GROUNDWATER TREATMENT TECHNOLOGIES: AIR STRIPPING VS. UV/OXIDATION

by

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S.B. Chemical Engineering
Massachusetts Institute of Technology, 1997

Submitted to the Department of Civil and Environmental Engineering In Partial Fulfillment of
the Requirements for the Degree of

MASTER OF ENGINEERING
IN CIVIL AND ENVIRONMENTAL ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
June 1998

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ABSTRACT

Ultraviolet Oxidation (UV/Ox) is a common ground-water treatment technique. It is a destruction process that utilizes ultraviolet light and strong oxidizers to break down organic and explosive components present in contaminated water. The reactions occur as a result of using ultraviolet light in combination with either ozone or hydrogen peroxide. The ozone or hydrogen peroxide, when activated by the light, forms hydroxyl radicals which can then destroy the ground-water contaminants. If the reaction goes to completion, the products are simply carbon dioxide and water.

UV/Ox is currently being used to treat the contaminated ground-water plume at Fuel Spill-12 (FS-12) at the Massachusetts Military Reserve (MMR). However, there are other remediation technologies which may be less costly and/or more effective at removing contaminants. Air stripping, one of these alternatives, is a commonly used ground-water remediation technology which relies on mass transfer of contaminants from water to air.

There are many reasons to consider air stripping as an alternative to other ground-water treatment technologies. Especially for high water flowrates and insufficient or non-existent steam supply, air stripping combined with exhaust air purification is preferred for economic and energetic reasons. Many studies have shown that air stripping can be more efficient and cost-effective than other treatment methods.

Air stripping was originally considered for application at FS-12, but it was not fully investigated. This thesis further considers air stripping. The current UV/Ox system at FS-12 is compared to a hypothetical air stripping system. This thesis proves that air stripping is a feasible, highly cost effective option that should be considered for implementation at FS-12 and other MMR plumes.

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ACKNOWLEGEMENTS

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1.1.1 Location

The Massachusetts Military Reservation (MMR) is located on the upper western part of Cape Cod, Massachusetts. It occupies 22,000 acres (35 square miles) within the towns of Bourne, Sandwich, Mashpee, and Falmouth in Barnstable County. The MMR consists of facilities operated by the U.S. Coast Guard, the Army National Guard, the U.S. Air Force, Air National Guard, Veterans Administration, and the Commonwealth of Massachusetts.

MMR is comprised of four principal functional areas (Jacobs, 1997a):

- Cantonment Area: This southern portion of the reservation is the most actively used section of the MMR. It occupies 5,000 acres and is the location of administration, operational, maintenance, housing, and support facilities for the base. The Otis Air Force Base facilities are located in the southeast portion of the Cantonment Area.

- Range Maneuver and Impact Area: This northern part of the MMR consists of 14,000 acres and is used for training and maneuvers.

- Massachusetts National Cemetery: This area occupies the western edge of the MMR and contains the Veterans Administration Cemetery and support facilities.

- Cape Cod Air Force Station (AFS): This 87-acre section is at the northern portion of the Range and Maneuver and Impact Area and is known as the Precision Acquisition Vehicle Entry - Phased Array Warning System.

A majority of the facilities at the MMR are located in the southern portion, while the northern portion consists of several firing ranges.

1.1.2 Hydrology

The humid, continental climate of Cape Cod is strongly influenced by the Atlantic Ocean. Proximity to the ocean results in mitigated temperature extremes. February is the coldest month of the year, with daily temperatures ranging from an average minimum of 23°F to an average

maximum of 38 °F (ANG, 1993). July, the warmest month of the year, typically experiences average temperatures ranging from daily lows of 63 °F to daily highs of 78 °F (ANG, 1995). The oceanic influence results in warmer winters and cooler summers than those experienced in the inland areas of Massachusetts (ANG, 1995).

Cape Cod receives an average rainfall of 47.8 inches per year (ANG, 1995). The precipitation is distributed fairly evenly throughout the year, although a slightly higher portion of the precipitation occurs in the winter months (LeBlanc et al., 1986). The one-year/24-hour rainfall event for Cape Cod is 2.7 inches (Baker et al., 1997).

Due to the highly permeable sand and gravel deposits prevalent on Cape Cod, surface water runoff is less than 1% of the total precipitation (LeBlanc et al., 1986). Approximately 55% of the total precipitation is returned to the atmosphere via evaporation or transpiration by plants (LeBlanc et al., 1986). The remaining 45% infiltrates to recharge the ground water (LeBlanc et al., 1986).

Although ground water provides the main source of water for Cape Cod, approximately 4% of Cape Cod is covered by surface-water bodies. These surface-water bodies, mainly intermittent streams or kettle holes, receive a net recharge of approximately 18 inches per year from direct precipitation (ANG, 1995).

The prevailing winds along Cape Cod are heavily influenced by the Atlantic Ocean and the Gulf Stream. From November through March, the prevailing winds arise from the northwest, whereas, from April through October, the prevailing winds originate from the southwest (ANG, 1995). Average wind speeds range from 9 miles per hour in the summer months to 12 miles per hour throughout the remainder of the year. Episodic tropical or ocean storms can result in exceedingly high wind velocities, ranging from 40 to 100 miles per hour (ANG, 1995).

1.1.3 Hydrogeology and Topography

The geology of western Cape Cod was shaped during the Wisconsin period, 85,000 to 7,000 years B.P. (Before Present), of the Pleistocene epoch, with the advance and retreat of two glacial lobes that resulted in glaciofluvial sedimentation. To the north and west, the Buzzards Bay and Sandwich Moraines are composed mostly of glacial till. South is the Mashpee Pitted Plain, an

outwash plain containing poorly sorted, fine- to coarse-grained outwash sands overlying finer-grained till and marine or lacustrine sediment. This lower layer of fine sediment has a hydraulic conductivity that is as much as five times less than that of the upper outwash layer, so that ground-water flow occurs mostly through the permeable upper layer. Seepage velocity within the sand and gravel outwash is estimated between 1 and 4.6 feet per day, with virtually no vertical flow. The entire plain is dotted with numerous kettle holes, bodies of water that resulted when large blocks of glacial ice, embedded in the sediment, melted. These ponds are maintained mostly by ground-water recharge and runoff.

The topography of the area can be characterized as a broad, flat, glacial outwash plain, dotted by kettle holes and other depressions, with marshy lowlands to the south, and flanked along the north and the west by recessional moraines and hummocky, irregular hills. Remnant river valleys cross the Mashpee Pitted Plain from north to south, while to the north and west the Buzzards Bay and Sandwich Moraines lend a higher degree of topographic relief.

1.1.4 Site History
Activities at the MMR began in 1911. Operational units at the MMR included the U.S. Air Force, U.S. Navy, U.S. Army, U.S. Marine Corps, U.S. National Guard, U.S. Army National Guard, and U.S. Coast Guard. Activities at the MMR have included troop development and deployment, fire-fighting, ordnance development, testing and training, aircraft and vehicle operation and maintenance, and fuels transport and storage. Most activities are associated with either army training, maneuvers, or military aircraft operations, maintenance, support, and associated functions. From 1955 to 1970, a substantial number of surveillance and air defense aircraft operated out of the ANG portion of the reservation. Since that time, the intensity of operations has decreased substantially.

Past releases of hazardous materials at the MMR have resulted in ground-water contamination in a number of areas. Documented sources of contamination include former motor pools, landfills, fire-fighting training areas, and drainage structures such as dry wells. Several major plumes of ground-water contamination have been found to be migrating from these source areas and have been defined during extensive ground-water investigations.

1.1.5 Demographics and Socio-Economic Impacts

The MMR is located on top of a recharge area that supplies water to all the towns surrounding the base. When in 1989 the MMR was named a Superfund site by the Environmental Protection Agency, it became clear that the contamination is a threat to the public as well as to the environment.

Sagamore Lens, the largest lens of the Cape Cod Aquifer, provides drinking water to over 70,000 homes and businesses in the towns of Sandwich, Falmouth, Mashpee, Barnstable, Bourne, and Yarmouth. The MMR itself has a yearly population of about 2000 people while the population of the surrounding towns fluctuates between the winter and summer seasons. During the off season of 1990, an average of 12.5 million gallons per day were supplied from the lens. Pumping rates double in the summer.

1.1.6 Ground Water Contamination

In 1978, the town of Falmouth detected detergents in a public water-supply well located south of the Massachusetts Military Reserve wastewater treatment plant. The United States Geological Survey (USGS) immediately began conducting ground-water investigations, and soon identified a ground-water plume extending south of the treatment plant and into Ashumet Valley. Subsequently, the Air National Guard (ANG) established an Installation Restoration Program (IRP) at Otis ANG Base. The IRP was initiated in 1982 with the purpose of identifying and evaluating potential hazardous waste sites at the MMR (MMRIRP, 1997).

Between 1982 and 1985, investigations at the MMR revealed 73 contaminated soil and ground-water sites. Since 1985, five additional sites have been identified, bringing the total number of contaminated sites to 78. As of September 1996, the ANG and various regulators concluded that 31 of the 78 sites at the MMR pose no threat to the public nor the environment and therefore, require no further action (MMRIRP, 1997). As a result of the investigations conducted at the base, seven major ground-water plumes have been identified:

- *Fuel Spill-12 (FS-12)*
- *Storm Drain-5 (SD-5)*
- *Chemical Spill-10 (CS-10)*

- *Landfill-1 (LF-1)*
- *Fuel Spill-28 (FS-28)*
- *Ashumet Valley*
- *Chemical Spill-4 (CS-4)*

1.2 Purpose

The current system being used to remediate the ground-water plume at FS-12 has its advantages and disadvantages. The system utilizes ultraviolet oxidation (UV/Ox) technology in combination with adsorption by granular activated carbon. There are many reasons why the Installation Restoration Program opted to use this system. However, it may not have been the most prudent decision. Not only are other treatment systems less expensive and more effective, but the current system has much potential for failure. In fact, the system was shut down in the fall of 1997 after only a few months of operation.

Many other treatment options were considered. However, they were not given equal attention. Air stripping, a commonly used, highly effective treatment option, was originally considered, but was not fully investigated. This thesis further considers air stripping. The current system at FS-12 is compared to a hypothetical air stripping system designed for the same application. The ultimate goal of this thesis is to determine whether or not air stripping is a feasible option that should be considered for implementation at the FS-12 plume or at other MMR plumes.

1.3 Scope

In order to compare the current remediation scheme at FS-12 to that of an air stripping system, it is necessary to perform a full analysis of each technology involved. This thesis first focuses on the current system. The FS-12 design fundamentals are presented. Then, a full description of UV/Ox technology and the reasons that it was chosen over other technologies are given. The current system is evaluated and then air stripping is introduced as a possible alternative. The sections on air stripping give a complete description of the technology and its limitations. Finally, a cost analysis is performed to provide a basis upon which the two technologies can be compared. The conclusion summarizes the findings and offers recommendations to the IRP.

2. FS-12 Background

The suspected source of the FS-12 ground-water plume is a leak that occurred in the 1970s in a fuel pipeline located on Greenway Road. The pipeline has since been abandoned, but the contamination problem remains. The main contaminants in the ground-water plume are benzene and EDB (ethylene dibromide). Since these two components of gasoline are suspected carcinogens, a treatment plan has been implemented. The system currently being used is called extraction, treatment, and reinjection (ETR). The contaminated ground water is removed via extraction wells and is then sent to a two-step treatment system. The first step is called ultraviolet oxidation (UV/Ox) and the second is called granular activated carbon adsorption (GAC).

3. FS-12 Design Fundamentals

In order to analyze the current remediation system at FS-12, some knowledge of the plume and its contaminants is needed. Furthermore, consideration of a new remediation technology must compare its contaminant removal capabilities to that of the current system. This section provides the background necessary for these analyses.

3.1 FS-12 Plume and Contaminants

The two main contaminants in the FS-12 ground-water plume are benzene and EDB. Sampling data shows that both contaminant plumes are migrating south-southeast. The benzene plume has gone so far as the Camp Good News entrance road and the EDB plume has migrated as far as J. Braden Thompson Road. The maximum projected width of the plume front normal to ground-water flow is approximately 2300 feet while its maximum thickness is about 150 feet (Jacobs, 1996).

In addition to benzene and EDB, other contaminants such as toluene, ethylbenzene, and xylenes have been detected in the ground water. However, their concentrations remain below their MCLs (maximum contaminant limits, defined by the Federal Safe Drinking Water Act) (MMRIRP, 1996).

