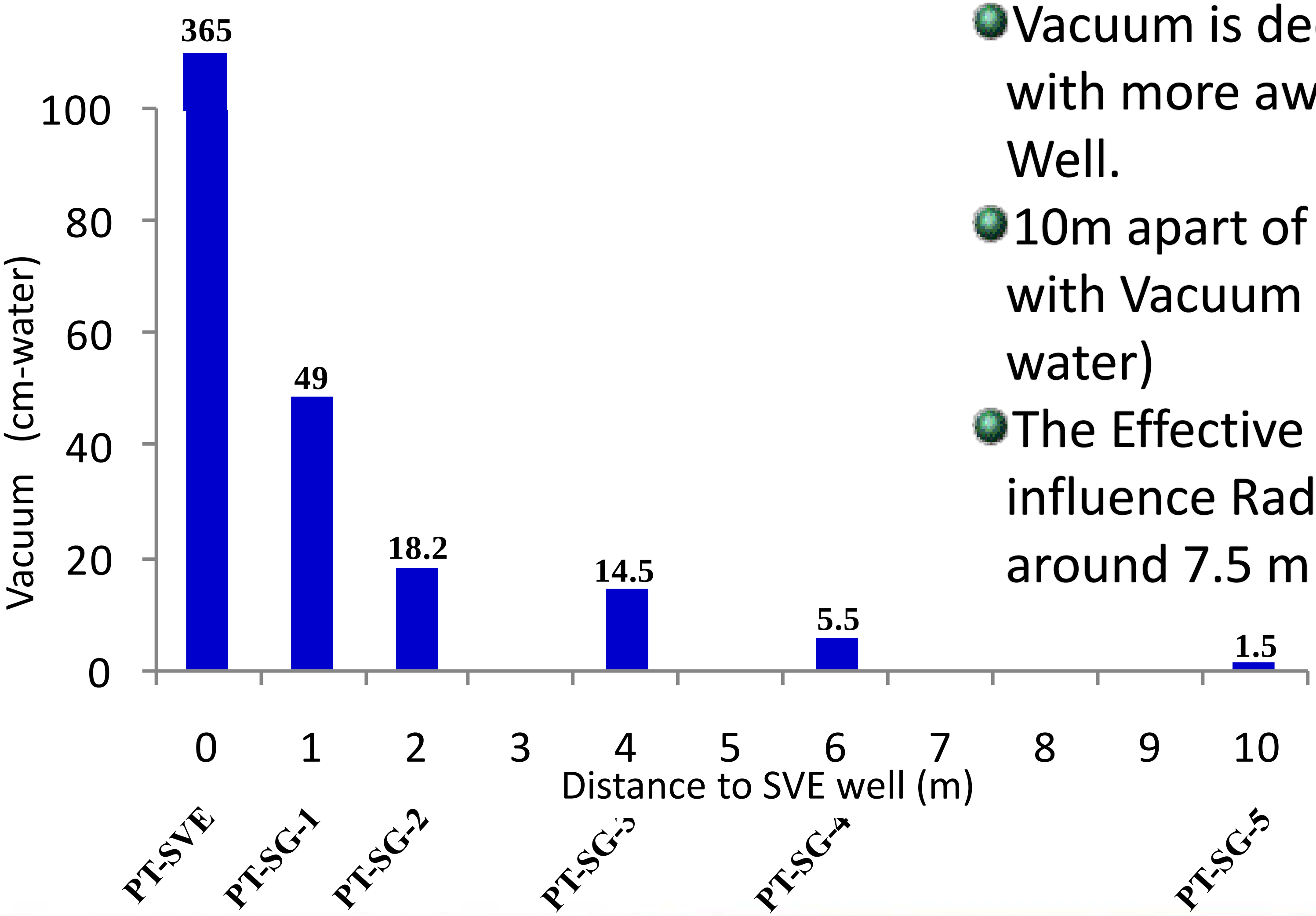
- 🔴 AS（PT-AS 1~3)
- ◉ SVE (PT SVE)
- 🔵 Soil Gas MW（PTSG 1~5)
- ○ GWM Well

Site Preparation

Remediation Equipment



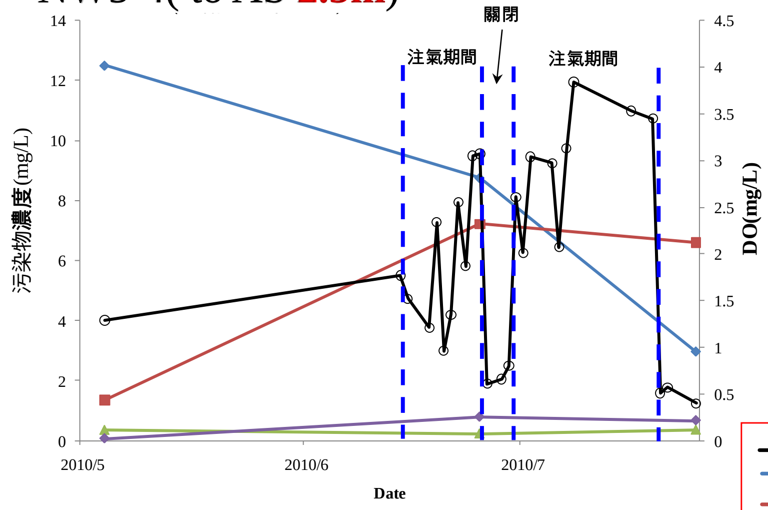
Single Well Test - SVE



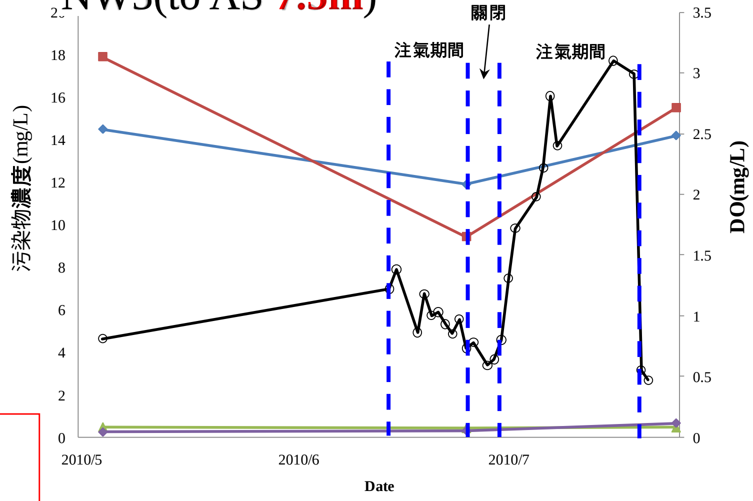
- Vacuum is decreased with more away of SVE Well.
- 10m apart of SVE Well with Vacuum of 1.5 (cm-water)
- The Effective SVE influence Radius is around 7.5 m (cm-water)

Single Well Test - AS

NW5-4(to AS **2.5m**)

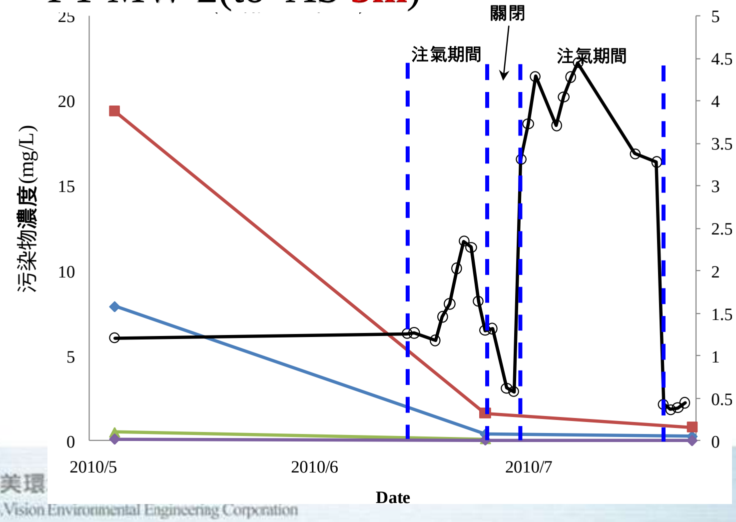


NW3(to AS **7.5m**)

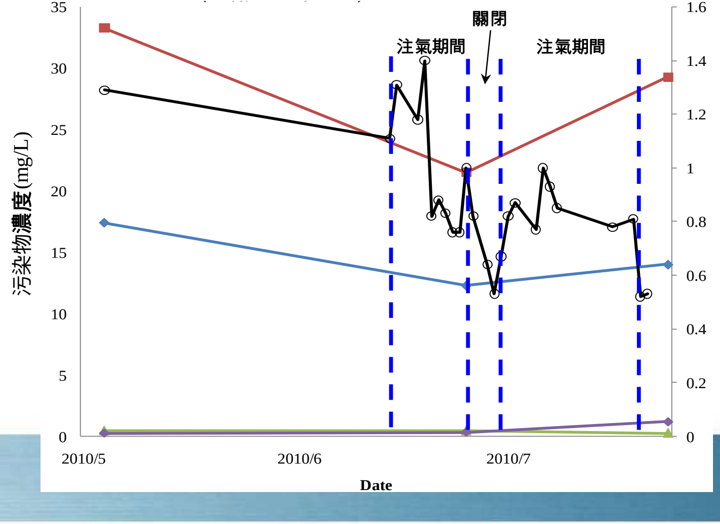


- Do
- Benzene
- Toluene
- Naphthalene
- Phenols

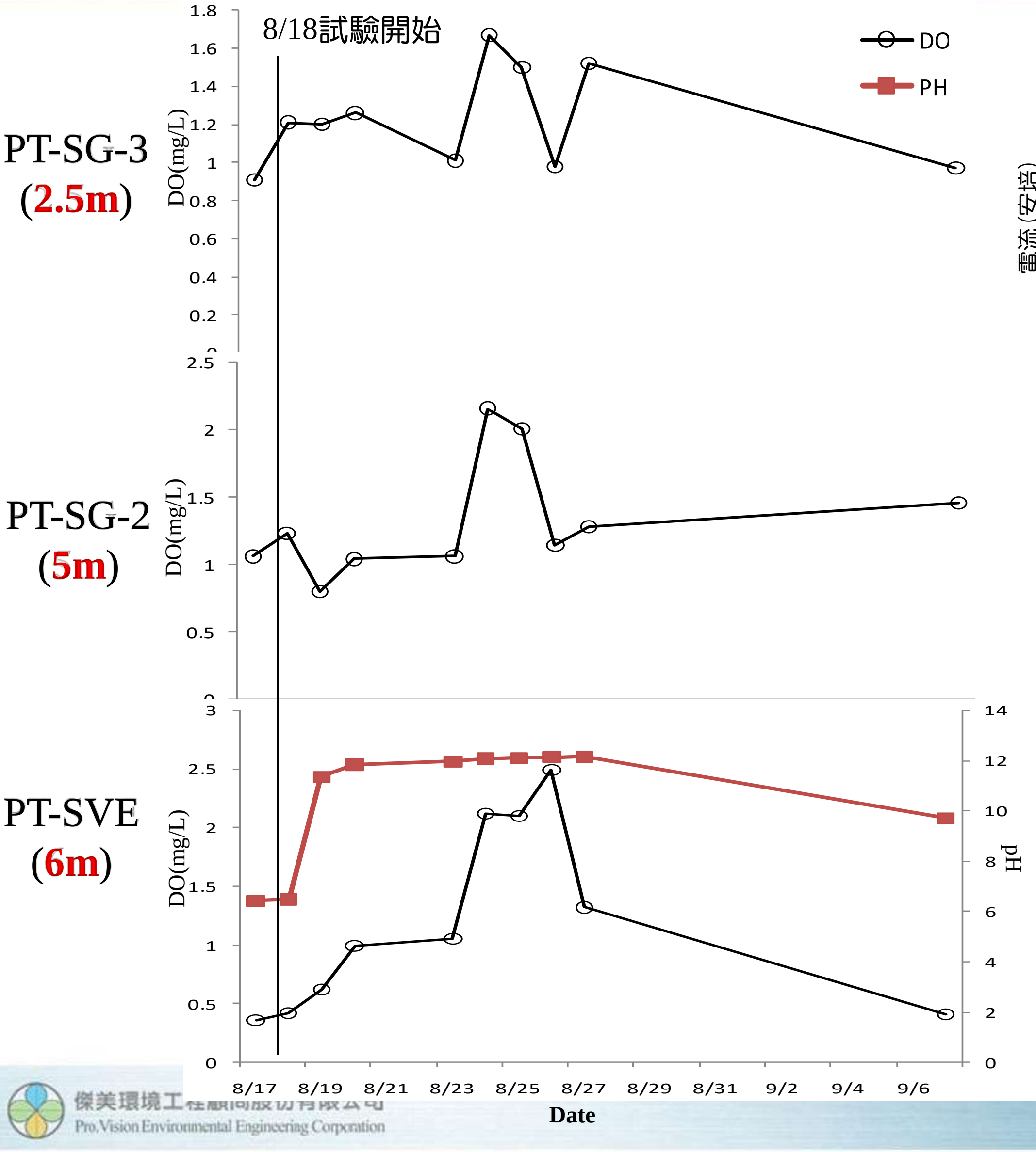
PT-MW-2(to AS **5m**)

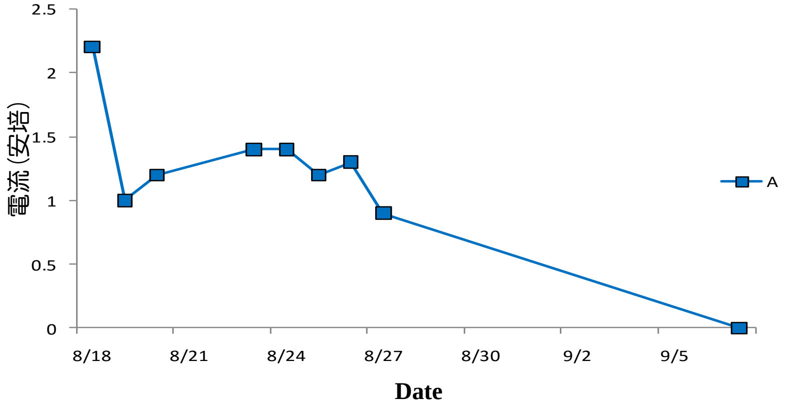


PT-MW-1(to AS **10m**)



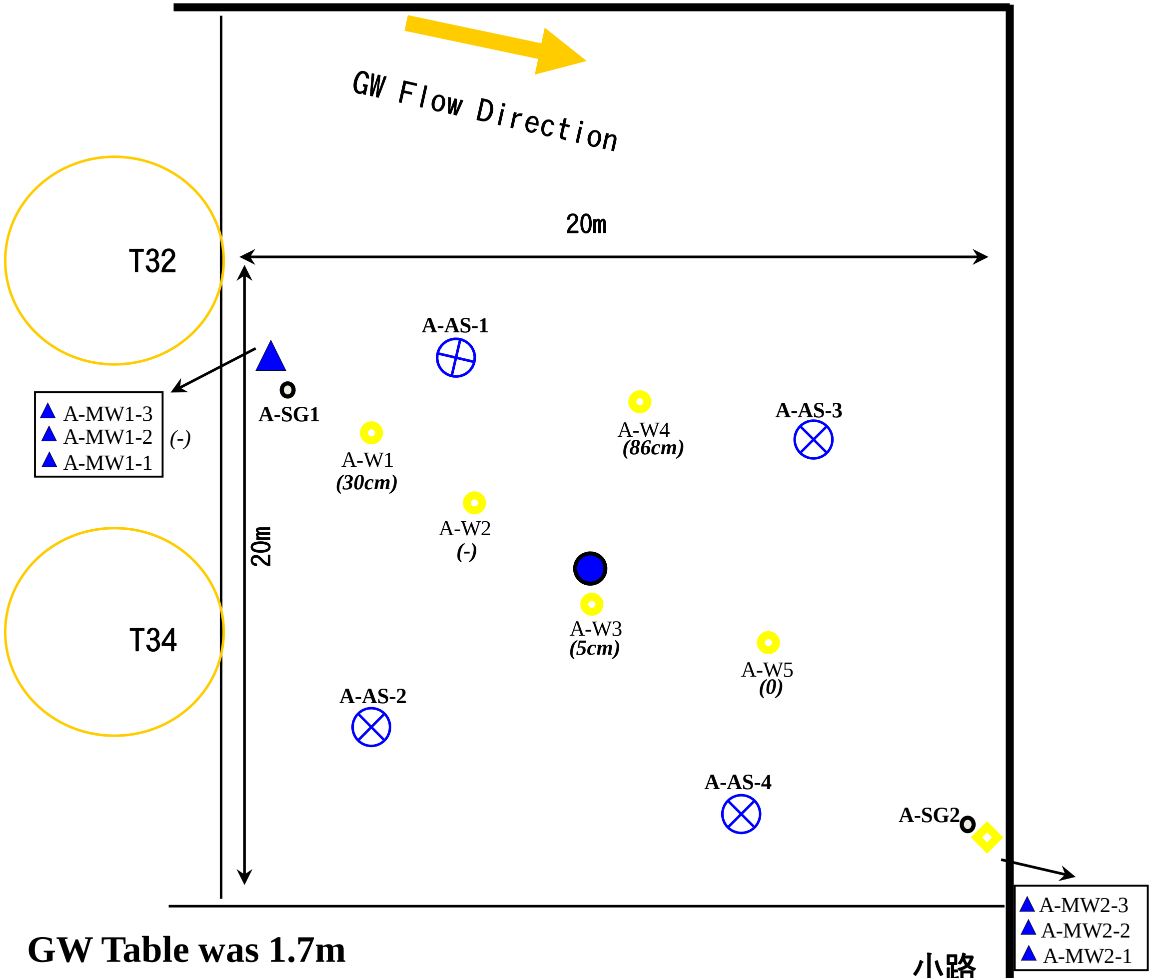
Single Well Test - EK





- PT-MW-2 is Anode(+), PT-SVE is Cathode, 6m apart.
- Anode injected ORC
- GW velocity was 0.45~1.85 m/yr , 6m needed 3.2 years
- Cathode DO was increased after EK turned on.

LNAPL Remediation Case 6 – Refinery Source Area Investigation



GW Table was 1.7m

- ▲ Multilevel well
- ⊗ AS(screen 8 ~8.5m)
- ◉ monitoring well (screen 2~5m)
- ◇ Multilevel well (g)
- ● SVE
- ○ multilevel soilgas (0.5,1,3m,screen=0.15)

Refinery Pilot Test - MPE For Source Area

MPE System Test

Refinery Pilot Test - MPE For Source Area

Oil & Water Separator

Oil and Water Flow Meters

Transfer Pump

Thank You !

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Case Studies of Remediation of Mercury Contaminated Soil

Speaker:

Yu-Ting (Phil) Wei, Ph. D.

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Outline

1. Background
2. Treatment Technologies for Mercury
3. Case I: Soil Washing Treatment
4. Case II: Thermal Treatment
5. Summary

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1

Background

Properties of Mercury

- Mercury is the most hazardous metal for human health and environment.
- Elemental mercury is a liquid at normal temperature.
- Industrial facilities use mercury in their processes / products such as chlor-alkali plants/ □ thermometers, barometers, fluorescent light.
- It has high toxicity, volatility and is tendency to bio-accumulate in human body.
- There are several kinds of mercury compounds in the environment.

Properties of Mercury Compounds

Compound Name	Elemental Mercury	Mercury(II) oxide	Mercury sulfide	Mercuric Chloride	Mercurous Chloride	Methyl-mercuric Chloride	Dimethyl Mercury
Molecular formula	Hg_0	HgO	HgS	$HgCl_2$	Hg_2Cl_2	CH_3HgCl	C_2H_6Hg
Molecular weight	200.59	216.59	232.66	271.52	472.09	251.1	230.66
Solubility (g/L)	5.6×10^{-5}	0.053	insoluble	69	2.0×10^{-3}	0.100	1
Density (g/cm^3)	13.534	11.14	8.10	5.4	7.15	4.06	3.1874
Boiling Point (°C)	357	Not available	Not available	302	384	Not available	93
Melting Point (°C)	-39	500	580	277	302	170	-43
Oxidation State	0	+2	+2	+2	+1	+2	+2

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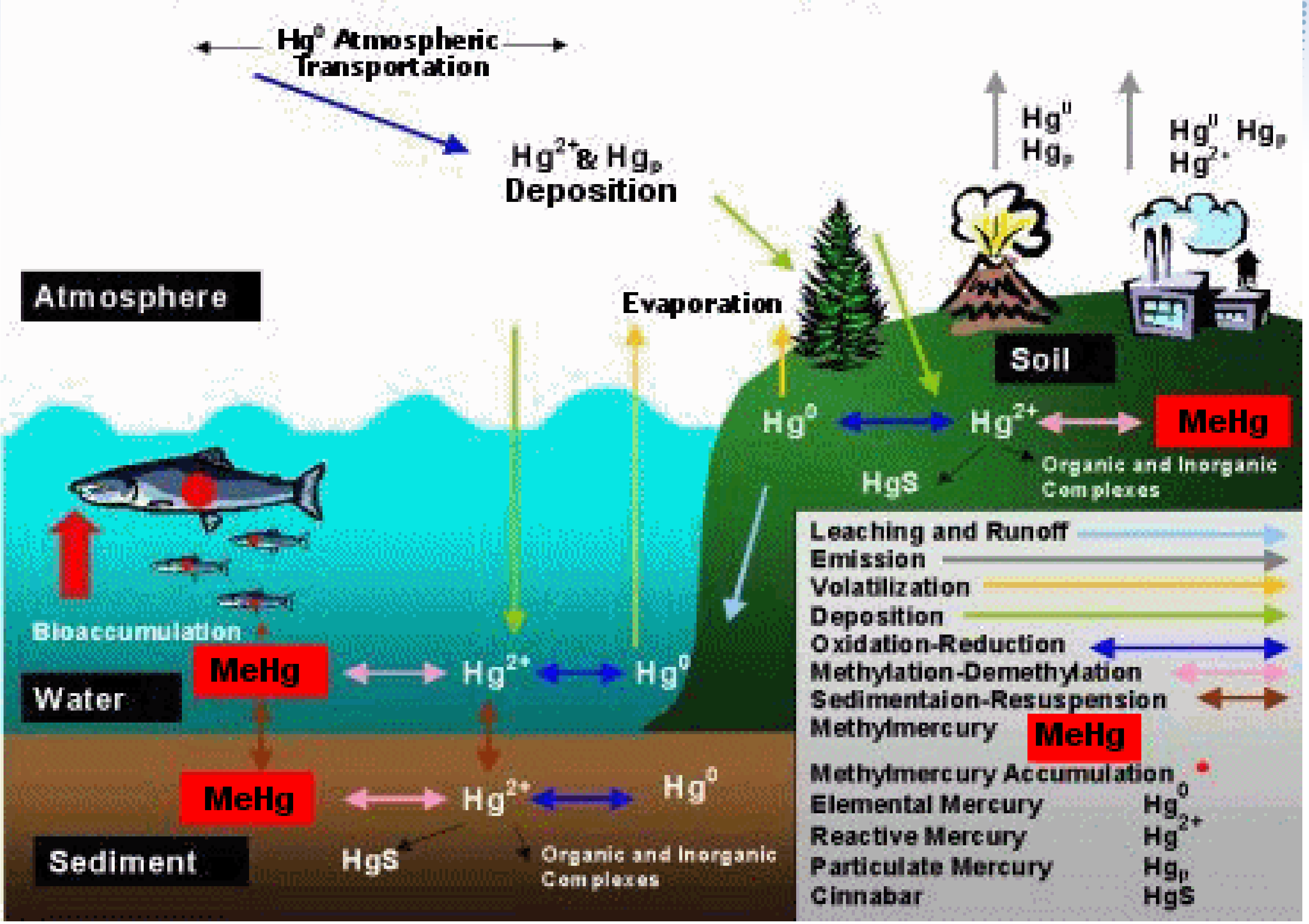
Conceptual Mercury Cycle



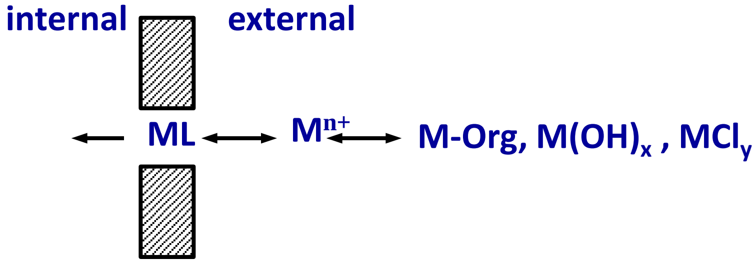
Ref: Environment Canada http://www.ec.gc.ca/mercure-mercury/default.asp?lang=En&n=67E16201-1

Mercury Species in Water

Hg^{2+}，$HgCl^{+}$，$HgCl_2$，$HgCl_3^{-}$，$HgOHCl$，$Hg(OH)_2$，HgS_2^{2-}，$HOHS^{-}$，$HgS(s)$，$Hg(liq)$，$Hg(OH)_2(s)$

❖ The mechanism of heavy metals transport across microbial cells

- Nutrient metal uptake systems
  - Ligand associated with facilitated transport system (L), complexes metal for transport.
  - M^{n+} can be “mistaken” for nutrient metals, e.g. Zn, Mn.

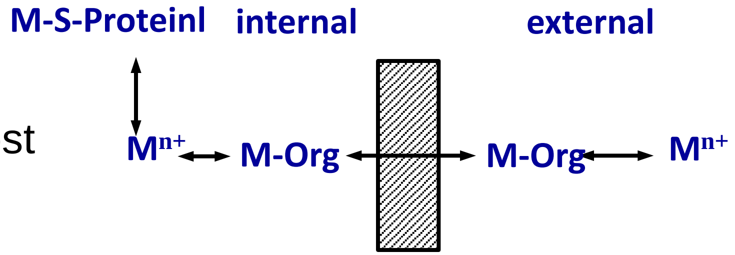


internal

external

← ML ↔ M^{n+} ↔ M-Org, $M(OH)_x$, MCl_y

- Passive diffusion through membrane
  - Membrane permeable species diffuse passively through plasma membrane.
  - Neutral species (e.g. M-Org) may be most permeable.



M-S-Proteinl ↕ M^{n+}

internal

external

M^{n+} ↔ M-Org ↔ M-Org ↔ M^{n+}

Ref：Biogeochemistry of Small Catchment: A Tool for Environmental Research, 13 Trace Metals Speciation and Cycling, 1994, by B. Moldan and J. Cemy.

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2

Treatment Technologies For Mercury

Regulatory Considerations

- In Taiwan, the Soil and Groundwater Pollution Remediation Act (SGWPR Act) was promulgated on February 2, 2000.
- The soil pollution control standard of Hg was set to be 5 mg/kg for food crop farmland soils and 20 mg/kg for other soils.
- The groundwater pollution control standards of Hg was set to be 0.002 mg/L for category I and 0.02 mg/L for category II.
- Sediment quality criteria: upper limit 0.87 mg/kg; lower limit 0.23 mg/kg
- Workplace air quality criteria: 0.05 mg/m^3 (mercury vapors), 0.01 mg/m^3 (Organic mercury)
- Effluent water quality of Hg: 0.005 mg/L, Organic mercury: ND
- Drinking water quality of Hg: 0.002 mg/L
- TCLP criteria：0.2 mg/L (Total mercury)

Treatment Technologies For Mercury

Technology	Description
Solidification / Stabilization	Physically binds or encloses contaminants within a stabilized mass and chemically reduces the hazard potential of a waste by converting the contaminants into less soluble, mobile, or toxic forms.
Soil Washing / Acid Extraction	Uses the principle that some contaminants preferentially adsorb onto the fines fraction of soil. The soil is suspended in a wash solution and the fines are separated from the suspension, thereby reducing the contaminant concentrations in the remaining soil. Acid extraction uses an extracting chemical, such as hydrochloric acid or sulfuric acid.
Thermal Desorption / Retorting	Application of heat and reduced pressure to volatilize mercury from the contaminated medium, followed by conversion of the mercury vapors into liquid elemental mercury by condensation. Off-gases may require further treatment through additional air pollution control devices such as carbon units.

Ref: U.S. EPA, Treatment Technologies For Mercury in Soil, Waste, and Water, 2007

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Mercury Enrichment

Particle size		Sand		Silt	Clay			total	Mercury distribution	
		0.1 cm	0.01 cm	0.002 cm	400 A°	50 A°	10 A°		Mass, mg	Concentration, ppm
Soil sample	Weight, g	40	30	15	10	3	2	100	20	200
	%	0.40	0.30	0.15	0.10	0.03	0.02	1	100 %	–
	Specific surface area, cm^2/gm	9.1	67.9	17.0	1.9×10^4	4.5×10^4	1.5×10^5	21.4×10^4	–	9.34×10^{-7} mg/cm^2
20 um screened	Weight, g	32	24	12	2	0.6	0.4	71 g	4.0	56
	%	0.45	0.34	0.17	0.028	0.007	0.005	1	20 %	–
	Specific surface area, cm^2/gm	10.2	77.0	192.5	0.53×10^4	1.1×10^4	3.8×10^4	5.46×10^4	–	9.34×10^{-7} mg/cm^2
overflow	Weight, g	8	6	3	8	2.4	1.6	29	16.0	552
	%	0.28	0.20	0.10	0.282	0.083	0.055	1	80 %	–
	Specific surface area, cm^2/gm	6.3	45.3	113.2	5.3×10^4	12.5×10^4	41.3×10^4	59.1×10^4	–	9.34×10^{-7} mg/cm^2

For sand and silt, specific surface area =2.3/d ; For clay, specific surface area =0.75/ℓ

Detection and Site Characterization

- The most commonly used site characterization technique for mercury is field-based X-ray fluorescence (XRF) analyzers. It can detect mercury concentration in less than 3 minutes.
- MA-3000 Mercury Analyzer: MA-3000 determines total mercury in Solid, Liquid and Gaseous matrices using the principle of thermal decomposition, gold amalgamation, and atomic absorption in accordance with USEPA 7473, ASTM D-6722-01, without any sample preparation. It can directly detect mercury in only 7 minutes. The measurement range is between 0.002ng-2000ng of mercury.
- A model EMP-2 is designed for measuring of gaseous mercury in work environments. The EMP-2 has sensitivity limits down to 0.1 ug/m^3.

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Case I
Soil Washing Treatment

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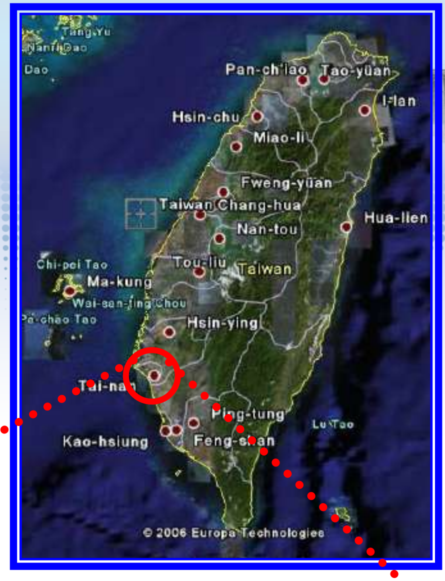
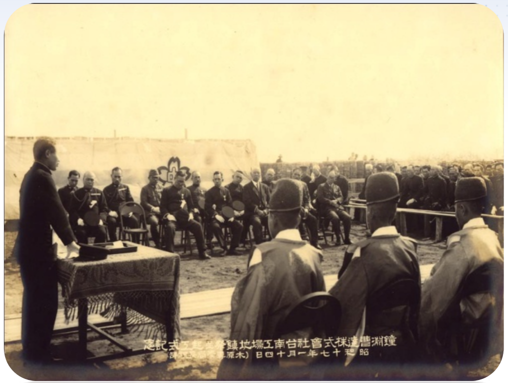
An-Shun Site

Taiwan, Tainan



Site History

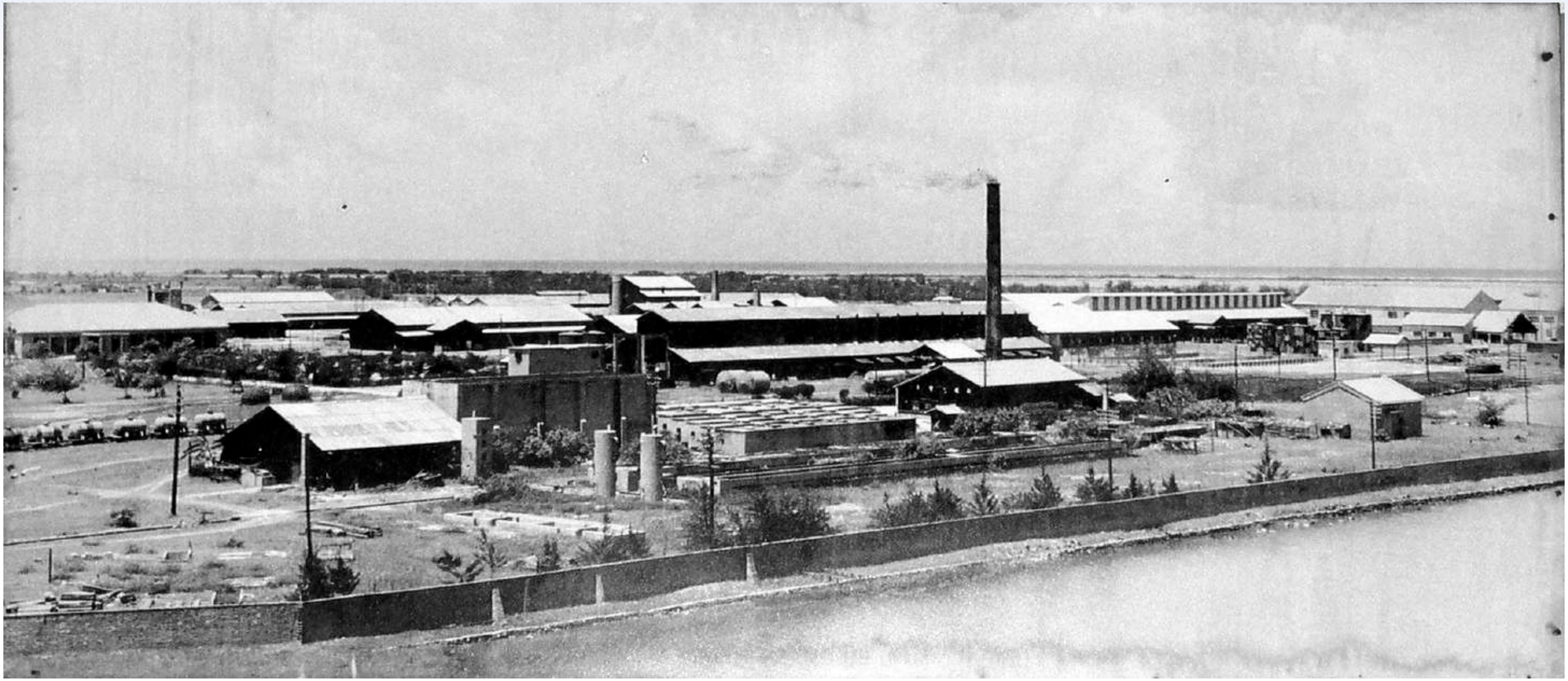
❖ 1940-1944 (World War II)



- Owner: Japan Kaneka Soda Co., Ltd.
  日本鐘淵曹達株式會社
- Object: Supply Military material
  (Use Soda to dissolve Aluminum)
  (Use Bromine as anti-knock agent)
- Factory: Salt land 600 Ha
  Bromine Plant 500kg/D
  NaOH Plant 100T/D (Mercury electrode)
- Construction: 1940-1944
- Operation: 1944
- Shut down: 1944/10 (ruined by US Air force Bomb)

Ref: CPDC, Remediation of CPDC An-shun Site: An Introduction

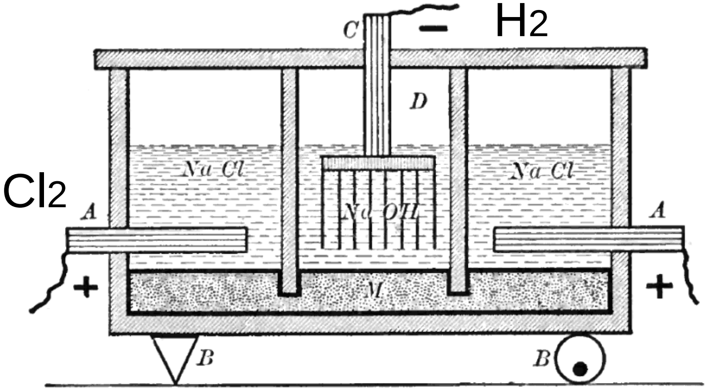
Site History



Ref: CPDC, Remediation of CPDC An-shun Site: An Introduction

Site History

- **1945-1964 (Mercury Pollution)**
- Owner: Taiwan Soda Company
- Factory: NaOH Plant 50T/D (Mercury electrode)
- Product: 45% Soda solu. / Flake soda
  Liq.CL$_2$ / H^2 / NaClO$_3$ Solu. /
  HCl Solu.
- Reconstruction: 1946
- Operation: 1946 - 3T/D
  1964 - 100T/D



Ref: CPDC, Remediation of CPDC An-shun Site: An Introduction
Wikipedia,: Castner–Kellner process

Site History

1964-1982 (Mercury / PCP Pollution)

- **Owner:** Taiwan Soda Company
- **Factory:** NaOH Plant 50T/D (Mercury electrode)
  Pentachlophenol plant 5T/D
- **Product:** 45% Soda solu. / Flake soda Liq.CL_2 /
  H^2 / $NaClO_3$ Solu. / HCl Solu.
  Na-PCP
- **Shut down:** 1982.07
  (Mercury Pollution
  Problem)

Ref: CPDC, Remediation of CPDC An-shun Site: An Introduction

Site History

1983-2009 (Mercury / PCP)

- Owner: China Petrochemical Develop. Company (CPDC)
  Before 1993 CPDC State-run
  After 1993 CPDC Private
- Remediation:
  - 1989 PCP-polluted groundwater remediation
  - 2003 An investigation of Dioxin
  - 2003 promulgated as Remediation Site
  - 2008 Court judged CPDC's responsibility
  - 2009 Remediation plan was approved by Tainan government, and started since May, 2009

Ref: CPDC, Remediation of CPDC An-shun Site: An Introduction

Before 2009.05.06 - by EPB

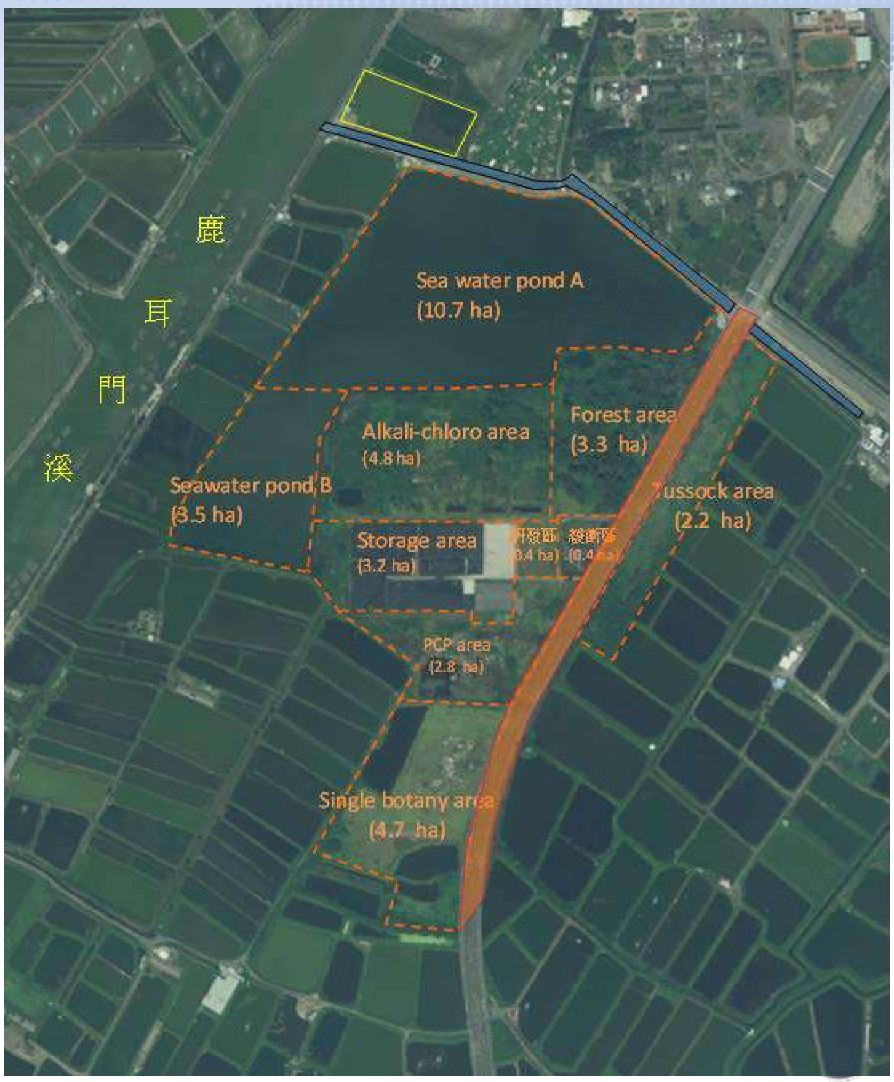
Cleaned Area

- 2003
  Road 2-9 was excavated
- 2005-
  Fish ponds were monitored (27 ha.)
- 2008
  Chu-Fa-Gun Stream (6000 m^3) was excavated

Ref: CPDC, Remediation of CPDC An-shun Site: An Introduction

After 2009.05.06 - by EPB

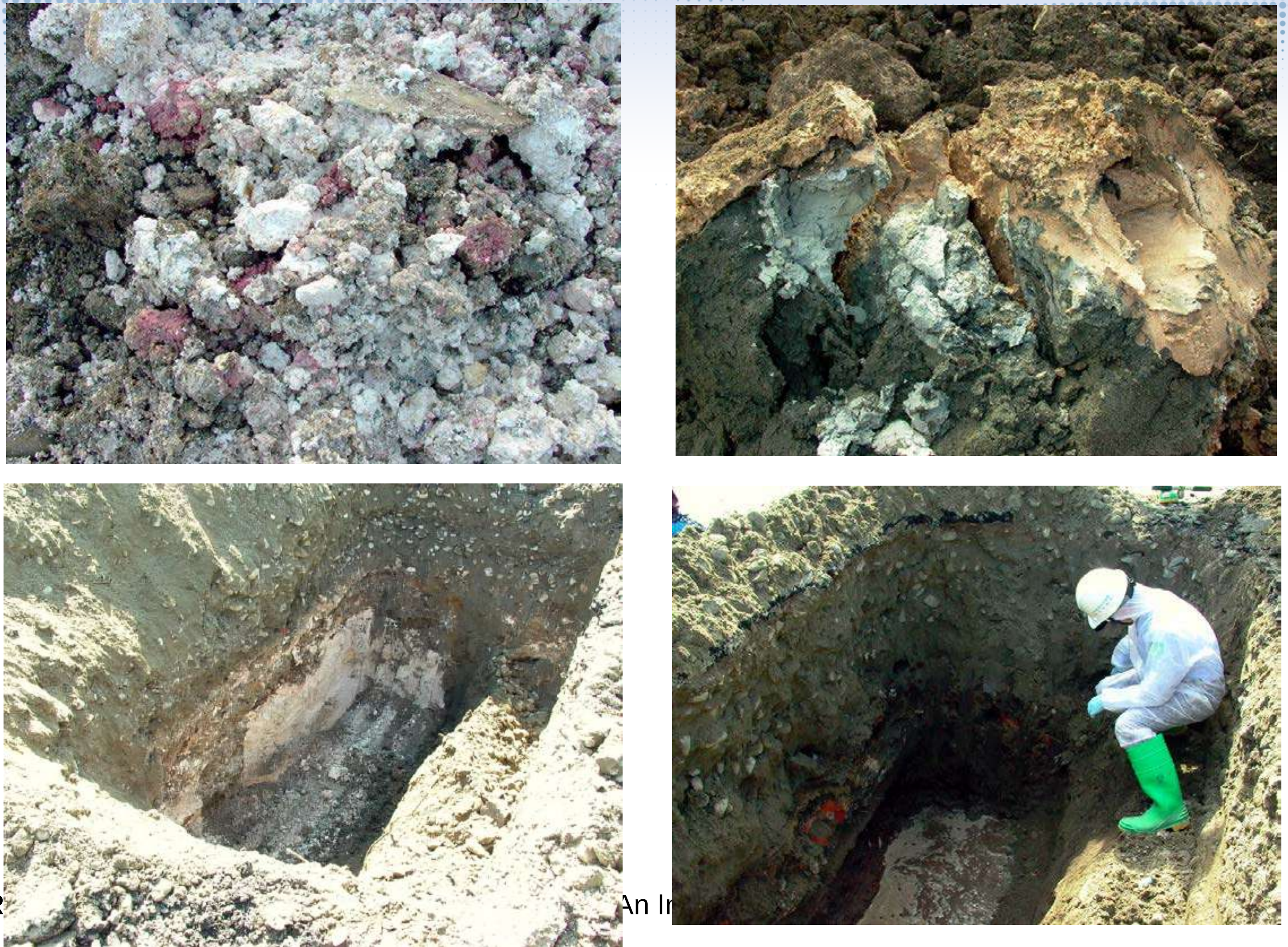
- **Remediation Criteria**
  - promulgated in 2003
- **Soil**
  - Dioxin < 1000 ng-I-TEQ/KG
    Hg < 20 mg/kg
- **Sediment**
  - Dioxin < 150 ng-I-TEQ/KG
    Hg < 1 mg/kg
- **Surrounding Air Quality**
  - Total Hg < $150\ ng/Nm^3$
    (WHO: $1000\ ng/Nm^3$)
    PM10 < $125\ ug/Nm^3$



