Evaluation of air stripping for the removal of organic drinking-water contaminants

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Abstract

Counter-current air stripping has emerged as one of the simplest and most effective technologies for reducing the level of organic contaminants in drinking-water. This paper applies air stripping theory to a broad range of organic contaminants which are of present concern to the water treatment industry. It demonstrates that Henry's constant is by far the most important parameter that affects the ease of stripping of a contaminant. Three categories of contaminants are identified; those which are not amenable to air stripping at all, those that are very easily stripped under almost any conditions; and a transitional group for which the stripping tower design must be carefully optimised for good results. Data on typical tower packings and typical contaminants are included.

Introduction

Little more than a decade has elapsed since the presence and health significance of organic contaminants became a concern for drinking-water purveyors and users. Despite their relatively recent arrival, the impact of the organic contaminants on the water treatment industry has been profound. In the United States, for example, the enormous concern over volatile and synthetic organic contaminants is manifested in the recent amendments to the US Safe Drinking Water Act (SDWA). In the short period from 1988 to 1991, primary standards for **more new** contaminants will become effective than during the entire previous history of the United States. The vast majority of these new contaminants will fall into the category of volatile or synthetic organic compounds.

The removal of organic contaminants requires more than the traditional skills from water treatment consultants and designers. Not only must they deal with a new generation of compounds whose properties are little known (at least on an intuitive level), but they also have to employ treatment technology that is relatively new to drinking-water treatment. Air stripping and activated carbon adsorption are based on mass transfer and adsorption fundamentals which do not play as large a role in the traditional solid/liquid separation and disinfection processes.

This paper deals specifically with counter-current air stripping in packed aeration towers, whose design theory has been adequately treated and verified in the literature (Kavanaugh and Trussell, 1980; Roberts et al., 1985; Hand et al., 1986). The emphasis here will, therefore, not be on the derivation and details of design theory, but rather on the general applicability of air stripping to the general group of organic drinking-water contaminants. Air stripping has been proved to be an efficient method for the satisfactory reduction of some of these compounds. Even where air stripping alone may not achieve adequate removal, it may still prove to be a cost-efficient pretreatment step directly ahead of activated carbon adsorption (O'Brien and Stenzel, 1984).

The objectives are to:

- compile or estimate those chemical properties that affect the ease of stripping of a number of organic drinking-water contaminants;

- obtain typical properties of a number of commercial random tower packings, and derive generalised values for preliminary design purposes; and
- establish the practical removal limits of air stripping for the selected organic contaminants, and develop general guidelines for air stripping evaluation.

Organic contaminant properties

The mass transfer rate of a compound across a phase boundary, such as exists between air and water in a stripping tower, directly depends on the flux rate of the compound across the air/water interface. According to the Lewis/Whitman two-film theory, the interface consists of two laminar layers, one of each phase. Diffusion through each laminar film will follow Fick's first law, which states that the transfer is driven by the concentration gradient across the film, but limited by the molecular diffusivity of the compound through the film medium. The transfer rate of a compound will thus be determined by the following:

- Its Henry's constant, which is the partition coefficient of the contaminant between the aqueous and gaseous phases. The difference between the actual contaminant concentration and the equilibrium concentration, predicted by Henry's law, provides the concentration gradient which drives the mass transfer process.
- The diffusion coefficients, or diffusivities, of the compound in water and air. Some mass transfer models neglect the diffusional resistance through the laminar air layer (e.g. Sherwood and Holloway, 1940), and only deal with the diffusional resistance through the water layer. More general models (e.g. Onda et al., 1968), take the diffusional resistance through both layers into account. In the latter case, the diffusivities of the compound in water and air need to be separately estimated.

