Case Study Abstract

Pump & Treat of Contaminated Groundwater at Twin Cities Army Ammunition Plant, New Brighton, Minnesota

Site Name:
Twin Cities Army Ammunition Plant (TCAAP)

Location:
New Brighton, Minnesota

Contaminants:
Chlorinated Aliphatics
- Contaminants of greatest concern in the groundwater are: 1,1-DCE, 1,1-DCA, 1,2-DCE, chloroform, 1,1,1-TCA, TCE, and PCE
- TCE is the most prevalent VOC on site, with concentrations greater than 10,000 ppb in groundwater

Period of Operation:
Status: Ongoing
Report covers - 10/87 to 9/92

Cleanup Type:
Full-scale cleanup (interim results)

Vendor:
Not Available

Technology:
Groundwater Extraction followed by Air Stripping
- 12 boundary recovery wells and 5 source area recovery wells
- Air stripping plant designed to treat 2,900 gal/min; 4 towers - 2 @ 7 feet diameter and 2 @ 8 feet diameter; all 36 feet tall with propylene packing
- Treated water discharged to a sand and gravel pit, or, alternately to an elevated tank
- Designed for an operating life of 30 years

Cleanup Authority:
CERCLA
- ROD Date: 10/88

SIC Code:
9711 (National Security)

Point of Contact:
Remedial Project Manager
Twin Cities Army Ammunition Plant
New Brighton, MN

Waste Source:
Other: Variety of Waste Disposal Practices, including Discharges to Sewer, Dumping, and Burning

Type/Quantity of Media Treated:
Groundwater
- Over 1.4 billion gallons of water pumped from 10/91 to 9/92
- Complex hydrogeology and heterogeneities in a multilayer aquifer system
- Fractured bedrock and discontinuous sand, clay, and till layers
- Hydraulic conductivity 0.001 to 137 ft/day; transmissivity 3,160 to 28,724 ft^2/day

Purpose/Significance of Application:
Pump and treat of large-volume of groundwater contaminated with VOCs.

Regulatory Requirements/Cleanup Goals:
- Several RODs apply to overall TCAAP remedial program, including a ROD for groundwater remediation
- Target cleanup criteria focus on residual levels of contamination in groundwater and containment of existing plume
- Target cleanup levels in groundwater include: TCE - 5 ppb; PCE - 6.9 ppb; 1,2-DCE - 70 ppb; and 1,1,1-TCA - 200 ppb

Case Study Abstract

Pump & Treat of Contaminated Groundwater at Twin Cities Army Ammunition Plant, New Brighton, Minnesota (Continued)

Results:
- Boundary Groundwater Recovery System (BGRS) recovered an average of 23 pounds of VOCs per day
- TCAAP Groundwater Recovery System (TGRS) recovered 19,510 pounds of VOCs in one year of operation
- Historical total of 92,700 pounds of VOCs recovered in 6 years of operation (BGRS and TGRS)
- Plume containment successful at site
- VOC plumes changed little after several years of treatment; estimate of remediation time increased to achieve a concentration of 17 ppb TCE in 50 to 70 years

Cost Factors:
- Capital costs - $8,034,454 (including construction of treatment plant, wells, force main and pump houses, startup, engineering, and project management)
- Annual operating costs - $588,599 (including power, labor, maintenance, laboratory charges, and replacement of tower packing)
- Total Life Cycle Costing estimated as $0.30 per 1,000 gallons of water treated
- Total cost of operation and maintenance calculated as $0.12 per 1,000 gallons of water treated

Description:

The Twin Cities Army Ammunition Plant, established in 1941, has been used for the production and storage of munitions. The site includes 7 major production buildings and over 300 auxiliary buildings. A series of hydrogeological investigations beginning in 1981 revealed elevated levels of VOCs in groundwater; 14 separate source areas have been identified at the site. Trichloroethene (TCE) has been measured at concentrations over 10,000 ppb in the groundwater. Target groundwater cleanup levels were established for four constituents - TCE, PCE, 1,2-DCE, and 1,1,1-TCA.

Groundwater extraction followed by air stripping has been used at this site since October 1987 to treat contaminated groundwater. The groundwater extraction system includes 12 boundary recovery wells and 5 source area recovery wells. Extracted groundwater is treated using four 36-feet tall air stripping towers. An estimated 92,700 pounds of VOCs have been recovered in 6 years of system operation. Although plume containment has been successful at the site, the plumes have changed little after several years of treatment.

An estimate of the time required for remediation has been revised from 30 years to 50 to 70 years, based on a review of data collected to date. Capital costs for this application were $8,034,454, and annual operating costs are $588,599.

TECHNOLOGY APPLICATION ANALYSIS

SITE

Twin Cities Army Ammunition Plant (TCAAP)
A CERCLA Site
New Brighton, Minnesota

TECHNOLOGY APPLICATION

This analysis covers an effort to **pump and treat groundwater** contaminated with volatile organic compounds (**VOCs**) by above ground **air stripping.** The treatment began in October 1987 and is currently ongoing. This analysis covers performance through September 1992.

