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EMERGING TECHNOLOGY REPORT: DEMONSTRATION OF **AMBERSORB®** 563 ADSORBENT TECHNOLOGY

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FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of pollution to air, land, water and subsurface resources; protection of water quality in public water systems ; remediation of contaminated sites and ground water; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

E. Timothy Oppelt, Director
National Risk Management Research Laboratory

ABSTRACT

Roy F. Weston, Inc., in conjunction with Rohm and Haas Company, conducted a field pilot study to demonstrate the technical feasibility and cost-effectiveness of Ambersorb' 563 carbonaceous adsorbent for the remediation of groundwater contaminated with volatile organic compounds (VOCs). The project was conducted under the Emerging Technology Program of the EPA Super-fund Innovative Technology Evaluation (SITE) program.

The Ambersorb adsorbent technology demonstration was conducted over a 12-week period during the period from 2 May to 20 July 1994 at Site 32/36 of the Pease Air Force Base (AFB) in Newington, New Hampshire. The groundwater in this area is contaminated with a number of chlorinated organics, including vinyl chloride, 1, I-dichloroethene, cis- 1,2-dichloroethene, trans-1,2dichloroethene, and trichloroethene.

The Ambersorb adsorbent technology demonstration included four service cycles, three steam regenerations, and one superloading cycle. The study was conducted using a l-gallon-per-minute (gpm) continuous pilot system, consisting of two adsorbent columns that can be operated in parallel or series.

The demonstration study showed that Ambersorb 563 adsorbent is an effective technology for the treatment of groundwater contaminated with chlorinated organics. The effluent groundwater from the Ambersorb 563 adsorbent system consistently met drinking water standards.

Direct comparison of the performance of Ambersorb 563 adsorbent with **Filtrasorb®** 400 granular activated carbon (GAC) showed that Ambersorb 563 adsorbent treated to the drinking water standard approximately two to five times the number of bed volumes of water as GAC while operating at five times the flow rate loading.

On-site steam regeneration was successfully demonstrated. The steam regenerations yielded a separate organic phase that contained approximately 73% to 87% of the total VOC mass loaded onto the adsorbent. The majority of VOC recovery was shown to occur within the first 3 bed volumes of steam as condensate.

The principle of superloading was demonstrated as an effective treatment method for the aqueous condensate layer generated during the steam regeneration of the Ambersorb adsorbent. A condensate stream containing approximately 700,000 **µg/L** VOCs was treated to below the drinking water standards using the superloading column of Ambersorb 563 adsorbent.

Based on the results of the Ambersorb adsorbent demonstration study, conceptual designs and cost estimates for full-scale groundwater treatment systems (100 gpm) using Ambersorb 563 adsorbent and GAC were developed. The installed costs for the lOO-gpm treatment systems using Ambersorb 563 adsorbent ($526,100) were significantly greater than those using GAC ($336,800). The total present worth cost analysis, however, showed that after approximately 2 years, the Ambersorb 563 adsorbent system would be less expensive due to its lower operating costs. The annual operating costs of the Ambersorb 563 adsorbent system were approximately $32,500/yr for the first 5 years, while the annual operating costs for the GAC system were approximately $125,800/yr for the first five years.

This report was submitted in fulfillment of Cooperative Agreement CR-821352-01-0 by Roy F. Weston, Inc. under the partial sponsorship of the U.S. Environmental Protection Agency. This report covers a period of performance from 1 October 1993 to 28 February 1995, and work was completed as of 28 February 1995.

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LIST OF ACRONYMS

l,l-DCE	1,l -dichloroethene
A563	Ambersorb 563 adsorbent
AEL	Analytics Environmental Laboratory
AFB	Air Force Base
BVs	bed volumes
cis- 1,2-DCE	cis- 1,2-dichloroethene
DA	Dubinin-Astakov
EBCT	empty bed contact time
EPA	U.S. Environmental Protection Agency
ETL	Environmental Technology Laboratory
F400	Filtrasorb 400 GAC
GAC	granular activated carbon
GFIC	ground fault interrupted circuits
gpm	gallon-per-minute
HCl	hydrochloric acid
IRP	Installation Restoration Program
MCLs	maximum contaminant levels
MDLs	minimum detectable levels
MS	matrix spike
MSD	matrix spike duplicate
NPL	National Priorities List
ppm	part per million
QA	quality assurance
QAPP	quality assurance project plan
RI	Remedial Investigation
RPD	relative percent difference
SITE	Super-fund Innovative Technology Evaluation
SOC's	synthetic organic chemicals
TCE	trkhloroethene
trans- 1,2-DCE	trans- 1,2dichloroethene
umhos/cm	micromhos per centimeter
UV	ultraviolet
v c	vinyl chloride
VOCs	volatile organic compounds

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The cooperation and assistance of the U.S. Air Force and personnel at Pease AFB, Newington, New Hampshire, in providing the site for this technology demonstration project is greatly appreciated.

The key project participants included Russell E. Turner, Joseph F. Martino, Russell W. Frye, and Anthony G. Bove of WESTON and Deborah A. Plantz, Eric G. Isacoff, and Richard D. Link of Rohm and Haas. Chemical analysis to support the technology demonstration was provided by Analytics Environmental Laboratory, Inc. (AEL) in Portsmouth, New Hampshire.

SECTION 1

INTRODUCTION

PROGRAM OVERVIEW

Roy F. Weston, Inc. (WESTON,), in conjunction with Rohm and Haas Company (Rohm and Haas), conducted a field pilot study to demonstrate the technical feasibility and cost-effectiveness of **Ambersorb®** 563 carbonaceous adsorbent for the remediation of groundwater contaminated with volatile organic compounds (VOCs). (Ambersorb is a registered trademark of Rohm and Haas Company, Philadelphia, Pennsylvania.) The Ambersorb 563 adsorbent technology is currently commercially available. The WESTON/Rohm and Haas team conducted the Ambersorb adsorbent technology demonstration under the Emerging Technology Program of the U.S. Environmental Protection Agency (EPA) Superfund Innovative Technology Evaluation (SITE) Program.

The Ambersorb carbonaceous adsorbent system can remove organic contaminants so that they can be isolated and disposed of or reclaimed. Ambersorb adsorbents are targeted for applications on long-term remediation projects where the advantages of on site regeneration will provide a cost-effective water treatment alternative to granular activated carbon (GAC).

The Ambersorb adsorbent technology demonstration was conducted at Pease Air Force Base (AFB) in Newington, New Hampshire. The base is included on the National Priorities List (NPL), and WESTON has been conducting an Installation Restoration Program (IRP) Stage 3 Remedial Investigation (RI) at Pease AFB over the past several years. Based on a review of groundwater data for various sites at Pease AFB, Site 32/36 was selected for the field trial to demonstrate the use of Ambersorb 563 adsorbent for the treatment of contaminated groundwater. The groundwater in this area is contaminated with a number of chlorinated organics, including vinyl chloride (VC), 1, ldichloroethene **(1** ,l-DCE), cis- 1,2dichloroethene (cis- 1,2-DCE), trans-1 ,2-dichloroethene (trans- 1,2-DCE), and trichloroethene (TCE).

The Ambersorb adsorbent technology demonstration used a l-gallon-per-minute (gpm) continuous pilot-scale system to evaluate the treatment of groundwater from Site 32/36 at Pease AFB. A slip stream from the influent line to the two air strippers currently operating at Site 32/36 was used as the groundwater source for the pilot-scale demonstration. The field study was performed over a 12-week period from 2 May through 27 July 1994 and consisted of four service cycles, three steam regenerations, and one superloading to obtain sufficient data to compare the performance and economics of an Ambersorb 563 adsorbent system with the performance and economics of a liquid-phase GAC system. Filtrasorb **400®** GAC was selected for use during the first service cycle for direct comparison with Ambersorb 563 adsorbent performance. (Filtrasorb is a registered trademark of Calgon Corporation, Pittsburgh, Pennsylvania.) Filtrasorb 400 GAC represents a commonly used GAC for liquid-phase fixed-bed groundwater treatment systems.

The field trial was performed using staff personnel from WESTON's Environmental Technology Laboratory (ETL) in Lionville, Pennsylvania; WESTON's on-site operations office at Pease AFB; WESTON's office in Concord, New Hampshire; and Rohm and Haas Research Laboratories. in Spring House, Pennsylvania. Chemical analyses to support the technology demonstration were provided by a local analytical laboratory, Analytics Environmental Laboratory, Inc. (AEL), in Portsmouth, New Hampshire.

This report describes the Ambersorb adsorbent technology study objectives and experimental procedures and equipment used; summarizes the test results; and provides discussions and recommendations on design parameters and treatment costs for full-scale treatment systems. A work plan for the Ambersorb adsorbent demonstration project was presented in a separate document.' A separate quality assurance project plan (QAPP) was also prepared for the Ambersorb adsorbent technology demonstration study? The QAPP was prepared in accordance with guidance for the development of a Category III project.

TREATMENT TECHNOLOGY DESCRIPTION

Current field-tested technologies available for the removal of VOCs from groundwater are based on carbon adsorption and air stripping or aeration.[3] Experimental technologies being investigated include powdered activated carbon, biodegradation, reverse osmosis, ultraviolet (UV) catalyzed oxidation, and ultrafiltration.[3] Generally, the lower the level of the contaminant concentration that is desired in the treated effluent, the more expensive the treatment technique.

Adsorption techniques using GAC are well-established for groundwater remediation: but require either disposal or thermal regeneration of the spent carbon. In these adsorbent systems, the GAC has to be removed from the remediation site and shipped as a hazardous material to the disposal or regeneration facility. For large systems, on-site regeneration of spent GAC is sometimes economically justified.

Ambersorb carbonaceous adsorbents are a family of synthetic, tailorable adsorbents that were first developed in the 1970s for the remediation of contaminated groundwater.[5,6] Rohm and Haas has commercialized several Ambersorb carbonaceous adsorbents.[7,8,9,10] One particular grade, Ambersorb 563 adsorbent, based on recently patented technology, has been found to be extremely effective in the removal of low-level VOCs and synthetic organic chemicals (SOC's) from contaminated water. The unique properties of Ambersorb 563 adsorbent result in several key performance benefits:[5,11,12,13,14,15]

> Ambersorb 563 adsorbent can be regenerated on-site using steam, thus eliminating the liability and cost of off-site regeneration or disposal associated with adsorbents such as GAC. Condensed contaminants are recovered through phase separation.

- Ambersorb 563 adsorbent has 5 to 10 times the capacity of GAC for adsorbing VOC contaminants, such as chlorinated hydrocarbons, when the contaminants are present at low concentrations (ppb to ppm levels). This higher adsorptive capacity translates into significantly longer service cycle times before regeneration is required

- Ambersorb 563 adsorbent can operate at much higher flow rates than G.AC, while maintaining effluent water quality below drinking water standards. This advantage results in a compact system with smaller, hence, less expensive components.

- Ambersorb adsorbents are comprised of hard, nondusting, spherical beads with excellent physical integrity, thus reducing or eliminating handling problems and attrition losses typically associated with GAC.

- Ambersorb adsorbent performance is not adversely affected by background levels of heavy metals or other ionic species in groundwater. Changes in groundwater pH, temperature, and alkalinity also have no deleterious effect on performance.

- Ambersorb 563 adsorbent is not prone to bacterial fouling.

- Ambersorb adsorbents can be manufactured with consistent reproducible characteristics.

This combination of performance benefits can result in a more cost-effective alternative to currently available technologies for the treatment of low-level VGC-contaminated groundwater. Ambersorb adsorbent technology can be considered for wellhead treatment as well as for a centralized treatment facility.

PROJECT OBJECTIVES

The objectives of the Ambersorb adsorbent technology demonstration project included the following:

- Demonstrate that Ambersorb adsorbents can offer a cost-effective alternative to GAC treatment, while maintaining effluent water quality that meets maximum contaminant levels (MCLs), as established in the National Revised Drinking Water Regulations (40 CFR 141.61).

- Validate design parameters and system performance to be used for scale-up to full-plant scale, including the evaluation of service cycles and establishing steam regeneration efficiency, superloading, and ease of phase separation. Superloading refers to the process whereby the aqueous condensate from the steam regeneration of an Ambersorb 563 adsorbent service column is treated using a smaller column containing Ambersorb 563 adsorbent. Following superloading treatment, the aqueous condensate is discharged as part of the treated water stream, The superloading process is not typically used for GAC system.

- Evaluate the performance/cost characteristics of the Ambersorb adsorbent groundwater remediation system.

SECTION 2

CONCLUSIONS

Based on the results of the Ambersorb 563 adsorbent technology demonstration, the following conclusions were developed:

1 Ambersorb 563 adsorbent is an effective technology for the treatment of groundwater contaminated with chlorinated organics. The effluent groundwater from the Ambersorb 563 adsorbent system consistently met drinking water standards.

2. Direct comparison of the performance of Ambersorb 563 adsorbent with Filtrasorb® 400 GAC, based on the number of bed volumes treated to the MCL, indicated that Ambersorb 563 adsorbent was able to treat approximately two to five times the bed volumes of water as Filtrasorb 400 GAC while operating at five times the flow rate loading [l/5 the empty bed contact time (EBCT)].

3. On-site steam regeneration was successfully conducted during the demonstration and yielded an easily separable condensate consisting of a VOC-saturated aqueous stream (top layer) and a concentrated organic phase (bottom layer). The steam regenerations recovered approximately 73% to 87% of the total VOC mass adsorbed on the Ambersorb 563 adsorbent column during the service cycle. The organic phase contained approximately 88% to 93% of the total VOC mass recovered. The majority of VOC recovery was shown to occur within 3 bed volumes of steam as condensate.

4. The principle of superloading was demonstrated as an effective treatment method for the aqueous condensate layer resulting from the steam regeneration of the Ambersorb adsorbent. A condensate stream containing 700,000 µg/L VOCs was treated to below the drinking water standards using a superloading column containing Ambersorb 563 adsorbent.

5. Preliminary cost estimates of the installed costs for a 100~gpm treatment system using Ambersorb 563 adsorbent were significantly greater than those using GAC. However, the annual operating cost of the Ambersorb 563 adsorbent system was significantly lower than the GAC system. The total present worth cost analysis showed that after approximately 2 years, the Ambersorb 563 adsorbent system would be more economical because of its lower operating costs.

6. The demonstration study enhanced the existing database for the Ambersorb 563 adsorbent technology and helped validate process design parameters and system performance for scale-up to full-scale treatment systems. Information pertaining to key parameters of process configuration. EBC'I' or flow rate loading, vessel configuration, and steam regeneration conditions was developed or confirmed as part of the demonstration project.

7. The removal of particulate matter from the influent groundwater prior to the adsorbent columns must be considered as part of the treatment system design. During the demonstration project, orange-brown particulate matter (likely iron precipitates) was observed to accumulate on the column inlet screens, causing higher than expected pressure drops. The particulate matter was passing through the pilot unit prefilters or precipitating out from a dissolved state after the filters. No negative impact on the performance of the Ambersorb 563 adsorbent or Filtrasorb 400 GAC was observed due to the particulate matter.

8. Based on a comparison of the measured performance results obtained during the demonstration project and the performance results predicted by the breakthrough capacity model developed by Rohm and Haas, the breakthrough capacity model is a useful tool in predicting the adsorption capacity and service cycle times to support full-scale system design and cost analysis for the Ambersorb 563 adsorbent technology.

9. The accurate quantification of vinyl chloride in the influent groundwater is critical in establishing the service cycle time for process operations of the Ambersorb adsorbent and GAC treatment systems. Based on the Rohm and Haas predictive model, levels of vinyl chloride in the groundwater result in significant decreases in adsorbent performance as compared to groundwater containing no vinyl chloride. As measured in the study and predicted by the model, incremental increases in vinyl chloride concentration result in decreases in adsorption capacity.

10. A 22% to 40% decrease in the number of bed volumes treated to the MCL was observed for certain contaminants (VC and 'TCE) following one steam regeneration of the virgin Ambersorb 563 adsorbent. The reduction in bed volumes treated to the MCL may be the result of the increase in influent vinyl chloride concentration during the study. Additional steam regenerations and service cycles with relatively constant vinyl chloride concentration are needed to estimate the long-term effect of multiple steam regenerations on Ambersorb 563 adsorbent performance.

SECTION 3

RECOMMENDATIONS

Ambersorb 563 adsorbent technology should be considered as an alternative treatment method to GAC for the remediation of groundwater contaminated with chlorinated organics. Specifically, for 100~gpm pump-and-treat systems that are expected to operate for several years, the Ambersorb 563 adsorbent technology is expected to perform as well as or better than GAC and at a lower overall cost. In addition, on-site regeneration of the Ambersorb 563 adsorbent columns provides the option of recycling or direct disposal of the contaminants recovered in the condensate organic phase. During feasibility studies for sites that require groundwater remediation, Ambersorb 563 adsorbent technology should be included among the list of viable treatment technologies considered for evaluation.

SECTION 4

EXPERIMENTAL DESIGN AND PROCEDURES

EXPERIMENTAL DESIGN

Overview

The Ambersorb adsorbent technology demonstration employed a l-gpm continuous pilot system. The pilot unit included prefilters to remove suspended solids, two adsorbent columns that could be operated in parallel or series, one superloading column, and a steam regeneration system.

The steam regeneration system enabled the direct, on-line regeneration of the Ambersorb adsorbent columns on-site and included a steam generator, condenser, collection/separation vessel, and vapor phase Ambersorb adsorbent trap for the condenser vent discharge. Steam was passed through the beds in a downflow mode to minimize condensate holdup in the vessels. To conduct a countercurrent regeneration, both adsorbent columns used an upflow, fixed bed configuration.

The Ambersorb adsorbent technology demonstration consisted of four service cycles, three steam regenerations, and one superloading test. During the first service cycle, the columns were operated in parallel for direct comparison of the performance of virgin Ambersorb 563 adsorbent to virgin Filtrasorb 400 GAC. For the remaining cycles, two Ambersorb 563 adsorbent columns were operated in series to investigate the effect of multiple service cycles and steam regeneration on Ambersorb adsorbent performance.

Breakthrough Capacitv Model

A breakthrough capacity computer model, developed by Rohm and Haas, was used to predict the service cycle times for the demonstration study based on the average contaminant concentrations measured in the Site 32/36 wells during the Stage 5 IRP at Pease AFB.

Liquid-phase static adsorption isotherms are commonly used to estimate adsorption capacity for organic contaminants from water over a range of concentrations. Although these isotherms cannot simulate an adsorbent's performance under dynamic conditions for a multicomponent system, isotherms are valuable tools in helping to predict service cycle time.

The linear Freundlich equation is commonly used to represent adsorption isotherms for GAC. Rohm and Haas has found, however, that the linear Freundlich isotherm is not appropriate for the curved isotherms that are typically obtained for Ambersorb adsorbents over the low part per million (ppm) concentration range.‘* A quadratic equation can model this behavior. An investigation of several isotherm functions showed that the Dubinin-Astakov (DA) equation was the optimum equation for representing typical VOCs.[17]

As a tool to assist in predicting estimated service cycle time, Rohm and Haas developed a computer model based on the DA equation.‘* Using the contaminants and. respective concentrations for a given influent water analysis, the model provides an estimate of the number of bed volumes that can be treated to a 50% stoichiometric breakthrough point for a given contaminant (i.e., $C_e/C_0 = 0.5$, where C_e is the effluent concentration and C_0 is the influent concentration). The model also predicts the first component to breakthrough based on the contaminant load.

Specifically. for this study, the model predicted that vinyl chloride would be the first component to break through and that service cycle times would be significantly affected by small changes in the influent vinyl chloride concentration. During the first 7 days of the Ambersorb adsorbent demonstration study, however, no detectable levels of vinyl chloride (<5 μg/L) were measured in the influent groundwater. Because of high TCE concentrations in the influent stream, the influent samples needed to be diluted 10-fold thus increasing the minimum level of detection for vinyl chloride from 0.5 μg/L to 5 μg/L. Based on the lower than expected influent VC concentrations (assumed to be zero), the Rohm and Haas model predicted that service cycle times would be almost twice the duration previously estimated. Therefore, after 7 days of operation, the estimated process flow rates for Cycle 1 were doubled. After final evaluation of all influent and effluent VOC concentrations measured during the demonstration study, it was estimated that vinyl chloride was present in the influent stream at concentrations ranging from 3 to 11 μg/L based on a volume-weighted average during the entire study.

The influent contaminant levels measured during the first service cycle were then used as input to set the operating parameters for subsequent cycles. The contaminant concentrations, specifically vinyl chloride, had a significant impact on breakthrough time and other performance parameters, including leakage during each cycle.

OPERATING CONDITIONS

Service Cycles

Operating conditions for each of the service cycles are presented in Table 1. During the first service cycle, the columns were operated in parallel for direct comparison of the performance of virgin Ambersorb 563 adsorbent (A563) to virgin Filtrasorb 400 GAC (F400). Initially, the virgin Ambersorb 563 adsorbent column designated by column identification number A563A and the virgin Filtrasorb 400 adsorbent column, designated by column identification number F400, were operated at flow rates of approximately 0.44 and 0.29 gpm (EBCT of 2.7 and 15.8 minutes), respectively. During the first 7 days of operation, no detectable levels (<5 μg/L)

TABLE 1. OPERATING CONDITIONS FOR SERVICE CYCLES*

Service Cycle	Cycle 1†		Cycle 2	Cycle 3	Cycle 4
Adsorbent Column	A563A	F400	A563B	A563A	A5638
Bed Geometry					
Diameter, inches	4.0	6.0	4.0	4.0	4.0
Length, inches	22.0	37.0	22.0	22.0	22.0
Volume, gallons	1.2	4.5	1.2	1.2	1.2
Orientation	up-flow	up-flow	up-flow	up-flow	up-flow
Process Operations Data‡					
Total Operation Time, days	16.8	30.6	12.8	7.8	12.9
Total Volume Treated, gallons	16,400	23,000	15,200	10.300	15,300
Total Volume Treated, BV	13,700	5.070	12,700	8,600	12,800
Process Flow Rate, gpm	0.44/0.84	0.29/0.59	0.83	0.91	0.82
Flow Rate Loading, BV/hr	22/42	3.8/7.8	41	46	41
Hydraulic Loading, gpm/ft^2	5.1/9.6	1.5/3.0	9.5	10.5	9.4
Empty Bed Contact Time, min.	2.7/1.4	15.8/7.7	1.4	1.3	1.5

* **During Cycle I. columns were operated** in parallel. During Cycles 2,3, and 4, two columns were operated in series. Operating conditions for Cycles 2,3, and 4 represent system loading to the lead column.

† During Cycle I the process flow rate was doubled after 7 days of operation to decrease service cycle times. VC was below detection limits in the influent stream.

‡ Time weighted averages and cumulative totals for the total operating period.

of vinyl chloride were measured in the influent groundwater. Therefore, after 7 days of operation, process flow rates of the Ambersorb adsorbent and Filtrasorb GAC columns were doubled to approximately 0.84 and 0.59 gpm (EBCT of 1.4 and 7.7 minutes), respectively.

During Cycle 1, the Ambersorb adsorbent and Filtrasorb GAC columns were operated well beyond vinyl chloride breakthrough to fully define the breakthrough curves for the remaining VOCs. Breakthrough for a specific VOC is defined as the condition at which the column effluent VOC concentration equals one half the influent VOC concentration. The Ambersorb adsorbent column was terminated after 13,700 bed volumes (16,400 gallons) had been treated (after 17 days of operation), and the Filtrasorb GAC column was terminated after 5,070 bed volumes (23,000 gallons) had been treated (after 31 days of operation).

Bed volumes as opposed to absolute gallons, are the units typically used to compare the performance of different adsorbents for varying sized systems. Bed volumes represent the relative volume of groundwater treated normalized to account for the size of the adsorbent column. The Ambersorb 563 adsorbent column had a bed volume of 1.20 gallons, and the Filtrasorb 400 GAC column had a bed volume of 4.53 gallons (i.e., approximately four times larger than the bed volume of the Ambersorb adsorbent column).

For the remaining cycles, two Ambersorb 563 adsorbent columns were operated in series to investigate the effect of multiple service cycles and steam regenerations on Ambersorb adsorbent performance.

After the first service cycle, the exhausted Ambersorb 563 adsorbent column (A563A) was steam regenerated on-site and placed in the lag position for the second service cycle. After steam regeneration, the column identification number changed from A563A to A563A-1 to designate that one steam regeneration was conducted on column A563A. The Filtrasorb 400 GAC column from the first service cycle was replaced by a new virgin Ambersorb 563 adsorbent column identical in dimension to the A563A column and placed in the lead position for Cycle 2. The new virgin Ambersorb adsorbent column was designated A563B.

For Cycles 3 and 4, the newly regenerated lead columns from the previous cycles (A563B-1 and A563A-2) were also placed in lag positions, and the lag columns from the previous cycles (A563A-1) andA563B-1) were placed in lead positions to simulate the operating mode in a full-scale system. For Cycles 3 and 4, therefore, the lead Ambersorb adsorbent columns were preloaded with VOC leakage from the previous service cycles.

During Cycles 2, 3, and 4, the Ambersorb adsorbent columns were operated in series at flow rates ranging from 0.83 to 0.91 gpm corresponding to 1.3- to 1.5-minute EBCTs for one column or 2.6- to 2.9-minute EBCTs for two columns in series. Each cycle was operated well beyond vinyl chloride breakthrough in the lead column to defme the breakthrough curves for the remaining VOC's Cycles 2, 3, and 4 were terminated after 13, 8, and 13 days of operation, respectively. During Cycle 3, the system was shutdown for approximately 2 days, resulting in 8 days of actual operating tune.

During each service cycle, influent and effluent samples of each column were collected daily and analyzed for VOCs. In addition. selected influent and effluent column samples were measured for pH, conductivity, and alkalinity. Process parameters, including groundwater influent flow rate, temperature, and pressure, were also monitored at periodic intervals throughout the service cycles.

Steam Regenerations

Steam regenerations were conducted on the Ambersorb adsorbent column at the end of Cycle 1 and on the lead Ambersorb adsorbent column at the end of Cycles 2 and **3** to evaluate the effect steam regeneration has on Ambersorb adsorbent performance. The steam regenerations were also conducted at various temperatures (307 °F, 293 °F, 280 °F) to evaluate the effect of regeneration temperature on contaminant recovery. Operating conditions for each of the steam regenerations are presented in Table 2.

Each steam regeneration was conducted directly on the lead Ambersorb adsorbent column on-site using a portable steam generator. Prior to the introduction of steam to the top of the column, the Ambersorb adsorbent columns were wrapped in electrical heating tape, insulated, and preheated to the target regeneration temperature. Steam was then applied to the column in a downflow direction. Desorbed contaminant vapors and water vapor were then condensed in a water-cooled condenser and collected in l-liter graduated glass burettes. The volumetric rate of condensate produced (regeneration rate) was increased incrementally over a 17- to 19-hour period from approximately 0.23 BV/hr to 0.82 BV/hr. Depending on the regeneration rate, the l-liter burettes were filled and recovered for sample collection every 15 to 60 minutes.

