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Engineering Bulletin
Air Stripping of Aqueous Solutions

Purpose

Section 121(b) of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) mandates the Environmental Protection Agency (EPA) to select remedies that "utilize permanent solutions and alternative treatment technologies or resource recovery technologies to the maximum extent practicable" and to prefer remedial actions in which treatment "permanently and significantly reduces the volume, toxicity, or mobility of hazardous substances, pollutants, and contaminants as a principal element." The Engineering Bulletins are a series of documents that summarize the latest information available on selected treatment and site remediation technologies and related issues. They provide summaries of and references for the latest information to help remedial project managers, on-scene coordinators, contractors, and other site cleanup managers understand the type of data and site characteristics needed to evaluate a technology for potential applicability to their Superfund or other hazardous waste site. Those documents that describe individual treatment technologies focus on remedial investigation scoping needs. Addenda will be issued periodically to update the original bulletins.

Abstract

Air stripping is a means to transfer contaminants from aqueous solutions to air. Contaminants are not destroyed by air stripping but are physically separated from the aqueous solutions. Contaminant vapors are transferred into the air stream and, if necessary, can be treated by incineration, adsorption, or oxidation. Most frequently, contaminants are collected in carbon adsorption systems and then treated or destroyed in this concentrated form. The concentrated contaminants may be recovered, incinerated for waste heat recovery, or destroyed by other treatment technologies. Generally, air stripping is used as one in a series of unit operations and can reduce the overall cost for managing a particular site. Air stripping is applicable to volatile and semivolatile organic compounds. It is not applicable for treating metals and inorganic compounds.

During 1988, air stripping was one of the selected remedies at 30 Superfund sites [1]*. In 1989, it was a component of the selected remedy at 38 Superfund sites [2]. An estimated 1,000 air-stripping units are presently in operation at sites throughout the United States [3]. Packed-tower systems typically provide the best removal efficiencies, but other equipment configurations exist, including diffused-air basins, surface aerators, and cross-flow towers [4, p. 2] [5, p. 10-48]. In packed-tower systems, there is no clear technology leader by virtue of the type of equipment used or mode of operation. The final determination of the lowest cost alternative will be more site specific than process equipment dominated.

This bulletin provides information on the technology applicability, the technology limitations, a description of the technology, the types of residuals produced, site requirements, the latest performance data, the status of the technology, and sources of further information.

Technology Applicability

Air stripping has been demonstrated in treating water contaminated with volatile organic compounds (VOCs) and semivolatile compounds. Removal efficiencies of greater than 98 percent for VOCs and greater than or equal to 80 percent for semivolatile compounds have been achieved. The technology is not effective in treating low-volatility compounds, metals, or inorganics [6, p. 5-3]. Air stripping has commonly been used with pump-and-treat methods for treating contaminated groundwater.

This technology has been used primarily for the treatment of VOCs in dilute aqueous waste streams. Effluent liquid quality is highly dependent on the influent contaminant concentration. Air stripping at specific design and operating conditions will yield a fixed, compound-specific percentage removal. Therefore, high influent contaminant concentrations may result in effluent concentrations above discharge standards. Enhancements, such as high temperature or rotary air stripping, will allow less-volatile organics, such as ketones, to be treated [6, p. 5-3].

Table 1 shows the effectiveness of air stripping on general contaminant groups present in aqueous solution. Examples of constituents within contaminant groups are provided in Reference 7, "Technology Screening Guide for Treatment of CERCLA Soils and Sludges." This table is based on the current available information or professional judgment

* [reference number, page number]

Table 1
Effectiveness of Air Stripping on General Contaminant Groups from Water

	Contaminant Groups	*Effectiveness*
Organic	Halogenated volatiles	■
	Halogenated semivolatiles *	▼
	Nonhalogenated volatiles	■
	Nonhalogenated semivolatiles	❏
	PCBs	❏
	Pesticides	❏
	Dioxins/Furans	❏
	Organic cyanides	❏
	Organic corrosives	❏
Inorganic	Volatile metals	❏
	Nonvolatile metals	❏
	Asbestos	❏
	Radioactive materials	❏
	Inorganic corrosives	❏
	Inorganic cyanides	❏
Reactive	Oxidizers	❏
	Reducers	❏

■ Demonstrated Effectiveness: Successful treatability test at some scale completed
▼ Potential Effectiveness: Expert opinion that technology will work
❏ No Expected Effectiveness: Expert opinion that technology will not work
* Only some compounds in this category are candidates for air stripping.