Benzene, C_6H_6, is a common component of gasoline. It is a clear colorless liquid which finds many uses in industry. Benzene is a proven carcinogen which has been found in at least 337 of 1177 National Priorities List (NPL) hazardous waste sites.

EDB, or 1,2-Dibromoethane, is also a colorless liquid. Its chemical formula is $BrCH_2CH_2Br$. EDB is a suspected human carcinogen.

3.2 Applicable or Relevant and Appropriate Requirements (ARARs)

Associated with any ground-water treatment system are federal and state standards and requirements. It is necessary to sort through these and select what are called the Applicable or Relevant and Appropriate Requirements (ARARs).

During the design and planning phases for the treatment system at FS-12 many aspects of the project were taken into consideration when determining the appropriate ARARs. They are as follows:

- construction of decontamination facilities
- the placement of support facilities
- access road improvement
- tree clearing, grubbing, and topsoil stripping
- extraction, monitoring well, and reinjection well installation and operation
- air emissions
- residuals management
- potable water supplies to the treatment units
- septic systems

The federal ARARs include the Clean Air Act (CAA), the Clean Water Act (CWA), the Safe Drinking Water Act (SDWA), and the Resource Conservation and Recovery Act (RCRA). The Commonwealth of Massachusetts ARARs include Air Pollution Control, Hazardous Waste, and Underground Water Source Protection among many others (Jacobs, 1996).

3.3 ETR System Design Basis

3.3.1 Influent Concentrations
The objectives for the FS-12 ETR system are to

- design, construct, and operate a full-scale ETR system

- contain, capture, and remediate the FS-12 plume
- minimize adverse impacts on Snake Pond and its surrounding environment
- monitor performance of the treatment system
- avoid influencing the remedial system on the J. Braden Thompson plume
- minimize disturbance to private property, and
- monitor ground-water quality to assess performance and assist future design at other sites.

During preliminary stages of design, an extraction well was used to determine the contaminant concentrations in the FS-12 area. Because the water was extracted from the toe of the plume, the initial concentrations were low, but were expected to increase as time passed. Therefore, an average contaminant concentration called the "60% design concentration" was assumed (Jacobs, 1996).

3.3.2 Effluent Design Goals

Table 1 shows the 60% design basis concentrations of benzene and EDB. It also shows the MCLs (maximum contaminant level) and cleanup goals.

Table 1: FS-12 Contaminant Concentrations.

contaminant	60% design (μg/L)	MCL (μg/L)	cleanup level (μg/L)
benzene	60	5	0.1
EDB	8.2	5	0.02

source: Jacobs, 1996

As shown, a 99.8% decrease in benzene concentration and a 99.7% decrease in EDB concentration are expected.

4. Description of Current Treatment Process—UV/Ox followed by GAC

4.1 System Description

There are nine steps in the treatment system being used at FS-12. They are:

- extraction wells,
- collection piping and an influent tank,
- pH control,

- Greensand filters to remove suspended solids, iron, and manganese,
- solids settling and collection facilities,
- UV/Ox system to partially oxidize the organic contaminant,
- GAC to complete the removal of the toxic organics to below the detection limit,
- effluent tank, and
- reinjection wells.

The sections that follow highlight some of the process steps that are relevant to this study (Jacobs, 1996).

4.1.1 Extraction

Thirty extraction wells supply the contaminated water at FS-12 to the treatment unit. The well pumps supply the water through a double walled pipe header which provides secondary containment for the influent stream. Leak detection sites at the low points along the header guard against leakage. The well operations are monitored from the treatment unit or the remote control center at the FS-12 site (Jacobs, 1996).

4.1.2 Neutralization

Before the influent water can be sent to the Greensand filters, the pH must be 6.2 or greater. The pH of the influent is between 5.2 and 5.5. The increase in pH is accomplished by the addition of 25% sodium hydroxide (NaOH) (Jacobs, 1996).

4.1.3 UV/Ox

4.1.3.1 UV/Ox Background Information

UV/Ox is a common ground-water treatment technique. It is a destruction process that uses ultraviolet light and strong oxidizers to break down organic and explosive components in contaminated ground water. The reactions are catalyzed by the use of ultraviolet light in combination with either ozone or hydrogen peroxide. The ozone or hydrogen peroxide, when activated by the light, forms hydroxyl radicals which can then destroy the ground-water contaminants. If the reaction goes to completion, the products are simply carbon dioxide and water.

The greatest advantage of using UV/Ox over other treatment techniques is that it actually breaks down the contaminants rather than simply extracting them. Another advantage to UV/Ox is that

it solves the contamination problem without creating hazardous waste. Furthermore, this treatment method has been proven to destroy over 99.9% of the explosive contaminants in ground water (Trach, 1996).

However, there are a number of disadvantages to using UV/Ox. First, the ultraviolet light cannot come into direct contact with the water. For this reason a quartz sleeve is used to cover the UV bulbs. Unfortunately, the tubes can easily be fouled as a result of coating by chemicals and minerals in the water (Nyer, 1992). Hence, the aqueous stream must be relatively free of heavy metal ions and oil or grease.

Another common issue is that of turbidity. The aqueous stream must provide for good transmission of the ultraviolet light in order for UV/Ox to be effective. Free radical scavengers, which are excess products of the oxidation reactions, represent another problem. They can inhibit contaminant destruction efficiency. Also, handling and storage of the oxidizer requires special handling and safety precautions (DOE, 1996).

High cost is another problem with UV/Ox. Oftentimes, systems using a UV/Ox step cost more than alternative systems because of the energy requirements of the reactor lamps. Pretreatment of the aqueous stream can add another cost (DOE, 1996).

4.1.3.2 UV/Ox at FS-12

After passage through the Greensand filters which remove iron and manganese from the influent stream, the water is sent to the ultraviolet oxidation unit. The system at FS-12 utilizes hydrogen peroxide as the oxidant. When the water is exposed to both ultraviolet light and hydrogen peroxide, over 99% of the benzene is oxidized and destroyed. However, UV/Ox is not as effective in removing EDB. The carbon adsorption step accomplishes this.

The UV/Ox reactor consists of a stainless steel vessel with a single high powered ultraviolet lamp at the center. The lamp is separated from the water by a quartz sleeve. The UV light splits the peroxide thereby produci

4.1.4 Carbon Adsorption

4.1.4.1 Carbon Adsorption Background Information

Granular Activated Carbon Adsorption (GAC) is another proven technology for the treatment of ground water. In this case, contaminated water is passed over small carbon particles that provide sites onto which the contaminants can be adsorbed. GAC works best when the concentration of contaminants is low and the flowrate of the ground water is low. Unfortunately it is a costly process and requires periodic changing of the carbon particles (Mittelhauser, 1996b).

4.1.4.2 Carbon Adsorption at FS-12

The carbon adsorption system in place at the FS-12 plume consists of three trains of two adsorbers each. The purpose of having two adsorbers in each train is to allow them to work in series. The adsorber with the fresher load of carbon is the polishing filter. When the carbon in an absorber is spent, it is sent to a licensed firm for reactivation (Jacobs, 1996).

4.2 Compliance with Regulation Requirements

The sections below outline the detail with which the current remediation system was designed to meet the requirements of the federal and state ARARs. Any alternative technology would need to be at least as successful.

4.2.1 Compliance with Requirements of Federal ARARs

4.2.1.1 Clean Air Act

Preliminary studies showed no expected air emissions from the treatment system at the FS-12 plume. Results showed no expected emissions of nitrogen dioxides or sulfur dioxides. The USEPA "Water 8" program was used to model the emissions. The results are shown in table 2.

4.2.1.2 The Safe Drinking Water Act

To comply with the Safe Drinking Water Act, the system design included Greensand filters which are used to reduce iron and manganese discharge concentrations. Also, the activated carbon filters were included to remove higher molecular weight organic contaminants. The effluent concentrations are shown in Table 3 (Jacobs, 1996).

Table 2: USEPA "Water 8" Program Calculated Air Emissions.

compound	air emissions (tonnes/year)
Benzene	0.0277
bis(2-Ethylhexyl) Phthalate	0.2514×10^{-7}
Chloroform	0.1298×10^{-4}
Dibromomethane	0.1692×10^{-2}
Dibutylphthalate	0.6326×10^{-8}
Dichloroethene (1,1)	0.2562×10^{-2}
Ethylbenzene	0.1361×10^{-2}
Methyl Naphthalene (2-)	0.7279×10^{-6}
Naphthalene	0.2132×10^{-4}
Phenol	0.2926×10^{-7}
Toluene	0.8803×10^{-4}
Trichloroethylene	0.3690×10^{-5}
Xylenes	0.1299×10^{-2}
Total All Compounds	0.03606

source: Jacobs, 1996

Table 3: Effluent Concentrations to meet MCLs.

contaminant	effluent concentration	MCL
iron	0.53 mg/L	0.3 mg/L
manganese	0.0065 mg/L	0.05 mg/L
benzene	non detect (<0.5 mg/L)	5 mg/L
EDB	non detect (<0.02 mg/L)	0.02 mg/L

source: Jacobs, 1996

4.2.1.3 Resource Conservation and Recovery Act

RCRA is a more difficult piece of legislation with which to comply. Expected solid waste residuals include drill cuttings, sludge removed from the Greensand filter, and spent activated carbon. Drill cuttings were not expected to amount to a significant problem, but the system plan did take them into consideration. Provisions were made for the sludge to be disposed at a facility permitted to receive the waste and for the spent activated carbon to be sent off site for regeneration.

4.2.2 Compliance with Commonwealth of Massachusetts ARARs

4.2.2.1 Air Pollution Control

Because the FS-12 plume response project was expected to produce air emissions of less than one ton/year, it was exempt from the air permitting requirements (Jacobs, 1996).

4.2.2.2 Hazardous Waste

The only hazardous wastes expected from the treatment plan include drill cuttings and water generated during the installation and development of the wells, solids collected during backwash of the filters, and spent activated carbon. The system design assumed that all three would be tested and handled according to the regulations. Additional preventative measures were made a part of the system as well (Jacobs, 1996).

4.2.2.3 Underground Water Source Protection

A list of classes of injection wells is presented in the Underground Water Source Protection Act. There are five classes of wells. Class I-IV wells are prohibited. The injection wells for FS-12 are Class V wells which are allowed as long as they do not cause or allow movement of contaminants into any underground drinking water sources (Jacobs, 1996).

5. Alternate Technologies Considered

Jacobs Engineering, the consultant firm for the IRP, considered a number of alternate technologies for the remediation system at FS-12. The technologies were evaluated with respect to technical implementability. The evaluation included tests for reliability, implementability, safety, and likelihood of meeting the treatment goals. Then, a cost analysis was performed. The following other concerns were considered as well:

- ability to meet regulations,
- on-site and off-site requirements,
- worker health and safety issues,
- worker and community relations benefits, and
- ability to maintain all environmental and ecological protection considerations.

The first step in choosing an appropriate remediation system was to determine the method by which large particles were to be removed from the ground water. Sand filters were chosen

because this technology is well known and is successful at removing sediment. This step also allowed the water to flow through the other process equipment with minimal likelihood of blockage.

Additionally, the heavy metals such as iron and manganese required a removal technology. Greensand filters were selected based on operational, maintenance, and reliability requirements and also because they can serve as filters to remove suspended solids.

The next step was to select a technology to remove the organics from the influent stream. The seven technologies that were considered include:

- UV/Oxidation,
- Ozonation,
- Clays,
- Air Stripping,
- Ion Exchange,
- Membrane Separation, and
- Synthetic Carbon.

The alternatives were evaluated against three broad criteria. They were effectiveness, implementability, and cost. The purpose of the first evaluation was simply to shorten the list of choices, so the first stage of analysis was a general screening. The alternatives were compared on an equivalent basis. After this phase came a detailed analysis in which the alternatives were evaluated against nine criteria and their individual factors as opposed to general criteria. The nine evaluation criteria are:

- overall protection of human health and the environment,
- compliance with ARARs,
- long-term effectiveness and permanence,
- reductions in toxicity, mobility, and volume through treatment,
- short-term effectiveness,
- implementability,
- cost,
- state acceptance, and
- community acceptance.

The seven technologies listed above passed the initial screening. Air stripping, however, was eliminated during the detailed analysis, as were many of the other technologies. It was

eliminated in the category of implementability. The comment noted in the process screening evaluation report was, "not acceptable to public/local government. Permit required."

6. Characteristics of Current System

6.1 Design Basis

The UV/Ox system used at FS-12 was designed by Calgon Carbon Oxidation Technologies (CCOT) and was based on the criteria shown in table 4 below.