SITE CHARACTERISTICS

Site History/Release Characteristics

- TCAAP is an approximately 4 square mile facility established in 1941 which primarily produced and stored munitions during the periods of 1941 to 1957 and 1966 to 1976. The site includes 7 major production buildings and over 300 auxiliary buildings. Most of the site is now in caretaker status, however, current lessees manufacture ammunition and other products.
- A series of hydrogeological investigations which began in 1981 revealed elevated levels of VOCs in groundwater. Fourteen separate source areas have been the focus of detailed site characterization and various remediation efforts.
- Contamination resulted from a variety of past waste disposal practices such as sewer disposal, dumping and burning which released process wastes, oil and grease, heavy metals and solvents to the environment.
- In October 1987 a Boundary Groundwater Recovery System (BGRS) started operation. An expanded system, the TCAAP Groundwater Recovery System (TGRS), began operation in January 1989. Additional smaller scale groundwater remediation efforts were implemented at the plant. Remedial actions were also conducted outside of the plant boundaries. This analysis will focus upon the performance of the BGRS and TGRS up through September 1992.

Contaminants of Concern

Contaminants of greatest concern in the groundwater are:

1,1-dichloroethylene
1,1-dichloroethane
cis-1,2-dichloroethylene (1,2-DCE)
chloroform
1,1,1-trichloroethane (1,1,1-TCE)
trichloroethylene (TRCLE)
tetrachloroethylene (TCLEE)

TRCLE, the most prevalent VOC on site, is the target compound used to measure system performance.

Contaminant Properties

Properties of contaminants focused upon during remediation are:

Property at STP*	Units	TRCLE	TCLEE	12DCE	1,1,1-TCE
Empirical Formula	-	$ClCH=CCl_2$	$Cl_2C=CCl_2$	CHCl=CHCl	CH_3CCl_3
Density	g/cm^3	1.46	1.62	-	1.31
Vapor Pressure	mmHg	73	19	208	124
Henry's Law Constant	$atm\cdot m^3/mole$	9.9E-3	2.9E-3	-	1.6E-2
Water Solubility	mg/L	1000-1470	150-485	3500	300-1334
Octanol-Water Partition Coefficient: K_{ow}	-	195	126	5	148
Organic Carbon Partition Coefficient: K_{oc}	-	66	209	-	105

**STP = Standard Temperature and Pressure; 1 atm, 25 °C*

Nature & Extent of Contamination

- Characterization of the nature and extent of contamination at TCAAP slowly evolved over several years of monitoring and treatment. In the mid 1980s it was known that a plume beneath the site had TRCLE concentrations as high as 3600 ppb (later analyses revealed levels over 10,000 ppb) as well as 1,2-DCE and 1,1,1-TCE levels of 160 and 950 ppb respectively. After installation of the BGRS, TGRS and associated monitoring wells more detailed plume delineation became possible.
- A plume extends over six miles downgradient (southwest) of the site; no contamination has been detected immediately upgradient of the site.
- Contaminants have been found to be fairly mobile in most geologic strata.

Contaminant Locations and Geologic Profiles

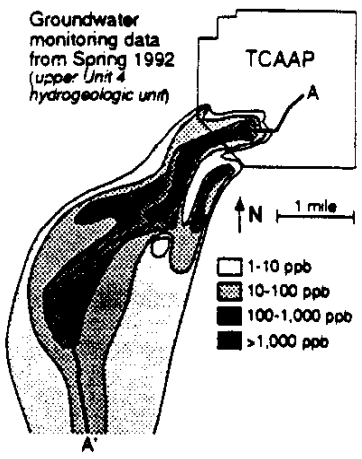
Remedial investigation field activities at the site have included:

- soil gas surveys
- surface soil sampling
- soil trenching and sampling
- soil boring installation and sampling
- groundwater well installation and sampling
- geophysical investigations (electromagnetic induction and ground penetrating radar)

Data from hundreds of soil borings and groundwater monitoring wells has allowed the development of numerous two-dimensional contour diagrams illustrating the upper and lower surface areas, groundwater elevations, and contaminant concentration profiles for various geologic units. Portions of some of these diagrams have been included here to provide a general conceptual understanding of site conditions.

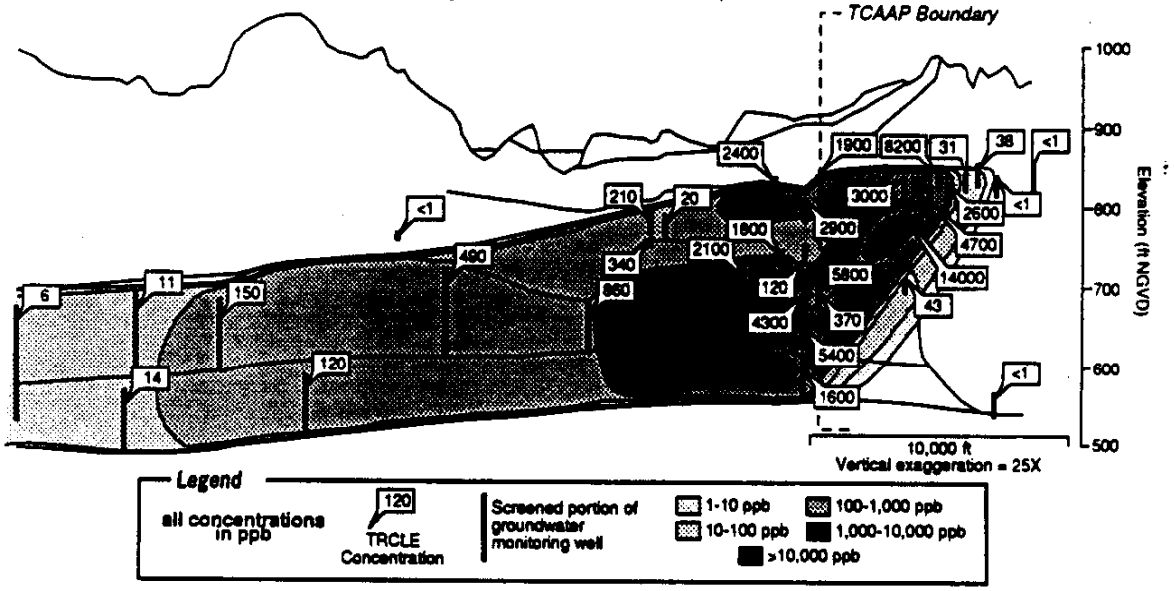
Recent (1992) data is used in these diagrams. Earlier plume delineation efforts were based upon less complete data sets. It is currently assumed that the plume outline has not changed significantly over the past several years.