where no information was available. The proven effectiveness of the technology for a particular site or contaminant does not ensure that it will be effective at all sites or that the treatment efficiencies achieved will be acceptable at other sites. For the ratings used for this table, demonstrated effectiveness means that, at some scale, treatability testing demonstrated the technology was effective for that particular contaminant group. The ratings of potential effectiveness and no expected effectiveness are both based upon expert judgment. Where potential effectiveness is indicated, the technology is believed capable of successfully treating the contaminant group in a particular matrix. When the technology is not applicable or will probably not work for a particular contaminant group, a no-expected-effectiveness rating is given.

Limitations

Because air stripping of aqueous solutions is a means of mass transfer of contaminants from the liquid to the air stream, air pollution control devices are typically required to capture or destroy contaminants in the offgas [8]. Even when offgas treatment is required, air stripping usually provides significant advantages over alternatives such as direct carbon adsorption from water because the contaminants are more favorably sorbed onto activated carbon from air than from water. Moreover, contaminant destruction via catalytic oxidation or incineration may be feasible when applied to the offgas air stream.

Aqueous solutions with high turbidity or elevated levels of iron, manganese, or carbonate may reduce removal efficiencies due to scaling and the resultant channeling effects. Influent aqueous media with pHs greater than 11 or less than 5 may corrode system components and auxiliary equipment. The air stripper may also be subject to biological fouling. The aqueous solution being air stripped may need pretreatment to neutralize the liquid, control biological fouling, or prevent scaling [6][9].

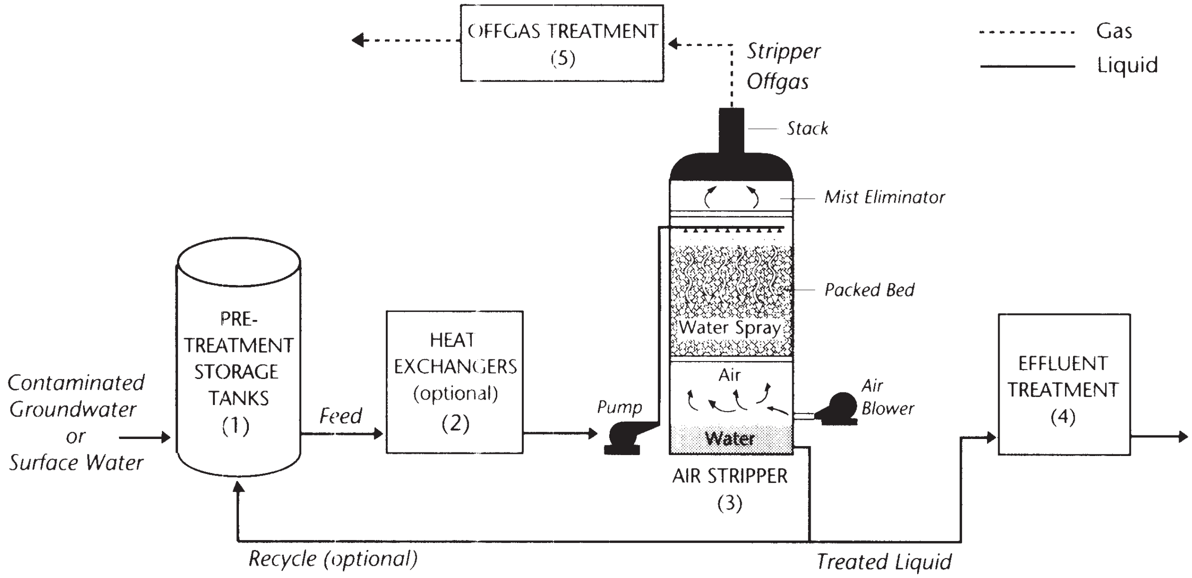
Contaminated water with VOC or semivolatile concentrations greater than 0.01 percent generally cannot be treated by air stripping. Even at lower influent concentrations, air stripping may not be able to achieve cleanup levels required at certain sites. For example, a 99 percent removal of trichloroethene (TCE) from groundwater containing 100 parts per million (ppm) would result in an effluent concentration of 1 ppm, well above drinking water standards. Without heating, only volatile organic contaminants with a dimensionless Henry's Law constant greater than 10^{-2} are amenable to continuous-flow air stripping in aqueous solutions [6][5]. In certain cases, where a high removal efficiency is not required, compounds with lower Henry's Law constants may be air stripped. Ashworth et al. published the Henry's Law constants for 45 chemicals [10, p. 25]. Nirmalakhandan and Speece published a method for predicting Henry's Law constants when published constants are unavailable [11]. Air strippers operated in a batch mode may be effective for treating water containing either high contaminant concentrations or contaminants with lower Henry's Law constants. However, batch systems are normally limited to relatively low average flow rates.