Site History

Ref: CPDC, Remediation of CPDC An-shun Site: An Introduction

Site History



Site History

Ref: CPDC, Remediation of CPDC An-shun Site: An Introduction

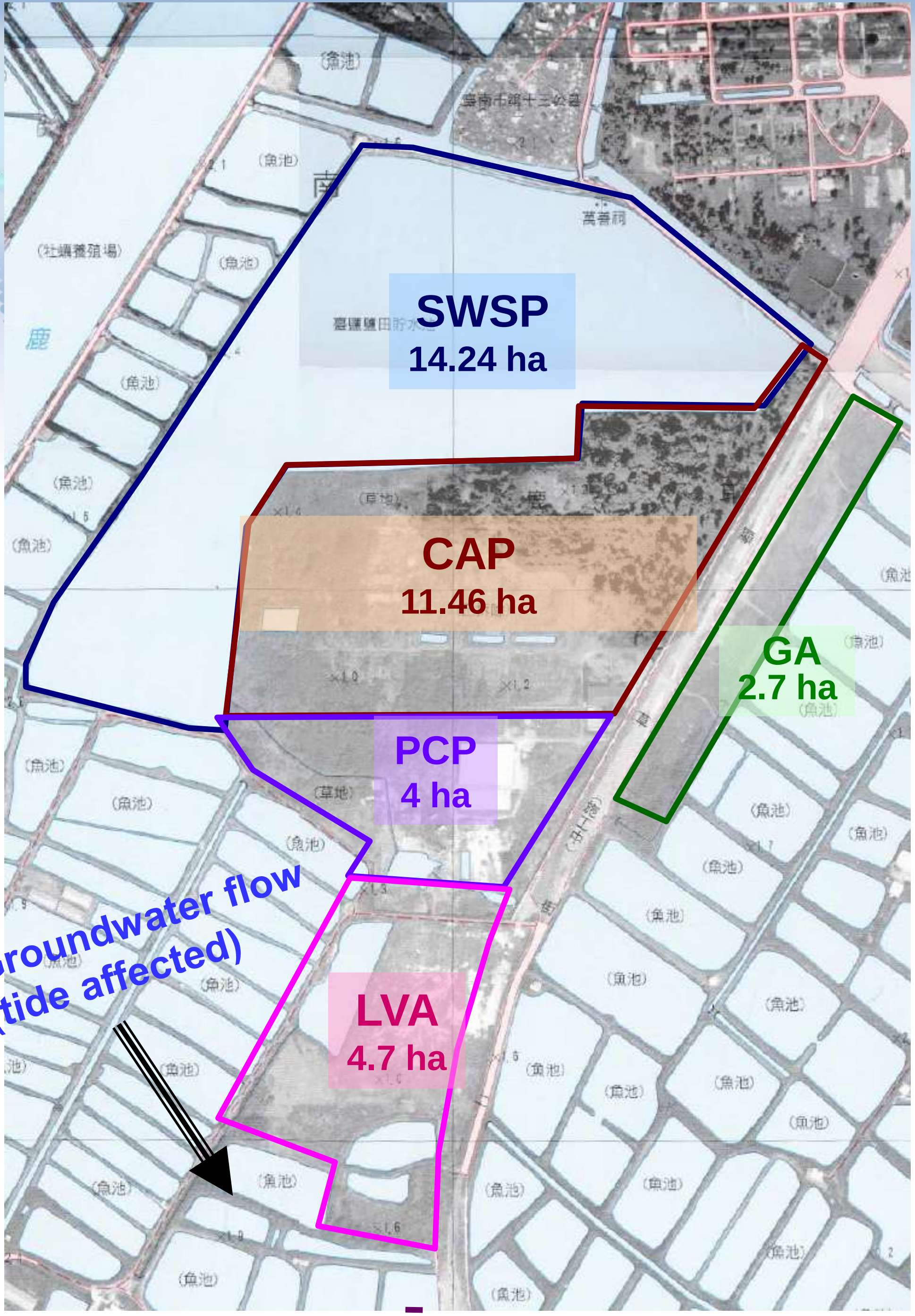
Site History

Ref: CPDC, Remediation of CPDC An-shun Site: An Introduction

Mercury Distribution in An-Shun Site

- **Highest concentrations detected**
  - In soil: 9,550 mg/kg (vs. 20 mg/kg standard)
  - In sediment: 1,410 mg/kg (vs. 1 mg/kg standard)
- **Total Hg mass estimated to be over 40 tons**
  - Some hot spots in soil have been removed and contained in temporary storage areas
  - The storage place zone contains highly contaminated soil
- **Mercury derivative**
  - React with CL_2/NaOH/S to form $HgCl_2$ /$Hg(OH)_2$ /amalgam/HgS

An-Shun Site



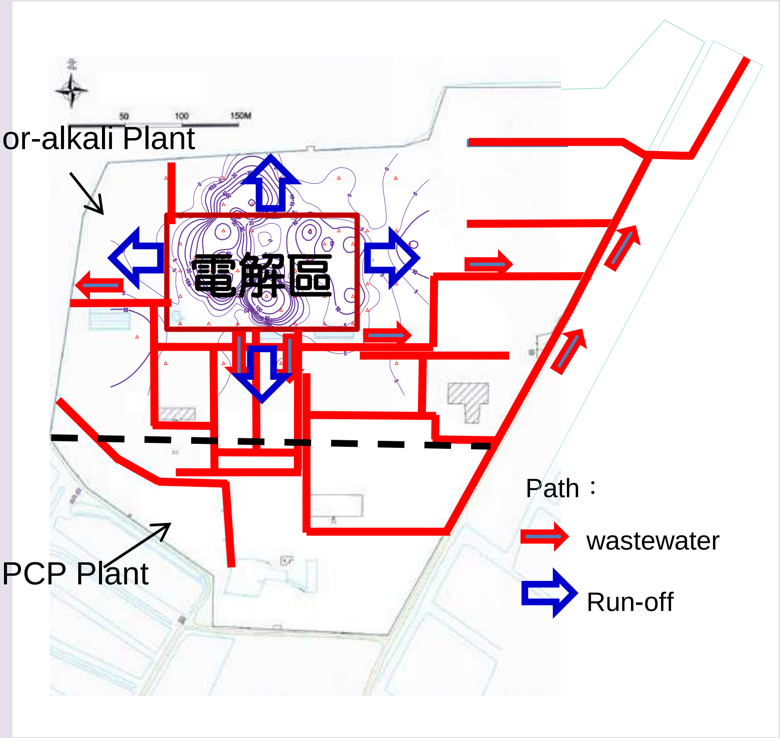
SWSP, Sea water storage pond
CAP, Chlor-alkali plant area
PCP, Pentachlorophenol-plant area
LVA, Lime vegetation area
GA, Grass area

Soil & sediment polluted: in 37.1 ha

Target contaminants:
Mercury, Dioxin
(and also Pentachlorophenol)

Mercury Transfer & Pollution Map

Mercury Transport Path



Chlor-alkali Plant

PCP Plant

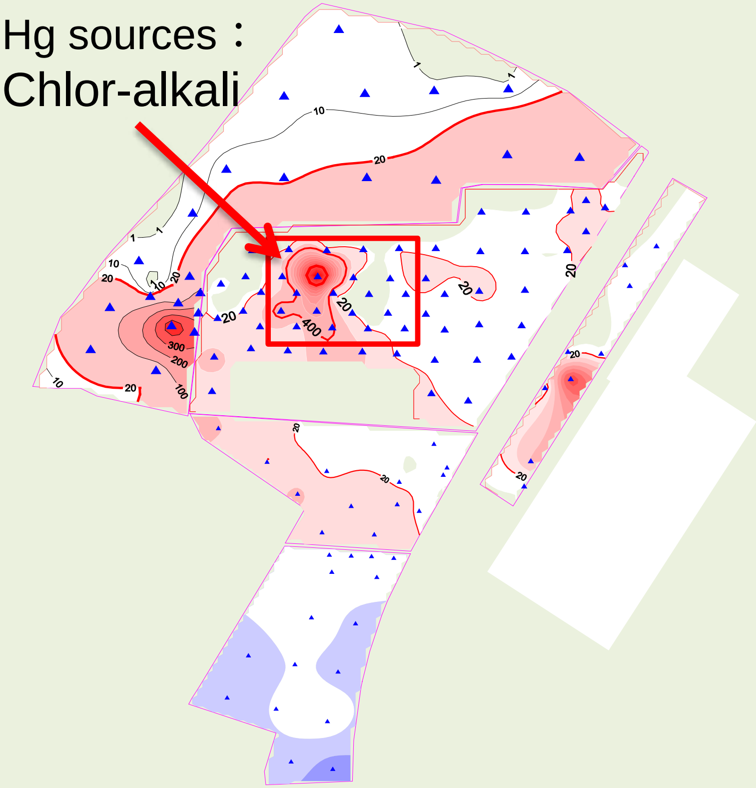
Path：

wastewater

Run-off

Mercury - Pollution Map

Hg sources：
Chlor-alkali



Ref: CPDC, Remediation of CPDC An-shun Site: An Introduction

Chlor-alkali Plant Area

- **Hg (average: 33 mg/kg; max: 3370 mg/kg)**
- **Dioxin (average: 1281 ng-TEQ/kg)**

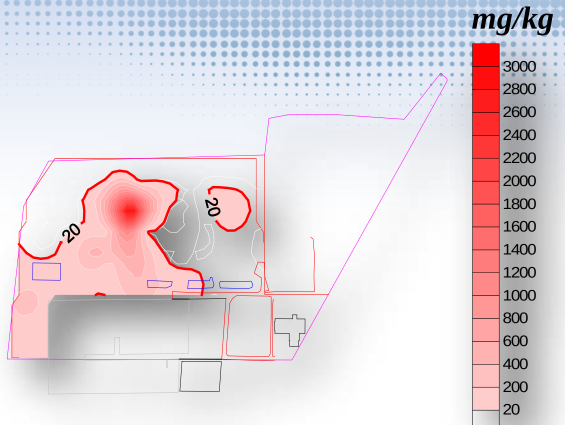
Detection Value Table

Item	Hg (mg/kg)	Dioxin (ng-TEQ/kg)
Number of samples	**696**	**151**
Maximum	**3,370**	**45,500**
Minimum	**0**	**1**
Average	**33**	**1,281**
Standard deviation	**152**	**3,935**
95% of the upper limit of the trustworthiness	**43**	**1,845**
95% of the lower limit of the trustworthiness	**23**	**717**

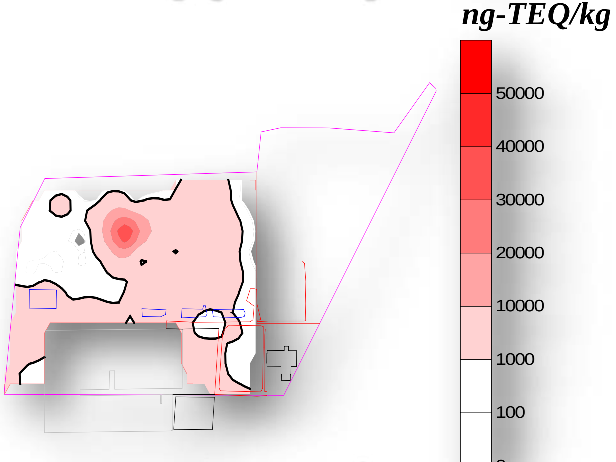
Particle size distribution

No.	Sampling depth (cm)	Material Proportion (%)	
		Sand	Silt and clay
G19	50-100	94.2	5.80
G39	200-250	95.12	4.88
G43	50-100	92.54	7.46
G47	200-250	93.91	6.09
G48	50-100	93.28	6.72
G38	50-100	88.10	11.90
G129	50-100	87.19	12.81
G81	50-100	84.47	15.53

No.	Sampling depth (cm)	Material Proportion (%)	
		Sand	Silt and clay
G82	50-100	86.59	13.41
G83	50-100	92.02	7.98
G84	50-100	92.01	7.99
G91	50-100	90.53	9.47
G92	50-100	78.49	21.51
G93	50-100	94.67	5.33
G104	50-100	93.41	6.59



Mercury (0-50 cm)

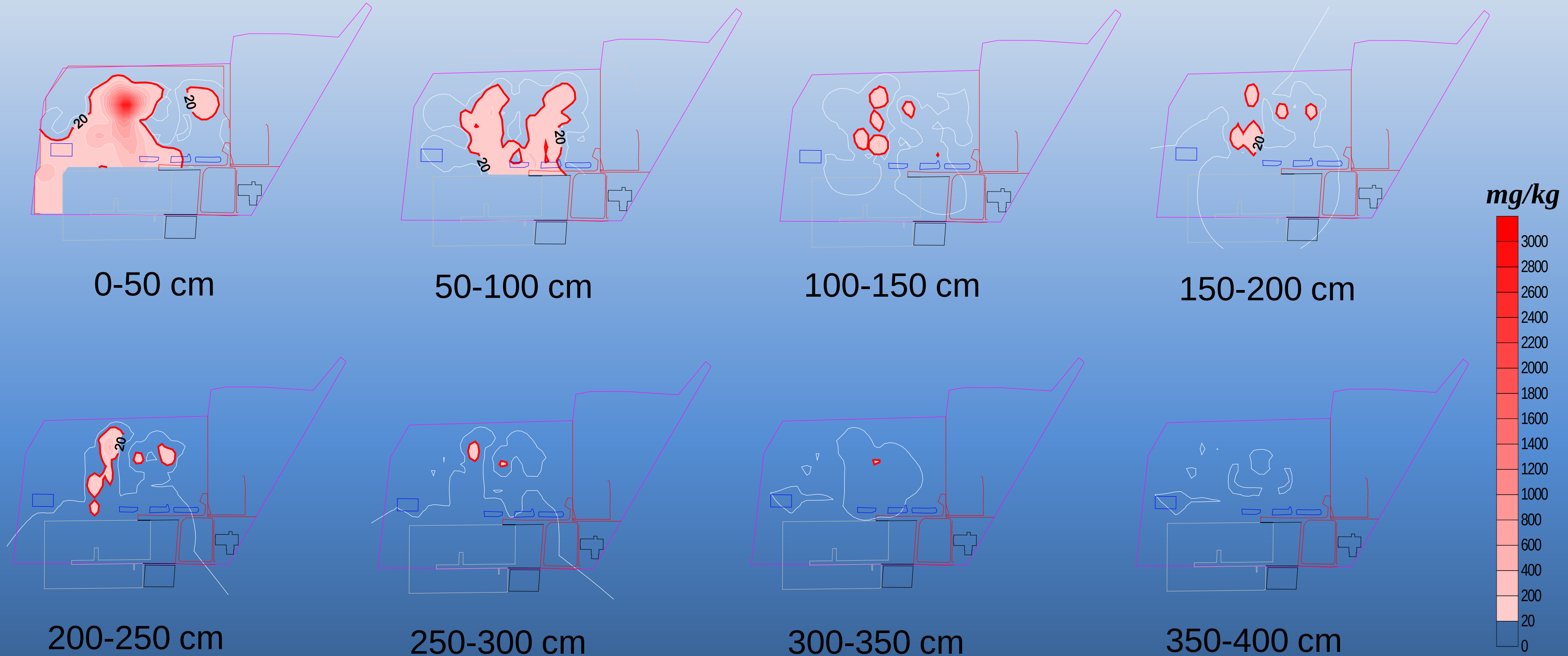


Dioxin (0-50 cm)

Ref: CPDC, Remediation of CPDC An-shun Site: An Introduction

Chlor-alkali Plant Area

❖ Mercury Map (depth: 3m)



0-50 cm

50-100 cm

100-150 cm

150-200 cm

200-250 cm

250-300 cm

300-350 cm

350-400 cm

Ref: CPDC, Remediation of CPDC An-shun Site: An Introduction

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PCP Area

- Hg (average: 40 mg/kg)
- Dioxin (average: 205,222 ng-TEQ/kg)
  (max: 14,100,000 ng-TEQ/kg)

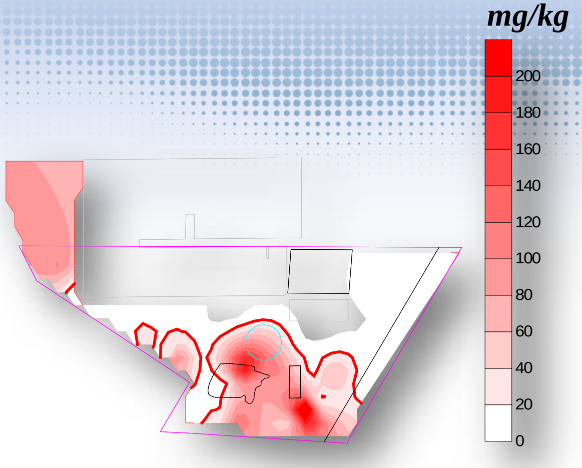
Detection Value Table

Item	Hg (mg/kg)	Dioxin (ng-TEQ/kg)
Number of samples	85	285
Maximum	444	14,100,000
Minimum	0	7
Average	40	205,222
Standard deviation	89	1,255,846
95% of the upper limit of the trustworthiness	56	336,223
95% of the lower limit of the trustworthiness	23	74,222

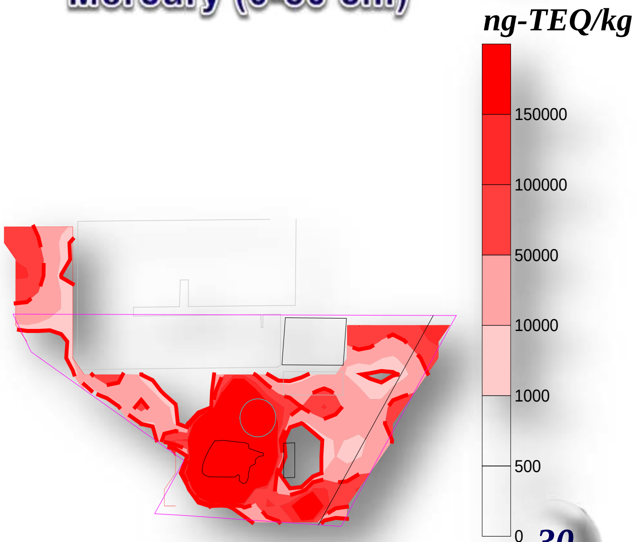
Particle size distribution

No.	Sampling depth (cm)	Material Proportion (%)	
		Sand	Silt and clay
CS017	0-50	92.34	7.66
CS017	200-250	98.80	1.20
CS019	50-100	83.30	16.70
CS021	0-50	83.00	17.00
CS025	0-50	88.41	11.59
CS028	100-150	92.18	7.82
CS033	150-200	91.55	8.46
CS034	0-50	83.13	16.87

No.	Sampling depth (cm)	Material Proportion (%)	
		Sand	Silt and clay
CS035	50-100	89.74	10.26
CS037	0-50	86.44	13.56
CS037	200-250	92.94	7.06
CS039	100-150	95.78	4.22
CS041	0-50	89.29	10.71
CS041	100-150	89.88	10.12
CS041	200-250	91.73	8.27



Mercury (0-50 cm)



Dioxin (0-50 cm)

Ref: CPDC, Remediation of CPDC An-shun Site: An Introduction

Sea Water Storage Pond A

- Hg (average: 11 mg/kg)
- Dioxin (average: 611ng-TEQ/kg)

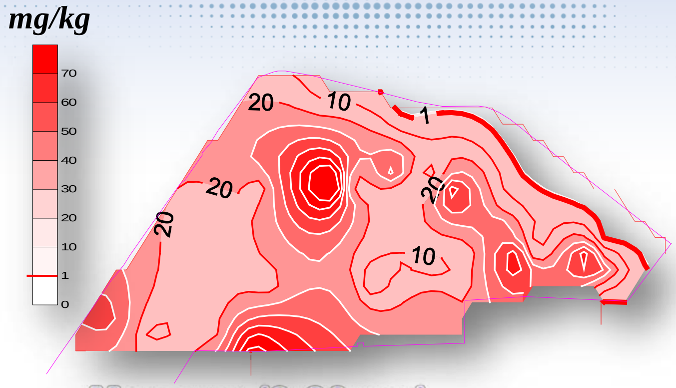
Detection Value Table

Item	Hg (mg/kg)	Dioxin (ng-TEQ/kg)
Number of samples	129	46
Maximum	104	4,460
Minimum	1	2
Average	11	611
Standard deviation	18	934
95% of the upper limit of the trustworthiness	13	853
95% of the lower limit of the trustworthiness	8	368

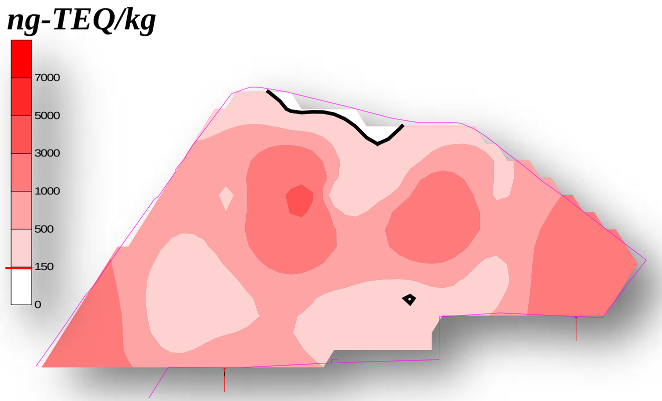
Granulometry

No.	Sampling depth (cm)	Material Proportion (%)	
		Sand	Silt and clay
A01	0-30	77.24	22.76
A03	0-30	43.17	56.83
A03	30-60	88.87	11.13

Ref: CPDC, Remediation of CPDC An-shun Site: An Introduction



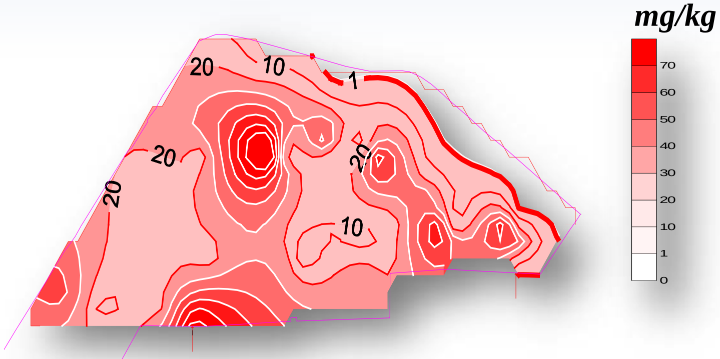
Mercury (0-30 cm)



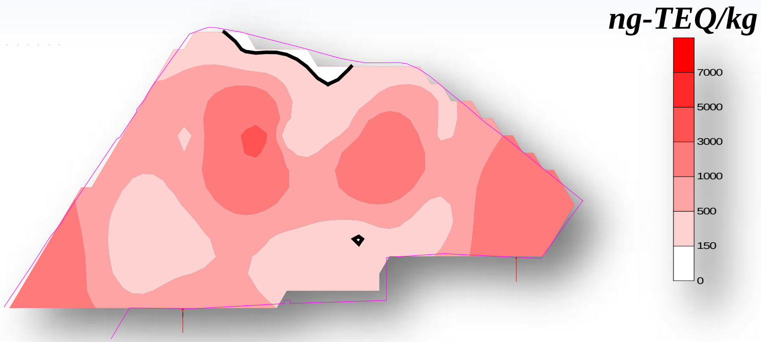
Dioxin (0-30 cm)

Sea Water Storage Pond A

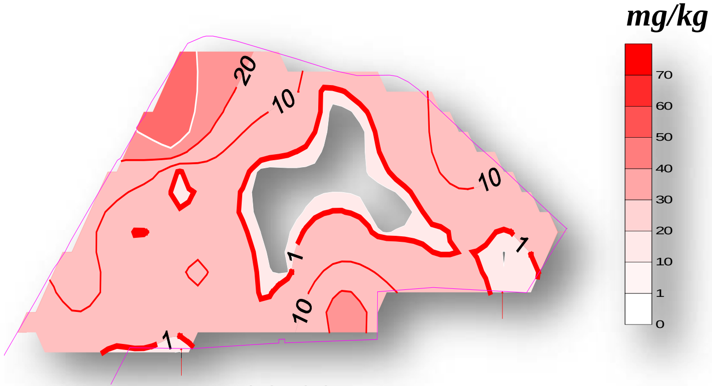
- **Mercury Map (depth: 0.6m)**
- **Dioxin Map (depth: 0.6m)**



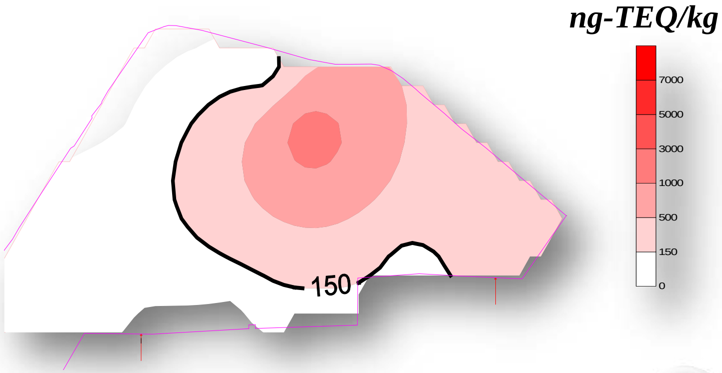
0-30 cm



0-30 cm



30-60 cm



30-60 cm

Ref: CPDC, Remediation of CPDC An-shun Site: An Introduction

Sea Water Storage Pond B

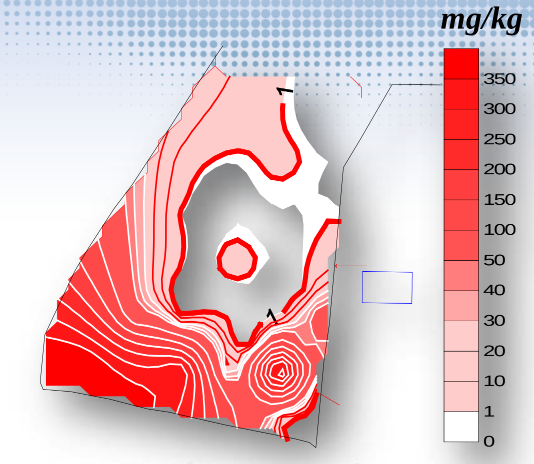
- **Hg (average: 42 mg/kg)**
- **Dioxin (average: 979 ng-TEQ/kg)**

Detection Value Table

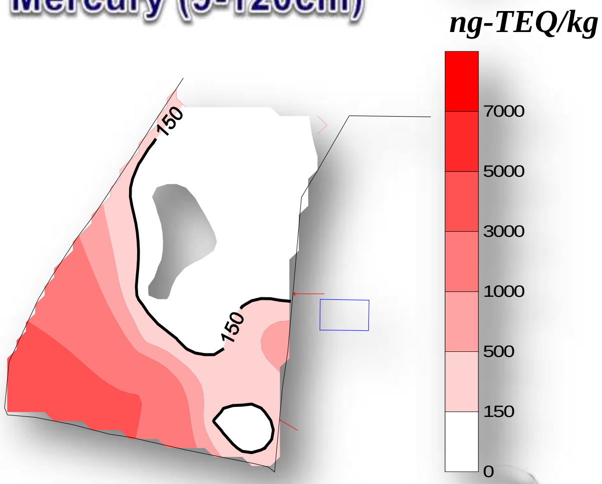
Item	Hg (mg/kg)	Dioxin (ng-TEQ/kg)
Number of samples	**207**	**42**
Maximum	**1,410**	**6,560**
Minimum	**0**	**3**
Average	**42**	**979**
Standard deviation	**164**	**1,648**
95% of the upper limit of the trustworthiness	**62**	**1,427**
95% of the lower limit of the trustworthiness	**22**	**531**

Particle size distribution

No.	Sampling depth (cm)	Material Proportion (%)	
		Sand	Silt and clay
B01	90-120	89.80	10.20
B03	90-120	63.36	36.64
B04	90-120	54.13	45.87
B06	90-120	50.36	49.64
B08	210-240	85.41	14.59
B17	90-120	92.41	7.59
B20	90-120	91.49	8.51



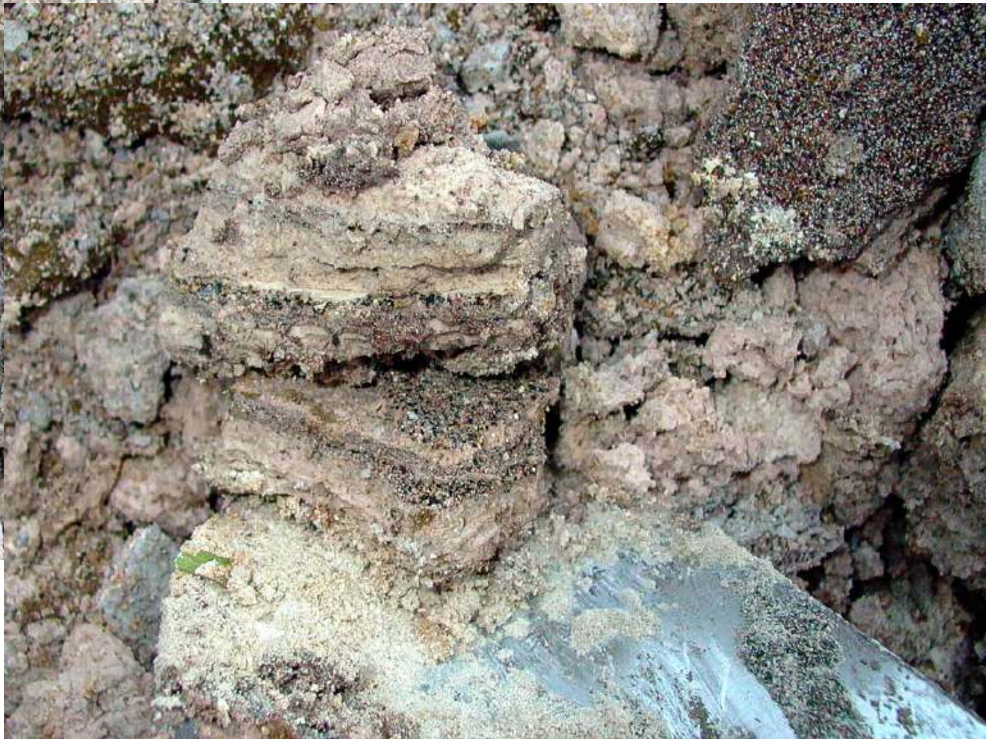
Mercury (9-120cm)



Dioxin (9-120cm)

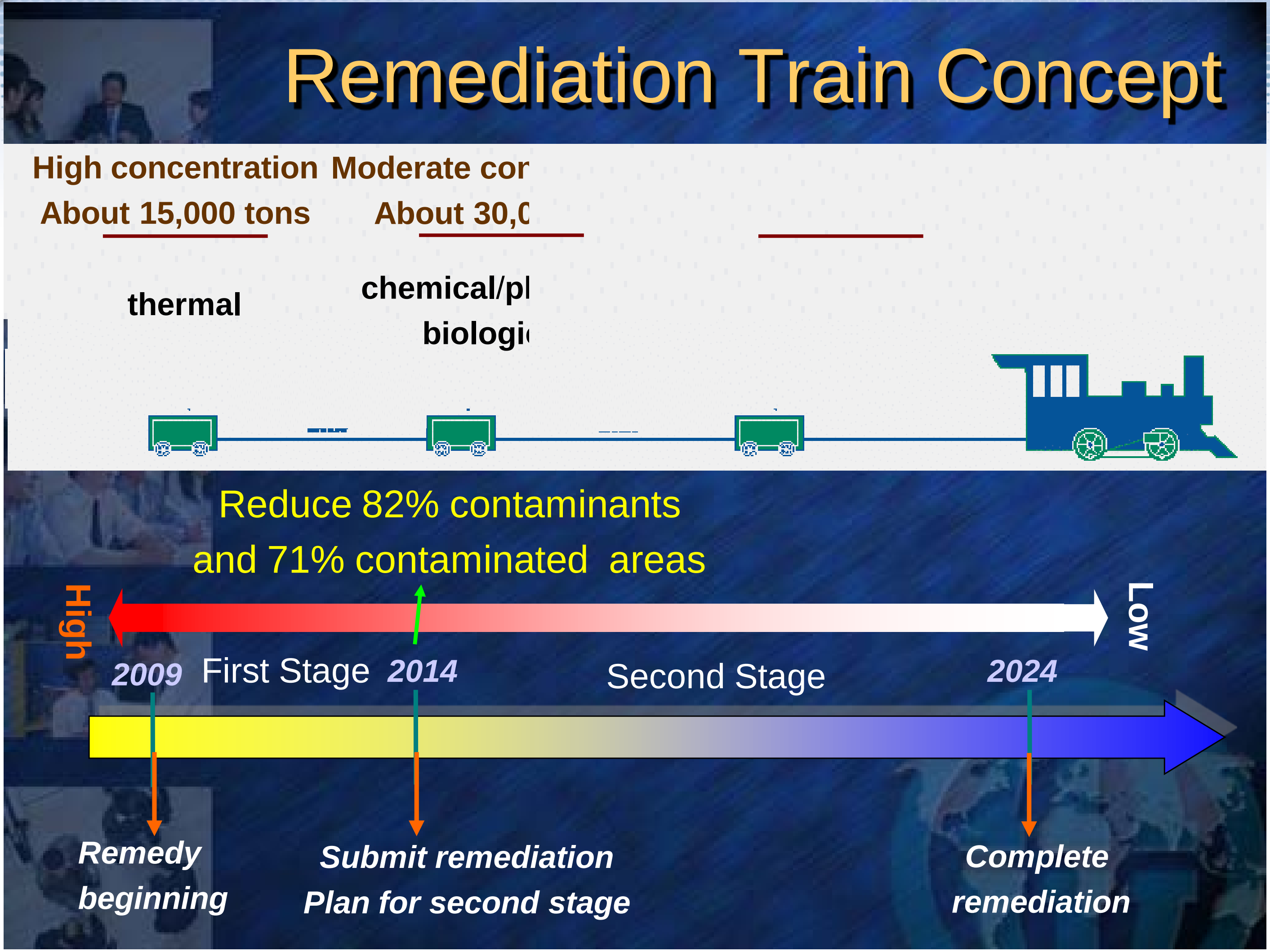
Ref: CPDC, Remediation of CPDC An-shun Site: An Introduction

How to clean up?



How to treat?

Remediation Plan 2009-2024



Remediation Train Concept

High concentration
About 15,000 tons

Moderate cor
About 30,0

thermal

chemical/pl
biologi

Reduce 82% contaminants
and 71% contaminated areas

2009 First Stage *2014* Second Stage *2024*

Remedy beginning

Submit remediation Plan for second stage

Complete remediation

Ref: CPDC, Remediation of CPDC An-shun Site: An Introduction

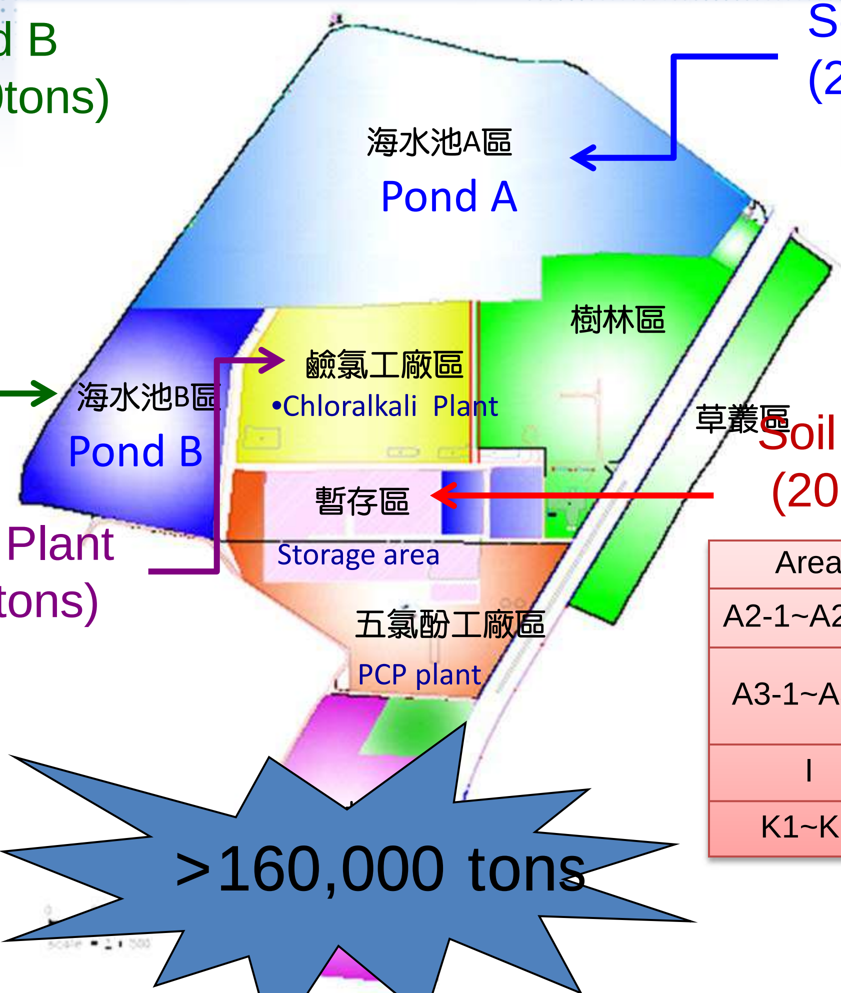
Quantities of Mercury Contaminated Soil / Sediment

Sediment from Pond B
(34,000 m^3，54,000tons)

Depth (cm)	Volume(m^3)
0-30	9,200
30-60	6,250
60-90	6,250
90-150	7,000
150-210	5,300

Soil from Chloralkali Plant
(30,000 m^3，48,000 tons)

Depth (cm)	Volume (m^3)
0-50	12,000
50-100	8,000
100-150	4,000
150-200	4,000
200-250	2,000



Sediment from Pond A
(21,000 m^3，34,000tons)

Depth (cm)	Volume (m^3)
0-30	21,000
30-60	0
30-90	0

Soil from Storage space
(20,000 m^3，32,000tons)

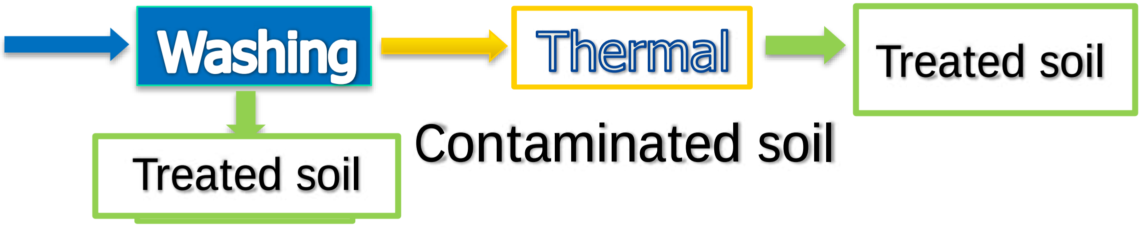
Area	Sources	Volume (m^3)
A2-1~A2-12	Chloralkali Plant	10,000
A3-1~A3-7	Chloralkali Plant	5,500
I	Grass Area	500
K1~K2	Grass Area	4,000

>160,000 tons

Introduction of Soil Washing

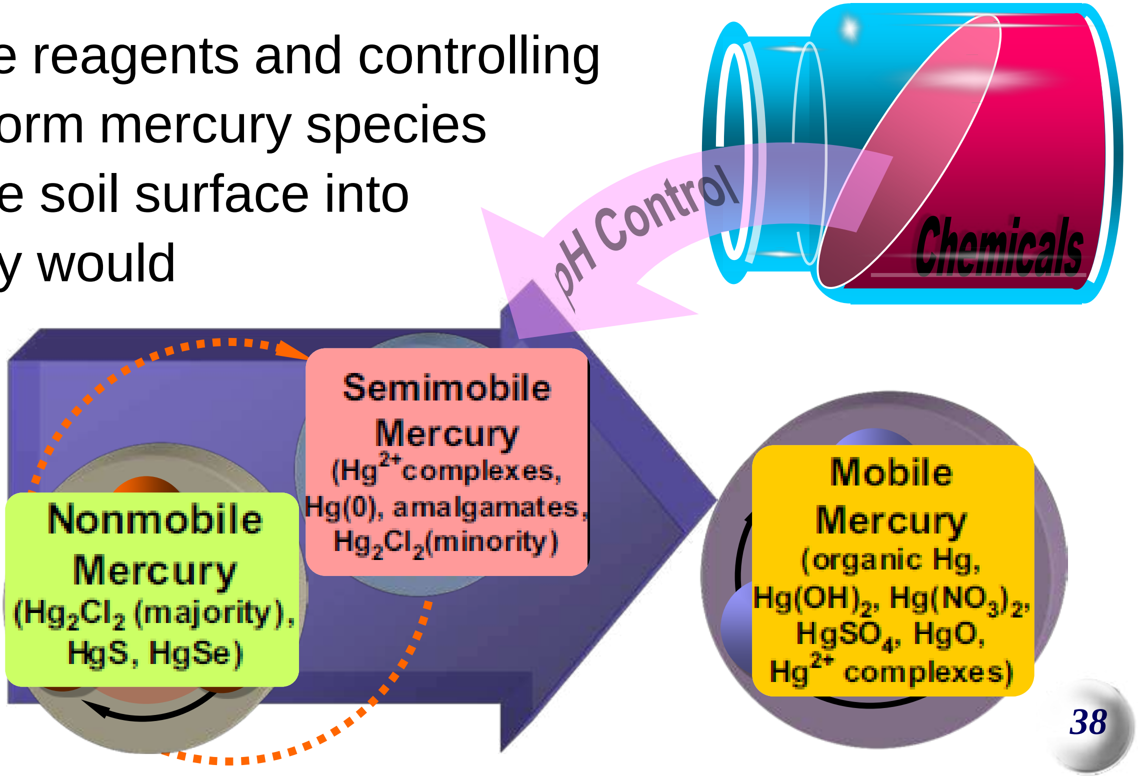
- With the limited available storage space at An-shun site, China Petrochemical Development Corporation (CPDC) was considering economical and efficient methods for soil treatment.
- Soil with low mercury concentration and with dioxin below regulation standard is targeted for priority treatment.
- The goal is to reduce the amount of soil required for thermal treatment or more complicated treatment in the future, in hope to reduce the overall remediation cost for soil treatment.

Hg	Dioxin
< 200 mg/kg	< 1,000
Soil / Sediment	


Washing
Thermal
Treated soil
Treated soil
Contaminated soil

The Concept of Soil Washing

- Interpreting the mercury speciation in soil
- Implementing a sequential extraction process of different operationally defined fractions (mobile Hg, semi-mobile Hg and non-mobile Hg)
- Applying the adequate reagents and controlling the pH value to transform mercury species that are adhered to the soil surface into mercury complex, they would dissolve in the water



Semimobile Mercury
(Hg^{2+}complexes, Hg(0), amalgamates, Hg_2Cl_2(minority))

Nonmobile Mercury
(Hg_2Cl_2 (majority), HgS, HgSe)

Mobile Mercury
(organic Hg, $Hg(OH)_2$, $Hg(NO_3)_2$, $HgSO_4$, HgO, Hg^{2+} complexes)

Mercury Analysis (Before Washing)

Samples	Mobile Hg (mg/kg)		Semimobile Hg (mg/kg)		Nonmobile Hg (mg/kg)	
	Conc.	%	Conc.	%	Conc.	%
Sea pond B	12.27	13%	30.82	34%	49.24	53%
Sea pond B	13.32	13%	30.66	31%	56.58	56%
Sea pond B	23.35	8%	138.9	51%	115.1	41%
Chlor-alkali area	11.66	22%	30.91	58%	11.07	20%
Grass area	5.37	15%	28.17	79%	2.06	6%
Grass area	3.42	10%	27.40	81%	3.00	9%

Mercury Analysis (After Washing)

Samples	Mobile Hg (mg/kg)		Semimobile Hg (mg/kg)		Nonmobile Hg (mg/kg)	
	Conc.	%	Conc.	%	Conc.	%
Sea pond B	0.62	4%	14.31	85%	1.83	11%
Sea pond B	1.88	13%	10.62	72%	2.29	15%
Sea pond B	7.61	57%	4.37	33%	1.38	10%
Chlor- alkali area	2.93	56%	1.71	33%	0.61	12%
Grass area	4.77	43%	5.73	52%	0.53	5%
Grass area	4.09	46%	4.47	50%	0.34	4%

The Feasibility Study – A Pilot Test

15 tons of mercury contaminated soil was treated by soil washing. The percentage of qualified treated soil is 78%. The unqualified soil includes wastewater mud cake, waste activated carbon and contaminated soil.