TRCLE Plume (Unit 4 Top View)



TRCLE Plume (Side View)

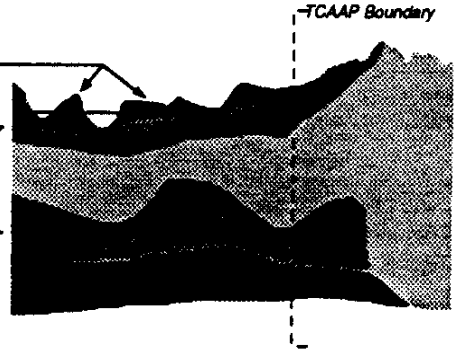
Groundwater monitoring data from Spring 1992 along cross-section A-A' shown in top view



Hydrogeologic Units

Four distinct hydrogeologic units have been identified beneath TCAAP and the surrounding regions:

Unit 1	New Brighton & Fridley Formations	Discontinuous recent alluvium and lacustrine deposits; discontinuous local water table aquifer; 0-50 ft thick
Unit 2	Twin Cities Formation	Discontinuous glacial till; acts as aquitard with some water bearing sand and gravel lenses; 0-150 ft thick
Unit 3	Hillside Sand	Overlain by Arsenal sand which forms kame in center of TCAAP; aquifer arbitrarily subdivided into upper middle and lower parts for monitoring; 25-450 ft thick
Unit 4	Prairie du Chien & Jordan Sandstone	Dolomite bedrock aquifer; 0-250 ft thick Sandstone bedrock aquifer; 0-100 ft thick



Site Conditions

- Surrounding region characterized by a continental climate with average yearly temperature of 44°F, rainfall of 25 inches, and snowfall of 40 inches.
- Topography at TCAAP ranges from 880 ft MSL at Rice Creek on the western edge to 1,000 ft MSL at the kame in the center of the site.
- Groundwater flow is generally to the west and southwest.
- The site possesses a complex hydrogeology arising from heterogeneities in the multilayer aquifer system, fractured bedrock, and discontinuous sand, clay and till layers.

Key Aquifer Characteristics

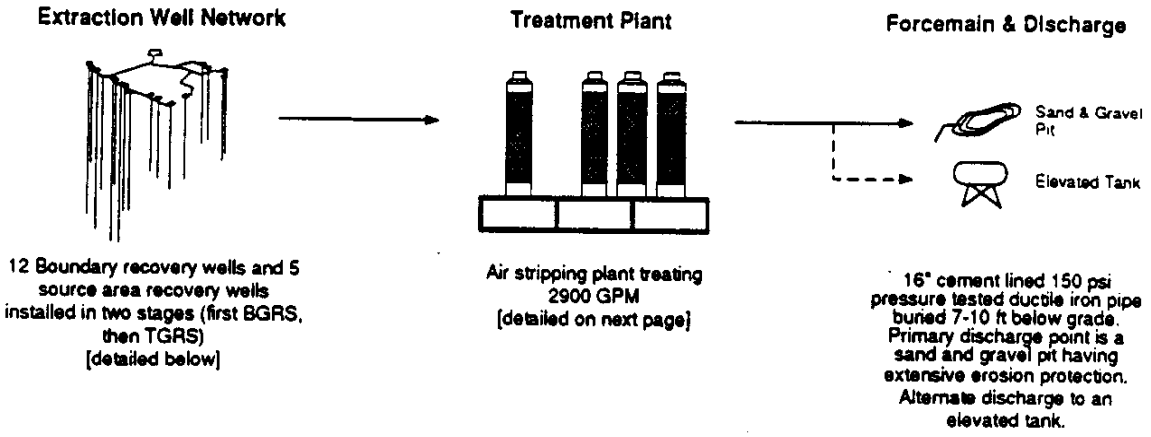
Aquifer parameters along the southwest TCAAP boundary have been estimated as:

Unit		Approximate Thickness [ft]	Hydraulic Conductivity [ft/day]	Transmissivity [ft^2/day]	Flow Direction
Unit 1	New Brighton and Fridley Formations	10	0.007-22	-	Recent alluvium. Reflects surface topography
Unit 2	Twin Cities Formation	63	0.001-0.01	-	Low conductivity aquitard; groundwater moves slowly downward to Unit 3
Unit 3	Hillside Sand	156	137	21,424	Generally horizontal and directed southwest and west; vertical gradient is downward and is <0.005
Unit 4	Prairie du Chien	37	85	3,160	Generally horizontal and directed southwest and west
Unit 4	Jordan Sandstone	90	46	4,140	Generally horizontal and directed southwest and west
Bulk Flow for Units 3 and 4		283	-	28,724	