Henry's constant

In a survey of published data on organic drinking-water contaminants only relatively few directly measured Henry's constants were found. In the absence of direct equilibrium measurements, it is recommended (Lyman et al., 1982) that Henry's constant is estimated from the water solubility and vapour pressure data, data

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TABLE 1
COMPILATION OF ORGANIC CONTAMINANT PROPERTIES AT 20°C

#	Compound name	Alternative name	SDWA status B	Mol. mass g/mol	Boiling point deg C	Molar volume ℓ/mol C	Water solubility mg/ℓ	Water solubility mmol/ℓ	Vapour pressure mm Hg	Henry's constant	Temperature constant deg K	Diffusivity in water m²/s D	Diffusivity in air m²/s E
1	Acrylonitrile		G	53,1	78	6,75E-02	7,90E+04 L	1,49E+03	1,00E+02 L	3,7E-03 R		1,11E-09	1,14E-05
2	Benzene		F	78,1	80	9,60E-02	1,75E+03 L	2,24E+01	9,52E+01 L	2,3E-01 R	1 850 Q	9,02E-10	9,37E-06
3	Bromobenzene	Phenylbromide	G,H	157,0	156	1,19E-01	5,00E+02 N	3,18E+00	3,30E+00 N	5,7E-02 R		7,93E-10	7,71E-06
4	Bromodichloromethane		G,H	163,8	90	9,47E-02				9,5E-02 P		9,09E-10	8,72E-06
5	Bromoform	Tribromomethane	G,H	252,8	150	9,95E-02	4,04E+03 S	1,60E+01	5,00E+00 L	1,7E-02K	1 910 K	8,83E-10	8,08E-06
6	Bromomethane	Methylbromide	G,H	95,0	4	5,29E-02	1,30E+04 M	1,37E+02	1,40E+03 L	5,6E-01 R		1,28E-09	1,20E-05
7	Carbontetrachloride	Tetrachloromethane	F	153,8	77	1,13E-01	7,69E+02 S	5,00+00	9,00E+01 L	9,9E-01 K	1 720 K	8,18E-10	8,22E-06
8	Chlorobenzene	Phenylchloride	H	112,6	132	1,32E-01	4,66E+02 L	4,14E+00	1,17E+01 L	1,6E-01 R		7,48E-10	7,70E-06
9	Chlorodibromomethane		G,H	208,3	119	9,71E-02	4,75E+03 S	2,28E+01	1,50E+01 L	3,6E-02 P		8,96E-10	8,37E-06
10	Chloroethane	Ethylchloride	H	64,5	12	7,27E-02				6,6E-01 P		1,06E-09	1,12E-05
11	Chloroform	Trichloromethane	G,H	119,4	62	9,23E-02	6,44E+03 S	5,40E+01	1,51E+02 L	1,5E-01 T	1 730 K	9,23E-10	9,18E-06
12	Chloromethane	Methylchloride	G,H	50,5	-24	5,05E-02	6,50E+03 L	1,29E+02	4,31E+03 L	1,8E+00 R	1 250 Q	1,32E-09	1,36E-05
13	Chloropicrin	Trichloronitromethane	G	164,4	112	1,17E-01	1,70E+03 O	1,03E+01	1,69E+01 N	8,9E-02 R		8,02E-10	7,91E-06
14	1,2-Dibromo-3-chloropropane		I	236,3	196	1,42E-01	1,00E+03 L	4,23E+00	1,00E+00 L	1,3E-02 R		7,17E-10	6,87E-06
15	o-Dichlorobenzene	1,2-Dichlorobenzene	H	147,0	181	1,38E-01	1,00E+02 L	6,80E-01	1,00E+00 L	8,0E-02 R		7,29E-10	7,22E-06
16	m-Dichlorobenzene	1,3-Dichlorobenzene	H	147,0	173	1,38E-01	1,23E+02 L	8,37E-01	2,28E+00 L	1,5E-01 R		7,29E-10	7,24E-06