Table 4: Design Criteria for FS-12 UV/Ox System.

Constituent	Influent Concentration (ppb)	Effluent to Carbon (ppb)
benzene	60	2.2
EDB	8.2	4.2

source: Calgon, 1996

Calgon recommended a UV/Ox step followed by carbon adsorption and noted that using UV/Ox (as opposed to using only carbon) significantly reduces the amount of carbon needed to remediate. The system was based on a treatment flowrate of 1015 gpm.

6.2 Cost of Implementation

Purchase of the UV/Ox equipment was estimated at $333,000. This was the cost for three 2 x 30 kW UV/Oxidation Systems as described by Calgon.

Table 5 represents a breakdown of the predicted operation costs involved with the UV/Ox system at FS-12.

Table 5: Estimated Operation Costs of UV/Ox at FS-12.

item	$/1000 gallons	$/year
electrical Power ($0.06/kWh)	$0.17	$29,900
lamp replacement	$0.06	$10,500
50% peroxide (at $0.34/lb, 15 ppm)	$0.09	$15,000
total operating cost	$0.32	$55,400

source: Calgon, 1996

7. Air Stripping as an Alternative

7.1 Introduction to Air Stripping

Air stripping involves the blowing of air into contaminated water for remediation purposes. Organics are transferred from the ground water into the air. The air is either directly discharged or treated and then discharged. Air stripping is effective on BTEX and chlorinated solvents. However, it is not effective on highly soluble organics such as ketones (Mittelhauser, 1996).

There are many reasons to consider air stripping as an alternative to other ground-water treatment technologies. Especially for high water flowrates and insufficient or non-existent steam supply, air stripping combined with exhaust air purification is preferred for economic and energetic reasons. Many studies have shown that air stripping is more efficient and cost-effective than other treatment methods (Kutzer, *et al.*, 1995).

There are numerous air stripping technologies that can be applied for the removal of VOCs from water. The most common ones include tray aeration, spray aeration, cascade aeration, rotary stripping, and packed tower aeration. Packed tower aeration (PTA), shown in Figure 1, is the most commonly applied technology for the removal of VOCs from water. The USEPA has acknowledged packed tower air stripping as a Best Available Technology (BAT) for the treatment of VOCs. For this reason, this thesis focuses on PTA (Nyer, 1992). In this study, the terms "air stripper" and "packed tower aerator" are used interchangeably.

In PTA, air and water are run counter-currently through a structured or randomly dumped medium. This mass transfer process involves exposing the liquid surface area to the air. The medium, in many cases, plastic packing, enhances the air/liquid contact. The medium also mixes the water to prevent any diffusion limitations. The contaminants are carried out of the tower and emitted to the atmosphere. They can then break down by natural UV degradation or other destruction processes. In some cases, the off-gas may need treatment before it can be discharged (Nyer, 1992).
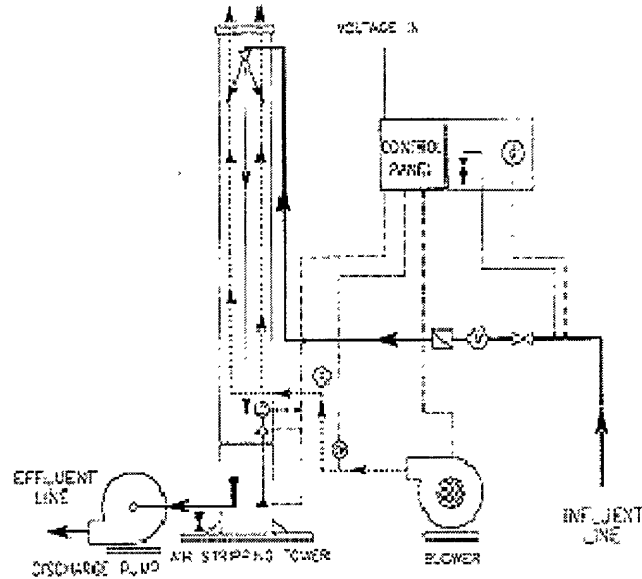
Figure 1: Packed Tower Air Stripper (Wes Inc, [no date]).

7.2 Evaluation of Packed Towers

7.2.1 Advantages

The first advantage of PTA is that it is highly effective. Removal rates are generally in the 90%-99% range. PTA is also a fairly cost effective technology. More information on the cost of PTA is provided in section 10.

7.2.2 Disadvantages

The most obvious disadvantage to using PTA to remediate ground water is the contaminated air stream that is emitted. This stream is generally called the off-gas. Because the contaminants are merely moved from the aqueous stream to the vapor stream, there are inevitable problems with this vapor phase effluent. Because Clean Air Act regulations limit the allowable emissions of organics, expensive treatment of the air stream may be necessary (PNL, 1997).

Another common problem with air stripping towers is that of fouling by solids. Particles in the ground water can become entrapped in the tower and cause loss of efficiency, loss of capacity, and increased pressure drop. While there is no such thing as an anti-plugging packing, there are methods by which fouling risk can be minimized (Jaeger, 1997).

7.3 Application of PTA to FS-12 Plume

7.3.1 Preliminary Considerations/Issues

Many factors come into play when determining the utility of PTA at FS-12. This section attempts to summarize these issues.

Air stripping was eliminated from consideration for a number of reasons that were mentioned in section 5. It seems that the main reason for which air stripping was eliminated stems from lack of education about the consequences of using the technology. Perhaps many of the voting townspeople were concerned about the off-gas. However, the air pollution problem is easily solved by use of a vapor-phase granular activated carbon adsorption (VPGAC) unit. The technique of following air stripping by VPGAC is a common one. This "air-stripping solvent recovery process", as it has been called by the American Water Works Association, is a process proven technically and economically feasible. A diagram of this process appears in figure 2.
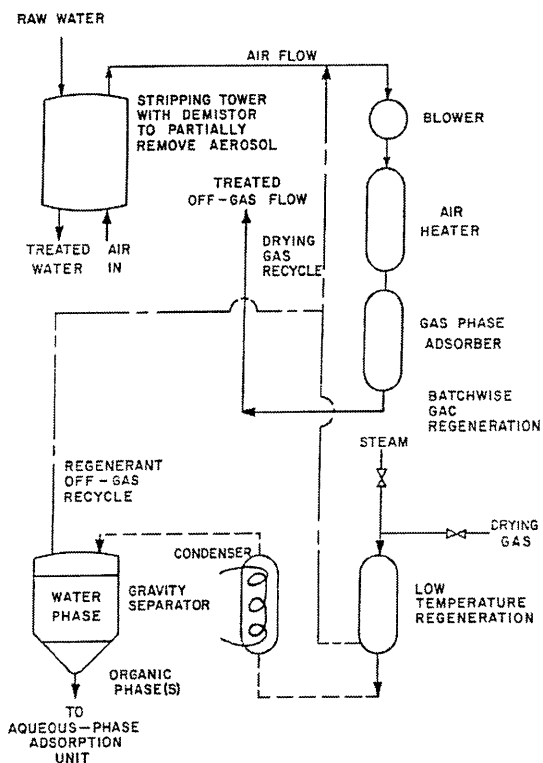
Figure 2: Process Flow for the Air Stripping Solvent Recovery Process.

(Crittenden, *et al.*, 1987)

Another issue is that of cost. It is difficult to determine whether or not, in the long run, air stripping will be more cost effective than UV/Ox. This kind of economic analysis can only take place after a preliminary design of the air stripping unit.

Other than the air pollution and cost issues, there remains no apparent reason for which air stripping could not be applied to FS-12. There are issues to consider such as the packing replacement and the unit cost, but these are minor factors which are dealt with during the preliminary design of any air stripping unit.

7.3.2 PTA Design Data

The interesting thing about air stripper design is that a number of air strippers can be designed to meet the same water treatment goal. This makes PTA design tedious. The influent contaminant concentration, the desired effluent contaminant concentration, and Henry's Law constants for the various contaminants are the essential variables that must be defined. Many factors must be considered when determining what stripper dimensions are best for a given application. Incorporating all of these can be a time consuming task. However, there is enough information in the chemical engineering literature to provide a method by which one can crudely estimate the dimensions and costs of a packed tower. Section 8 describes the method used in this study.

8. Design of PTA for FS-12

In this section, the design of a typical packed tower air stripper which could be applied to FS-12 is presented. Because there are so many different air stripper designs which can be created, it is necessary to perform calculations for a number of units which cover a range of options. In cases such as this where there is more than one major contaminant of concern, the design procedure is to be carried out for each contaminant. The final design is selected to accommodate the compound whose effluent standard is most difficult to achieve. In this section, background information on PTA design is given. This is followed by a set of sample calculations for the packed towers designed in this study. Calculations appear in appendices A and B. Comparisons and analyses of the results are presented in section 12.

8.1 Design Variables

This section presents the many design variables which are involved in packed tower air stripper design.

Table 6 contains each variable with a brief description and the units typically used in calculations.

Table 6: Definitions of Design Variables.

VARIABLE	DEFINITION	UNITS
x_1	influent concentration	$\mu g/L$
x_2	effluent concentration	$\mu g/L$
Z	column height	m
HTU	height of transfer unit	m
NTU	number of transfer units	unitless
H_A	Henry's Law constant	atm
R	stripping factor	unitless
G	superficial molar air flowrate	k mole m^2 sec
L	superficial molar liquid flowrate	k mole m^2 sec
G'	superficial air mass velocity	kg/m^2 sec
L'	superficial liquid mass velocity	kg/m^2 sec
Q_L	volumetric flowrate	L/sec
C_o	molar density of water	kmol/m^3
p_T	total pressure	atm
K_L	overall liquid mass transfer coefficient	m/s
a	interfacial area per volume of packing across which mass transfer occurs	m^2/m^3
D_A	molecular diffusion coefficient of the solute in water	ft^2/hr, m^2/sec
C_f	packing factor	unitless
μ_L	liquid viscosity	kg/m sec, lb/ft hr
ρ_L	liquid density	kg/m^3
MW	molecular weight	kg/k mole
m	empirical constant	unitless (20-200)
n	empirical constant	unitless (0.2-0.5)
T	absolute temperature	Kelvin (K)

8.1.1 Tower Height

Tower height is a strong function of the removal efficiency required. The tower must be taller when a greater efficiency is required (Nyer, 1992). Tower height also depends on the volatility

of the compounds, the air-to-water ratio, the water flowrate, and the physical and chemical conditions that affect the mass transfer rates (Kutzer *et al.*, 1995).

8.1.2 Air-to-Water Ratio

Air-to-water ratio varies with the contaminant being removed. If the substance is highly volatile, a smaller volume of air is required. Air-to-water ratios can range from 10:1 to 200:1 (Nyer, 1992).

8.1.3 Water Temperature

Water temperature can affect the effectiveness of PTA. Higher temperatures enhance constituent volatility. Ground-water temperatures vary throughout the country so it is necessary to determine its value at the site being considered. Fortunately, while air temperatures change with the season, ground-water temperatures stay nearly constant year round. Furthermore, in a PTA system, the majority of the thermal mass is made up of water rather than air. If necessary, preheaters can be used on the water stream to increase volatility. However, this technique is usually limited to application for hazardous waste site cleanups of short durations or in places with very high organic levels (Nyer, 1992).

8.2 Mass Transfer Process

The general mass transfer process is the design basis of any packed tower air stripper. The transfer of VOCs from water to air is driven by the concentration gradient between the two phases. The rate by which any compound is transferred depends on its Henry's Law constant. The Henry's Law constant is a ratio of the partial pressure of the compound in air to its mole fraction in water at equilibrium. The higher the Henry's Law constant, the greater the maximum load of a contaminant in air. It is easier to strip compounds with high Henry's Law constants. Table 7 gives Henry's Law constants for benzene and EDB.

Table 7: Henry's Law Constants for Benzene and EDB at Water Temperature 20°C.

compound	Henry's Law Constant (atm)
Benzene	230
EDB	33

source: Nyer, 1992

The mass transfer equations for PTA are given in equations 1 through 3.

$$Z = HTU \times NTU \tag{1}$$

$$HTU = L'/K_L a \tag{2}$$

$$NTU = \left(\frac{R}{R-1}\right) \times \ln\left[\frac{\left(\dfrac{C_{inf}}{C_{eff}}\right) \times (R-1) + 1}{R}\right] \tag{3}$$

It is very important to be careful in selecting these variables. For example, published Henry's Law constants can vary by more than an order of magnitude. The mass transfer coefficient must also be selected with caution. It varies with tower design and packing type. It is common to select the mass transfer coefficient based on field data such as pilot test results or operating data from a system similar to the one being designed. However, since chemical characteristics vary, it is better to actually test the water that will be treated. In the case where pilot tests are not practical, theoretical correlations can be used (Nyer, 1992).

