Air Stripping

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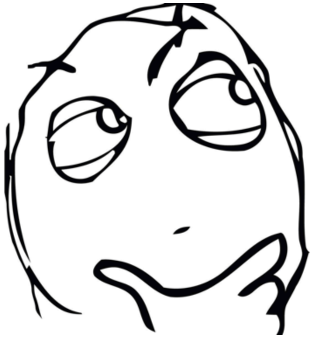
Physical Mechanisms

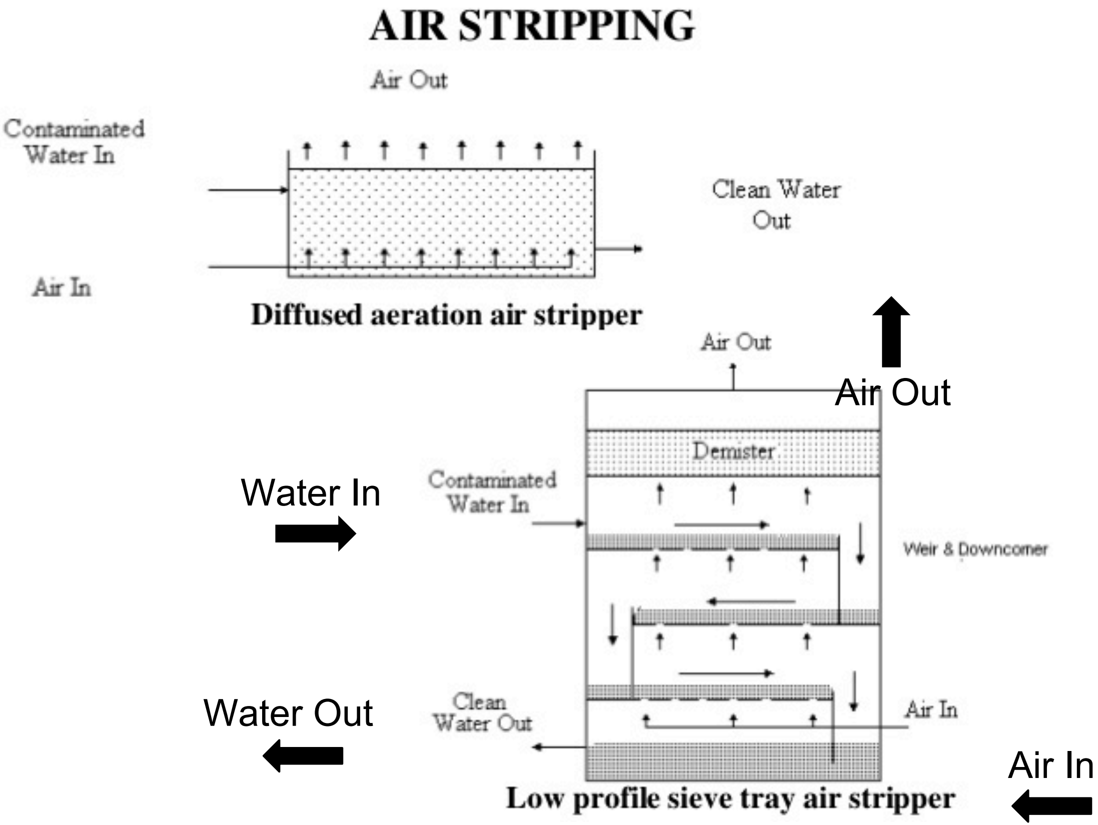
- Air Stripping- the process of moving air through water contaminated with volatile contaminants in a treatment system above ground
- The air movement causes volatiles (VOCs such as TCE, PCE, BTEX) to evaporate at a faster rate



How Air Stripping Works

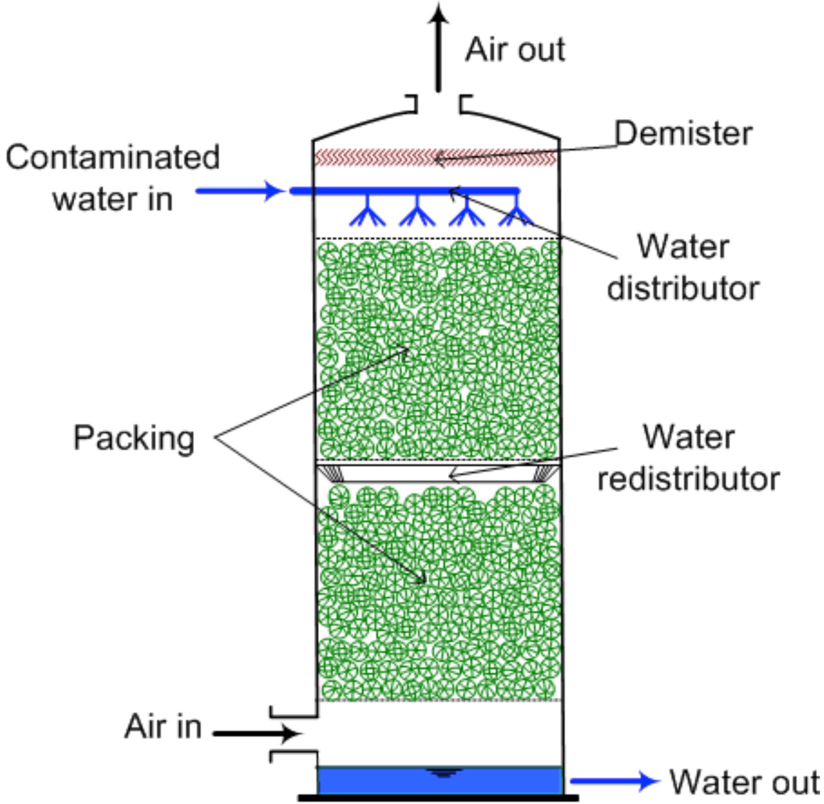
- 2 types of air strippers:
  - Sieve tray system
  - Packed tower system
- Low Profile Sieve Tray System (less common)
  - Contaminated water is pumped to top of tank, where it flows over inlet weir onto aeration trays (which acts like a sieve)
  - Air is forced upward through tray, which creates turbulence to prevent contact between air and water
- Packed Column System (popular)
  - Contaminated water flows downward through column (via gravity) through randomly or structured packed material (steel, plastic or ceramic)
  - Air flows into bottom of column and blows countercurrent to water flow

Low Profile (Sieve Tray) Air Stripper



https://www.slideshare.net/BakrYou/water-quality-control-and-treatment-water-treatment

Packed Column Air Stripper



https://en.wikipedia.org/wiki/Air_stripping#/
media/File:Air_Stripper_for_Wikipedia.png

Packed Column or Sieve Tray?

- Packed Column Systems most popular choice
  - Economic
  - Efficient
  - Effective for larger flows (>50 gpm)
  - Less pressure drop required

http://carbonair.com/wp-content/uploads/2012/12/TOWER1-11.jpg

What Happens After Stripping?