Several environmental impacts are associated with air stripping. Air emissions of volatile organics are produced and must be treated. The treated wastewater may need additional treatment to remove metals and nonvolatiles. Deposits, such as metal (e.g., iron) precipitates may occur, necessitating periodic cleaning of air-stripping towers [6, p. 5-5]. In cases where heavy metals are present and additional treatment will be required, it may be beneficial to precipitate those metals prior to air stripping.

Technology Description

Air stripping is a mass transfer process used to treat groundwater or surface water contaminated with volatile or semivolatile organic contaminants. At a given site, the system is designed based on the type of contaminant present, the contaminant concentration, the required effluent concentration, water temperature, and water flow rate. The major design variables are gas pressure drop, air-to-water ratio, and type of packing. Given those design variables, the gas and liquid loading (i.e., flows per cross-sectional area), tower diameter and packing height can be determined. Flexibility in the system design should allow for changes in contaminant concentration, air and water flow rates, and water temperature. Figure 1 is a schematic of a typical process for the air stripping of contaminated water.

Figure 1
Schematic Diagram of Air-Stripping System [8, p. 20][13, p. 43]



In an air-stripping process, the contaminated liquid is pumped from a groundwater or surface water source. Water to be processed is directed to a storage tank (1) along with any recycle from the air-stripping unit.

Air stripping is typically performed at ambient temperature. In some cases, the feed stream temperature is increased in a heat exchanger (2). Heating the influent liquid increases air-stripping efficiency and has been used to obtain a greater removal of semi-volatile organics such as ketones. At temperatures close to 100°C, steam stripping may be a more practical treatment technique [8, p. 3].

The feed stream (combination of the influent and recycle) is pumped to the air stripper (3). Three basic designs are used for air strippers: surface aeration, diffused-air systems, and specially designed liquid-gas contactors [4, p. 3]. The first two of these have limited application to the treatment of contaminated water due to their lower contaminant removal efficiency. In addition, air emissions from surface-aeration and diffused-air systems are frequently more difficult to capture and control. These two types of air strippers will not be discussed further. The air stripper in Figure 1 is an example of a liquid-gas contactor.

The most efficient type of liquid-gas contactor is the packed tower [4, p. 3]. Within the packed tower, structures called packing provide surface area on which the contaminated water can form a thin film and come in contact with a countercurrent flow of air. Air-to-water ratios may range from 10:1 to 300:1 on a volumetric basis [14, p. 8]. Selecting packing material that will maximize the wetted surface area will enhance air stripping. Packed towers are usually cylindrical and are filled with either random or structured packing. Random packing consists of pieces of packing dumped onto a support structure within the tower. Metal, plastic, or ceramic pieces come in standard sizes and a variety of shapes. Smaller packing sizes generally increase the interfacial area for stripping and improve the mass-transfer kinetics. However, smaller packing sizes result in an increased pressure drop of the air stream and an increased potential for precipitate fouling. Tripacks®, saddles, and slotted rings are the shapes most commonly used for commercial applications. Structured packing consists of trays fitted to the inner diameter of the tower and placed at designated points along the height of the tower. These trays are made of metal gauze, sheet metal, or plastic. The choice of which type of packing to use depends on budget and design constraints. Random packing is generally less expensive. However, structured packing reportedly provides advantages such as lower pressure-drop and better liquid distribution characteristics [4, p. 5].

The processed liquid from the air-stripper tower may contain trace amounts of contaminants. If required, this effluent is treated (4) with carbon adsorption or other appropriate treatments.

The offgas can be treated (5) using carbon adsorption, thermal incineration, or catalytic oxidation. Carbon adsorption is used more frequently than the other control technologies because of its ability to remove hydrocarbons cost-effectively from dilute (< 1 percent) air streams [8, p. 5].