The condensate produced during each regeneration consisted of a visible and separable concentrated organic phase (bottom layer) and a VOC-saturated aqueous phase (top layer). A photograph of the condensate phase separation following steam regeneration is presented in Figure 1. The volumes of both the organic and aqueous layers were measured directly in the burettes. The organic layer was then drained from the burette into a volumetric flask and diluted with methanol to a known volume (typically 250 mL) for analytical purposes. Samples of the diluted organic phase were collected from the volumetric flask and analyzed for VOCs Samples of the aqueous phase were collected directly from the graduated burette and analyzed for VOCs, pH, and conductivity.

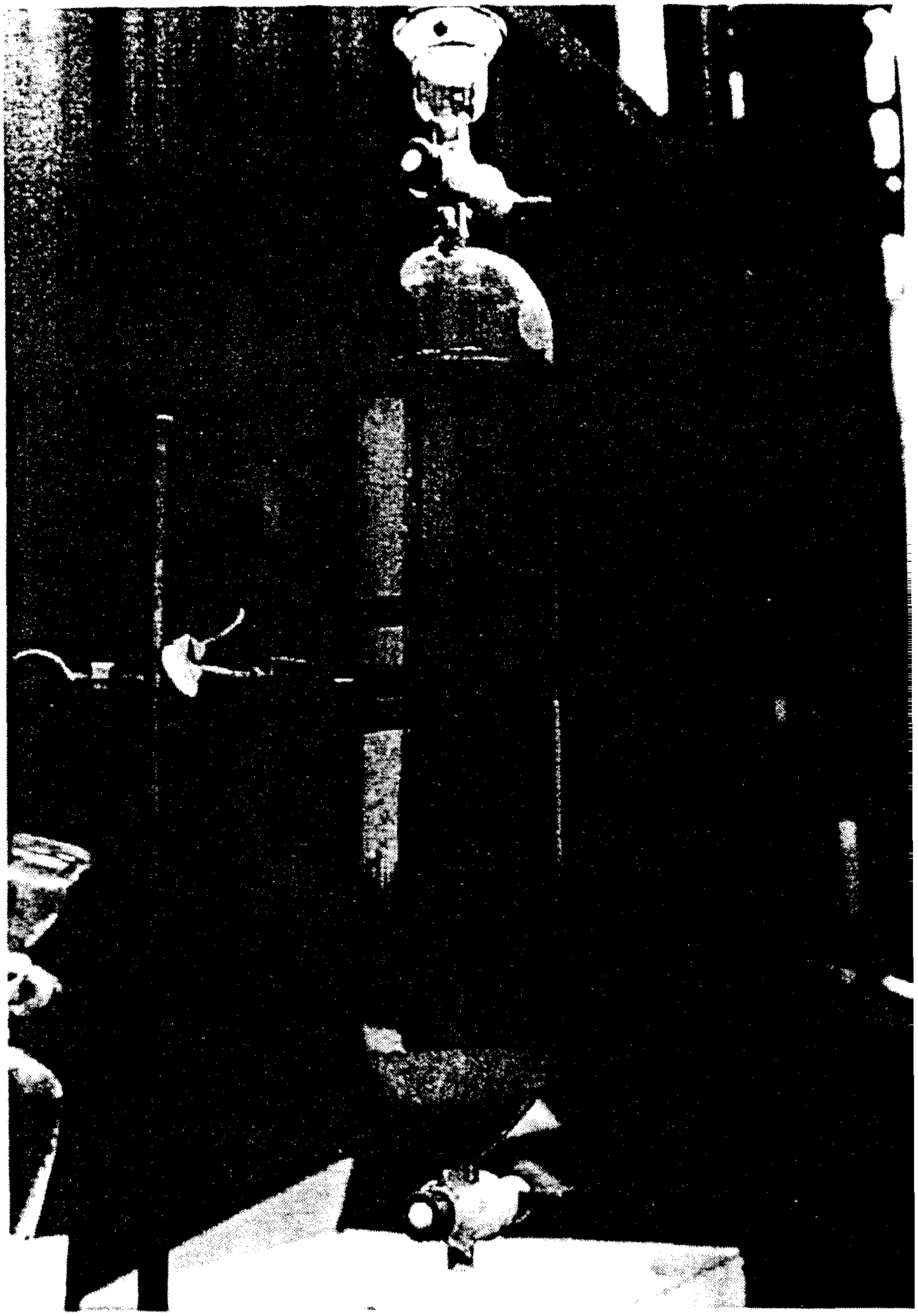
During the field trial, the regeneration was extended significantly beyond what would be practiced during full-scale commercial operation, and considerably more samples were taken in order to fully define the mass recovery curve and to complete an accurate mass balance.

To ensure that there was no VOC vapor discharged during each steam regeneration, a trap containing Ambersorb 563 adsorbent was used on the vapor discharge from the condenser. At the end of each regeneration, the vapor trap adsorbent was recovered and extracted twice using a 2:l ratio of methanol to adsorbent volume. The two extracts were combined and the final volume of methanol measured. Duplicate samples of the combined extracts were collected and analyzed.

TABLE 2. OPERATING CONDITIONS FOR STEAM REGENERATIONS

Steam Regeneration	Regeneration 1	Regeneration 2	Regeneration 3
Adsorbent Column	A563A	A563B	A563A
Bed Geometry			
Diameter, inches	4.0	4.0	4.0
Length, inches	22.0	22.0	22.0
Volume, gallons	1.20	1.20	.20
Orientation	down-flow	down-flow	down-flow
Process Operations Data*			
Total Operation Time, hours	17.4	17.1	18.5
Total Volume Condensate Generated, gallons	9.1	8.4	10.7
Total Volume Condensate Generated, bed volumes	7.6	7.0	8.9
Column Temperature, °F	307	293	280
Column Temperature, °C	153	145	138

* Time weighted averages and cumulative totals for the total operating period



95P-0871 Figure 1. Photo of Condensate Separation Following Steam Regeneration

After steam regeneration was completed. the adsorbent column was allowed to cool to approximately 194 °F. Then the adsorbent column was flushed with tap water in a up-flow direction to rehydrate the adsorbent. After reaching ambient temperature. the adsorbent column was then placed in the lag position and the subsequent service cycle was initiated.

Superloading

A test to demonstrate the use of an Ambersorb 563 adsorbent superloading column to treat the aqueous condensate from a typical steam regeneration process was also conducted during the field trial. This test was performed to demonstrate the concept of a closed loop Ambersorb adsorbent treatment system in which the only discharge is the separable organic layer resulting from steam regeneration. Ambersorb adsorbent was chosen for the superloading column because of its high adsorption capacity and superior kinetics while operating at a high flow rate loading. Operating conditions for the superloading test are presented in Table 3.

Superloading was conducted by passing the saturated aqueous phase from the third steam regeneration (approximately 4 gallons) through an Ambersorb 563 adsorbent superloading column (A563S) with a diameter of 2 inches and a bed height of 21 inches. Superloading was conducted at an approximate rate of 8 BV/hr for approximately 1.8 hours and treated approximately 14 BVs of saturated condensate. Influent and effluent samples from the superloading column were collected for VOC analysis initially and every hour during the test.

SAMPLE COLLECTION AND ANALYSIS

Service Cycles

The VOC sampling and analysis program for the service cycles is summarized in Table 4. Samples were collected from ports located before and after each column directly into sample containers. Initially during Cycle 1, samples of the influent to the pilot unit and the effluent streams from each of the two columns were collected three times per day at approximately 7 a.m., 11 a.m., and 3 p.m.

Once the VOC breakthrough curves were defined in Cycle 1, sampling frequency was reduced for the remaining cycles. During Cycles 2, 3, and 4, column influent and effluent samples were collected twice per day at approximately 7 am. and 3 p.m. All samples for VOC analysis were collected in duplicate.

During Cycle 1, two of the three daily sample sets (typically the 7 a.m. and 3 p.m. sample sets) were analyzed for VOCs. During the remaining cycles, one of the two daily sample sets (usually the 3 p.m. sample set) was analyzed for VOCs.

During each cycle, column influent and effluent samples were collected once a day (typically during the 7 a.m. sample set) for pH and conductivity measurements. In addition. during Cycle 1, selected influent and effluent samples of the Filtrasorb 400 GAC column were

TABLE 3. OPERATING CONDITIONS FOR SUPERLOADMG

Adsorbent Column	A563S
Bed Geometry	
Diameter, inches	2.0
Length, inches	21.0
Volume, gallons	0.29
Orientation	up-flow
Process Operations Data*	
Total Operation Time, hours	1.8
Total Volume Treated, gallons	4.0
Total Volume Treated, bed volumes	14.0
Process Flow Rate, gpm	0.038
Flow Rate Loading, bed volumes/hr	8.0
Hydraulic Loading, gpm/ft^2	1.7
Empty Bed Contact Time, minutes	7.5

•*Time weighted averages and cumulative totals for the total operating period.

TABLE 4. VOC SAMPLING AND ANALYSIS PROGRAM FOR SERVICE CYCLES

Service Cycle		Number of Samples Analyzed per Service Cycle*									
		Base Samples			QA Samples						Total
		Column Influent	Column Effluent Lead	Column Effluent Lag	Duplicates	Matrix Spikes	Confirmatory	Blanks Field	Blanks Trip		
1	31†	62	35	62	16	11	11	11	11		219
	13	13	13	13	4	4	4	4	4		59
	8	8	8	8	3	3	3	3	3		39
	13	13	13	13	4	4	4	4	4		59
	34	96	69	96	27	22	22	22	22		376

* For each service cycle, conductivity and pH were measured on influent and cfllucnt samples collected each day during the 7:00 am sampling event (not shown in table). For the Filtrasorb 400 GAC column, alkalinity was measured on one initial and one final influcnt sample and each day on one effluent sample for the tint I7 days. After I7 days, alkalinity was measured once every other day on the Filtrasorb 400 GAC column.

† During Cycle I, the Ambersorb 563 adsorbent column operated I7 days and Filtrasorb 400 GAC column operated 3 I days.

analyzed for alkalinity as identified in Table 4. Alkalinity was measured on the Filtersorb 400 GAC influent and effluent streams to determine if pH control would be required for the full-scale design. GAC typically imparts some alkalinity into the effluent stream when treating groundwater. If the effluent pH increases above the discharge criterion, then pH control will be required.

Quality assurance samples were collected and analyzed during each service cycle to determine accuracy, precision, and other data quality parameters. All VOC samples were collected in duplicate, from which three samples were randomly selected for analysis every 6 days during Cycle 1, and two were randomly selected for analysis every 6 days during the remaining cycles. Two trip blanks, field blanks, matrix spike/matrix spike duplicates, and confirmatory samples were collected and analyzed every 6 days during each cycle.

Steam Regenerations

The VOC sampling and analysis program for each steam regeneration is summarized in Table 5. The condensate produced during each regeneration consisted of a visible and separable concentrated organic phase (bottom layer) and a VOC-saturated aqueous phase (top layer). The organic layer was drained from the burette into a volumetric flask and diluted with methanol to a known volume (typically 250 mL). Samples of the diluted organic phase were collected from the volumetric flask and analyzed for VOCs. Samples of the aqueous phase were collected directly from the graduated burette and analyzed for VOCs, pH, and conductivity. In addition, VOC analyses were performed on the methanol extract of the vapor traps for each regeneration.

Quality assurance samples were collected and analyzed during each regeneration to determine accuracy, precision, and other data quality parameters. All VOC samples were collected in duplicate, from which one sample was randomly selected for analysis for each regeneration. Trip blanks, field blanks, matrix spike/matrix spike duplicates, and confirmatory samples were collected and analyzed at a frequency of one per regeneration. In addition, a duplicate VOC sample of the vapor trap extract was analyzed for the first regeneration.

Superloading

The VOC sampling and analysis program for the superloading test is summarized in Table 6. Steam regeneration was not conducted on the superloading column. Influent and effluent VOC samples were collected from the superloading column every 30 minutes during the test.

Quality assurance samples were collected and analyzed for the superloading test to determine accuracy, precision, and other data quality parameters. All VOC samples were collected in duplicate, from which one sample was randomly selected for analysis. One trip blank, field blank, and confirmatory sample were also collected and analyzed for the superloading test.

TABLE 5. VOC SAMPLING AND ANALYSIS PROGRAM FOR STEAM REGENERATIONS

Regeneration	Column I.D.	Number of Samples Analyzed per Regeneration*							
		Base Samples			Quality Assurance Samples				
		Condensate Phases		Vapor Trap	Dupli-	Confirm-			
		Aqueous	Organic	Extract	cates	atory	Field	Trip	Total
1	A563A	23	19	1	2†	1	1	1	46
2	A563B	17	13	1	1	1	1	1	35
3	A563A-1	26	14	1	1	1	1	1	45
Total	--	66	46	3	2	3	3	3	126

* During each rcgcncration, conductivity and pH were measured on the aqueous condensate collected during each sample event (not included in table).

† During the first regeneration. one VOC duplicate from the vapor trap extract was analyzed.

TABLE 6. VOC SAMPLING AND ANALYSIS PROGRAM FOR SUPERLOADING

Number of Samples Analyzed*						
Base Samples		Quality Assurance Samples				
Influent	Effluent	Duplicates	Confirmatory	Field Blanks	Trip Blanks	Total
4	4	1	1	1	1	12

* Conductivity and pH were measured on all influent and effluent samples collected (not included in table).

Analytical Procedures

Table 7 identifies the laboratory, method, and holding time for the parameters tested during the field trial program. Analyses for temperature, pH. and conductivity were performed on-site immediately upon collection. Samples collected during the service cycles, steam regenerations, and superloading were analyzed for target VOCs (i.e., VC, 1, I-DCE, cis- 1.2-DCE. trans- 1,2DCE, and TCE) at AEL, located on the Pease AFB property. These analyses were performed on a quick turnaround basis (i.e., 24 to 48 hours). Selected samples were analyzed for VOCs (i.e., full list) at AEL's off-site laboratory for confirmation purposes.

The testing procedures used for sample analysis were based upon EPA-approved methods. The deliverables consisted of commercial data packages.

DATA COLLECTION AND ANALYSIS

Data Collection

Process operating data were collected during each sampling event during the demonstration study and recorded directly onto data spreadsheets or into bound logbooks. The data parameters measured and recorded on the data spreadsheets were influent stream flow rate and temperature, column dimensions, pressure drops, and totalizer readings. Observations, notes, process upsets, key incidents, and influent and effluent stream pH and conductivity measurements were recorded in the field logbook. At the end of each day of operation, copies of operations data and VOC analytical results were faxed to WESTON's project engineer for review, data validation, and key entry into the computer spreadsheets. The original operations data sheets were kept secured in the field laboratory during each service cycle and, after each service cycle, were transferred by the project engineer to the project file at WESTON.

In addition, photographs of the site, field laboratory, pilot plant system, and condensate samples from the steam regenerations were taken during the demonstration project and maintained in the project files.

Data Summary

Operations data and VOC analytical results were summarized in graphical and tabular forms using computer-based spreadsheets (Microsoft Excel).

All quantitative data, such as operations data and VOC analytical results, entered into computer spreadsheets were checked against the original data records to ensure that the correct values had been transferred. Following this, the data were reviewed and inconsistencies were resolved by seeking clarification from the study personnel responsible for collecting the data.

TABLE 7. ANALYTICAL LABORATORIES AND METHODS

Parameter	Matrix	Laboratory	Method	Holding Time
Temperature	Groundwater	On-site	SM 212	Immediately
PH	Groundwater	On-site	EPA 150.1	24 hours
Conductivity	Groundwater	On-site	EPA 120.1	28 days
Alkalinity	Groundwater	On-Site	SM2320	7 days
VOCs (target list)	Groundwater	AEL Pease	SW846 8010	14 days
VOCs (target list)	Aqueous Phase, organic Phase, Vapor Trap	AEL Pease	SW846 8010	7 days
VOCs (full list)	Groundwater	AEL Off-Site	SW846	14 days

Qualitative data. such as field notes recorded in the logbook. were checked by the project engineer by direct interview with the study personnel recording the notes. Random checks of sampling and testing conditions were made by the project engineer to confirm the recorded observations. Peer review also was incorporated into the data summary process, particularly for qualitative data, to maximize consistency between study personnel.

VOC analytical results for QA/QC samples collected were also checked to assess data precision, accuracy, and completeness.

Data Analysis

Based on the summarized test results, the data were analyzed to develop specific information concerning the following key design parameters investigated during the study:

- Confirm the ability of Ambersorb adsorbent to meet drinking water standards while maximizing flow rate loading.
- Establish working capacity over several cycles.
- Compare performance of Ambersorb adsorbent and GAC in terms of treatment effectiveness.
- Identify regeneration conditions, including:

  Steam temperature
  Steam flow rate
  Total steam consumption.

The information developed during the demonstration study was used to expand the existing technical database on the Ambersorb adsorbent technology and to enhance information on scale-up and estimates of treatment costs.

SECTION 5

EQUIPMENT AND MATERIALS

PILOT UNIT

The key equipment item required to conduct the technology demonstration was the pilot unit. This unit, designed and owned by Rohm and Haas, consists of a 1-gpm, transportable assembly that is designed for 24-hour continuous operation with two adsorbent columns that can operate either in parallel or in series. The pilot unit also includes a self-contained steam generator for direct on-line, on-site steam regeneration. A schematic of the pilot system is presented in Figure 2, and a photograph is presented in Figure 3.

The portable 1-gpm rig is housed in a 4-ft-wide by 7-ft-high enclosure that can be easily moved using a forklift truck. The enclosure has a vent fan, a rubber-lined roof for protection against rain, and a front door that can be locked for security. The steam generator is enclosed in a separate 4-ft-wide by 4-ft-high container.

Key equipment for the pilot unit includes the following:

1. Two lo-micron cartridge filters to remove particulate matter.

2. Two glass adsorption columns (4- or 6-inch diameter) that can operate either in series or in parallel. Each is equipped with a flow meter, influent and effluent pressure gauges, and sampling ports.

3. Self-contained portable steam generator.

4. Condenser.

5. Condensate collection burette (phase separation vessel).

6. Vapor trap containing Ambersorb adsorbent to capture any gaseous emissions.

SITE REQUIREMENTS AND UTILITIES

The pilot unit was set up within the fenced area surrounding the existing Site 32/36 treatment plant at Pease AFB The pilot unit was located on the northern side of and

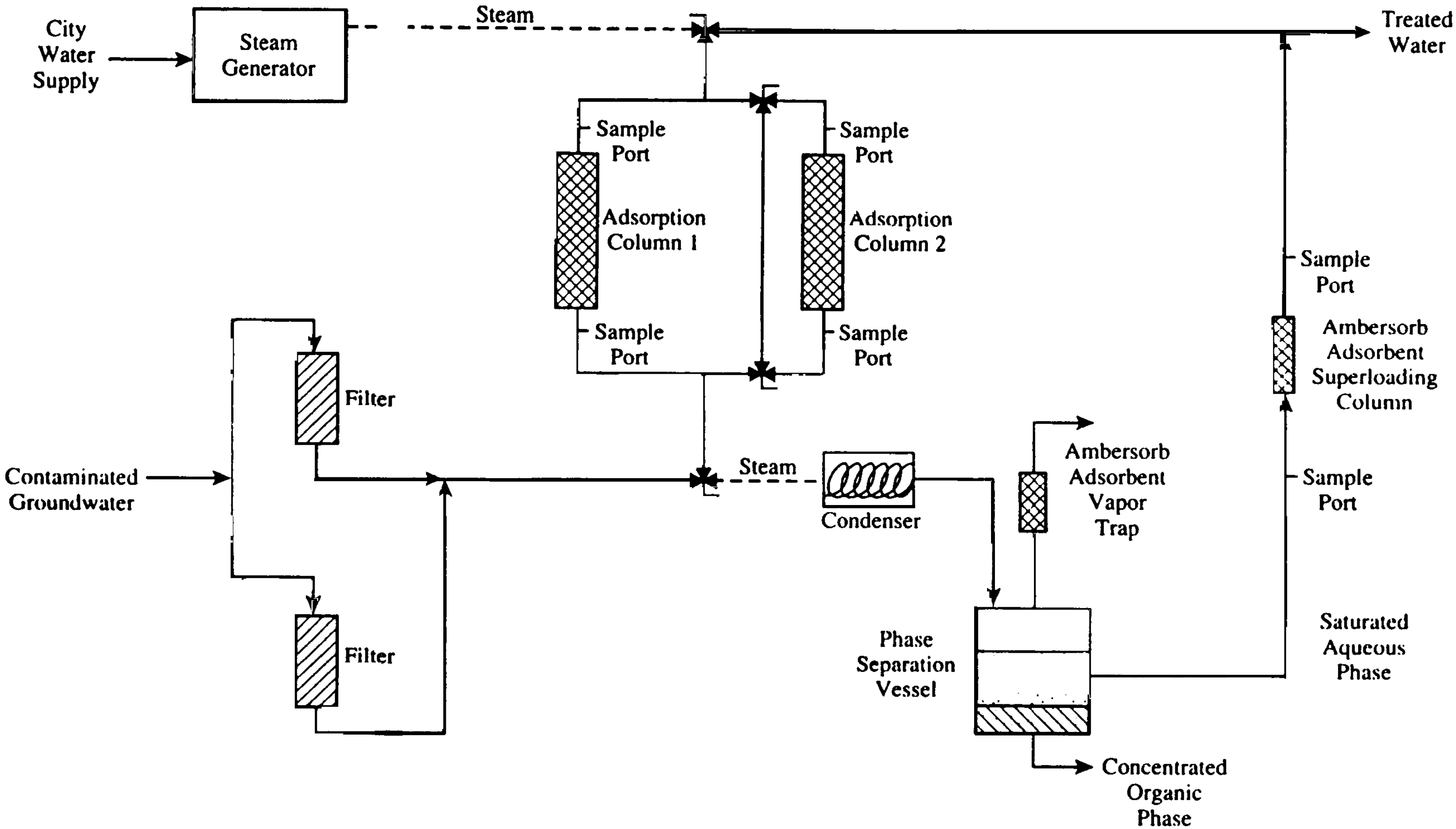


Figure 2. Schematic of Ambersorb Adsorbent Pilot Unit

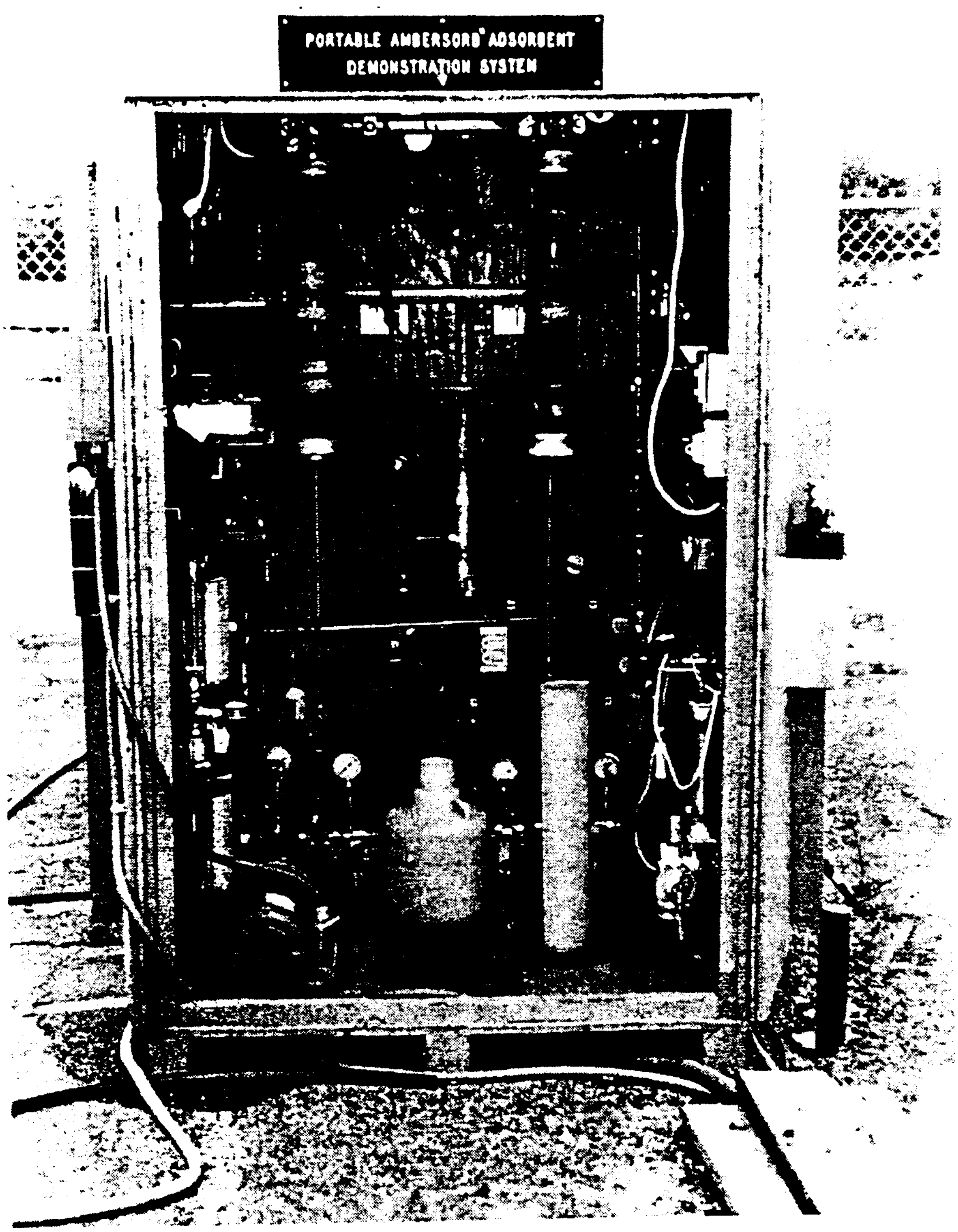


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Figure 3. Photo of Ambersorb® Adsorbent Pilot Unit

adjacent to the air stripping towers at the existing treatment plant. The existing treatment plant at Site 32/36 was in normal operation during the demonstration period.

Untreated groundwater was delivered to the pilot unit from an existing 10,000-gallon holding tank at the site. which was used for flow equalization and storage of contaminated groundwater recovered by several remediation wells installed in the Site 32/36 area.

The treated effluent from the pilot unit was passed through a GAC polishing filter prior to discharge to the site sewer to ensure that there was no VOC discharge from the pilot unit.

City water was available for flushing and rehydrating the columns prior to starting each cycle and to provide water for the portable steam generator and condenser (minimum flow rate of 5 gpm at a pressure of 50 to 60 psi).

The electrical service required for the pilot unit and portable steam generator consisted Of:

- Two 208-40~amp hookups (three-phase).
- Six ground fault interrupted circuits (GF'IC) with 20-amp breakers.