- Air Stripping is NOT the treatment, but rather just a way to transfer contaminants to one phase from another
- Contaminated air is stored at top of column or tank until it is collected or released
- Newly contaminated air will need to be filtered through gas phase carbon adsorption or combusted to dispose of VOCs
- Treated water that flows to bottom of stripper can be:
  - Released back to freshwater supply
  - Further treated to meet regulations
  - Shipped to wastewater treatment facilities

When is air stripping the right option?

- Influencing factors include:
  - Volatility
  - Contaminant concentration levels
  - Properties of the water

Volatility

- Air stripping efficiency is limited by the volatility of the contaminant
- Volatility = tendency of a compound to evaporate under normal atmospheric conditions
- More likely to become gas when more volatile
- Extremely efficient at removing volatile organic compounds (VOCs)
- Can be used for semi-volatile compounds with limited efficiency
    - Thermal heating needed

TABLE 1
SOME COMMON VOCs FOUND IN WATER

VOC	FOUND IN	SOURCE
benzene	ground waters	gasoline leaks
	waste waters	process drains and effluents
toluene/xylene	ground waters	gasoline leaks
trichloroethylene		solvent leaks into water table
tetrachloroethylene		
trichloroethane		
dichloroethanes		
trihalomethanes	source waters	chlorination/ozonation of
	waste waters	treated waters
vinyl chloride	waste waters	plastics manufacture
carbon tetrachloride	ground waters	solvent spills
naphthalene	ground waters	diesel spills
acetone	waste waters	solvent spills
	ground waters	
methyliso-butyl ketone	ground waters	gasoline leaks
chlorobenzenes	waste waters	process spills
	source waters	solvent spills

Influence of the Henry's Law Constant

- Henry's Law, like volatility, describes the tendency for a compound to transfer from a liquid to gas at equilibrium
- Henry's Law Constant is the ratio of the contaminant at equilibrium in the liquid phase and the gas phase.
- As Henry's Law Constant increases, typically volatility also increases

$$H_C = C_G/C_L$$

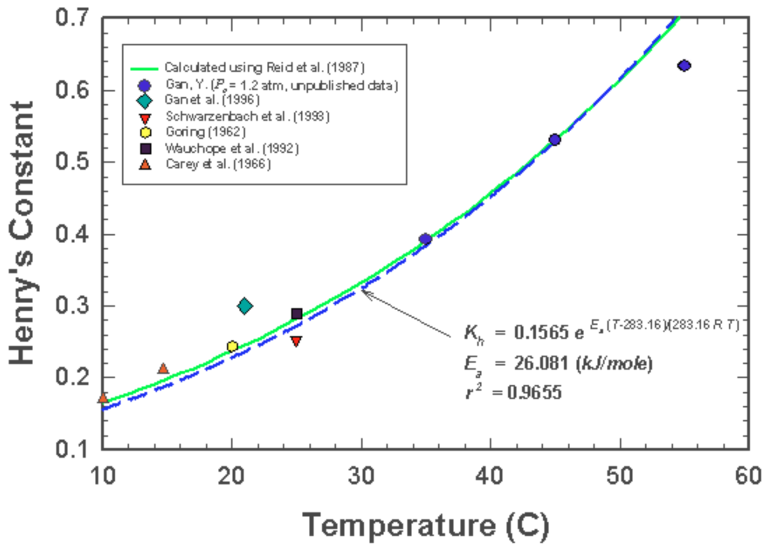


Table 3.B.2 Henry's Law Constants for Selected Species

Species	Formula	K_H (M atm^{-1})	H_g (atm M^{-1})	Temperature (°C)
Ammonia[a]	NH_3	62	0.016	25
Benzene	C_6H_6	0.18	5.6	20
Benzo(*a*)pyrene	$C_{20}H_{12}$	2040	4.9×10^{-4}	20
Carbon dioxide[a]	CO_2	0.034	29	25
Carbon monoxide	CO	0.0010	1000	20
Chloroform	$CHCl_3$	0.31	3.2	20
Ethylbenzene	C_8H_{10}	0.11	9.1	20
Formaldehyde	$HCHO$	6300	1.6×10^{-4}	25
Hydrogen sulfide[a]	H_2S	0.115	8.7	20
Methane	CH_4	0.0015	670	20
Naphthalene	$C_{10}H_8$	2.2	0.45	20
Nitric acid[a]	HNO_3	2.1×10^5	4.8×10^{-6}	25
Nitrogen	N_2	0.00067	1500	20
Oxygen	O_2	0.00138	720	20
Phenol	C_6H_6O	2200	4.5×10^{-4}	20
Sulfur dioxide[a]	SO_2	1.24	0.81	25
Tetrachloroethylene	C_2Cl_4	0.083	12	20
Toluene	C_7H_8	0.15	6.7	20
1,1,1-Trichloroethane	$C_2H_3Cl_3$	0.055	18	20
Trichloroethylene	C_2HCl_3	0.11	9.1	20

[a]These species participate in acid-base reactions when dissolved in water. The coefficients listed refer to the solubility of the unreacted species only.

Air/Water Ratio

- Air/water ratio flowing through the air stripper is extremely important in determining efficiency
- It is dependent on the concentration and physical properties of the contaminant. One can look at the Henry’s constant to determine the needed ratio. Typically a good first estimate is:

$$A/W = 16{,}000 * H_C$$

- Typically, as the ratio increases, efficiency will increase until a point of flooding is reached

High vs. Low Concentrations

- At low concentrations (below 0.5 ppb) stripping becomes difficult
- Slight inaccuracies in the A/W ratio calculations can result in the system not functioning properly
- Safety factors are often put in place and measures must be taken to ensure no VOC's are present in the air entering the system
- High concentrations (above 100 ppm) also cause issues
- Many cleanup sites must meet mandated standards that air strippers cannot achieve
- For higher concentrations, batch air strippers can be used

Scaling and Fouling

- Physical characteristics of the influent from the aquifer can lead to scaling, fouling, and corrosion
- High turbidity and high concentrations of solute can lead to precipitation
- Biological fouling occurs when the influent contains large quantities of organic matter
- To prevent these problems regular maintenance is required


Field Implementation

Stat 180 Air Stripper (Low Profile)