Process Residuals

The primary process residual streams created with air-stripping systems are the offgas and liquid effluent. The offgas is released to the atmosphere after treatment; activated carbon is the treatment most frequently applied to the offgas stream. Where activated carbon is used, it is recommended that the relative humidity of the air stream be reduced. Once spent, the carbon can be regenerated onsite or shipped to the original supplier for reactivation. If spent carbon is replaced, it may have to be handled as a hazardous waste. Catalytic oxidation and thermal incineration also may be used for offgas treatment [15, p. 10] [8, p. 5]. Sludges, such as iron precipitates, build up

within the tower and must be removed periodically [6, p. 5-5]. Spent carbon can also result if carbon filters are used to treat effluent water from the air-stripper system. Effluent water containing nonvolatile contaminants may need additional treatment. Such liquids are treated onsite or stored and removed to an appropriate facility. Biological, chemical, activated carbon, or other appropriate treatment technologies may be used to treat the effluent liquid. Once satisfactorily treated, the water is sent to a sewage treatment facility, discharged to surface water, or returned to the source, such as an underground aquifer.

Site Requirements

Air strippers are most frequently permanent installations, although mobile systems may be available for limited use. Permanent installations may be fabricated onsite or may be shipped in modular form and constructed onsite. Packing is installed after fabrication or construction of the tower. A concrete pad will be required to support the air-stripper tower in either case. Access roads or compacted soil will be needed to transport the necessary materials.

Standard 440V, three-phase electrical service is needed. Water should be available at the site to periodically clean scale or deposits from packing materials. The quantity of water needed is site specific. Typically, treated effluent can be used to wash scale from packing.

Contaminated liquids are hazardous, and their handling requires that a site safety plan be developed to provide for personnel protection and special handling measures. Spent activated carbon may be hazardous and require similar handling. Storage may be needed to hold the treated liquid until it has been tested to determine its acceptability for disposal or release. Depending upon the site, a method to store liquid that has been pretreated may be necessary. Storage capacity will depend on liquid volume.

Onsite analytical equipment for conducting various analyses, including gas chromatography capable of determining site-specific organic compounds for performance assessment, make the operation more efficient and provide better information for process control.

Performance Data

System performance is measured by comparing contaminant concentrations in the untreated liquid with those in the treated liquid. Performance data on air-stripping systems, ranging from pilot-scale to full-scale operation, have been reported by several sources, including equipment vendors. Data obtained on air strippers at Superfund sites also are discussed below. The data are presented as originally reported in the referenced documents. The quality of this information has not been determined. The key operating and design variables are provided when they were available in the reference.

An air-stripping system, which employed liquid-phase GAC to polish the effluent, was installed at the Sydney Mine site in Valrico, Florida. The air-stripping tower was 4 feet in diameter, 42 feet tall, and contained a 24-foot bed of 3.5-inch diameter polyethylene packing. The average design water flow was 150 gallons per minute (gpm) with a hydraulic loading rate of 12 gpm/ft^2 and a volumetric air-to-water ratio of approximately 200:1. The air-stripping tower was oversized for use at future treatment sites. Effluent water from the air stripper was polished in a carbon adsorption unit. Table 2 summarizes the performance data for the complete system; it is unclear how much removal was accomplished by the air stripper and how much by the activated carbon. Influent concentrations of total organics varied from approximately 25 parts per billion (ppb) to 700 ppb [13, p. 41].

Table 2
Performance Data for the Groundwater Treatment System at the Sydney Mine Site, FL. [13, p. 42]

	Concentration	
Contaminant	*Influent* (μg/L)	*Effluent* (μg/L)
Volatile organics		
Benzene	11	ND[a]
Chlorobenzene	1	ND
1,1-dichloroethane	39	ND
Trans-1,2-dichloropropane	1	ND
Ethylbenzene	5	ND
Methylene chloride	503	ND
Toluene	10	ND
Trichlorofluoromethane	71	ND
Meta-xylene	3	ND
Ortho-xylene	2	ND
Extractable organics		
3-(1,1-dimethylethyl) phenol	32	ND
Pesticides		
2,4-D	4	ND
2,4,5-TP	1	ND
Inorganics		
Iron (mg/L)	11	< 0.03

[a]ND = Not detected at method detection limit of 1 μg/L for volatile organics and 10 μg/L for extractable organics and pesticides

Air stripping was used at well 12A in the city of Tacoma, Washington. Well 12A had a capacity of 3,500 gpm and was contaminated with chlorinated hydrocarbons, including 1,1,2,2-tetrachloroethane; trans-1,2-dichloroethene (DCE); TCE; and perchloroethylene. The total VOC concentration was approximately 100 ppb. Five towers were installed and began operation on July 15, 1983. Each tower was 12 feet in diameter and was packed with 1-inch polypropylene saddles to a depth of 20 feet. The water flow rate was 700 gpm for each tower, and the volumetric air-to-water ratio was 310:1. The towers consistently removed 94 to 98 percent of the influent 1,1,2,2-tetrachloroethane with an overall average of 95.5 percent removal. For the other contaminants, removal efficiencies in excess of 98 percent were achieved [16, p. 112].