A typically used empirical correlation for liquid-phase mass transfer coefficients in towers containing randomly packed materials is shown in equation 4.

$$\frac{K_L a}{D_A} = \alpha \left(\frac{L'}{\mu_L}\right)^{1-n} \left(\frac{\mu_L}{\rho_L D_A}\right)^{0.5} \tag{4}$$

Correlations such as these were developed using bench scale data to design curves which relate the $K_L a$ and physical properties of the air, water, organic compounds, and packing.

Once all constants are known, the equations can be solved for different combinations of stripping factors and gas pressure drops. Options can be generated and then discarded based on site-specific constraints. Capital and operating cost data can then be used to select a final design (Nyer, 1992).

8.3 Packed Tower Design Sample Calculations

The column designed in these sample calculations is a counter-current packed tower in which the liquid feed (influent groundwater from FS-12) will flow downward counter-current to the rising airflow. The rate of mass transfer is based on the Henry's Law constant of benzene.

In order to estimate the cost of air stripping, the volumetric air-water ratio, the dimensions of the column, the size of the packing, the water and air loading rates (superficial velocities), and the gas pressure drop must be known. The air flowrate is based on the required degree of contaminant removal. The following sections include a step by step description of the design method used in this study. It is further explained by Michael C. Kavanaugh and R. Rhodes Trussell in "Designs of Aeration Towers to Strip Volatile Contaminants from Drinking Water," (Kavanaugh and Trussell, 1980) and by James M. Montgomery Consulting Engineers, Inc. in "Water Treatment Principles and Design." (Montgomery, 1985).

8.3.1 Design Characteristics

The following sections describe the characteristics of the packed tower designed in the sample calculations.

8.3.1.1 Benzene Data

The sample calculations shown are based on the FS-12 system with the following characteristics:

benzene influent concentration = 60 μg/L
benzene effluent concentration = 0.1 μg/L
ground water temperature = 20 °C
Henry's Law constant for benzene = 230 atm at 20 °C

8.3.1.2 Stripping Factor

When designing air stripping systems, various stripping factors must be tested. These sample calculations assume a stripping factor of 3.

Based on the current system design at FS-12, the liquid flowrate should be in the range of 400-1400 gallons per minute. The expected flowrate was listed as 830 gpm (Jacobs, 1997b). Design requirements for both the UV/Ox system and the air stripper in this section call for a flowrate of 1015 gpm (Calgon, 1996).

8.3.2 Packing Material

The first step in the PTA system design is to select an efficient packing material that will provide good mass transfer with low gas head loss. For these sample calculations, 2-inch Super Intalox is used because it is a light, low cost packing material with good mass transfer characteristics. For this packing material, C_f, the packing factor, is 21. The packing factors for other common packings are shown in table 8.

Table 8: Packing Factor C_f for common Plastic Packings and Raschig Rings.

Packing Type	C_f for Nominal Packing Size Shown				
	1 inch	1.5 inch	2 inch	3 inch	3.5 inch
Super intalox	33	--	21	16	--
Pall rings	52	32	25	--	16
Tellerettes	40	--	20	--	--
Maspack	--	--	32	20	--
Heil-Pack	45	--	18	15	--
Raschig rings	155	95	65	37	--
Berl saddles	110	65	45	--	--

source: Montgomery, 1985

8.3.3 NTU

As shown in section 8.2, the height of the column packing, Z, needed to reach the desired contaminant level is equal to the product of the height of a transfer unit and the number of transfer units. This is shown in equation 1.

$$Z = HTU \times NTU \quad (1)$$

NTU represents the difficulty of removing the solute(s) (EDB and benzene) from the liquid phase. If the difference between the equilibrium and actual concentration of the solute is large, the rate of removal is large. However, as the actual concentration approaches the equilibrium

value, a larger number of transfer units is required. That also means using an unreasonably tall column.

Assuming that the solution is dilute and that the solute obeys Henry's law, the expression for NTU can be solved analytically because the mole fractions of the solute in the gas and liquid phases are always related by a material balance around the upper or lower section of the column. Henry's law is used to determine the mole fraction of the solute in the air. Equation 3 describes the relationship between NTU and stripping factor.

$$NTU = \left(\frac{R}{R-1}\right) \times \ln\left[\frac{\left(\frac{C_{inf}}{C_{eff}}\right) \times (R-1) + 1}{R}\right] \tag{3}$$

Figure 3 shows the dependence of NTU on removal efficiency and stripping factor. It is interesting to note that for a stripping factor above 3 or 4, very little improvement is seen in the NTU.

NTU is calculated with equation 3, and a stripping factor of R = 3.

$$NTU = \left(\frac{3}{3-1}\right) \times \ln\left[\frac{\left(\frac{60}{0.1}\right) \times (3-1) + 1}{3}\right]$$
$$= 8.99$$

8.3.4 Gas Flowrate
The gas phase pressure drop depends on the gas rate and on the liquid mass superficial velocity. Figure 4 shows the influence of liquid and gas rates on pressure drop.

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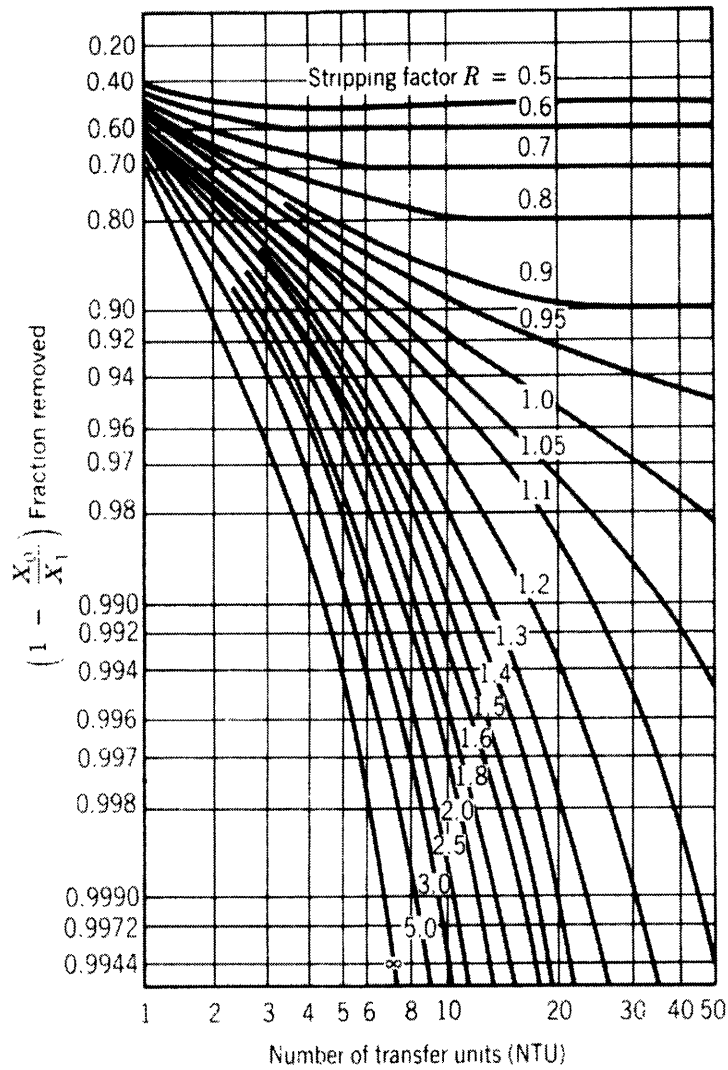
Figure 3: Dependence of NTU on removal efficiency and stripping factor.
source: Montgomery, 1985

It is important to design a packed tower with a gas pressure drop well below flooding conditions. For this reason, most are designed for gas pressure drops of 200 - 400 N/m^2 per meter of packing depth (0.25-0.5 in H_2O/ft). However, for compounds with H_A >100 atm, as is the case with benzene, lower design pressure drops may be more cost-effective.
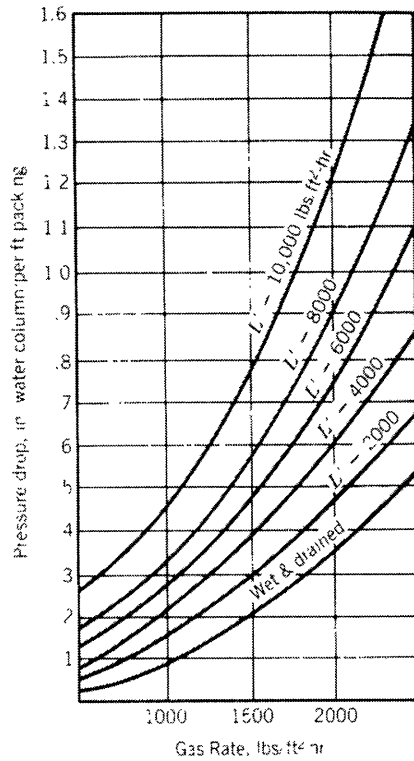
**Figure 4: Influence of liquid and gas rates on pressure drop.
source: Montgomery, 1985**

Figure 5 shows a correlation that is commonly used to determine the pressure drop in towers with random packing.

In order to perform the calculations for air pressure drop, the packing factor must be known. These are found in table 8.

The gas-loading rate can be estimated once the stripping factor and the gas pressure drop are chosen. In the event that the abscissa value is less than 0.02 or greater than 4, pilot studies are recommended to determine the effect of high or low gas flowrates on removal efficiencies.
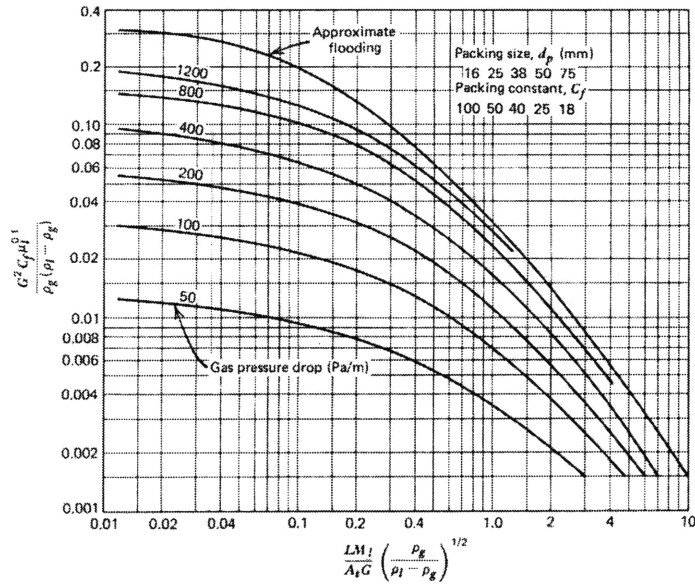
Figure 5: Generalized air pressure drop correlation in packed towers.
source: Montgomery, 1985

The allowable gas flow is determined by assuming a gas pressure drop. Table 9 shows the assumptions used to calculate the gas flowrate for these sample calculations.