https://www.youtube.com/watch?v=lFMmvfsoFBU

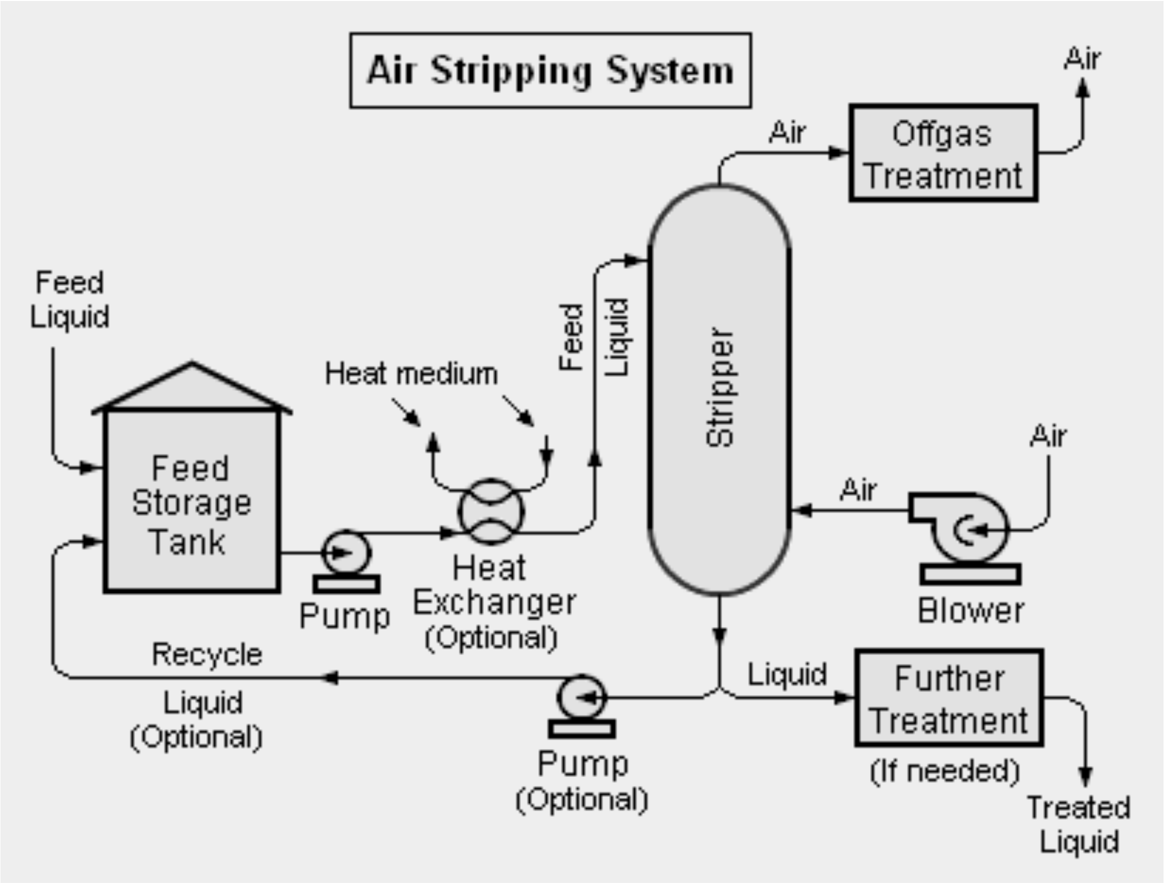
Packed Tower Air Stripper

- Pretreatment
  - PH adjustment, water softening, water heating, iron precipitation, and oil/water separation
  - Systems without it may encounter
    - More operational difficulties associated with scaling and biofouling
- Air Stripper System
  - Determined by the system flow rate
  - >100gpm packed tower
    - More compact and require a reduced footprint area
  - <100gpm low profile air strippers

Air Stripper Systems

- Long Term vs Permanent
    - Vary from site to site due to desired amount of redundancy and desired effluent quality
- Over designing vs under designing
    - Is very situational
    - Must take into account
        - Long term site plans
        - Available funding
        - State, local, and owner perceptions of acceptable system reliability and redundancy must be taken into account
- Potential Decline in MTBE influent concentrations
    - The ability to scale-down

Packed Air Stripper



Case Study #1 - LaCrosse, Kansas

LaCrosse, Kansas proclaims itself the _____ capital of the world:

A) Lacrosse

B) Tornado

C) Uncultured whole milk (sold by the pint)

D) Barbed wire

E) Corniest

Case Study #1 - LaCrosse, Kansas

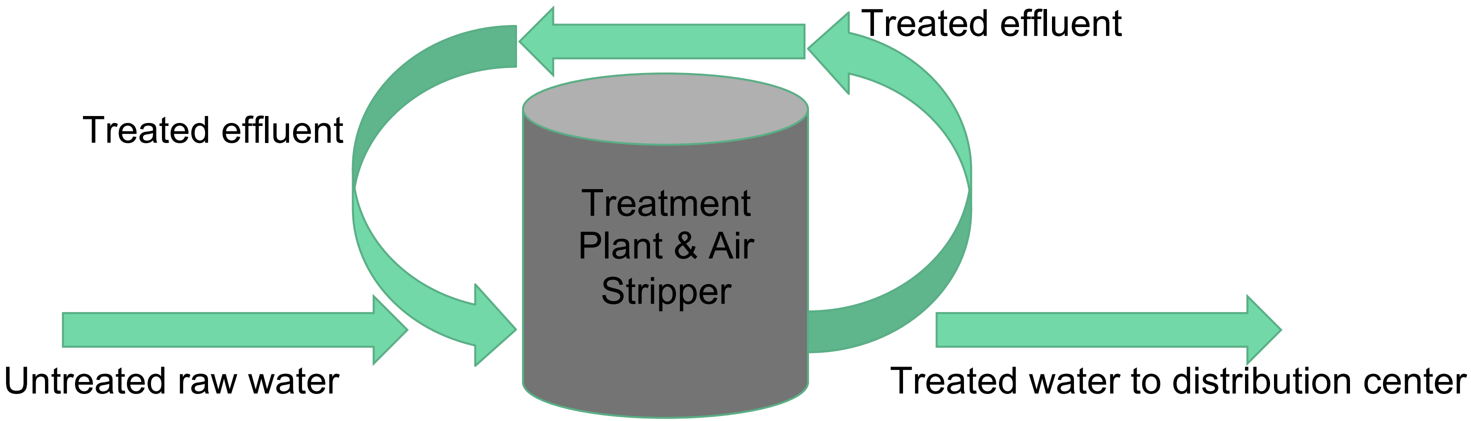
- LaCrosse gets water from 2 public water supply wells
- 3 gas stations were identified as sources of soil and groundwater contamination
- free-phase gasoline product and a petroleum hydrocarbon plume
  - MTBE concentrations exceeding 55,000 ppb
  - Methyl tert-butyl ether → EPA standard = 13 ppb
- Needed an emergency response

Case Study #1 - LaCrosse, Kansas

- Temporary air stripping system was installed to allow for continued use of the wells during treatment
  - Five-tray air stripper: took effluent of the treatment plant and returned it as influent to dilute the MTBE concentration before treatment
  - Tray stripper flow rates were limited to 250 gpm