Another remedial action site was Wurtsmith Air Force Base in Oscoda, Michigan. The contamination at this site was the result of a leaking underground storage tank near a mainte-

Table 3
Air-Stripper Performance Summary At Wurtsmith AFB
[17, p. 121]

G/L (vol)	*Water Flow (L/min)*	*Single Tower (% Removed)*	*Series Operation (% Removed)*
10	1,135	95	99.8
10	1,700	94	99.8
10	2,270	86	96.0
18	1,135	98	99.9
18	1,700	97	99.9
18	2,270	90	99.7
25	1,135	98	99.9
25 '	1,700	98	99.9
25	2,270	98	99.9

Influent TCE concentration: 50-8,000 μg/L Water temperature 283°K

nance facility. Two packed-tower air strippers were installed to remove TCE. Each tower was 5 feet in diameter and 30 feet tall, with 18 feet of 16mm pall ring packing. The performance summary for the towers, presented in Table 3, is based on evaluations conducted in May and August 1982 and January 1983. Excessive biological growth decreased performance and required repeated removal and cleaning of the packing. Operation of the towers in series, with a volumetric air-to-water ratio of 25:1 and a water flow of 600 gpm (2,270 L/min), removed 99.9 percent of the contaminant [17, p. 119]

A 2,500 gpm air stripper was used to treat contaminated groundwater during the initial remedial action at the Verona Well field site in Battle Creek, Michigan. This well field is the major source of public potable water for the city of Battle Creek. The air stripper was a 10-foot diameter tower packed to a height of 40 feet with 3.5 inch pall rings. The air stripper was operated at 2,000 gpm with a 20:1 volumetric air-to-water ratio. Initial problems with iron oxide precipitating on the packed rings were solved by recirculating sodium hypochlorite through the stripper about four times per year [8, p. 8-9]. The total VOC concentration of 131 ppb was reduced by approximately 82.9 percent [15, p. 56]. The air stripper offgas was treated via vapor phase granular activated carbon beds. The offgas was heated prior to entering the carbon beds to reduce its humidity to 40 percent.

An air stripper is currently operating at the Hyde Park Superfund site in New York. Treatek, Inc., which operates the unit, reports the system is treating about 80,000 gallons per day (gpd) of landfill leachate. The contaminants are in the range of 4,000 ppm total organic carbon (TOC). The air stripper is reportedly able to remove about 90 percent of the TOCs [18]. A report describing the performance of the air stripper is expected to be published during 1991.

The primary VOCs at the Des Moines Superfund site were TCE; 1,2-DCE; and vinyl chloride. The TCE initial concentration was approximately 2,800 ppb and gradually declined to the 800 to 1,000 ppb range after 5 months. Initial groundwater concentrations of 1,2-DCE were unreported while the concentration of vinyl chloride ranged from 38 ppb down to 1 ppb. The water flow rate to the air stripper ranged from 500 to 1,850 gpm and averaged approximately 1,300 gpm. No other design data were provided. TCE removal efficiencies were generally above 96 percent, while the removal efficiencies for 1,2-DCE were in the 85 to 96 percent range. No detectable levels of vinyl chloride were observed in the effluent water [12, p. B-1].

VOCs were detected in the Eau Claire municipal well field in Eau Claire, Wisconsin, as part of an EPA groundwater supply survey in 1981. An air stripper was placed on-line in 1987 to protect public health and welfare until completion of the remedial investigation/feasibility study (RI/FS) and final remedy selection. Data reported on the Eau Claire site were for the period beginning August 31, 1987 and ending February 15,1989. During this period, the average removal efficiency was greater than 88 percent for the four chlorinated organic compounds studied. The average removal efficiencies are shown in Table 4. The air stripper had a 12-foot diameter and was 60 feet tall, with a packed bed of 26 feet. Water feed rates were approximately 5 to 6 million gallons per day (mgd). No other design parameters were reported [12, p. C-1].