A portion of the on-site building, currently used by WESTON on-site operations staff at Pease AFB was used as an office for on-site personnel from the WESTON/Rohm and Haas SITE project team. This building is located within 0.5 mile of the Site 32/36 treatment plant. The office area was equipped with a desk, table, chairs, telephone, fax machine, copy machine, and personal computer.

ON-SITE FIELD LABORATORY

The control room for the Site 32/36 treatment plant was used as an on-site laboratory for sample storage, equipment calibration and storage, conducting pH and conductivity measurements, and logbook and data sheet entry and filing.

Daily influent and effluent samples, collected for VOC analysis, were stored in two 4-cubic-foot refrigerators. Influent and effluent samples collected during service cycles were separated from the highly contaminated samples, such as steam regeneration samples and vapor trap extracts. VOC samples were stored until analysis by AEL or held for a maximum of 14 days or until data validation was completed for that day's VOC analytical results. VOC samples selected for analysis were transferred directly from the refrigerators to small coolers with blue ice for transport to AEL.

SECTION 6

RESULTS AND DISCUSSION

SERVICE CYCLE RESULTS

Cycle 1

Cycle 1 was a direct comparison of the performance of the Ambersorb 563 adsorbent and Filtrasorb 400 GAC. Cycle 1 process operations data are presented in Table 8 and include the influent average VOC concentrations measured over the total operating period for each column. Because of analytical limitations such as elevated TCE concentrations (as discussed in Section 4, page 9) influent average VC and 1 ,I-DCE concentrations were estimated, based on the mass of VC and l,l-DCE that was subsequently recovered during the first steam regeneration.

Process operations data presented for each service cycle are reported as time-weighted averages and cumulative totals for the total operating period. Time-weighted averages were calculated by integration of the cumulative operating time and process operating parameter (such as flow rate) measured during each service cycle.

In addition, during Cycle 1 and throughout the entire study, orange-brown particulate matter (likely iron precipitates) was observed to build up on the column inlet screens, causing higher than expected pressure drops. The particulate matter was either passing through the pilot unit pre-filters or precipitating out from a dissolved state after the pre-filters. The particulate matter was periodically cleaned from the column inlet screens during the study. In spite of the presence of particulate matter, there was no negative impact on the performance of the Ambersorb 563 adsorbent or Filtrasorb 400 GAC.

During Cycle 1, the virgin Ambersorb 563 adsorbent column (A563A) was operated for 17 days at an average flow rate of 0.68 gpm (1.8-minute EBCT) treating a total of 13,700 bed volumes (16,400 gallons) of groundwater. The virgin Filtrasorb 400 GAC column **(F4OOA) was** operated for 31 days at an average flow rate of 0.52 gpm (8.7-minute EBCT) treating a total of 5,070 bed volumes (23,000 gallons) of groundwater.

Cycle 1 process operations data show that the average VOC concentrations in the influent stream exceeded the MCL, except for l,l-DCE. In addition, the pH of the influent groundwater

TABLE 8. CYCLE PROCESS OPERATIONS DATA+

	Ambersorb 563 Adsorbent	Filtrasorb 400 GAC
Column I.D.	A563A	F400
Bed Geometry		
Diameter, inches	4.0	6.0
Length, inches	22.0	37.0
Volume, gallons	I.20	4.53
Orientation	up-flow	up-flow
Process Operations Data		
Total Operation Time, hours	403	735
Total Volume Treated, gallons	16,400	23,000
Total Volume Treated, bed volumes	13,700	5,070
Process Flow Rate, gpm	0.68	0.52
Flow Rate Loading, bed volumes/hr	34	6.9
Hydraulic Loading, gpm/ft²	7.8	2.7
Empty Bed Contact Time, minutes	I.8	8.7
Column Skin Temperature, °F	62	64
Pressure Drop Across Bed, psi	8.4	9.3
Influent Characteristics		
pH, standard units	7.3	7.2
Specific Conductance, μmhos/cm	575	606
Alkalinity, mg/L as CaC03	200	200
VOC Concentrations, μg/L		
Vinyl Chloride	**3.4†**	**3.9†**
I, I -Dichloroethene	**0.31†**	**0.31†**
cis- 1,2-Dichloroethene	312	329
trans- 1,2-Dichloroethene	102	101
Trichloroethene	4,330	4,120
Effluent Characteristics		
pH, standard units	7.3	7.2
Specific Conductance, μmhos/cm	574	608
Alkalinity, mg/L as CaC03	**NA‡**	203

• Time weighted averages and cumulative totals for the total operating period.

† VC and I. l -DCE concentrations estimated based on the mass recovery results for the first steam regeneration of column A563A.

‡ NA = not analyzed.

during Cycle I ranged from 5.9 to 8.1. The pH of the effluent stream from the Ambersorb 563 adsorbent column ranged from 6.3 to 7.8 and the pH of the effluent stream from the Filtrasorb 400 GAC column ranged from 5.8 to 8.1 during Cycle 1. The average conductivity of the influent groundwater and effluent streams ranged from 574 to 608 micromhos per centimeter (umhos/cm). The average alkalinity of the influent groundwater and effluent stream from the Filtrasorb 400 GAC column was 200 and 203 mg/L as $CaCO_3$, respectively. No significant difference was observed between the influent and effluent pH. conductivity, and alkalinity of each column during Cycle 1. Cycle 1 performance results, based on treatment to the MCL, are presented in Table 9. The number of bed volumes treated to the MCL were determined by analysis of the VOC breakthrough and leakage curves for each column. Cycle 1 VOC breakthrough curves for the Ambersorb 563 absorbent and Filtrasorb 400 GAC columns are presented in Figures 4 and 5, respectively. Cycle 1 VOC leakage curves, presented in Figures 6 and 7, expand the values of the ordinate (concentration levels) to a maximum concentration of 20 µg/L, which shows the effluent quality of each column more clearly.

Cycle 1 performance results show that both Ambersorb 563 adsorbent and Filtrasorb 400 GAC adsorbents achieved effluent water quality below the MCL for each VOC. Specifically, the Ambersorb 563 adsorbent column treated approximately 8,120 bed volumes before the first VOC (VC) broke through at a concentration above the MCL. For the Filtrasorb 400 GAC column, approximately 1,730 bed volumes were treated before the first VOC (VC) broke through at a concentration above the MCL. During Cycle 1, concentrations of 1 ,l-DCE and trans- 1 ,2-DCE in the effluent of the Ambersorb 563 adsorbent column and trans-1,2-DCE in the effluent of the Filtrasorb 400 GAC column never exceeded the MCL.

A comparison of bed volumes treated to the MCL for each VOC shows that, while operating at approximately five times the flow rate (l/5 the EBCT), Ambersorh 563 adsorbent treated approximately two to five times the bed volumes of groundwater as Filtrasorb 400 GAC.

Cvcle 2

Cycle 2 was conducted using two Ambersorb adsorbent columns in series. A virgin Ambersorb 563 adsorbent column (A563B) was placed in the lead position, and the steam regenerated Ambersorb 563 adsorbent column (A563A-1) from Cycle 1 was placed in the lag position.

Cycle 2 process operations data are presented in Table 10 and include the influent average VOC concentrations measured over the total operating period. Because of the analytical limitations discussed in Section 4, page 9, the influent average 1 ,l-DCE concentrations were estimated based on the mass of that was subsequently recovered during the second steam regeneration.

TABLE 9. CYCLE I PERFORMANCE RESULTS

Volatile Organic Compound	MCL+ µg/L	Bed Volumes Treated to MCL: Ambersorb 563 Adsorbent	Bed Volumes Treated to MCL: Filtrasorb 400 GAC	Difference Factor†
Vinyl Chloride	2	8,120	1,730	4.7
,1-Dichloroethene	7	>13,700	>5,070	-2.7
cis- 1,2-Dichloroethene	70	9,690	3,710	2.6
trans- 1,2-Dichloroethene	100	>13,700	5,040	>2.7
Trichloroethene	5	8,190	4,850	7

* Maximum Contaminant Levels from National Revised Primary Drinking Water Regulations, 40 CFR 141.61.

† Difference Factor = (BV Treated by Ambersorb 563 Adsorbent)/(BV Treated by Filtrasorb 400 GAC).

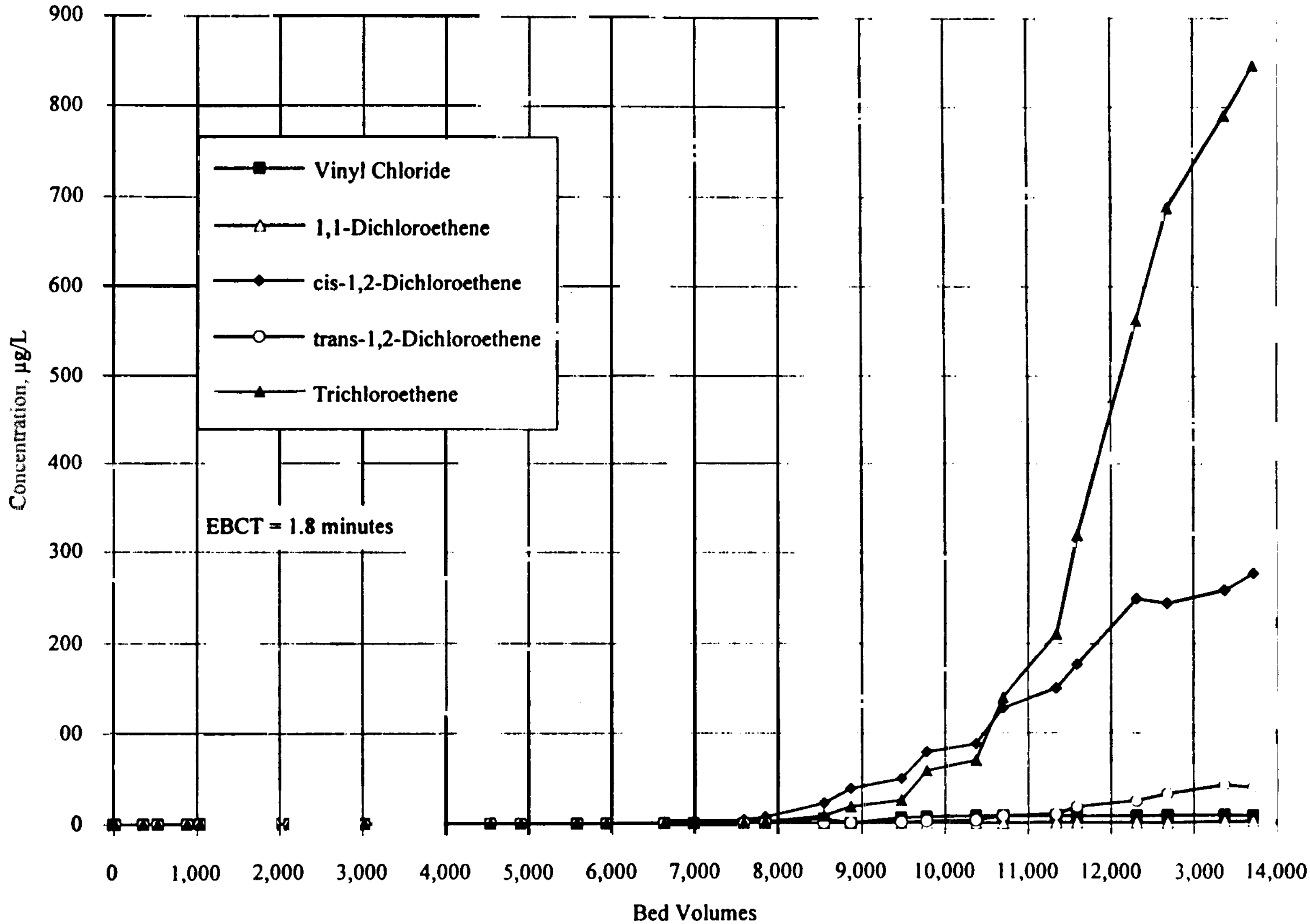

Figure 4. Cycle I Ambersorb 563 Adsorbent VOC Breakthrough Curves

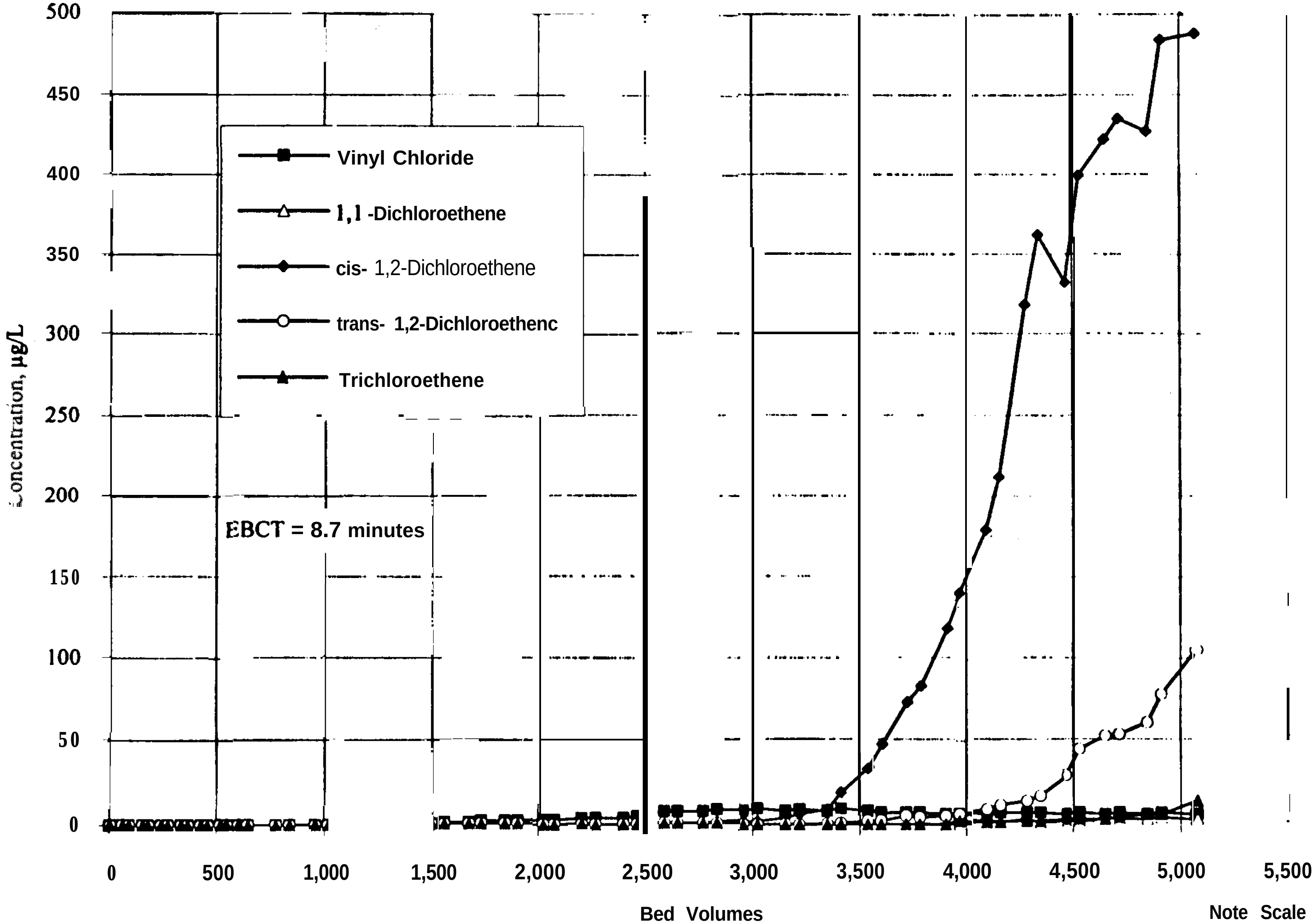

Figure 5. Cycle Filtrasorb 400 GAC VOC Breakthrough Curves

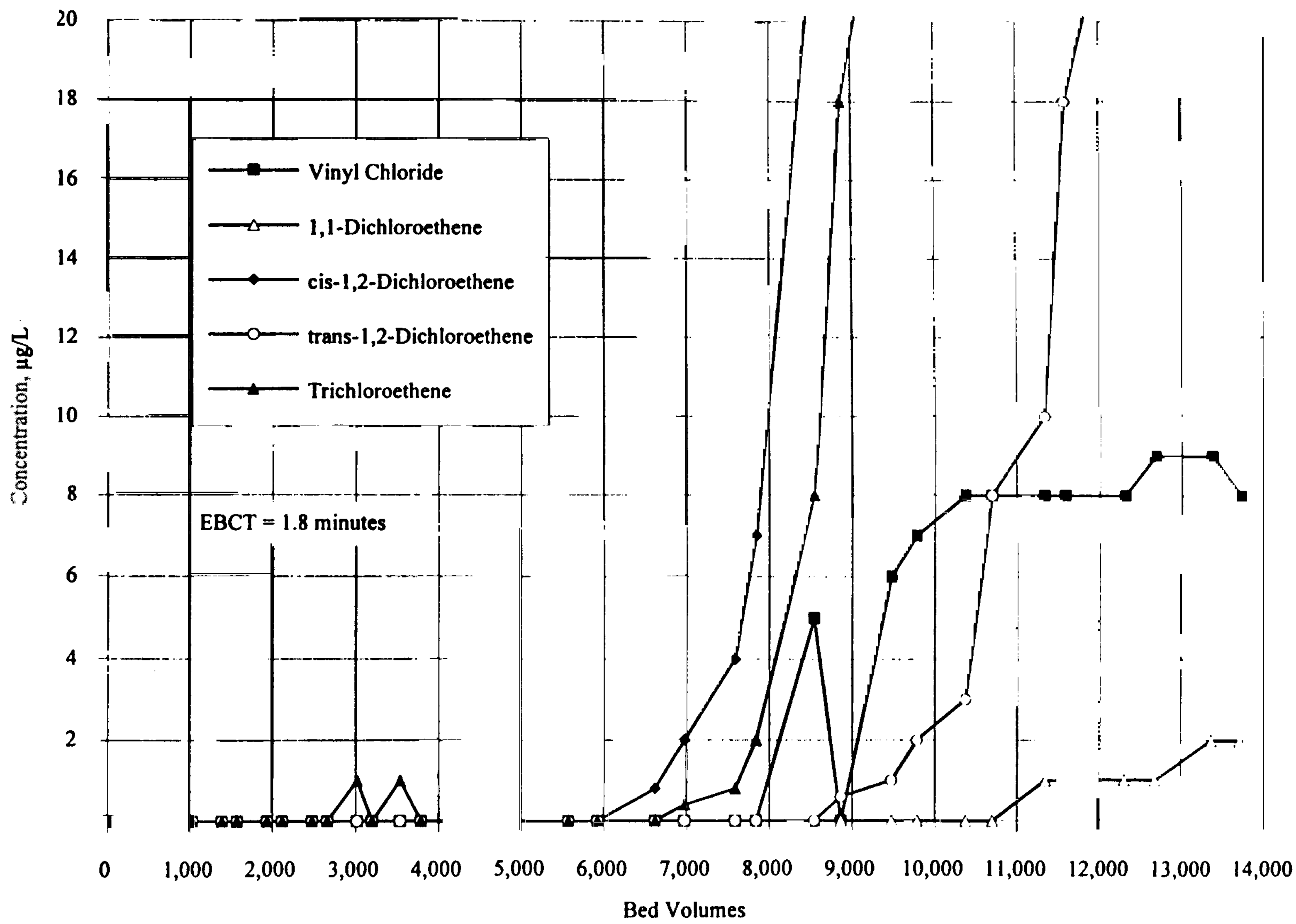

Figure 6. Cycle 1 Ambersorb 563 Adsorbent VOC Leakage Curves (Expanded Ordinate)

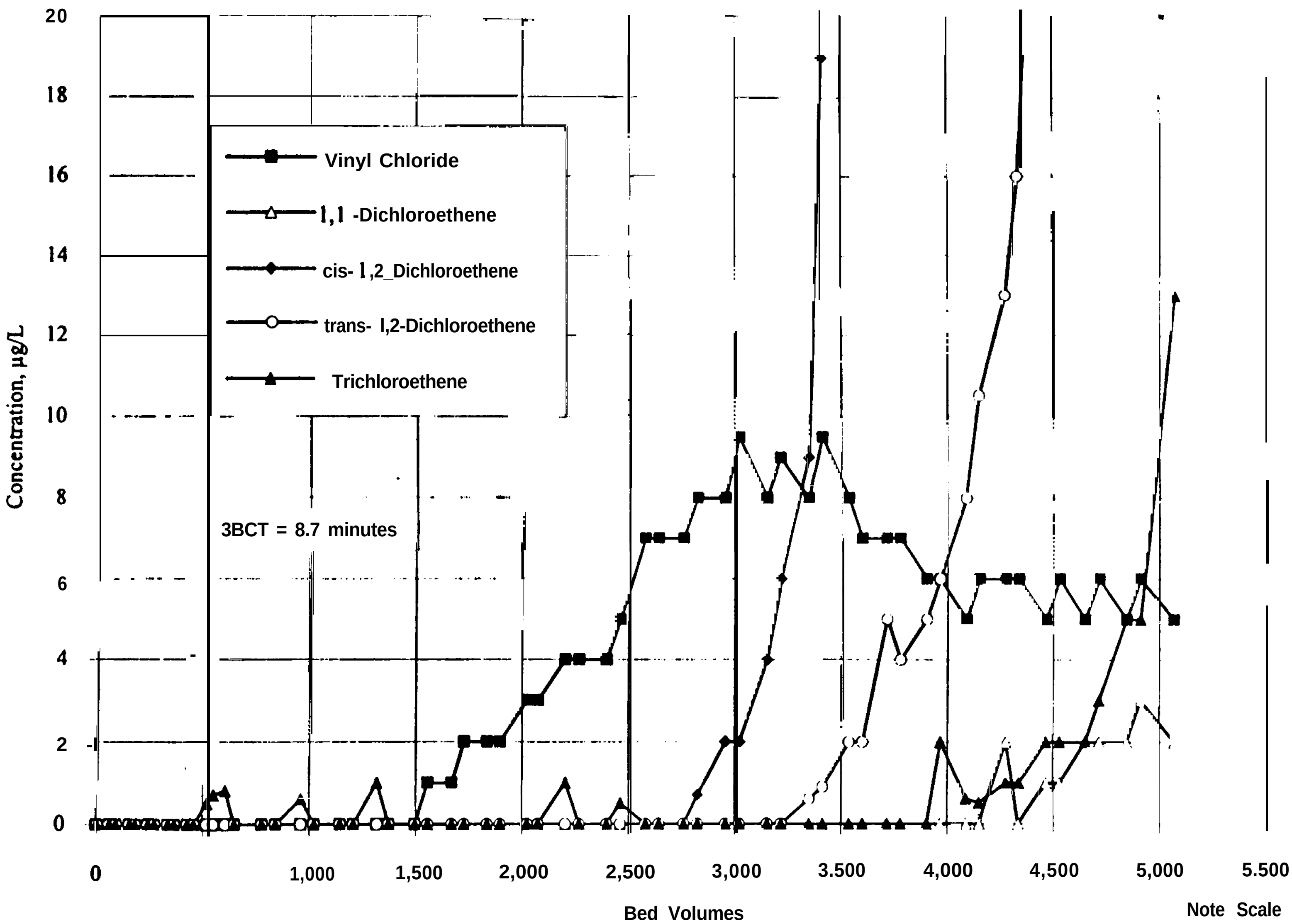

Figure 7. Cycle Filtrasorb 400 GAC VOC Leakage Curves (Expanded Ordinate)

TABLE IO. CYCLE 2 PROCESS OPERATIONS DATA'

	Lead	Lag	Series
Column I.D.	A563B	A563A-I	A563B & A563A-
Bed Geometry			
Diameter, inches	4.0	4.0	4.0
Length, inches	22.0	22.0	44.0
Volume, gallons	1.20	I .20	2.39
Orientation	up-flow	up-flow	up-flow
Process Operations Data			
Total Operation Time, hours	307	307	307
Total Volume Treated, gallons	15,200	15,200	15,200
Total Volume Treated, bed volumes	12,700	12,700	6,370
Process Flow Rate, gpm	0.83	0.83	0.83
Flow Rate Loading, bed volumes/hr	41	41	20.8
Hydraulic Loading, gpm/ft^2	9.5	9.5	9.5
Empty Bed Contact Time, minutes	1.4	1.4	2.9
Column Skin Temperature, °F	70	70	70
Pressure Drop Across Bed, psi	15.0	8.0	23.0
Influent Characteristics			
pH, standard units	6.7	6.7	6.7
Specific Conductance, µmhos/cm	654	654	654
VOC Concentrations, µg/L			
Vinyl Chloride	4.9	3.1	4.9
1.1 -Dichloroethene	**6.33†**	**0.10†**	**6.33†**
cis- 1,2-Dichloroethene	353	29	353
trans- 1,2_Dichloroethene	122	1	122
Trichloroethene	4,510	18	4,510
Emuent Characteristics			
pH, standard units	6.7	6.7	6.7
Specific Conductance, µmhos/cm	654	653	653

• Time weighted averages and cumulative totals for the total operating period.

† I.I-DCE concentrations estimated based on the mass r~~vcry results for the first steam regeneration of column A563B.

During Cycle 2. the system was operated for 13 days at an average flow rate of 0.83 gpm and treated a total of 15,200 gallons of groundwater. For the individual lead or lag columns, this corresponds to operating at a 1.4-minute EBCT for a total 12,700 bed volumes. For the total system in series, this corresponds to operating at a 2.9-minute EBCT for a total 6,370 bed volumes.

Cycle 2 process operations data show that the average VOC concentrations in the influent stream exceeded the MCL, except l,l-DCE. In addition. the pH of the influent and effluent streams for each column ranged from 6.2 to 7.6, and the average conductivity of the influent and effluent streams was approximately 654 umhos/cm. No significant difference was observed between the influent and effluent pH and conductivity of each column during Cycle 2.

Cycle 2 performance results, based on treatment to the MCL, are presented in Table 11. The number of bed volumes treated to the MCL were determined by analysis of the VOC breakthrough and leakage curves for the lead column. VOC breakthrough and leakage curves for the lead column, representing a 1.4-minute EBCT, arc presented in Figures 8 and 9, respectively. The VOC leakage curves for the lag Ambersorb adsorbent column, representing a 2.9-minute EBCT, are presented in Figure 10.

Cycle 2 performance results show that both the lead and regenerated lag Ambersorb adsorbent columns achieved effluent water quality below the MCL for each VOC. Specifically, the lead Ambersorb adsorbent column treated approximately 8,320 bed volumes before the first VOC (VC) broke through at a concentration above the MCL. During Cycle 2, concentrations of 1.1~DCE and trans-1 ,2-DCE in the effluent of the lead Ambersorb adsorbent column never exceeded the MCL. Because virgin Ambersorb 563 adsorbent was loaded in the lead column and the influent VOC concentrations were similar to those measured in Cycle 1, the bed volumes treated to the MCL during Cycle 2 are similar to the Cycle 1 results.