Mobile Shelter

- **Application**
  - Special excavation
    *when PM10 or vapor
    Hg over regulation
  - Low material cost
    *no steel-structure
  - Dismantle & Buildup
    * in 20 min.
- **Protection**
  - Protect environment & human health

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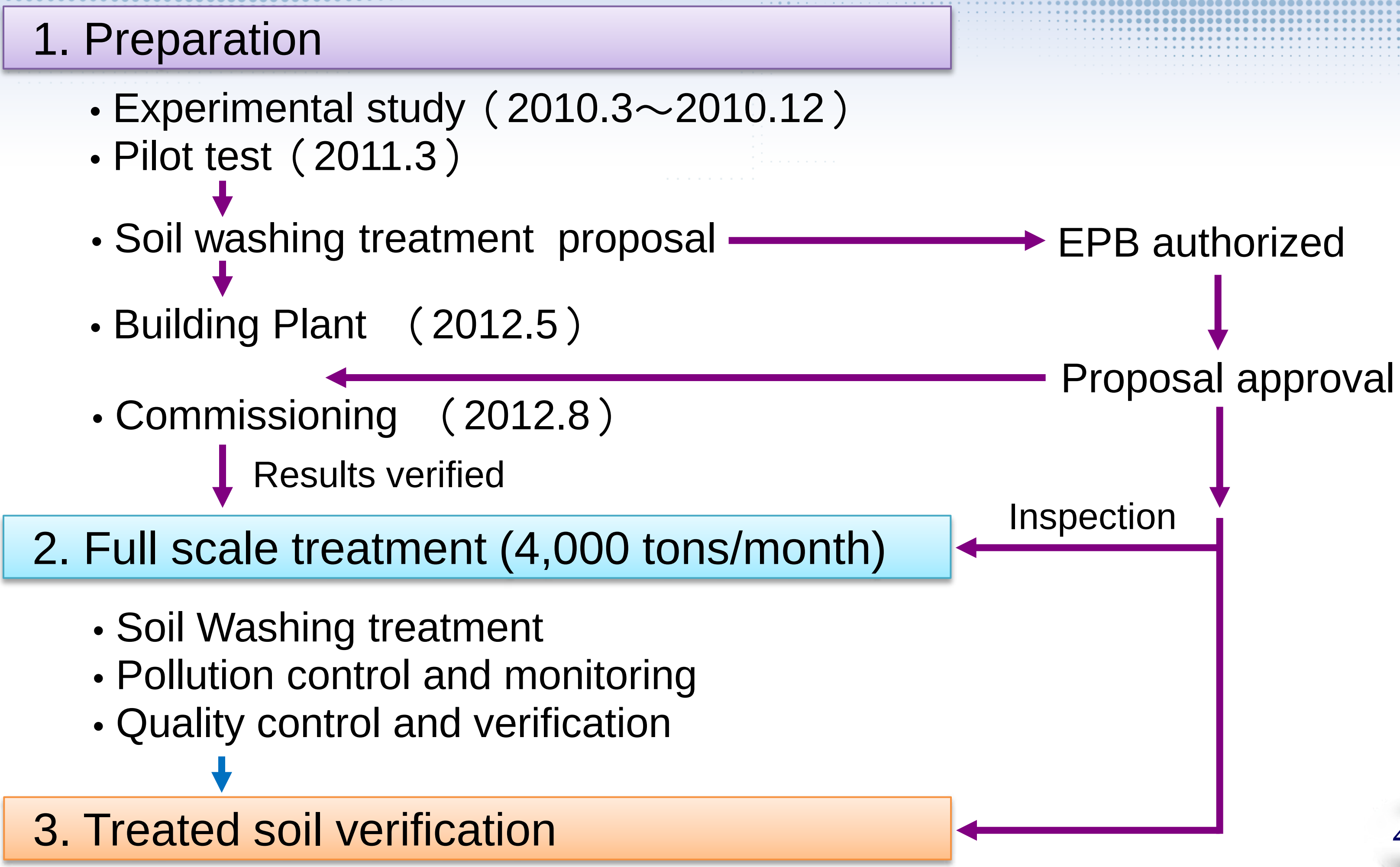
Project Flow Chart



1. Preparation

- Experimental study（2010.3～2010.12）
- Pilot test（2011.3）
- Soil washing treatment proposal → EPB authorized
- Building Plant （2012.5）
- Commissioning （2012.8） ← Proposal approval

Results verified

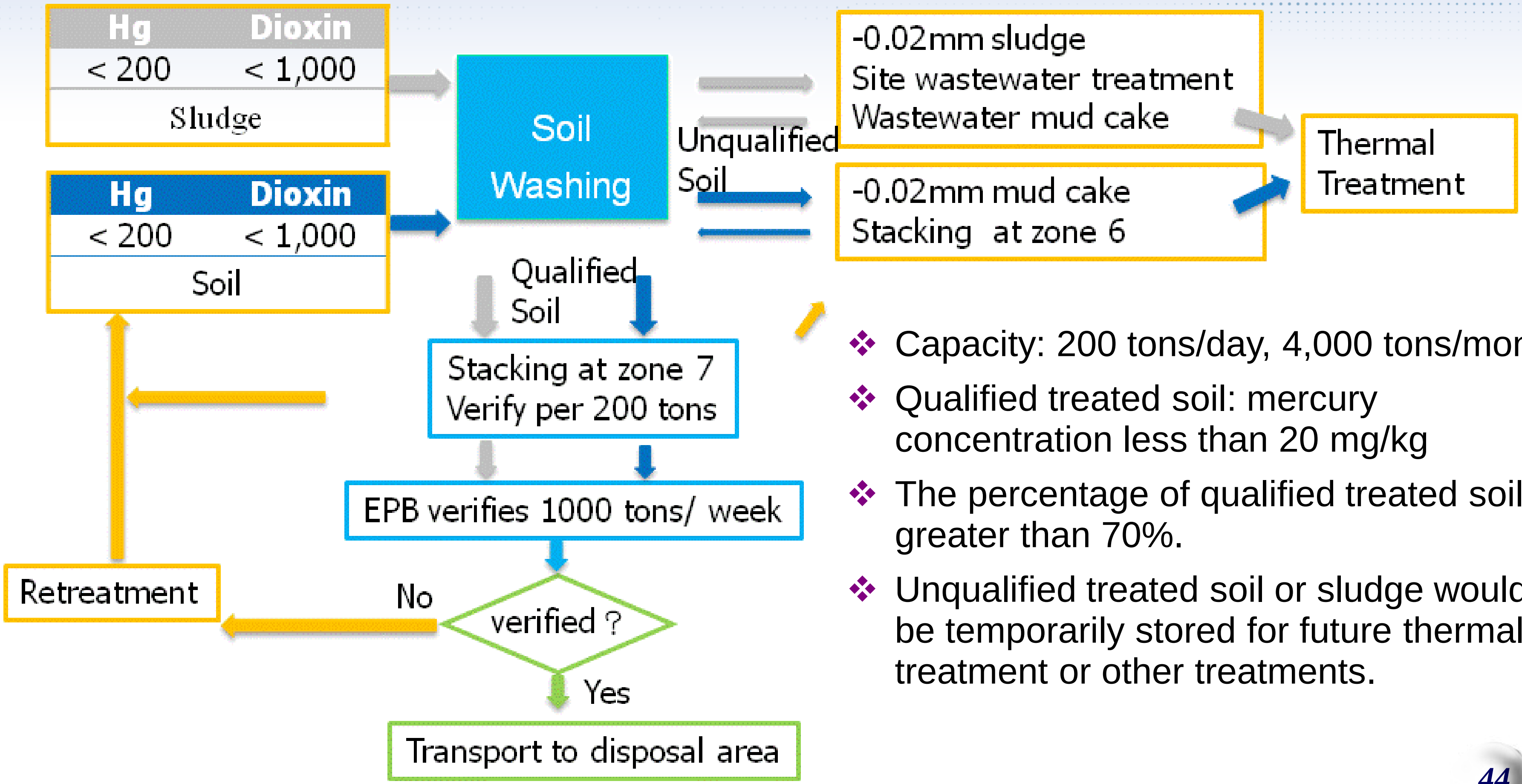
Inspection

2. Full scale treatment (4,000 tons/month)

- Soil Washing treatment
- Pollution control and monitoring
- Quality control and verification

3. Treated soil verification

Design Capacity



Hg	Dioxin
< 200	< 1,000
Sludge	

Hg	Dioxin
< 200	< 1,000
Soil	

- Capacity: 200 tons/day, 4,000 tons/month
- Qualified treated soil: mercury concentration less than 20 mg/kg
- The percentage of qualified treated soil is greater than 70%.
- Unqualified treated soil or sludge would be temporarily stored for future thermal treatment or other treatments.

Building Soil Washing Plant

Land preparation

The sedimentation tank

Concrete foundation

Physical washing equipment

Chemical washing equipment

Pipeline installation

Factory Installation

Washing plant

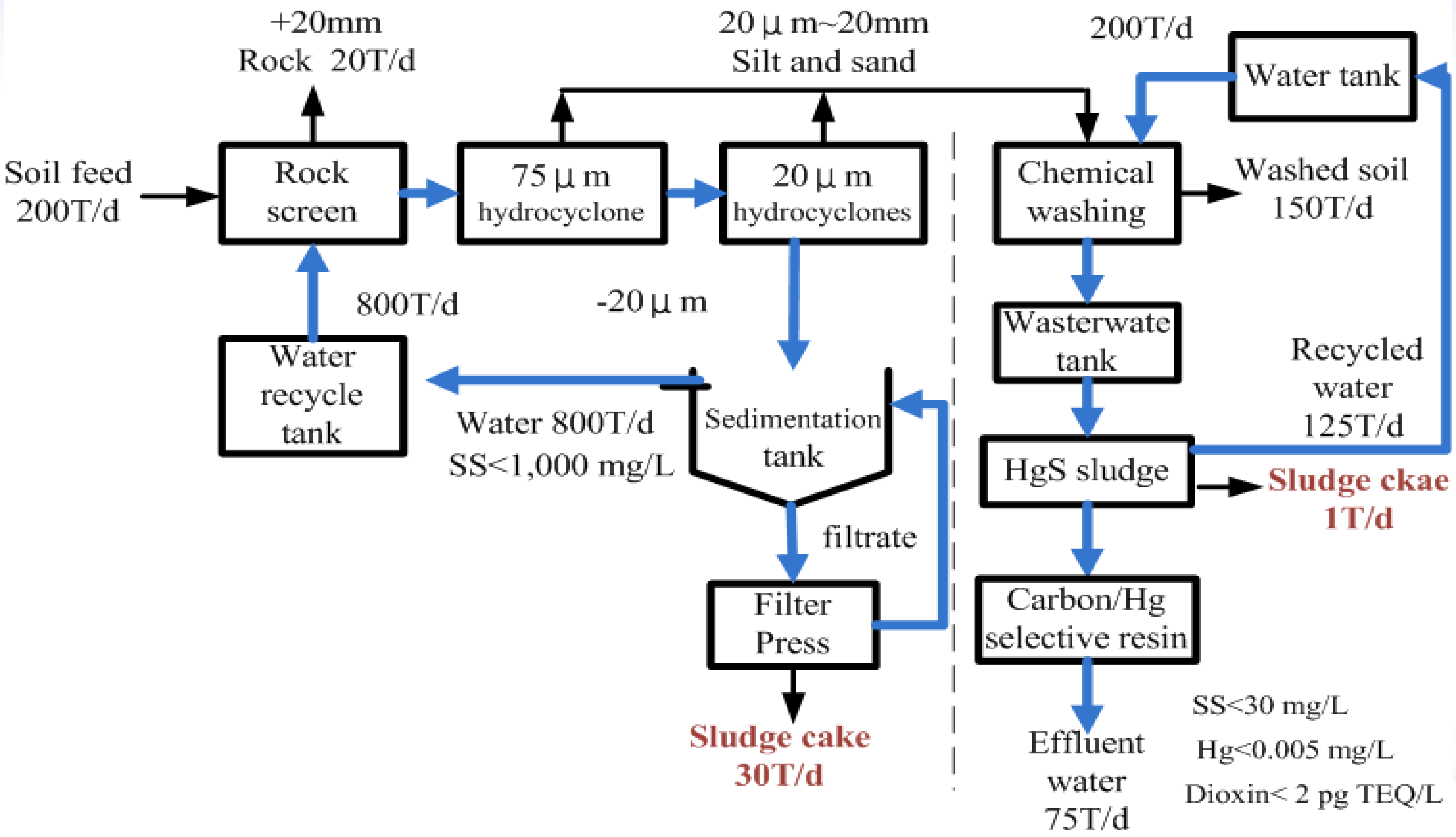
Commissioning

APOLL TECH

Soil Washing Treatment Process

Physical washing

Chemical washing



+20mm
Rock 20T/d

20 µ m~20mm
Silt and sand

200T/d

Water tank

Soil feed
200T/d

Rock
screen

75 µ m
hydrocyclone

20 µ m
hydrocyclones

Chemical
washing

Washed soil
150T/d

800T/d

-20 µ m

Wasterwate
tank

Water
recycle
tank

Recycled
water
125T/d

Water 800T/d
SS<1,000 mg/L

Sedimentation
tank

HgS sludge

Sludge ckae
1T/d

filtrate

Filter
Press

Carbon/Hg
selective resin

Sludge cake
30T/d

Effluent
water
75T/d

SS<30 mg/L
Hg<0.005 mg/L
Dioxin< 2 pg TEQ/L

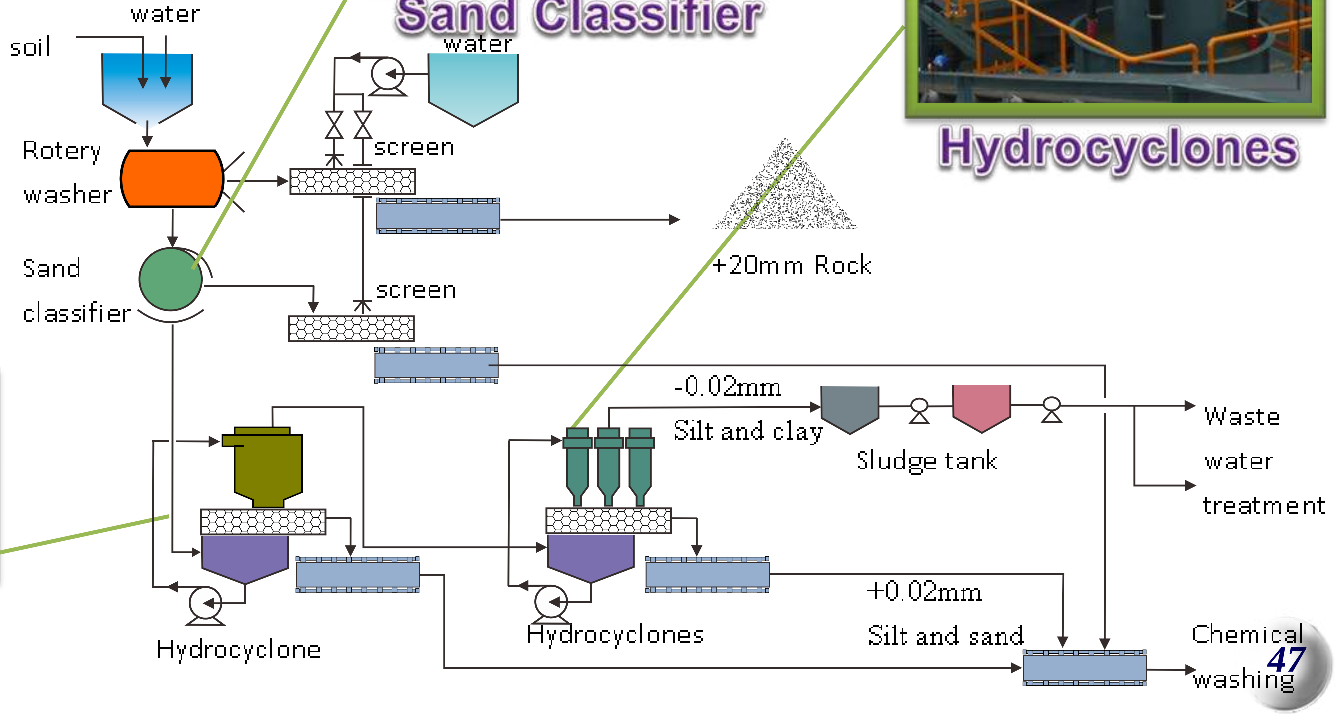
Soil Washing – Physical Washing

Rotary Washer

Sand Classifier

Hydrocyclones

Hydrocyclones



water

soil

water

Rotery washer

screen

+20mm Rock

Sand classifier

screen

-0.02mm

Silt and clay

Sludge tank

Waste water treatment

Hydrocyclone

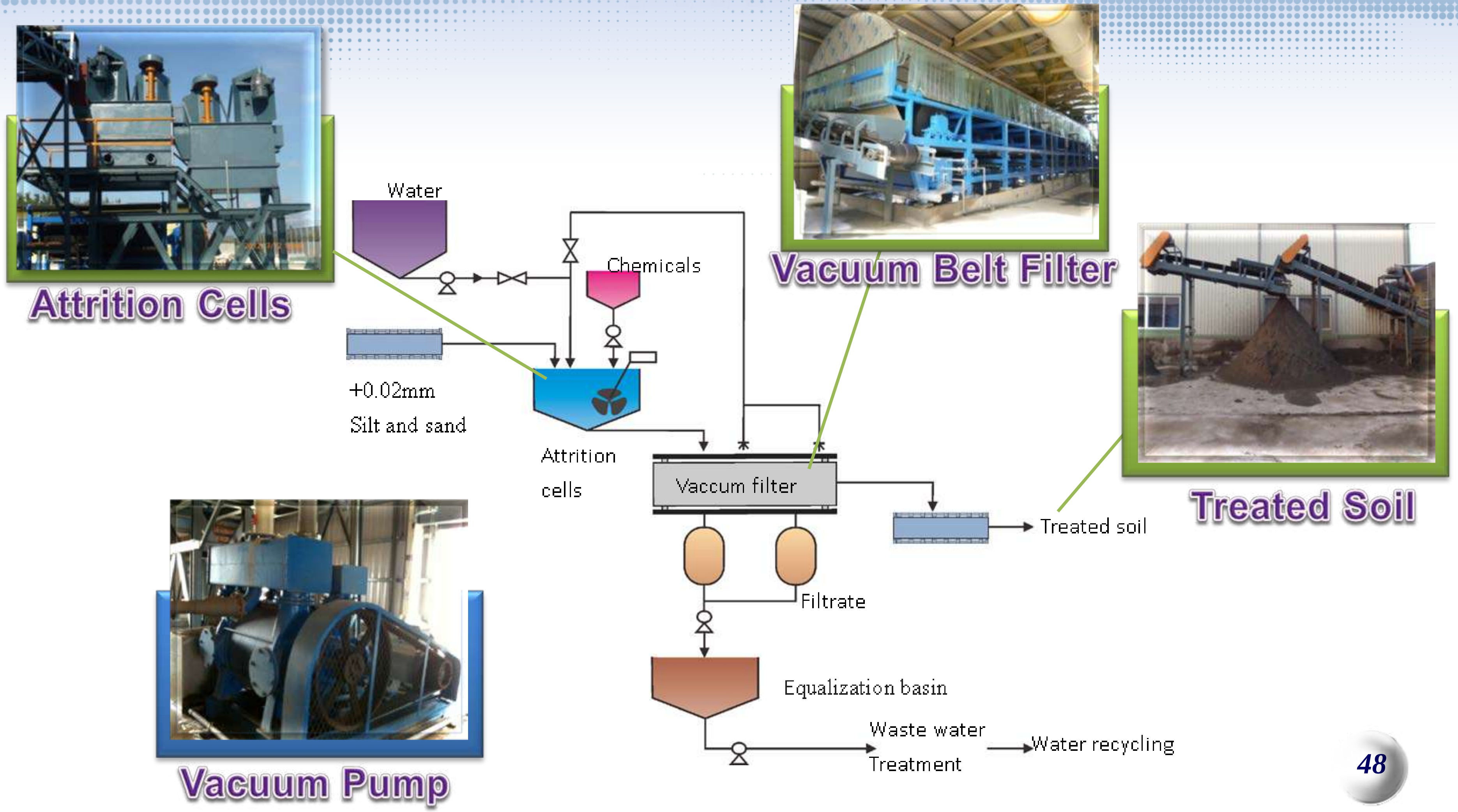
Hydrocyclones

+0.02mm

Silt and sand

Chemical washing

Soil Washing – Chemical Washing



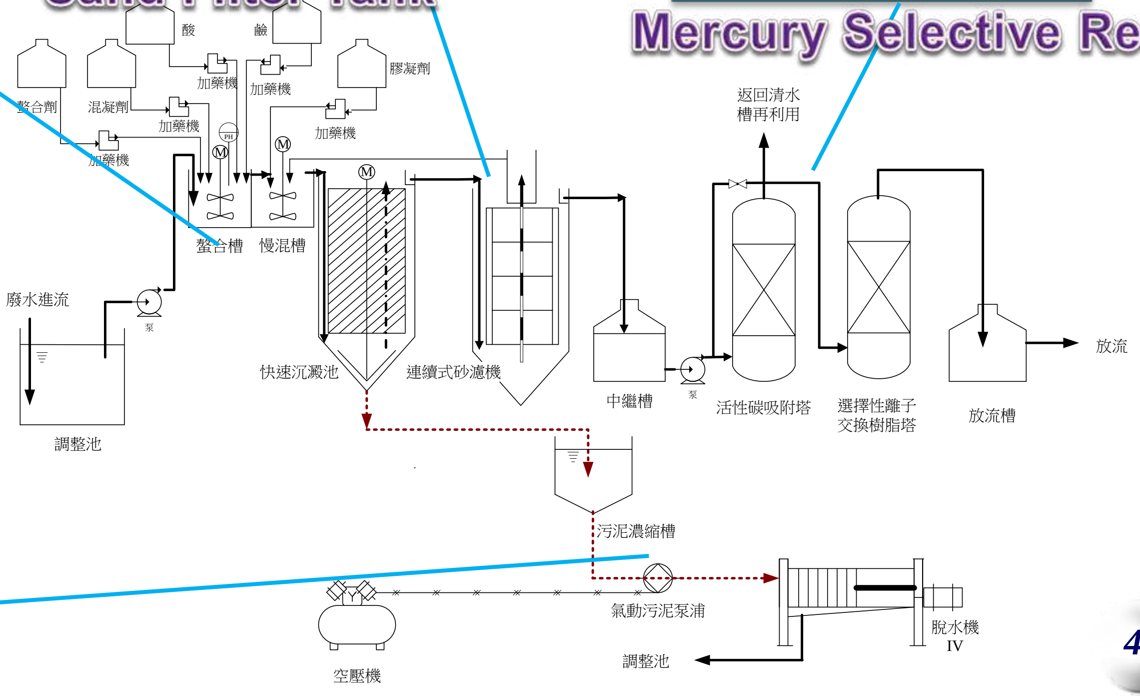
Wastewater Treatment

Sand Filter Tank

Mercury Selective Resin

Fast Sedimentation Tank

Press Filter



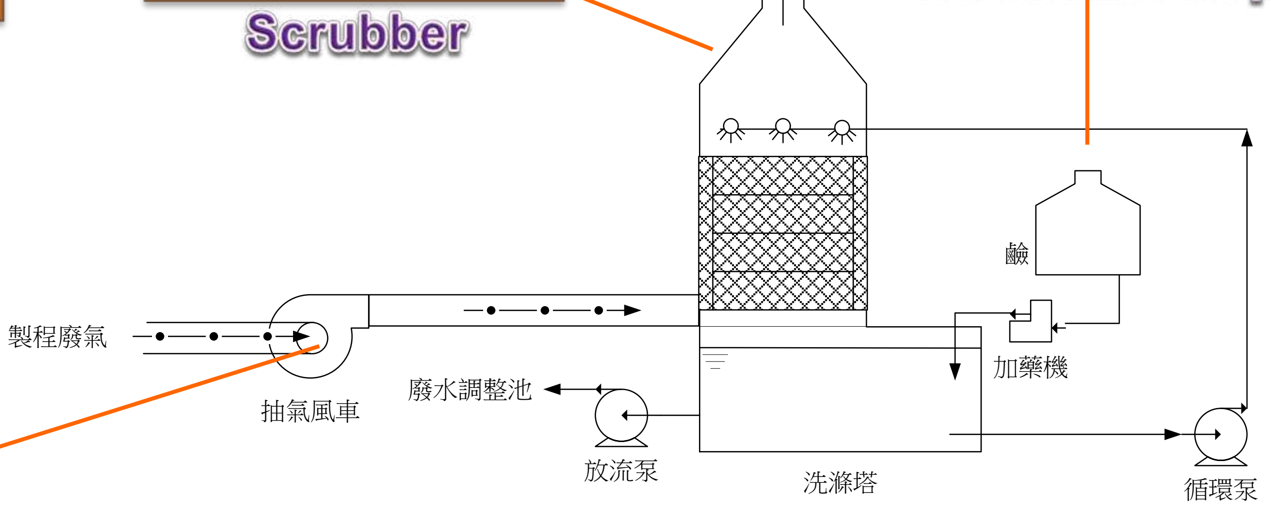
Waste gas treatment

Hood

Scrubber

Chemical Pump

FRP Fan

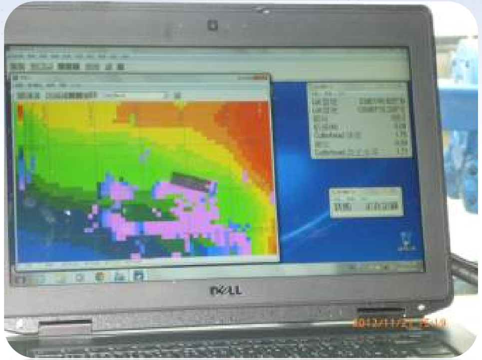


Feed Control

- Surveying the investigation data to exclude high pollution areas
- In sea pond area, dredging the sediment layer by layer according to the investigation data
- In Chlor-alkali and storage area, applying XRF to identify the available feed soil
- Weekly detect the dioxin concentration to control feed quality
- Three stages to qualify treated soil : self-quality control, self-verification and EPB verification

Sediment Transport

Dredging Boat



GPS System

Cutter Suction

Pipeline on the pond

Pipeline on the ground

Feed location

Quality Control

Field XRF

Portable XRF

MA-3000 mercury analyzer

EMP-2 mercury vapor analyzer

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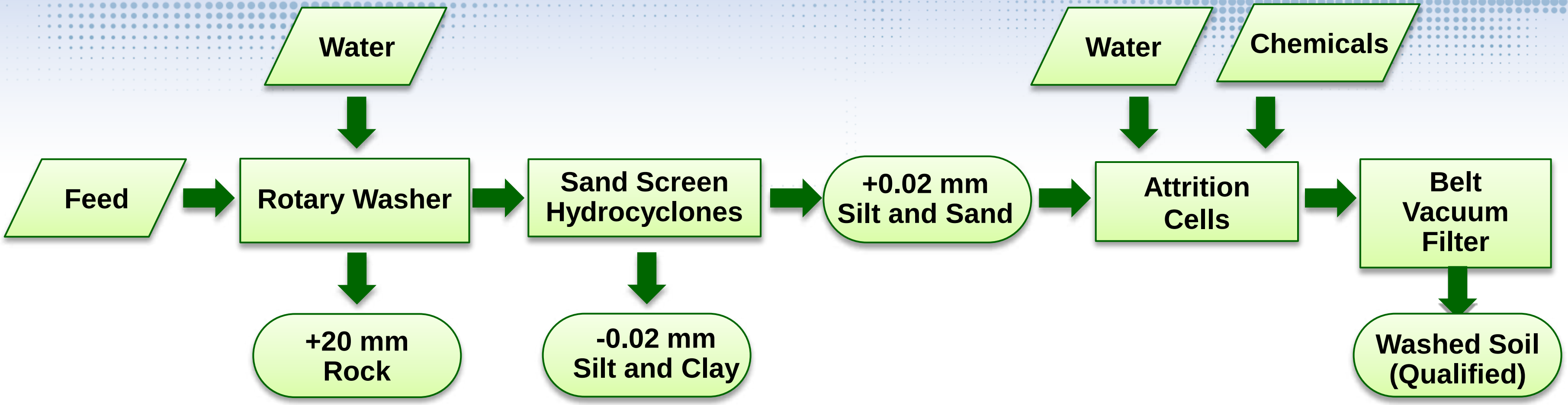
Plant Commissioning



Soil	Feed	Rock	Treated soil
Weight (tons)	1140	190	709
Sediment	**Feed**	**Rock**	**Treated soil**
Weight (tons)	1100.75	few	787.55

Qualified soil >70%

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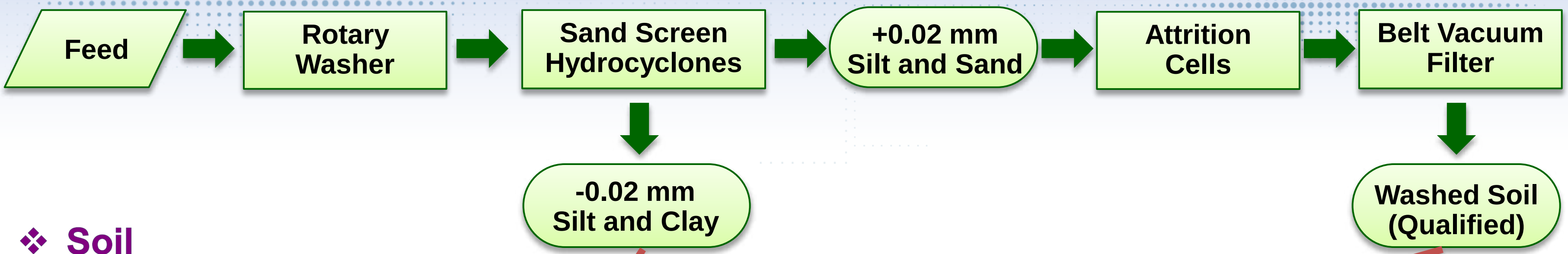
Mercury Mass Balance During Commissioning



Feed → Rotary Washer → Sand Screen Hydrocyclones → +0.02 mm Silt and Sand → Attrition Cells → Belt Vacuum Filter

Sand Screen Hydrocyclones → -0.02 mm Silt and Clay

Belt Vacuum Filter → Washed Soil (Qualified)

❖ Soil

	Input Hg	Output Hg				
	Feed	Silt and Clay (unqualified soil)	Silt and Clay Filtrate	Washed Soil	Washed Filtrate	Total
Conc. (mg/kg)	27.8~283	115~835	0~0.5	0~49.7	1.09~62.6	
Hg Mass (kg)	108.82	89.05	0.36	12.36	16.86	118.62

Difference 9%

❖ Sediment

	Input Hg	Output Hg				
	Feed	Silt and Clay (unqualified soil)	Silt and Clay Filtrate	Washed Soil	Washed Filtrate	Total
Hg Mass (kg)	203.15	179.02	-	6.21	2.02	187.25

Difference 8%

Dioxin Enrichment During Commissioning

❖ Soil

Unit: ng-TEQ/kg Date	Input Dioxin	Output Dioxin	
	Feed	Silt and Clay (unqualified soil)	Washed Soil (qualified soil)
2012/9/26	438	1,230	82.9
2012/9/28	1,120	1,800	323
2012/10/5	1,128	6,948	585
2012/10/7	1,640	5,329	1,007

❖ Sediment

Unit: ng-TEQ/kg Date	Input Dioxin	Output Dioxin	
	Feed	Silt and Clay (unqualified soil)	Washed Soil (qualified soil)
101.11.21	11,800	6,900	504
101.11.26	1,020	6,000	274
101.11.28	7,180	16,200	702
101.11.30	28,500	16,200	222
101.12.04	328	5,400	217

Quantities of washed Soil

Up to 2015.10.31

Feed	Feed Weight (tons)	Washed Soil Weight (tons)	
		Self verified	Washed rock
Soil	43,696.95	27,387.13	7,058.92
Sediment	36,314.07	30,640.26	--
subtotal	80,011.02	58,027.39	7,058.92
Total	80,011.02	65,086.31	

The percentage of qualified treated soil = $\dfrac{65,086.31}{80,011.02}\times 100\% = 81\%$

EPB verified soil: 53,436 tons

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4

Case II
Thermal Treatment

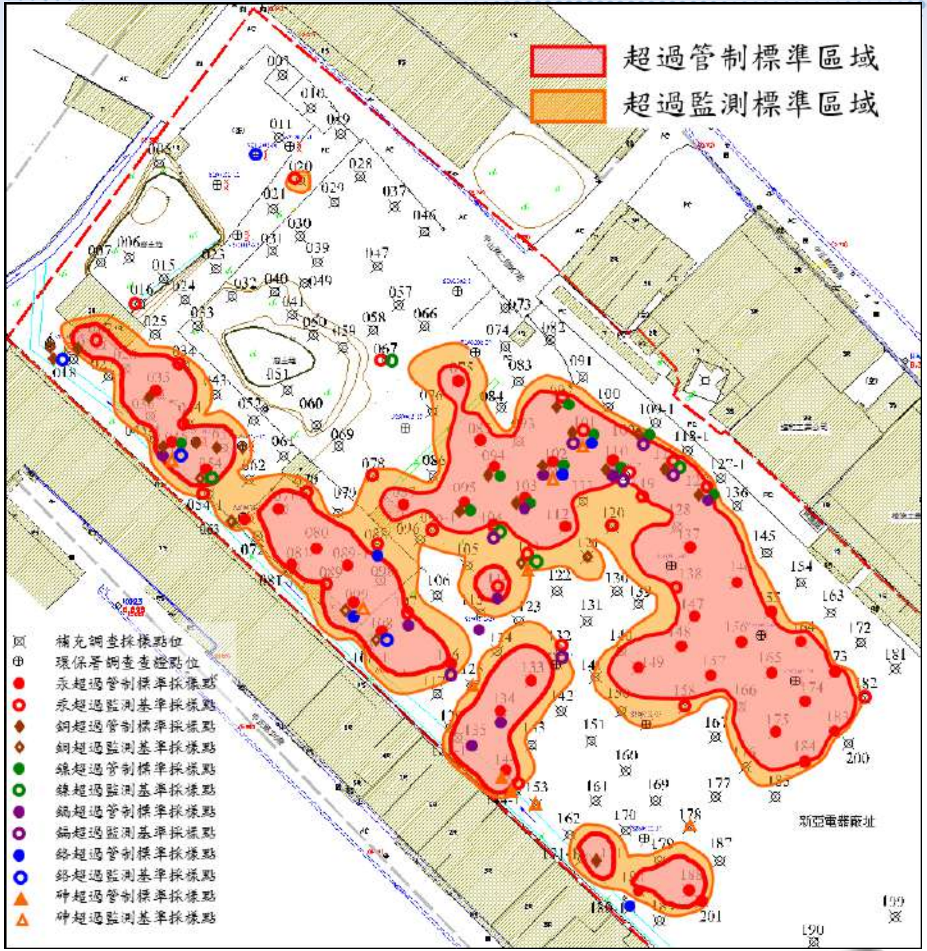
Plan Overview - Ex-Shin Ya Light Bulb Plant

- 1969 Shin Ya Electronics started manufacturing light bulbs at XinZhung, Taipei County
- 1989 ceased operation
- 1997 business closed
- 2006 an investigations done by EPA on discarded plants, soil found contaminated with mercury
- 2007 on the watch list promulgated by EPB
- 2010 FarGlory won bid on land
- 2010 contamination investigation commissioned by FarGlory approved
- 2010 FarGlory commissioned ApolloTech in the execution of contamination remediation project
- 2012 Remediation completed by Apollo Tech

Aerial photograph of Ex-Shin Ya Light Bulb Plant

Pollution Distribution

- Contaminated soil: 21,043 m^2
- After investigation: 16,300 m^2
- Additional investigation: 10mx10m grids，taking 201 core samples in different depths , the total is 725 soil samples
- Contaminated depths: 0.5 to 2 meters below ground level
- Samples exceed the regulation standards:
  Mercury: 44 samples
  Copper: 16 samples
  Cadmium: 10 samples
  Chrome: 5 samples
  Arsenic: 2 samples



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Project Flow Chart

Preparation

Excavation

Waste Disposal

Screening and Washing

Low Conc. -->Mixing Dilution

High Conc. --> Thermal Treatment

QC

Qualified Treated Soil

Backfill

EPB Verification

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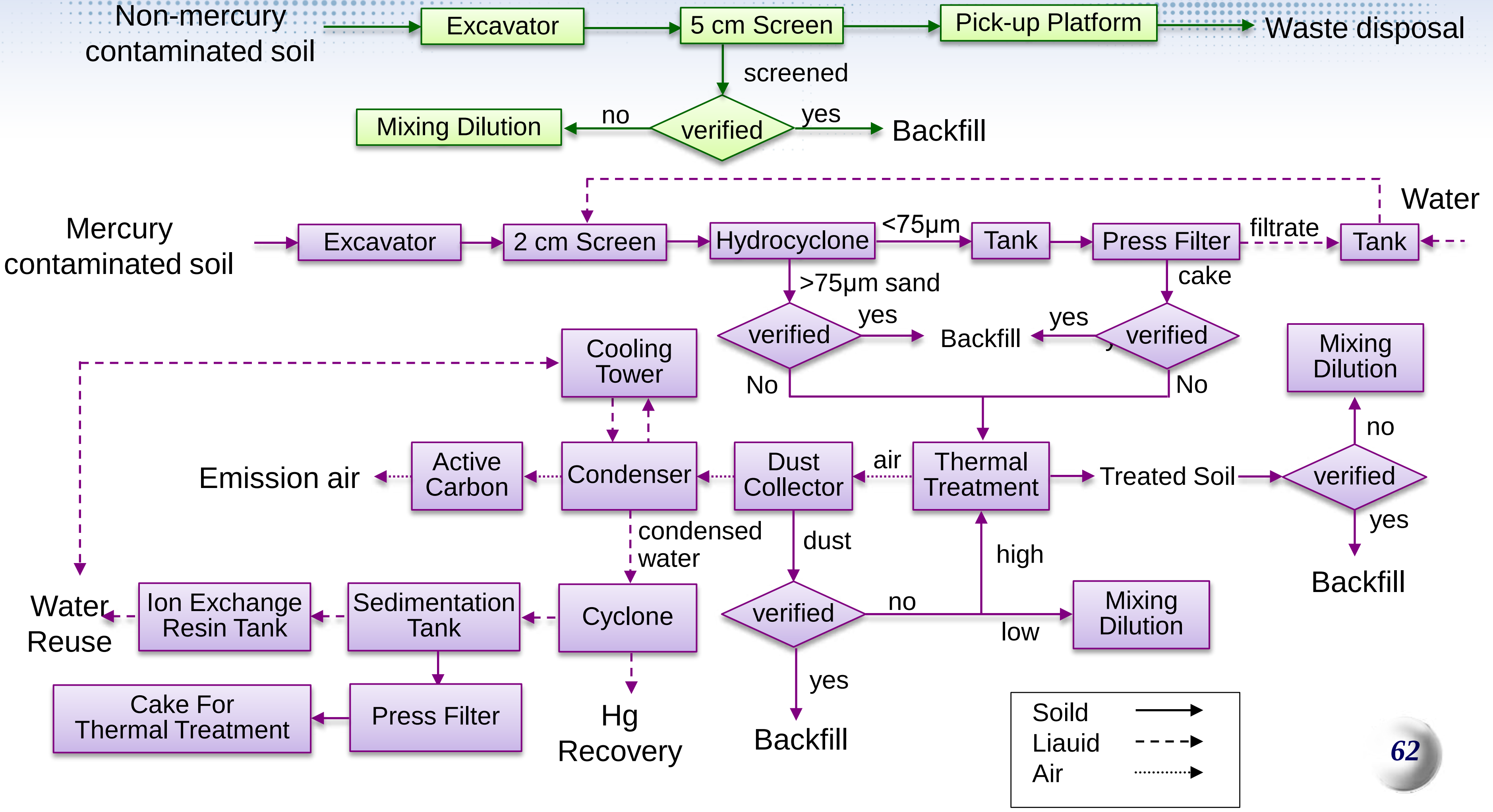
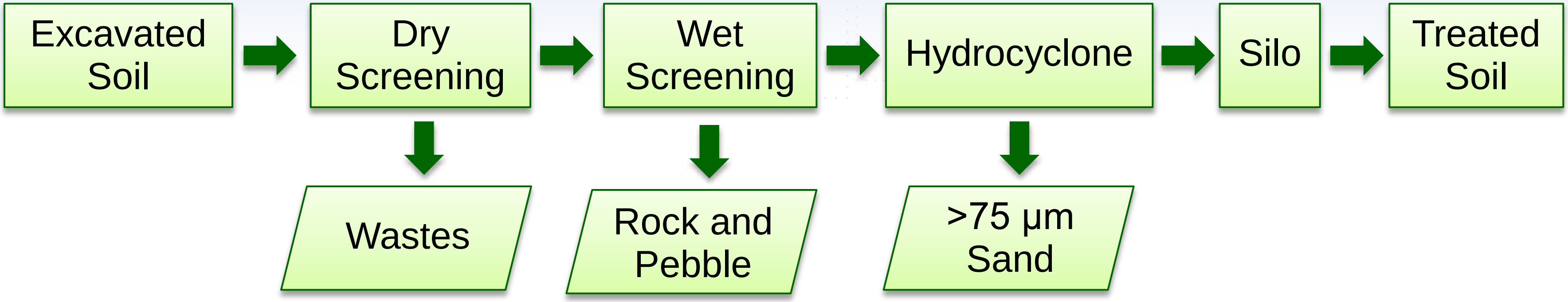
Processes



Pretreatment: Screening and Soil Washing



Excavated Soil → Dry Screening → Wet Screening → Hydrocyclone → Silo → Treated Soil

Dry Screening → Wastes

Wet Screening → Rock and Pebble

Hydrocyclone → >75 μm Sand

Dry Screening

Wet Screening

Washed Soil

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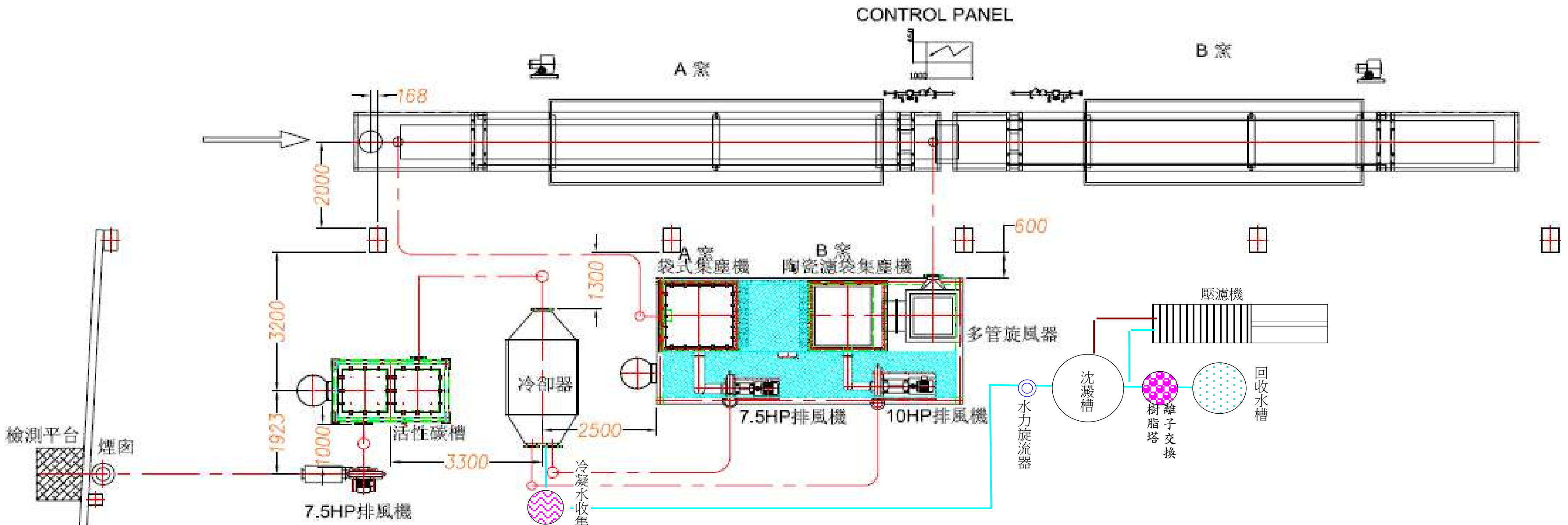
Thermal Treatment



Thermal Equipment

Indirect Fired
Rotary Kiln

First Section
0.76m(dia.)x12.0m(L)

Second Section
0.95m(dia.)x12.0m(L)

Soil Feed and
Flue Gas (I)

Flue Gas (II)