Case Study #1 - LaCrosse, Kansas

Temporary five-tray air stripper



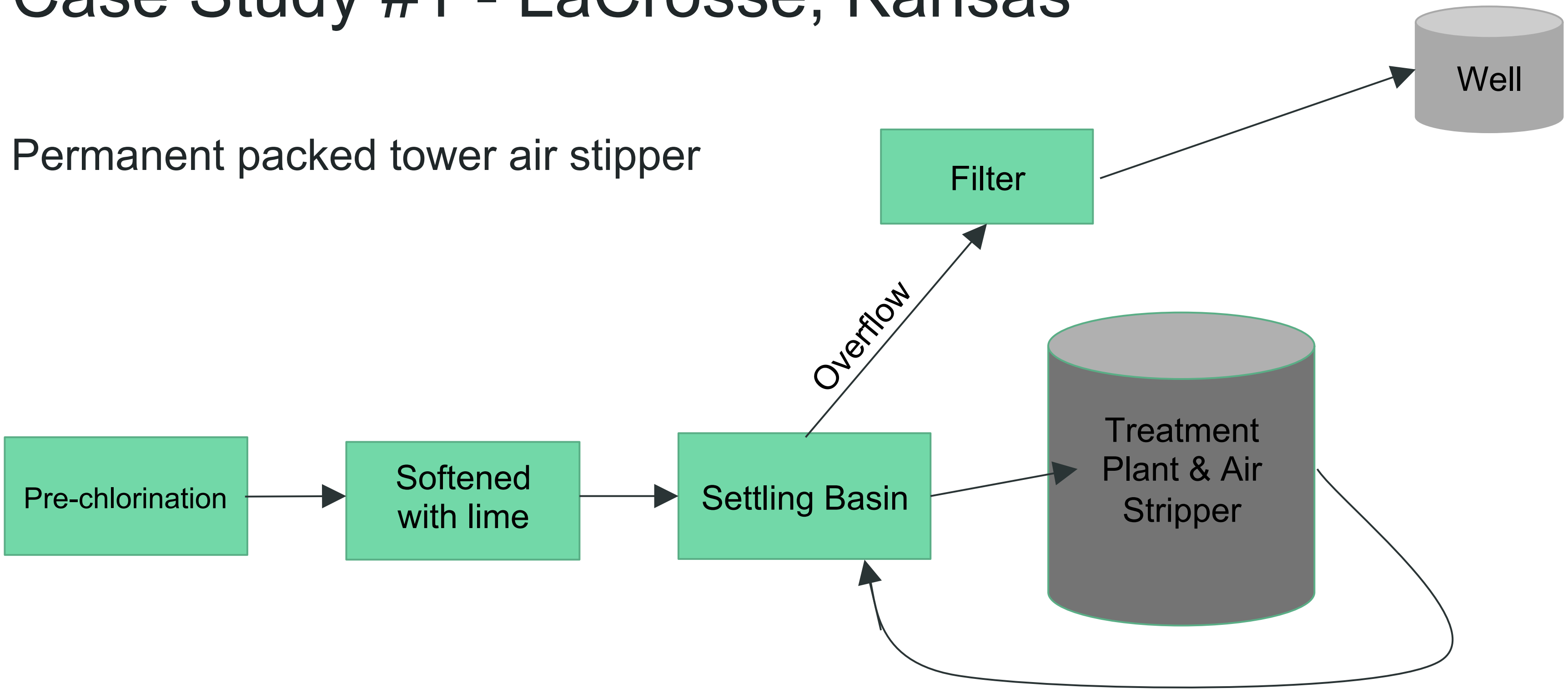
Case Study #1 - LaCrosse, Kansas

- Permanent packed tower air stripping system was installed

    1. Influent was pre-chlorinated, softened with lime, and routed to a settling basin
    2. Pumped into air stripper towers
    3. Recycled back to the settling basin
    4. Basin overflow is directed through a sand and anthracite filter bed to the distribution system

Case Study #1 - LaCrosse, Kansas

Permanent packed tower air stipper



Case Study #1 - LaCrosse, Kansas

- Temporary air stripper:
  - reduced MTBE concentrations by about 40%
  - 200 to 600 ug/L → 17 to 375 ug/L
- Permanent air stripper:
  - Concentrations less than 10 ug/L

Case Study #1 - LaCrosse, Kansas

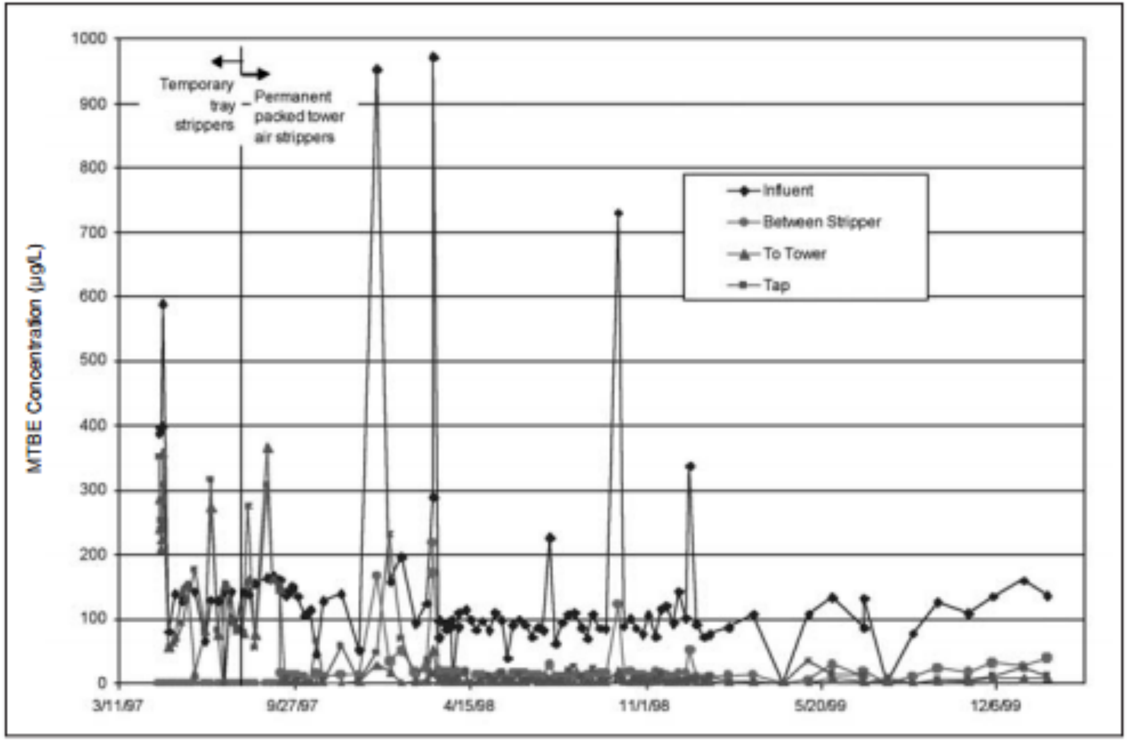


Figure 1.
MTBE concentrations at LaCrosse, Kansas.