Cycle 3

Cycle 3 was also conducted using two Ambersorb 563 adsorbent columns in series. The lag Ambersorb adsorbent column (A563A-1) from Cycle 2 was placed in the lead position for Cycle 3. The steam-regenerated lead Amber-sorb adsorbent column (A563B-1) from Cycle 2 was placed in the lag position.

Cycle 3 process operations data, which are presented in Table 12, include the influent average VOC concentrations measured over the total operating period. Because of the analytical limitations discussed in Section 4, the influent average 1 ,l -DCE concentrations were estimated based on the mass of 1.1~DCE that was subsequently recovered during the third steam regeneration.

TABLE I 1. CYCLE 2 PERFORMANCE RESULTS

Volatile Organic Compound	MCL' µg/L	Bed Volumes Treated to MCL
Vinyl Chloride	2	8,320
1,1-Dichloroethene	7	>12,700
cis-1,2-Dichloroethene	70	10,600
trans-1,2-Dichloroethene	100	>12,700
Trichloroethene	5	9,400

• Maximum Contaminant Levels from National Revised Primary Drinking Water Regulations, 40 CFR 141.61

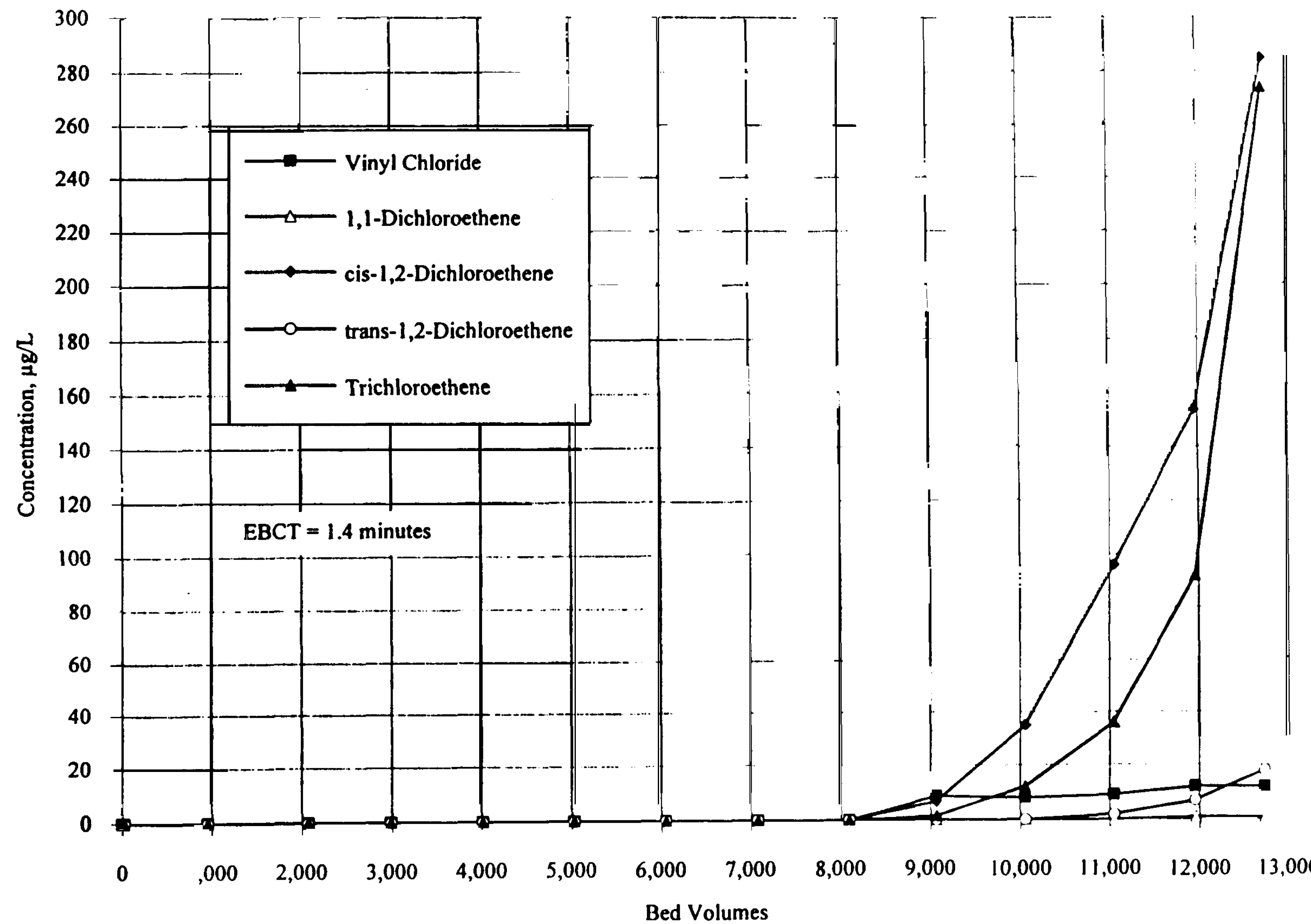

Figure 8. Cycle 2 Ambersorb 563 Adsorbent Lead Column VOC Breakthrough Curves

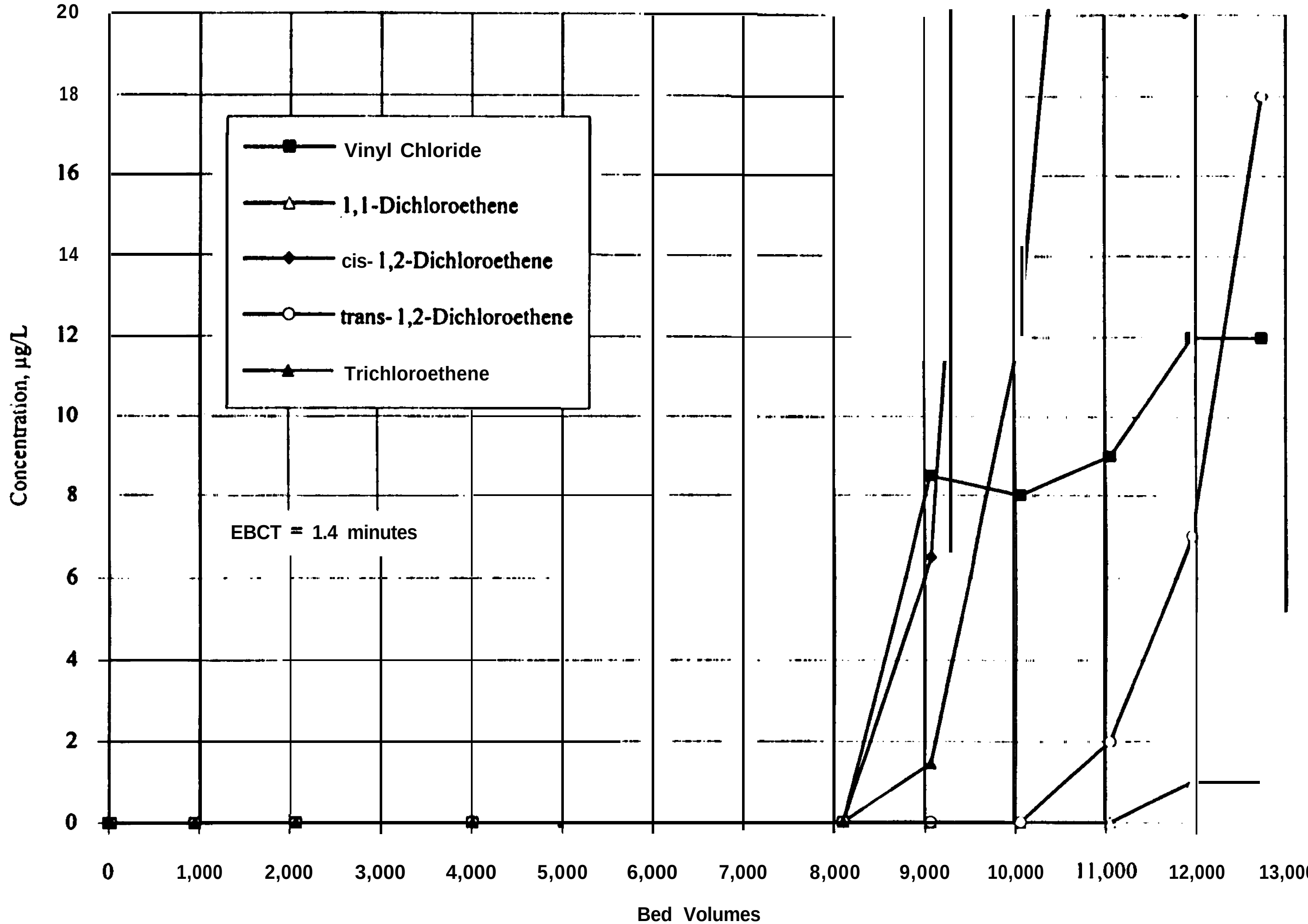

Figure 9. Cycle 2 Ambersorb 563 Adsorbent Lead Column VOC Leakage Curves

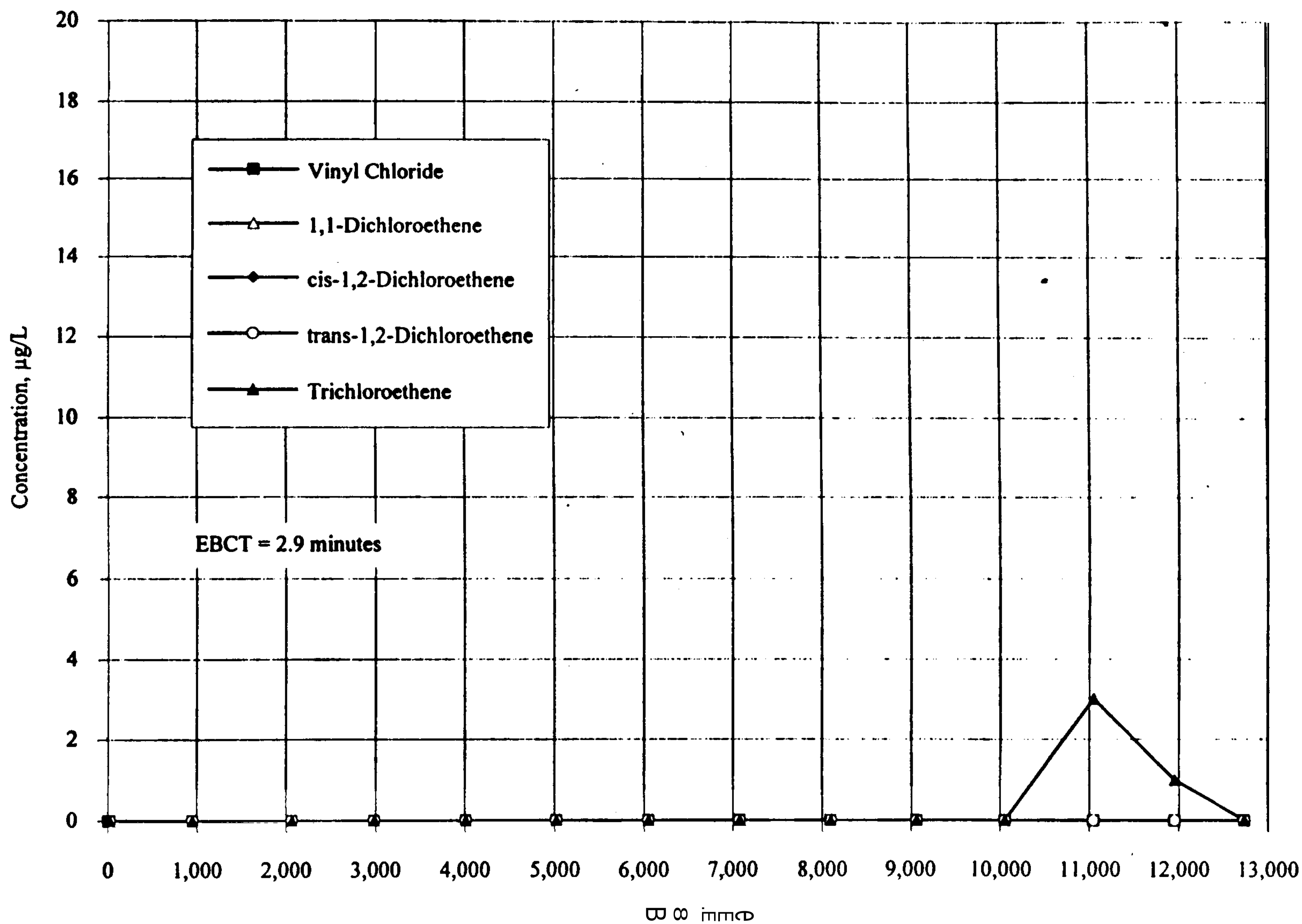

Figure10. Cycle 2 Ambersorb 563 Adsorbent Lag Column VOC Leakage Curves

TABLE 12. CYCLE 3 PROCESS OPERATIONS DATA'

	Lead	Lag	Series
Column I.D.	A563A-I	A563B-I	A563A- I & A563B- I
Bed Geometry			
Diameter, inches	4.0	4.0	4.0
Length, inches	22.0	22.0	44.0
Volume, gallons	I.20	1.20	2.39
Orientation	up-flow	up-flow	up-flow
Process Operations Data			
Cycle Operation Time, hours	I88	188	I88
Cycle Volume Treated, gallons	10,300	10,300	10,300
Cycle Volume Treated, bed volumes	8.600	8,600	4,300
P .:!oad Volume Treated, bed volumes†	4,000	--	
T. ·al Volume Treated, bed volumes	12,600	8,600	4,300
Pr .ess Flow Rate, gpm	0.91	0.91	0.91
Flow Rate Loading, bed volumes/hr	46	46	22.9
Hydraulic Loading, gpm/ft²	IO.5	10.5	10.5
Empty Bed Contact Time, minutes	1.3	1.3	2.6
Column Skin Temperature, °F	68	68	68
Pressure Drop Across Bed, psi	16.0	6.1	22.1
Influent Characteristics			
pH, standard units	7.0	6.8	7.0
Specific Conductance, µmhos/cm	628	631	628
VOC Concentrations, µg/L			
Vinyl Chloride	5.7	5.8	5.7
1,l -Dichloroethene		0.15†	6.10-t
cis-,l,2-Dichloroethene	373	70	373
trans- l ,2_Dichloroethene	116	5	116
Trichloroethene	3.600	157	3,600
Effluent Characteristics			
pH, standard units	6.8	6.9	6.9
Specific Conductance, µmhos/cm	631	624	624

• Time weighted averages and cumulative totals for the total operating period.

t Prcloadcd volume treated based on Cycle 2 lead column VC leakage profile.

‡ I.I-DCE concentrations estimated based on the mass recovery results for the first steam regeneration of column A563A-I,

During Cycle 3, the system was operated for approximately 8 days at an average flow rate of 0.91 gpm and treated a total of 10,300 gallons of groundwater. For the individual lead or lag columns, this corresponds to operating at a 1.3-minute EBCT for a total 8,600 bed volumes. For the total system in series, this corresponds to operating at a 2.6-minute EBCT for a total 4.300 bed volumes.

As shown in Table 12, a preload volume of 4.000 bed volumes was added **to the** cycle volume treated for the lead Ambersorb adsorbent column (A563A-1). The preload volume accounts for the bed volumes of water treated during the previous cycle (Cycle 2) when A563A- 1 was in the lag position and was loaded with VOC leakage from the Cycle 2 lead column.

Cycle 3 process operations data show that the average VOC concentrations in the influent stream exceeded the MCL, except for 1,l DCE In addition, the pH of the influent and effluent streams for each column ranged from 6.5 to 7.5, and the average conductivity of the influent and effluent stteams ranged from 624 to 631 umhos/cm No significant difference was observed between the influent and effluent pH and conductivity of each column during Cycle 3.

Cycle 3 performance results based on treatment to the MCL are presented in Table 13. The number of bed volumes treated to the MCL was determined by analysis of the VOC breakthrough and leakage curves for the lead column, which include the estimated preload volume. VOC breakthrough and leakage curves for the lead column, representing a 1.3-minute EBCT, are presented in Figures 11 and 12, respectively. The VOC leakage curves for the lag Ambersorb adsorbent column, representing a 2.6-minute EBCT, are presented in Figure 13.

Cycle 3 performance results show that both the regenerated lead and regenerated lag Ambersorb adsorbent columns achieved effluent water quality below the MCL for each VOC. Specifically, the lead Ambersorb adsorbent column treated approximately 5,130 bed volumes before the first VOC (VC) broke through at a concentration above the MCL. During Cycle 3, concentrations of **1**,l-DCE and trans-1,2-DCE in the effluent of the lead Ambersorb adsorbent column never exceeded the MCL. The estimated average vinyl chloride concentration in **the** influent increased from 4.9 **μg/L** during Cycle 2 to 5.7 **μg/L** during Cycle 3, which may have decreased the number of bed volumes treated to the MCL during Cycle 3.

Cycle 4

Cycle 4 also was conducted using two Ambersorb adsorbent columns in series. The lag Ambersorb adsorbent column (A563B-1) from Cycle 3 was placed in the lead position for Cycle 4. The steam-regenerated lead Ambersorb adsorbent column (A563A-2) from Cycle 3 was placed in the lag position.

TABLE 13. CYCLE 3 PERFORMANCE RESULTS

Volatile Organic Compound	MCL+ µg/L	Bed Volumes Treated to MCL†
Vinyl Chloride	2	
1, l -Dichloroethene		>12.600
cis- l ,2-Dichloroethene	70	
trans- l ,2-Dichloroethene	100	>12,600
Trichloroethene	5	

• Maximum Contaminant Levels from National Revised Primary Drinking Water Regulations, 40 CFR 141.61

† Includes bed volumes preloaded during Cycle 2.

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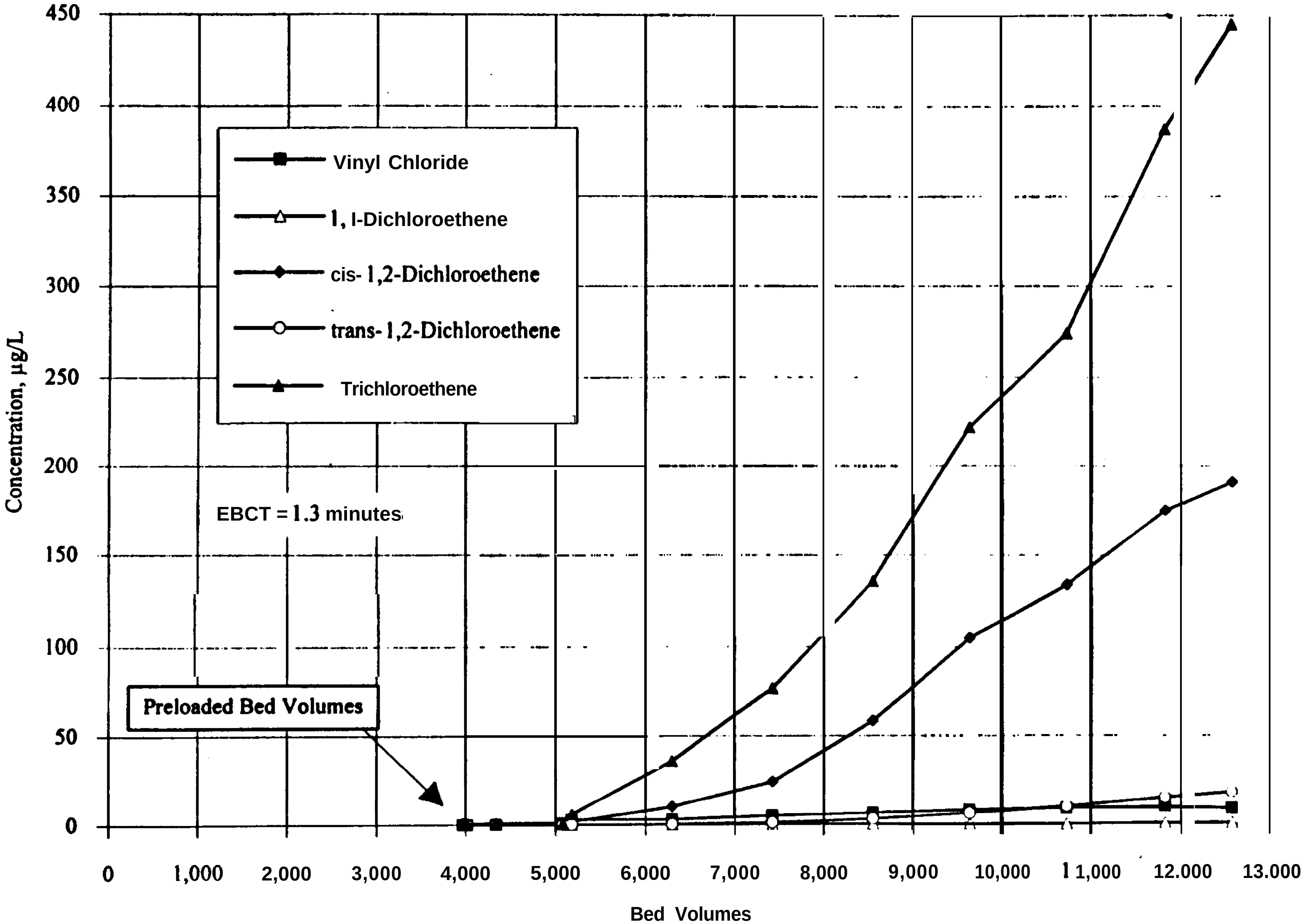


Figure 1 l. Cycle 3 Ambersorb 563 Adsorbent Lead Column VOC Breakthrough Curves

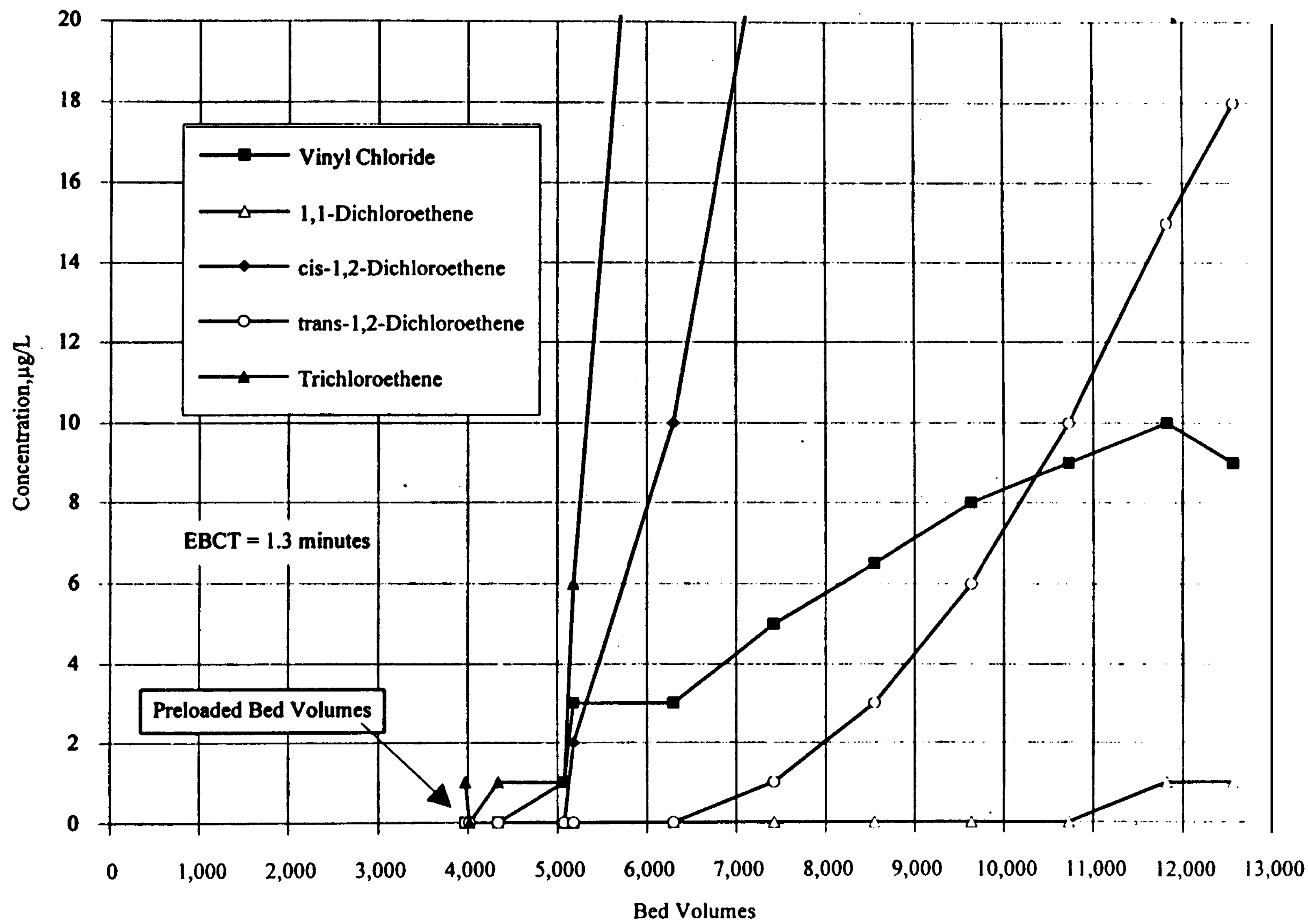


Figure 12. Cycle 3 Ambersorb 563 Adsorbent Lead Column VOC Leakage Curves

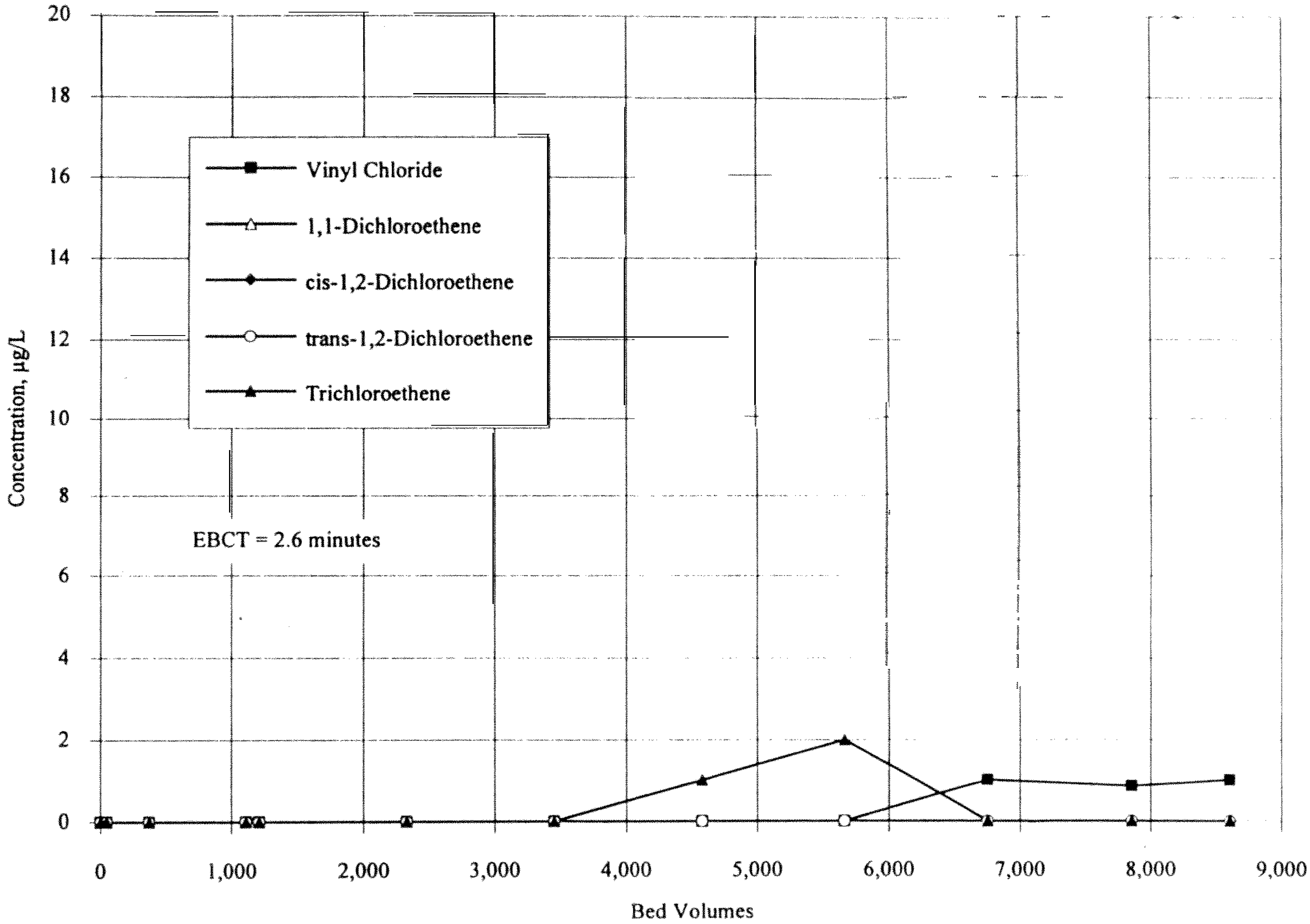


Figure 13. Cycle 3 Ambersorb 563 Adsorbent Lag Column VOC Leakage Curves

Cycle 4 process operations data are presented in Table 14 and include the influent average VOC concentrations measured over the total operating period. Because of the analytical limitations discussed in Section 4. page 9, the influent average VC and l,l-DCE concentrations were estimated based on reanalysis of selected influent samples at lower dilutions.