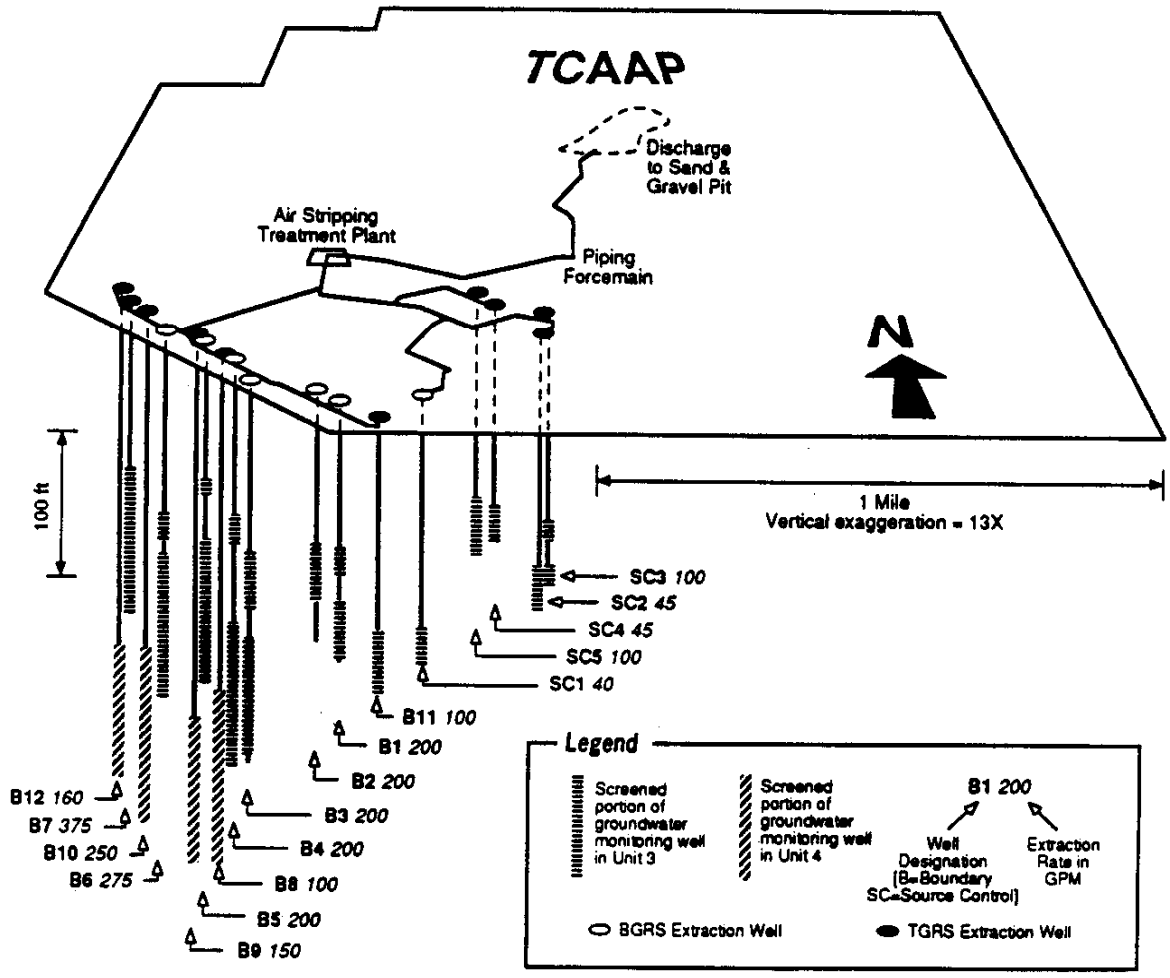
- A wide range of values has been used to describe regional aquifer characteristics. Uncertainties stem from difficulties in aquifer testing and interpretation methods applied to the hydrogeological complexities noted above under Site Conditions.
- Groundwater along the southwest TCAAP boundary is unconfined but becomes confined to the west and north. The confining boundary may change throughout the year due to seasonal groundwater table fluctuations.

TREATMENT SYSTEM

Overall Process Schematic

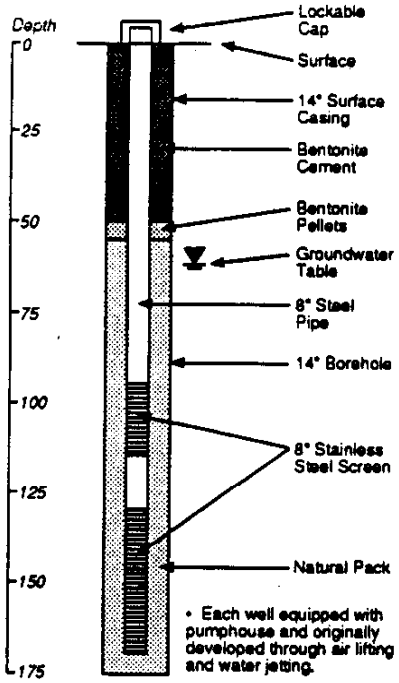


Extraction Well Network



Extraction Well Close-Up

Typical Unit 3 Extraction Well
(Well Shown is B1)



Key Design Criteria

- Operating life of 30 years (estimated remediation time).
- Handle maximum flow rates throughout system.
- Discharge to multiple points.
- Handle changes in flow rates.
- Operate with portions of system shut down.
- Minimal operating labor requirements.