Case Study #2 - Culver City, California

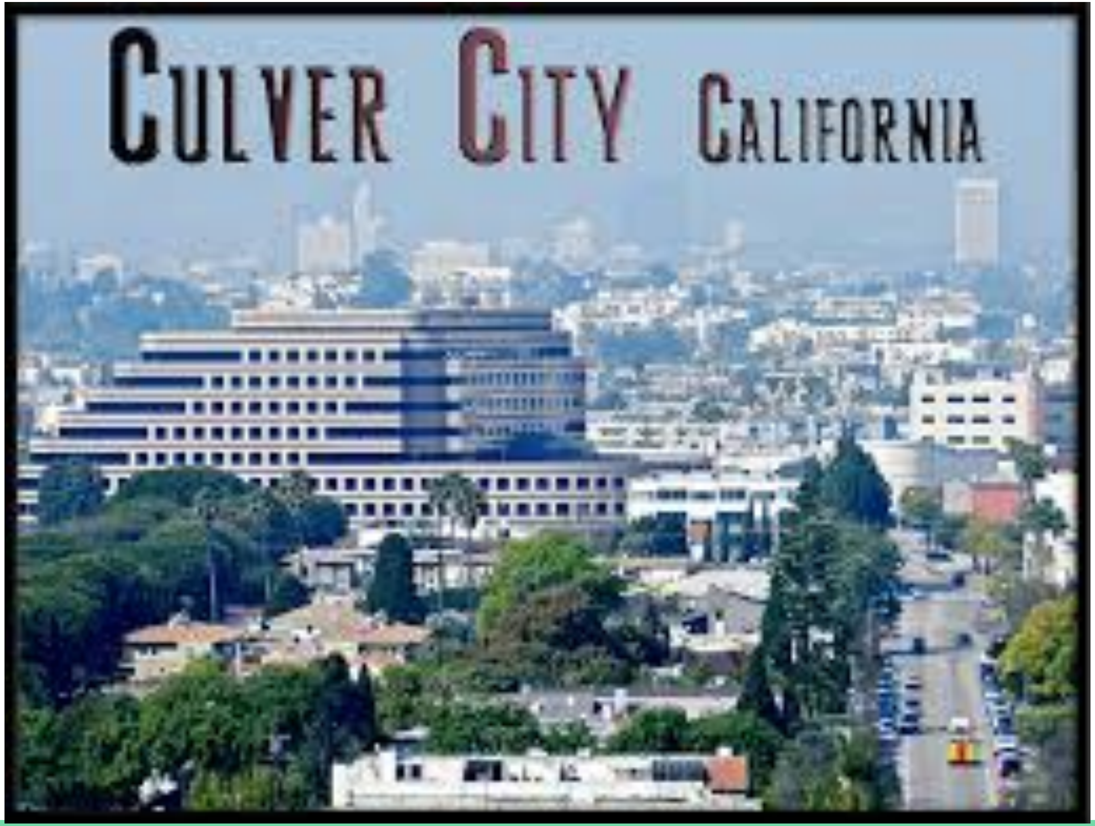
Culver City is part of Los Angeles. #1 on ‘The Top 10 Things to do in Culver City 2017’ is:

A) Museum of Jurassic Technology

B) La Brea Tar Pits and Museum

C) Hollywood Boulevard

D) L.A. Coroner’s Gift Shop



Case Study #2 - Culver City, California

- Culver City gets their drinking water from two aquifers
- Both aquifers contaminated in late 1995 due to a leaking underground storage tank at a gas station
    - Hydrocarbons, BTEX, MTBE, TBA
    - MTBE concentrations exceeding 17,000 ppb
    - NPDES standard = 13 ppb

Case Study #2 - Culver City, California

http://petrotowery.com/product/underground-storage-tanks/

Case Study #2 - Culver City, California

- Groundwater had high iron concentrations
  - Treated with hydrogen peroxide and passed through surge tanks to precipitate the metal
- Then passed through three air strippers in series
  - Each stripper could be bypassed, if needed

Case Study #2 - Culver City, California

http://encyclopedia.che.engin.umich.edu/Pages/SeparationsChemical/Strippers/Strippers.html

Case Study #2 - Culver City, California

- MTBE influent = 17,000 ppb
- MTBE effluent = 2 ppb
  - (efficiency = 99.9%)
- BTEX influent = 1660 ppb
- BTEX effluent = 1 ppb (below detection limits)
  - (efficiency = 99.9%)

Case Study #2 - Culver City, California

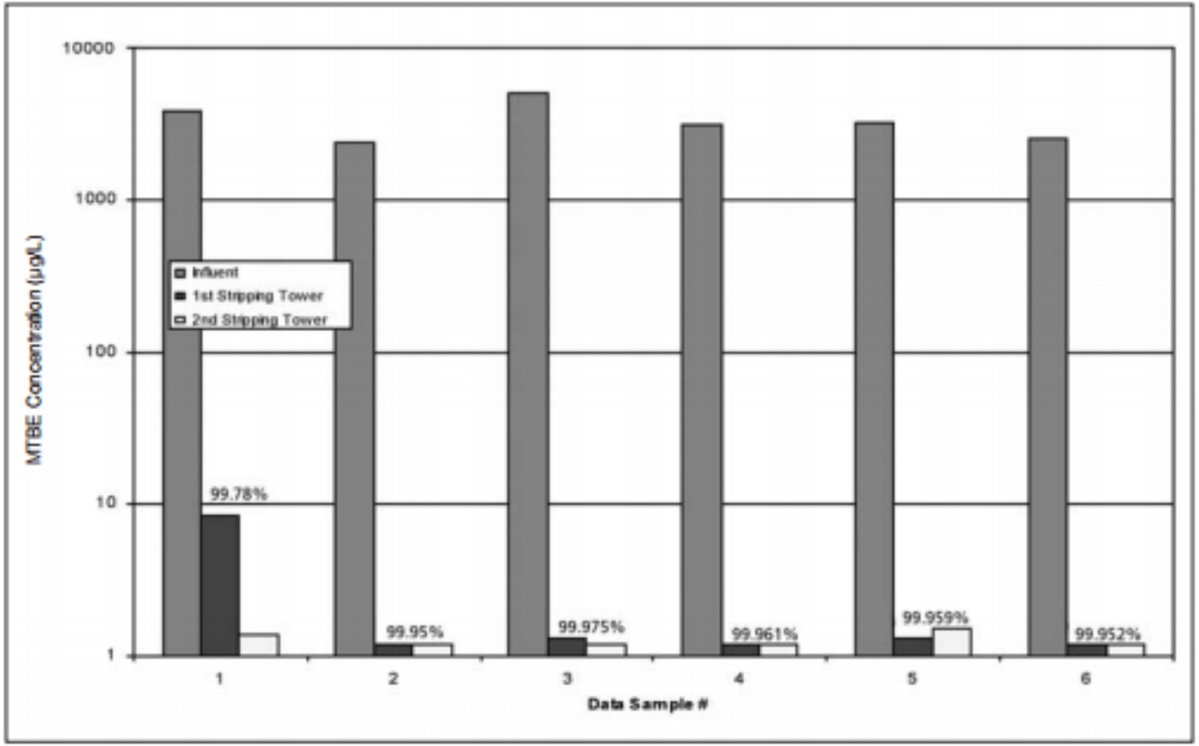


Figure 8.
Air stripping performance at Culver City, California.