During Cycle 4, the system was operated for approximately 13 days at an average flow rate of 0.82 gpm and treated 15,300 gallons of groundwater. For the individual lead or lag columns, this corresponds to operating at a 1.5-minute EBCT for a total 12,800 bed volumes. For the total system in series, this corresponds to operating at a 2.9-minute EBCT for a total 6,390 bed volumes.

As shown in Table 14, a preload volume of 4,000 bed volumes was added to the cycle volume treated for the lead Ambersorb adsorbent column (A563B-1). The preload volume accounts for the bed volumes of water treated during the previous cycle (Cycle 3) when A563B- 1 was in the lag position and was loaded with VOC leakage from the Cycle 3 lead column.

Cycle 4 process operations data show that the average VOC concentrations in the influent stream exceeded the MCL, except for 1 ,I-DCE and trans-1,2-DCE. In addition, the pH of the influent and effluent streams for each column ranged from 6.9 to 8.0 and the average conductivity of the influent and effluent streams was approximately 666 µmhos/cm. No significant difference was observed between the influent and effluent pH and conductivity of each column during Cycle 4.

Cycle 4 performance results, based on treatment to the MCL, are presented in Table 15. The number of bed volumes treated to the MCL was determined by analysis of the VOC breakthrough and leakage curves for the lead column, which include the estimated preload volume. VOC breakthrough and leakage curves for the lead column, representing a 1.5minute EBCT, are presented in Figures 14 and 15, respectively. The VOC leakage curves for the lag Ambersorb adsorbent column, representing a 2.9-minute EBCT, are presented in Figure 16.

Cycle 4 performance results show that both the regenerated lead and the twice-regenerated lag Ambersorb adsorbent columns achieved effluent water quality below the MCL for each VOC. Specifically, the lead Ambersorb adsorbent column treated approximately 5,010 bed volumes before the first VOC (VC) broke through at a concentration above the MCL. Concentrations of trans-1,2-DCE in the effluent of the lead Ambersorb adsorbent column never exceeded the MCL during Cycle 4. Furthermore, the influent average VC concentration increased from 5.7 µg/L during Cycle 3 to 10 µg/L during Cycle 4, which may have decreased the number of bed volumes treated to the MCL during Cycle 4. The leakage curve for the lag column in Cycle 4, shown in Figure 16, indicates some leakage of VC above the MCL after 7,500 bed volumes. This may be because the previous steam regeneration was performed at the lowest temperature.

TABLE 14. CYCLE 4 PROCESS OPERATIONS DATA*

	Lead	Lag	Series
Column I.D.	A563B- I	A563A-2	A563B- I & A563A-2
Bed Geometry			
Diameter, inches	4.0	4.0	4.0
Length, inches	32.0	22.0	44.0
Volume, gallons	I.20	I.20	2.39
Orientation	up-flow	up-flow	up-flow
Process Operations Data			
Cycle Operation Time, hours	311	311	311
Cycle Volume Treated, gallons	15.300	15,300	15,300
Cycle Volume Treated, bed volumes	12.800	12,800	6,390
Preload Volume Treated, bed volumes†	4.000	--	--
Total Volume Treated, bed volumes	16,800	12,800	6,390
Process Flow Rate, gpm	0.82	0.82	0.82
Flow Rate Loading, bed volumes/hr	41	41	20.6
Hydraulic Loading, gpm/ft²	9.4	9.4	9.4
Empty Bed Contact Time, minutes	I.5	I.5	2.9
Column Skin Temperature, °F	68	68	68
Pressure Drop Across Bed, psi	14.0	5.6	19.7
Influent Characteristics			
pH, standard units	7.7	7.7	7.7
Specific Conductance, μmhos/cm	666	666	666
VOC Concentrations, μg/L			
Vinyl Chloride	10.1	8.8	10.1
1, I-Dichloroethene	0.13-t		0.13†
cis- I &Dichloroethene	350	120	350
trans- 1,2_Dichloroethene	85	7	85
Trichloroethene	3,920	268	3,920
Effluent Characteristics			
pH, standard units	7.7	7.7	7.7
Specific Conductance, μmhos/cm	666	667	667

• Time weighted averages and cumulative totals for the total operating period

† Preloadcd volume treated based on Cycle 3 lead column VC leakage profile

‡ VC and I,I-DCE concentrations estimated based on re-analysis of sclcctcd influent at lower dilution.

TABLE IS. CYCLE 4 PERFORMANCE RESULTS

Volatile Organic Compound	MCL* µg/L	Bed Volumes Treated to MCL†
Vinyl Chloride	2	
,I-Dichloroethene	7	
cis- 1,2-Dichloroethene	70	11,140
trans- 1,2-Dichloroethene	100	>16,800
Trichloroethene	5	

• Maximum Contaminant Levels From National Revised Primary Drinking Water Regulations, 40 CFR 14 l .61

† Includes bed volumes preloaded during Cycle 3.

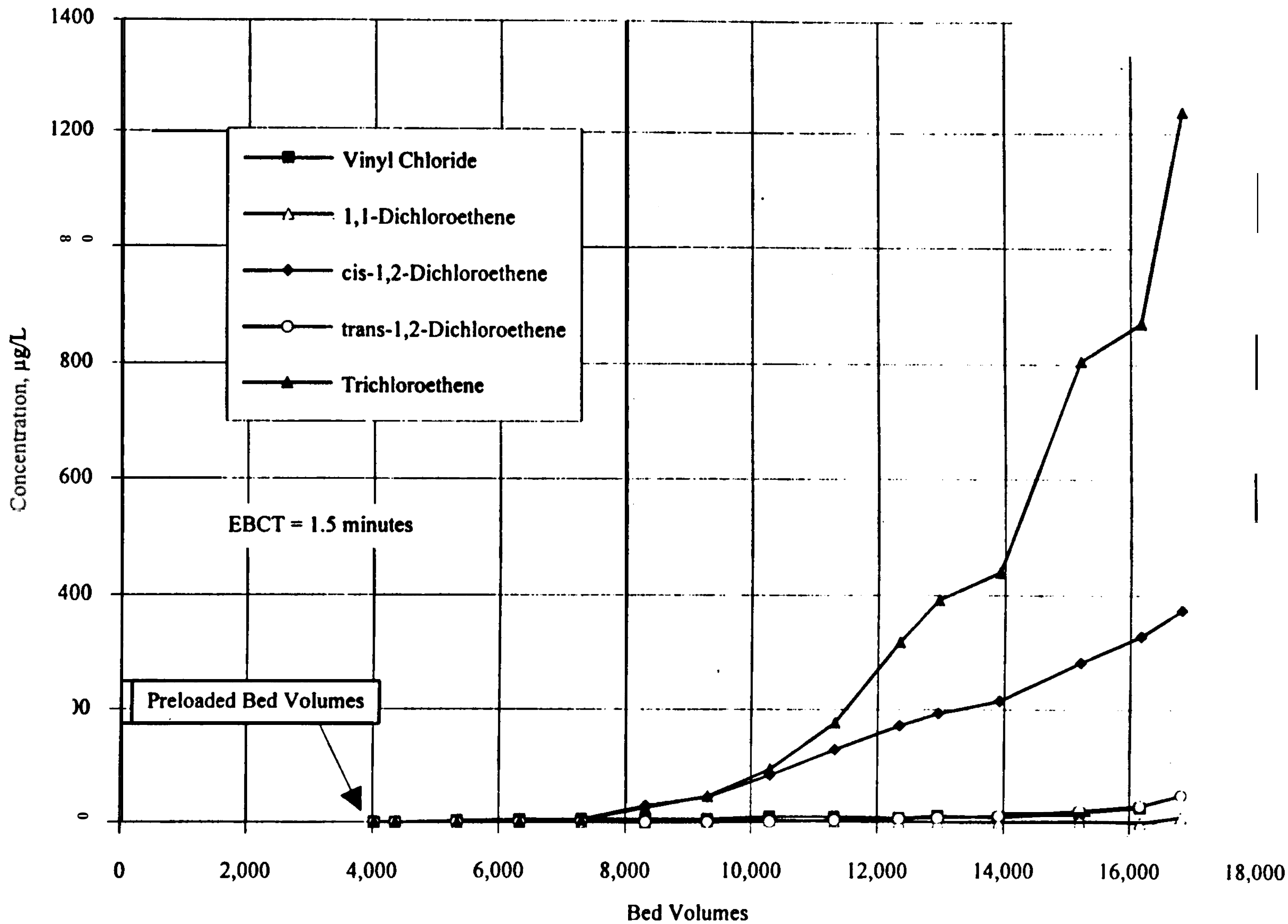


Figure 14. Cycle 4 Ambersorb 563 Adsorbent Lead Column VOC Breakthrough Curves

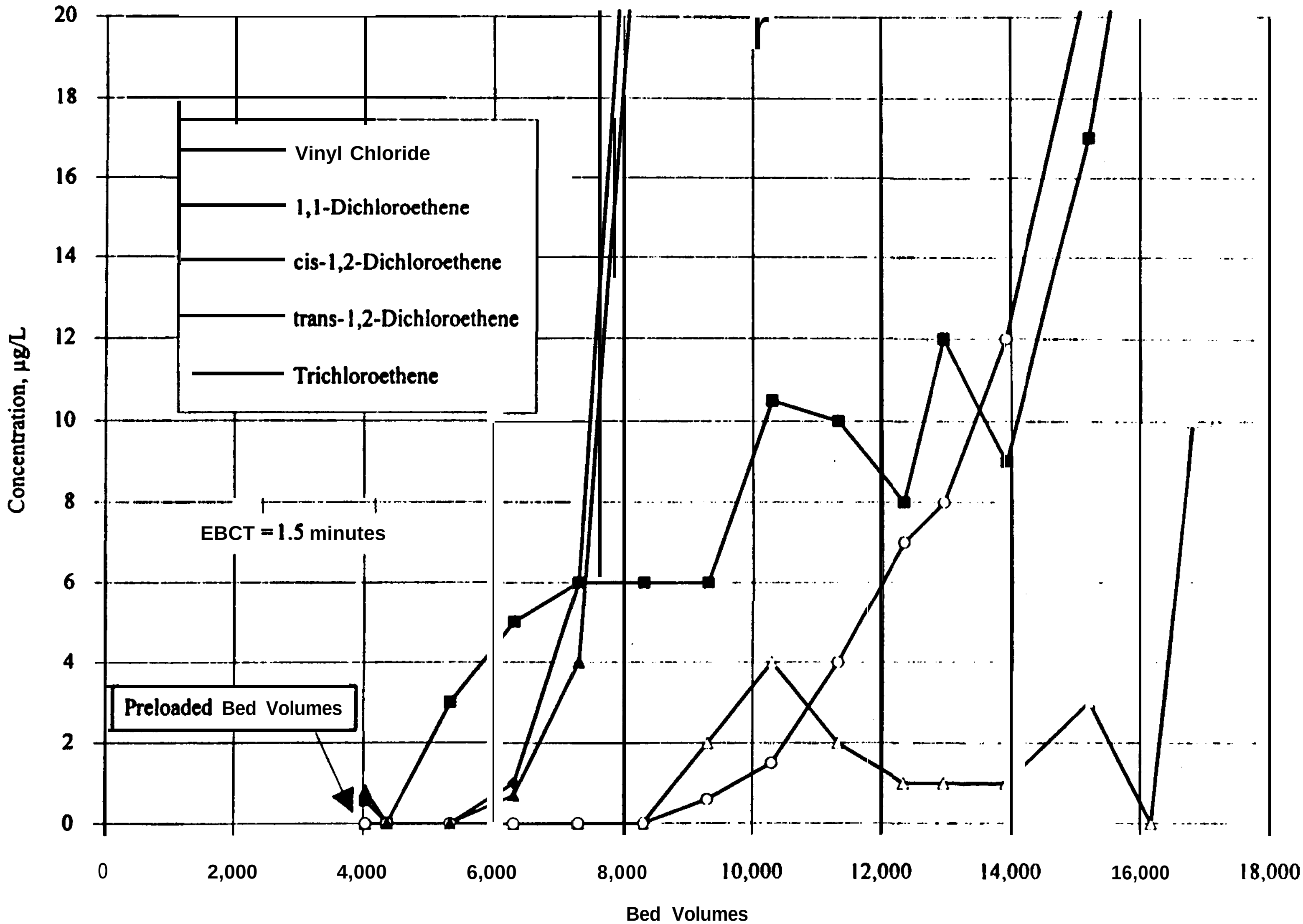


Figure 15. Cycle 4 Ambersorb 563 Adsorbent Lead Column VOC Leakage Curves

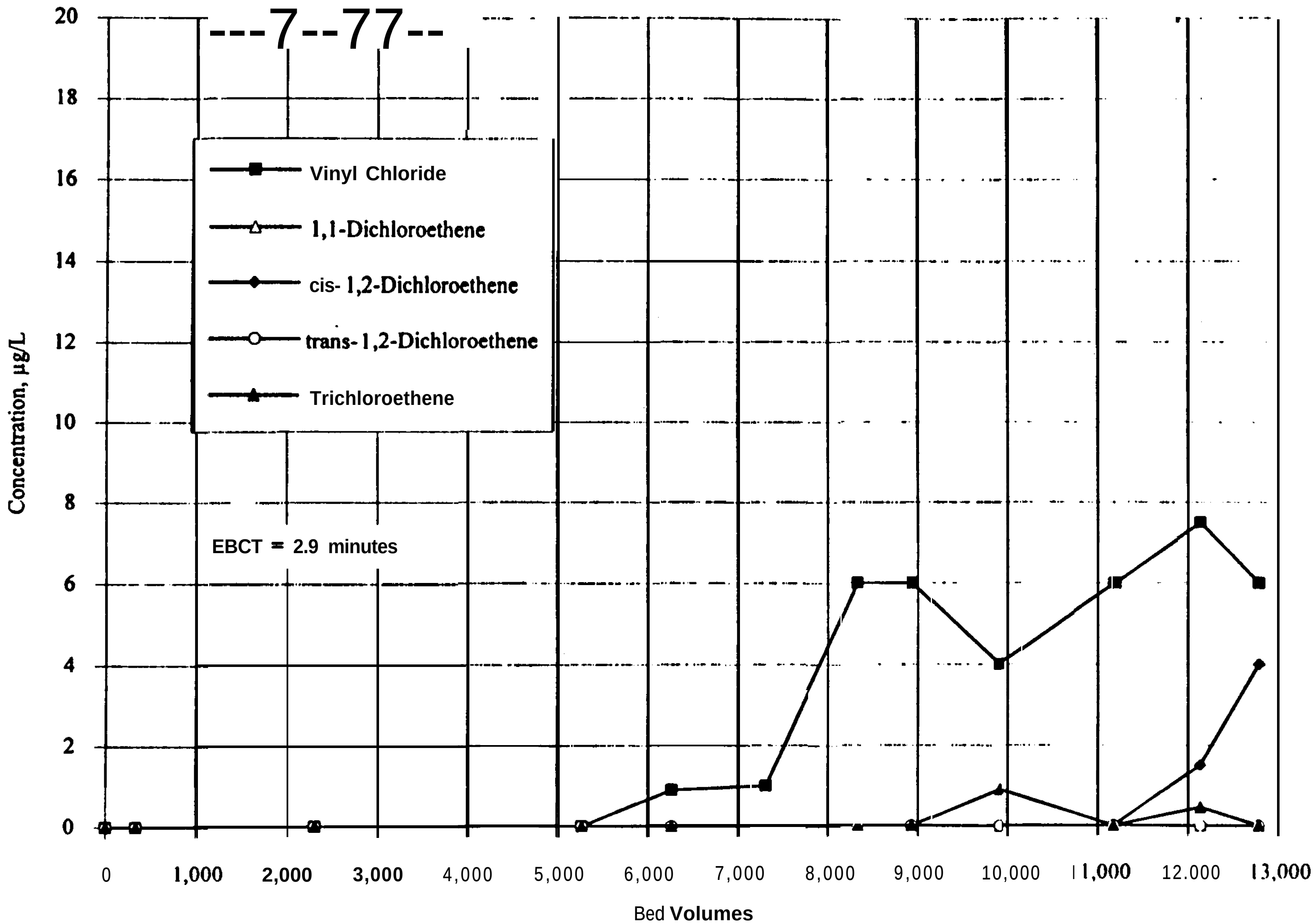


Figure 16. Cycle 4 Ambersorb 563 Adsorbent Lag Column VOC Leakage Curves

STEAM REGENERATION RESULTS

Steam regeneration was conducted on the Ambersorb 563 adsorbent column at the end of Cycle 1 and on the lead Ambersorb adsorbent columns at the end of Cycles 2 and 3 to evaluate the steam regeneration efficiency and the effect on subsequent Ambersorb adsorbent performance. The steam regenerations were also conducted at various temperatures to evaluate the effect of regeneration temperature on contaminant recovery. Process operations data for the steam regenerations are presented in Table 16.

The condensate produced during each regeneration consisted of a visible and separable concentrated organic phase and a WC-saturated aqueous phase. To ensure that there was no VOC vapor discharge during each steam regeneration, a trap containing Ambersorb 563 adsorbent was used on the vapor discharge from the condenser. The VOC mass recovery results reflect the VOC levels measured for each phase (aqueous, organic, vapor).

The VOC mass recovery results, presented in the following subsections, were based on the VOC mass adsorbed onto the lead Ambersorb adsorbent column during each service cycle and the VOC mass recovered from each subsequent steam regeneration. The VOC mass adsorbed onto the lead Ambersorb adsorbent column was calculated by integration of the cumulative volume and VOC concentrations measured in the influent stream during each service cycle. The VOC mass recovered during each subsequent steam regeneration was calculated by integration of the cumulative volumes and VOC concentrations measured in each phase (aqueous, organic, and vapor). Integration was conducted using the trapezoid rule. VOC concentrations reported as less than the detection limit were assigned a zero value for purposes of integration.

Steam Regeneration 1

Steam Regeneration 1 was conducted on column A563A at an average temperature of 307 °F over a 17-hour period and generated approximately 9.1 gallons (7.6 bed volumes) of condensate. Steam flow rates (as condensate) were increased incrementally over the operating period from 0.23 BV/hr to 0.82 BV/hr, as shown in Table 16.

VOC mass recovery results for Steam Regeneration I (see Table 17) show individual VOC mass recoveries for the 3 bed volumes of condensate and for the total bed volumes of condensate produced. Table 17 also shows the VOC mass recoveries for each condensate phase. Total VOC mass recovery profiles for Steam Regeneration 1 are presented in Figure 17. The VC and 1.1-DCE mass recoveries were assumed to be 100% as the basis for estimating Cycle 1 influent VC and 1,1-DCE concentrations.

Steam Regeneration 1 recovery results show that 73% of the total VOC mass was recovered in the first 3 bed volumes and that 78% was recovered overall. Approximately 85% of the total VOC mass recovered was collected in a separable organic phase.

TABLE 16. STEAM REGENERATIONS PROCESS OPERATIONS DATA*

Steam Regeneration	Regeneration 1	Regeneration 2	Regeneration 3
Column I.D.	A563A-0	A563B-0	A563A-1
Bed Geometry			
Diameter, inches	4.0	4.0	4.0
Length, inches	22.0	22.0	22.0
Volume, gallons	1.20	1.20	1.20
Orientation	down-flow	down-flow	down-flow
Process Operations Data			
Total Operation Time, hours	17.4	17.1	18.5
Total Volume Condensate Generated, gallons	9.1	8.4	10.7
Total Volume Condensate Generated, bed volumes	7.6	7.0	8.9
Column Temperature, °F	307	293	280
Steam Generator Pressure, psi	58	54	53
Column Inlet Pressure, psi	52	46	41
Condensate pH, standard units	4.5	4.1	5.5
Condensate Conductivity, umhos/cm	489	344	280
Steam Regeneration Flow Rate 1†			
Steam Flow Rate as Condensate, BV/hr	0.23	0.25	0.28
Time at Reported Flow Rate, hours	7.1	5.9	6.5
Steam Regeneration Flow Rate 2†			
Steam Flow Rate as Condensate, BV/hr	0.41	0.35	0.43
Time at Reported Flow Rate, hours	6.3	5.9	6.3
Steam Regeneration Flow Rate 3†			
Steam Flow Rate as Condensate, BV/hr	0.82	0.80	0.82
Time at Reported Flow Rate, hours	4.0	4.5	5.7

* Time weighted averages and cumulative totals for the total operating period.

† Average value for specified time interval.

TABLE 17. STEAM REGENERATION 1 V0C MASS RECOVERY RESULTS

	After 3 Bed Volumes					After 7.6 Bed Volumes (Total)				
	Mass Recovery, %				Fraction	Mass Recovery, %				Fraction
Volatile Organic Compound	Aqueous Phase	Organic Phase	Vapor Phase	Total Phases	in Organic Phase, %	Aqueous Phase	Organic Phase	Vapor Phase	Total Phases	in Organic Phase, %
Vinyl Chloride	27.9	0.0	72.1	100.0*	0.0	27.9	0.0	72.1	100.0*	0.0
I, I-Dichloroethene	0.0	0.0	100.0*	100.0*	0.0	0.0	0.0	100.0’	100.0*	0.0
cis-l,2-Dichloroethene	12.3	54.5	1.3	68.2	80.0	12.4	54.5	1.3	68.2	80.0
trans- 1,2-Dichloroethene	8.1	68.2	2.3	78.6	86.8	8.1	68.2	2.3	78.6	86.8
Trichloroethene	7.1	66.2	0.2	73.4	90. I	11.4	67.0	0.2	78.5	85.3
Total V0Cs	7.4	65.6	0.3	73.2	89.5	11.3	66.3	0.3	78.0	85. I

* VC and I,I-DCE total recovery assumed to be 100% as basis for estimating Cycle I VC and I ,I-DCE concentrations.

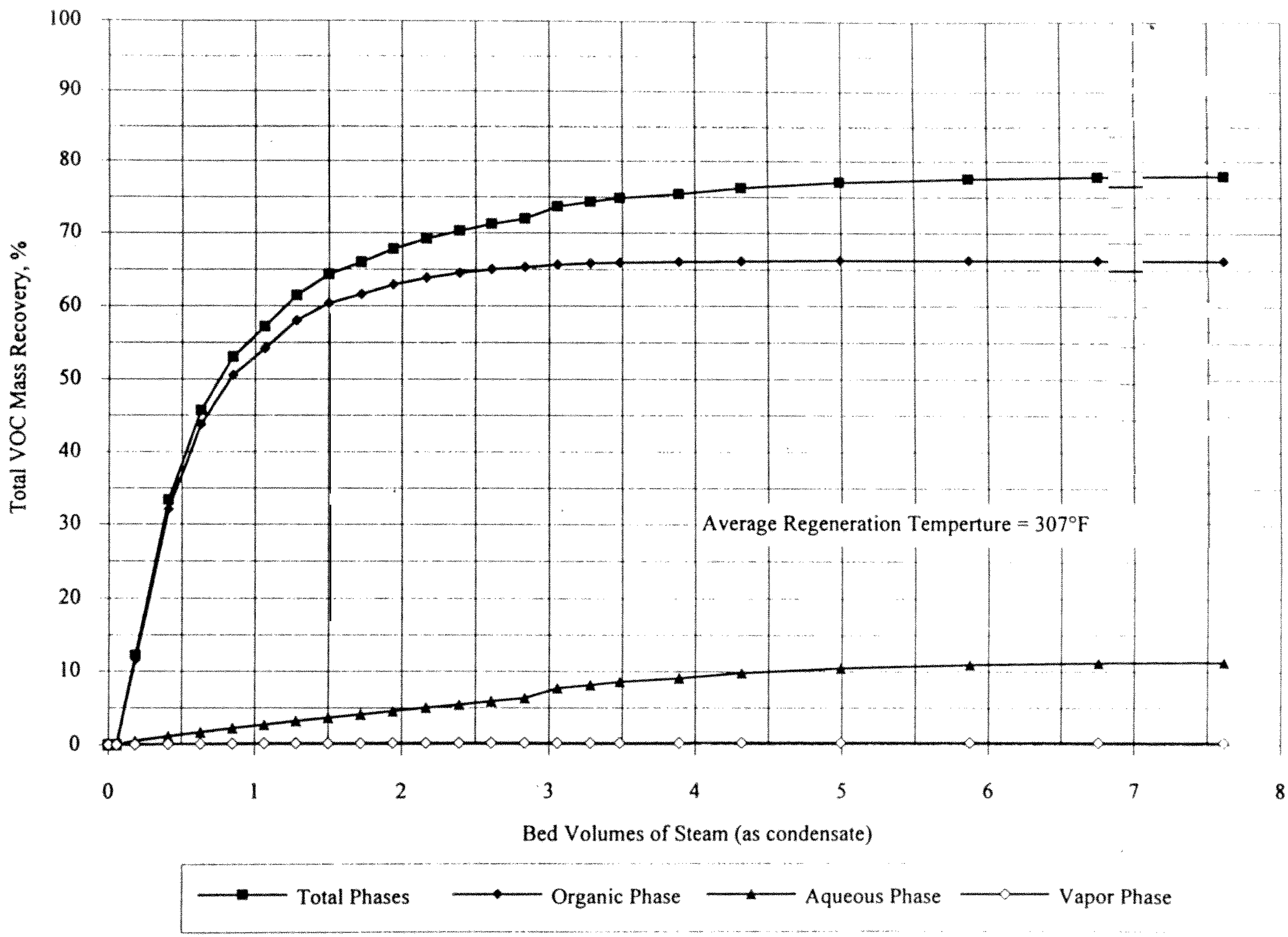


Figure 17. Steam Regeneration 1 Total VOC Mass Recovery Profile

Steam Regeneration 2

Steam Regeneration 2 was conducted on column A563B at an average temperature of 293 °F over a 17-hour period and generated approximately 8.4 gallons (7.0 bed volumes) of condensate. Steam flow rates (as condensate) were increased incrementally over the operating period from 0.25 BV/hr to 0.80 BV/hr, as shown in Table 16.