Control Panel

Air Pollution Control System

Cyclone, Bag Filter and Ceramic Filter

Bag and Ceramic Filter

- Resistant to the high temperature flue gas
- Capacity: 45 m^3/min
- Advantage: Avoid the mercury vapor being condensed on the dust

Sulfur Enhanced Active Carbon Tank

- Adsorb the mercury vapor in the flue gas to comply with the air emission standard

Active Carbon Tank

Mercury Recovery

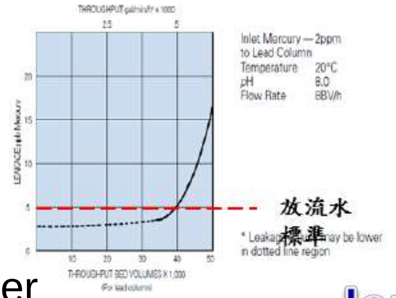
Fine tube condenser

Fine Tube Condenser and Cyclone

- ❖ To condense and recover mercury
- ❖ Heat exchange capacity: 1,000,000 kcal/hr
- ❖ Indirect heat exchange method to prevent the further pollution

Ion Exchanger Resin Tower

- ❖ To remove the mercury from condensed water
- ❖ Advantage: high efficiency
- ❖ Compliance with the effluent water standards



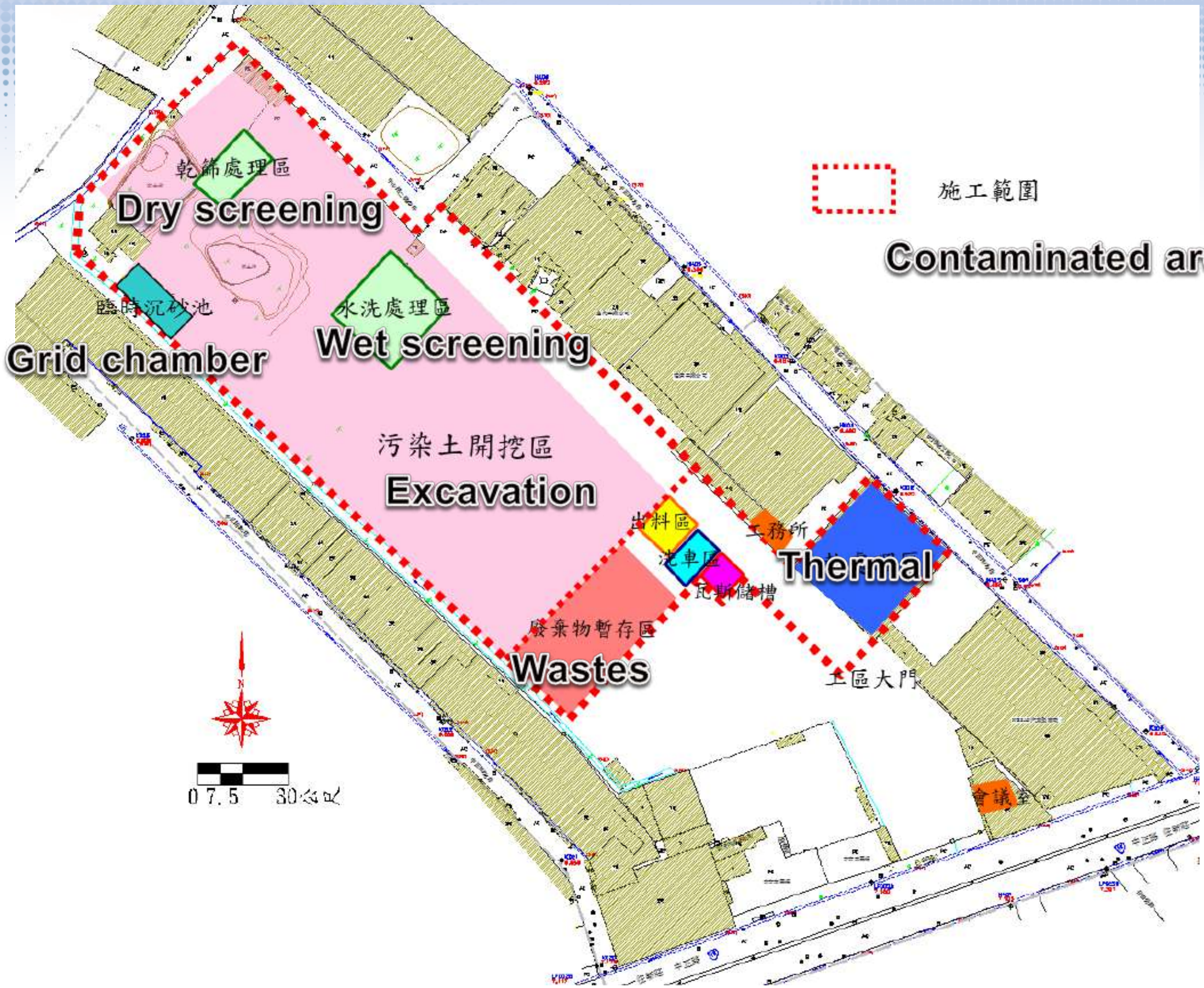
樹脂操作資料表

Ion Exchanger Resin Tower

Quantities of Treated Soil

Treatment	Amount	Notes
Excavation	27,800 m^3	Investigated area was 11,500 m^2 and 2 m depth Contaminated area was 4,800 m^2 and 1 m depth
Dry screening	15,100 m^3	Screened soil was 9,800 m^3 and soil contamination by other heavy metals was 5,300 m^3
Wet screening (washing)	8,900 m^3	To reduce the amount of contaminated soil for further thermal treatment

Site Plan


施工範圍
Contaminated area
乾篩處理區
Dry screening
臨時沉砂池
Grid chamber
水洗處理區
Wet screening
污染土開挖區
Excavation
出料區
洗車區
瓦斯儲槽
工務所
Thermal
廢棄物暫存區
Wastes
工區大門
會議室
N
0 7.5 30公尺

Excavation and Backfill


Excavation


Excavation


Excavation


Excavation

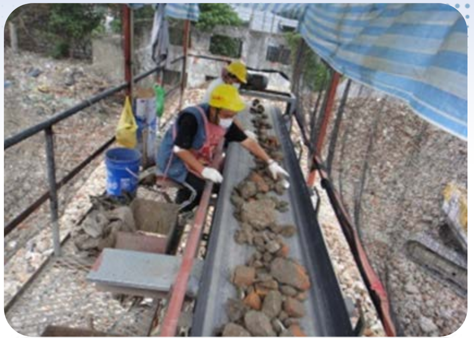

Backfill


Backfill

Screening

Dry screening

Dry screening



Pick up wastes

Pick up wastes

Dry screening

Dry screening

Washing


Washing feed


Washing feed


Washed soil discharge


Washing


Water recycling


Water recycling

APOLLOTECH

Thermal Treatment

Control panel

Temperature control

Feed area

Feed area

Discharge area

Discharge area

Quality Control

- Field-based X-ray fluorescence (XRF) analyzers It can detect mercury concentration in less than 3 minutes
- MA-3000 Mercury Analyzer: MA-3000 can directly detect mercury in only 7 minutes. The measurement range is between 0.002ng-2000ng of mercury
- A model EMP-2 is designed for measuring of gaseous mercury in work environments. The EMP-2 has sensitivity limits down to 0.1 ug/m^3

NITON XL3t-700 Gold

NIC MA-3000

NIC EMP-2

On-site Quality Control

Excavated soil

Washed soil

Sludge cake

Thermal treated soil

Mixing dilution

Labtoratory test

Water Pollution Control

- Rain gutters are placed around the site perimeters. Runoffs are connected in the temporary grit chamber for recycling. Effluent water meet the runoff standards of construction sites.
- Excavation and backfill were done in sections to prevent extensive exposure of excavated areas and rain wash.
- Condensed water in thermal treatment was treated to reuse for cooling water and car wash.


Grit chamber


Wastewater treatment

Air Pollution Control

Spray to prevent dust

Road wash

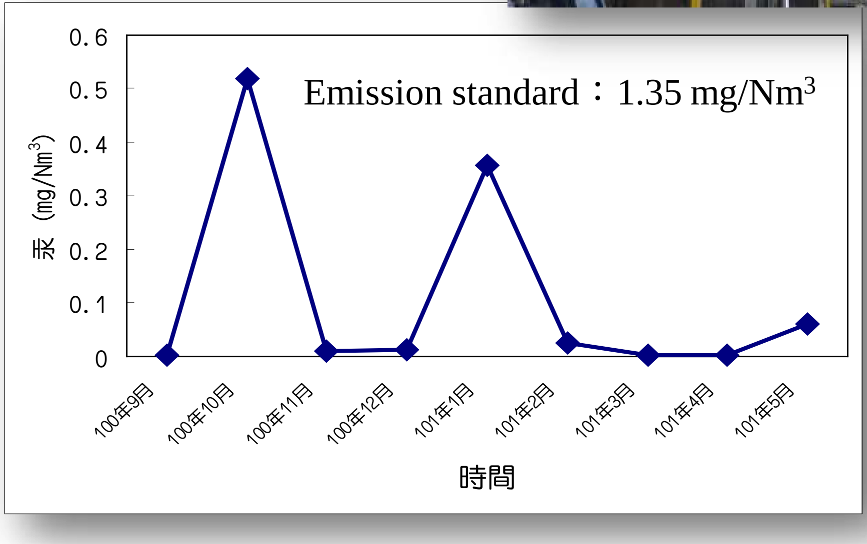
Cover by canvas

Dust network

Change the active carbon periodically

Flue Gas Monitoring

- Taiwan EPA Certified laboratory for analysis
- Monthly detect flue gas
- Weekly detect mercury vapor surrounding the thermal plant
- Using NIC EMP-2 to detect mercury vapor every day



Monitoring the Mercury Vapor Surrounding thermal Plant

- Four spots surrounding the thermal plant were chosen
- Overall, 33 monitoring data were all less than 0.00022 mg/Nm^3

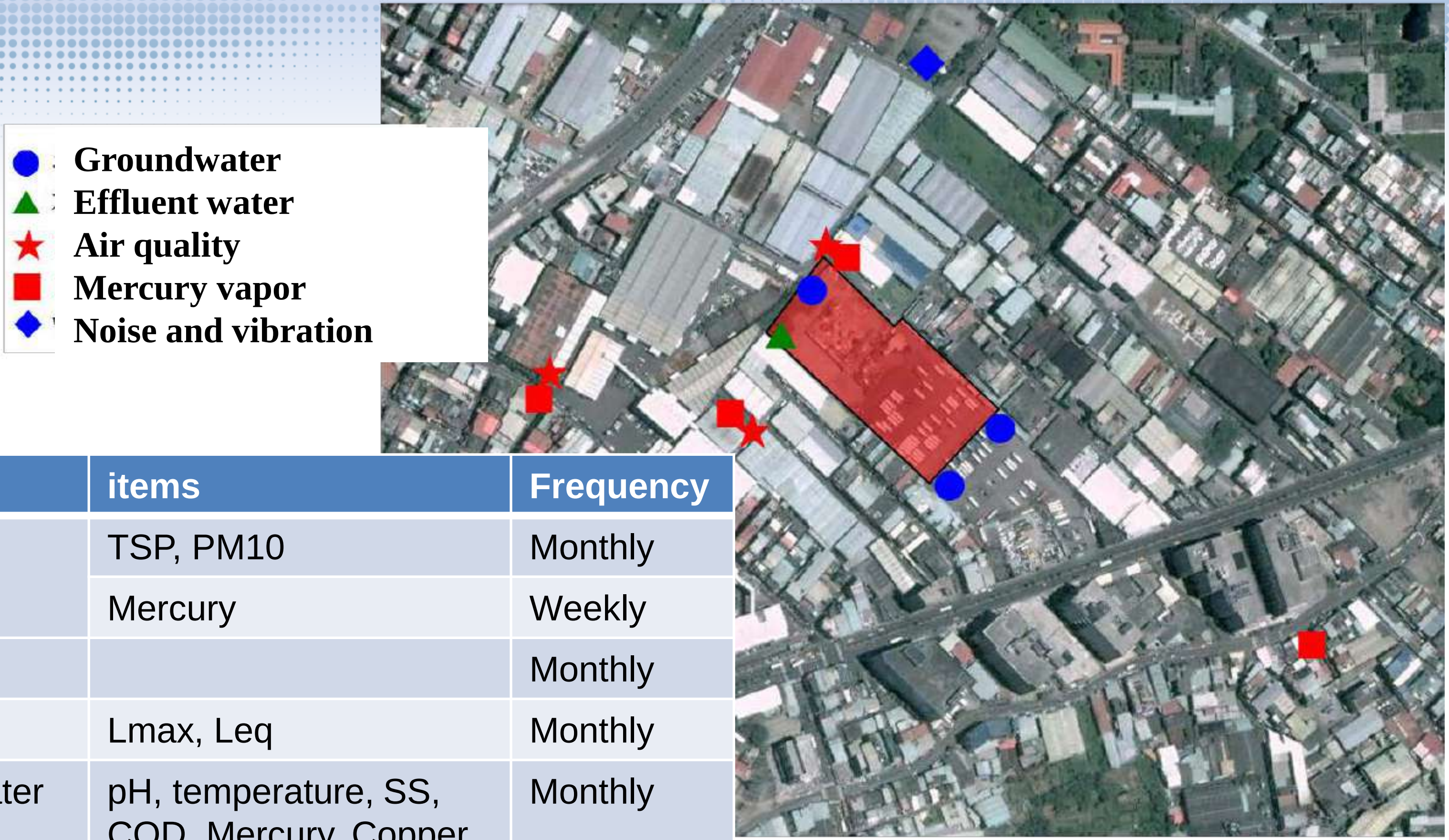
VOCs and Odor Monitoring

- Taiwan EPA Certified laboratory for analysis
- EPB also randomly monitored the odor on site

Items	Standards	Detected
Stack	1,000	733
Surrounding area	50	<10

Compliance with regulatory standards

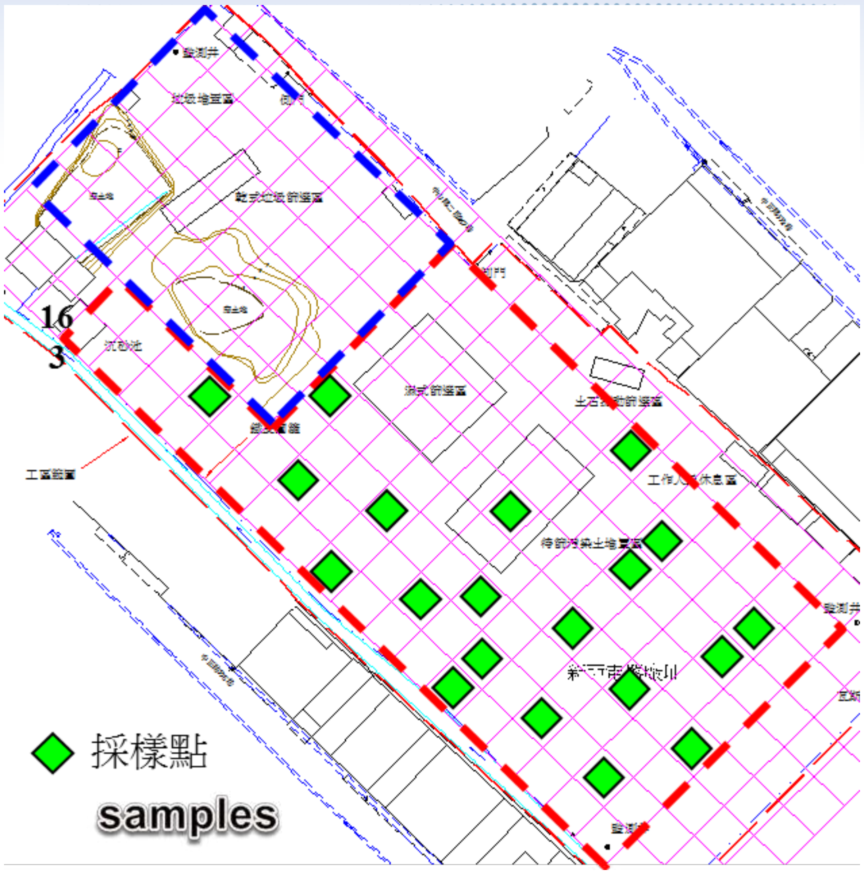
Surrounding Area Monitoring



	items	Frequency
Air	TSP, PM10	Monthly
	Mercury	Weekly
Vibration		Monthly
Noise	Lmax, Leq	Monthly
Effluent water	pH, temperature, SS, COD, Mercury, Copper, Cadmium, Nickel	Monthly
Groundwater	Heavy metals and VOCs	Monthly

Quality Control Process

- **Quality Control Process**
  - Randomly select 20 samples to verify the treated soil
  - Taiwan EPA Certified laboratory for analysis
- **QC**
  - Mercury: ND - 12.3 mg/kg
  - Copper: 8.22 - 232 mg/kg
  - Nickel: 17.0 - 67.1 mg/kg
  - Cadmium: ND - 6.06 mg/kg
  - Arsenic: 4.97 - 16.2 mg/kg
  - Chrome: 17.1 - 64.2 mg/kg
  - Lead: 10.8 - 192 mg/kg
  - Zinc: 49.6 - 487 mg/kg



Quality Control – Mass Balance

Feed (input)		
Average Conc.	Amount	Mercury Mass
37.5 mg/kg	4,700 ton	176.25 kg (100%)

Treated Soil (output)		
Average Conc.	Amount	Mercury Mass
1.5 mg/kg	2,820 ton	4.23 kg (2.4%)

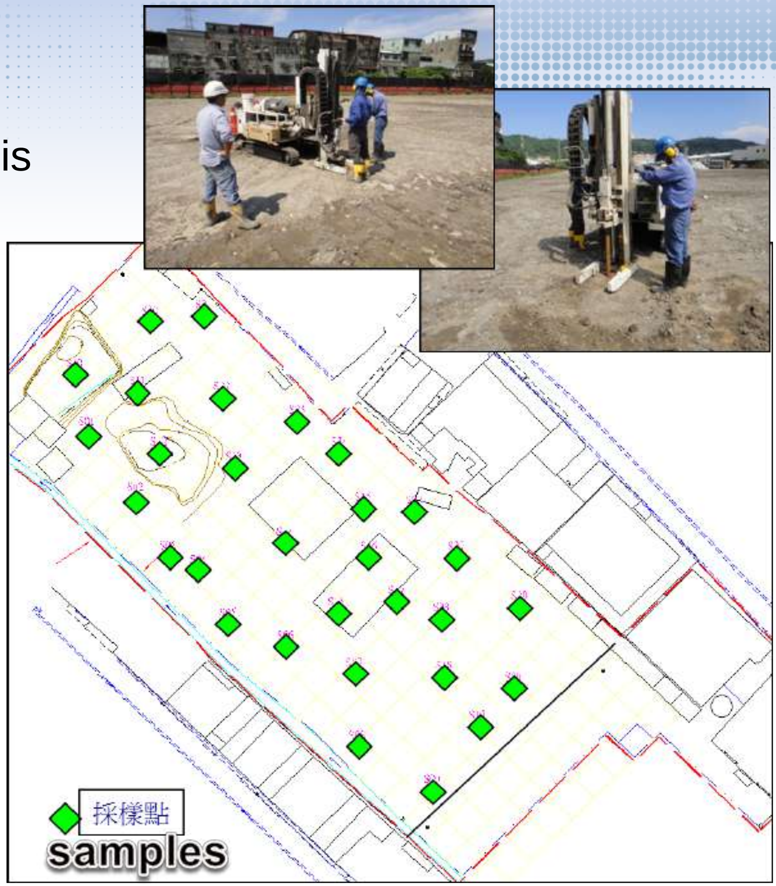
Active Carbon Absorbed		
Average Conc.	Amount	Mercury Mass
18,800 mg/kg	6.5 ton	122.2 kg (69.3%)

Emission Gas		
Average Conc.	Amount	Mercury Mass
300 μg/m³	4,512,000 m³	1.35 kg (0.77%)

Verification

❖ Self-verification

- Taiwan EPA Certified laboratory for analysis
- Randomly select 30 samples to verify the treated soil
- Quality control by XRF



❖ Verified Data

- Mercury: 0.36 - 8.44 mg/kg
- Copper: 24.8 - 138 mg/kg
- Nickel: 28.3 - 67.9 mg/kg
- Cadmium: 0.06 - 4.74mg/kg
- Arsenic: 5.70 - 14.1 mg/kg
- Chrome: 21.5 - 55.9 mg/kg
- Lead: 22.1 - 121 mg/kg
- Zinc: 84.9 - 358 mg/kg

❖ EPB Verification

- Taiwan EPA Certified laboratory for analysis
- Randomly take 15 samples to verify the treated soil
- Verification results: all comply with the regulation standards

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Summary

Summary

- Two cases of mercury remediation are included in this report. Thermal treatment was completed, and the soil washing treatment is currently in process. Other than detection equipment, all other equipment are purchased locally for the flexibility and efficiency of maintenance and updates.
- Key to successful remediation not only depends on understanding the ppm concentration level of the contamination, but also on the soil properties. Due to the complexity of the soil, remediation techniques should be assessed and specialized case by case.
- While thermal treatment is a common practice, soil washing treatment could be another practice that can be used effectively in mercury remediation. Furthermore, if the two treatments can be combined in the remediation process, the results is not only effective, but economical.

Thank you for your attention

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Remediation techniques of soil contamination

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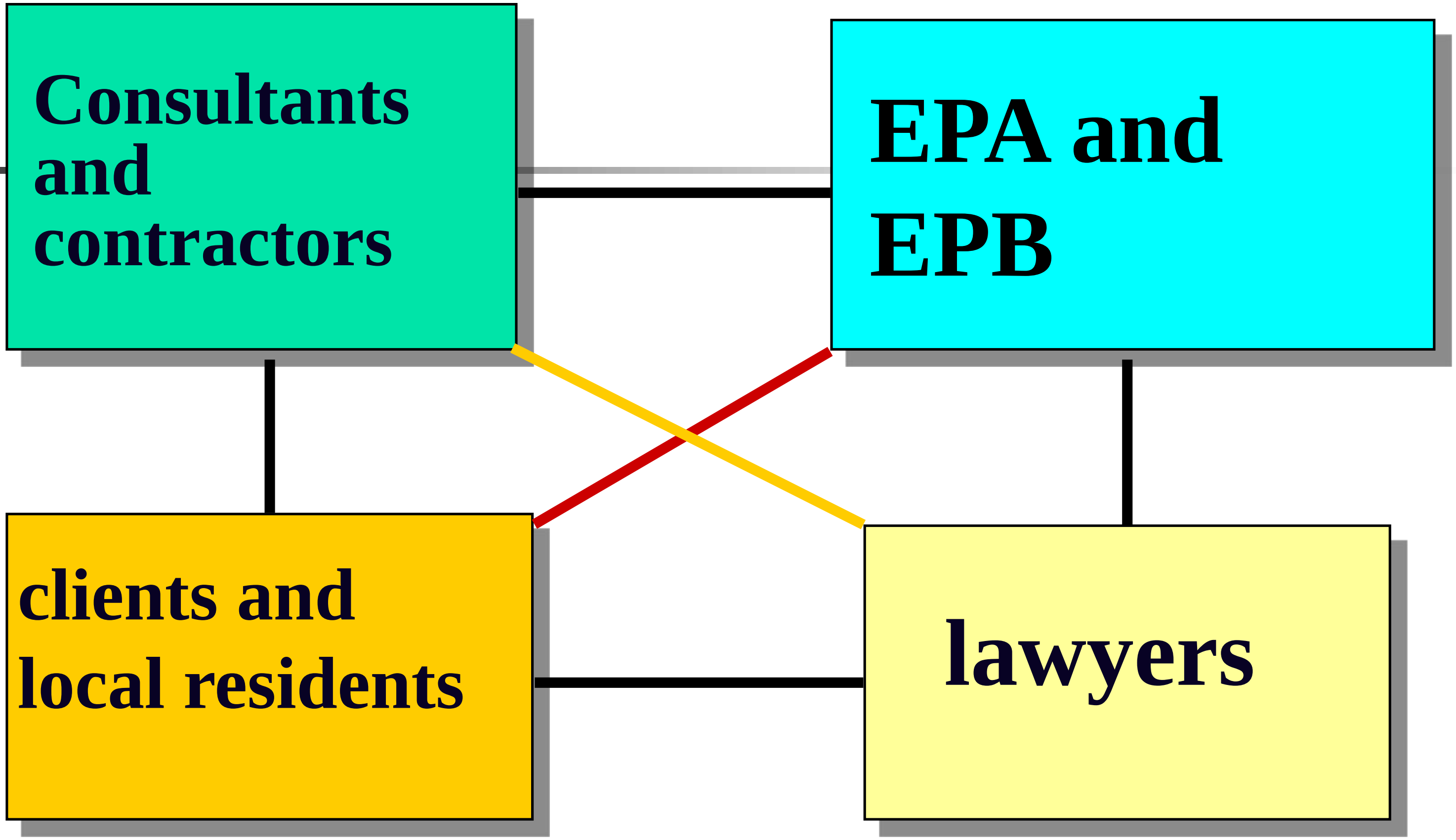
International Training Course
March 21-28, 2016

Content

- **Management of soil remediation project**
- **Development and application of soil remediation techniques**
- **In-situ (in site) remediation techniques and assessment of contaminated sites**
- **Ex-situ (off site) remediation techniques and assessment of contaminated sites**
- **Case studies**
- **Discussions**

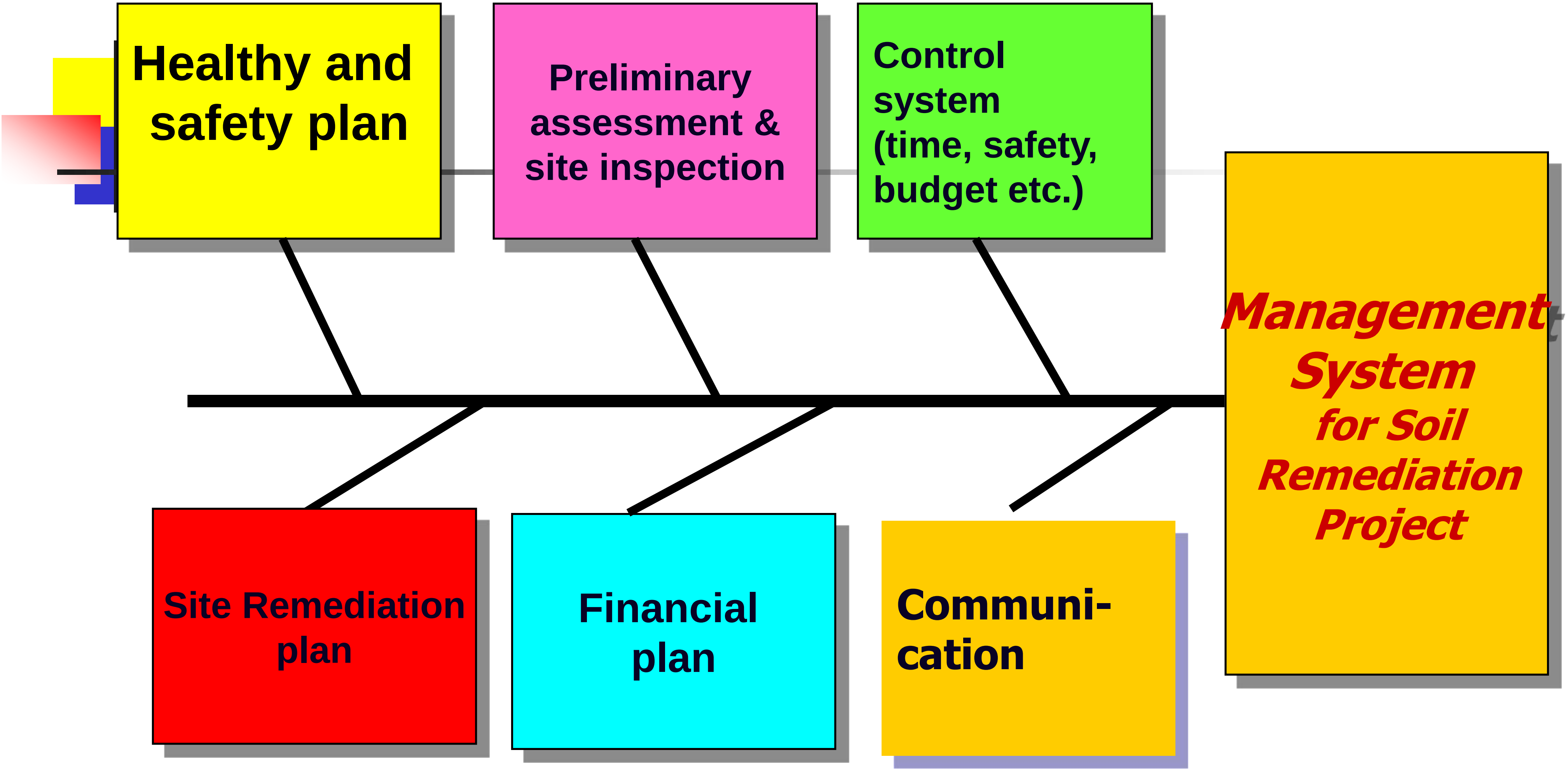


Consultants and contractors

EPA and EPB

clients and local residents

lawyers



Healthy and safety plan

Preliminary assessment & site inspection

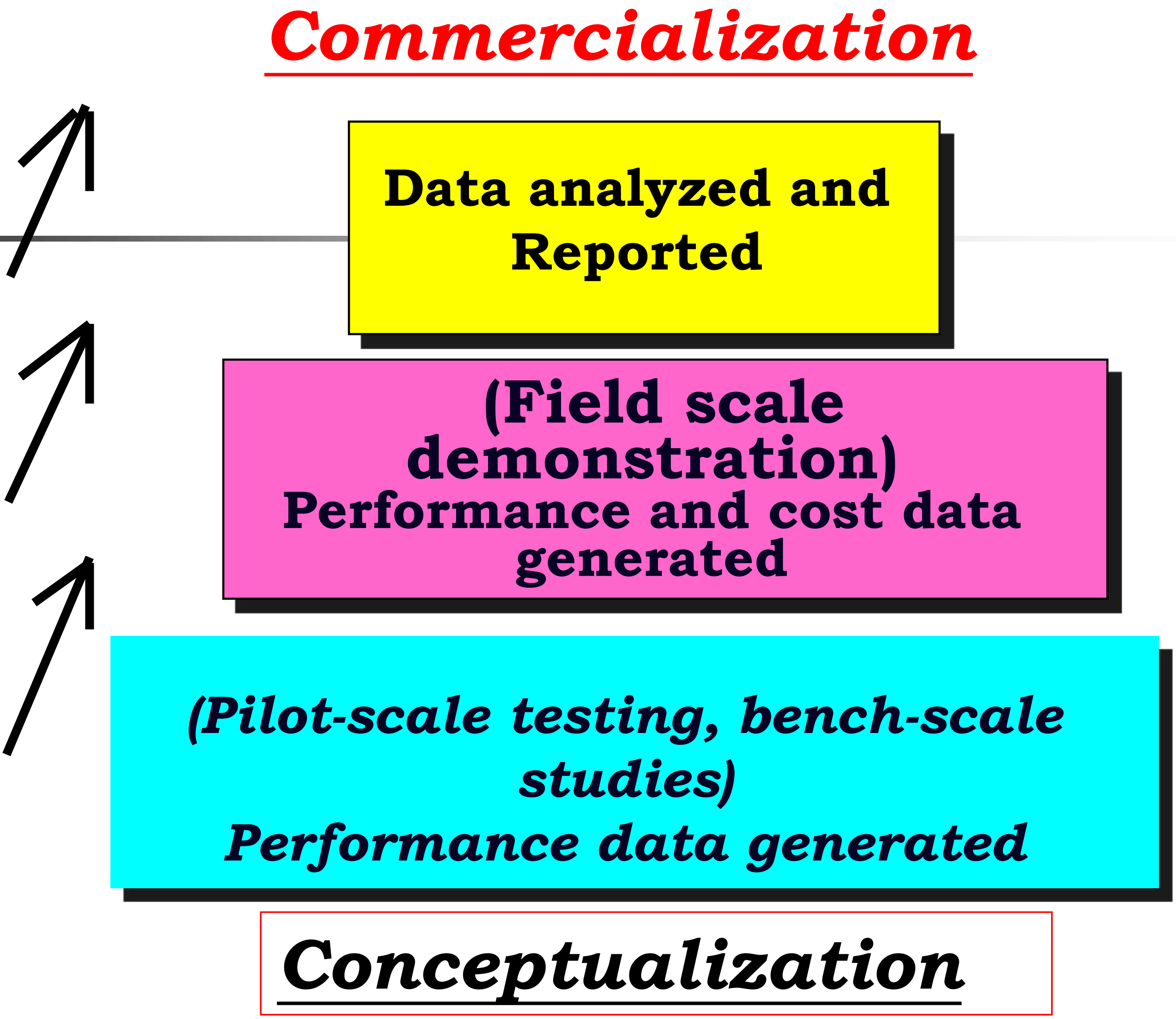
Control system (time, safety, budget etc.)

Site Remediation plan

Financial plan

Communi-cation

Management System for Soil Remediation Project



Commercialization

Data analyzed and Reported

**(Field scale demonstration)
Performance and cost data generated**

***(Pilot-scale testing, bench-scale studies)
Performance data generated***

Conceptualization

USEPA

General soil remediation Techniques (since 1985)

- ***soil vapor extraction*** **(13%)**
- ***bioremediation*** **(13%)**
- ***air stripping*** **(9%)**
- **soil washing (9%)**
- **immobilization) (solidification or stabilizing method) (9%)**
- **thermal desorption (5%)**
- **chemical oxidation (5%)**
- **radio/electric heating (5%)**

Summary of soil remediations for rural soils

- **Chemical methods** a. extraction method
  b. reduced condition
  c. stabilization
- **Engineering methods**
  a. removal contaminated soils and cover with clean soils
  b. cover with clean soils
  c. soil washing
  d. electrokinetics
- **Biological methods** a. phytoremediation
  b. phytostabilization

in-situ physico-chemical method

Solidification

- By adding the chemical materials to mix or react with the pollutants in the soil
- To solid the contaminated soil as very low release material under natural raining system
- To reduce the pollutants released from the solid materials.
- Cost effective?

in-situ physico-chemical method

Soil amendments

- To reduce the bioavailability of metals treated with different non-toxic materials as soil amendments
- Reduce the bioavailability of metals in soils by addition of lime materials, phosphate materials, zeolite, hydrous metal oxides, or organic materials, etc.
- Cost-effective?
- Any other materials can be used?

in-situ physico-chemical method

Attenuation

- **To mixture and dilute the soils of whole soil depths**
- **Dilution the surface contaminated soils by mixing with the subsurface clean soils by machines. About 200 ha of Taiwan rural soils were cleaned up by this method.**
- **How to approve it is effective?**
- **What is the limit factor to apply this method?**

in-situ physico-chemical method

Soil Flushing

- The soils treated with different reagents or surfactants
- Only for contaminated sandy soils or course soil texture soils, not for sticky clay soils
- Need to treat the waste water
- Cost-effective?

in-situ physico-chemical method

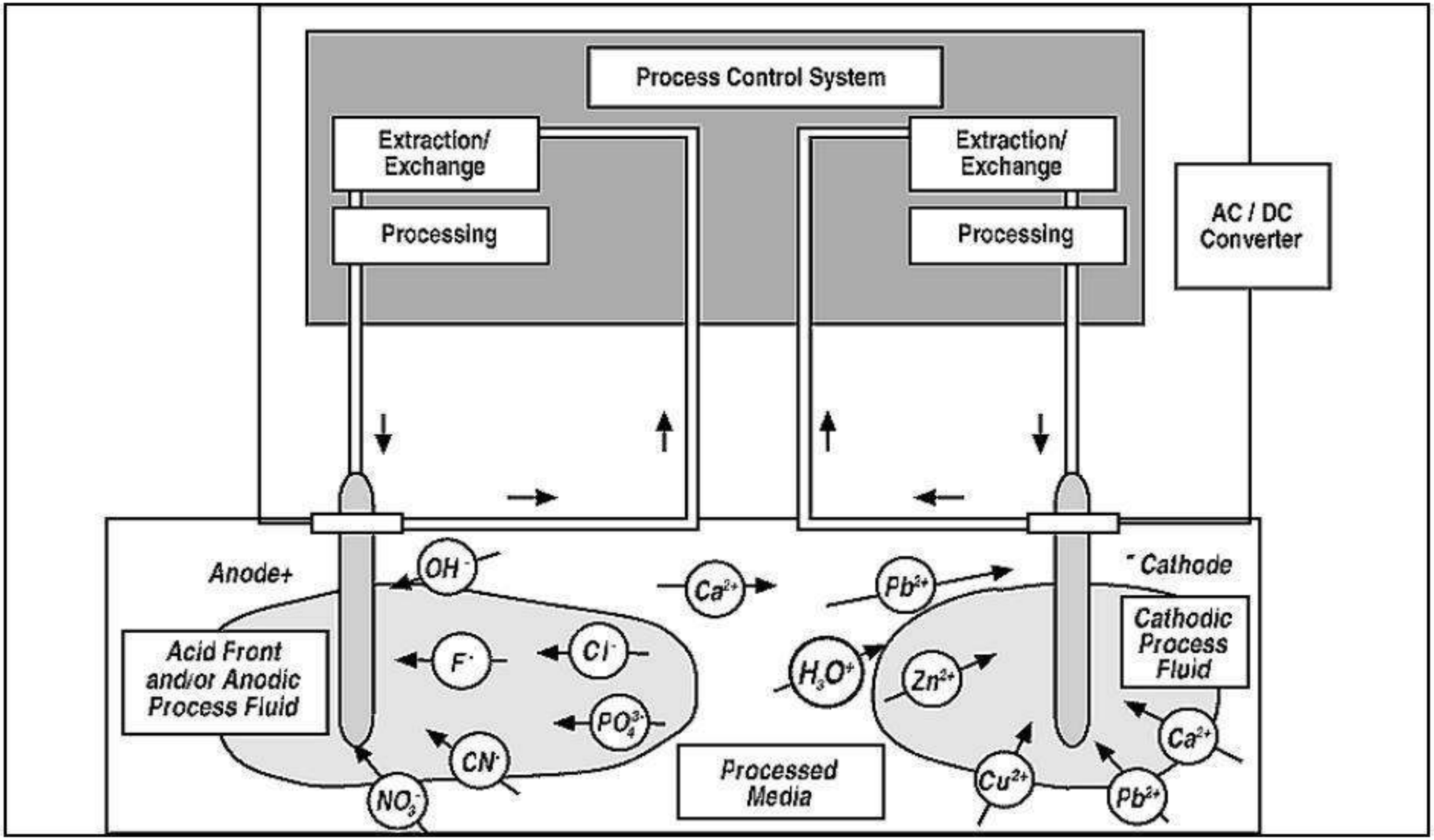
Soil Washing

- **Treated with different acids including HCl, HNO_3, phosphoric acid, etc.**
- **Must be recycled of the chemical acids to reduce the remediation cost**
- **Need to treat the waste water to discharge into the environment**
- **Need to recovery the soil characteristics and soil function for crop productivity.**
- **Very high cost including remediation, waste water treatment and soil function recovery**

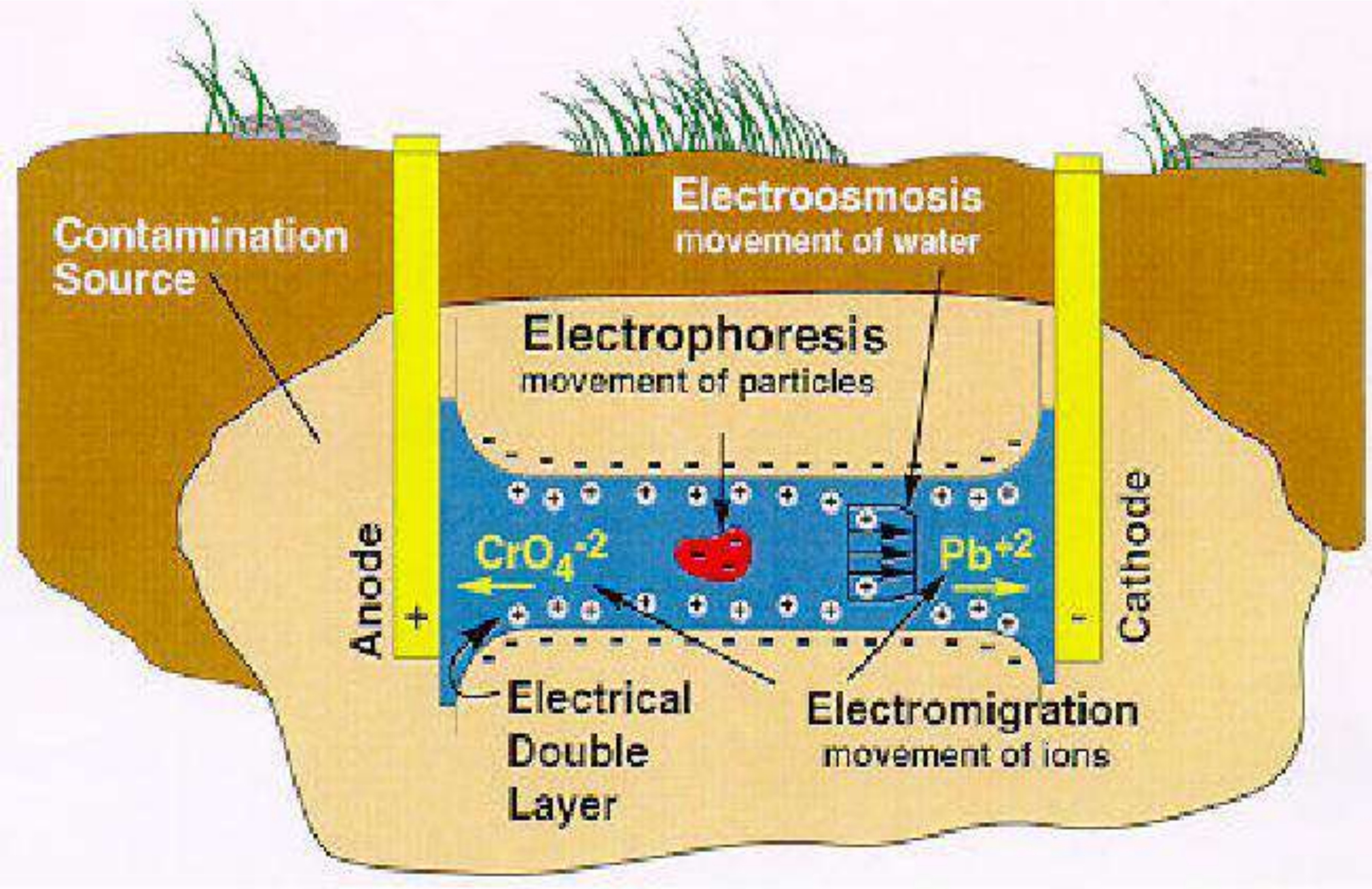
in-situ physico-chemical method

Electrokinetics Separation (EK)

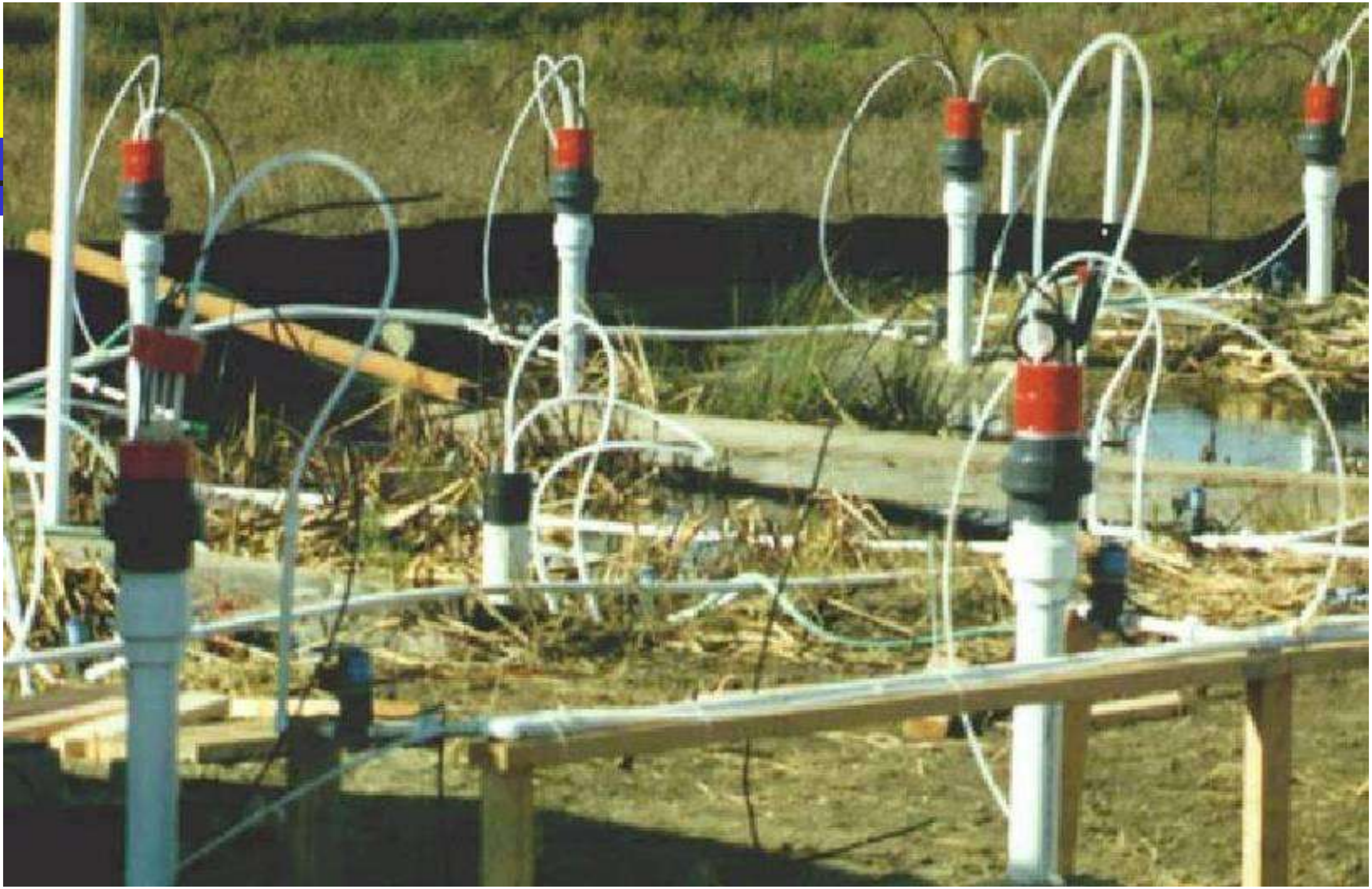
- Electric current induced movement of ions to electrodes and to remove the pollutants.
- Need to evauate the efficiency to remove the pollutants
- Cost-effective? High energy?
- Why it is not successful in the field site?