Case Study #3 - Somersworth, New Hampshire

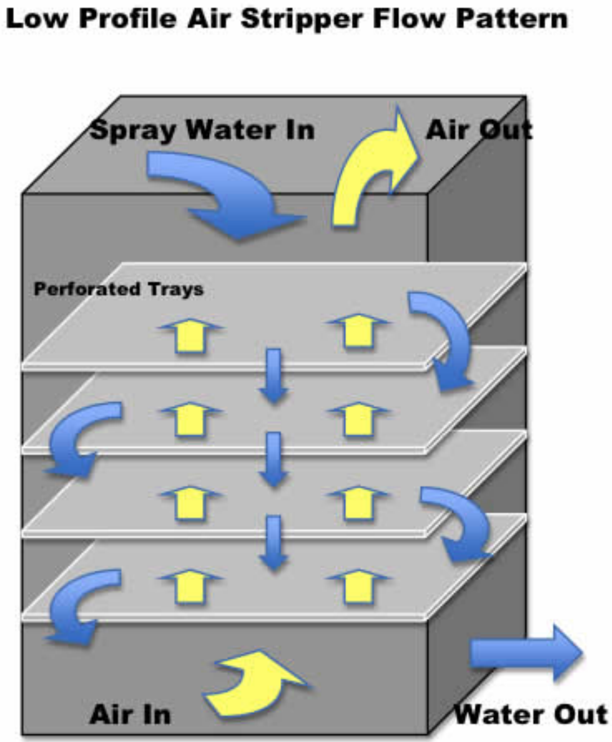
- September 1996- 2,200 gallons of gasoline leaked from an underground storage tank

- Resulted in presence of SPH in subsurface and a dissolved-phase hydrocarbon plume

Case Study #3 - Somersworth, New Hampshire

Milestone/Event	Date
Gasoline leak detected	September 26, 1996
Temporary treatment system start-up	November 22, 1996
Permanent treatment system start-up	December 10, 1996
Treated effluent ceases discharge to wastewater treatment plant and begins discharge to stormwater system	August 4, 1999
Treatment system shut-down, due to low concentrations in the influent to the air stripper and low concentrations in the groundwater monitoring wells	May 2000

Case Study #3 - Somersworth, New Hampshire



Case Study #3 - Somersworth, New Hampshire

- Operated automatically and continuously with sampling done once a month

- Efficiency of removal averaged at 98%

Case Study #3 - Somersworth, New Hampshire

- Total cost for treatment at this site exceeded $1 million
- 2,566,300 gallons of water had been recovered, treated, and discharged from the start-up date of December 10, 1996, to February 28, 2000

Case Study #4 - Elmira, California

- 1997- Petroleum leak discovered after residents complain about strange odors
- Groundwater extracted at a rate of 25 gpm
- Continuous operation besides shut downs for maintenance

Case Study #4 - Elmira, California

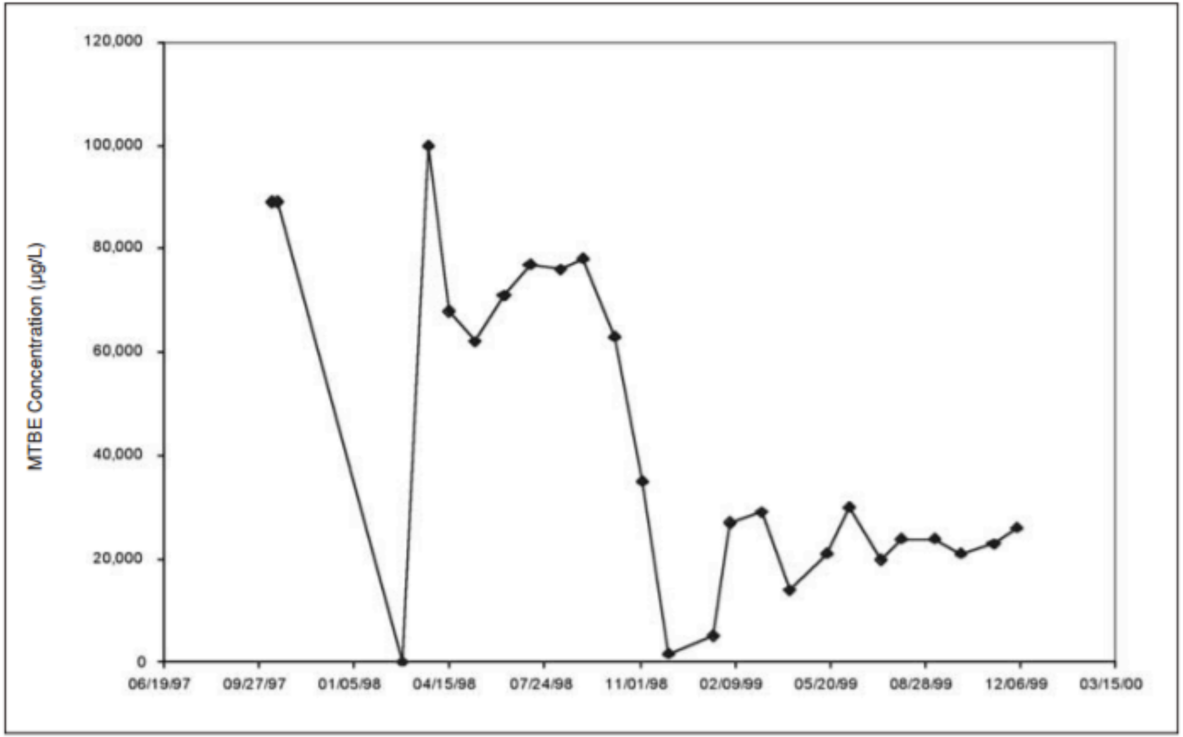


Figure 15.
MTBE influent concentrations at Elmira, California. *Note: Effluent MTBE data are not available.*

Case Study #4 - Elmira, California

- 23,300,000 gallons removed and treated as of 2000
- In 2000 NEEP’s ADDOX6 was installed for treatment
- Efficiency was greater than 99% before and after 2000

Case Study #4 - Elmira, California

Capital Costs	
Air stripper	$25,000 to $30,000
ADDOX™	$70,000
Controls and appurtenances	$75,000 to $100,000
Total Capital Costs[1]	**$185,000**
Amortized annual costs at 7 percent for 30 years	$14,910
Annual O&M Costs	
Labor (4 to 6 hours/week at $110/hour)	$23,400 to $33,800
Electricity	$7,500 to $10,000
Electricity for ADDOX6	$4,205
Parts for cleaning, maintenance, and repairs	$10,000 to $20,000
Sampling (once per month at $400)	$4,800
Total Annual O&M Costs[1]	**$61,355**
Total annual costs	$76,263
Amortized Costs/1,000 Gallons[2]	**$3.53**

[1]Total amounts are based on an average of the given amounts.

[2]Based on continuous operation at 25 gpm.

Applicability and Limitations

- Applicability
  - Effectiveness
  - Site requirements
- Limitations
  - Does not remove all compounds
  - Does not destroy compounds

Effectiveness

- >98% removal for volatile organic compounds
- >80% removal semi-volatile compounds

Although the removal percentage is high, it may not be enough. For example, take a site that is contaminated with 100 ppm of TCE. If an air stripper removes 99% of the TCE, that leaves 1 ppm of TCE remaining. The acceptable level of TCE in drinking water is 5 ppb.

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 in 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.