Table 9: Conditions used for Sample Calculations.

variable	value
temperature	20°C
p_T	1 atm
MW_{air}	28.8 kg/k mole (dry)
ρ_{air}	1.205 kg/m³
ρ_{water}	998 kg/m³

The ratio of gas to liquid flowrates is found by using equation 5.

$$R = \left(\frac{H_A}{p_T}\right) \times \left(\frac{G}{L}\right) \tag{5}$$

Substituting values for H_A and p_T gives

$$R = \left(\frac{H_A}{p_T}\right) \times \left(\frac{G}{L}\right) = \left(\frac{230\text{atm}}{1\text{atm}}\right) \times \left(\frac{G}{L}\right) = 230\frac{G}{L} = 368\frac{G'}{L'}.$$

For R = 3,

$$\frac{G'}{L'} = 8.2 \times 10^{-3} \text{ (kg/kg)}$$

$$\frac{L'}{G'} = 123.$$

Figure 5 is used to determine G'. The abscissa is determined by equation 6.

$$\left(\frac{L'}{G'}\right) \times \left(\frac{\rho_{air}}{\rho_{water} - \rho_{air}}\right)^{1/2} \tag{6}$$

In this case,

$$\text{abscissa} = (123) \times \left(\frac{1.205\text{kg} / \text{m}^3}{998\text{kg} / \text{m}^3 - 1.205\text{kg} / \text{m}^3}\right)^{1/2}$$

$$= 4.28$$

With this value for the abscissa,

$$G' = \left[\frac{(\rho_{air}) \times (\rho_{water} - \rho_{air}) \times (0.0027)}{C_f \mu_L^{0.1}}\right]^{1/2} \tag{7}$$

$$G' = \left[\frac{(1.205) \times (998 - 1.205) \times (0.0027)}{(21) \times (0.001)^{0.1}}\right]^{1/2}$$

$$= 0.56 \text{ kg/m}^2 \text{ sec.}$$

Therefore, since $\frac{L'}{G'} = 123$

$$L' = 123(0.56 \text{ kg/m}^2 \text{ sec})$$
$$= 68.9 \text{ kg/m}^2 \text{ sec.}$$

8.3.5 Column Diameter

The column diameter can be determined by equation 8

$$\phi = \left[\left(\frac{4}{\pi}\right) \times \left(\frac{Q_L \rho_L}{L'}\right)\right]^{1/2} \tag{8}$$

where Q_L is the flowrate. The UV/Ox system at FS-12 was designed on a 1015 gallons/min basis. Therefore,

$$\phi = \left[\left(\frac{4}{\pi}\right) \times \left(\frac{(0.064)(998)}{(68.9)}\right)\right]^{1/2}$$

$$= 1.09 \text{ m}$$

8.3.6 Mass transfer coefficient

In order to calculate the height of the transfer unit, mass transfer data must be known. $K_L a$ values can be estimated from pilot studies on similar systems. This information is also sometimes provided by packing manufacturers (as a function of temperature and flowrates). However, even in the absence of this data, fairly accurate estimates can be made from the literature. Equation 4 gives an empirical method for determining $K_L a$.

$$\frac{K_L a}{D_A} = \alpha \left(\frac{L'}{\mu_L}\right)^{1-n} \left(\frac{\mu_L}{\rho_L D_A}\right)^{0.5} \tag{4}$$

The variables m and n are empirical constants that depend on type and size of packing materials. Values of m range between 20 and 200. Values of n range between 0.2 and 0.5. D_A for most nonelectrolytes in water at low concentrations ranges from 0.5 to 2×10^{-9} m^2/sec. The literature shows a value of 3.63×10^{-5} for the diffusion coefficient of benzene (Montgomery, 1985).

Using equation 4, with n = 0.28 gives,

$$\frac{K_L a}{D_A} = \alpha \left(\frac{L'}{\mu_L}\right)^{1-n} \left(\frac{\mu_L}{\rho_L D_A}\right)^{0.5}$$

$$K_L a = (3.64 x 10^{-5}) \times (196) \times \left(\frac{50,811}{2.41}\right)^{1-0.28} \left(\frac{(2.41)}{(62.3) \times (3.63 x 10^{-5})}\right)^{0.5}$$

$$= 302 \ hr^{-1}, \ 5.03 \ min^{-1}.$$

8.3.7 Height of Transfer Unit

Again, HTU is found by using $K_L a$ and equation 2.

$$HTU = \frac{L'}{K_L a} \qquad\qquad (2)$$

$$= \frac{68.9 \ kg / m^2 \ sec}{5.03 \ min^{-1}}$$

after unit conversion, HTU = 0.82 m.

8.3.8 Packing Height, Z

The packing height of the air stripping column is found with equation 1,

$$\begin{aligned} Z \quad &= HTU \ x \ NTU \\ &= (0.82 \ m) \ x \ (8.99) \\ &= 7.38 \ m \end{aligned}$$

8.3.9 Column Dimensions with Safety Factor

A safety factor of 1.5 (50% greater than design specifications) is used on the height to ensure proper sizing. The column diameter and height with the safety factor are as follows:

$$\begin{aligned} Z \quad &= (1.5)(7.38m) \\ &= 11.07 \ m \end{aligned}$$

$$\phi \quad = 1.09m$$

8.4 Optimization

The above calculations can be repeated for various values of the stripping factor and the gas pressure drop. Annual costs can then be computed and the optimal system can be selected based on the economic results. Appendices A and B include calculations done for additional stripping factors and gas pressure drops. Tables 10 and 11 give the results from the calculations found in the appendices.

Table 10: Results of Preliminary Packed Tower Air Strippers Designed for FS-12, Benzene.

stripping factor	gas pressure drop (N/m^2 m)	column height (m)	column diameter (m)	column volume (m^3)
2	50	--	--	--
	100	13.8	1.1	13.6
	200	14.3	1.1	12.6
	400	14.5	1.0	11.9
3	50	9.8	1.3	13.9
	100	10.4	1.2	12.0
	200	11.0	1.1	10.3
	400	11.3	1.0	9.6
4	50	8.4	1.5	14.6
	100	9.1	1.3	12.0
	200	9.6	1.2	10.5
	400	10.0	1.1	9.4
5	50	7.8	1.6	14.9
	100	8.4	1.4	12.2
	200	8.8	1.2	10.7
	400	9.3	1.1	9.4

Table 11: Results of Preliminary Packed Tower Air Strippers Designed for FS-12, EDB.

stripping factor	gas pressure drop (N/m² m)	column height (m)	column diameter (m)	column volume (m³)
2	50	11.2	2.2	41.2
	100	12.4	1.8	32.0
	200	13.3	1.6	26.9
	400	14.0	1.5	23.4
3	50	8.2	2.5	40.0
	100	9.1	2.1	30.8
	200	9.8	1.8	25.4
	400	10.3	1.6	22.0
4	50	7.0	2.8	42.9
	100	7.9	2.2	30.9
	200	8.4	2.0	26.7
	400	8.9	1.8	23.2
5	50	6.3	3.0	45.7
	100	7.3	2.3	31.3
	200	7.7	2.1	27.1
	400	8.1	1.9	24.1

It is clear that EDB is the more difficult component to strip from the influent ground water at FS-12 because the EDB air stripper volumes are much greater than those air strippers based on benzene removal.

9. Treatment of the Off-gas

Before analysis of the air stripping system is complete, there is one more issue to consider. That is the problem of the off-gas. While the water stream is treated and reinjected as a clean stream of liquid, there is also an air stream which must be emitted from the air stripper. This stream of air contains all of the contaminants that are stripped from the water. The discharge of these volatile organics is a major concern when using air stripping for the treatment of contaminated water. Unlike other treatment systems, such as UV/Ox, where the volatile organics are destroyed, in air striping, they are simply transported from the water stream to the air stream. However, the air stream can be effectively treated before emission into the atmosphere.

There are currently a number of methods by which the off gas from an air stripping column may be treated. A few of these are activated carbon treatment, incineration, or chemical destruction. The following sections describe the first two treatment options, as they are the most commonly used methods.

9.1 Off-gas Treatment via Vapor Phase Granular Activated Carbon Adsorption (VPGAC)

Treatment of off-gas via activated carbon adsorption, also known as VPGAC, is very similar to the carbon adsorption method used with the UV/Ox system at FS-12. It may seem foolish to use VPGAC to treat off-gas when liquid phase carbon can be used as a treatment step on its own. However it is oftentimes less expensive to use air stripping followed by VPGAC than it is to use UV/Ox followed by GAC. Mass transfer with vapor phase carbon is much faster than with liquid phase carbon so smaller carbon beds can be used. This decreases carbon usage. Furthermore, vapor phase carbon is designed to allow more carbon surface area to be used for adsorption. Also, any nonvolatile compounds present in the water remain there after air stripping. Hence, the vapor phase contains a lower load of contaminants to transfer than is the case with water and liquid phase carbon (Nyer, 1992).

After the carbon is used for adsorption of contaminants, it must be treated. There are two options for carbon treatment. The used carbon can either be disposed or regenerated off-site or it can be treated at an on-site regeneration facility. Disposable carbon is more commonly used since it is relatively cheap to purchase carbon for off-gas treatment. However, there is the added inconvenience of removing, disposing, and replacing the used carbon. For regenerable VPGAC systems, steam regeneration is generally used. The carbon does not need to be removed with this method. Once breakthrough occurs, steam is flowed counter-currently through the carbon bed. The steam desorbs the contaminants from the carbon particles. While regenerative carbon is a viable option, eventually the carbon loses its original capacity and requires replacement (Nyer, 1992).

9.2 Off-gas Treatment via Incineration

The off-gas can also be treated via incineration. There are a number of incineration methods that may be employed. The first of these is thermal incineration. Methane flares are used at temperatures around 1400°F. Another type of incineration is catalytic incineration. With this method a catalyst is used to enhance the destruction of the organics (Nyer, 1992).

Unfortunately, treatment of off-gas via any method can nearly double the overall cost of air stripping (Nyer, 1992). An analysis of the cost of treating the off-gas from air stripping is provided in section 11.

10. The Cost of Air Stripping

There are a number of costs involved with any ground-water treatment system such as PTA. There are capital costs involved with the purchase of the equipment. There are also operation and maintenance costs involved with the system. While there are other costs, for the purposes of this study, only capital and operation and maintenance costs will be considered. This should provide enough information to determine whether or not air stripping should be further considered for use at FS-12.

The purpose of this section is to elaborate on the costs involved with packed tower aeration and to illustrate the method by which the cost estimates in this study were compiled.

10.1 Capital Costs

Included in the capital cost for an air stripper is the cost of the tower itself, the packing, the pump which transports the untreated water to the top of the tower, a flow distributor at the top of the tower, and an air blower to force air into the bottom of the tower (Gumerman, Burris and Hansen, 1986). All of these costs are incorporated into Figure 6 which provides a crude estimation of tower volume versus cost.

Construction cost estimates for selected air stripper designs appear in table 12. Not every air stripper designed in the appendix appears in the table. For each contaminant, one air stripper was chosen from each group of air strippers designed with the same stripping factor. In all cases, the air stripper designed with a gas pressure drop of 400 N/m² is the smallest air stripper. Therefore,

cost estimates are based on these. However, if air stripping is to be further considered for FS-12, it may be beneficial to select a lower value for gas pressure drop. Only a pilot study can truly determine the optimal gas pressure drop.
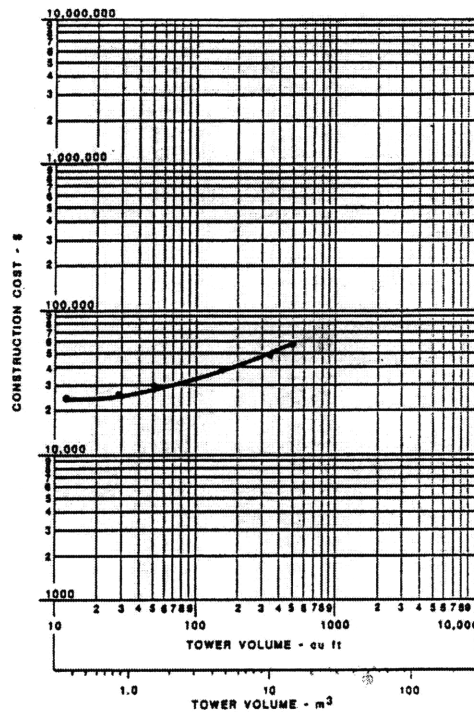
**Figure 6: Construction Cost for Counter-current Packed Tower Aerators.
source: Gumerman, Burris, and Hansen, 1986**

Table 12: Construction Cost for Selected Air Stripper Designs (from figure 6).

contaminant	stripping factor	volume (m³)	construction cost
benzene	2	11.9	$52,000
	3	9.6	$49,000
	4	9.4	$47,000
	5	9.4	$47,000
EDB	2	23.4	$75,000
	3	22.0	$70,000
	4	23.2	$73,000
	5	24.1	$76,000

There are other costs that must be added to the construction cost of the tower. As these additional costs are difficult to determine, Gumerman, Burris and Hansen have designed a method by which they can be estimated. The key costs that must be considered are

- general contractor's overhead and profit,
- engineering fees,
- legal, fiscal, and administrative costs, and,
- interest during construction.