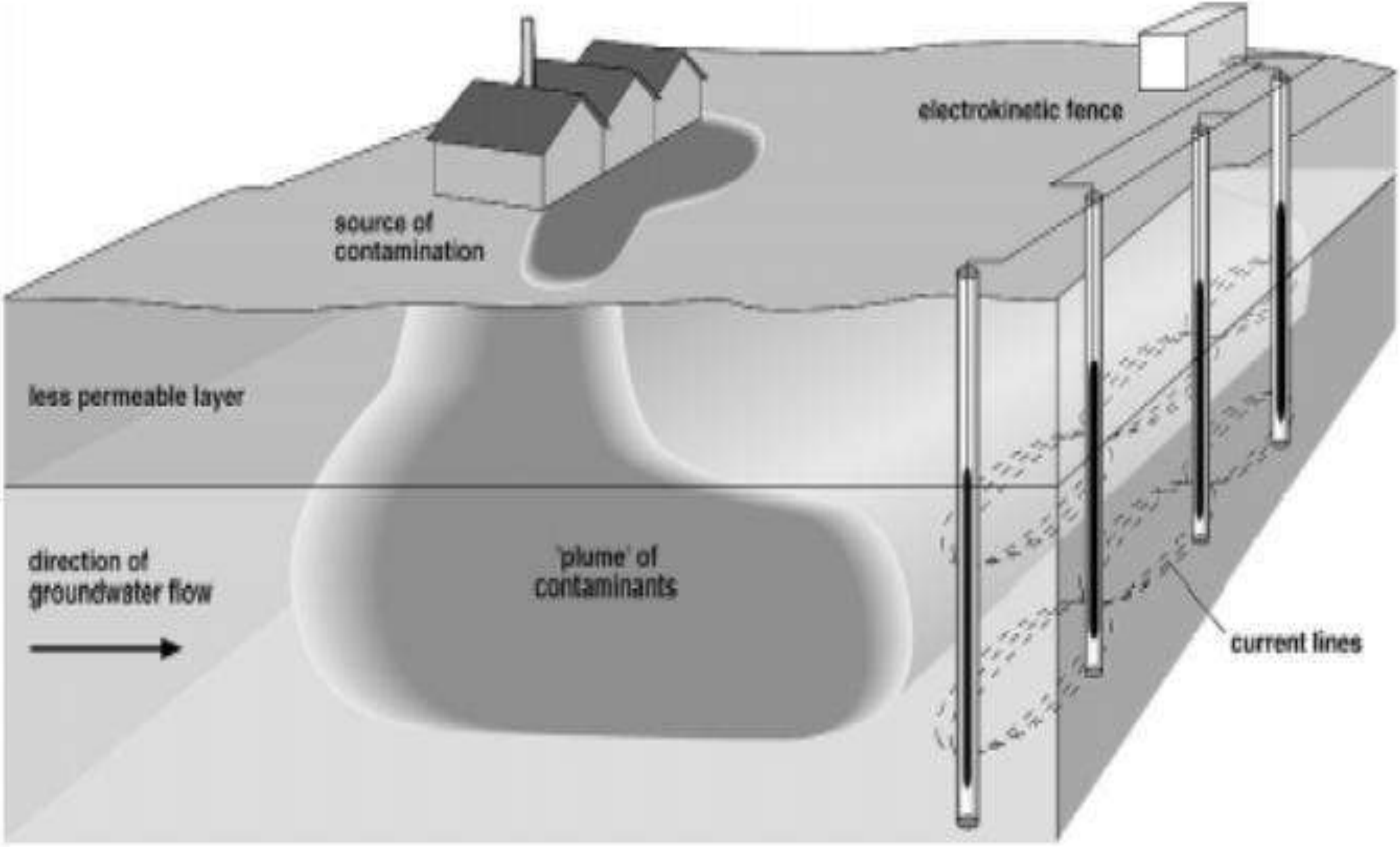


Schematic Diagram of One Electrode Configuration and Geometry Used in Field Implementation of Electrokinetic Remediation



Contamination Source
Electroosmosis
movement of water
Electrophoresis
movement of particles
Anode
+
CrO_4^{-2}
Pb^{+2}
-
Cathode
Electrical Double Layer
Electromigration
movement of ions





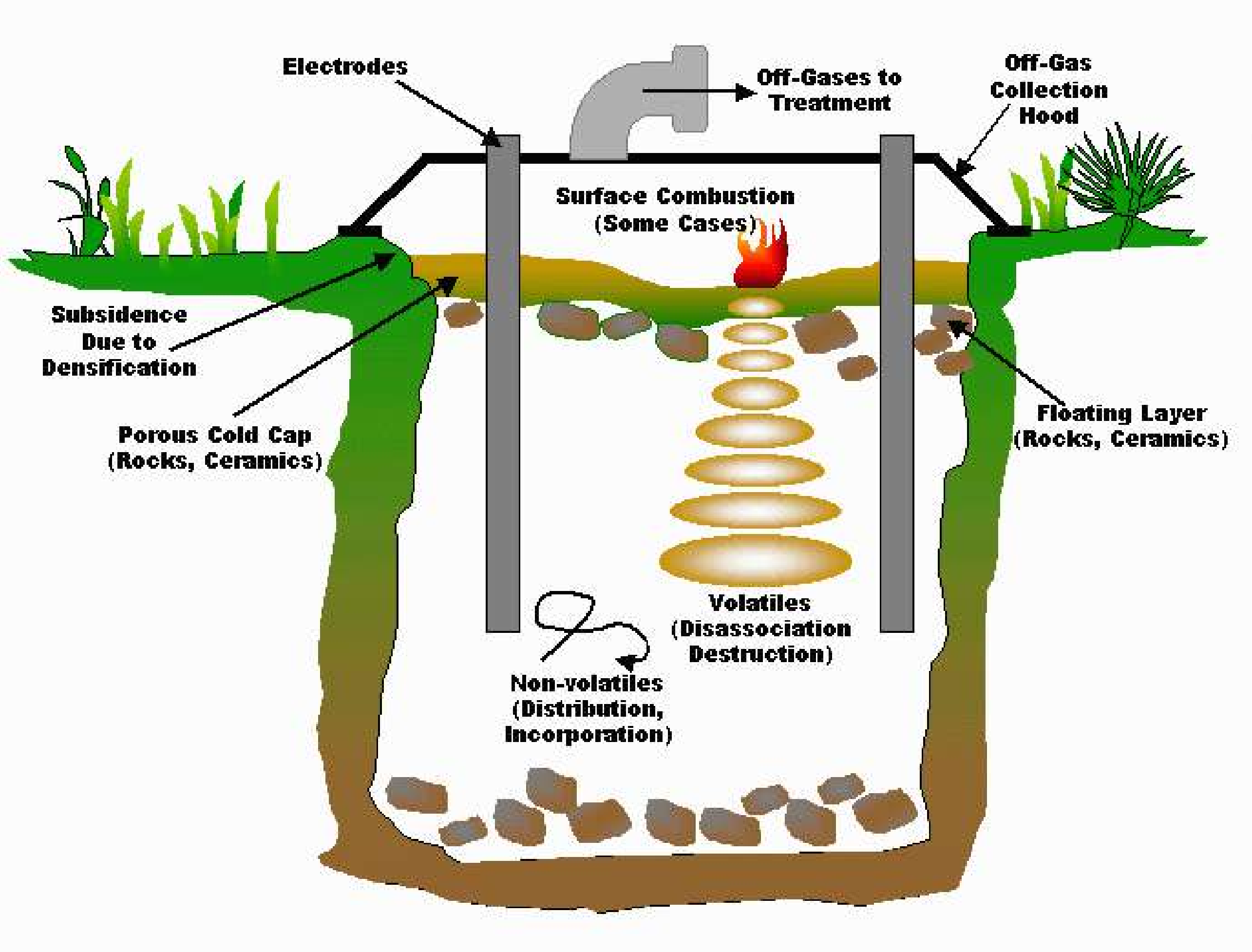
Schematic View of Contaminated Plume Stopped by An Electrokinetic Fence

In-situ: electrokinetics and heating

Vitrification

- **Heating to produce a glass-like, nonporous materials.**
- **300-600 degree C for Hg sites and pesticides sites**
- **More than 1000 degree C for high concentration of Hg sites and dioxin sites**
- **Very high cost techniques.**

Vitrification



U.S. EPA TIO

In-situ: biological method

Phytostabilization

- To promote vegetative growth to immobilize metals of contamination site (eg. vetiver grass)
- To produce the green landscape and to stabilize the contaminated sites
- Can not significant remove the pollutants from the sites
- Very low cost (< US$ 10/ton soil)
- ONLY recommendation for low contaminated sites

Phytostabilization

Vetiver grass

Different species

2 meter

In-situ: biological method

Phytoremediation (or phytoextraction)

- To significantly remove the metals by plants.
- 420 plant species found for different metals uptake
- Higher than 100 times of general plant species (>100 mg/kg for Cd, >1000 mg/kg for Cu, Cr, Ni, Pb, or >10000 mg/kg for Zn)
- Highly accepted by the local community for low contamination sites, especially for European Union.
- Very low cost (< US$ 10/ton soil)
- ONLY recommendation for low contaminated sites
- Cost-effective ?

Phyto-stabilization

(42 species tested in the field of Taoyuan, Taiwan)

12 species (total 24,000 plants) were studied in 1 ha of Cu, Zn, Cr and Ni-contaminated soils

(Lai et al., 2010)

Hyperaccumulator

Thlaspi caerulescens

Pb 8,500 mg/kg
Cd 164-2,800 mg/kg
Zn 27,000 mg/kg

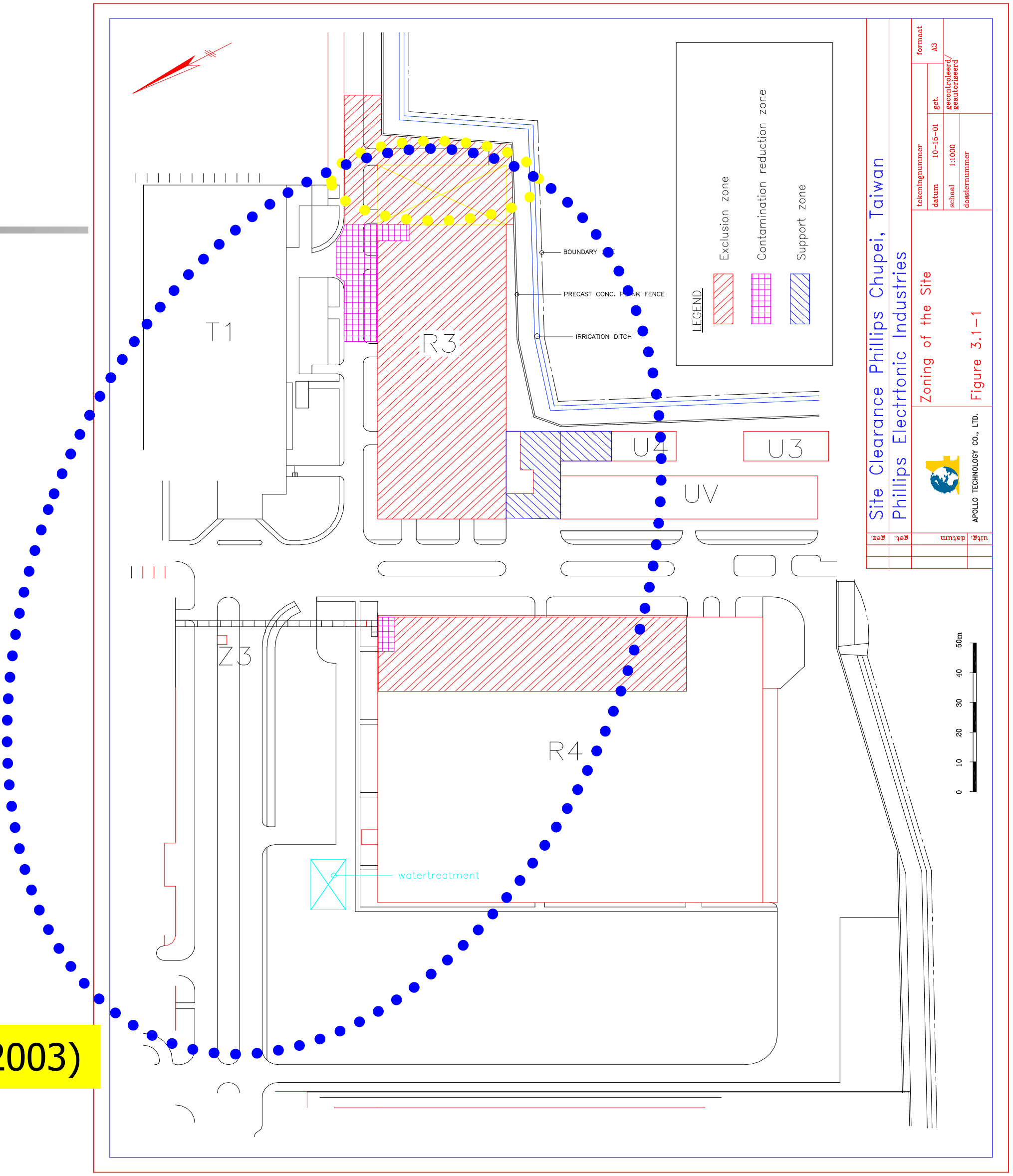
in situ physico-chemical method for oil contaminated soils:

Soil vapor extraction (SVE)

- **Inject the air into deep contaminated soils of the site and pump out the pollutants from the site**
- **Install at the suitable depth of the contaminated soils of site**
- **Need to model the effectives of the SVE installation**
- **Need to evaluate the effectives and removal time of site**
- **Cost-effective**
- **Need to check to cut the pollution sources**

Case study in semiconductor plant

- pollutant
  - PCE
- concentration
  - few 100 mg/kg of soil
  - Few 100 ug/kg in GW
  - Controlling in the siote
- duration of remediation
  - 2.5 years

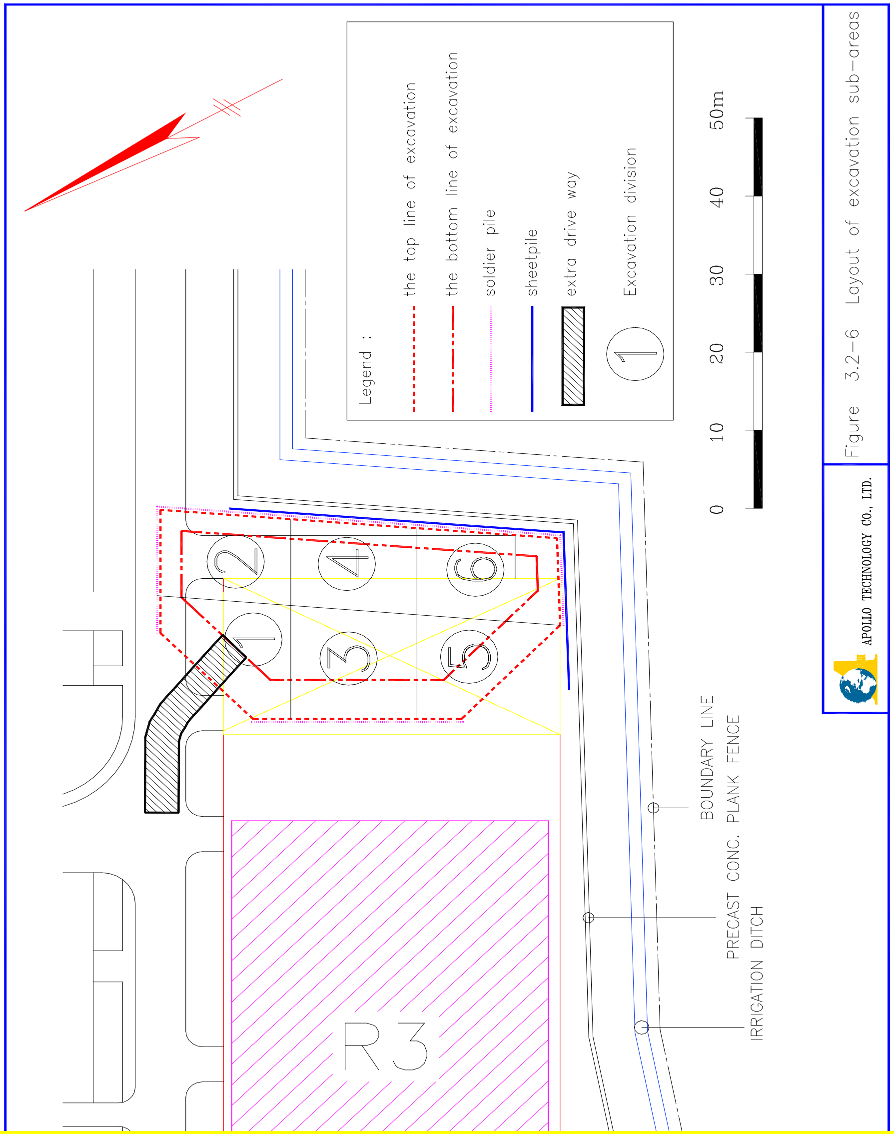


(資料摘自 瑞昶科技顧問公司史麗芬於環保署演講內容, 2003)

Excavation or removal of high concentration area

Removal of surface soils

excavation

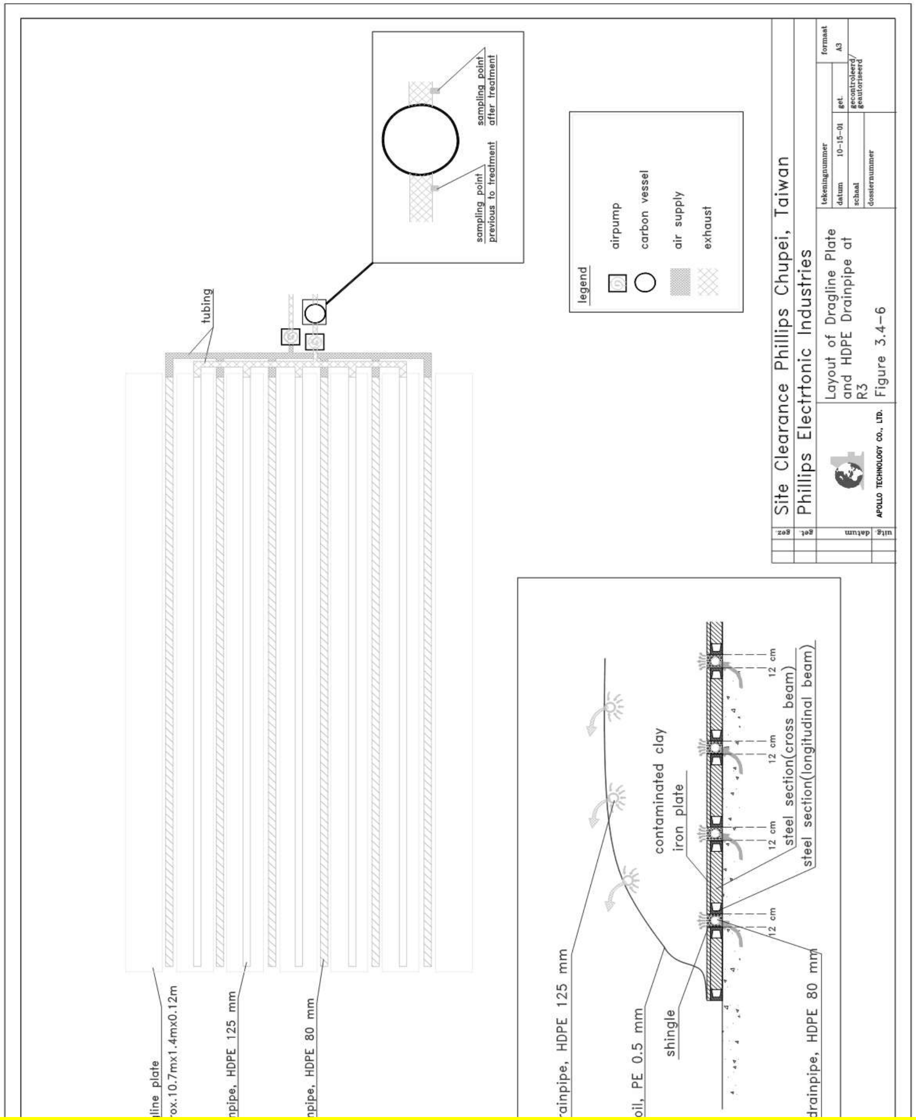


(資料摘自 瑞昶科技顧問公司史麗芬於環保署演講內容, 2003)

Soil vapor extraction (SVE)

Total volume is 5000 m3

SVA and active carbon adsorption



(資料摘自 瑞昶科技顧問公司史麗芬於環保署演講內容, 2003)

Soil vapor extraction SVE

- **vapor extraction**
  - **300 M3/hr**
  - **Adsorption of the pollutants gas**
- **injection of air**
  - **To increase the VOC extraction rate**
- **PLC controller**
  - **Inter-mediate or regional vapor extraction**

Vacuum pump and active carbon adsorption

Vacuum pump

(資料摘自 瑞昶科技顧問公司史麗芬於環保署演講內容, 2003)

PLC controller

safety and health plan

- Emergency in SVE
- Monitoring Air quality in site
- Operator protection working in the site

Monitoring Air quality in site

室内施工人員之防護

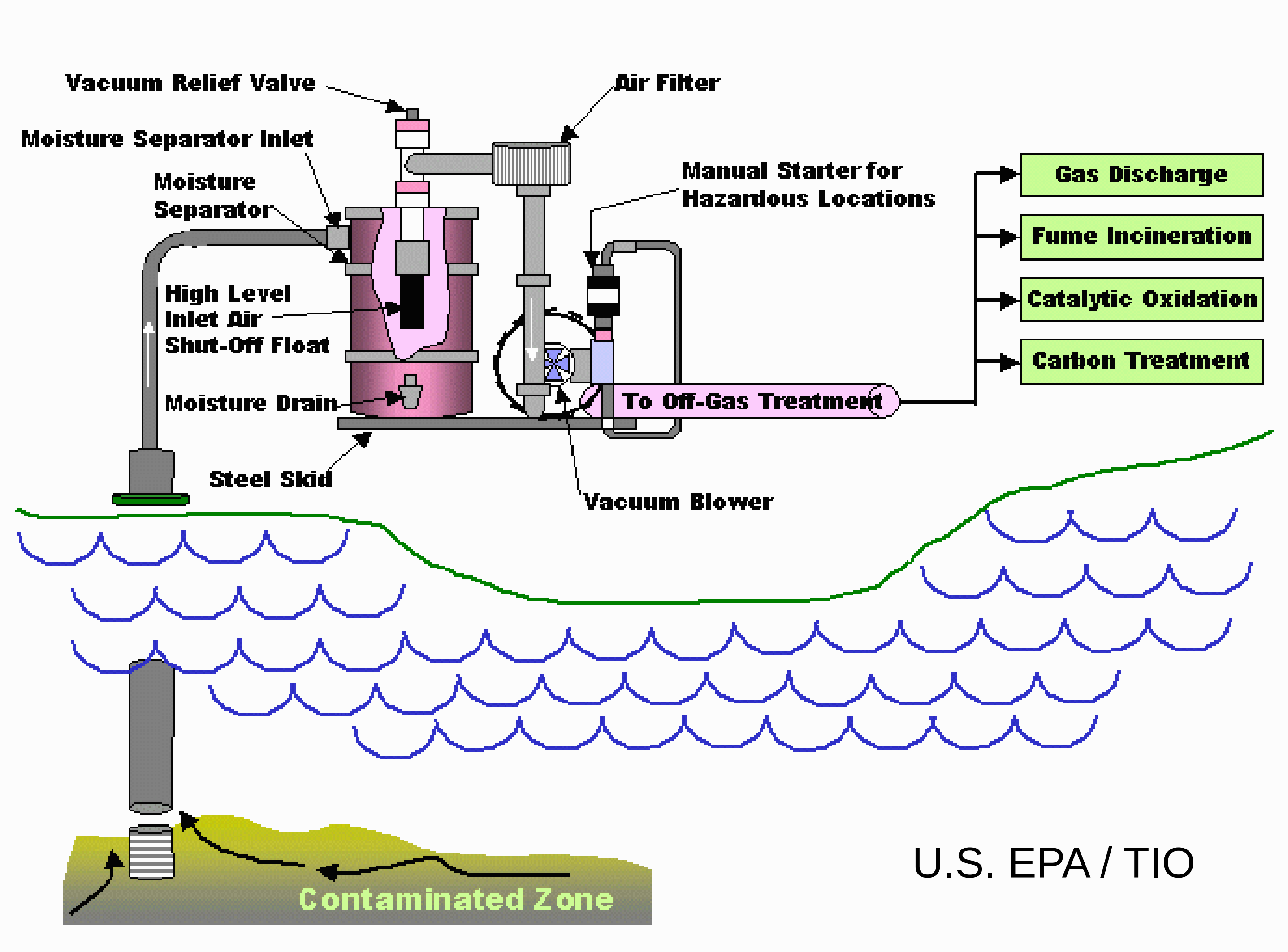
(資料摘自 瑞昶科技顧問公司史麗芬於環保署演講內容, 2003)

Operator protection working in the site

in situ physico-chemical method for oil contaminated soils (need new technology?)

- **Attenuation: Dilute the pollutant concentration under natural soil condition.**
- **Soil Flushing : soil flushing with reagents or surfactants**
- **Oxygen Release Compound (ORCs): Adding the Calcium peroxide or other compounds to continuously release the oxygen gas**

Soil vapor extraction: oil contaminated soils

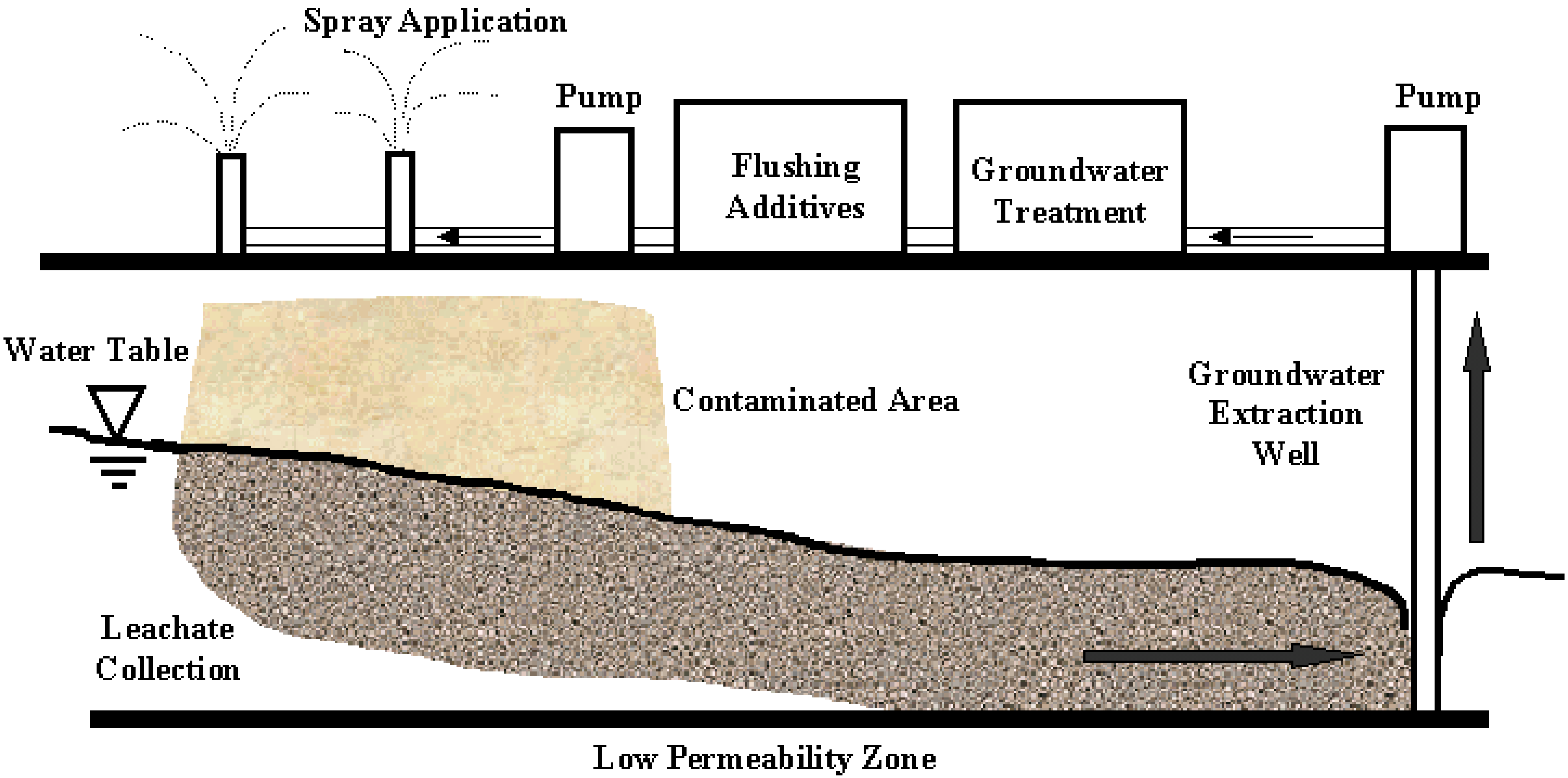


U.S. EPA / TIO

in situ physico-chemical method
for oil contaminated soils: Soil Flushing

- **Polluted soil treated with reagents or surfactants**
- **More suitable for course soil texture soils, not for cleyey soil**
- **The reagents are most chemcial trong acidic reagents**
- **High potential cost**
- **Need to pump and treat of the groundwater in the downriver**

Soil Flushing: oil contaminated soils



U.S. EPA TIO

in situ physico-chemical method for organic contaminated soils

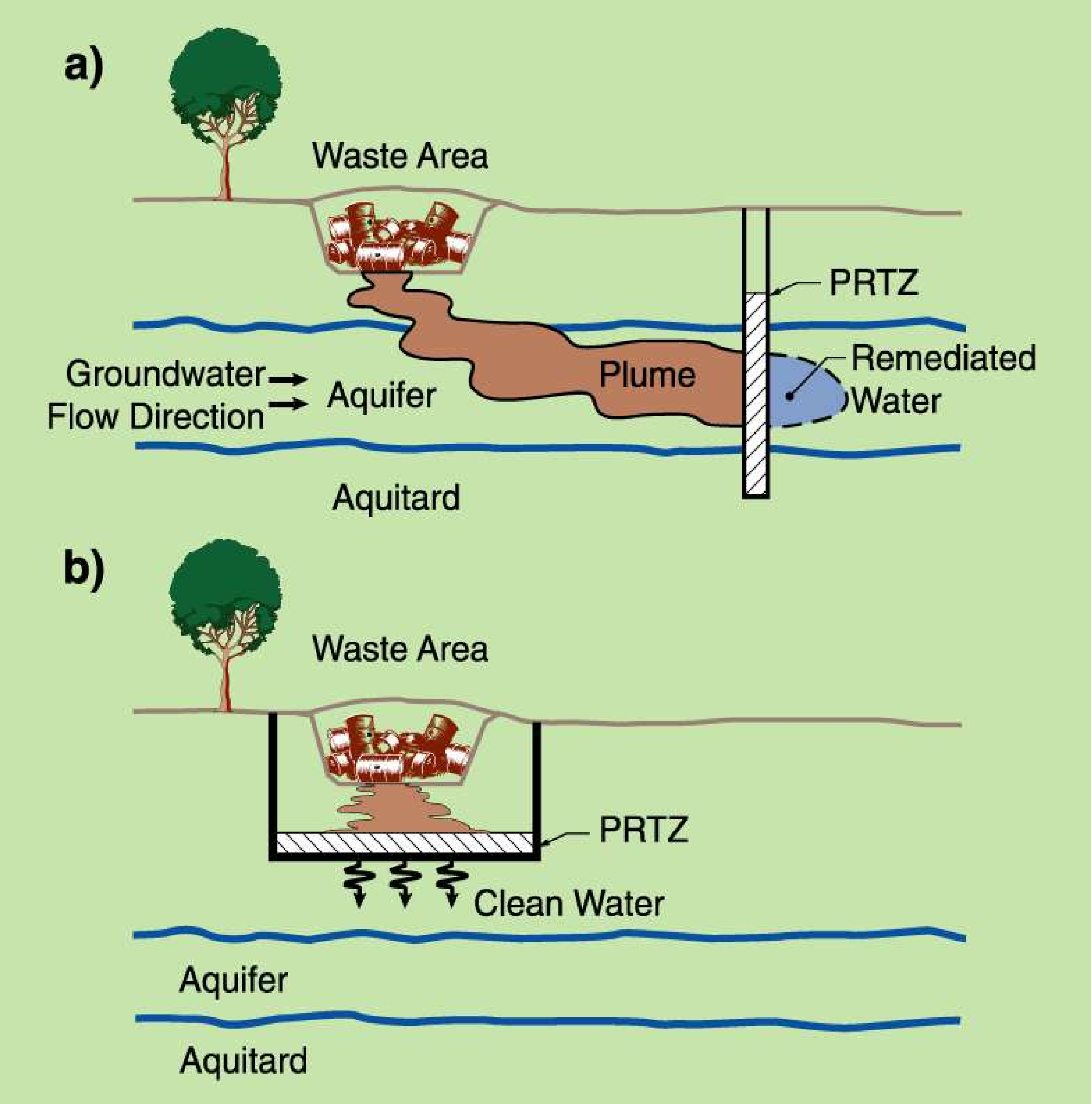
Permeable reactive barriers, PRB

A Permeable Reactive Barrier (PRB):

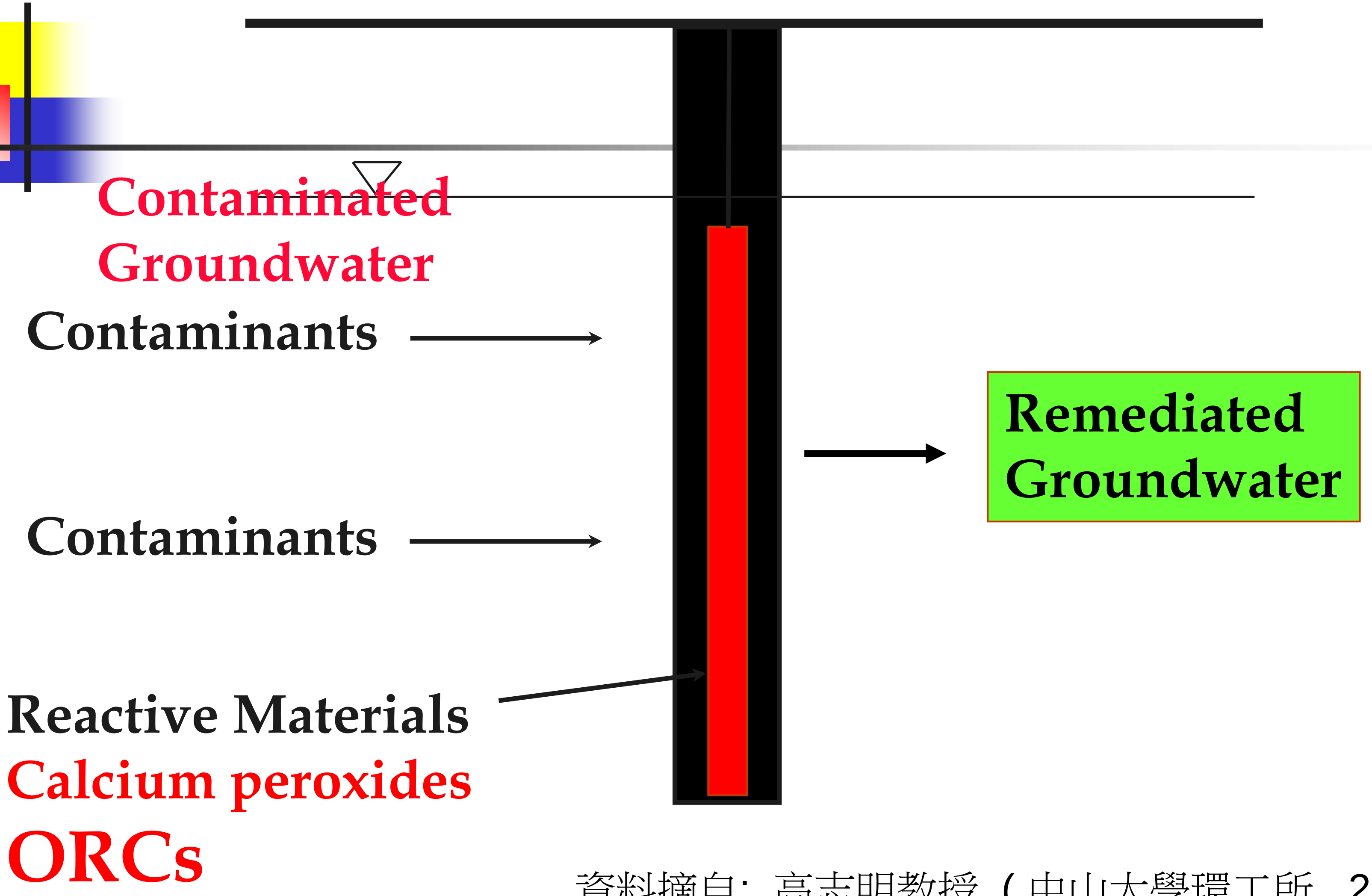
- **is a permeable zone containing or creating a reactive treatment area oriented to intercept and remediate a contaminant plume**
- **removes contaminants from the ground water flow system by physical, chemical, or biological processes**

PRB Concept

(USEPA, 2013)



In site: Permeable reactive barriers, PRB



資料摘自：高志明教授（中山大學環工所 , 2003)

PRBs – Introduction and Overview

Why Use a PRB?

- Treatment occurs in the subsurface
- Typical treatment is passive
- Lower costs than conventional methods
- Allows full economic use of a property
- Robust
- Monitoring can be focused

(USEPA, 2013)

Permeable reactive barriers, PRB

- **mechnisum**
  - **physical**
  - **chemical**
  - **biological**

- **pollutants**
  - **VOCs**
  - **SVOCs**
  - **BTEX**
  - **Heavy metals**
  - **Inorganic salts**

PRBs – Introduction and Overview

Contaminants Treated and Reactive Media Used

CONTAMINANT	BARRIERTYPE	REACTIVE MEDIA	STATUS
Organicss - DCE, TCE, PCE - BTEX - nitrobenzene - DCA, TCA - PCBs, PAHs	Degradation	zero-valent iron iron(II) porphyrins resting-state microorganisms oxygen-releasing compound dithionite	commercial laboratory field field field
	Sorption	zeolite surfactant modified silicates organobentonites activated carbon	laboratory laboratory laboratory laboratory
Inorganics - heavy metals (Ni, Pb, Cd, Cr, V, Hg) - radioactive (U, Ra, Sr, Cs, Tc) - nitrate	Sorption	peat ferric oxyhydroxide bentonite zeolites and modified zeolites chitosan beads	laboratory field laboratory laboratory laboratory
	Precipitation	hydroxyapatite zero-valent iron dithionite lime or limestone	laboratory commercial field commercial
	Degradation	saw dust	field

(USEPA, 2013)

Off ***site: physico-chemical methods -1***

- ***Solidification*** **:** addition of a cementing agent to produce a hardened, nonporous materials.
- **Soil Washing :** Chelate or acid extraction
- **Chemical /Solvent extraction :** extraction by chemical reagents (EDTA, citric acid etc.) and separate the pollutants from the solution
- **Chemical Oxidation** : oxidation of organic materials to produce CO_2 and H_2O

Off *site: physico-chemical methods* -2

- **Soil Flushing**
- **Soil vapor extraction (SVE)**
- **Particle-size segragation : selected removal of fine particle (clay) that have high concentration**
- **Soil excavation : soil removal and disposal.**

in situ physico-chemical method for oil contaminated soils

- **Soil vapor extraction (SVE): Sent air into deep soils of the site and pump out the pollutants from the site**
- **Attenuation: Dilute the conc. In the natural condition**
- **Soil Flushing : soil flushing with reagents or surfactants**
- **Oxygen Release Compound (ORCs): Adding the Calcium peroxide to release oxygen**

Chemical remediation techniques

- **acid washing or extraction method**
- **Stabilization or solidification**
- **chemical oxidation, reduction or neutralization)**
- **Electrokinetics**

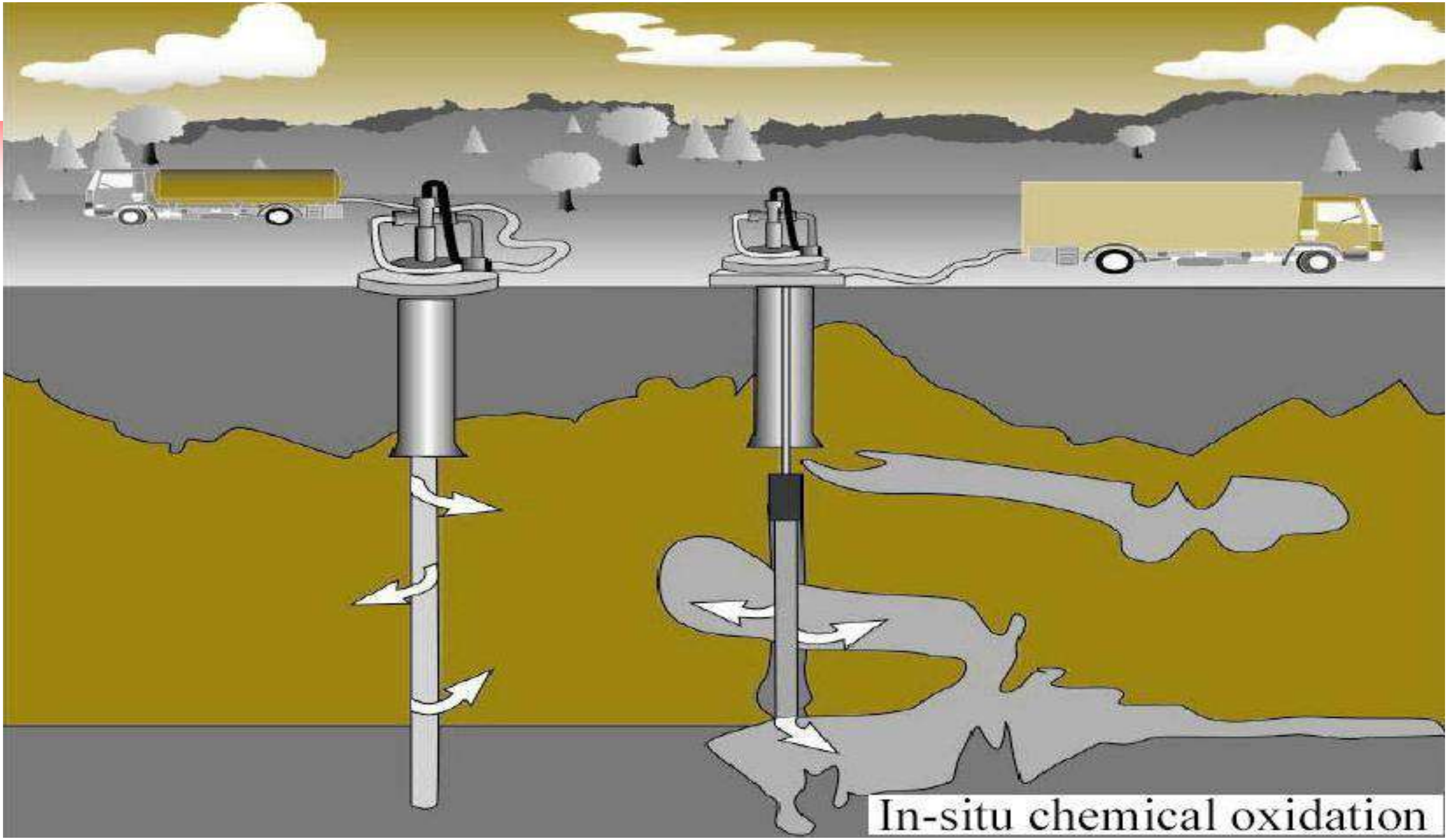
ISCO (In-Situ Chemical Oxidation)

- **Put the oxidant into the soil to transfer or reduce the concentration, mass, mobility or toxicity of pollutants (contaminants of concern, COC) in soil or groundwater**
- **Can combine with other treatments (ex. bioremediation**

Benefit of ISCO method

- **oxidation of DNAPL materials**
- **reduce the reaction time**
- **reduce the cost of pump and treatment**
- **do not change the building structure**
- **reduce the cost of excavation and treated soils**

In situ chemical oxidation



Case Study

- SA17 Naval Training Center Orlando, Florida, USA

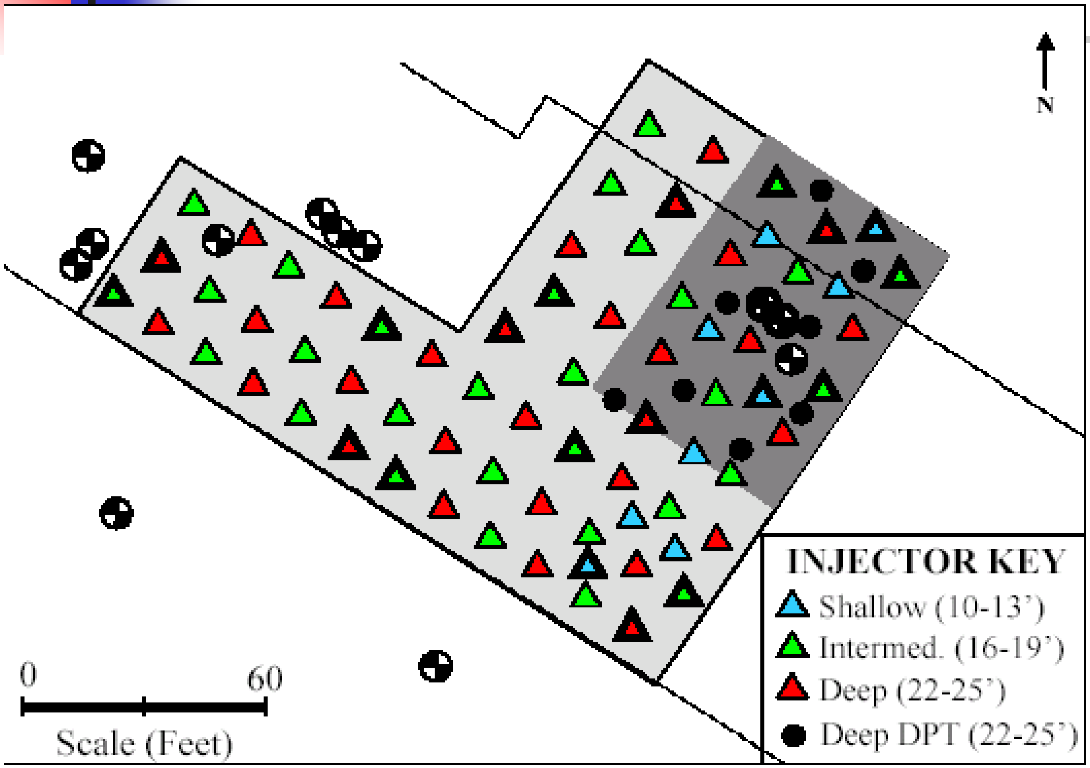
-former pool area、vehicle

wash rack、storage area for waste fuel & oil

-19,000 ft^2

-Initial site investigations began in 1995

Case Study



-Gasoline-range organics

-CVOCs (TCE and VC)

-maximum conc.