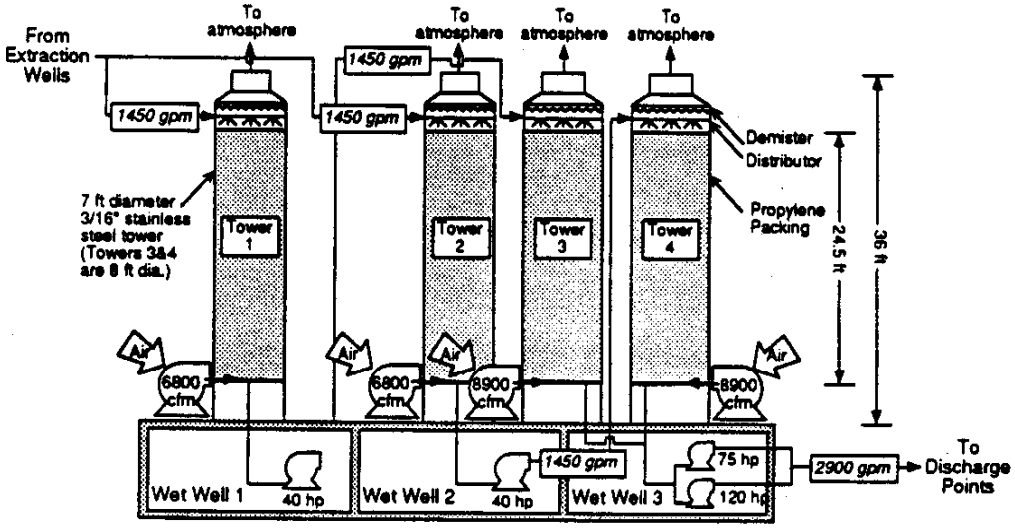
Key Monitored Operating Parameters

- Water flows
- Air flows
- Pump discharge pressures
- Automated processes

(to assess system operation)

- Groundwater levels
  (to assess zone of capture)
- Contaminant concentrations in treatment plant influent & effluent
  (to assess treatment effectiveness)
- Contaminant concentrations in groundwater
  (to assess achievement of remediation goals)

Air Stripper System Schematic



- Tower 4 was added for the TGRS arrangement. Previously, the BGRS system split 1200 gpm between Towers 1 and 2 with discharge from both going to Tower 3.
- Air compressor ratings represent minimum operating levels.
- Drawing not to scale.

PERFORMANCE

Performance Objectives

- Achieve cleanup goals including TRCLE concentrations of 5 ppb in groundwater (other criteria detailed within Regulatory/Institutional section).
- Prevent migration of contaminants off the TCAAP site.
- Design and operate treatment system such that its zone of capture contains the plume within the TCAAP boundary.

Treatment Plan

A phased approach was utilized to implement an overall TCAAP groundwater remediation program:

- Installation of BGRS
- Execution of a Performance Assessment Review (PAR) evaluating the first 90 days of BGRS operation.
- Recommendations from the PAR used to develop criteria for the TGRS.
- Installation of the TGRS.
- Further modifications to the system identified through yearly monitoring and performance assessment reports.

BGRS Startup
↓
90-Day Review
1-Year Review
↓
TGRS Startup
↓
Annual Reviews &
System Modifications

Initial Process Optimization Efforts

BRGS Performance Assessment

Conclusions drawn after 90 days of BGRS operation and confirmed by 1 year of operating experience included:

- A substantial portion of Unit 3 & 4 groundwater and VOC plumes were captured based upon observed drawdowns.
- The treatment system processed an average of 23 lbs of VOCs/day (range of 17 to 29 lbs/day).
- VOC plumes showed little variation during treatment.
- Treated effluent satisfied contaminant specific requirements established in the Record of Decision (ROD) for interim measures.
- Air emissions met ROD requirements and were not detected upwind or downwind of the BGRS.
- The TGRS expansion should include four Unit 4 and two Unit 3 boundary extraction wells and four Unit 3 source control extraction wells and corresponding increases in flow handling and treatment facility capacities.

TGRS Performance Assessment

Conclusions drawn after 1 year of TGRS operation included:

- Hydraulic capture extended beyond the 5 ppb TRCLE contour at the TCAAP boundary in both Units 3 & 4.
- The TGRS extracted and treated 19,510 lbs of VOCs.
- VOC plumes showed little variation during treatment.
- Treated effluent satisfied contaminant specific requirements established in the ROD for interim measures.

Operational Performance

Volume of Water Pumped

- From Oct 1991 through Sept 1992 over 1.4 billion gallons of water were pumped from the 17 different extraction wells; monthly flow rates ranged from 112 to 123 million gallons.
- During this period 112% more water was pumped than was previously determined to be necessary to maintain a capture zone encompassing the VOC plume.