Table 4
Air-Stripper Performance at Eau Claire Municipal Well Field [12, p. C-1]

Contaminant	*Influent Concentration (ppb)*	*Removal Efficiency (%)*
1,1-Dichloroethene	0.17-2.78	88
1,1-Dichloroethane	0.38-1.81	93
1,1,1-Trichloroethane	4.32-14.99	99
Trichloroethene	2.53-11.18	98

In March 1990, an EPA study reviewed the performance data from a number of Superfund sites, including the Brewster Well Field, Hicksville MEK Spill, Rockaway Township, Western Processing, and Gilson Road Sites [15].

Reported removal efficiencies at the Brewster Well Field site in New York were 98.50 percent, 93.33 percent, and 95.59 percent for tetrachloroethene (PCE); TCE; and 1,2-DCE; respectively. Initial concentrations of the three contaminants were 200 ppb (PCE), 30 ppb (TCE) and 38 ppb (1,2-DCE) [15, p. 55]. The 300 gpm air stripper had a tower diameter of 4.75 feet, packing height of 17.75 feet, air-to-water ratio of 50:1, and used 1-inch saddles for packing material [15, p. 24].

A removal efficiency of 98.41 percent was reported for methyl ethyl ketone (MEK) at the Hicksville MEK spill site in New York. The reported influent MEK concentration was 15 ppm. The air stripper had a 100 gpm flowrate, an air-to-water ratio of 120:1, a tower diameter of 3.6 feet, a packing height of 15 feet, and used 2-inch Jaeger Tripack packing material. Water entering the air stripper was heated to approximately 180° to195°F by heat exchangers [15, p. 38].

Table 5
Air Stripper Performance at Rockaway Township, NJ [15, p. 53]

Contaminant	*Influent Concentration (ppb)*	*Removal Efficiency (%)*
Trichloroethylene	28.3	99.99
Methyl-tert-butyl ether	3.2	99.99
1,1-Dichloroethylene	4.0	99.99
cis-1,2-Dichloroethylene	6.4	99.99
Chloroform	1.3	99.99
1,1,1-Trichloroethane	20.0	99.99
1,1-Dichloroethane	2.0	99.99
Total VOC	65.2	99.99

The Rockaway Township air stripper had a flowrate of 1,400 gpm, tower diameter of 9 feet, packing height of 25 feet, air-to-water ratio of 200:1, and used 3-inch Tellerettes packing material. The performance data are shown in Table 5 [15, p. 18].

The Western Processing site had two air-stripping towers treating different wells in parallel. The first tower had a 100 gpm (initial) and 200 gpm (maximum) flowrate, a tower diameter of 40 feet, a packing height of 40.5 feet, an air-to-water ratio of 160:1 (initial) and 100:1 (maximum), and used 2-inch Jaeger Tripack packing material. The second tower had a 45 gpm (initial) and 60 gpm (maximum) flowrate, a tower diameter of 2 feet, packing height of 22.5 feet, air-to-water ratio of 83.1:1 (initial) and 62.3:1 (maximum), and used 2-inch Jaeger Tripack packing material [15, p. 31]. The performance data are presented in Table 6.

Table 6
Air-Stripper Performance at Western Processing, WA [15, p. 61]

Contaminant	*Influent Concentration (ppb)*	*Removal Efficiency (%)*
Benzene	73	93.15
Carbon tetrachloride	5	—
Chloroform	781	99.36
1,2-Dichloroethane	22	77.27
1,1-Dichloroethylene	89	94.38
1,1,1-Trichloroethane	1,440	99.65
Trichloroethylene	8,220	99.94
Vinyl chloride	159	99.37
Dichloromethane	8,170	99.63
Tetrachloroethylene	378	98.68
Toluene	551	99.09
1,2-Dichlorobenzene	11	54.55
Hexachlorobutadiene	250	96.00
Hexachloroethane	250	96.00
Isobutanol	10	0.00
Methyl ethyl ketone	1,480	70.27

Table 7
Air-Stripper Performance at the Gilson Road Site, NH [15, p. 65]

Contaminant	*Influent Concentration (ppb)*	*Average Removal Efficiency (%)*
Isopropyl alcohol	532	95.30
Acetone	473	91.93
Toluene	14,884	99.87
Dichloromethane	236	93.79
1,1,1-Trichloroethane	1,340	99.45
Trichloroethylene	1,017	99.71
Chloroform	469	99.06
Total VOC	18,951	99.41

The Gilson Road Site used a single column high-temperature air stripper (HTAS) which had a 300 gpm flowrate (heated influent), tower diameter of 4 feet, packing height of 16 feet, air-to-water ratio of 51.4:1, and used 16 Koch-type trays at 1-foot intervals [15, p. 42-45]. The performance data are provided in Table 7. Due to the relatively high influent concentration and the high (average) removal efficiency, this system required supplemental control of the volatiles in the offgas.