The proposed method assumes that the general contractor's overhead and profit amounts to 12% of the total construction cost. The engineering fees are estimated at 10% of this subtotal. The legal, fiscal, and administrative costs are estimated from figure 7.
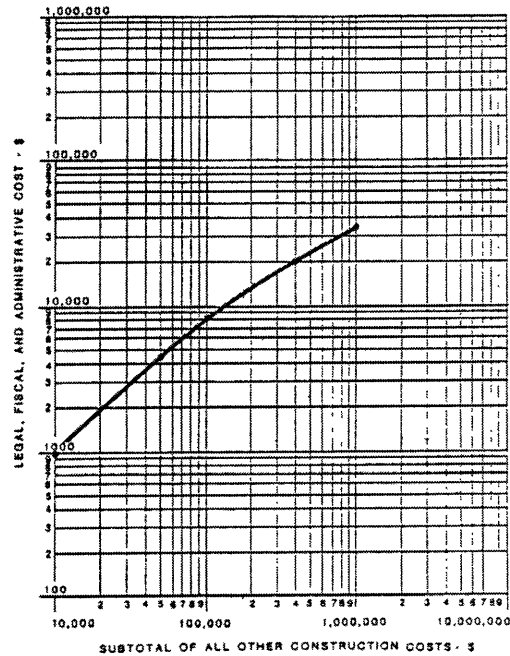
Figure 7: Legal, fiscal, and administrative costs.
source: Gumerman, Burris, and Hansen

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These fees are added to the previous subtotal. Finally, 10% interest accumulated during construction is added. The sample calculation below further explains this cost estimation method.

construction cost =	$52,000
general contractor's overhead	
and profit (12%) = (0.12)*($52,000)	
	$6,240
subtotal	$58,240
engineering (10%) = (0.10)*($58,240)	$5,824
subtotal	$64,064
legal, fiscal, administrative	$5,400
interest (10%) = (0.10)*($52,000)	$5,200
Total Capital Cost	**$74,664**

The total capital costs for packed tower aerators in table 12 are shown in table 13.

Table 13: Total Capital Cost for Selected Air Stripper Designs (from table 12).

contaminant	stripping factor	construction cost	general contractor's overhead and profit	engineering	legal, fiscal, administrative costs	interest	total capital cost
benzene	2	$52,000	$6,240	$5,824	$5,400	$5,200	$74,664
	3	$49,000	$5,880	$5,488	$5,200	$4,900	$70,468
	4	$47,000	$5,640	$5,264	$5,000	$4,700	$67,604
	5	$47,000	$5,640	$5,264	$5,000	$4,700	$67,604
EDB	2	$75,000	$9,000	$8,400	$7,700	$7,500	$107,600
	3	$70,000	$8,400	$7,840	$7,000	$7,000	$100,240
	4	$73,000	$8,760	$8,176	$7,400	$7,300	$104,636
	5	$76,000	$9,120	$8,512	$7,800	$7,600	$109,032

The data in figures 6 and 7 are based on 1986 economic data. Therefore, the values must be scaled up to reflect the effects of inflation. There are a number of different indices which are commonly used by engineers to determine current costs estimated from older data. The oldest of these is probably the Engineering News Record (ENR) index. It is based on the value of 100 at a specific year. Figure 8 shows the growth of ENR.
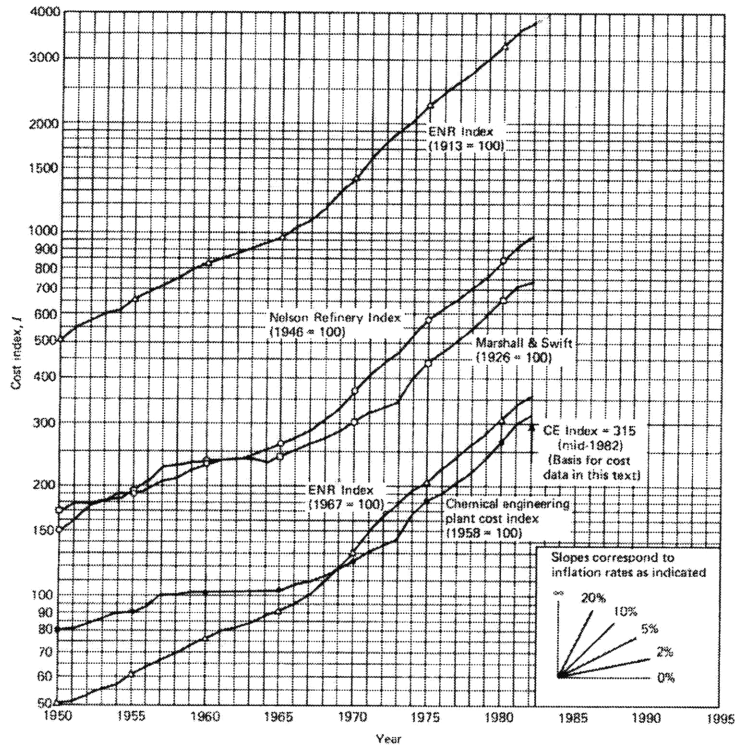
Figure 8: History of Selected Cost Indices.
source: Ulrich, 1984

The formula used to convert data from one year to another is shown in equation 9. Current ENR data is shown in table 14.

$$\text{Updated cost} = \text{construction cost (construction cost index/4000)} \qquad (9)$$

Table 14: ENR Data, April 20, 1998.

category	index value
construction	5882.73
common labor	11908.95
building cost	3375.31
skilled labor	5317.36

source: ENR, 1998

Updated capital costs are shown in table 15.

Table 15: Updated Capital Costs.

contaminant	stripping factor	1998 capital cost equivalent
benzene	2	$109,807
	3	$103,636
	4	$99,424
	5	$99,424
EDB	2	$158,245
	3	$147,421
	4	$153,886
	5	$160,351

10.2 Operation and Maintenance Costs

There is a variety of costs associated with the operation and maintenance of a PTA system. These include labor, materials, chemicals, repairs, and energy for the processes and enclosures. For the purposes of this study, the only operation and maintenance costs considered are those associated with energy usage, material replacement (UV lamps, polyethylene packing, granular activated carbon), and other necessary equipment (peroxide in the case of UV/Ox).

The operation and maintenance costs for a PTA system include the process energy needed for influent pumping and for the air blower. The lower the air-to-water ratio, the smaller the blower, and the lower the energy requirement for the blower (Gumerman, Burris and Hansen, 1986).

Operating costs for a packed tower are strongly affected by the power consumption of the air pump and blower (Ball and Edwards, 1992). Figure 9 is a graph which shows the cost of operation and maintenance of a packed tower aerator as a function of average flowrate. This figure is used to determine operation and maintenance cost for the systems designed in this study. In order to perform the calculations, the air-to-water ratio must be known. The air-to-water ratio can be determined with equation 10.
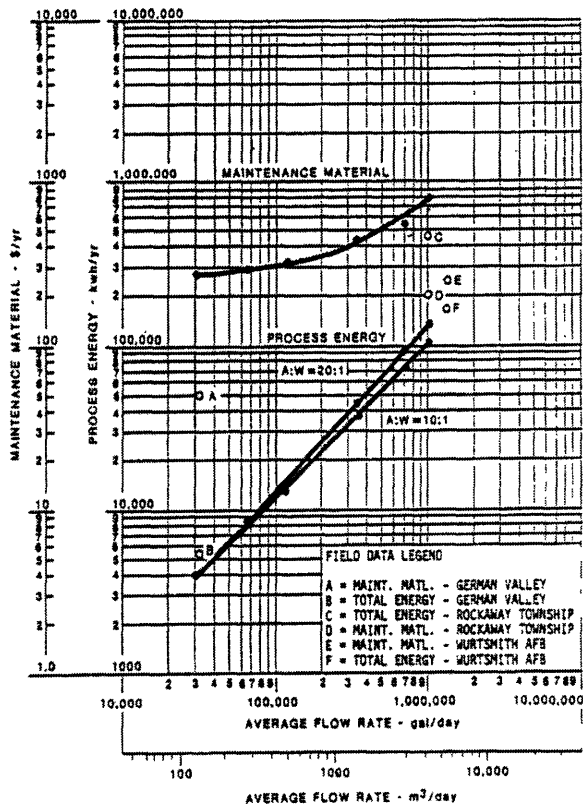
Figure 9: Operation and Maintenance Requirements for Counter-current Packed Tower Aerators--Process Energy and Maintenance Material.
source: Gumerman, Burris and Hansen, 1986

$$\text{Air-to-water ratio} = \left(\frac{R}{H_A} \frac{\text{mol wt. air}}{\text{molwt. water}} \frac{\rho_{water}}{\rho_{air}} \right) \quad (10)$$

$$= 1325 \left(\frac{R}{H_A} \right) \text{ (at 20°C)}$$

The air-to-water ratios for the selected air strippers are found in table 16.

Table 16: Air-to-Water Ratio for Selected Stripper Designs.

contaminant	stripping factor	air-to-water ratio
benzene	2	12
	3	17
	4	23
	5	29
EDB	2	80
	3	120
	4	160
	5	200

Figure 9 can be used to estimate the operation and maintenance costs for air strippers with air-to-water ratios around 10-20. Operation costs are expressed in energy requirements of kilowatt-hours per year and maintenance costs are expressed in dollars per year. Both are expressed as functions of average flowrate. The average flowrate is 1015 gallons per minute, or 1,461,600 gallons per day. Maintenance costs for this flowrate are approximately $1,000 per year.

Updated maintenance cost (1998) = $1,471

Results for benzene air stripper designs are shown in table 17.

Table 17: Operation Costs for Selected Benzene Packed Tower Aerator Designs

(from figure 9)

stripping factor	kWh/year
2	150,000
3	175,000
4	200,000
5	220,000

Calgon Corporation assumed a cost of electrical power for the purposes of their UV/Ox design. This cost was $0.06/kWh. In order to provide a parallel comparison, this value is used in this study. At this price, the operation costs for the selected benzene air stripper designs are shown in table 18.

Table 18: Energy Costs for selected Benzene Packed Tower Aerator Designs.

stripping factor	1998 energy cost estimation
2	$13,236
3	$15,442
4	$17,648
5	$19,413

Due to the high air-to-water ratios for EDB air stripper designs, it is necessary to employ an alternate method to calculate the energy requirements. It has been shown that the cost of labor, energy, and chemicals for typical plants account for 91% to 95% of the total operation and maintenance costs. Therefore, for the purposes of this study, the projected energy cost is used to provide an estimate for operation cost.

For any packed tower aerator, the major energy cost comes from the use of the pump and the air blower. The chemical engineering literature provides correlations by which the energy requirements of a blower and pump can be estimated. The power required by a blower or pump can be found by using equation 11.

$$P = \left(\frac{m\Delta P}{\rho \varepsilon_i \varepsilon_d} \right)$$ (11)

where,

m = gas flowrate or air flowrate (for pump and blower respectively)
ΔP = pressure drop in Pa/m
ρ = average gas density or liquid density (for pump and blower respectively),

and,

ε_l and ε_d represent efficiencies

Using this correlation, energy requirements and costs were estimated for EDB air stripper designs. The results are shown in table 19 for the selected air strippers. Table 20 shows the total cost estimations for the selected air strippers.

Table 19: Energy Requirements/Operation Cost Estimates for EDB Packed Tower Aerator Designs.

	stripping factor	power (kWh/year)	energy cost ($/year)
air blower	2	276,073	$16,564
	3	306,763	$18,405
	4	350,331	$21,019
	5	400,092	$24,005
water pump	2	8,800	$528
	3	6,518	$391
	4	5,583	$335
	5	5,101	$306

Table 20 Total Cost Estimation for Selected Packed Tower Aerator Designs (Capital Cost + Operation and Maintenance).

contaminant	stripping factor	total capital cost	operation cost	maintenance cost	TOTAL COST
benzene	2	$109,807	$13,236	$1,471	$124,514
	3	$103,636	$15,442	$1,471	$120,549
	4	$99,424	$17,648	$1,471	$118,543
	5	$99,424	$19,413	$1,471	$120,308
EDB	2	$158,245	$17,092	$1,471	$176,808
	3	$147,421	$18,797	$1,471	$167,689
	4	$153,886	$21,355	$1,471	$176,712
	5	$160,351	$24,312	$1,471	$186,134

Once design parameters and cost information are gathered for a number of PTA systems, the final step is optimization. This involves selection of the most effective design. It is apparent that EDB is the more difficult contaminant to strip. Therefore, for optimization, only the EDB designs are considered. It is also apparent from the data that the air stripper designed with a stripping factor of 2 is the most cost effective of the four selected designs.

Replacement of the packing is the only other issue to consider. The iron content of the influent stream is one of the most important factors to consider when determining how often air stripper packing needs cleaning. As a rule of thumb, if the influent stream has an iron content of

<1mg/L, the packing will need little maintenance (Nyer, 1992). The influent ground water at FS-12 has an estimated iron concentration of 526µg/L. This is well below the threshold. Therefore, the packing used in an air stripper designed for FS-12 will require relatively infrequent maintenance checks. However, approximately every five years, the tower packing requires replacement. For a column with a diameter of approximately two meters and a height of 14 meters, purchase cost of packing is approximately $25,000 ($5,000 annually). This cost must be included in the final cost analysis.