System Downtime

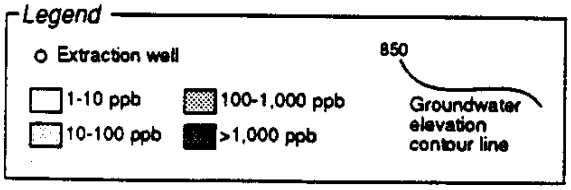
- The TGRS was operational 98% of the year ending Sept '92; this performance represented a slight improvement over '90 and '91 and a significant improvement over '89.
- A preventive maintenance program was instrumental in reducing system downtime.

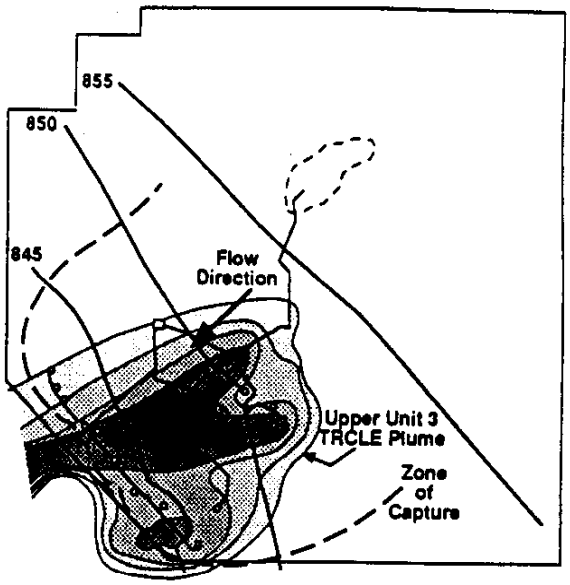
Causes of downtime 10/91 to 9/92:

Repair to pumphouse	*1.0 day*
Repair to treatment plant	*0.9*
Preventive maintenance	*0.1*
TCAAP power system failures	*4.2*
Total	*6.2 days*

Hydrodynamic Performance

- The zone of capture created by the TGRS extends beyond the 5 ppb TRCLE contour along the entire southwest TCAAP boundary. There is some ongoing debate among parties at TCAAP concerning the extent to which any part of the onsite contaminant plume may be breaking through the system of boundary extraction wells.
- The horizontal extent of capture is nearly identical throughout Units 3 & 4.
- Groundwater contours were manually constructed due to the complexities of the flow field and were based upon elevation measurements, pumping test analyses, drawdown analyses and vertical gradient analyses.





Treatment Performance

Effects on Plume

- VOC levels appear to have been reduced near source areas. Interim measures on soil may be the cause.
- Overall, VOC plumes have changed little. The plume configurations identified in 1992 are similar to those identified earlier. Original estimates of a 30 year remediation time have been revised and project achievement of 17 ppm TERCLE concentrations in 50 to 70 years.

TRCLE vs Time at Influent

- The concentration of TRCLE in groundwater extracted from each well and sent as influent to the air stripping plant:
  - has decreased over time for wells: B1, B2, B7, B10, B12, SC1, SC2 and SC3
  - has increased over time for wells: B5, SC4 and SC5
  - has shown no clear trend for wells: B3, B4, B6, B8, B9 and B11
- The trends may indicate plume redistribution and may also represent a decline in plume strength.
- There has been no clear reduction in overall contaminant concentrations sent to the treatment plant.

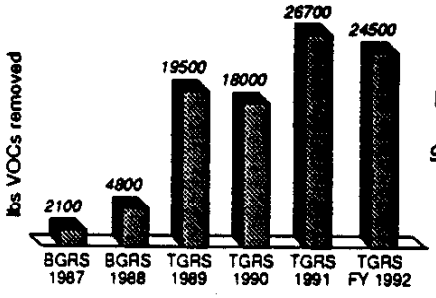
Influent vs Effluent

- Average TRCLE removal efficiency of 99.9%
- All VOCs, priority pollutants and metals treated below ROD discharge criteria.

	Influent			Effluent		
Compound	Lo	Ave	Hi	Lo	Ave	Hi
TRCLE	1200	1637	1900	bd	0.62	1.3
TCLEE	bd	bd	3	bd	bd	bd
1,2-DCE	-	-	-	bd	bd	bd
1,1,1-TCE	210	407	560	bd	bd	bd

bd = below detection

Total Pounds VOCs Removed



Historical Total: *92,700 lbs*

- Wells located near the center of the plume (B1, B4, B5, B6, SC2 and SC5) accounted for 95% of VOC mass removed.
- The five source control wells (SC1-5) removed 41% of the VOCs while pumping only 12% of the groundwater.

COST

An economic evaluation of the TCAAP air stripping facility was performed in 1990. The evaluation focused on determining (1) total capital cost, (2) operating costs and (3) significant cost elements.

In addition, the installed cost of the TCAAP facility was compared to two other groundwater air stripping facilities using total life cycle costing (TLCC) analysis based upon treatment of 1,000 gallons of water over the life of each plant. The TCAAP facility compared favorably based on the TLCC approach, however, theTCAAP system handled flow rates one order of magnitude larger than the other facilities. ***The TLCC at TCAAP was estimated to be $0.30 per 1,000 gallons of water treated. The total cost of operation and maintenance was calculated to be $0.12 per 1,000 gallons.***

Other results of the evaluation are summarized below in 1990 dollars.