17	p-Dichlorobenzene	1,4-Dichlorobenzene	F	147,0	174	1,38E-01	7,90E+01 L	5,37E-01	1,18E+00 L	1,2E-01 R		7,29E-10	7,24E-06
18	Dichlorodifluoromethane		J	120,9	-30	8,14E-02	2,94E+03 S	2,43E+01	4,87E+03 L	1,1E+01 K	1 400 K	9,94E-10	1,02E-05
19	1,1-Dichloroethane	Ethylidenedichloride	H	99,0	57	9,36E-02	4,48E+03 S	4,53E+01	1,82E+02 L	2,2E-01 T	1 900 Q	9,15E-10	9,33E-06
20	1,2-Dichloroethane	Ethylenedichloride	F	99,0	84	9,36E-02	5,87E+03 S	5,93E+01	6,40E+01 L	5,9E-02 T	1 820 Q	9,15E-10	9,19E-06
21	1,1-Dichloroethylene	Vinylidenechloride	F	97,0	37	8,62E-02	2,25E+03 L	2,32E+01	6,00E+02 L	1,4E+00 R		9,61E-10	9,77E-06
22	cis-1,2-Dichloroethylene		H	97,0	60	8,62E-02	3,50E+03 L	3,61E+01	2,08E+02 L	3,2E-01 R		9,61E-10	9,64E-06
23	trans-1,2-Dichloroethylene		H	97,0	48	8,62E-02	6,30E+03 L	6,50E+01	3,24E+02 L	2,7E-01 R		9,61E-10	9,71E-06
24	Dichloromethane	Methylenechloride	H	84,9	40	7,14E-02	2,00E+04 L	2,35E+02	3,62E+02 L	8,4E-02 R		1,07E-09	1,06E-05
25	1,2-Dichloropropane		H	113,0	96	1,16E-01	2,70E+03 L	2,39E+01	4,20E+01 L	9,6E-02 R		8,07E-10	8,27E-06
26	cis-1,3-Dichloro-1-propylene		G,H	111,0	104	1,08E-01	2,70E+03 N	2,43E+01	2,50E+01 L	5,6E-02 R		8,39E-10	8,47E-06
27	trans-1,3-Dichloro-1-propylene			111,0	112	1,08E-01	2,80E+03 L	2,52E+01	2,50E+01 L	5,4E-02 R		8,39E-10	8,44E-06
28	2,4-Dinitrotoluene	1-Methyl-2,4-dinitrobenzene	G	182,1	300	1,68E-01	2,40E+02 L	1,32E+00	5,10E-03 L	2,1E-04 R		6,48E-10	6,22E-06
29	Ethylbenzene	Phenylethane	H	106,2	136	1,40E-01	1,52E+02 L	1,43E+00	7,00E+00 L	2,7E-01 R		7,21E-10	7,53E-06
30	Ethylenedibromide		I	187,9	132	9,84E-02	4,30E+03 L	2,29E+01	1,17E+01 L	2,8E-02 R		8,89E-10	8,32E-06
31	Fluorotrichloromethane		J	137,4	25	9,73E-02	1,10E+03 L	8,01E+00	6,67E+02 L	4,6E+00 R		8,94E-10	9,08E-06
32	Hexachloro-1,3-butadiene		J	260,8	215	2,07E-01	1,50E-01 L	5,75E-04	2,00E+00 L	1,9E+02 R		5,74E-10	5,77E-06
33	Hexachloroethane	Perchloroethane	G	236,8	186	1,77E-01	4,42E+01 S	1,87E-01	4,00E-01 L	1,2E-01 K	2 320 K	6,28E-10	6,28E-06
34	Isopropylbenzene	Cumene	J	120,2	152	1,63E-01	5,00E+00 M	4,16E-02	4,60E+00 M	6,1E-01 R		6,61E-10	6,94E-06
35	Naphthalene		J	128,2	218	1,48E-01	3,30E+01 M	2,57E-01	2,30E-01 M	4,9E-02 R		7,00E-10	6,98E-06
36	n-Propylbenzene	1-Phenylpropane	J	120,2	159	1,63E-01	6,00E+01 N	4,99E-01	2,50E+00 N	2,7E-01 R		6,61E-10	6,92E-06
37	1,1,2-Tetrachloroethane		G,H	167,9	131	1,35E-01	2,90E+03 L	1,73E+01	5,00E+00 L	1,6E-02 R		7,36E-10	7,37E-06