306,000μg/L for TCE

78,500μg/L for GRO

SA 17

Case Study

-remediation time

11/6-12/1, 2000

-69 Injectors in 3 levels

-8,700 gallons H_2O_2 (25%)

6,900 gallons Fe (II)

Case Study

remediation results

- CVOCs reduced from 306,000 µg/L to 27,000 µg/L (removal rate : **92%)**
- GRO removal from 78,500 µg/L to 9,190 µg/L (removal rate : **90%)**

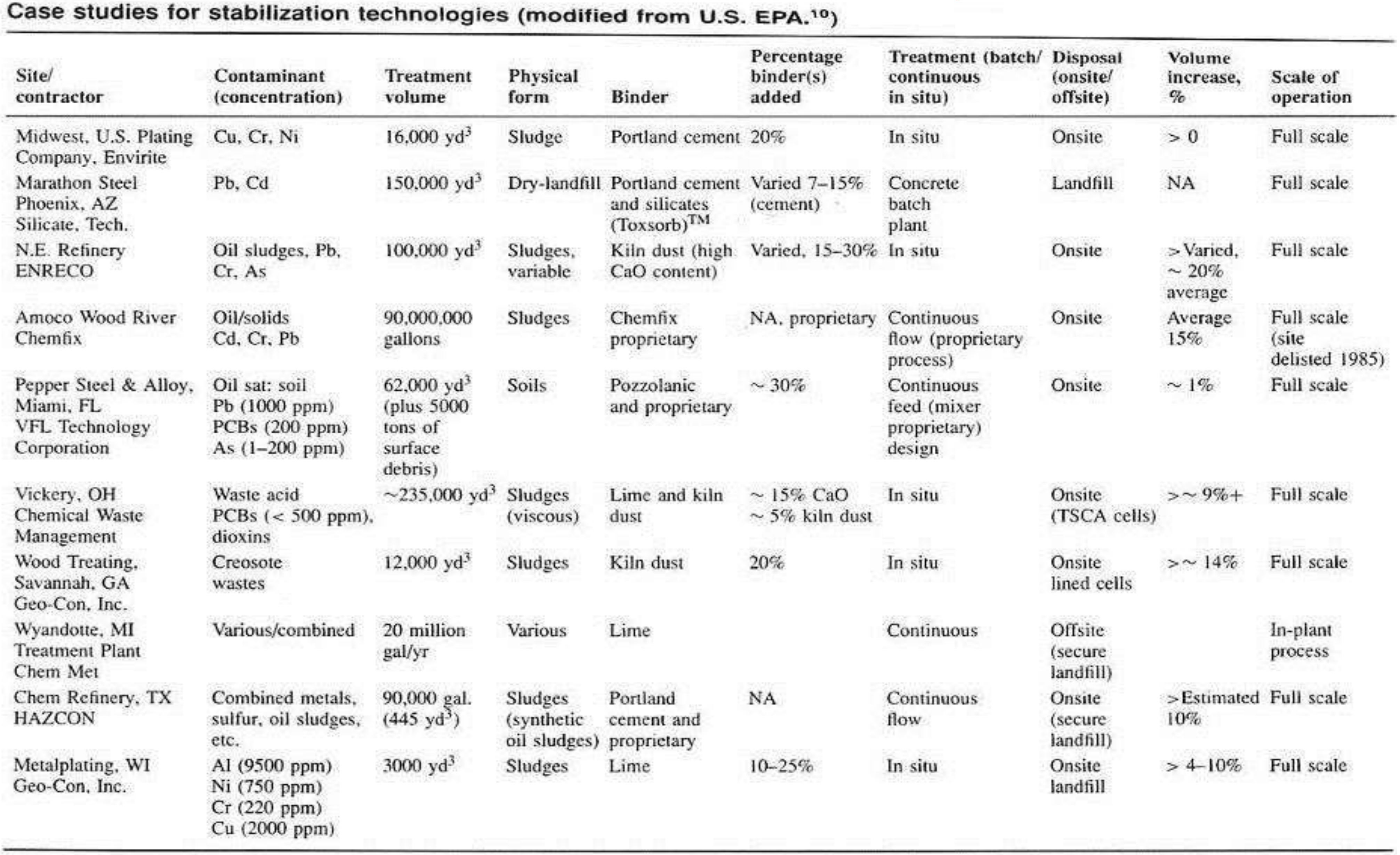
Target value:

- **500 µg/L** → by addition of H_2O_2 injection

Chemical Stabilization/solidification method

- By adding the chemical materials to stabilize or react with the pollutants in the soil
- To solid the contaminated soil as very low release material under natural raining system
- To reduce the pollutants released from the solid materials.
- Cost effective?

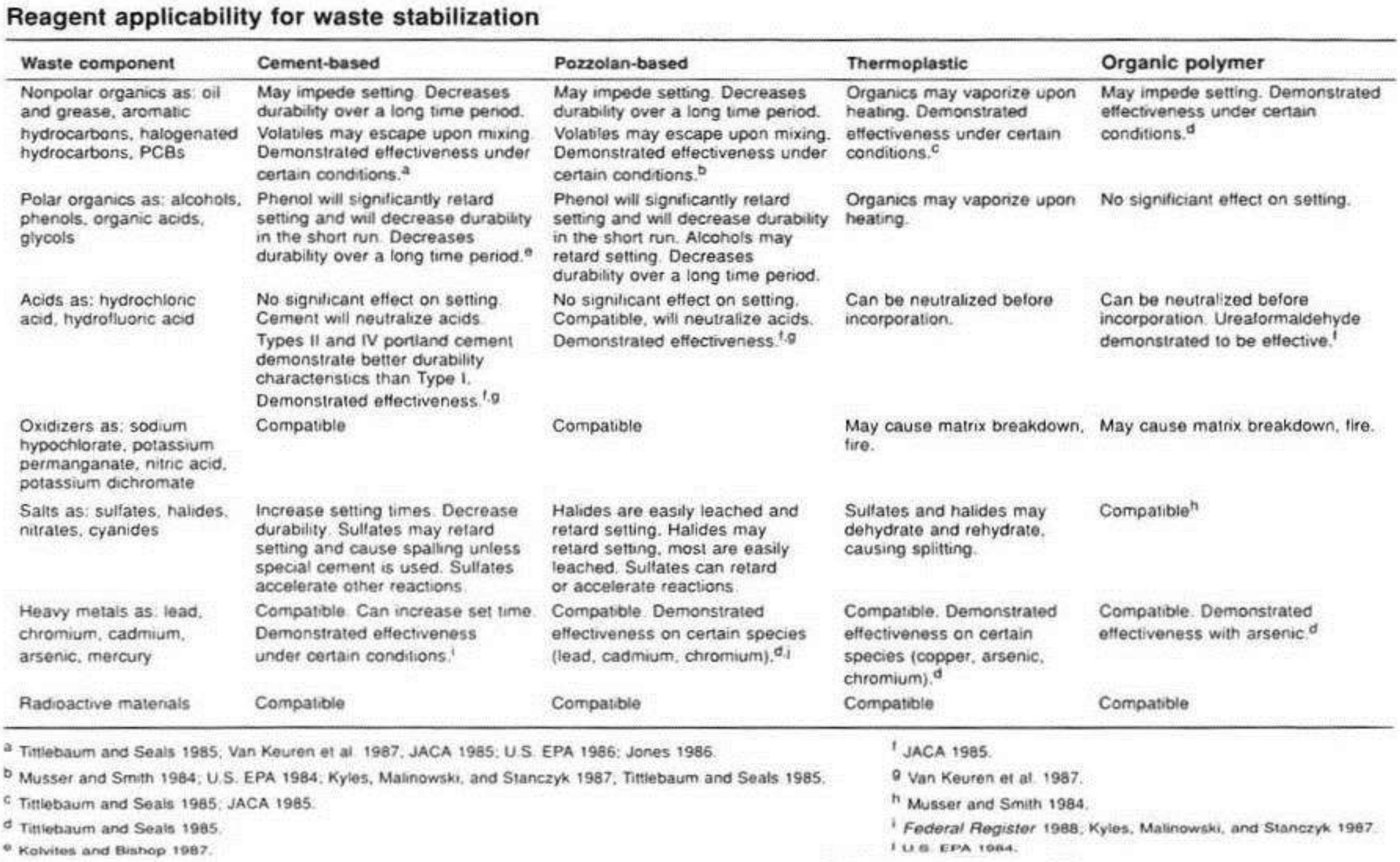
Case study for *stabilization technology* in USEPA



Case studies for stabilization technologies (modified from U.S. EPA.[10])

Site/ contractor	Contaminant (concentration)	Treatment volume	Physical form	Binder	Percentage binder(s) added	Treatment (batch/ continuous in situ)	Disposal (onsite/ offsite)	Volume increase, %	Scale of operation
Midwest, U.S. Plating Company, Envirite	Cu, Cr, Ni	16,000 yd^3	Sludge	Portland cement	20%	In situ	Onsite	> 0	Full scale
Marathon Steel Phoenix, AZ Silicate, Tech.	Pb, Cd	150,000 yd^3	Dry-landfill	Portland cement and silicates (Toxsorb)^{TM}	Varied 7–15% (cement)	Concrete batch plant	Landfill	NA	Full scale
N.E. Refinery ENRECO	Oil sludges, Pb, Cr, As	100,000 yd^3	Sludges, variable	Kiln dust (high CaO content)	Varied, 15–30%	In situ	Onsite	> Varied, ~ 20% average	Full scale
Amoco Wood River Chemfix	Oil/solids Cd, Cr, Pb	90,000,000 gallons	Sludges	Chemfix proprietary	NA, proprietary	Continuous flow (proprietary process)	Onsite	Average 15%	Full scale (site delisted 1985)
Pepper Steel & Alloy, Miami, FL VFL Technology Corporation	Oil sat: soil Pb (1000 ppm) PCBs (200 ppm) As (1–200 ppm)	62,000 yd^3 (plus 5000 tons of surface debris)	Soils	Pozzolanic and proprietary	~ 30%	Continuous feed (mixer proprietary) design	Onsite	~ 1%	Full scale
Vickery, OH Chemical Waste Management	Waste acid PCBs (< 500 ppm), dioxins	~235,000 yd^3	Sludges (viscous)	Lime and kiln dust	~ 15% CaO ~ 5% kiln dust	In situ	Onsite (TSCA cells)	> ~ 9%+	Full scale
Wood Treating, Savannah, GA Geo-Con, Inc.	Creosote wastes	12,000 yd^3	Sludges	Kiln dust	20%	In situ	Onsite lined cells	> ~ 14%	Full scale
Wyandotte, MI Treatment Plant Chem Met	Various/combined	20 million gal/yr	Various	Lime		Continuous	Offsite (secure landfill)		In-plant process
Chem Refinery, TX HAZCON	Combined metals, sulfur, oil sludges, etc.	90,000 gal. (445 yd^3)	Sludges (synthetic oil sludges)	Portland cement and proprietary	NA	Continuous flow	Onsite (secure landfill)	> Estimated 10%	Full scale
Metalplating, WI Geo-Con, Inc.	Al (9500 ppm) Ni (750 ppm) Cr (220 ppm) Cu (2000 ppm)	3000 yd^3	Sludges	Lime	10–25%	In situ	Onsite landfill	> 4–10%	Full scale

Case study for Reagents for stabilization in USEPA



Reagent applicability for waste stabilization

Waste component	Cement-based	Pozzolan-based	Thermoplastic	Organic polymer
Nonpolar organics as: oil and grease, aromatic hydrocarbons, halogenated hydrocarbons, PCBs	May impede setting. Decreases durability over a long time period. Volatiles may escape upon mixing. Demonstrated effectiveness under certain conditions.[a]	May impede setting. Decreases durability over a long time period. Volatiles may escape upon mixing. Demonstrated effectiveness under certain conditions.[b]	Organics may vaporize upon heating. Demonstrated effectiveness under certain conditions.[c]	May impede setting. Demonstrated effectiveness under certain conditions.[d]
Polar organics as: alcohols, phenols, organic acids, glycols	Phenol will significantly retard setting and will decrease durability in the short run. Decreases durability over a long time period.[e]	Phenol will significantly retard setting and will decrease durability in the short run. Alcohols may retard setting. Decreases durability over a long time period.	Organics may vaporize upon heating.	No significiant effect on setting.
Acids as: hydrochloric acid, hydrofluoric acid	No significant effect on setting. Cement will neutralize acids. Types II and IV portland cement demonstrate better durability characteristics than Type I. Demonstrated effectiveness.[f,g]	No significant effect on setting. Compatible, will neutralize acids. Demonstrated effectiveness.[f,g]	Can be neutralized before incorporation.	Can be neutralized before incorporation. Ureaformaldehyde demonstrated to be effective.[f]
Oxidizers as: sodium hypochlorate, potassium permanganate, nitric acid, potassium dichromate	Compatible	Compatible	May cause matrix breakdown, fire.	May cause matrix breakdown, fire.
Salts as: sulfates, halides, nitrates, cyanides	Increase setting times. Decrease durability. Sulfates may retard setting and cause spalling unless special cement is used. Sulfates accelerate other reactions.	Halides are easily leached and retard setting. Halides may retard setting, most are easily leached. Sulfates can retard or accelerate reactions.	Sulfates and halides may dehydrate and rehydrate, causing splitting.	Compatible[h]
Heavy metals as: lead, chromium, cadmium, arsenic, mercury	Compatible. Can increase set time. Demonstrated effectiveness under certain conditions.[i]	Compatible. Demonstrated effectiveness on certain species (lead, cadmium, chromium).[d,j]	Compatible. Demonstrated effectiveness on certain species (copper, arsenic, chromium).[d]	Compatible. Demonstrated effectiveness with arsenic.[d]
Radioactive materials	Compatible	Compatible	Compatible	Compatible

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[a] Tittlebaum and Seals 1985; Van Keuren et al. 1987; JACA 1985; U.S. EPA 1986; Jones 1986.

[b] Musser and Smith 1984; U.S. EPA 1984; Kyles, Malinowski, and Stanczyk 1987; Tittlebaum and Seals 1985.

[c] Tittlebaum and Seals 1985; JACA 1985.

[d] Tittlebaum and Seals 1985.

[e] Kolvites and Bishop 1987.

[f] JACA 1985.

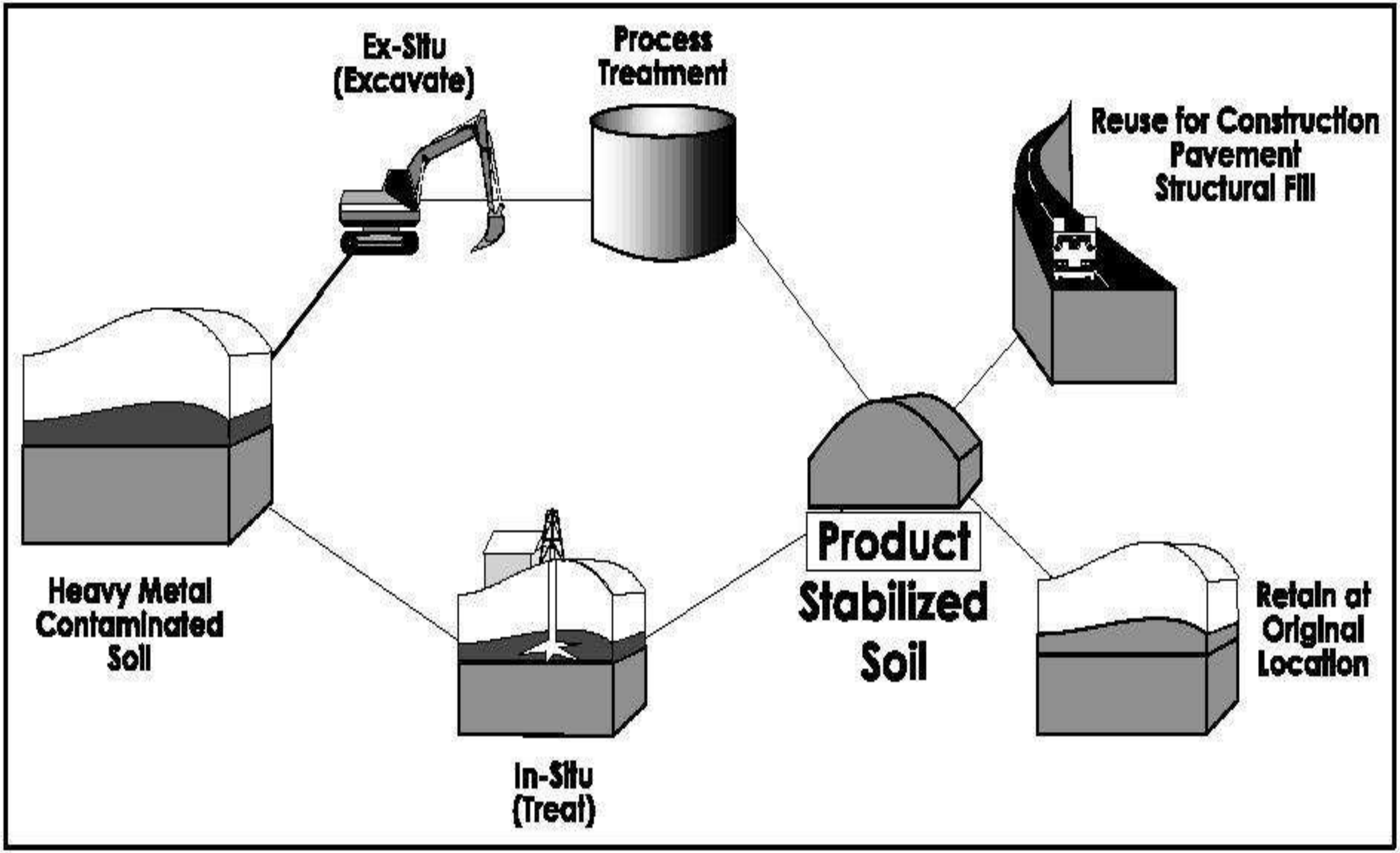
[g] Van Keuren et al. 1987.

[h] Musser and Smith 1984.

[i] *Federal Register* 1988; Kyles, Malinowski, and Stanczyk 1987.

[j] U.S. EPA 1984.

Model demonstration of chemical stabilization



Off *site* : *Heating*

- **Vitrification**: heating to produce a glass-like, nonporous materials (<600 degree C) (soil properties will be changed
- **Incineration**: heating the organic pollutants to remove the pollutants
- **Pyrolysis**: heating the organic pollutants to remove the pollutants in no oxygen conditions (>1000 degree C)
- **Thermal desorption** : heating the organic pollutants to remove the pollutants in low or high temperature conditions

Bioremediation:
biological treated methods

- oxidation and reduction decomposed by microorganisms
- biofilm treatment, biological adsorption, etc
- bio-restoration

Bioremediation treatments -1

- **Best benefit: stable and no side effects**
- **suitable for organic pollutants: TCE or gasoline**
- **Different remediation types：**
  - **oxidized and reduced methods**
  - **in-situ and ex-situ**
  - **microbiological approach and microbial ecology approach**

Bioremediation treatments -2

- **General methods: bioventing, slurry reactor, land farming, composting, enhanced in-site bioremediation, etc.**

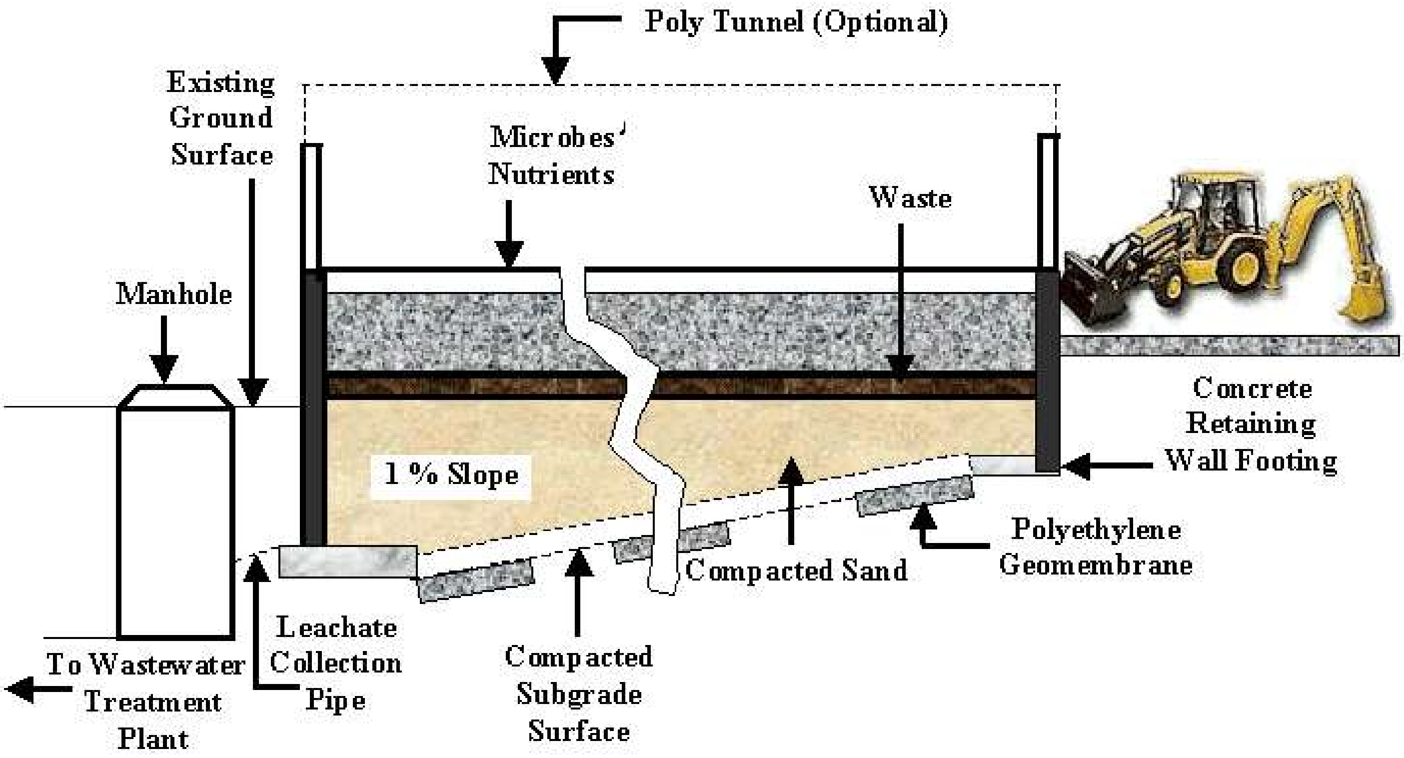
- **Most sites were treated by in-situ for biological decomposition process**

Indicators of Natural attenuation by microorganisms

- **key factors:** collected the information of bio-transportation and the evidence of effective biological activity.
- **three evidences：** (1) reduce the conc. of pollutants, (2) do have the biological reactions, and (3) have by-product produced through reactions

Off site : biological method

- **Land farming**: The excavation materials were filled on the land surface for biological decomposition
- **remediation for oil pollution**



U.S. EPA TIO

Suitability of natural bioremediation

- Evidences of natural bioremediation)
- Total assimilative capacity can be used for the decomposition of BTEX comp
- Structural analysis of pollution plume

Non-technical factors

- budget and time
- idea of communities
- layout of the site and surrounding area
- target value of soil remediation

Summary of remediation techniques used in Taiwan

- Phytostabilization (** field scale)
- Dilution attenuation (*field scale) : heavy metals pollution
- Soil amendments (soil addition) (pilot scale)
- Soil washing (by acidic solution) : (*field scale)
- Soil vapor extraction (SVE) (*field scale)
- Thermal desorption (*field scale) (pesticides)
- Solidification (pilot): (in pilot) :heavy metals pollution
- Chemical oxidation (gas station pollution) (*field scale)
- Electrokinetics separation (EK) (pilot)
- Bioremediation (oil pollution) (*field scale)
- Land farming (oil pollution sites) (*field scale)

Analysis of soil remediation techniques and regulations -1

- The reasonable soil remediation proceduresscy makers
- Cut the pollution sources
- Is the cleanup the sediment of irrigation water, then do the soil remediation project ?
- **How to recover the minimum soil fertility requirements fo crop productivity after the soil remediation?**
- How to establish the standard operation procedures (SOP) to evaluate the soil condition after soil remediation project ?

Analysis of soil remediation techniques and regulations -2

- How to recover the minimum soil fertility requirements fo crop productivity after the soil remediation?
- **Do we have other evaluation methods to evaluate the status of soil pollution by bioavailability extraction methods?**
- **Where is the pollution sources in the contaminated sites by environmental forensics?**

Analysis of remediation techniques and regulations of oil pollution-1

- Risk-based assessment approach
- Remediation target
- Remediation strategy, and
- Budget consideration

Analysis of remediation techniques and regulations of oil pollution-2

- How to establish the "technical guidelines" to be followed?
- How to finish the remediation project in a reasonable time?

Factors to select the suitable remediation techniques

- Technical consideration : evaluated on performance, reliability, implementability, time, and safety
- Environmental concerns : environmental standard of pollutants, short and long term effects, irreversible commitments of resources, and their costs
- Public health concerns : site evaluation and analysis of human exposure to site, comparisons of projected clean up level, and ability to be removed
- Institutional concerns : the effects of national and local government standards and other institutional considerations of each alternative techniques
- Costs : include operation and maintenance (O&M) costs

Factors affecting the options of remediation

- Safety
- Reliability
- Reduce the toxicity, volume and mobility (20% of cost to reduce 80% risk)
- Necessity for process proof monitoring
- Treatment rate
- Treatment by-product
- Acceptability to regulators and local residents,
- Reclamation cost

Procedure to select the good remediation techniques

- **Remedial Goal (Health Risk assessment)**
- **Identification of response action**
- **Screening of soil remediation technology**
- **Development and screening of remedial action alternatives**
- **Detailed evaluation**

Factors for selecting remediation techniques of contaminated soils by heavy metals

- conc. of heavy metals
- soil texture
- depth of groundwater level
- the efficiency
- budget and benefits
- time
- opinion of people)

Conclusions

- **The soil remediation techniques and their development for rural soil contaminated by heavy metals and oil.**
- **Technical and non-technical factors**
- **The regulations should be revised**
- **Problems and statistic analysis of techniques and regulation**

Case studies of Bioremediation and Phytoremediation on PetroleumContaminated Site

侯善麟 *Frank S. L. Hou*
台灣中油 *CPC Corporation, Taiwan*
中國醫藥大學 *China Medical University*

台灣中油股份有限公司
CPC Corporation, Taiwan

Bioremediation

- Using subsurface microorganisms to transform hazardous contaminants into relatively harmless byproducts, such as ethene and water
  - Biodegrade
  - Mineralize
  - Biotransform
- Techniques or types of bioremediation:
  - A component of Natural Attenuation
  - Enhanced Bioremediation
  - Bioaugmentation

Bioremediation Background

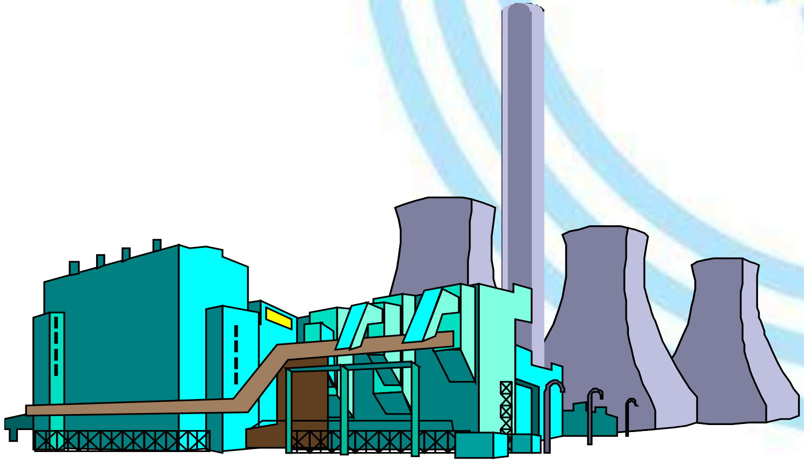
- Natural Attenuation is Not fast enough, Not complete enough, Not frequently occurring enough to be broadly used for some compounds, especially chlorinated solvents
- The current trend is to stimulate/enhance a site's indigenous subsurface microorganisms by the addition of nutrients and electron donor
- In some cases, bioaugmentation is necessary when metabolic capabilities are not naturally present.

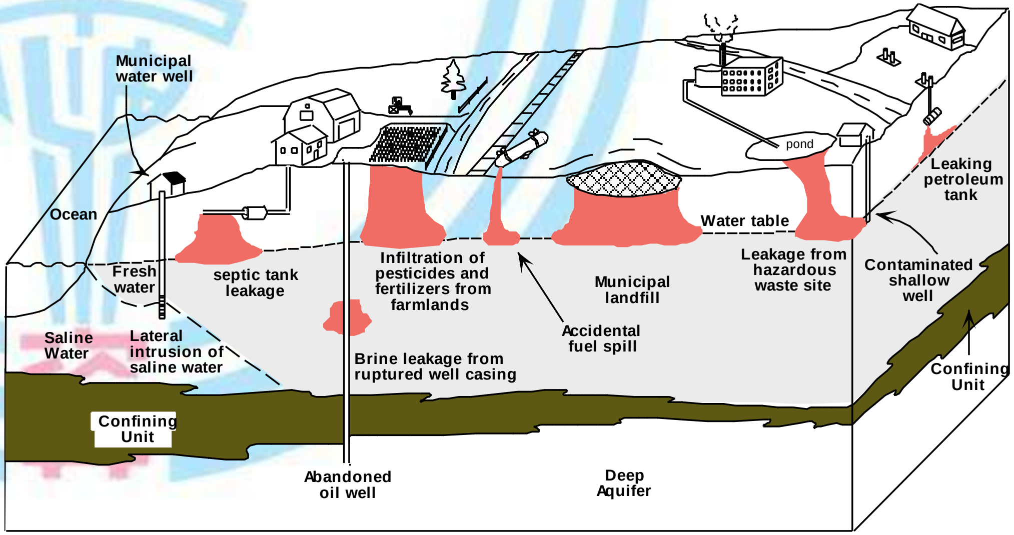
Soil and Subsurface Contaminants

- Benzene and related fuel components (BTEX)
- Pyrene and other polynuclear aromatics
- Chlorinated aromatics and solvents
- Herbicides and pesticides
- Nitroaromatic explosives and plasticizers

Sources of Contamination

- Industrial spills and leaks
- Surface impoundments
- Storage tanks and pipes
- Landfills
- Burial areas and dumps
- Injection wells

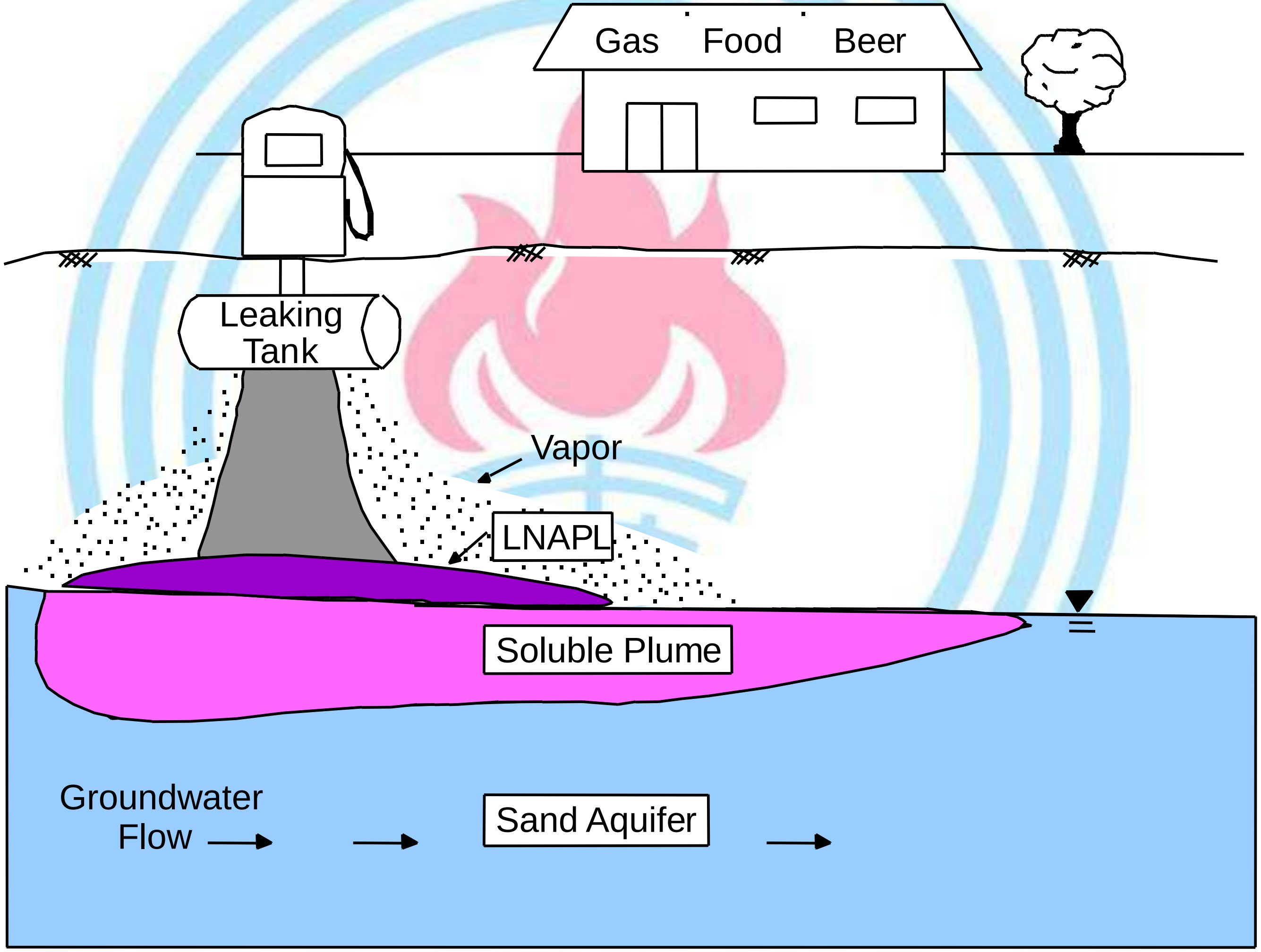




Current Water Issues Associated with Gasoline Use

- Widespread contamination
- Major threat to drinking water resources
- Components of fuels are known carcinogens
- Current fuel oxygenate, MTBE, very mobile and not very degradable
- Ethanol is due to replace MTBE, but its behavior in the subsurface is not yet understood

Typical Fuel (BTEX) Spill



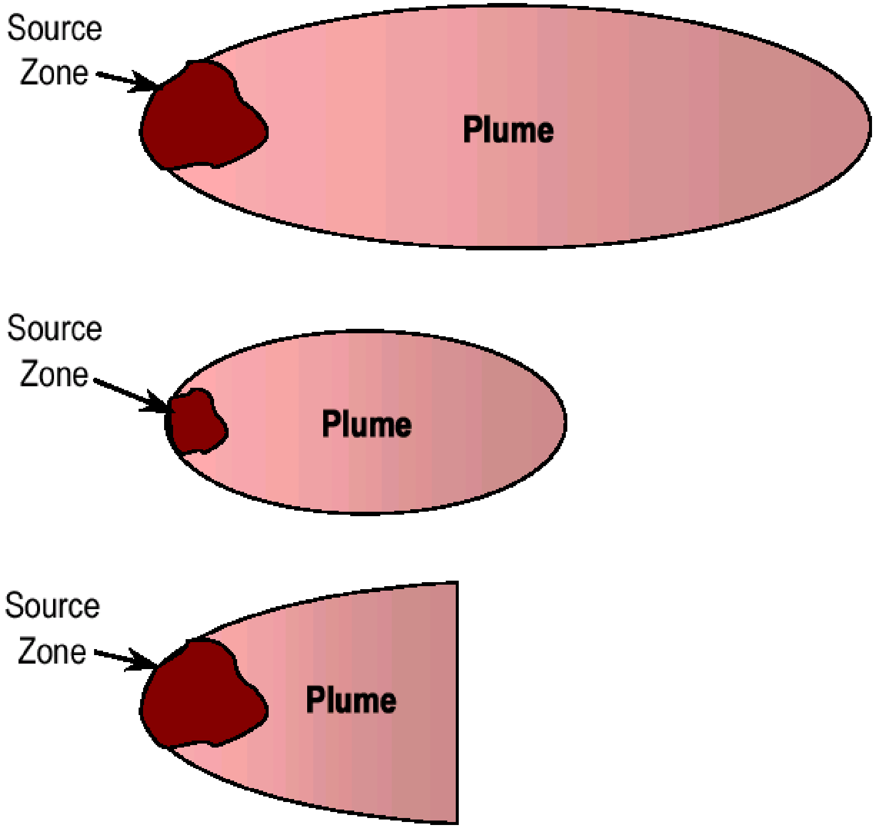
Treatment Techniques

- Soil Extraction
- Pump and Treat
- Physical and/or reactive barriers
- Air and Hydrogen Sparging
- Biological (microbes)
- Chemical (surfactants)

Why Bioremediation?

- No additional disposal costs
- Low maintenance
- Does not create an eyesore
- Capable of impacting source zones and thus, decreasing site clean-up time

Source Zone Treatment vs. Plume Treatment



Scenario

Do Nothing

Source Zone Treatment

Plume Treatment

Fundamentals of Biodegradation

- All organics are biodegradable, BUT biodegradation requires specific conditions
- There is no Superbug
- Contaminants must be bioavailable
- Biodegradation rate and extent is controlled by a "limiting factor"

Biotic Transformations

- Result of metabolic activity of microbes
- Aerobic and anaerobic biodegradation
- Reduces aqueous concentrations of contaminant
- **Reduction of contaminant mass**
- **Most significant process resulting in reduction of contaminant mass in a system**

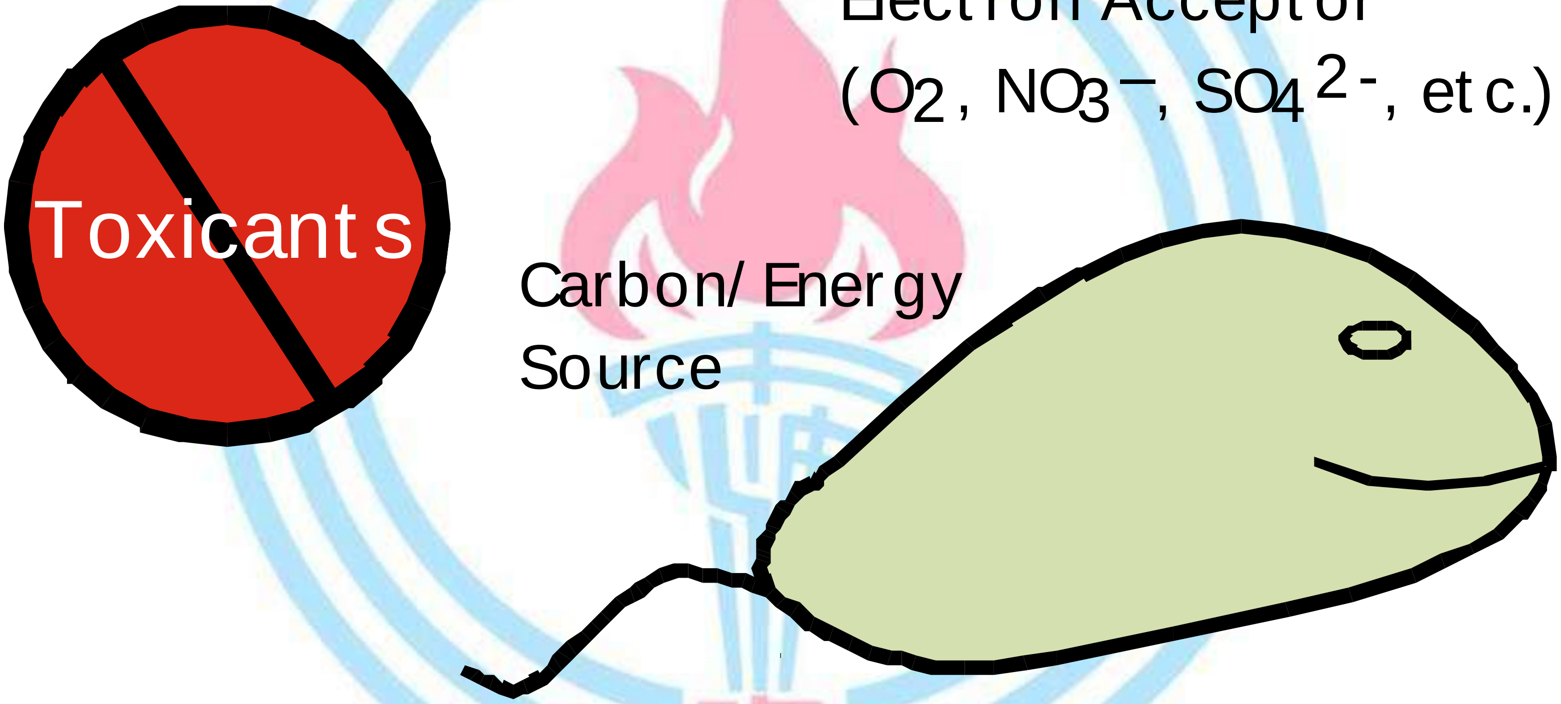
Bioremediation Processes

- Conversion of contaminants to mineralized (e.g. CO_2, H_2O, and salts) end-products via biological mechanisms
- Biotransformation refers to a biological process where the end-products are not minerals (e.g., transforming TCE to DCE)
- Biodegradation involves the process of extracting energy from organic chemicals via oxidation of the organic chemicals

How Microbes Use the Contaminant

- Contaminants may serve as:
  - Primary substrate
    - enough available to be the sole energy source
  - Secondary substrate
    - provides energy, not available in high enough concentration
  - Cometabolic substrate
    - fortuitous transformation of a compound by a microbe relying on some other primary substrate

Requirements for Microbial Growth



Electron Acceptor

(O_2, NO_3^-, SO_4^{2-}, etc.)