Another EPA study, completed in August 1987, analyzed performance data from 177 air-stripping systems in the United States. The study presented data on systems design, contaminant types, and loading rates, and reported removal efficiencies for 52 sites. Table 8 summarizes data from 46 of those sites, illustrating experiences with a wide range of contaminants [19]. Reported efficiencies should be interpreted with caution. Low efficiencies reported in some instances may not reflect the true potential of air stripping, but may instead reflect designs intended to achieve only modest removals from low-level contaminant sources. It is also important to recognize that, because different system designs were used for these sites, the results are not directly comparable from site to site.

Technology Status

Air stripping is a well-developed technology with wide application. During 1988, air stripping of aqueous solutions was a part of the selected remedy at 30 Superfund sites [1]. In 1989, air stripping was a part of the selected remedy at 38 Superfund Sites [2].

The factors determining the cost of an air stripper can be categorized as those affecting design, emission controls, and operation and maintenance (O&M). Design considerations such as the size and number of towers, the materials of construction, and the desired capacity influence the capital costs. Equipment cost components associated with a typical packed-tower air strip-

Table 8
Summary of Reported Air-Stripper Removal Efficiencies from 46 Sites [19]

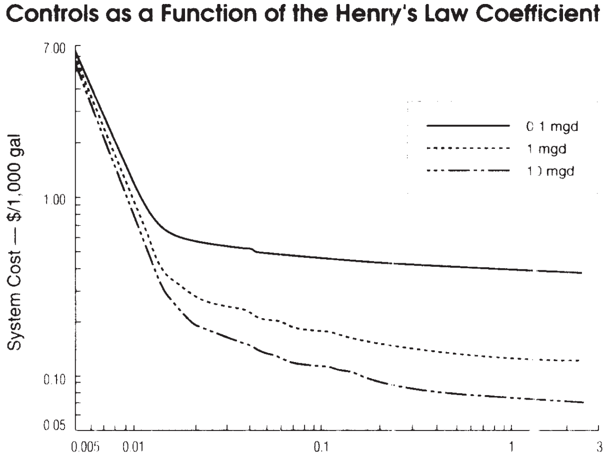
Contaminant	No. of Data Points	Influent Concentration (μg/L)		Reported Removal Efficiency[a] (%)	
		Average	Range	Average	Range
Aniline	1	226	NA[b]	58	NA
Benzene	3	3,730	200-10,000	99.6	99-100
Bromodichloromethane	1	36	NA	81	NA
Bromoform	1	8	NA	44	NA
Chloroform	1	530	1500	48	NA
Chlorobenzene	0	95	NA	ND[c]	ND
Dibromochloromethane	1	34	NA	60	NA
Dichloroethylene	7	409	2-3,000	98.6	96-100
Diisopropyl ether	2	35	20-50	97.0	95-99
Ethylbenzene	1	6,370	100-1,400	99.8	NA
Ethylene dichloride	7	173	5-1,000	99.3	79-100
Methylene chloride	1	15	9-20	100	NA
Methyl ethyl ketone	1	100	NA	99	NA
2-Methylphenol	1	160	NA	70	NA
Methyl tertiary butylether	2	90	50-130	97.0	95-99
Perchloroethylene	17	355	3-4,700	96.5	86-100
Phenol	1	198	NA	74	NA
1,1,2,2-Tetrachloroethane	1	300	NA	95	NA
Trichloroethane	8	81	5-300	95.4	70-100
Trichloroethylene	34	7,660	1-200,000	98.3	76-100
1,2,3-Trichloropropane	1	29,000	NA	99	NA
Toluene	2	6,710	30-23,000	98	96-100
Xylene	4	14,823	17-53,000	98.4	96-100
Volatile organic compounds	3	44,000	57-130,000	98.8	98-99.5
Total Volatile Organics	46	11,120	12-205,000	97.5	58.1-100

[a]Note that the averages and ranges presented n this column represent more data points than are presented in the second column of this table because the removal efficiencies were not available for all air strippers.