VOC mass recovery results for Steam Regeneration 2 (see Table 18) show individual VOC mass recoveries for the first 3 bed volumes of condensate and for the total bed volumes of condensate produced. Table 18 also shows the VOC mass recoveries for each condensate phase. Total VOC mass recovery profiles for Steam Regeneration 2 are presented in Figure 18. The 1.1 -DCE mass recovery was assumed to be 100% as the basis for estimating Cycle 2 influent 1.1 -DCE concentration.

Steam Regeneration 2 recovery results show that 7 1% of the total VOC mass was recovered in the first 3 bed volumes and that 73% was recovered overall. Approximately 90% of the total VOC mass recovered was collected in a separable organic phase.

Steam Regeneration 3

Steam Regeneration 3 was conducted on column A563A-1 at an average temperature of 280° F over a 19-hour period and generated approximately 10.7 gallons (8.9 bed volumes) of condensate. Steam flow rates (as condensate) were increased incrementally over the operating period from 0.28 BV/hr to 0.82 BV/hr, as shown in Table 16.

VOC mass recovery results for Steam Regeneration 3 (see Table 19) show individual VOC mass recoveries for the first 3 bed volumes of condensate and for the total bed volumes of condensate produced. Table 19 also shows the VOC mass recoveries for each condensate phase. Total VOC mass recovery profiles for Steam Regeneration 3 are presented in Figure 19. The 1.1~DCE mass recovery was assumed to be 100% as the basis for estimating the Cycle 3 influent 1 ,l-DCE concentration.

Steam Regeneration 3 recovery results show that 79% of the total VOC mass was recovered in the first 3 bed volumes and that 87% was recovered overall. Approximately 80% of the total VOC mass recovered was collected in a separable organic phase.

Summary of Steam Regeneration Results

Total VOC mass recovery results for the steam regenerations, as summarized in Table 20, include the average pH measured for the condensate aqueous phase. Total VOC mass recovery profiles for each steam regeneration. are presented in Figure 20. Condensate pH profiles for the operation period of each steam regeneration are presented in Figurc 21.

TABLE 18. STEAM REGENERATION 2 VOC MASS RECOVERY RESULTS

	After 3 Bed Volumes					After 7.6 Bed Volumes (Total)				
	Mass Recovery, %				Fraction	Mass Recovery, %				Fraction
Volatile Organic Compound	Aqueous Phase	Organic Phase	Vapor Phase	Total Phases	in Organic Phase, %	Aqueous Phase	Organic Phase	Vapor Phase	Total Phases	in Organic Phase, %
Vinyl Chloride	15.6	0.0	25.5	41.1	0.0	15.6	0.0	25.5	41.1	8.0
1,1-Dichloroethene	0.0	99.0	1.0	100.0*	99.0	0.0	99.0	1.0	100.0*	99.0
cis- 1,2-Dichloroethene	15.3	81.8	1.0	98. 1	83.4	15.3	81.8	1.0	98.2	83.3
trans- I ,2-Dichloroethene	7.0	64.4	1.4	72.8	88.5	7.1	64.4	1.4	72.9	88.4
Trichloroethene	4.3	64.2	0.1	68.7	93.6	6.9	64.6	0.2	71.6	90.2
Total VOCs	5.1	65.4	0.2	70.7	92.5	7.4	65.7	8.2	73.4	89.5

• I, I-DCE total recovery assumed to be 100% as basis for estimating Cycle 2 influent VC and l, l concentrations

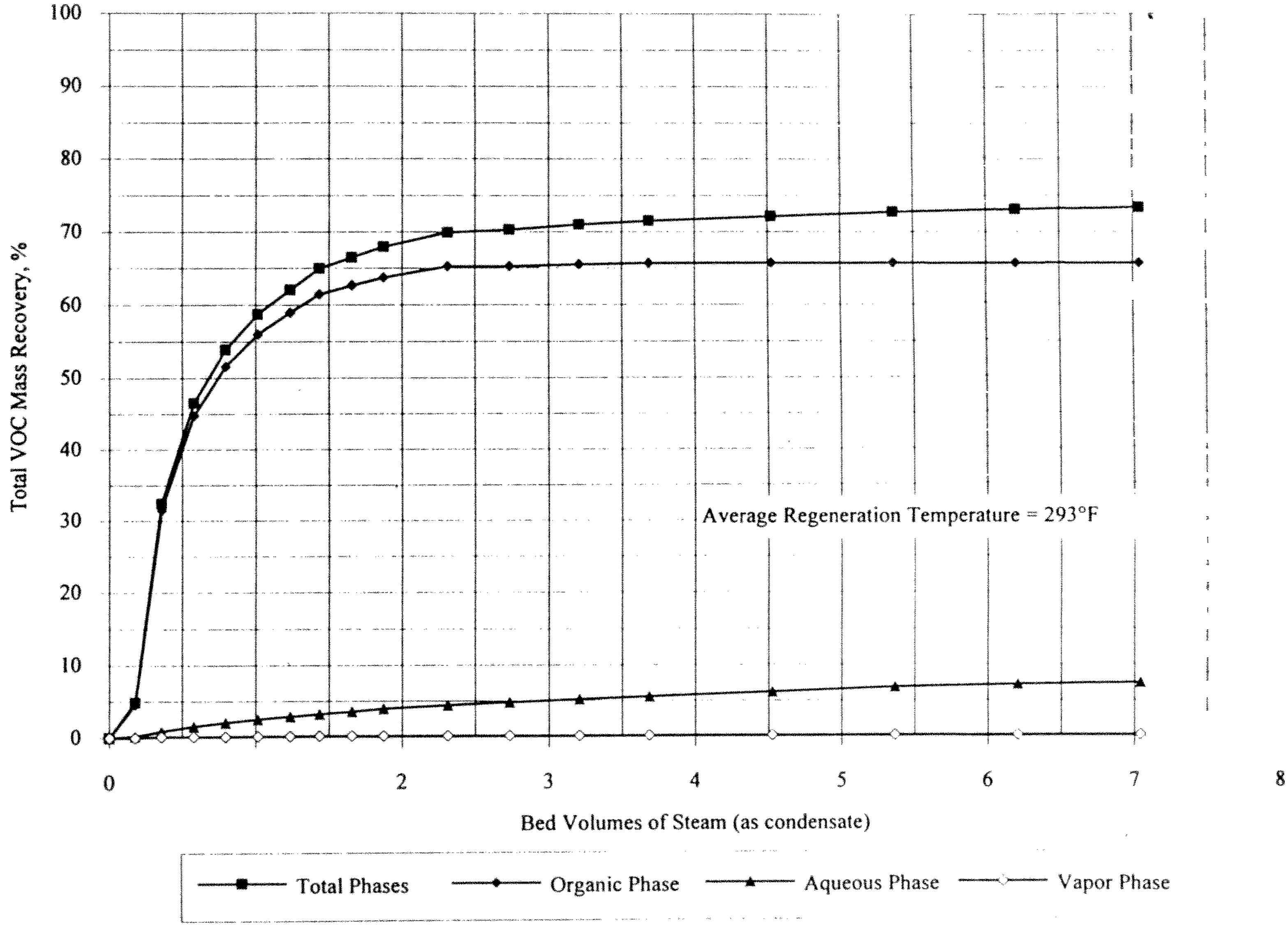


Figure 18. Steam Regeneration 2 Total VOC Mass Recovery Profile

TABLE 19. STEAM REGENERATION 3 VOC MASS RECOVERY RESULTS

	.Afier 3 Bed Volumes					After 7.6 Bed Volumes (Total)				
	Mass Recovery, %				Fraction	Mass Recovery, %				Fraction
Volatile Organic Compound	Aqueous Phase	Organic Phase	Vapor Phase	Total Phases	in Organic Phase, %	Aqueous Phase	Organic Phase	Vapor Phase	Total Phases	in Organic Phase, %
Vinyl Chloride	14.1	0.0	28.0	42. I	0.0	14.1	0.0	28.0	42.1	0.0
1, I -Dichloroethene	29.2	66.6	4.2	100.0*	66.6	29.2	66.6	4.2	100.0'	66.6
cis- I ,2-Dichloroethene	23.1	48.2	2.4	73.7	65.4	23.3	48.2	2.4	73.9	65.2
trans- I ,2-Dichloroethene	u4.4	41.1	3.6	59. I	59.6	14.8	41.1	3.6	59.5	69.
Trichloroethene	6.4	73.1	0.8	80.3	91.0	15.4	73.2	0.9	89.5	81.8
Total VOCs	8.1	69.9	1.1	79.1	88.4	16.1	70.0	1.2	87.2	80.2

I ,I -DCE total recovery assumed IO be 100% as basis for estimating Cycle 3 influent VC and I.1-DCE concentrations

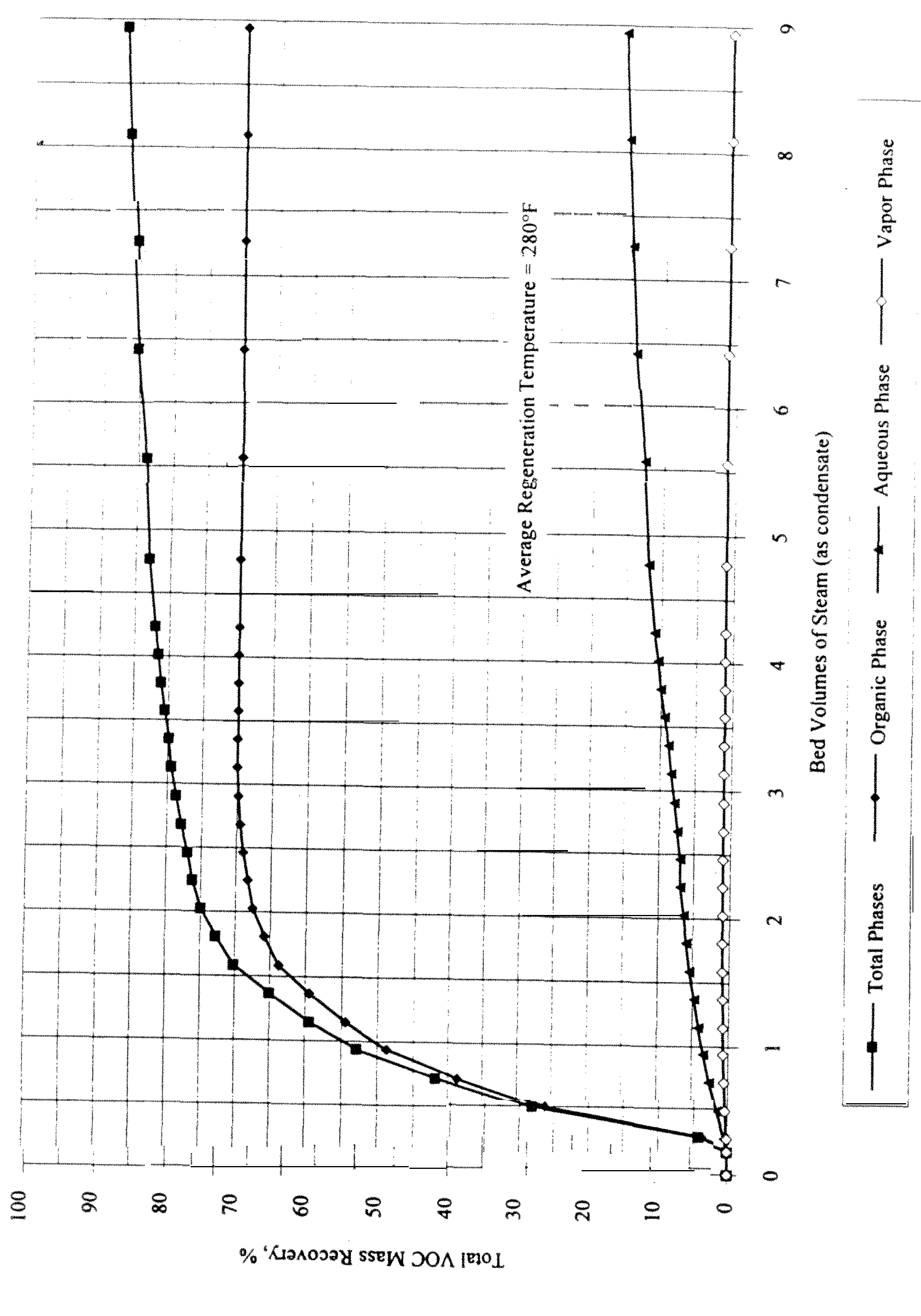


Figure 19. Steam Regeneration 3 Total VOC Mass Recovery Profile

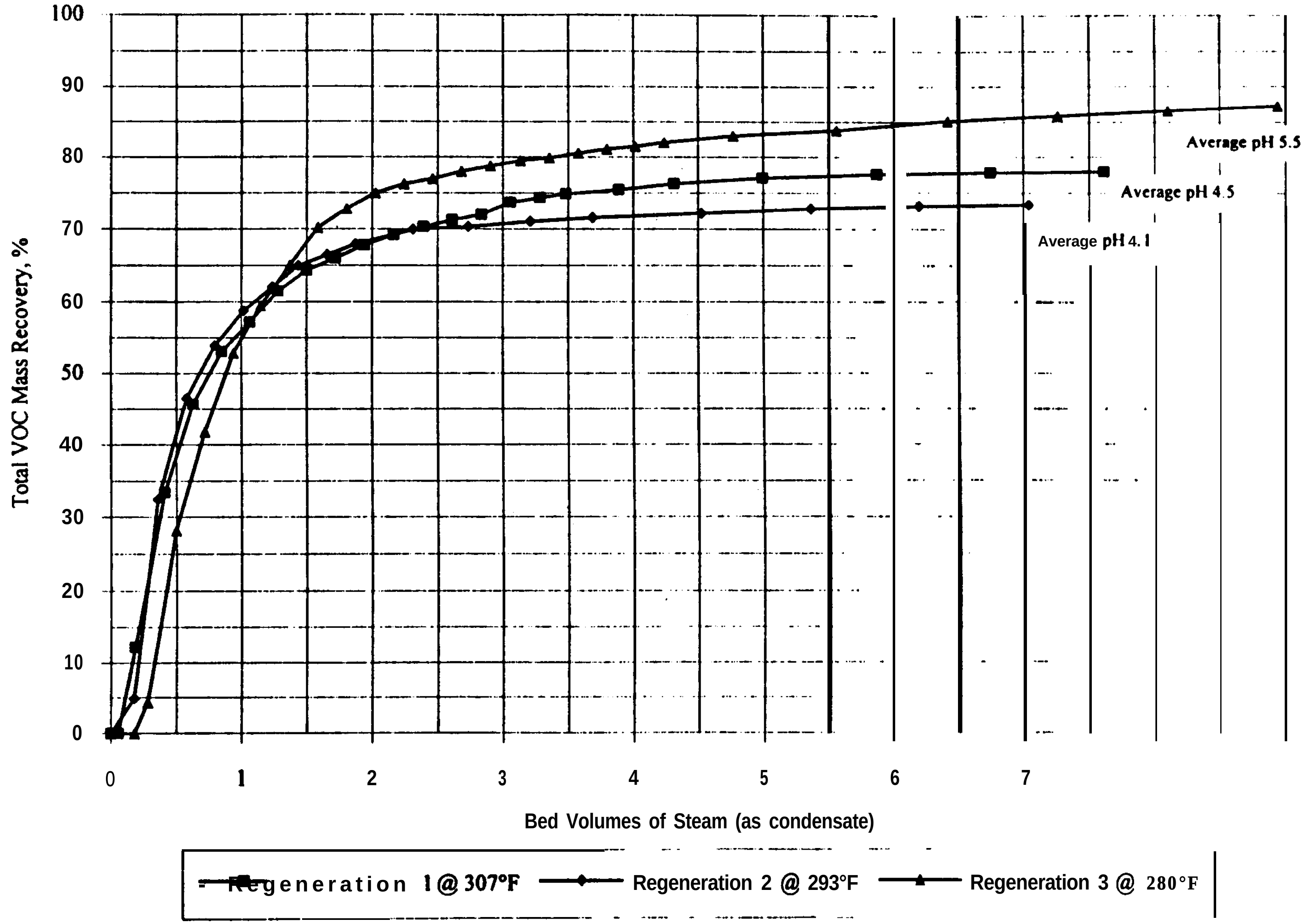


Figure 20. Steam Regenerations Total VOC Mass Recovery Profiles

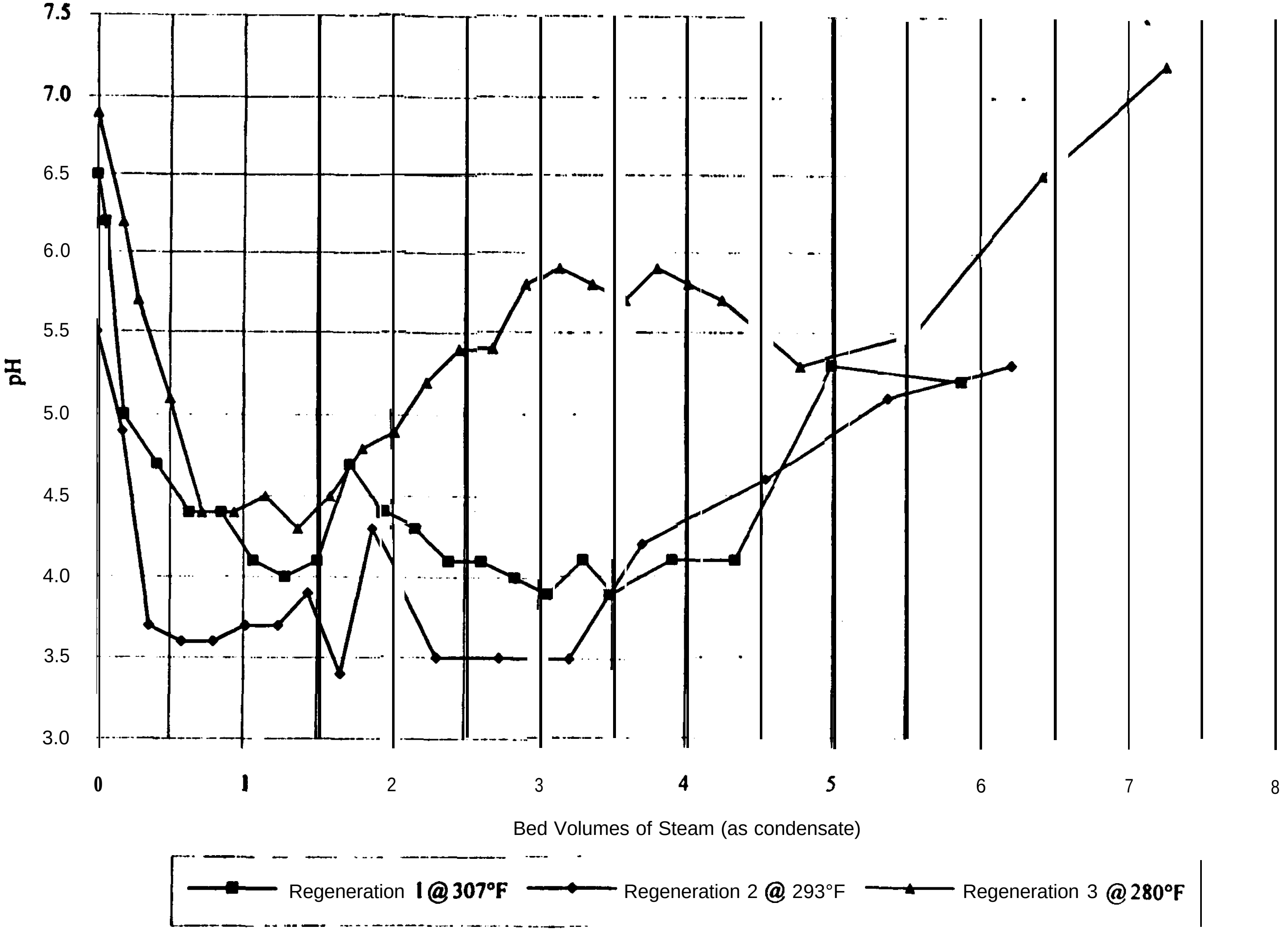


Figure 2 1. Steam Regenerations Condensate Aqueous Phase pH Profiles

The overall recovery results show that maximum recovery was achieved during Steam Regeneration 3, which was operated at the lowest temperature (280 °F) and generated condensate with the highest range of pH values (4.3 to 7.2) of all three steam regenerations. VOC mass recovery decreased with decreasing condensate pH, based on the results in Table 20. An explanation for the differences observed for the three different steam regenerations may be related to the mechanism of dehydrohalogenation. Chlorinated organics under elevated temperatures may dehydrohalogenate and thereby produce an acidic stream containing hydrochloric acid (HCl). Therefore, the lower recoveries observed during the higher temperature regenerations may be due to dehydrohalogenation resulting in a reduction of chlorinated organic concentration in the condensate.

The incomplete mass recovery of VOCs may be due to the following:

- Volatilization of VOCs during sampling of the condensate aqueous and organic phases.
- Inaccuracies during analysis of the steam regeneration samples.
- VOCs retained in the highest energy micropores of the Ambersorb adsorbent were not removed during steam regeneration.
- Dehydrohalogenation of the chlorinated organics.

SUPERLOADING RESULTS

The superloading process operations data (see Table 2 1) include the influent average VOC concentrations and effluent maximum VOC concentrations measured over the total operating period for the superloading column.

During superloading, the virgin Ambersorb 563 adsorbent superloading column (A563S) was operated for 1.8 hours at an average flow rate of 0.038 gpm (7.5~minute EBCT) and treated 4 gallons (14 bed volumes) of VOC-saturated condensate generated during Steam Regeneration 3.

The superloading process operations data show that the influent stream consisted of 73,000 µg/L cis-1,2-DCE, 7,500 µg/L trans-1,2-DCE, and 621,000 µg/L TCE. The pH of the influent and effluent streams were 5.9 and 4.3, respectively. The average conductivity of the influent and effluent streams were 286 and 485 µmhos/cm, respectively.

Superloading performance results based on treatment to the MCL are presented in Table 22. Superloading VOC leakage curves are presented in Figure 22. The performance results show that the Ambersorb 563 adsorbent superloading column treated 14 bed volumes of VOC-saturated condensate (700,000 µg/L total VOC's to an effluent water quality below the MCL for each VOC TCE was the only VOC detected in the effluent stream and was first detected at a concentration of 2.5 µg/L after 14 bed volumes had been treated.