Site Requirements

- An air stripper is normally a permanent installation but can also be mobile
- Electrical service required
- Safety plan and special handling measures required
- Storage needed to test liquid that is produced from the air stripper

Compound Limitations

- Not all compounds can be removed through air stripping
- Air stripping is limited to removing volatile and semi-volatile organic compounds
- Metals and inorganic compounds cannot be removed from groundwater through air stripping
- Aqueous solutions with high turbidity may reduce removal efficiencies
- Aqueous media with a pH greater than 11 or less than 5 can corrode equipment

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.

Compound Destruction

- Air stripping simply removes compounds from the water and does not destroy them
- Compounds in the air must be treated through off-gas treatment
- Necessity of off-gas treatment raises cost

Cost and Availability

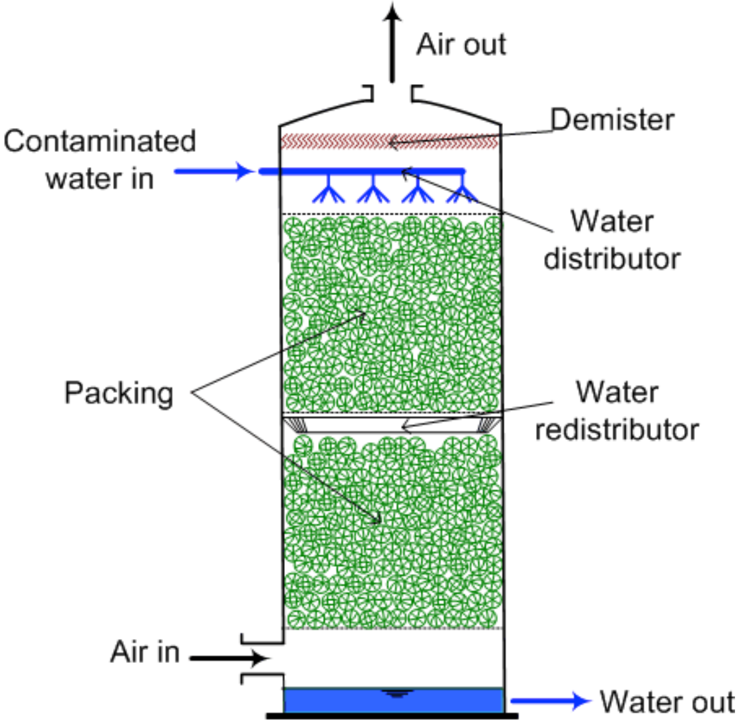
http://www.envrisk.com/wp-content/uploads/2014/08/air-stripping.jpg

Packed Air Stripper Vs Tray Air Stripper

- Packed air stripper unanimously more economical choice.
- Capable of handling more than 50 gpm (gallons per minute)
- Packed strippers require less of a pressure drop, reducing energy input; saving money on fuel for engine
- Packed stripper a better economical option when handling low volatility VOCs.
    - Higher Air/Water ratio required, easier to generate ratio with a packed stripper.

- Tray Stripper more economical at lower flow rates
- Tray stripper more resistant to fouling than the material in a packed stripper
- Tray requires less frequent maintenance.
- Increase of flow rate requires more units making trays less cost efficient.
- Smaller, easier to analyze for maintenace.

Packed Air Stripper Cost Analysis

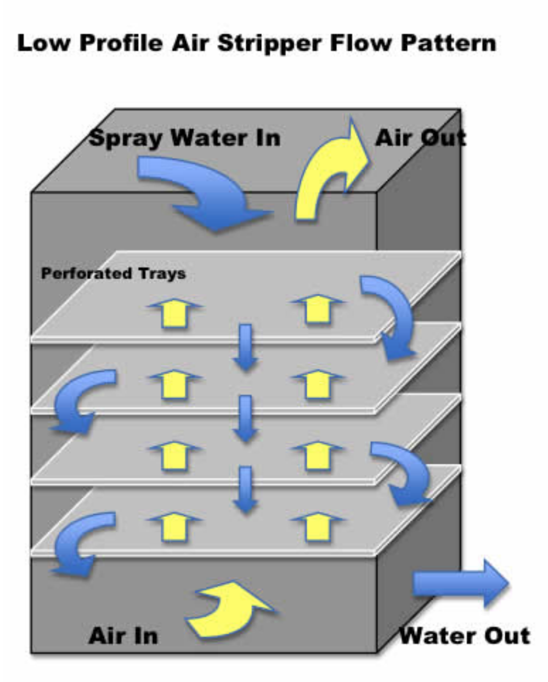


https://upload.wikimedia.org/wikipedia/commons/4/4e/Air_Stripper_for_Wikipedia.png

http://www.acwa.co.uk/node/92

Flow (gpm)	System Configuration	Influent (µg/L)	Effluent (µg/L)	Removal (%)	Capital Cost ($)	Annual O&M ($)	Unit Cost ($/1000 gal)*
60	2.6' dia. tower	20	5	75.00%	$66,654	$46,844	$1.66
60	2.6' dia. tower	20	0.5	97.50%	$88,872	$47,888	$1.75
60	2.6' dia. tower	200	20	90.00%	$66,654	$46,844	$1.66
60	2.6' dia. tower	200	5	97.50%	$88,872	$47,888	$1.75
60	2.6' dia. tower	200	0.5	99.75%	$111,090	$48,410	$1.82
60	2.6' dia. tower	2000	20	99.00%	$99,981	$48,410	$1.79
60	2.6' dia. tower	2000	5	99.75%	$111,090	$48,410	$1.82
60	ND	2000	0.5	99.98%	ND	ND	ND
600	8.3' dia. tower	20	5	75.00%	$222,180	$77,587	$0.30
600	8.3' dia. tower	20	0.5	97.50%	$288,834	$83,852	$0.34
600	8.3' dia. tower	200	20	90.00%	$233,289	$81,242	$0.32
600	8.3' dia. tower	200	5	97.50%	$288,834	$83,852	$0.34
600	8.3' dia. tower	200	0.5	99.75%	$299,943	$91,684	$0.37
600	8.3' dia. tower	2000	20	99.00%	$277,725	$91,684	$0.36
600	8.3' dia. tower	2000	5	99.75%	$299,943	$91,684	$0.37
600	ND	2000	0.5	99.98%	ND	ND	ND
6000	6 x 11.5' dia. parallel towers	20	5	75.00%	$1,999,620	$257,620	$0.13
6000	6 x 11.5' dia. parallel towers	20	0.5	97.50%	$2,221,800	$312,440	$0.16
6000	6 x 11.5' dia. parallel towers	200	20	90.00%	$2,021,838	$296,777	$0.15
6000	6 x 11.5' dia. parallel towers	200	5	97.50%	$2,221,800	$312,440	$0.16
6000	6 x 11.5' dia. parallel towers	200	0.5	99.75%	$2,788,359	$312,440	$0.17
6000	6 x 11.5' dia. parallel towers	2000	20	99.00%	$2,532,852	$328,103	$0.17
6000	6 x 11.5' dia. parallel towers	2000	5	99.75%	$2,788,359	$328,103	$0.18