[b]NA = Not Applicable. Data available for only one stripper.

[c]ND = No Data. Insufficient data available.

Figure 2
Cost Estimates for Air Stripping without Air Emission Controls as a Function of the Henry's Law Coefficient



per include tower shell, packing support, water distributor, mist eliminator, packing, blower and motor, engineering, and contractor overhead and profit. The addition of an air treatment system roughly doubles the cost of an air-stripping system [3][6, p. 5-5]. Onsite regeneration or incineration of carbon may increase the cost associated with emission controls. The primary O&M cost components are operating labor, repair and upkeep, and energy requirements of blower motor and pumps [12].

Adams et al. made cost estimates based on flows from 0.1 to 10 mgd assuming a removal efficiency of 99 percent. The process was optimized for packed tower volume and energy consumption. Figure 2 presents general cost curves for three flow rates based on their work. Air emissions controls were not included in the costs. Within the range of Henry's Law Coefficients of 0.01 to 1.0, the cost ranged from $0.07/1,000 gallons to $0.70/1,000 gallons. As the Henry's Law Coefficient approached 0.005, the costs rapidly rose to $7.00/1,000 gallons [20, p. 52].

According to Hydro Group, Inc., the cost of air stripping may range from $0.04 to $0.17 per 1,000 gallons [21, p. 7]. The Des Moines Superfund site unit cost for groundwater treatment is estimated to be about $0.45/1,000 gallons based on a 1,250 gpm treatment rate and an average O&M cost of $200,000/year for 10 years at 10 percent interest. The Eau Claire site had a unit cost of roughly $0.14/1,000 gallons assuming a 5-year operation period and an average treatment rate of 7 million gpd [12, p. C-6].

Recent developments in this technology include high-temperature air stripping (HTAS) and rotary air stripping. A full-scale HTAS system was demonstrated at McClellan AFB to treat groundwater contaminated with fuel and solvents from spills and storage tank leaks. The combined recycle and makeup was heated to 65°C, and a removal efficiency of greater than 99 percent was achieved [8, p. 9]. The rotary design, marketed under the name HIGEE, was demonstrated at a U.S. Coast Guard air station in East Bay Township, Michigan. At a gas-to-liquid ratio of 30:1 and a rotor speed of 435 rpm, removal efficiencies for all contaminants, except 1, 2-DCE, exceeded 99 percent. The removal efficiency for 1,2-DCE was not reported [4, p. 19].

Raising influent liquid temperature increases mass-transfer rates and the Henry's Law Constants. This results in improved removal efficiencies for VOCs and the capability to remove contaminants that are less volatile. Table 9 illustrates the influence that changes in liquid temperature have on contaminant removal efficiencies. Note that steam stripping may be the preferred treatment technology at a feed temperature approaching 100°C, because the higher temperatures associated with steam stripping allow organics to be removed more efficiently than in HTAS systems. However, steam stripping uses more fuel and therefore will have higher operating costs. Additionally, the capital costs for steam stripping may be higher than for HTAS if higher-grade construction materials are needed at the elevated temperatures used in steam stripping [8, p. 3].

Table 9
Influence of Feed Temperature on Removal of Water Soluble Compounds from Groundwater [8, p. 15]

Compound	*Percent Removed at Selected Temperature*		
	12°C	*35°C*	*73°C*
2 - Propanol	10	23	70
Acetone	35	80	95
Tetrahydrofuran	50	92	>99

Rotary air strippers use centrifugal force rather than gravity to drive aqueous solutions through the specially designed packing. This packing, consisting of thin sheets of metal wound together tightly, was developed for rotary air strippers because of the strain of high centrifugal forces. The use of centrifugal force reportedly results in high removal efficiencies due to formation of a very thin liquid film on wetted surfaces. The rotary motion also causes a high degree of turbulence in the gas phase. The turbulence results in improved liquid distribution over conventional gravity-driven air strippers. The biggest advantage of rotary strippers is the high capacity for a relatively small device. Disadvantages include the potential for mechanical failures and additional energy requirements for the drive motor. Water carryover into the air effluent stream may cause problems with certain emission control devices used to treat the contaminated air. Cost and performance data on rotary air strippers are very limited [4, p. 16].

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