TABLE 20. SUMMARY OF STEAM REGENERATIONS TOTAL VOC MASS RECOVERY RESULTS

Steam Regeneration	Regeneration	Regeneration 2	Regeneration 3
Column Temperature, °F	307	293	280
Total Bed Volumes Generated	7.6	7.0	8.9
Total VOC Mass Recovery @ 3 BV, %	73.2	70.7	79. I
Total VOC Mass Recovery @ End, %	78.0	73.4	87.2
Total VOC Fraction In Organic Phase @ End, %	89.5	92.5	88.4
Condensate Aqueous Phase pH	4.5	4.1	5.5

TABLE 21. SUPERLOADING PROCESS OPERATIONS DATA*

	Ambersorb 563 Adsorbent
Column I.D.	A563S
Bed Geometry	
Diameter, inches	2.0
Length, inches	21.0
Volume, gallons	0.29
Orientation	up-flow
Process Operations Data	
Total Operation Time, hours	1.8
Total Volume Treated, gallons	4.0
Total Volume Treated, bed volumes	14.0
Process Flow Rate, gpm	0.038
Flow Rate Loading, bed volumes/hr	8.0
Hydraulic Loading, gpm/ft²	1.7
Empty Bed Contact Time, minutes	7.5
Pressure Drop Across Bed, psi	<I
Influent Characteristics	
pH, standard units	5.9
Specific Conductance, µmhos/cm	286
VOC Concentrations, µg/L	
Vinyl Chloride	0
1,l -Dichloroethene	0
cis- 1,2-Dichloroethene	72,888
trans- 1,2_Dichloroethene	7,469
Trichloroethene	620,510
Effluent Characteristics	
pH, standard units	4.3
Specific Conductance, µmhos/cm	485

• Time weighted averages and cumulative totals for the total operating period

TABLE 22. SUPERLOADMG PERFORMANCE RESULTS

Volatile Organic Compound	MCL* µg/L	Bed Volumes Treated to MCL
Vinyl Chloride	2	> 14.0
-Dichloroethene	7	> 14.0
cis- 1,2-Dichloroethene	70	> 14.0
trans- 1,2-Dichloroethene	100	> 14.0
Trichloroethene	5	> 14.0

* Maximum Contaminant Levels from National Revised Primary Drinking Water Regulations, 40 CFR 141 .61

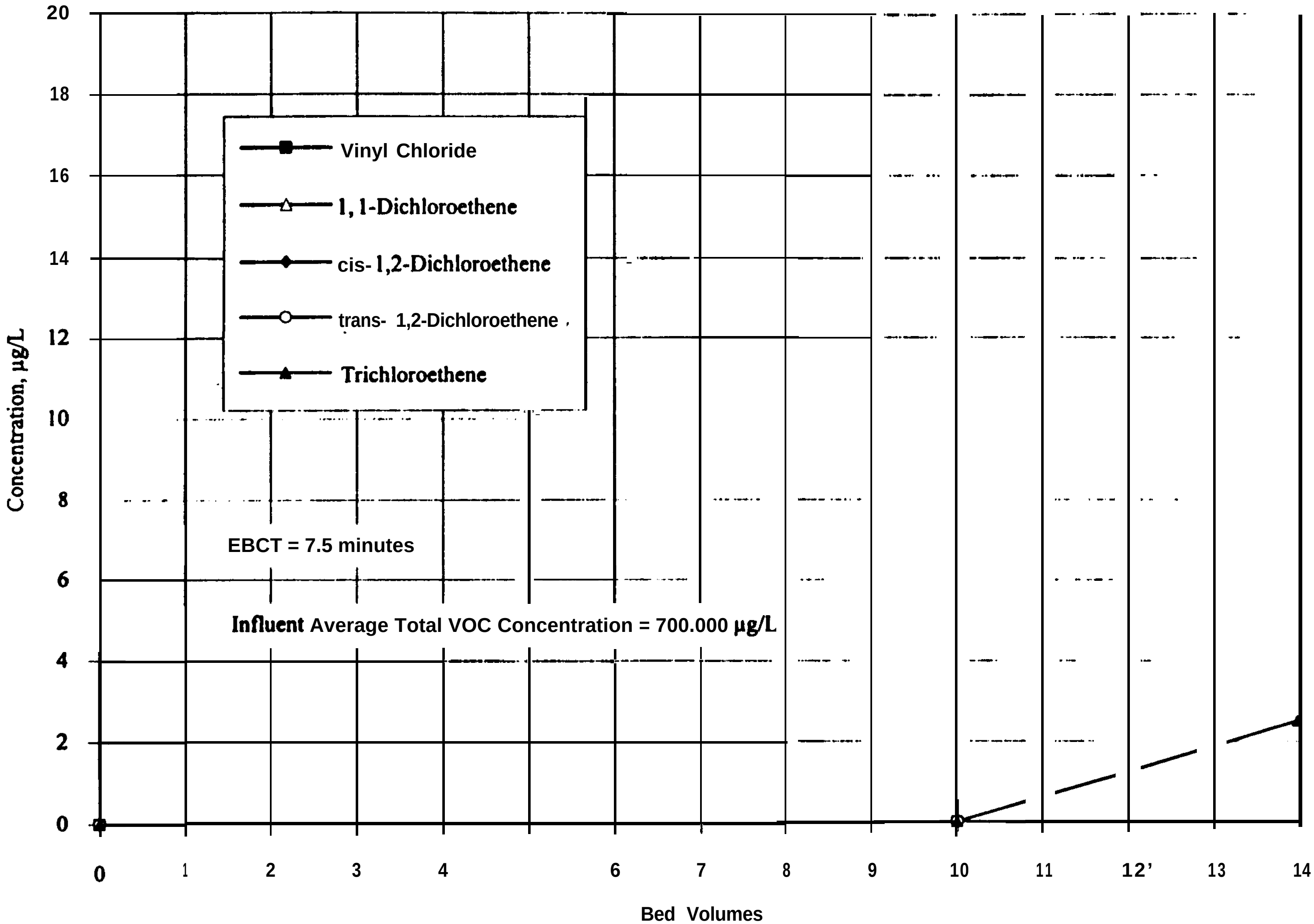


Figure 22. Ambersorb 563 Adsorbent Superloading Column VOC Leakage Curves

DATA QUALITY REVIEW

Overview

The overall QA objective for the project was to produce data of sufficient and known quality to evaluate the effectiveness of Ambersorb 563 adsorbent technology for the treatment of VOCs in groundwater. Specifically, the primary objective of the project was to demonstrate that the effluent from the Ambersorb adsorbent columns contained VOCs at concentrations less than the MCL.

A list of the target VOCs, along with their MCLs and the detection limits achieved for the column influent and effluent samples, is provided in Table 23. The detection limits for the target VOCs achieved in the effluent samples were below the MCL values and, as such, the data were useable to evaluate Ambersorb adsorbent performance. The higher detection limits for the target VOCs in the influent samples resulted from the sample dilutions required because of the contaminant levels, primarily TCE, present in the groundwater.

Table 24 provides a summary of the sample analysis program for the service cycle, regeneration, and superloading phases of the demonstration. A total of 404 field samples were analyzed for target VOCs by Method SW846 8010. This equates to 2,020 data points that were available to evaluate treatment performance during the project

Analytical data packages for the field samples as well as the QA samples are available for review at EPA

Accuracy

The accuracy of the analytical data was monitored by the use of the matrix spike and matrix spike duplicate samples. The percent recovery acceptance limits for each of the target VOCs was established in the QAPP. Forty-four matrix spike/matrix spike duplicate samples, representing 220 data points, were analyzed during the project. Table 25 provides a summary of the accuracy data for the matrix spike/matrix duplicate samples.

Overall, 95% of the data points associated with spike samples were within the established recovery range. Eleven data points fell outside the established recovery acceptance limits. TCE was the compound that typically was outside the recovery acceptance limit. For these data points, recoveries (i.e., 62% to 76%) were consistently below the lower end of the recovery range of 77%.

TABLE 23. TYPICAL DETECTION LIMITS FOR TARGET VOCs

Compound	MCL (µg/L)	Detection Limit (µg/L)	
		Influent Samples	Effluent Samples
Vinyl Chloride	2	5	0.5
1, I-Dichloroethene	7	10	1
cis-1.2-Dichloroethene	70	5	0.5
trans-1,2-Dichloroethene	100	5	0.5
Trichloroethene	5	5	0.5

TABLE 24. SUMMARY OF SAMPLE ANALYSIS PROGRAM

Test Phase	No. of Samples								
	Field samples	Confirmatory samples	Field Duplicates	Laboratory Duplicates	Matrix Spikes	Matrix Spike Duplicates	Field Blanks	Trip Blanks	Iustrument Blanks
cycle 1	159	11	16	1	11	11	11	I1	35
Cycle 2	42	4	3	0	3	3	4	5	23
Cycle 3	33	3	3	2	3	3	3	3	10
Cycle 4	45	5	4	0	5	5	5	5	15
Regemration 1	44	1	2	0	0	0	1		12
Regeneration 2	21	0	2	0	0	0	1	1	6
Regeneration 3	42	1	1	0	0	0	1	1	7
Superloading	8	1	2	0	0	0	1	1	3
Total	404	26	33	3	22	22	27	28	111

TABLE 25. SUMMARY OF ACCURACY DATA FOR TARGET VOCs

Test Phase	Measurement	Target VOCs: Vinyl chloride MS*	Vinyl chloride MSD*'	1, I-Dichloroethene MS	1, I-Dichloroethene MSD	cis-1,2-Dichloroethene MS	cis-1,2-Dichloroethene MSD	trans-1,2-Dichloroethene MS	trans-1,2-Dichloroethene MSD	Trichloroethene MS	Trichloroethene MSD
	QAPP Acceptance Criteria (% Recovery)	59-141		63-137		64-139		64-139		77-123	
Cycle 1	**Range** (% Recovery)	66-99	60-l 17	79-109	77-125	77-l 17	69-116	69-121	68-l 14	62-112	66-I I5
	Average (% Recovery)	81	80	94	95	97	98	90	89	88	88
	Number of Samples	11	11	11	11	11	11	11	11	I1	II
	Number of Samples Meeting Criteria	11	11	11	11	11	11	11	11	8	8
Cycle 2	**Range** (% Recovery)	75-89	79-92	101-122	106-l 18	100-l 12	107-l 10	85-l 14	90-111	81-101	80-111
	Average (% Recovery)	81	86	111	110	106	108	101	100	94	92
	Number of Samples	3	3	3	3	3	3	3	3	3	3
	Number of Samples Meeting Criteria	3	3	3	3	3	3	3	3	3	3
Cycle 3	**Range** (% **Recovery)**	65-81	71-84	99-l 16	108-l 15	87-12 l	87-123	97-l 19	100-I I9	7%-101	75-l 13
	Average (% Recovery)	72	78	107	111	100	103	106	112	90	88
	Number of Samples	3	3	3	3	3	3	3	3	3	3
	Number of Samples Meeting Criteria	3	3	3	3	3	3	3	3	3	l
Cycle 4	**Range** (% Recovery)	62-97	66-93	73-121	71-l 10	73-123	67-122	78-l 10	80- 108	71-132	77-126
	Average (% Recovery)	75	76	92	89	100	96	92	89	98	98
	Number of Samples	5	5	5	5	5	5	5	5	5	5
	Number of Samples Meeting Criteria	5	5	5	5	5	5	5	5	3	4
Total Project	Range (% **Recovery)**	62-99	60-I 17	73-122	71-125	73-123	67-123	69-121	68-1 19	62-132	66-126
	Average (% Recovery)	78	80	98	98	99	100	94	93	91	91
	Number of Samples	22	22	22	22	22	22	22	22	22	22
	Number of Samples Meeting Criteria	**22**	**22**	**22**	**22**	**22**	**22**	**22**	**22**	**17**	I6

• MS - matrix spike.

**MSD matrix spike duplicate.

Precision

The precision of the analytical data was assessed by the use of field duplicate and laboratory duplicate samples. The acceptance criteria for precision data established in the QAPP was a relative percent difference (RPD) value of ≤ 50%. Thirty-three duplicate samples, representing 165 data points, were analyzed during the project. Table 26 provides a summary of the precision data for the duplicate samples. Overall. 95% of the data points associated with duplicate samples met the established precision criteria.

Other Data Quality Measures

Surrogate Recovery--

Surrogate compounds were added to each sample to assess the efficiency of the analysis. The percent acceptance limits for each of the surrogate compounds were established in the QAPP. During the project, 673 samples were analyzed, which represented 2,019 surrogate recovery data points. Overall, greater than 99% of the surrogate recovery data points were within the established recovery range.

Confirmatory Samples--

Selected influent and effluent samples were analyzed for VQCs (i.e., full list) by Method SW846 8260 for confirmation purposes. Twenty-six confirmatory samples were analyzed during the project. A comparison of the confirmatory sample results with the associated field sample results showed agreement in both the compounds detected and the measured concentrations for detected compounds.

Blank Samples--

Field, trip, and instrument blank samples were incorporated in the project to provide field and laboratory checks of data quality.

During the project, 27 field blanks, representing 135 data points, were analyzed. Overall, 95% of the field blank data points consisted of nondetectable values for the target VOCs. TCE was the compound most frequently detected in the field blanks, typically at low ppb values.

Twenty-eight trip blanks, representing 140 data points, also were analyzed. Overall, 97% of the trip blank data points consisted of nondetectable values for the target VOCs. TCE was the compound detected in the trip blanks, typically at low ppb levels. TCE contamination in trip blanks may be due to cross-contamination from the influent or steam regeneration samples containing elevated levels of TCE. Trip blank contamination could have occurred during storage, transport, or analysis.

TABLE 26. SUMMARY OF PRECISION DATA FOR TARGET VOCs

Test Phase	Measurement QAPP Acceptance Criteria (% Recovery)	Target VOCs Vinyl chloride **≤ 50**	 1. I-Dichloroethene ≤ 50	 cis-I ,2-Dichloroelhene ≤ 50	 trans- I ,2-Dichloroethene ≤ 50	 Trichloroelhene ≤ 50
Cycle 1		0-105	0	0-42	0-49	0-67
	Average (% Recovery)	10	0	5	14	13
	Number of Samples	16	16	16	16	16
	Number of Samples Meeting Criteria	15	16	16	16	14
Cycle 2	Range (% Recovery)	0-120	0	0-15	0-9	0-76
	Average (% Recovery)	52	0	6	3	26
	Number of Samples	3	3	3	3	3
	Number of Samples Meeting Criteria	2	3	3	3	2
Cycle 3	Range (% Recovery)	0-15	0	0-5	0-67	0-18
	Average (% Recovery)	9	0	3	32	9
	Number of Samples	3	3	3	3	3
	Number of Samples Meeting Criteria	3	3	3	2	3
Cycle 4	Range (% Recovery)	0-29	0-100	0-5	0-67	0-11
	Average (% Recovery)	7	25	3	22	6
	Number of Samples	4	4	4	4	4
	Number of Samples Meeting Criteria	4	3	4	3	4

TABLE 26. SUMMARY OF PRECISION DATA FOR TARGET VOCs
(Continued)

Test Phase	Measurement	Target VOCs: Vinyl Chloride	1,l -Dichloroethene	cis- l .2-Dichloroethene	trans- 1,2-Dichloroethene	Trichloroethene
	QAPP Acceptance Criteria (% Recovery)	≤ 50	≤ 50	≤ 50	≤ 50	≤ 50
Regeneration 1	Range (% Recovery)	O-24	O-29	5-20	17-24	4-14
	Average (% Recovery)	12	14	12	20	9
	Number of Samples	2	2	2	2	2
	Number of Samples Meeting Criteria	2	2	2	2	2
Regeneration 2	Range (% Recovery)	0	0	7-23	15-22	IO-23
	Average (% Recovery)	0	0	15	I9	16
	Number of Samples	2	2	2	2	2
	Number of Samples Meeting Criteria	2	2	2	2	2
Regeneration 3	Range (% Recovery)	0	5	0	2	3
	Average (% Recovery)	0	5	0	2	3
	Number of Samples	1	1	1		1
	Number of Samples Meeting Criteria	1	1	1	1	1
SUPER-LOAD	Range (% Recovery)	0	0	O-8	0-15	4-40
	Average (% Recovery)	0	0	4	8	22
	Number of Samples	2	2	2	2	2
	Number of Samples Meeting Criteria	2	2	2	2	2
Total Project	Range (% Recovery)	O-120	O-100	0-42	0-67	O-76
	Average (% Recovery)	12	4	6	16	13
	Number of Samples	33	33	33	33	33
	Number of Samples Meeting Criteria	31	32	33		30

During the project, 111 instrument blanks, representing 555 data points, were analyzed. All of the instrument blank data points consisted of nondetectable values for the target VOCs.

Summarv

The data quality review of the VOC analytical data for the Ambersorb adsorbent demonstration project indicates that the acceptance criteria established in the QAPP were met on a consistent basis. The QA objectives identified in the QAPP are presented in Table 27. As a result, the overall completeness goal of 95% was achieved. The detection limits achieved and the accuracy, precision, and internal quality control checks indicate that the field sampling and laboratory analysis methods used throughout the course of the study generated data that was representative, comparable, and of sufficient quality for its intended use in the Ambersorb adsorbent technology demonstration project.

COMPARISON OF AMBERSORB ADSORBENT AND FILTRASORB GAC PERFORMANCE

The performance results for Cycle 1, presented in Table 9, are a direct comparison of Ambersorb 563 adsorbent and Filtrasorb 400 GAC performance. A direct comparison of Ambersorb 563 adsorbent and Filtrasorb 400 GAC VC and TCE leakage curves is also presented in Figure 23. The results for Cycle 1, as illustrated in Figure 23, show that, while operating at approximately five times the flow rate (l/5 the EBCI'), Ambersorb 563 adsorbent treated approximately two to five times the bed volumes of groundwater as Filtrasorb 400 GAC. Specifically, the bed volumes treated to the TCE MCL (5 µg/L) using Ambersorb 563 adsorbent were 8,190, whereas the bed volumes treated using Filtrasorb 400 GAC were 4,850 (approximately two times the water). For the VC MCL (2 µg/L), Ambersorb 563 adsorbent treated 8,120 BVs, whereas Filtrasorb 400 GAC treated 1,730 BVs (approximately five times the water).

SUMMARY OF AMBERSORB ADSORBENT PERFORMANCE

Performance results for the four service cycles are summarized in Table 28. Virgin Ambersorb adsorbent was used in Cycle 1, and the adsorbent used in Cycle 1 was regenerated and used in Cycle 3 (Cycle 2 also used virgin Ambersorb adsorbent, and Cycle 4 used the regenerated adsorbent). Therefore, Cycles 1 and 3 and Cycles 2 and 4 are grouped together in the table to facilitate evaluating the effect of one steam regeneration on Ambersorb 563 adsorbent performance. In addition, Table 28 presents the average influent VC concentrations for each service cycle.

Performance results show there was a 37% to 40% decrease in bed volumes treated to the VC MCL and a 22% to 37% decrease in bed volumes treated to the TCE MCL after the first steam regeneration of Ambersorb 563 adsorbent. For the remaining VOC's however, there was no consistent decrease in the capacity of Ambersorb 563 adsorbent after steam regeneration, based on bed volumes treated to the MCL.

TABLE 27. QA OBJECTIVES FOR PRECISION, ACCURACY, AND MDL FOR TARGET VOCS

Matrix	Method	Reporting Units	MDL	Precision (RPD)	Accuracy (96 Recovery)	Completeness
Groundwater (influent and effluent)	SW846 8010	µg/L	1*	≤50	50-150†	95
Aqueous Phase, Organic Phase	SW846 8010	µg/L	100	≤50	NA‡	95

*Minimum MDL listed can be attained for undiluted samples only. MDL will increase when dilutions are necessary to meet instrument response linearity (i.e., likely for influent groundwater samples).

criteria for the critical VOCs in matrix spike samples are:

Spike Compound	***Percent Recovery Acceptance Limits***
Vinyl Chloride	***59-141***
l,l-Dichloroethene	***63-137***
cis-1,2-Dichloroethene	***64-139***
Trans-1,2-Dichloroethene	***64-139***
Trichloroethene	***77-123***

‡NA - Not applicable, matrix spike and matrix spike duplicates analyses were not performed for the aqueous and organic phase samples from steam regeneration.

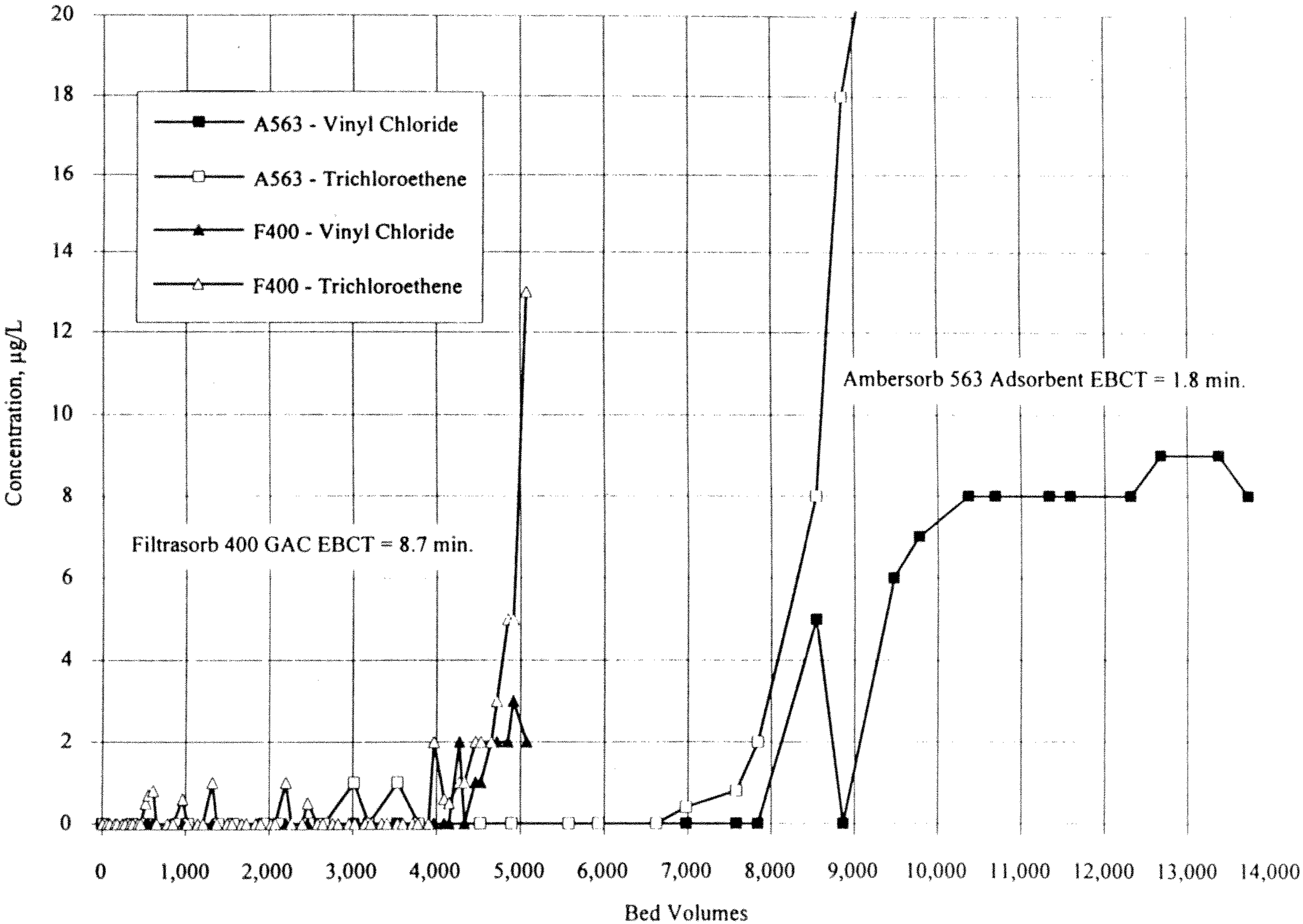


Figure 23. Comparison of Ambersorb 563 Adsorbent and Filtrasorb 400 GAC VC and TCE Leakage Curves

TABLE 28. SUMMARY OF AMBERSORB 563 ADSORBENT PERFORMANCE RESULTS

	MCL*	Bed Volumes Treated to MCL		Change†	Bed Volumes Treated to MCL		Change†
	μg/L	Cycle 1	Cycle 3‡	%	Cycle 2	Cycle 4‡	%
Column I.D.		A563A	A563A-I		A563B	A563B- I	
Volatile Organic Compound							
Vinyl Chloride	2	8,120	5.130	-37	8,320	5,010	-40
I, I -Dichloroethene	7	>13,700	> 12,600	~-8	> 12,700	16,600	<31
cis- I ,2-Dichloroethene	70	9,690	8,810	-9	IO.600	11,140	5
trans- I ,ZDichloroethene	100	>13,700	> 12,600	~-8	> 12.700	> 16,800	~32
Trichloroethene	5	8,190	5,160	-37	9,400	7,350	-22
Influent VC Concentration, μg/L		3.4§	5.7		4.9	10.1#	

*National Revised Primary Drinking Water Standards Maximum Contaminant Levels (MCL). 40 CFR 141.61

† Change = (Performance Before Steam Regeneration - Performance AAer Steam Regeneration)/Performance Before Steam Regeneration • 100

‡ Includes bed volumes prcloadcd during previous cycle.

§ VC concentration estimated based on the mass recovery results for the first steam regeneration of column A563A.

VC concentration estimated based on reanalysis of selected influent samples lower dilution.

The reduction in bed volumes treated to the VC and TCE MCLs is partially attributed to the increase in influent VC concentration during the study. Influent VC concentrations almost doubled between each steam regeneration cycle. As predicted by the Rohm and Haas computer model, small increases in influent VC concentration result in significant decreases in adsorption capacity.

After the first regeneration, the adsorption capacity for most adsorbents, including GAC. will be reduced. Additional steam regenerations and service cycles with constant influent VC concentrations are needed to determine the long-term effect of multiple steam regenerations on Ambersorb 563 adsorbent performance. Studies conducted by Rohm and Haas show that after multiple service cycles of VOC loading and steam regeneration, Ambersorb 563 adsorbent does not lose its adsorptive capacity. (Memorandum from D.N. Smith to S.G. Maroldo, "EDC Multi-Cycling Summary Report," SR-94- 137. 29 April 1994.)

COMPARISON OF PREDICTED AND MEASURED PERFORMANCE RESULTS

Predicted and measured performance results for Filtrasorb 400 GAC and Ambersorb 563 adsorbent, based on bed volumes treated to VC MCL, are presented in Table 29. Table 29 also presents the average influent VOC concentrations measured during each service cycle. The results show that the breakthrough capacity model underestimated the number of bed volumes actually treated to the VC MCL during Cycles 1 and 2 by 32% to 45% and overestimated the number of bed volumes treated to the VC MCL during Cycles 3 and 4 by 8% to 12%. The bed volumes treated by Filtrasorb 400 GAC during Cycle 1 and Ambersorb 563 adsorbent during Cycles 1 and 2 may have been underestimated due to the use of estimated VC and l,l-DCE concentrations from the steam regeneration recoveries.

The model appears to be a useful tool in predicting service cycle time when actual contaminant levels can be used as input. This emphasizes the importance of obtaining accurate analyses for VC, 1 ,l-DCE, and other less strongly adsorbed contaminants, especially in the presence of other high concentration VOCs. Based on these results, the Rohm and Haas breakthrough capacity model is a useful tool in predicting adsorbent capacities and service cycle times for bench- and pilot-scale column studies and for full-scale system design and cost analysis.

SCALEUP PARAMETERS

The information developed during the demonstration study enhanced the existing database for the Ambersorb 563 adsorbent technology and helped validate process design parameters and system performance for scale-up to full-scale treatment systems. The key process operating parameters for the preliminary engineering design of an Ambersorb 563 adsorbent system are:

- Process configuration.
- EBCT or flow rate loading.
- Vessel configuration.

TABLE 29. COMPARISON OF PREDICTED AND MEASURED PERFORMANCE RESULTS

Service Cycle	**Cycle** 1	**Cycle** 1	Cycle 3	Cycle 2	Cycle 4
Column I.D.	F400	A563A	A563A-1	A563B	A563B-1
Influent VOC Concentration, µg/L					
Vinyl Chloride	3.9*	3.4*	5.7	4.9	**10.1†**
1,1-Dichloroethene	0.31*	0.31*	6.10*	6.33*	**0.13†**
cis-1,2-Dichloroethene	329	312	373	353	350
trans-1,2-Dichloroethene	101	102	116	122	85
Trichloroethene	4,120	4,330	3,600	4,510	3,920
Bed Volumes Treated to VC MCL					
Predicted	1,200	6,160	5,860	5,740	5,440
Measured	1,730	8,120	5,130 ‡	8,320	5,010 ‡
Difference, %§	44	32	-12	45	-8

* VC and/or 1,1-DCE concentrations estimated based on the mass recovery results for each subsequent steam regeneration.

† VC and 1,1-DCE concentrations estimated based on reanalysis of selected influcnt samples at lower dilution.

‡ Includes bed volumes preloaded during previous cycle.

§ Difference = (Measured BV - Predicted BV)/Predicted BV • 100

- Steam regeneration conditions.

A full characterization of the contaminants in the influent, as well as the effluent discharge limitations, are required to predict service cycle time for the Ambersorb adsorbent system operations. The values provided below are typical and are for preliminary purposes only. Design parameters for a full-scale system need to be derived specifically for that treatment application.