Low Profile Tray Air Stripper



http://www.jdiinc.com/product-images/low-profile-air-stripper-flow-pattern.jpg

http://www.epgco.com/images/Air-Stripper.jpg

Flow (gpm)	System Configuration	Influent (µg/L)	Effluent (µg/L)	Removal (%)	Capital Cost ($)	Annual O&M ($)	Unit Cost ($/1000 gal)*
60	Single unit	20	5	75.00%	ND	ND	ND
60	Single unit	20	0.5	97.50%	$95,537	$51,021	$1.86
60	Single unit	200	20	90.00%	$45,880	$49,977	$1.70
60	Single unit	200	5	97.50%	$71,149	$51,021	$1.80
60	Single unit	200	0.5	99.75%	$88,845	$52,587	$1.89
60	Single unit	2000	20	99.00%	$52,443	$55,720	$1.90
60	Single unit	2000	5	99.75%	$58,955	$58,852	$2.02
60	ND	2000	0.5	99.98%	ND	ND	ND
600	3 in parallel	20	5	75.00%	$259,871	$226,294	$0.78
600	6 in parallel	20	0.5	97.50%	$519,741	$249,789	$0.92
600	3 in parallel	200	20	90.00%	$337,543	$241,957	$0.85
600	6 in parallel	200	5	97.50%	$675,085	$249,789	$0.96
600	6 in parallel	200	0.5	99.75%	$776,172	$281,114	$1.09
600	6 in parallel	2000	20	99.00%	$675,085	$249,789	$0.96
600	6 in parallel	2000	5	99.75%	$776,172	$281,114	$1.09
600	ND	2000	0.5	99.98%	ND	ND	ND
6000	30 in parallel	20	5	75.00%	$2,598,706	$857,343	$0.34
6000	60 in parallel	20	0.5	97.50%	$5,197,412	$1,092,286	$0.48
6000	30 in parallel	200	20	90.00%	$3,375,425	$1,013,972	$0.41
6000	60 in parallel	200	5	97.50%	$5,197,412	$1,092,286	$0.48
6000	60 in parallel	200	0.5	99.75%	$7,761,725	$1,405,544	$0.64
6000	ND	2000	20	99.00%	ND	ND	ND

Summary of Tables

- Packed tower air stripper provided cheapest option amongst every available criteria.

- For comparison, the EPA standard of removal is 99%, (influent: 2000 ug/L; effluent: 20 ug/L):

Packed tower:
- 600 gpm, 8.3' diameter tower, $0.36/1000 gal
- 6000 gpm, 6 x 11.5' diameter, $0.17/1000 gal

Low profile tray:
- 600 gpm, 6 in parallel with each other, $0.96/1000 gal
- 6000 gpm, Not Doable

The above cost estimates include the capital costs and the annual Operation and maintenance costs.

Post Treatment Air

- Post water treatment, now infected air must be treated
- Overall treatment cost heavily based on post treatment air
- Smart design promotes lower air flow rate. Less air flow = less air to treat, dramatically reducing costs.
- There are different methods of air treatment with costs associated with each such as: granulated activated carbon, thermal oxidation, catalytic oxidation, and biofilitration
- The next slide graphs the price per year of each air treatment process.

Tables and graphs found at: http://www.nwri-usa.org/pdfs/TTChapter2AirStripping.pdf

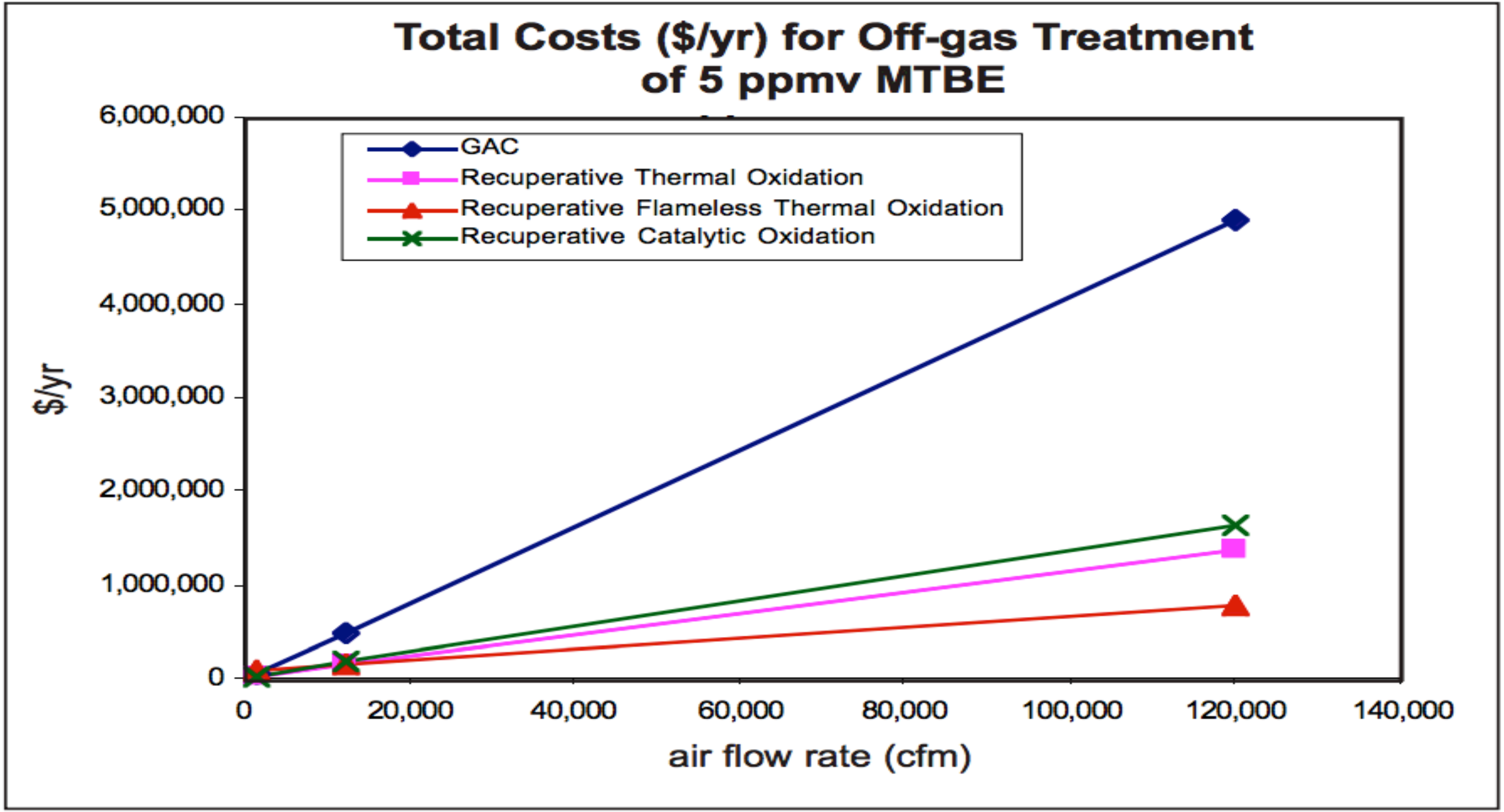


Figure 2-5. Cost of off-gas treatment technologies as a function of air flow rate.