Carbon/Energy Source

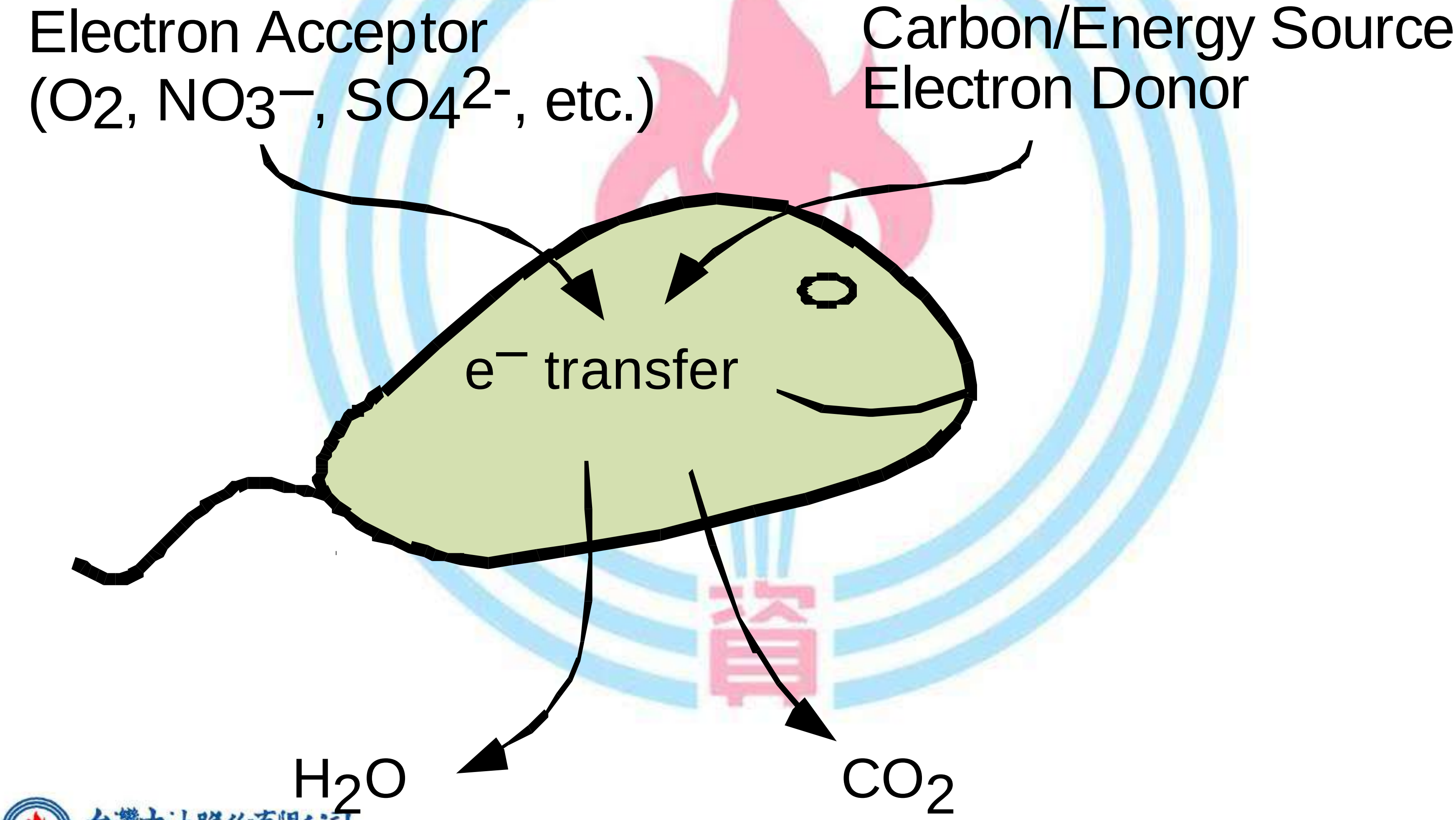
Environmental Conditions

(Temp, pH, Eh)

Nutrients (N, P)

Trace Elements

Electron Exchange



Electron Acceptor
(O_2, NO_3^-, SO_4^{2-}, etc.)

Carbon/Energy Source
Electron Donor

e^- transfer

H_2O

CO_2

Aerobic v. Anaerobic

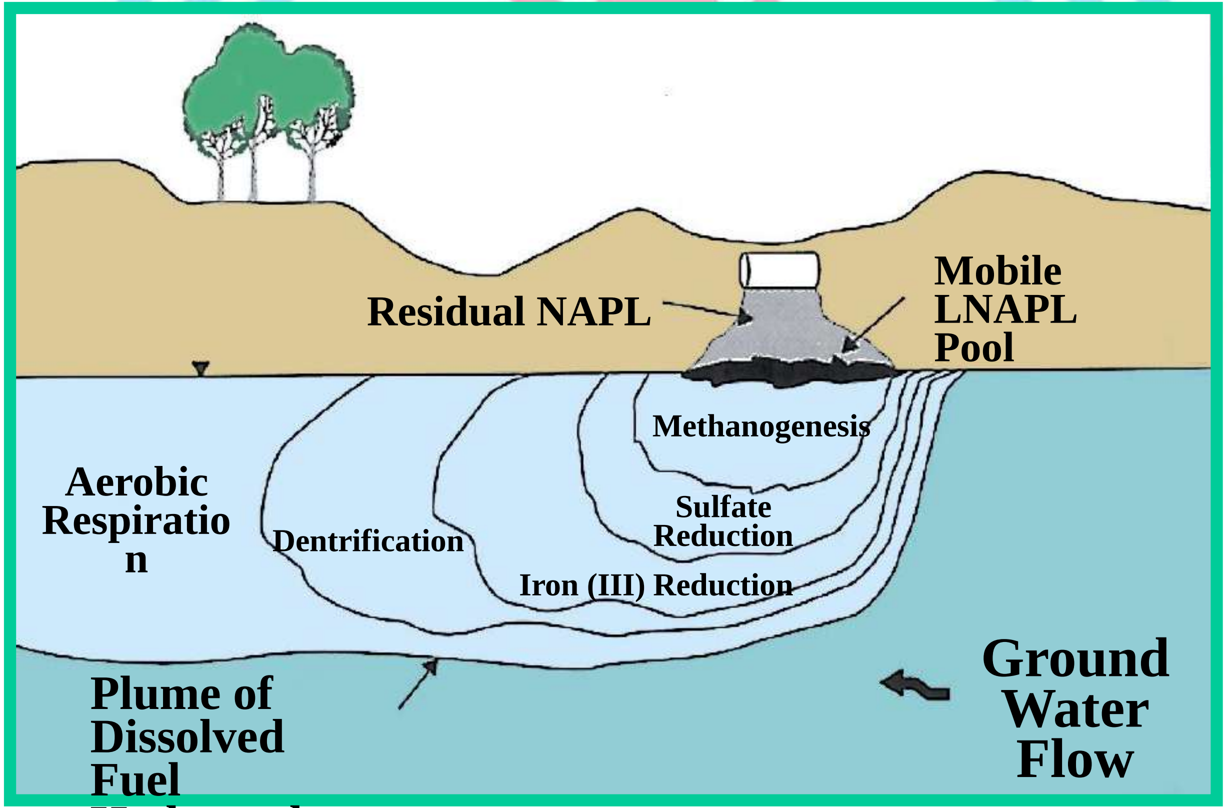
- If oxygen is the terminal electron acceptor, the process is called aerobic biodegradation
- All other biological degradation processes are classified as anaerobic biodegradation
- In most cases, bacteria can only use one terminal electron acceptor
- Facultative aerobes use oxygen, but can switch to nitrate in the absence of oxygen

Bacterial Metabolism

Aerobic	Anaerobic
Oxidation	Denitrification
Cometabolism	Manganese reduction
	Iron reduction
	Sulfate reduction
	Methanogenesis

Electron Acceptor Zones

- After O_2 is depleted, begin using NO_3^-
- Continue down the list in this order
  - O_2 —> NO_3^- —> Fe^{3+} —> SO_4^{2-} —> CO_2



Electron Acceptor Condition

Compound(s)	Aerobic	Anaerobic
Acetone	1	1
BTEX	1	2 to 4
PAH	1	3 to 4
PCB		
highly substituted	4	2
minimally substituted	2	4
Chlorinated ethenes		
PCE	4	1 to 2
TCE	3	1 to 2
DCEs	3	2 to 3
Vinyl chloride	1 to 2	3 to 4

1 Highly biodegradable 2 Moderately biodegradable
3 Slow biodegradation 4 Not biodegraded

Bioremediation Practice

- Understand physical and chemical characteristics of the contaminants of interest
- Understand the possible catabolic pathways of metabolism and the organisms that possess that capability
- Understand the environmental conditions required to:
  - Promote growth of desirable organisms
  - Provide for the expression of needed organisms
- Engineer the environmental conditions needed to establish favorable conditions and contact organisms and contaminants

Oxygen is of Primary Importance

- **Most of the time oxygen is the primary factor limiting *in situ* biodegradation**
- **In most cases if adequate oxygen can be supplied then biodegradation rates are adequate for remediation**
- **Other limiting factors exist, but are usually secondary to oxygen**

Degradation for Benzene: $C_6H_6 + 7.5O_2 \longrightarrow 6CO_2 + 3H_2O$

Oxygen Supply is the Key to Aerobic In Situ Bioremediation

- Two ways to introduce oxygen in situ
- Dissolved in water :
  - Actively pumped: $H_2 O_2$, aerated water
  - Passively: ORC ® , membrane, aeration
- In gaseous form, usually air
  - Bioventing above the water table
  - Air sparging below the water table

Electron Donors

- Alcohols and acids
- Almost any common fermentable compound
- Hydrogen apparently universal electron donor, but no universal substrate
- Laboratory or small-scale field studies required to determine if particular substrate will support dechlorination at particular site

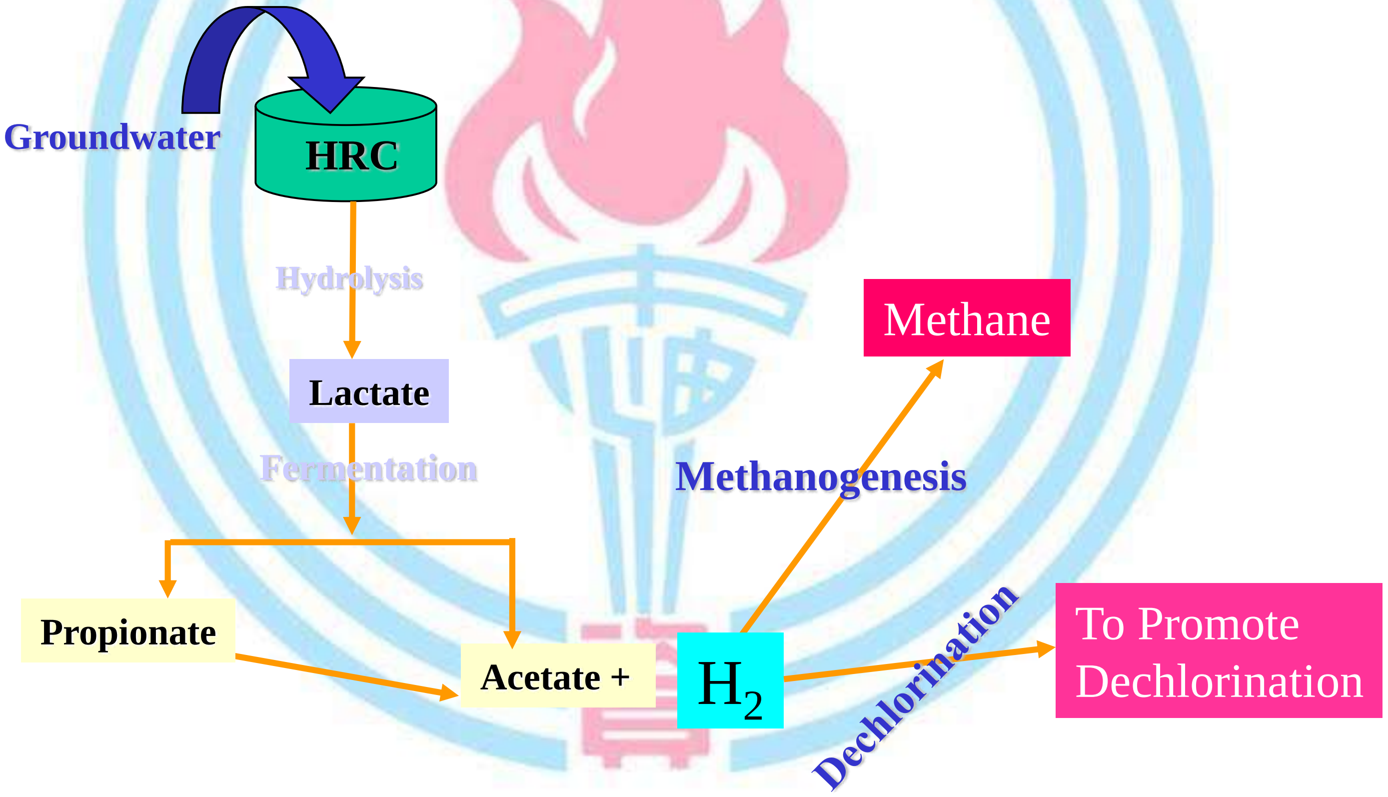
Electron Donors

- Acetate
- Acetic acid
- Benzoate
- Butyrate
- Cheese whey
- Chicken manure
- Corn steep liquor
- Ethanol
- Glucose
- Hydrocarbon contaminants
- Hydrogen -
  - biochemical
  - electrochemical
  - gas sparge
- Humic acids -
  - naturally occurring
- Isopropanol
- Lactate
- Lactic acid
- Methanol
- Molasses
- Mulch
- Pickle liquor
- Polylactate esters
- Propionate
- Propionic acid
- Sucrose
- Surfactants -
  - Terigitol5-S-12
  - Witconol 2722
- Tetraalkoxsilanes
- Wastewater
- Yeast extract

Enhanced Bioattenuation

Technology	Petroleum Hydrocarbons (e^- acceptor)	Chlorinated Solvents (e^- donor)
Liquid Delivery	Oxygen Nitrate Sulfate	Benzoate Lactate Molasses Carbohydrates
Biosparge	Air (oxygen)	Ammonia Hydrogen Propane
Slow-release	Oxygen (ORC)	Hydrogen (HRC)

Formation of a Usable Form of Electron Donor



Groundwater

HRC

Hydrolysis

Lactate

Fermentation

Propionate

Acetate + H_2

Methanogenesis

Methane

Dechlorination

To Promote Dechlorination

COD=Lactate + Acetate + Propionate

Phytoremediation

Phytoremediation is the use of higher plants to bioremediate contamination in soil, water, or sediments. Variations of phytoremediation that have been used in the past include wetlands to treat municipal sewage or neutralize acidic mine drainage.

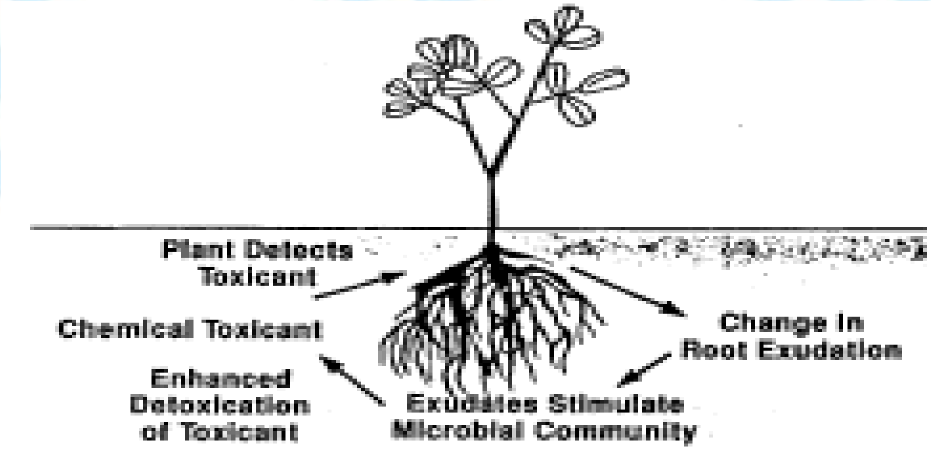
Currently, phytoremediation is proposed for remediation of both organic and inorganic contaminants in soil, sediments and water.

Phytoremediation

Plants may transport oxygen into the subsurface; lower the water table by transpiration, thereby pulling oxygen into the soil from the atmosphere; and increase hydraulic conductivity of the soil as roots produce channels in soil.

Flood-tolerant and wetland plants are especially efficient at transporting oxygen into the subsurface. These processes are thought to enhance aerobic biodegradation by increasing oxygen in the subsurface.

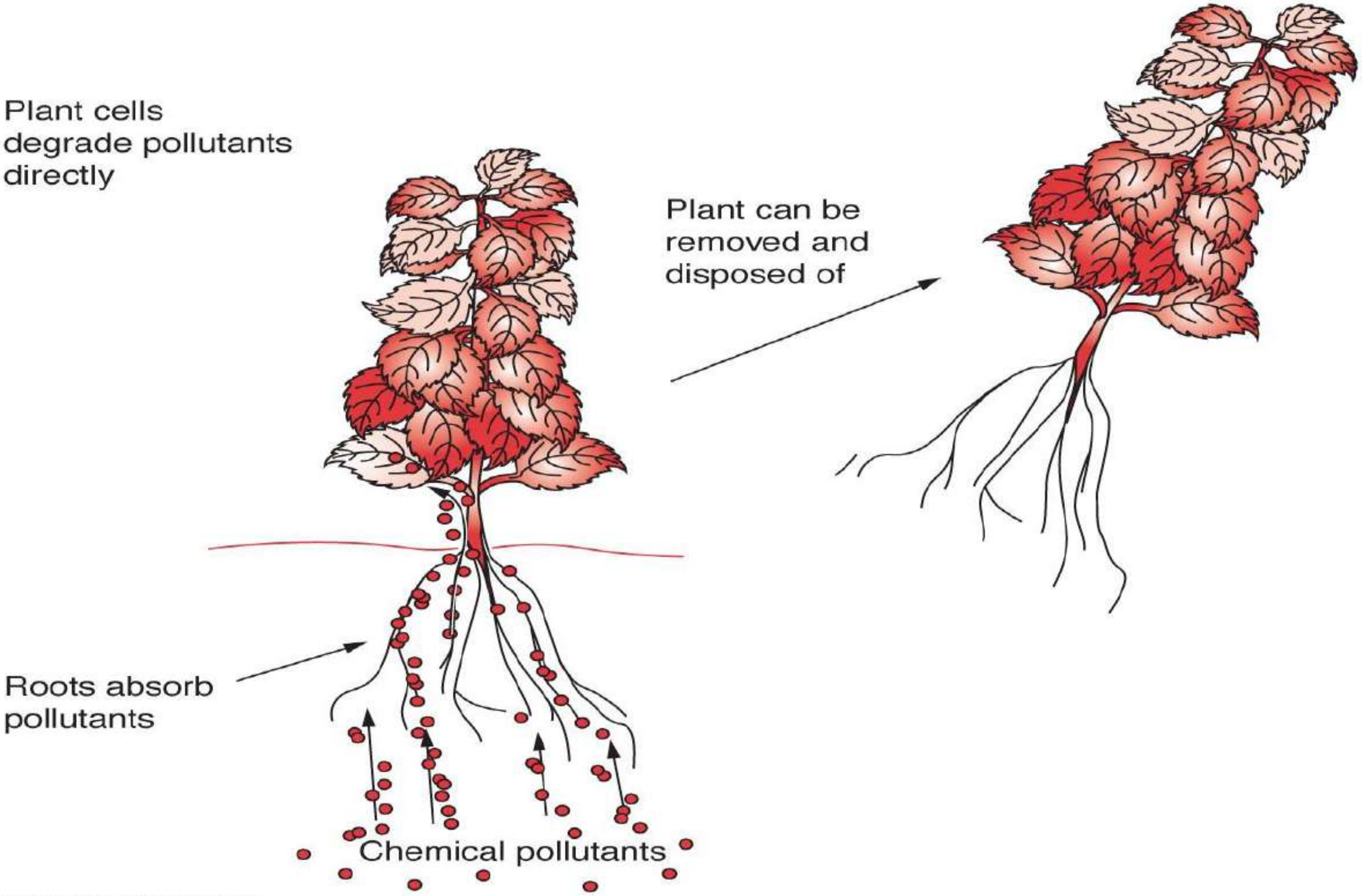
As plants transpire, the movement of water through the plant also carries along dissolved components. Dissolved contaminants such as chlorinated solvents can be removed from the soil in the transpiration stream and emitted to the atmosphere through the plant leaves. This type of "remediation" could be undesirable



Phytoremediation

- ≈350 plant species naturally take up toxic materials
  - Sunflowers used to remove radioactive cesium and strontium from Chrenobyl site
  - Water hyacinths used to remove arsenic from water supplies in Bangladesh, India

Phytoremediation



Phytoremediation

- Drawbacks
  - Only surface soil (root zone) can be treated
  - Cleanup takes several years

SITE REMEDIATION

PROCEDURES

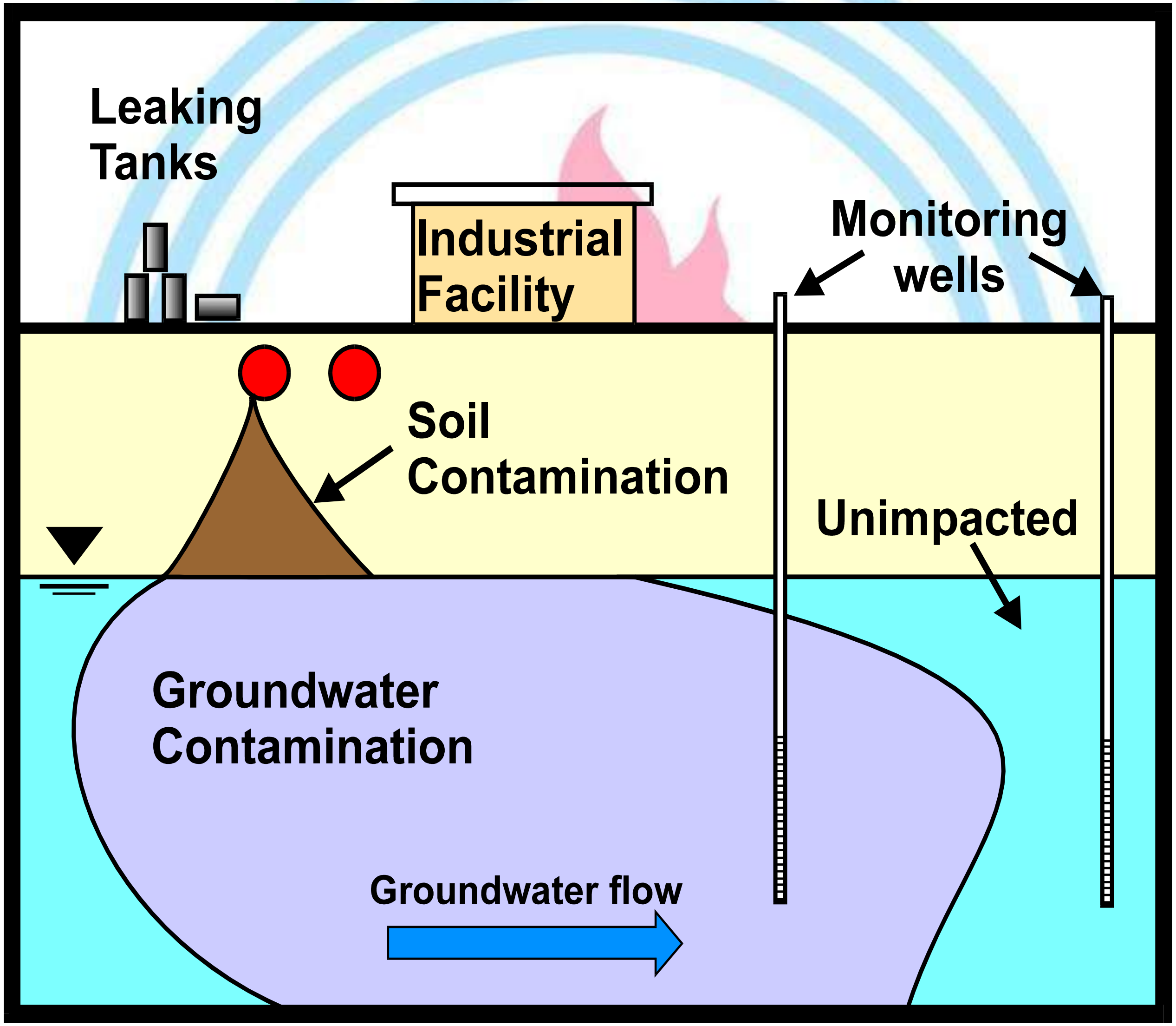
- SITE CHARACTERIZATION
- REMEDIAL ALTERNATIVES ANALYSIS
- DESIGN, CONSTRUCT AND OPERATE

GOALS OF SITE CHARACTERIZATION

The goals of site characterization are to:

1. Determine the extent and magnitude of contamination
2. Identify contaminant transport pathways and receptors
3. Determine risk of exposure

Zones of Contamination



Leaking Tanks

Industrial Facility

Monitoring wells

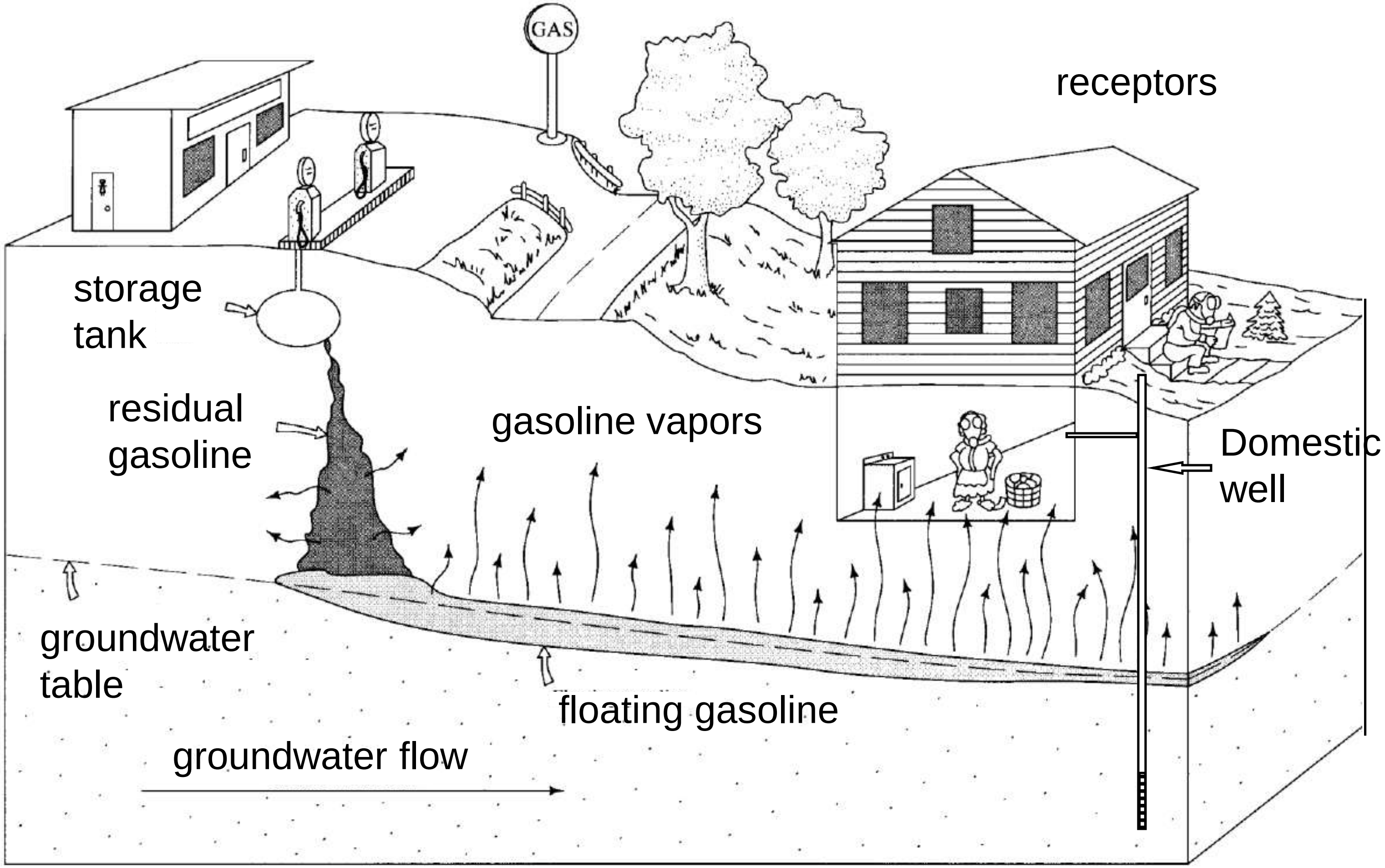
Soil Contamination

Unimpacted

Groundwater Contamination

Groundwater flow

Identification of Receptors and Pathways



receptors

storage tank

residual gasoline

gasoline vapors

Domestic well

groundwater table

floating gasoline

groundwater flow

METHODS OF SITE CHARACTERIZATION

Remote Methods

- Seismic Survey
- Soil Resistivity
- Ground Penetrating Radar
- Magnetometer Survey

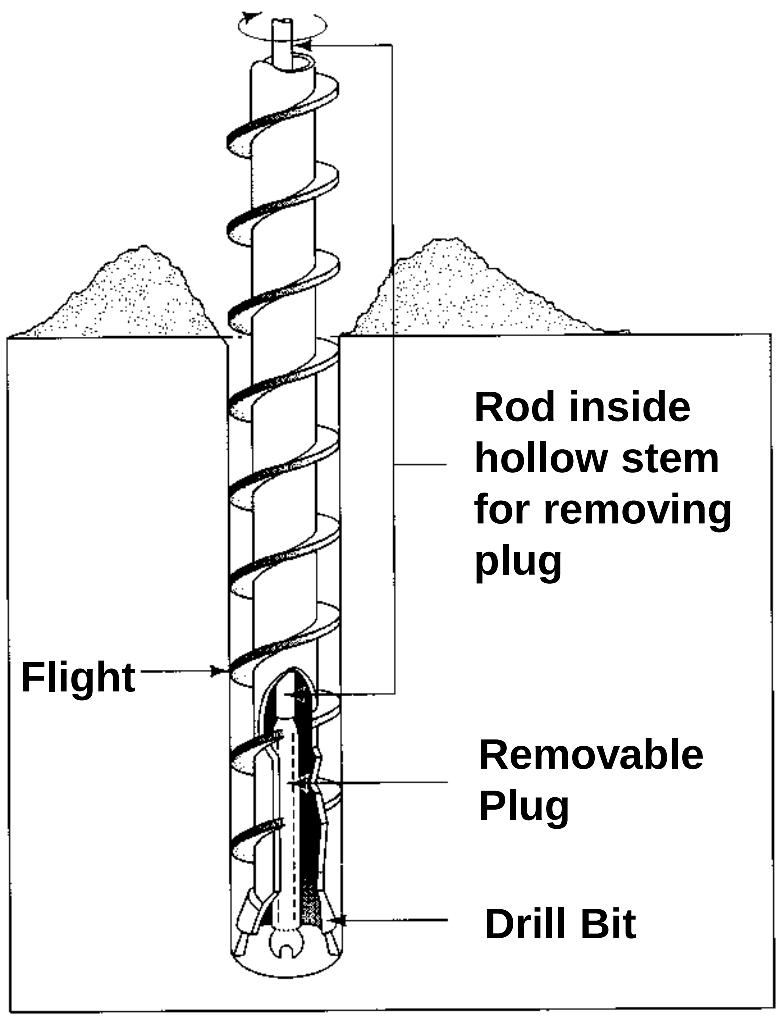
Direct Methods

- Auger Drilling
- Rotary Drilling
- Soil Excavation

DIRECT SUBSURFACE SAMPLING

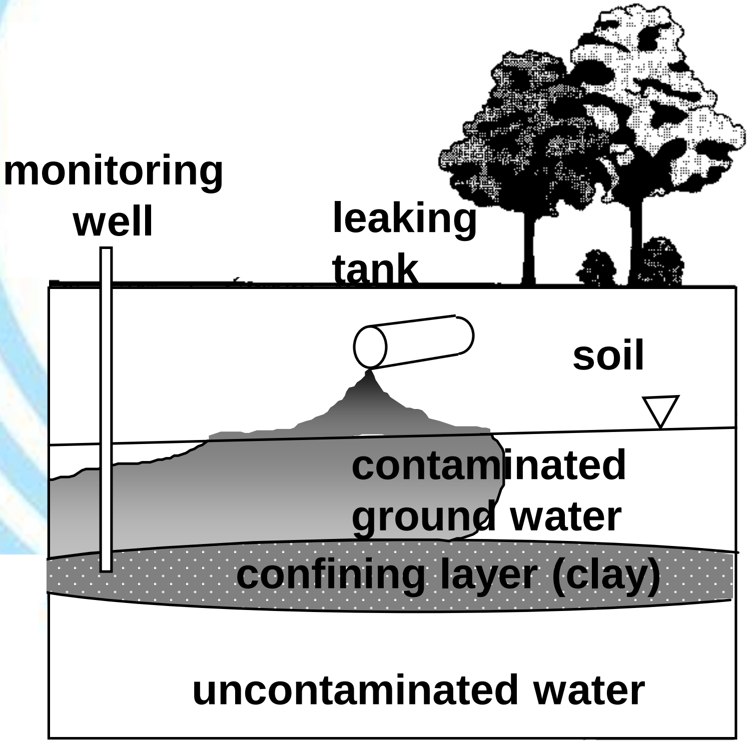
Auger Drilling

- Useful in unconsolidated geologic materials.
- Sample collection easy, intact samples can be collected with hollow-stem auger.
- Cannot be used where significant consolidated rock is present.
- Does not alter subsurface geo-chemistry.



SPECIAL CONCERNS FOR DIRECT SUBSURFACE CHARACTERIZATION

Drilling through confining layers may allow the spread of contamination from one hydrologic unit to another.



SOIL CHARACTERIZATION

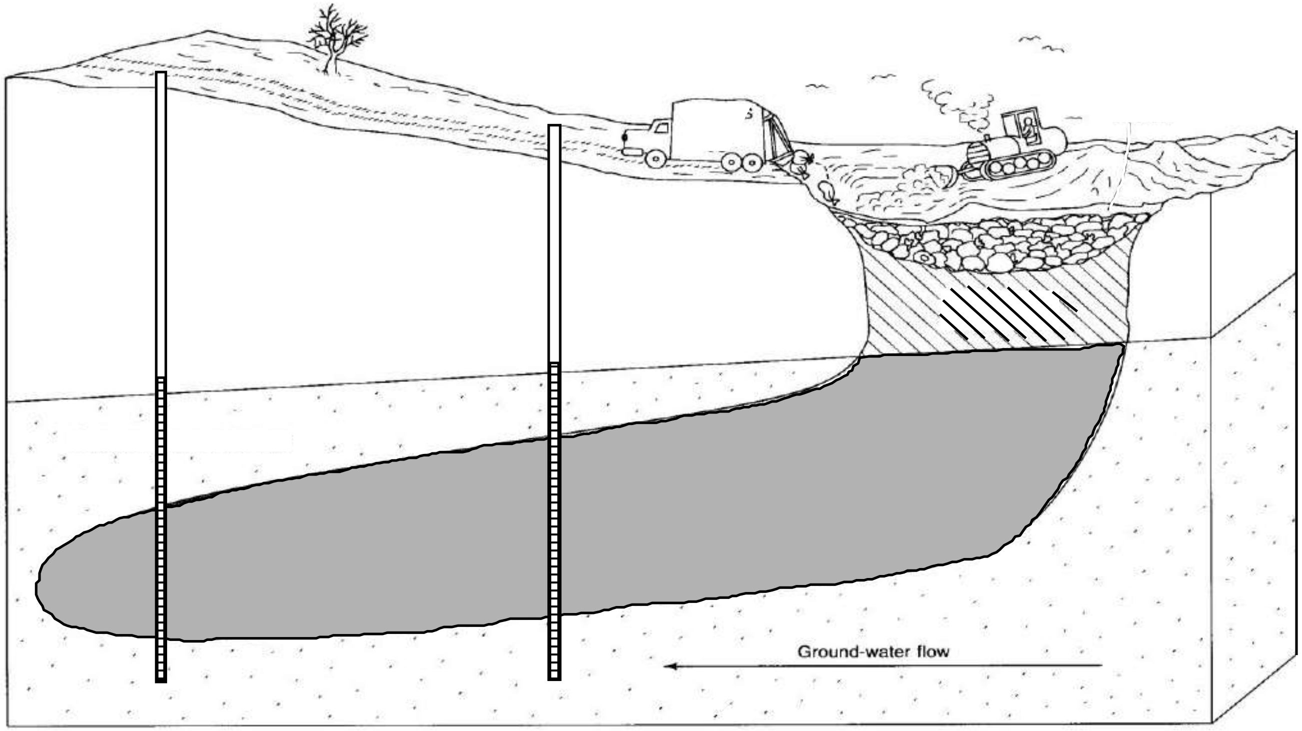
Soil Contaminant Sampling

- Performed during drilling or excavation.
- Collection of samples from several depths within the soil profile.
- Where volatile compounds are present, sampling should be done in air-tight glass containers. No headspace should be left in the containers.
- Samples should be chilled for transportation to the laboratory.

GROUNDWATER CHARACTERIZATION

Extent of Contamination:

Successive wells should be drilled until the extent of the groundwater contaminant plume is defined.