Process Configuration

The decision to use a single column or two columns operating in series depends on a number of factors, including the need for continuous operation, space constraints for downstream regeneration equipment, effluent criteria, and service cycle time constraints or operation logistics.

Typically, the recommended process configuration consists of two columns operating in series. Such a design offers the following advantages:

- The system can remain in operation at full flow while the lead column is being regenerated.

- A lag column provides extra insurance that the effluent water quality will meet extremely stringent effluent criteria.

- A lag column also allows higher utilization of adsorption capacity for the lead column. In a single column mode, the vessel would have to be regenerated once the effluent quality exceeded the effluent criteria. With two columns operating in series, the lead column can operate to 50% stoichiometric breakpoint for the first contaminant measured in the effluent (i.e., $C_e/C_0 = 0.5$, where C_e is the effluent concentration and C_0 is the influent concentration). Depending on the contaminant load, this could have a significant impact on operation by greatly increasing service cycle time prior to regeneration.

- The downstream regeneration equipment is smaller for the regeneration of one column at a time.

The field trial demonstrated the viability of operating in a lead/lag mode.

The impact of operating to a 50% stoichiometric breakthrough point, rather than when the effluent quality exceeded the MCL, is clearly shown in the breakthrough profiles for Ambersorb 563 adsorbent for every service cycle. For instance, in Cycle 1, the actual bed volumes treated to the vinyl chloride MCL break point was 8,120 bed volumes, whereas the unit was taken off line for regeneration after 13,700 bed volumes when the vinyl chloride level was approximately 9 µg/L. This operations approach allowed an additional 5,600 bed volumes to be treated prior to regeneration.

EBCT or Flow Rate Loading

Empty bed contact time or flow rate loading is used to estimate the volume of adsorbent required. The recommended flow rate loading depends on the effluent criteria, service cycle time constraints, pressure drop, or other site constraints.

Typically, an EBCT of 3.0 minutes is recommended for preliminary process designs. This EBCT translates to a flow rate loading of 2.5 gpm/ft^3 of adsorbent required.

The field trial results showed that even while operating at a short EBCT of 1.3 minutes, the Ambersorb 563 adsorbent column could produce effluent water quality that was below the MCL for each contaminant, The total system EBCT for the field trial ranged from 2.6 to 3.0 minutes. Multicycling performance, taking into account the changing concentrations of vinyl chloride and l,l-dichloroethene, showed no loss in ability to consistently produce effluent water quality below the MCL for each contaminant. The demonstration study results reinforce the recommendation of an EBCT of 3.0 minutes (flow rate loading of 2.5 gpm/ft^3) as a conservative starting point for estimating adsorbent requirements.

Vessel Configuration

The height to diameter ratio of the adsorber vessels is a function of flow distribution requirements, pressure drop, or space constraints.

A minimum bed height of 2 to 3 feet is typically recommended for each adsorber vessel. For treatment applications where the influent contains contaminants that are less strongly adsorbed (such as vinyl chloride), bed depths of 4 to 6 feet may be advantageous. A deeper bed provides a margin of safety by providing a larger treatment zone for the less strongly adsorbed compounds. The deeper bed also enhances flow distribution and water contact within the adsorption vessel.

Typically, the maximum hydraulic loading (i.e., linear flow rate) recommended for process operation is 30 gpm/ft^2. The hydraulic loading for the field trial ranged from 7.8 gpm/ft^2 to 10.5 gpm/ft^2.

The estimated pressure drop for a hydraulic loading of 10 gpm/ft^2, based on the Ambersorb adsorbent technical literature, is approximately 1.5 psi per foot of bed depth. The field trial used a bed depth of 22.0 inches (1.83 feet), equating to an estimated pressure drop across the bed of 2.7 psi. The actual pressure drop across the beds measured during the study ranged from 8.4 to 16 psi. This higher pressure drop is attributed to accumulation of orange-brown particulate matter (likely iron precipitates) at the influent screen of the column. The presence of particulate matter did not, however, result in a negative impact on effluent water quality or service cycle time.

Steam Regeneration Conditions

The temperature/pressure, flow rate, and total volume of steam required for regeneration of the Amber-sorb adsorbent is dictated by the contaminants present, effluent criteria, time constraints, and space or manpower issues for the regeneration equipment.

Depending on the chlorinated organic contaminants present, a starting regeneration temperature of approximately 300 °F (150 °C) is typically recommended. The field trial results for the three steam regenerations were conducted at three different temperatures (307 °F, 293 °F, and 280 °F). The results showed that the percent mass recovery and subsequent cycle performance were not adversely affected at the lower steam regeneration temperatures.

The field trial results also clearly showed that the bulk of the mass desorbed during regeneration occurred after the first 3 bed volumes of steam (as condensate). The steam flow as condensate used during the regenerations for the demonstration project was incrementally increased over a period of approximately 20 hours from approximately 0.25 BV/hr to 0.80 BV/hr.

SECTION 7

CONCEPTUAL DESIGN AND PRELIMINARY COST ESTIMATE

The results of the Ambersorb adsorbent demonstration study were used to develop conceptual designs and preliminary cost estimates for full-scale groundwater treatment systems (average design flow of 100 gpm) using Ambersorb 563 adsorbent and GAC. The discharge criteria for the effluent from the treatment systems were assumed to be drinking water standards (i.e., MCL).

CONCEPTUAL DESIGN

Design parameters for the Ambersorb 563 adsorbent and GAC treatment systems are presented in Table 30. Key design assumptions derived directly from the pilot study included:

- Average influent groundwater quality as measured during Cycle 1 (see Table 8).
- EBCT consistent with Cycle 1 (1.5 minutes for each Ambersorb 563 adsorbent unit and 9.6 minutes for each GAC unit).
- Adsorbent performance as measured during Cycle 1 (see Table 9).

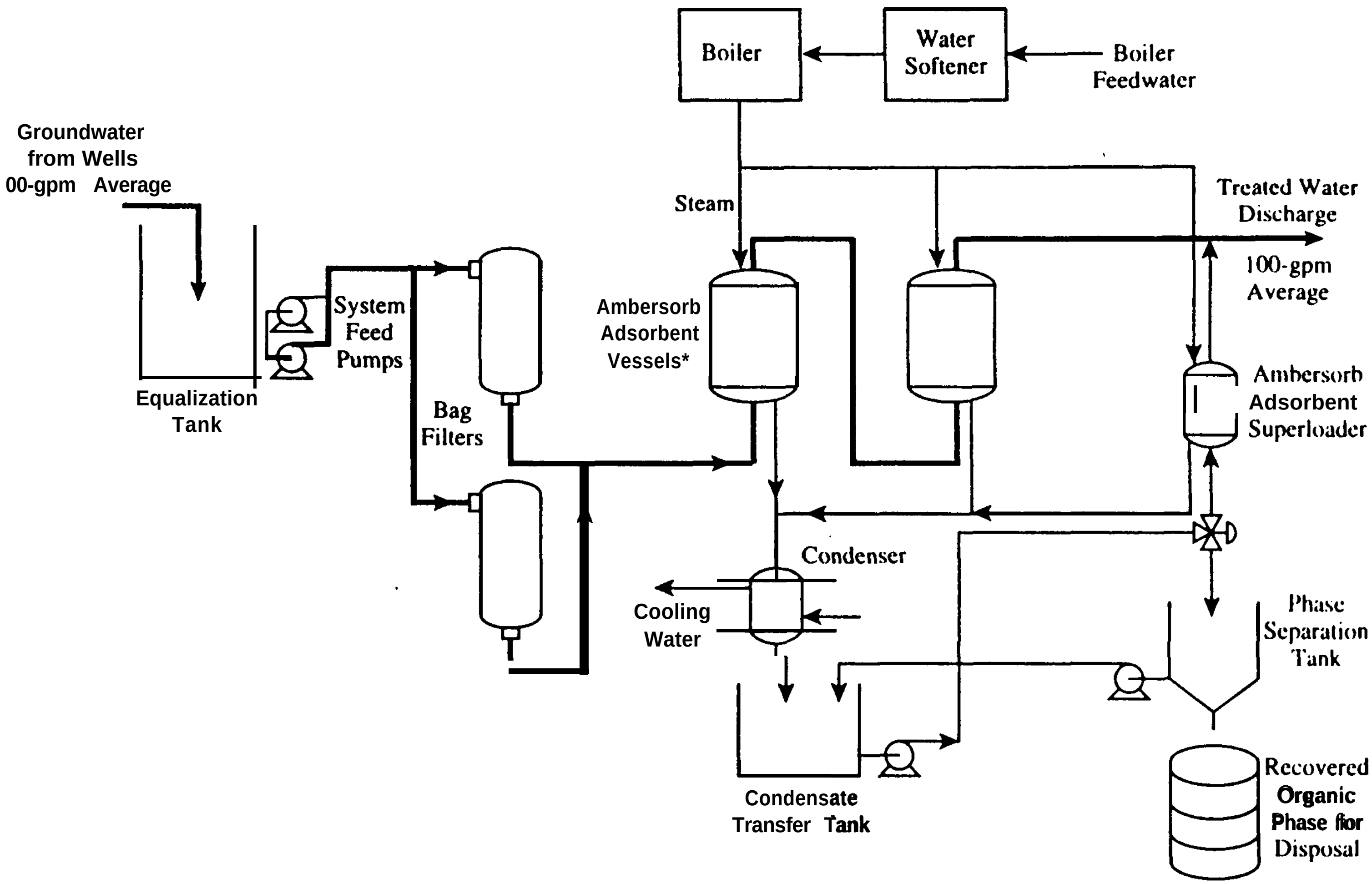
The designs for each treatment system also provide filters for the removal of particulate matter upstream of the adsorbent columns.

A process flow diagram and major equipment list for the Ambersorb 563 adsorbent treatment system are provided in Figure 24 and Table 31, respectively. The Ambersorb 563 adsorbent system is designed as an up-flow, fixed bed system, with two 660-lb adsorbent beds in series, each having a 1.5-minute EBCT at 100 gpm. In addition, the Ambersorb 563 adsorbent system includes on-line steam-regeneration and a condensate treatment superloading system. The lead Ambersorb adsorbent bed is regenerated approximately every 8 days or 8,000 bed volumes.

A process flow diagram and major equipment list for the GAC treatment system are provided in Figure 25 and Table 32, respectively. The GAC adsorbent system is designed with four 1,800-lb adsorbent beds (two parallel systems of two GAC beds in series). Each GAC bed has a 9.6-minute EBCT at 50 gpm. In addition, the GAC system uses commercially available transportable GAC units, as manufactured by Carbtrol Corporation, that are replaced approximately every 11 days or 1,600 bed volumes.

TABLE 30. DESIGN PARAMETERS FOR 100-GPM TREATMENT SYSTEMS

Design Parameter	Ambersorb 563 Adsorbent Treatment System	GAC Treatment System
Number of Adsorbent Vessels	2	6 (2 spare)
Vessel Construction	Stainless Steel	Commercially Available Units (Carbtrol Corporation)
Arrangement	Series	Two parallel systems of two vessels in series
Orientation	Upflow	As designed
Bed Geometry Each Vessel)		
Diameter, ft	2.0	3.8
Depth, ft	6.5	5.8
Area, ft^2	3.1	11
Volume, ft^3	20	64
Adsorbent Weight, lb	660	1,800
Process Operations (Each Vessel)		
Process Flow Rate, gpm	100	50
EBCT, minutes	1.5	9.6
Hydraulic Loading, gpm/ft^2	32.3	4.5
Flow Rate Loading, gpm/ft^3	5.0	0.78
BV Flow Rate, BV/hr	40	6.3
Volume Treated to Break-through, BV	8,000	1,600
Time to Regeneration/ Replacement, days	8.3	10.6



*Vessels configured in series. Lead/lag mode reversed after every steam regeneration cycle.

Figure 24. Process Flow Diagram for 100-gpm Ambersorb 563 Adsorbent Treatment System

TABLE 31. MAJOR EQUIPMENT LIST FOR 100-GPM AMBERSORB 563 ADSORBENT TREATMENT SYSTEM

Item	Number	Function
Groundwater Equalization Tank	1	Provide up to 30 minutes detention of influent groundwater at plant throughput
Feed Pump	2	Provide sufficient head to pump groundwater through filters and adsorbs
Bag Filter	2	Remove influent suspended solids
Adsorber*	2	Remove VOCs from groundwater
Superloader Adsorber	1	Remove VOCs from aqueous phase of condensate from steam regeneration
Condenser	1	Condense steam regenerant containing desorbed VOCS
Condensate Transfer Tank	1	Collect condensate for transfer to phase separator rank or superloader
Condensate Transfer Pump	1	Provide sufficient head to pump condensate to phase separation tank or aqueous phase to superloader
Phase Separation Tank	1	Provide for phase separation of condensate from steam regeneration
Aqueous Phase Transfer Pump	1	Provide sufficient head to pump aqueous phase to condensate transfer tank
Steam Generator	1	Provide sufficient steam at 300 °F for regeneration of Ambersorb adsorbent
Water Softener	1	Treat boiler feedwater

*See Table 30 for details.

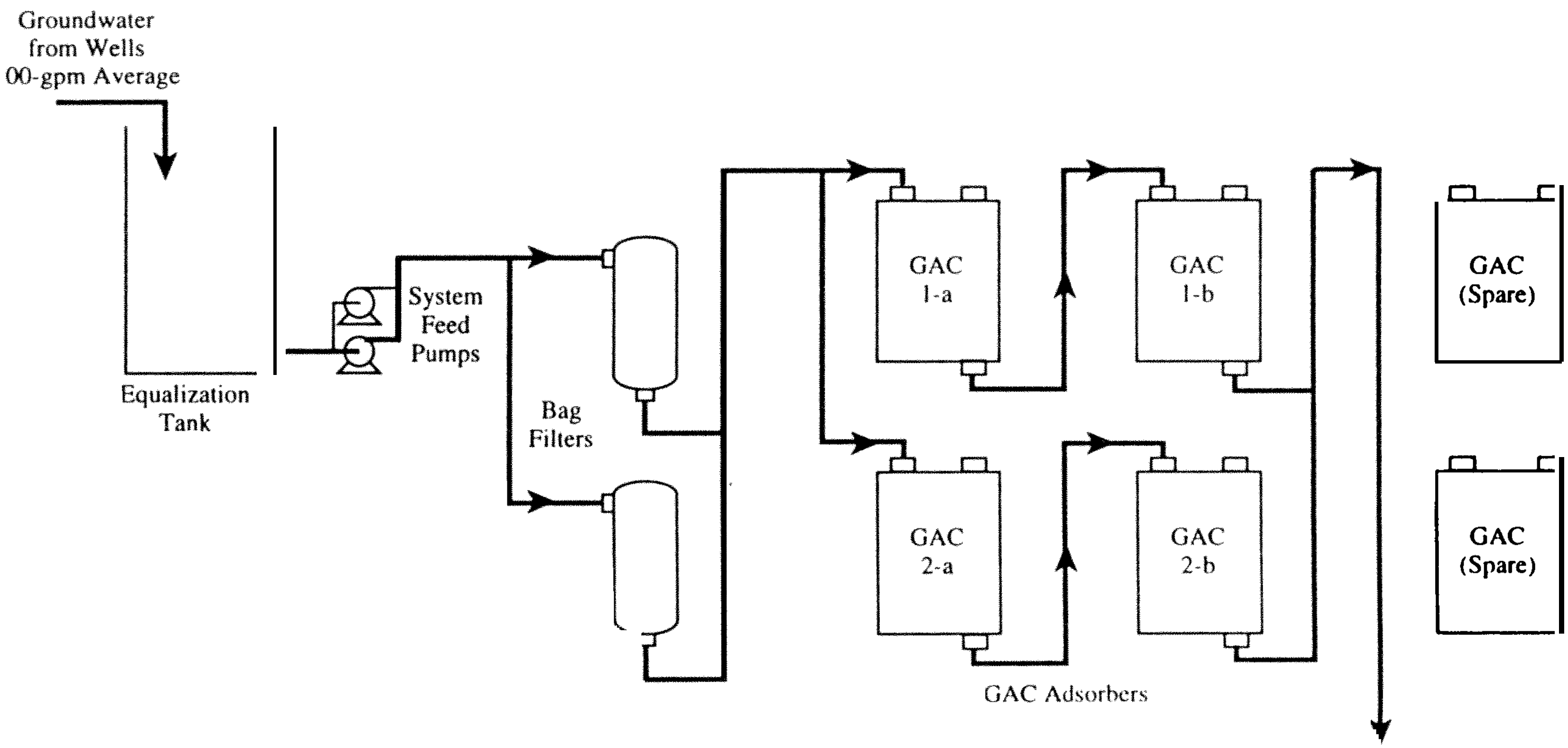


Figure 25. Process Flow Diagram for 100-gpm GAC Treatment System.

TABLE 32. MAJOR EQUIPMENT LIST FOR 100-GPM GAC TREATMENT SYSTEM

Item	Number	Function
Groundwater Equalization Tank		Provide up to 30 minutes detention of influent groundwater at plant throughput
Feed Pump	2	Provide sufficient head to pump groundwater through filters and adsorbers
Bag Filter	2	Remove influent suspended solids
Adsorber*	6	Remove VOCs from groundwater

*See Table 30 for details,

PRELIMINARY COST ESTIMATE

Preliminary estimates (+30% to- 15%) for the total installed costs of the Ambersorb 563 adsorbent and GAC treatment systems are provided in Tables 33 and 34, respectively. The cost estimates assume the construction location to be Pease AFB. New Hampshire.

The installed costs of the Ambersorb 563 adsorbent treatment system ($526100) are significantly greater than the installed costs of the GAC treatment system ($336,800). The installed costs of the Ambersorb 563 adsorbent system are greater for the following reasons:

- Additional costs for engineering and design of the adsorber vessels and steam regeneration and superloading systems.

- Higher costs of materials compatible with the steam regeneration process (i.e. stainless steel).

- The higher cost of Ambersorb 563 adsorbent media.

The lower installed costs for the GAC treatment system result primarily from the use of commercially available predesigned units ($86,860 for six vessels) with off-site regeneration. Such a system requires minimal engineering design and less costly construction materials.

Present worth cost estimates for the Ambersorb 563 adsorbent and GAC treatment systems are provided in Tables 35 and 36, respectively. These estimates are based on a discount rate of 7.0%. Present worth costs are provided for 5, 10, 15, and 20 years of operation and include the installed, operating, maintenance, and replacement costs, as well as salvage value for the treatment system. The operating costs for the GAC system includes the routine replacement and off-site regeneration of the GAC adsorber units.

The total present worth costs of the Ambersorb 563 adsorbent and GAC treatment systems are plotted in Figure 26. This analysis indicates that, after approximately 2 years, the total present worth cost of the Ambersorb 563 adsorbent treatment system is less than the GAC treatment system. The reduced costs over time result from the significantly lower operating costs for the Ambersorb 563 adsorbent system as compared to the GAC system.

TABLE 33. INSTALLED COSTS FOR 100-GPM AMBERSORB 563 ADSORBENT TREATMENT SYSTEM

Item	Number	Total Installed Cost ($)
Major Process Equipment		
Groundwater Equalization Tank	1	10,030
Feed Pump	2	8,620
Bag Filter	2	28,780
Adsorber*	2	85,600
Superloader Adsorber*	1	12,670
Condenser	1	6,200
Condensate Transfer Tank	1	5,230
Condensate Transfer Pump	1	1,980
Phase Separation Tank	1	6,540
Aqueous Phase Transfer Pump	1	2,060
Steam Generator	1	22,400
Water Softener	1	3,420
SUBTOTAL		193,530
Other Equipment		
Control Building (Pre-Engineered Structure)	1	28,000
Effluent Flowmeter and Totalizer	1	4,500
Process Piping	--	37,700
Electrical	--	14,710
SUBTOTAL		84,910
TOTAL EQUIPMENT (ROUNDED)		278.400
Other Project Direct and Indirect Costs		
Engineering and Design Fee		60,000
Project Construction and Facilities		22,300
Mobilization and Demobilization		3,100
Construction Equipment		8,400
Small Tools and Consumable Items		3,400
Permits and Fees		
SUBTOTAL		101,400

*Includes cost of adsorbent media

(Continued)

TABLE 33.
(Continued)

Item	Number	Total Installed Cost ($1
Project/Construction Contract Costs		
General and Administrative Overhead Costs		36.100
Contractor Markup and Profit		41,600
SUBTOTAL		77,700
CONTINGENCY (15%)		68,600
TOTAL PROJECT COST		526,100

TABLE 34. INSTALLED COSTS FOR IOO-GPM GAC TREATMENT SYSTEM

Item	Number	Total Installed Cost (S)
Major Process Equipment		
Groundwater Equalization Tank	1	10,030
Feed Pump	2	8,620
Bag Filter	2	28,780
Adsorber*	4	61,600
Spare Adsorber*	2	25,260
SUBTOTAL		134,290
Other Equipment		
Control Building @e-Engineered Structure)	1	28,ooo
Effluent Flowmeter and Totalizer	1	
Process Piping		
Electrical		14,710
SUBTOTAL		77,850
TOTAL EQUIPMENT (ROUNDED)		212,100
Other Proiect Direct and Indirect Costs		
Project Construction and Facilities		17,000
Mobilization and Demobilization		
Construction Equipment		
SmaIl Tools and Consumable Items		
Permits and Fees		3,200
SUBTOTAL		31,100
Proiect/Construction Contract Costs		
General and Administrative Overhead Costs		23,100
Contractor Markup and Profit		26,600
SUBTOTAL		49,700
CONTlNGENCY (15%)		43,900
PROJECI' TOTAL COST		336,800

*includes cost of adsorbent media.

TABLE 35. PRESENT WORTH COSTS FOR 100-GPM AMBERSORB 563 ADSORBENT TREATMENT SYSTEM*

Cost Category	5-Year	10-Year	15-Year	20-Year
Installed Costs	$526,100	$526,100	$526,100	$526.100
Operating Costs	$104,391	$178,820	$231,887	$269,724
Maintenance Costs	$75,854	$129,936	$168,496	$195,989
Replacement Costs	$0	$7,005	$12,000	$15,561
Salvage Value	($17,825)	($10,167)	($5,437)	($2,584)
Total Present Worth	$688,520	$831,695	$933,047	$1,004,789

* Estimate based on discount rate of 7.0%.

TABLE 36. PRESENT WORTH COSTS FOR 100-GPM GAC TREATMENT SYSTEM*

Cost Category	5-Year	10-Year	15-Year	20-Year
Installed Costs	$336,800	$336,800	$336,800	$336,800
Operating Costs	$556,684	$953,592	$1,236,581	$1,438,349
Maintenance Costs	$75,854	$129,936	$168,496	$195,989
Replacement Costs	$0	$7,005	$12,000	$15,561
Salvage Value	($3,565)	($2,033)	($1,087)	($517)
Total Present Worth	$965,773	$1,425,300	$1,752,790	$1,986,182

* Estimate based on discount rate of

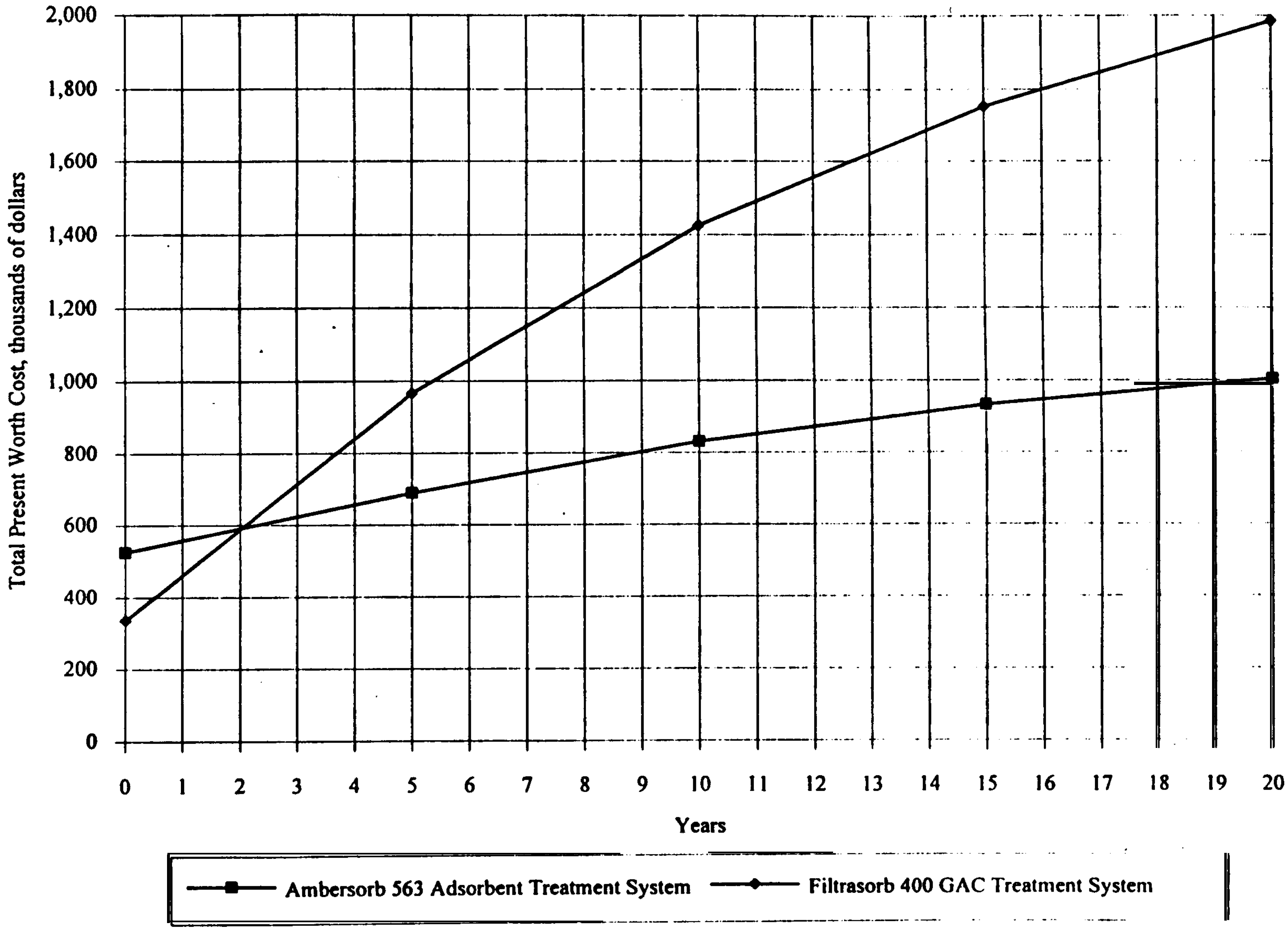


Figure 26. Total Present Worth Cost Profiles for 100-gpm Treatment Systems

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