In order to perform a parallel comparison between UV/Oxidation and air stripping, it is necessary to consider the total treatment system package. The current system at FS-12 utilizes GAC to remove the contaminants remaining in the effluent stream after UV/Oxidation. Air stripping, on the other hand, does not require any further treatment to remove contaminants from the water. The only additional cost that may or may not be added to air stripping is that of off-gas treatment. Therefore, section 11 provides a detailed description of the costs associated with off-gas treatment.

11. Analysis of Off-gas Treatment

As was mentioned in previous sections, the off-gas emitted from an air stripper is a major economic concern. This is especially true for air stripper systems that are located in areas with strict air emissions regulations. The purpose of this section is to evaluate the situation which would occur at FS-12 if air stripping were employed.

11.1 Compliance with Air Emissions Standards

As was mentioned in section 4.2, it is important to ensure that emissions from any treatment system fall below the standards set by the state and federal regulatory requirements. The Clean Air Act (CAA) contains standards for six pollutants (carbon monoxide, lead, nitrogen dioxide, particulate matter, ozone, and sulfur oxides). The only FS-12 plume activity that could incur pollution that falls under CAA regulation is VOC emissions that can contribute to ozone formation. However, since the concentrations are so low (micrograms/liter range), compliance with federal standards is not an issue (Jacobs, 1996).

The Commonwealth of Massachusetts provides standards for air emissions as well. According to subsection (4)(a)(8) of section 7.02 of code 310 CMR 7, "Air Pollution Control," a facility is exempt if emissions are less than one ton per year. States are responsible for implementing and enforcing the federal standards.

To meet its commitment, the Massachusetts state air pollution control program requires stationary sources of emissions to file various forms which indicate the plans, specifications, and operating and maintenance procedures involved. Massachusetts air pollution regulations contain various emissions standards and limitations for airborne pollutants, such as volatile organic compounds (Mundi, 1998). However, exemptions from this requirement include projects with emission levels under one ton/year.

In order to determine whether or not the emissions from the optimal air stripper designed in this project fall below the state standard, the VOC concentration in the effluent air stream must be determined. Equation 12 describes a method by which VOC concentration in air stripper off-gas is calculated.

$$C_{i,a} = \frac{\left(C_{i,w} - C_{e,w}\right)}{\dfrac{V}{Q}} \tag{12}$$

where $C_{i,a}$ is the off-gas VOC concentration

$C_{i,w}$ is the inlet water VOC concentration

$C_{e,w}$ is the desired outlet VOC concentration from the air stripper, and

V/Q is the volumetric air-to-water ratio.

With the optimal air stripper designed in this study, the off-gas VOC concentration is based on an influent EDB concentration of 8.2 µg/L, a VOC outlet concentration of 0.02 µg/L, and an air-to-water ratio of 80. Therefore, for EDB,

$$C_{i,a} = \frac{\left(C_{i,w} - C_{e,w}\right)}{\dfrac{V}{Q}}$$

$$C_{i,a} = \frac{(8.2 - 0.02)}{80}$$

$C_{i,a} = 0.10$ μg/L.

Using the same air stripper, the benzene concentration is found by the same method.

$$C_{i,a} = \frac{(60 - 0.1)}{80}$$

$C_{i,a} = 0.75$ μg/L.

This translates to a total yearly emission of 0.018 tons/year and 0.13 tons/year for EDB and benzene respectively. Therefore, the air stripper designed in this study would not require off-gas treatment to comply with state or federal legislation. However, in the event that one was interested in determining how the addition of off-gas treatment affects the cost of air stripping, it is beneficial to consider the various costs involved in this type of process.

11.2 The Cost of Off-gas Treatment

This section provides an estimation of the costs that would be involved with treating the off-gas from this air stripper in the event that treatment was necessary. Crittenden, *et al.*, presented the cost estimation scheme in a 1988 article published in *The Journal of the American Water Works Association.*

The first step in determining the cost of off-gas treatment via granular activated carbon adsorption is to consider the cost of heating the air. The relative humidity of the off-gas stream is very crucial when considering vapor phase granular activated carbon adsorption. It has been shown that reducing the relative humidity in the air stream improves VOC adsorption capacity of granular activated carbon. At lower relative humidities, the problem of capillary condensation also becomes insignificant. For a utility cost of $0.06/kWh, which is the value used in this study, heating of the off-gas amounts to a cost of approximately $0.03/1,000 gallons. With a volumetric flowrate of 1015 gallons per minute, the yearly cost of heating is $16,015.

The second cost to consider is that of carbon purchase. Granular activated carbon capacity for VOCs is much greater for vapor phase adsorption that it is for aqueous phase adsorption

(Crittenden, *et al.*, 1987). Therefore, carbon usage rates are low. The literature provides carbon loading data based on off-gas concentration. Table 21 shows the carbon loading for benzene and EDB.

Table 21: Carbon Loading for Vapor Phase Carbon Adsorption

contaminant	off-gas concentration	carbon loading (g VOC/g carbon)
benzene	0.75µg/L	2.5×10^{-2}
EDB	0.10µg/L	2.0×10^{-3}

Therefore, the carbon requirement can be found in units of g carbon/liter of air.

For benzene:

$$\frac{g \text{ carbon}}{2.5 \times 10^{-2} \text{ g benzene}} \times \frac{7.5 \times 10^{-7} \text{ g benzene}}{L \text{ air}} = 3 \times 10^{-5} \text{ g carbon / L air}$$

For EDB

$$\frac{g \text{ carbon}}{2.0 \times 10^{-3} \text{ g EDB}} \times \frac{1.0 \times 10^{-7} \text{ g EDB}}{L \text{ air}} = 5.0 \times 10^{-5} \text{ g carbon / L air}$$

There is the issue of competitive interactions. With both EDB and benzene present, more carbon will be required. However, the usage rates only increase slightly, so for this preliminary analysis, it is assumed that the yearly usage rates for the two contaminants can be combined to give a fairly accurate estimate of carbon cost.

The next cost to include is the capital cost of the carbon vessel. Systems similar to the one designed here make use of two 10,000-pound vessels. Based on estimates given for the current system being used at FS-12, it is likely that Calgon Corporation could provide two 10,000 pound vessels for under $100,000 (Calgon, 1996). The carbon purchase cost, based on a carbon price of $1.00 per pound, is $20,000.

The next cost to consider is that of carbon regeneration. This can be estimated at $0.67/lb of carbon. Regeneration costs for this amount of carbon add to an annual cost of $13,400. Annual

operation and maintenance costs range from 10 to 15 percent of the total equipment cost. An estimate of the total cost of off-gas treatment is provided in table 22.

Table 22: Cost of Off-Gas Treatment.

item	cost
capital cost of VPGAC vessels	$100,000
heating of the off-gas	$ 16,015
carbon purchase	$ 20,000
carbon regeneration	$ 13,400
TOTAL COST OF OFF-GAS TREATMENT	$120,000 (capital) $ 47,415 (operation and maintenance)

*Operation and maintenance cost includes annual cost of heating off-gas and carbon regeneration.

Although the method described by Crittenden, *et al.*, is an accurate one, the estimates provided here are very crude. Many assumptions were taken into consideration to simplify the calculations. However, this information can provide some insight into how much the cost of air stripping is increased when off-gas treatment is included.

12. Comparison of Treatment Options

All of the data and calculations included in this study can be expressed through a simple cost estimation of each treatment option considered. As was previously mentioned, in order to provide a parallel comparison between UV/Ox and air stripping, the whole of the treatment options must be considered. The three options are UV/Ox followed by GAC, air stripping alone, and air stripping followed by treatment of off-gas via VPGAC. Table 23 provides the capital and annual operation and maintenance costs associated with each option.

Table 23: Cost Comparison between UV/Oxidation and Air Stripping.

	UV/Oxidation with GAC	air stripping	air stripping with VPGAC
capital cost	$763,000	$158,000	$278,000
annual operation and maintenance cost	$109,400	$ 23,000	$ 71,000

From the results shown in this table, it is apparent that air stripping, even when followed by VPGAC is a much more cost effective treatment option than UV/Ox followed by granular activated carbon adsorption. The capital cost of air stripping is nearly a third that of UV/Ox followed by GAC even if the additional cost of off-gas treatment is included! Furthermore, for an application such as this, off-gas treatment would not be necessary. Additionally, the annual operation and maintenance costs for air stripping followed by VPGAC are significantly lower than those of UV/Ox followed by GAC.

Although the calculations performed in this study are crude estimates, one must keep in mind that there are still more reasons to consider air stripping over UV/Oxidation. For example the chemical engineering literature indicates that the optimum stripping factor varies between 1.3 and 1.7 (Kutzer, *et al.*, 1995). For the purposes of this study, a stripping factor of 2 was used. Also, all of the costs used in this study are overestimated. Therefore, it is likely that an even greater cost savings (than that shown in table 23) can be gained by using air stripping as opposed to UV/Ox.

13. Conclusions

Based on the results of this study, it is obvious that air stripping is a viable alternative to UV/Ox and GAC. All of the documented data about air stripping proves that it can be as effective, if not more effective than UV/Oxidation, at removing benzene. Also, in most cases, it ends up being more cost effective. Data in this study shows that even a highly exaggerated air stripping system designed to strip EDB, a very difficult substance to remove from ground water, can prove economically beneficial for use at FS-12 and perhaps at other MMR plumes as well. Unfortunately, there is only one way to determine if air stripping is truly a better choice than UV/Ox. That is to perform a pilot study using actual conditions at the site. However, the material presented here proves useful in that it further implies that the option of air stripping deserves further consideration.

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Appendix A: Benzene Calculations

Benzene, R=1

R, stripping factor	NTU	G'/L' (kg/kg)	L'/G' (kg/kg)	abscissa		
1	41 (from fig 9)	0.002717391	368	12.7949448		
				off the charts		
gas pressure drop	ordinate	G'	L' (kg/m2 sec)	L' (lb/ft2 hour)	column diameter	
400						
200						
100						
50						
Kla (/hour)	Kla (/min)	HTU	Z=HTU*NTU	Z'	diameter'	
CONSTANTS						
4/pi	alpha	Cf	Co (kmol/m3)	Dbenzene (ft2/hour)	(Ha/pT)*1.6	pg/(pl-pg)
1.273239545	196	21	55.6	3.64E-04	368	0.001208874
pg(pl-pg) (kg/m3)	pl (kg/m3)	pl (lb/ft3))	QL (m3/sec)	ul (lb/ft hour)	ul^0.1 (kg/m sec)	
1201.137975	62.3	998	0.064	2.41	0.501187234	

Benzene, R=2

R, stripping factor	NTU	G'/L' (kg/kg)	L'/G' (kg/kg)	abscissa		
2	11.41089551	0.005434783	184	6.397472402		
gas pressure drop	ordinate	G'	L' (kg/m2 sec)	L' (lb/ft2 hour)	column diameter	
400	0.00157	0.423288654	77.88511235	57437.01429	1.021840453	
200	0.00135	0.392512675	72.22233224	53260.9507	1.061144586	
100	0.0011	0.354309783	65.19300009	48077.11211	1.116888536	
50	off the chart					
Kla (/hour)	Kla (/min)	HTU	Z=HTU*NTU	Z' (m)	diameter' (m)	column volume (m3)
329.7138017	5.495230029	0.849713519	9.695992175	14.54398826	1.021840453	11.92722961
312.2722617	5.204537695	0.831942487	9.493208787	14.23981318	1.061144586	12.5934087
290.077884	4.8346314	0.808428383	9.224891799	13.8373377	1.116888536	13.55695293
CONSTANTS						
4/pi	alpha	Cf	Co (kmol/m3)	Dbenzene (ft2/hour)	(Ha/pT)*1.6	pg/(pl-pg)
1.273239545	196	21	55.6	3.64E-05	368	0.001208874
pg(pl-pg) (kg/m3)	pl (kg/m3)	pl (lb/ft3))	QL (m3/sec)	ul (lb/ft hour)	ul^0.1 (kg/m sec)	
1201.137975	62.3	998	0.064	2.41	0.501187234	