Capital Costs

Construction of Treatment Plant	$774,757
Construction of Wells (16 extraction, 48 monitoring and 17 return wells)	1,026,406
Construction of Forcemain & Pumphouses (17,800 ft buried pipe, 16 pumphouses)	2,386,712
Startup	358,220
Health & Safety (Medical monitoring of employees)	110,125
Engineering	1,575,710
Project Management	928,267
Overhead & Profit	874,257
Total	**$8,034,454**

Operating Costs

Power (@ $0.04/Kwhr)	$148,846
Operating Labor	219,502
Maintenance Labor & Parts	150,054
Laboratory Charges	25,175
Other O&M Charges	39,518
Replacement of Tower Packing ($20,865 occurring every 5 years, annualized at 10% interest)	5,504
Total Annual Operating Cost	**$588,599**

Cost Sensitivities

Significant cost elements were:

Capital

• Pumphouses (16)	$775,964
• Extraction, monitoring & return well drilling (81)	399,633
• Stripping towers	296,821
• Extraction, monitoring & return well casings (81)	241,095
• Wet wells at base of stripping towers (3)	142,740

Operating

• Operating Labor	$219,502
• Maintenance labor & parts	150,054
• Electricity	148,846

REGULATORY/INSTITUTIONAL ISSUES

• BGRS construction was completed in April 1987 but startup was delayed until October 1987 due to administrative delays in obtaining regulatory approval to operate.

• Extraction well B1 was relocated from the original design since access to private property adjacent tc TCAAP was denied.

• Groundwater in the New Brighton/Arden Hills area near TCAAP has led to abandonment of some municipal water supplies and private wells and necessitated the provision of bottled water in some instances. Municipal wells near TCAAP have added granular activated carbon treatment to meet water supply and remediation objectives.

• It is likely that the contaminant plume emanating from TCAAP has mixed offsite with plumes from other sources complicating allocation of responsibility and coordination of remedial response plans. More evaluation is needed.

• Various responsible parties at TCAAP have hired different consultants to manage aspects of the remedial response. In some cases, parties and their consultants have disagreed in their interpretations of environmental conditions and the performace of treatment systems. Responsible parties are bound by past lawsuits by the City of New Brighton, the City of St. Anthony, and 96 other plaintiffs.

• Regulatory oversight requires reporting any shutdowns or operational problems over 24 hours in duration and rapid development of accompanying plans for correction.

Cleanup Criteria

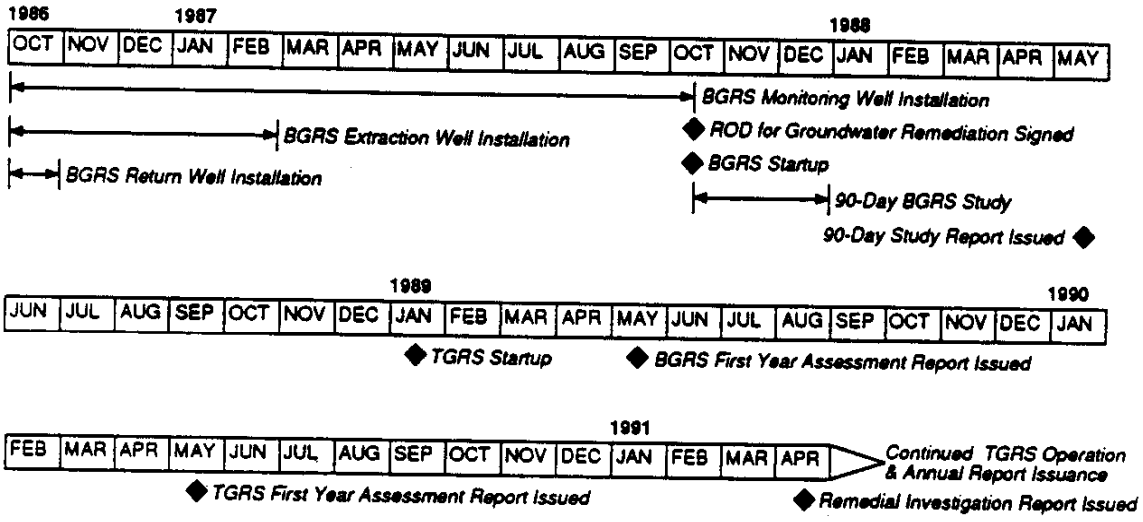
Several Records of Decision (RODs) apply to the overall TCAAP remedial program. Target cleanup criteria applicable to the BGRS and TGRS systems focus upon 1) residual levels of contamination in the groundwater and 2) containment of existing plumes.

Applicable target cleanup levels for major contaminants include:

Compound	Criteria Level (ppb)	Compound	Criteria Level (ppb)
TRCLE	5	1,2-DCE	70
TCLEE	6.9	1,1,1-TCE	200

SCHEDULE

BGRS & TGRS Installation History



LESSONS LEARNED

Key Operating Parameters

Implementation Considerations

• An understanding of the nature and extent of contamination at the site evolved over several years of monitoring and treatment. **Phased design** of the treatment system helped insure its proper sizing and effectiveness.

• Extensive **efforts to quantify and model aquifer properties** were of limited utility due to the presence of many hydrogeological complexities.

• A **preventive maintenance** program was instrumental in increasing the operational performance of the treatment facility.

Technology Limitations

• Original estimates of a 30 year **treatment period** have been extended. Minimum concentrations of target contaminants are projected to be achieved after 50-70 years of treatment. **Perpetual operation** of the system will be necessary to ensure continued containment of the VOC plume.