DEVELOPMENT OF ALTERNATIVES

- Identify general response to actions for each objective
- Characterise media to be remediated
- Identify potential technologies
- Screen the potential technologies
- Assemble the screened technologies into alternatives

ALTERNATIVE SELECTION

1. Long term effectiveness
2. Long term reliability
3. Implementability
4. Short term effectiveness
5. Cost

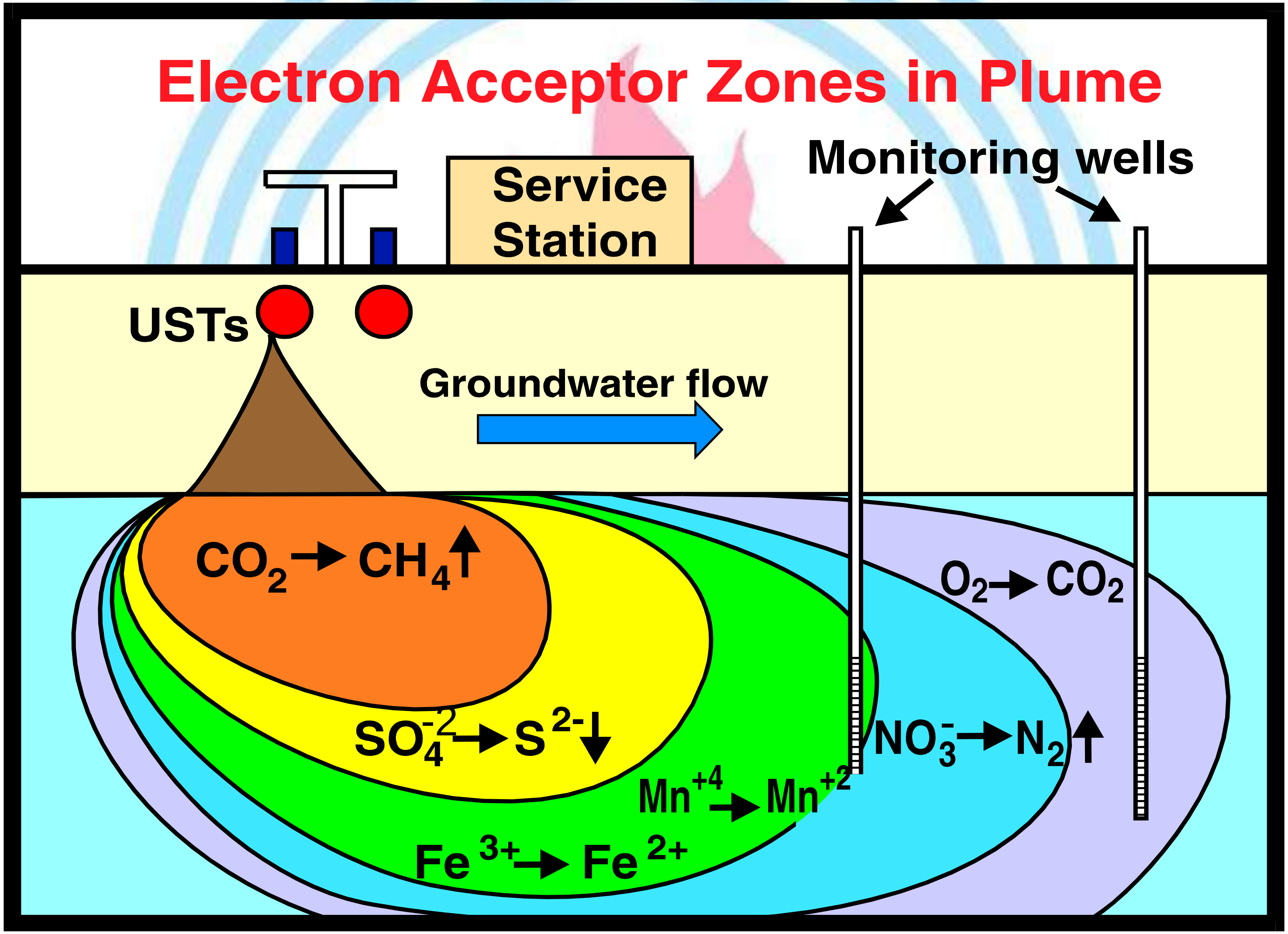
TREATMENT ALTERNATIVES

On site

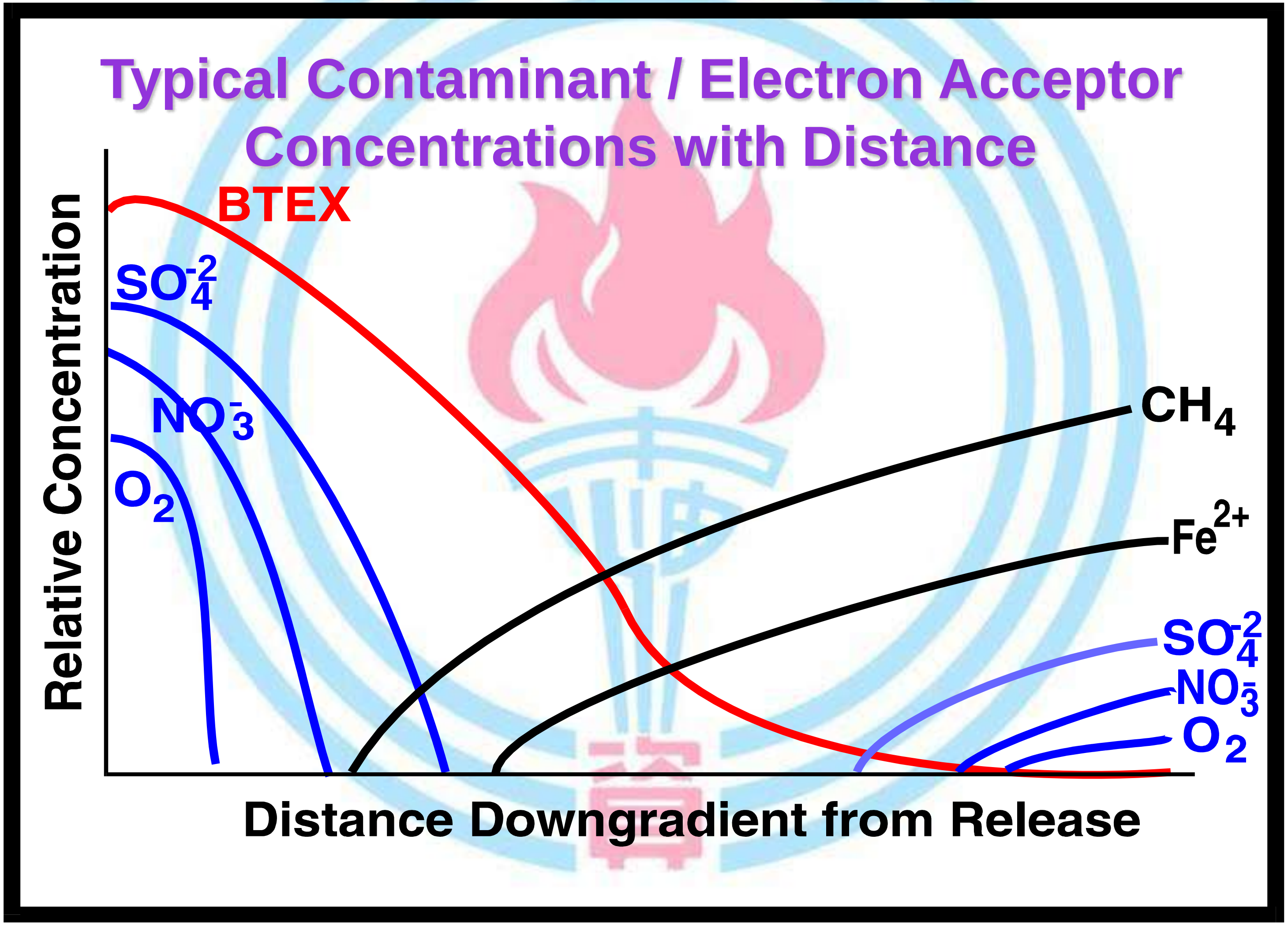
- In situ
- Ex situ (Excavation)

Off site (Excavation & Transportation)

In-Situ Biodegradation - Natural Attenuation

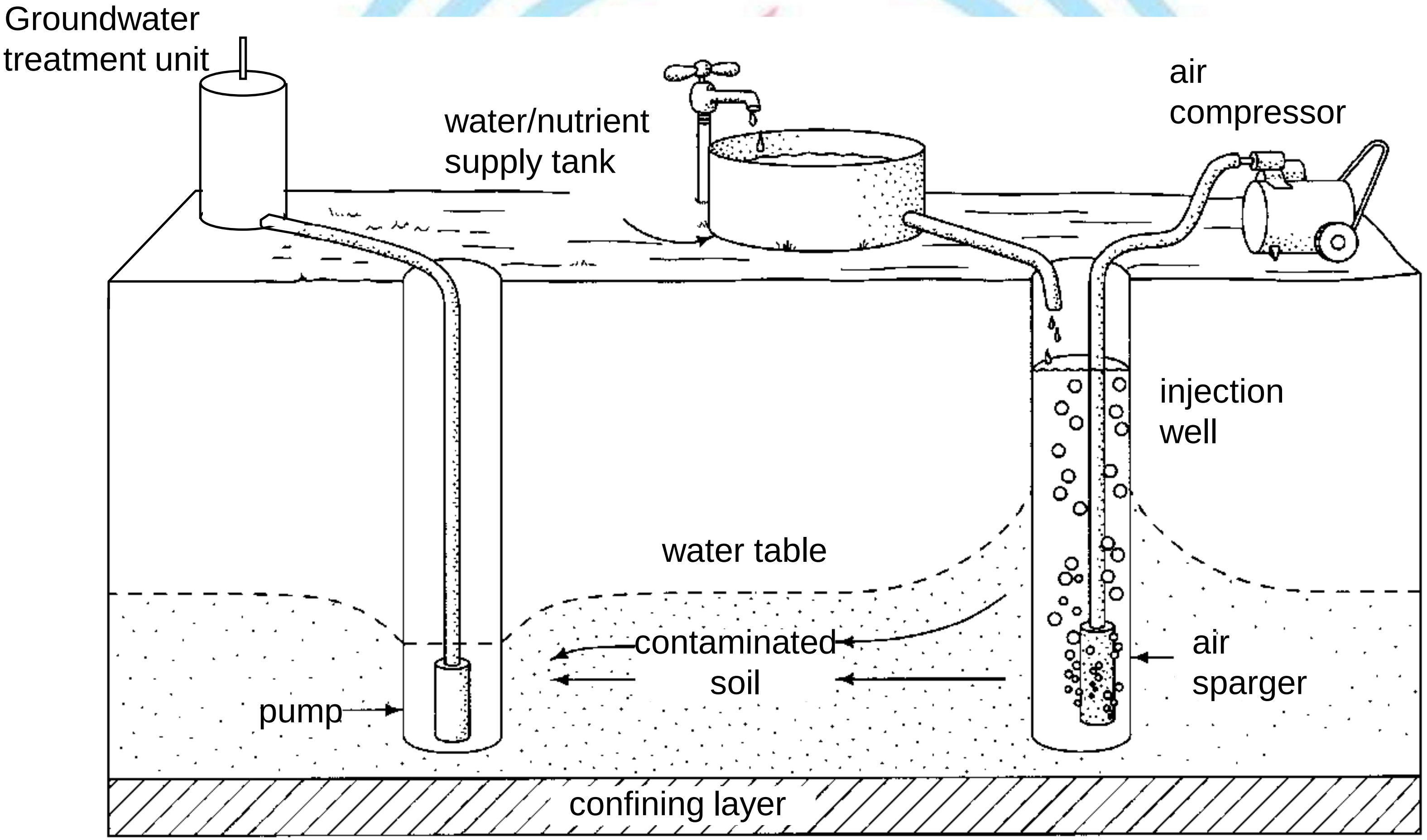


Natural Attenuation of Contaminants



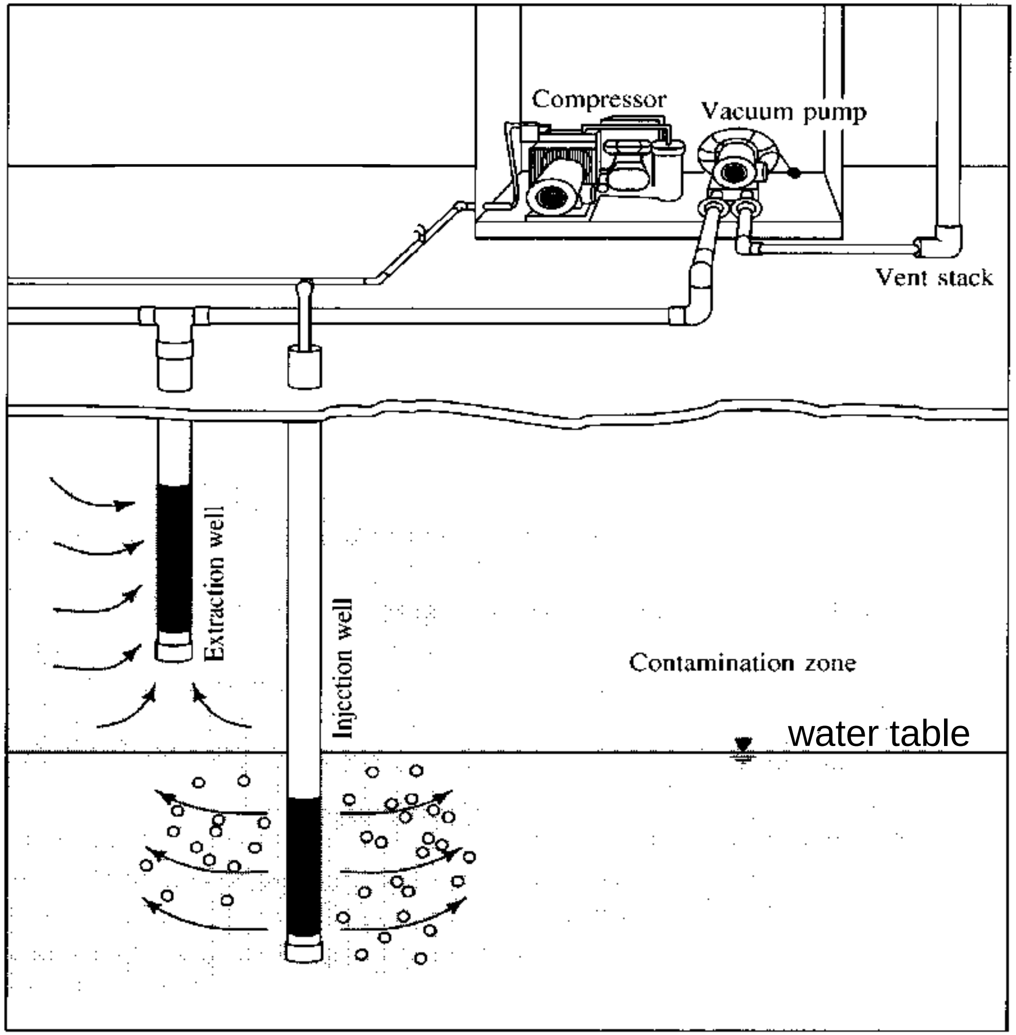
In-Situ Biodegradation - Engineered Systems

Air-sparging/nutrient addition system

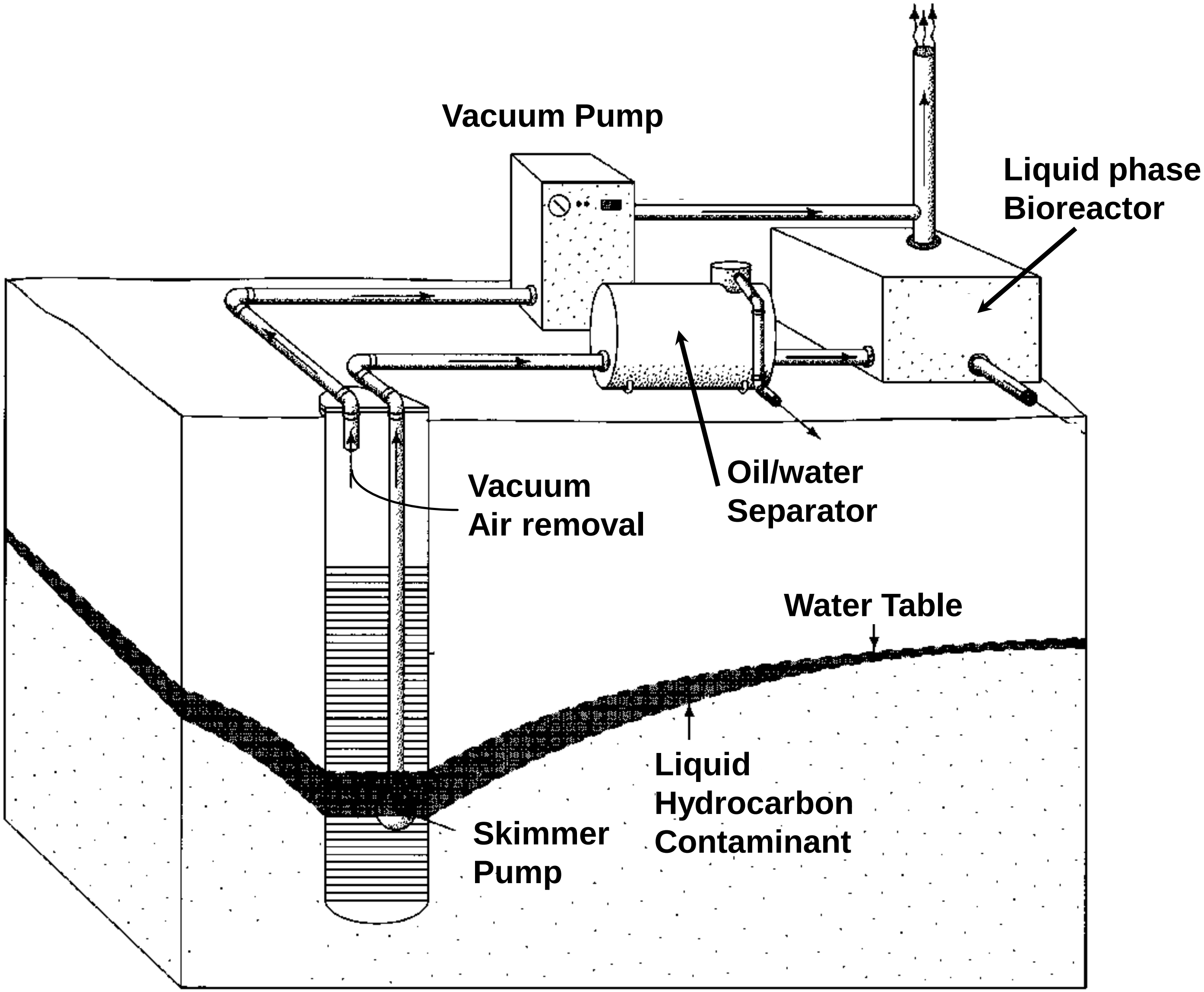


In-Situ Biodegradation - Engineered Systems

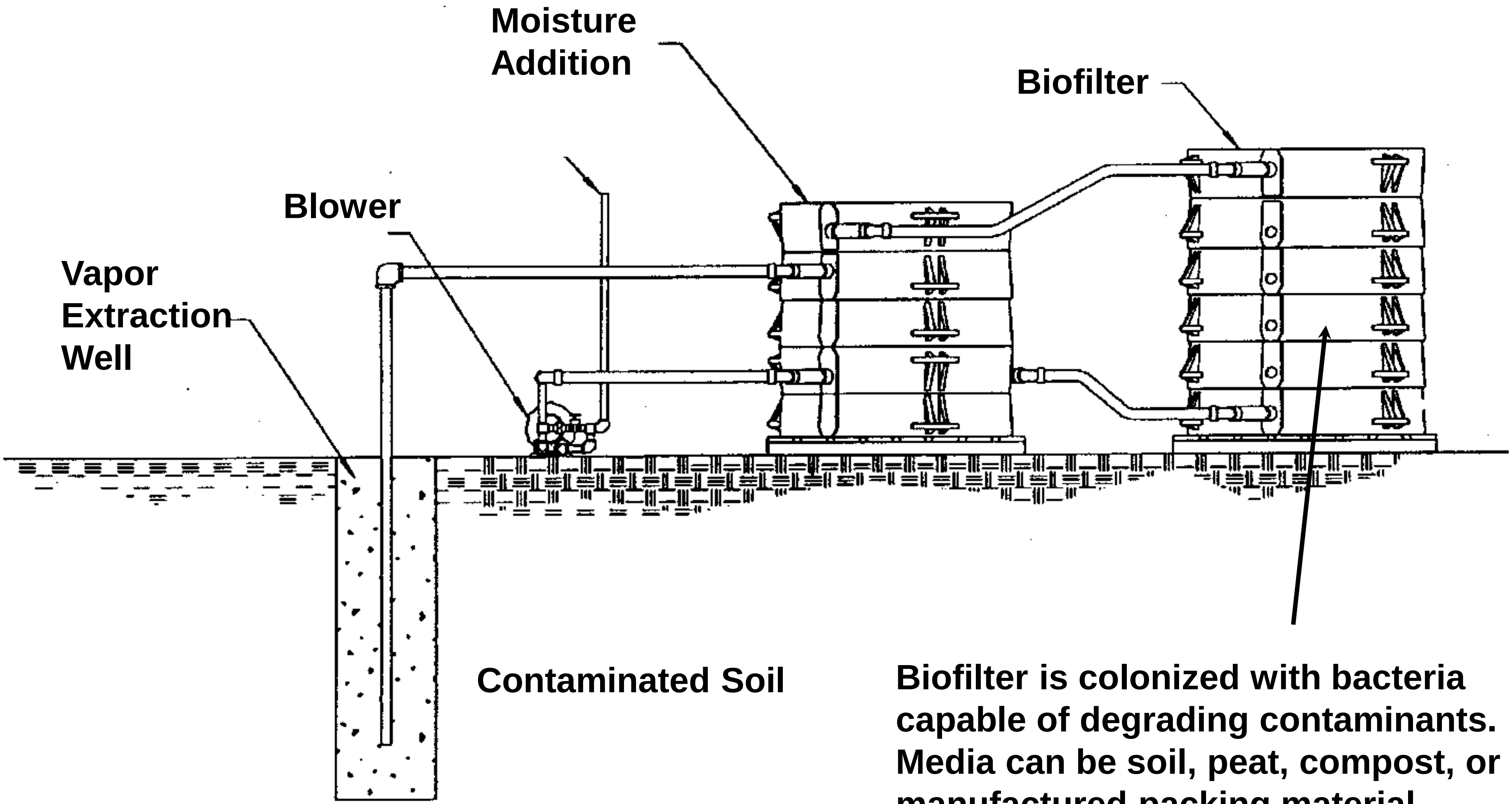
Combination air injection/extraction system



Ex-Situ Biodegradation - Pump and treat

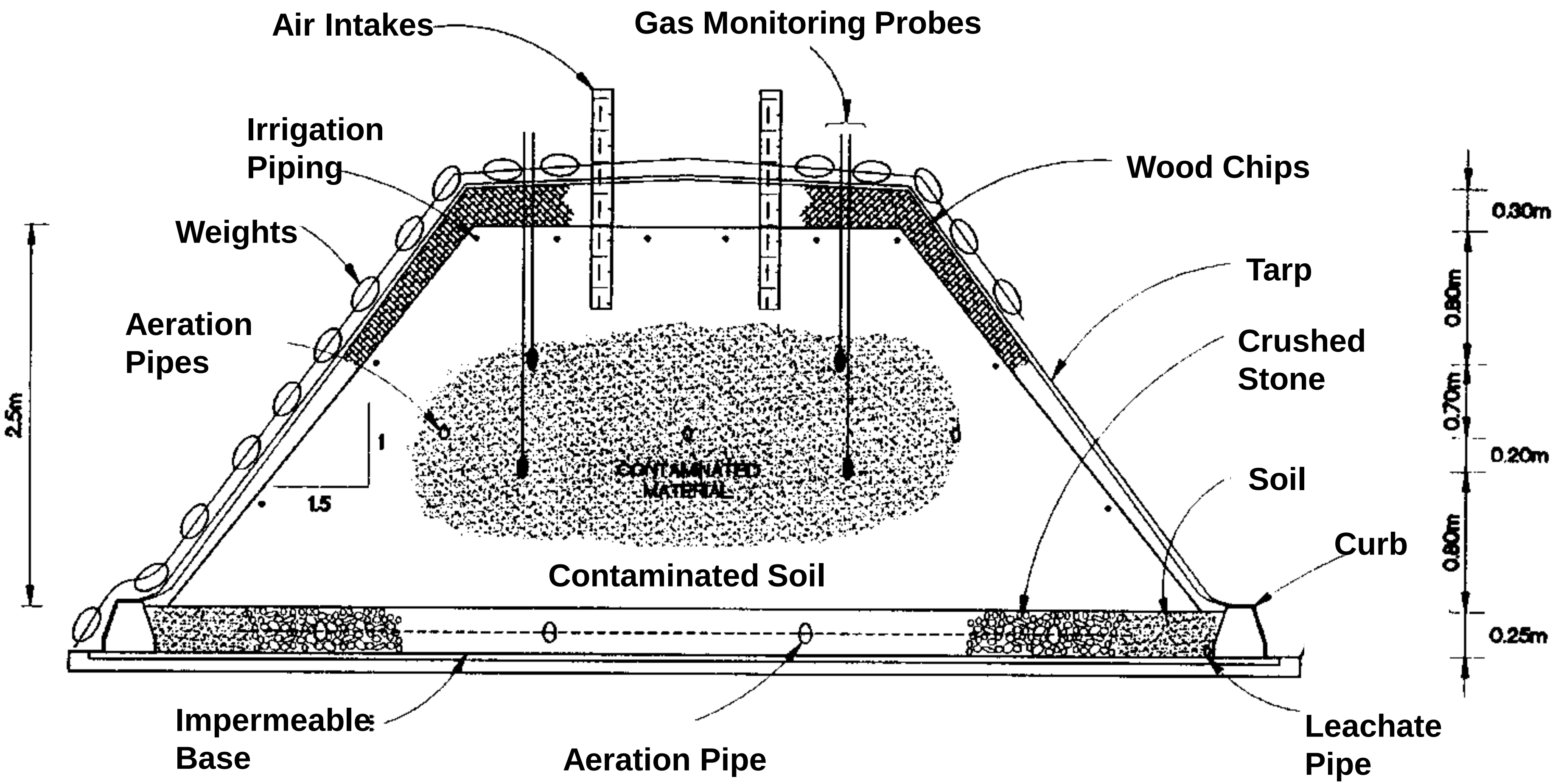


Ex-Situ Biodegradation - Biofiltration



Biofilter is colonized with bacteria capable of degrading contaminants. Media can be soil, peat, compost, or manufactured packing material.

Ex-Situ Biodegradation - Biopiles



Air Intakes

Gas Monitoring Probes

Irrigation Piping

Wood Chips

Weights

Tarp

Aeration Pipes

Crushed Stone

Soil

Curb

Contaminated Soil

Impermeable Base

Aeration Pipe

Leachate Pipe

Ex-Situ Biodegradation - Landfarming

Procedures:

- Excavated soils are spread onto the ground surface to a depth of less than 0.5 meters.
- Underlying soils should be low permeability, or a clay liner or impermeable membrane should be used to prevent contaminant migration to groundwater.
- Landfarmed soils should be tilled every 2-3 months and kept moist.

Gasoline Station Bioremediation

The gas station at Phillip and Columbia Street was sold to a new company and any soil and groundwater contamination of the site due to its previous operation by Sunoco had to be removed.

The old gasoline tanks were removed and holes bored to detect gasoline and then a deeper excavation was done to the groundwater level to check for this contamination

The water surface showed visible signs of oil contamination.

The soil that was contaminated was excavated and removed to a secure landfill site

To remove, or at least reduce, the contamination of the groundwater below the soil, holes were drilled and pipes were installed around the edge of the contaminated zone

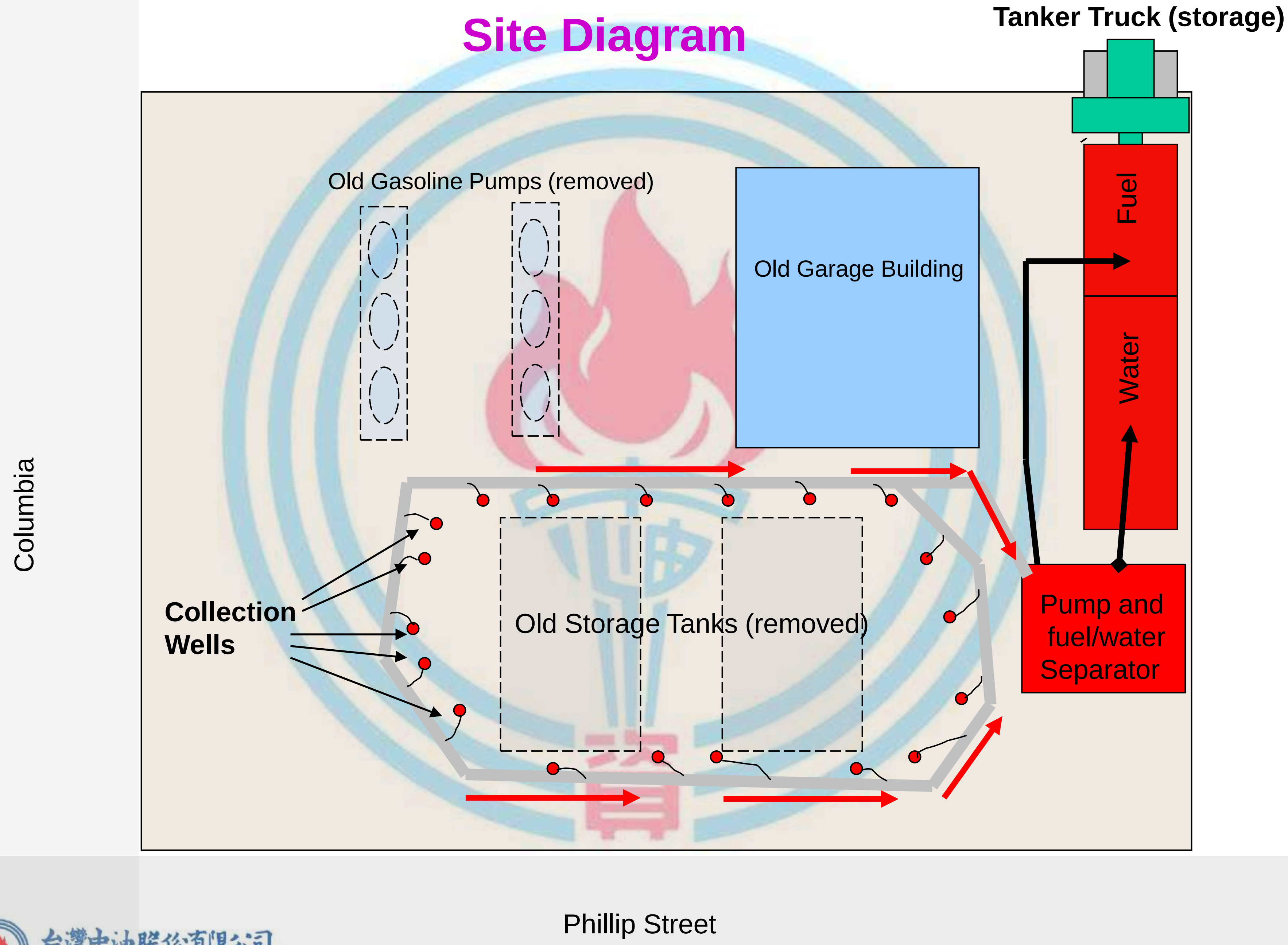
These pipes had perforated sections spanning the soil and groundwater regions and going a few feet below the water table

The larger pipes surrounded the contaminated areas and were all then joined to the vacuum pumping systems

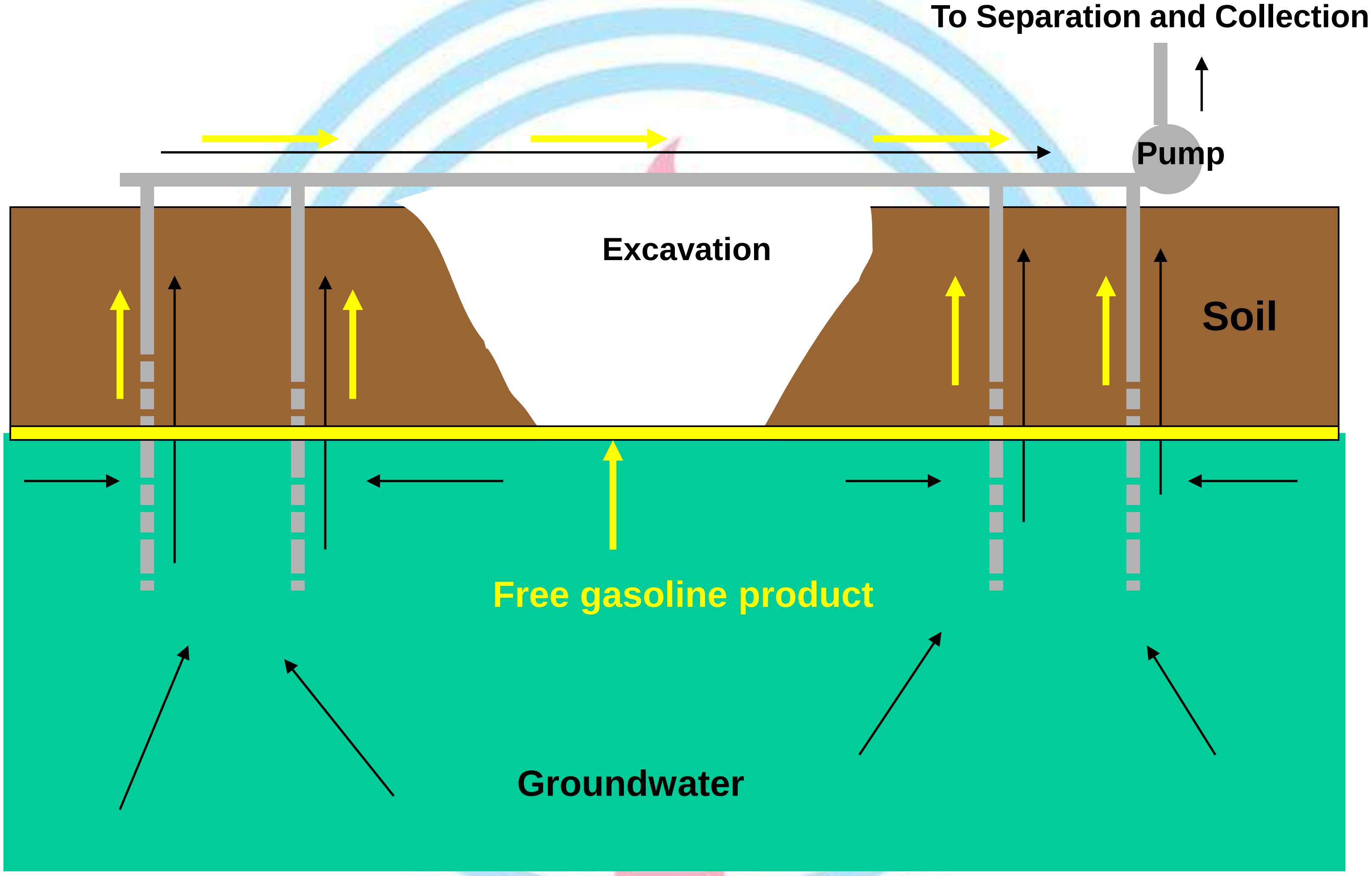
Gasoline removal

The pipes were joined together at the surface and pumps were attached to these pipes.
The pumping systems pumped a mixture of groundwater, pure gasoline product floating on the surface of the groundwater and soluble products from gasoline that had entered the groundwater. These soluble products would have included benzene, ethylbenzene, toluene and xylenes.
The mixture of gasoline, soluble products from gasoline products and water was pumped into a tanker truck on the property and disposed of after separation into the two phases of water and gasoline. The water would have contained the water-soluble components.

Site Diagram



Cross Sectional Diagram



Cross Sectional Diagram of excavation and wells

Final Operations

- Pumping continued for some months until most of the free product and soluble components had been removed from the immediate vicinity of the site. Pumping also ensured that no more migration of the soluble components in the groundwater could occur. A negative gradient was established during pumping so that surrounding contaminated water flowed into the site and not away from it.

- Pumping would have to have been continued for many years if ALL of the soluble components in the groundwater needed removal through this “pump & treat” methodology.

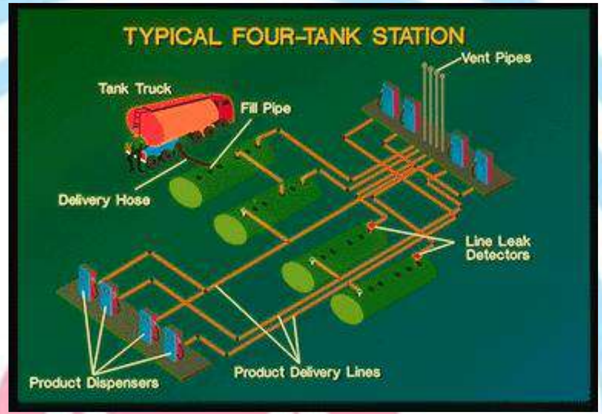
- The residual soluble components were assumed to have been remediated through biological mechanisms in the groundwater.

- In this particular case, bioremediation was used as a final cleanup operation, but the bulk of the materials were removed via the pump and treat method. This is often referred to as “polishing” – that is, removal of the residual, low levels of soluble components through bioremediation activities performed by indigenous microorganisms

End

Petroleum Contaminated Sites

- **Service Stations**
- **Tank Farms**
- **Oil Spill Sites**



Petroleum Contaminated Soil

(Soil and Groundwater Pollution Remediation Act)

土壤管制項目及管制標準

Clean-up Standards for Petroleum Contaminated Soil Remediation

管制標準項目/Item	單位Unit(毫克/公斤mg/kg)
苯（Benzene）	**5**
甲苯（Toluene）	**500**
乙苯（Ethyl benzene）	**250**
二甲苯（Xylene）	**500**
總石油碳氫化合物(TPH)	**1000**

Events of Oil Spill, Leakage

加油站地下儲槽及管線系統洩漏

UST leakage at M. L. Service Station

May 2000, 200立方米(m^3) Soil Excavation

Events of Oil Spill, Leakage

加油站地下儲槽及管線系統洩漏

UST leakage at L. C. Service Station

Aug. 2000, 5197立方米(m^3) Soil Excavation

地下輸油管線系統洩漏

Underground Pipeline Oil Spill at K. M. Island

Oct. 2002, 2570立方米(m^3) Petroleum Contaminated Soil

地下輸油管線系統洩漏

Underground Pipeline Oil Spill at Tainan

Apr. 2003, 7500立方米(m^3) Soil Excavation

地下輸油管線系統洩漏
Underground Pipeline Oil Spill at Tainan

Apr. 2003, 7500立方米(m^3) Soil Excavation

Remediation Strategy/Technologies for Petroleum Contaminated Soil Treatment

現地復育 In-situ Remediation

離場復育 Ex-situ Remediation

生物復育法 Bioremediation (Landfarming, Biopile) ---(A)

植物復育法 Phytoremediation ---------------------------------(B)

自然衰減法 N. A. ---(C)

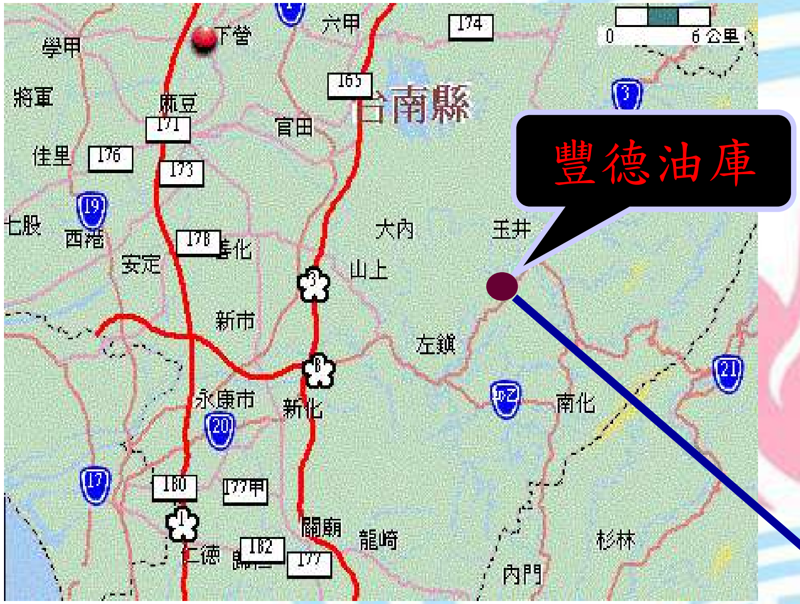
生物復育法 + 植物復育法 (A + B)

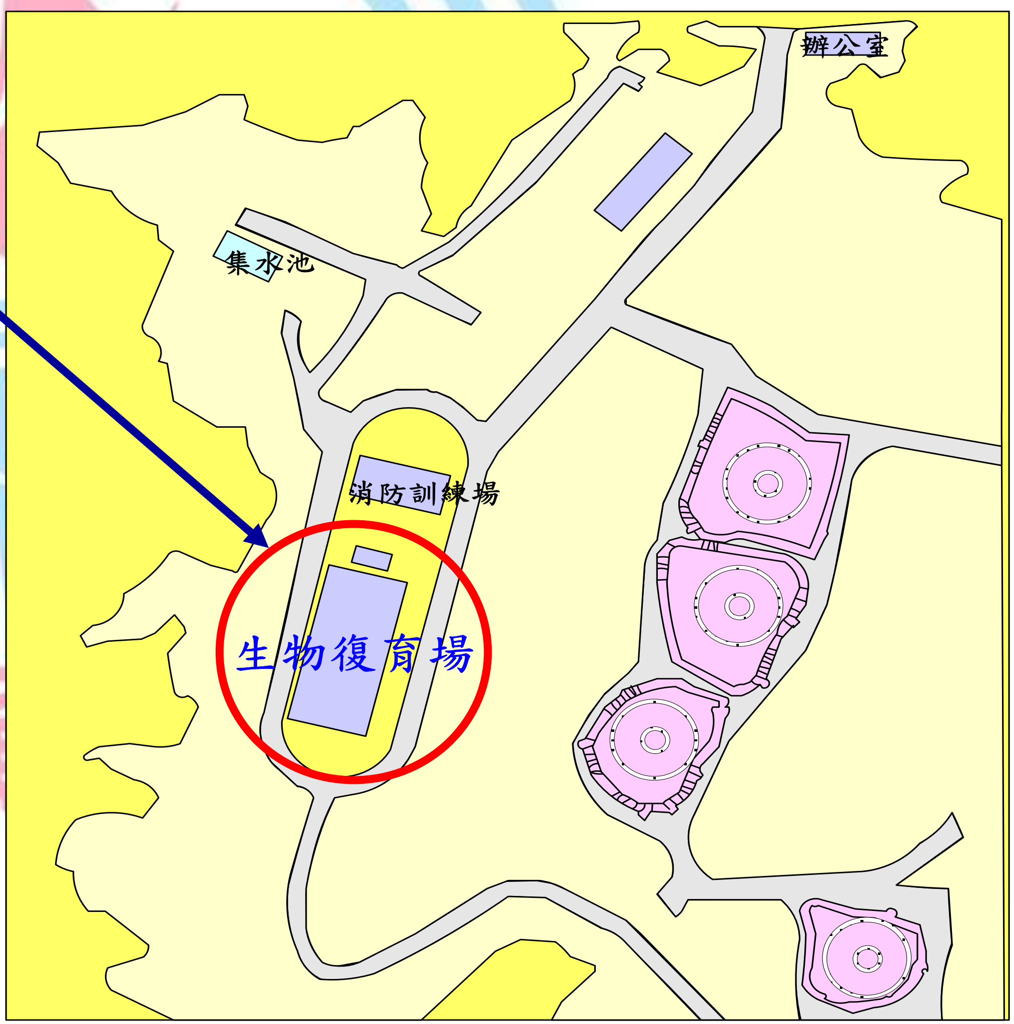
生物復育法 + 植物復育法 + 自然衰減法 (A + B + C)

Factors influencing biodegradation of hydrocarbons in soil:

- Contaminant type
- Bioavailability
- Toxicity
- Temperature
- Moisture, pH, nutrients and soil type

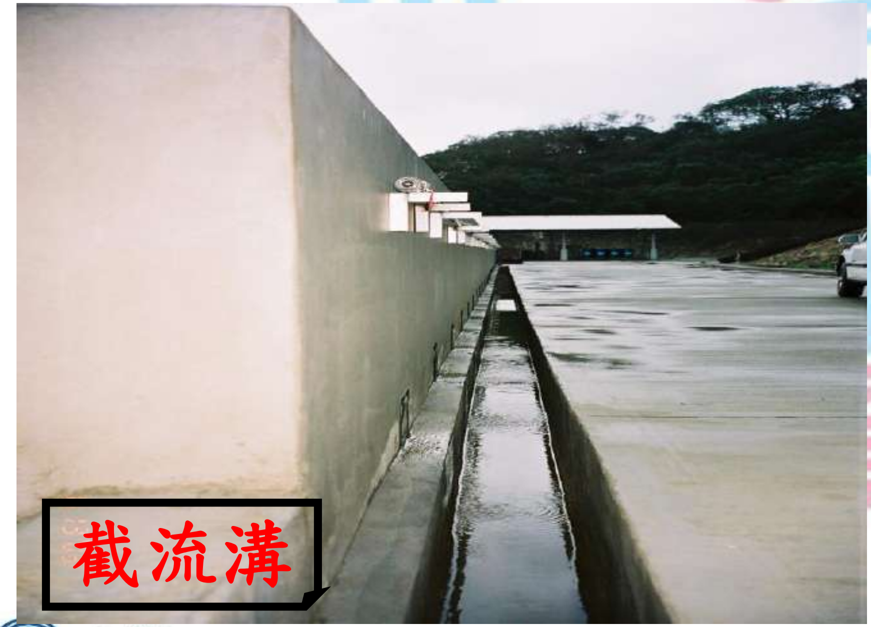
Treatment Facilities (Tainan)





Treatment Facilities (Tainan)

鼓風機



截流溝

篩選機

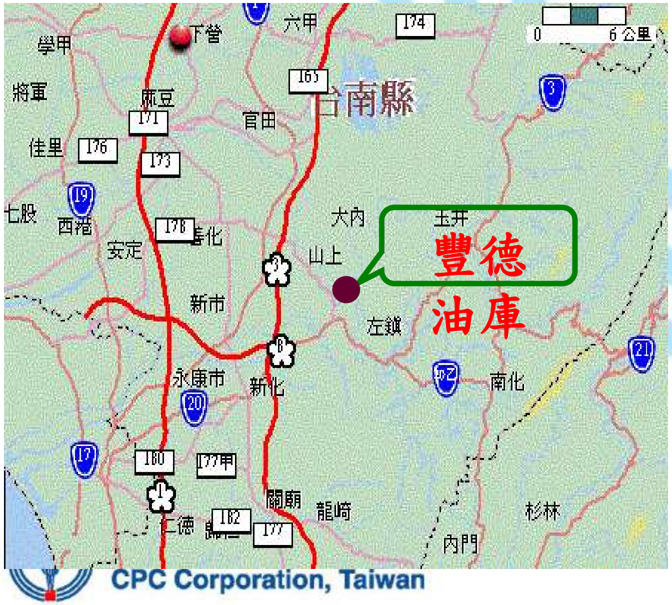
Treatment Facilities (Taichung)

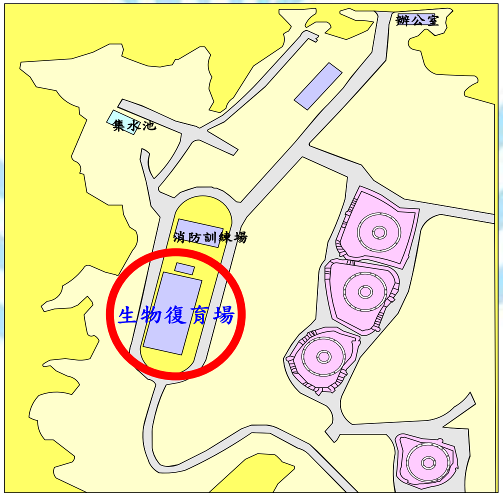
Soil：Diesel & Gasoline Contaminated Soil From A Pipeline Leakage Site Near Tainan

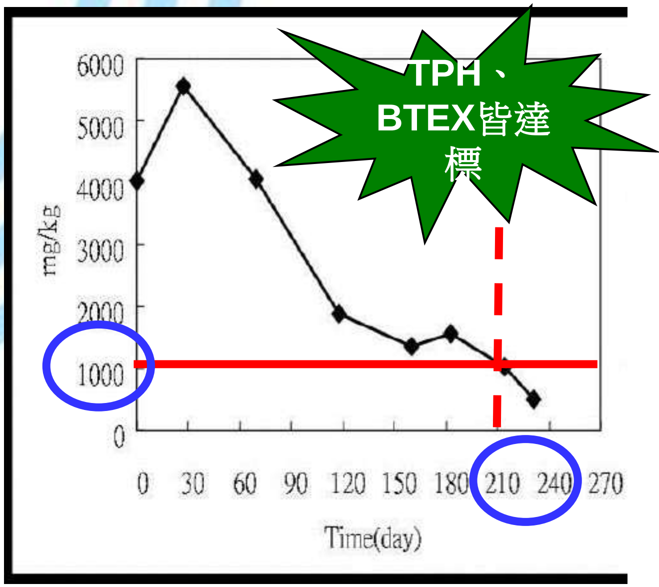
Volume: 644m^3

Method： Land farming & Biopile

Results：Soil TPH degrade from 6000 mg/kg to150mg/kg in 240 days.







Remediation Operation

Remediation Operation

Soil Remediation Project at a Tank Truck Accident Site

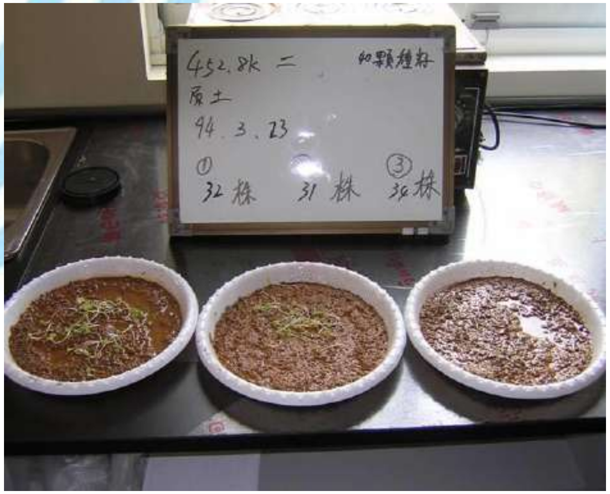
Soil：Diesel Contaminated Soil

Volume: 13 m3 (Ex-situ)

Method： Land farming

Results：Soil TPH degrade from 3000 mg/kg to 200mg/kg in 300 days.

Remediation Operation



Remediation Operation

Thank You!

簡報完畢

敬請指教