Benzene, R=3

R, stripping factor	NTU	G'/L' (kg/kg)	L'/G' (kg/kg)	abscissa		
3	8.9884463	0.008152174	122.6666667	4.264981601		
gas pressure drop	ordinate	G'	L' (kg/m2 sec)	L' (lb/ft2 hour)	column diameter (m)	
400	0.0033	0.613682546	75.2783923	55514.66723	1.039381899	
200	0.0027	0.555096749	68.09186784	50214.90588	1.092855376	
100	0.0018	0.453234597	55.59677728	41000.29896	1.209443286	
50	0.0012	0.370064499	45.39457856	33476.60392	1.338469017	
Kla (/hour)	Kla (/min)	HTU	Z=HTU*NTU	Z' (m)	diameter' (m)	column volume (m3)
321.7307445	5.36217907	0.841652806	7.565151048	11.34772657	1.039381899	9.628287341
299.3081211	4.98846868	0.818336554	7.355574171	11.03336126	1.092855376	10.34958906
258.6578405	4.31096401	0.773177442	6.949663918	10.42449588	1.209443286	11.97611504
223.5284436	3.72547406	0.730510392	6.56615343	9.849230145	1.338469017	13.85826343
CONSTANTS						
4/pi	alpha	Cf	Co (kmol/m3)	Dbenzene (ft2/hour)	(Ha/pT)*1.6	pg/(pl-pg)
1.273239545	196	21	55.6	3.64E-05	368	0.001208874
pg(pl-pg) (kg/m3)	pl (kg/m3)	pl (lb/ft3))	QL (m3/sec)	ul (lb/ft hour)	ul^0.1 (kg/m sec)	
1201.137975	62.3	998	0.064	2.41	0.501187234	

Benzene, R=4

R, stripping factor	NTU	G'/L' (kg/kg)	L'/G' (kg/kg)	abscissa		
4	8.146403979	0.010869565	92	3.198736201		
gas pressure drop	ordinate	G'	L' (kg/m2 sec)	L' (lb/ft2 hour)	column diameter (m)	
400	0.0048	0.740128998	68.09186784	50214.90588	1.092855376	
200	0.0035	0.63200545	58.14450144	42879.13902	1.182649334	
100	0.0024	0.523350234	48.14822149	35507.30047	1.299631389	
50	0.0014	0.399715343	36.7738116	27119.14868	1.487102808	
Kla (/hour)	Kla (/min)	HTU	Z=HTU*NTU	Z' (m)	diameter' (m)	column volume (m3)
299.3081211	4.988468685	0.818336554	6.66650016	9.999750239	1.092855376	9.380034173
267.1382959	4.452304931	0.782938598	6.378134112	9.567201167	1.182649334	10.50961411
233.2102864	3.886838106	0.742656098	6.049976594	9.074964891	1.299631389	12.03857878
192.0780544	3.201300907	0.688677831	5.610247819	8.415371729	1.487102808	14.61655999
CONSTANTS						
4/pi	alpha	Cf	Co (kmol/m3)	Dbenzene (ft2/hour)	(Ha/pT)*1.6	pg/(pl-pg)
1.273239545	196	21	55.6	3.64E-05	368	0.001208874
pg(pl-pg) (kg/m3)	pl (kg/m3)	pl (lb/ft3))	QL (m3/sec)	ul (lb/ft hour)	ul^0.1 (kg/m sec)	
1201.137975	62.3	998	0.064	2.41	0.501187234	

Benzene, R=5

R, stripping factor	NTU	G'/L' (kg/kg)	L'/G' (kg/kg)	abscissa		
5	7.717753355	0.013586957	73.6	2.558988961		
gas pressure drop	ordinate	G'	L' (kg/m2 sec)	L' (lb/ft2 hour)	column diameter (m)	
400	0.0065	0.86127825	63.39007917	46747.5333	1.132660277	
200	0.0045	0.716626821	52.74373403	38896.29884	1.241723443	
100	0.0031	0.594795465	43.77694621	32283.66769	1.362974045	
50	0.0018	0.453234597	33.35806637	24600.17938	1.561384568	
Kla (/hour)	Kla (/min)	HTU	Z=HTU*NTU	Z' (m)	diameter' (m)	column volume (m3)
284.279311	4.737988517	0.802105038	6.190448846	9.285673269	1.132660277	9.356267271
249.0307352	4.150512254	0.76185641	5.879819866	8.819729799	1.241723443	10.6805821
217.764286	3.629404766	0.723126057	5.580908554	8.371362831	1.362974045	12.21409287
179.0583374	2.984305624	0.670133802	5.171927401	7.757891102	1.561384568	14.85433883
CONSTANTS						
4/pi	alpha	Cf	Co (kmol/m3)	Dbenzene (ft2/hour)	(Ha/pT)*1.6	pg/(pl-pg)
1.273239545	196	21	55.6	3.64E-05	368	0.001208874
pg(pl-pg) (kg/m3)	pl (kg/m3)	pl (lb/ft3))	QL (m3/sec)	ul (lb/ft hour)	ul^0.1 (kg/m sec)	
1201.137975	62.3	998	0.064	2.41	0.501187234	

Appendix B: EDB Calculations

EDB, R=1

R, stripping factor	NTU	G'/L' (kg/kg)	L'/G' (kg/kg)	abscissa		
1	off the charts					
gas pressure drop	ordinate	G'	L' (kg/m2 sec)	L' (lb/ft2 hour)	column diameter	
400						
200						
100						
50						
Kla (/hour)	Kla (/min)	HTU	Z=HTU*NTU	Z'	diameter'	
CONSTANTS						
4/pi	alpha	Cf	Co (kmol/m3)	Dedb (ft2/hour)	(Ha/pT)*1.6	pg/(pl-pg)
1.273239545	196	21	55.6	2.30E-04	52.8	0.001208874
pg(pl-pg) (kg/m3)	pl (kg/m3)	pl (lb/ft3))	QL (m3/sec)	ul (lb/ft hour)	ul^0.1 (kg/m sec)	
1201.137975	62.3	998	0.064	2.41	0.501187234	

EDB, R=2

R, stripping factor	NTU	G'/L' (kg/kg)	L'/G' (kg/kg)	abscissa		
2	10.65089207	0.037878788	26.4	0.917898214		
gas pressure drop	ordinate	G'	L' (kg/m2 sec)	L' (lb/ft2 hour)	column diameter (m)	
400	0.018	1.433253642	37.83789615	27903.86656	1.466043398	
200	0.0125	1.194378035	31.53158013	23253.22213	1.605970079	
100	0.0077	0.937415573	24.74777113	18250.4466	1.812768189	
50	0.0038	0.658534603	17.38531351	12820.9419	2.16281341	
Kla (/hour)	Kla (/min)	HTU	Z=HTU*NTU	Z' (m)	diameter' (m)	column volume (m3)
155.8513523	2.597522538	0.873316389	9.301598595	13.95239789	1.466043398	23.55224917
136.6784603	2.277974338	0.829852413	8.838668485	13.25800273	1.605970079	26.85609623
114.8019154	1.913365257	0.775429218	8.259012904	12.38851936	1.812768189	31.97376863
89.02962987	1.483827164	0.70243018	7.481508035	11.22226205	2.16281341	41.22953097
CONSTANTS						
4/pi	alpha	Cf	Co (kmol/m3)	Dedb (ft2/hour)	(Ha/pT)*1.6	pg/(pl-pg)
1.273239545	196	21	55.6	2.30E-05	52.8	0.001208874
pg(pl-pg) (kg/m3)	pl (kg/m3)	pl (lb/ft3))	QL (m3/sec)	ul (lb/ft hour)	ul^0.1 (kg/m sec)	
1201.137975	62.3	998	0.064	2.41	0.501187234	

EDB, R=3

R, stripping factor	NTU	G'/L' (kg/kg)	L'/G' (kg/kg)	abscissa		
3	8.417866231	0.056818182	17.6	0.611932143		
gas pressure drop	ordinate	G'	L' (kg/m2 sec)	L' (lb/ft2 hour)	column diameter (m)	
400	0.0255	1.705913051	30.0240697	22141.49621	1.645794237	
200	0.017	1.392872173	24.51455025	18078.45596	1.821370725	
100	0.01	1.068284191	18.80180176	13865.54277	2.079747363	
50	0.00485	0.74397385	13.09393976	9656.233169	2.492155561	
Kla (/hour)	Kla (/min)	HTU	Z=HTU*NTU	Z' (m)	diameter' (m)	column volume (m3)
131.9414436	2.19902406	0.818546832	6.890417738	10.33562661	1.645794237	21.98759693
114.0219275	1.900365458	0.773376116	6.510176693	9.76526504	1.821370725	25.44313488
94.19476491	1.569912748	0.718005725	6.044076143	9.066114215	2.079747363	30.79868911
72.59284085	1.209880681	0.648831237	5.461774561	8.192661842	2.492155561	39.96365545
CONSTANTS						
4/pi	alpha	Cf	Co (kmol/m3)	Dedb (ft2/hour)	(Ha/pT)*1.6	pg/(pl-pg)
1.273239545	196	21	55.6	2.30E-05	52.8	0.001208874
pg(pl-pg) (kg/m3)	pl (kg/m3)	pl (lb/ft3))	QL (m3/sec)	ul (lb/ft hour)	ul^0.1 (kg/m sec)	
1201.137975	62.3	998	0.064	2.41	0.501187234	

EDB, R=4

R, stripping factor	NTU	G'/L' (kg/kg)	L'/G' (kg/kg)	abscissa		
4	7.639050353	0.075757576	13.2	0.458949107		
gas pressure drop	ordinate	G'	L' (kg/m2 sec)	L' (lb/ft2 hour)	column diameter (m)	
400	0.03	1.850322496	24.42425694	18011.86841	1.824734305	
200	0.02	1.510781991	19.94232229	14706.62898	2.019400464	
100	0.0135	1.241234064	16.38428965	12082.72865	2.227904181	
50	0.0054	0.78502535	10.36233463	7641.788579	2.801441195	
Kla (/hour)	Kla (/min)	HTU	Z=HTU*NTU	Z' (m)	diameter' (m)	column volume (m3)
113.7193917	1.895323195	0.772577465	5.901758158	8.852637237	1.824734305	23.15057719
98.27468821	1.63791147	0.729943524	5.576075337	8.364113005	2.019400464	26.78888738
85.30824997	1.421804166	0.690862768	5.277535471	7.916303207	2.227904181	30.86066771
61.33842633	1.022307105	0.607687338	4.642154171	6.963231256	2.801441195	42.92039611
CONSTANTS						
4/pi	alpha	Cf	Co (kmol/m3)	Dedb (ft2/hour)	(Ha/pT)*1.6	pg/(pl-pg)
1.273239545	196	21	55.6	2.30E-05	52.8	0.001208874
pg(pl-pg) (kg/m3)	pl (kg/m3)	pl (lb/ft3))	QL (m3/sec)	ul (lb/ft hour)	ul^0.1 (kg/m sec)	
1201.137975	62.3	998	0.064	2.41	0.501187234	

EDB, R=5

R, stripping factor	NTU	G'/L' (kg/kg)	L'/G' (kg/kg)	abscissa		
5	7.242028973	0.09469697	10.56	0.367159286		
gas pressure drop	ordinate	G'	L' (kg/m2 sec)	L' (lb/ft2 hour)	column diameter (m)	
400	0.036	2.026926739	21.40434636	15784.81061	1.949213147	
200	0.026	1.722556499	18.19019663	13414.50956	2.114421763	
100	0.0175	1.413207149	14.9234675	11005.43339	2.334400916	
50	0.0061	0.834356626	8.810805967	6497.601056	3.038103034	
Kla (/hour)	Kla (/min)	HTU	Z=HTU*NTU	Z'	diameter' (m)	column volume (m3)
103.4104831	1.723508052	0.744547838	5.392037018	8.088055526	1.949213147	24.13529821
91.97844691	1.532974115	0.711387985	5.151892396	7.727838595	2.114421763	27.13508362
79.76077485	1.329346247	0.673031799	4.874115786	7.311173679	2.334400916	31.29160735
54.57759665	0.909626611	0.580706161	4.205490845	6.308236267	3.038103034	45.73017138
CONSTANTS						
4/pi	alpha	Cf	Co (kmol/m3)	Dedb (ft2/hour)	(Ha/pT)*1.6	pg/(pl-pg)
1.273239545	196	21	55.6	2.30E-05	52.8	0.001208874
pg(pl-pg) (kg/m3)	pl (kg/m3)	pl (lb/ft3))	QL (m3/sec)	ul (lb/ft hour)	ul^0.1 (kg/m sec)	
1201.137975	62.3	998	0.064	2.41	0.501187234	