• As anticipated earlier, the technology is **not expected to achieve the 5 ppb target cleanup level** for TRCLE. It is projected that levels of 17 ppb may be achieved after 50 to 70 years of operation. **No alternative technology or system enhancements have been identified** to improve upon this performance to date.

• While plume containment appears to be successful, overall **VOC plumes appear to have changed little** after several years of treatment. Influent concentrations of contaminants to the the treatment plant have exhibited no clear downward trend. Extraction wells have experienced both increases and decreases in TRCLE concentrations from extracted groundwater. However, **only interim measures have been taken thus** far to clean up source areas. Permanent solutions are scheduled to be implemented in the 1995-1997 time frame.

Future Technology Selection Considerations

• The **zone of capture** created by the treatment system encompasses the entire contaminant plume of concern. There is some ongoing debate among parties at TCAAP concerning the extent to which any part of the onsite contaminant plume may be breaking through the system of boundary extraction wells.

• Operation of the treatment system in conjunction with **surface remediation of soils has been effective** at reducing VOC plume strengths near source areas.

• **Bioremediation is being considered** by regulators as a viable long-term solution to restore the aquifer to ≤ 5 ppb TRCLE. While selection of bioremediation is not currently anticipated, some technology must be implemented over the next 20-50 years to go below 17 ppb TRCLE.

• The **above ground air stripping system has been effective** at removing all VOCs, priority pollutants and metals to concentrations below discharge criteria. However, the air strippers simply transfer contaminants from the groundwater to the air. Granular activated carbon or other **emission control technology may be needed** in 1995 when new Clean Air Act requirements take effect.

• Groundwater treated by the air stripping systems is used as drinking water at TCAAP following post-treatment by granular activated carbon. **Identification of long-term drinking water used for treated effluent** will be part of future planning efforts.

• The system has been **effective at containing** further migration of the VOC plume off of the TCAAP site while **treatment of groundwater within subsurface aquifers to drinking water levels has not and is not expected to be achieved.**

ANALYSIS PREPARATION

This analysis was prepared by:

Stone & Webster Environmental
Technology & Services

245 Summer Street
Boston, MA 02210
Contact: Bruno Brodfeld (617) 589-2767

SOURCES

Major Sources For Each Section

Site Characteristics:	Source #s (from list below) 1, 3 and 8
Treatment System:	Source #s 5 ,7 and 8
Performance:	Source #s 1, 4, 6 and 8
Cost:	Source # 2
Regulatory/Institutional Issues:	Source #s 1,2, 3, 4, 5, 6 and 8
Schedule:	Source #s 1,3,5 and 7
Lessons Learned:	Source #s 1,2, 3, 4, 6,8 and personal communications with Marty McCleary, Project Manager, TCAAP (612) 633-2301 ext. 651.

Chronological List of Sources and Additional References

1. *Fiscal Year 1992 Annual Monitoring Report; Installation Restoration Program Twin Cities Army Ammunition Plant*, prepared for Commander of Twin Cities Army Ammunition Plant and Commander of U.S. Army Toxic and Hazardous Materials Agency, prepared by Federal Cartridge Company, Wenck Associates, Inc., Alliant Techsystems, Inc., and Conestoga-Rovers & Associates, Ltd., July 1993.

2. *Technical and Economic Evaluation of Air Stripping for Volatile Organic Compound (VOC) Removal from Contaminated Groundwater at Selected Army Sites*, CETHA-TE-91023, prepared for U.S. Army Toxic and Hazardous Materials Agency, prepared by Tennessee Valley Authority National Fertilizer and Environmental Research Center, July 1991.

3. *Installation Restoration Program: Remedial Investigation Report for the Twin Cities Army Ammunition Plant*, (4 volumes), prepared for the U.S. Army Toxic and Hazardous Materials Agency (USATHAMA), prepared by the Environmental Assessment and Information Sciences Division, Argonne National Laboratory, April 1991.

4. *IRA-TGRS 1990 Annual Monitoring Report Installation Restoration Program Twin Cities Army Ammunition Plant*, (2 volumes), prepared for Commander of Twin Cities Army Ammunition Plant and Commander of U.S. Army Toxic and Hazardous Materials Agency, prepared by Alliant Techsystems, Inc., and Conestoga-Rovers & Associates, Ltd., February 1991.

5. *Final Engineering Report: Boundary Groundwater Recovery System (BGRS)*, prepared by Conestoga-Rovers & Associates, January 1991.

6. *IRA-TGRS 1989 Annual Monitoring Report Installation Restoration Program Twin Cities Army Ammunition Plant*, (2 volumes), prepared for Commander of Twin Cities Army Ammunition Plant and Commander of U.S. Army Toxic and Hazardous Materials Agency, prepared by Honeywell, Inc., and Conestoga-Rovers & Associates, Ltd., May 1990.

7. *TGRS Operations and Maintenance Manual; Installation Restoration Program Twin Cities Army Ammunition Plant*, (5 volumes), prepared for Commander of Twin Cities Army Ammunition Plant and Commander of U.S. Army Toxic and Hazardous Materials Agency, prepared by Honeywell, Inc., and Conestoga-Rovers & Associates, Ltd., October 1989.

8. *SMCTC-EV Review Comments on the Technology Application Analysis Draft Report*, prepared by U.S. Army Environmental Center, September 1993.