TABLE 1 (continued)
COMPILATION OF ORGANIC CONTAMINANT PROPERTIES AT 20°C

	Compound name	Alternative name	SDWA status B	Mol. mass g/mol	Boiling point deg C	Molar volume ℓ/mol C	Water solubility mg/ℓ	Water solubility mmol/ℓ	Vapour pressure mm Hg	Henry's constant	Temperature constant deg K	Diffusivity in water m²/s D	Diffusivity in air m²/s E
38	1,1,2,2-Tetrachloroethane		H	167,9	146	1,35E-01	2,90E+03 L	1,73E+01	5,00E+00 L	1,6E-02 R		7,36E-10	7,32E-06
39	Tetrachloroethylene	Perchloroethylene	H	165,8	121	1,28E-01	2,72E+02 S	1,64E+00	1,78E+01 L	5,9E-01 K	1 800 K	7,61E-10	7,59E-06
40	Toluene	Methylbenzene	H	92,2	111	1,18E-01	7,49E+02 S	8,13E+00	2,81E+01 L	1,9E-01 T	3 820 T	7,98E-10	8,31E-06
41	1,2,4-Trichlorobenzene		J	181,5	214	1,59E-01	3,00E+01 L	1,65E-01	2,90E -01 L	9,6E-02 R		6,71E-10	6,60E-06
42	1,1,1-Trichloroethane	Methylchloroform	F	133,4	74	1,15E-01	1,61E+03 S	1,20E+01	1,23E+02 L	5,6E-01 K	1 640 K	8,13E-10	8,28E-06
43	1,1,2-Trichloroethane	Vinyltrichloride	H	133,4	114	1,15E-01	4,50E+03 L	3,37E+01	3,00E+01 L	4,9E-02 R		8,13E-10	8,11E-06
44	Trichloroethylene	Ethylenetrichloride	F	131,3	87	1,07E-01	1,11E+03 S	8,45E+00	5,79E+01 L	3,8E-01 T	1 910 K	8,45E-10	8,46E-06
45	Vinylchloride	Chloroethylene	F	62,5	-13	6,53E-02	2,67E+03 L	4,27E+01	2,66E+03 L	3,4E+00 R		1,13E-09	1,19E-05
46	o-Xylene	1,2-Dimethylbenzene	H	106,2	144	1,40E-01	1,75E+02 L	1,65E+00	1,00E+01 L	3,3E-01 R		7,21E-10	7,50E-06
47	m-Xylene	1,3-Dimethylbenzene	H	106,2	139	1,40E-01	1,30E+02 L	1,22E+00	1,00E+01 L	4,5E-01 R		7,21E-10	7,52E-06
48	p-Xylene	1,4-Dimethylbenzene	H	106,2	138	1,40E-01	1,98E+02 L	1,86E+00	1,00E+01 L	2,9E-01 R		7,21E-10	7,52E-06

EXPLANATION OF SYMBOLS USED IN TABLE 1

A   Identifying number used in Fig. 1
B   From AWWA *Mainstream* (1984)
C   Estimated with the method of LeBas (Lyman et al., 1982)
D   Estimated with the method of Hayduk and Laudie (Lyman et al., 1982)
E   Estimated with the method of Wilke and Lee (Lyman et al., 1982)
F   Primary standard established (in the US)
G   Designated candidate for future regulation (in the US)
H   Monitoring compulsory (in the US)
I   Monitoring for vulnerable systems only (in the US)
J   Monitoring at states' discretion (in the US)

K   From Munz and Robert (1987)
L   From Superfund Manual (1986)
M   From Lyman et al. (1982)
N   From Verschueren (1984)
O   From Perry's Handbook (1984)
P   From Cummins (1984)
Q   From Kavanaugh and Trussell (1980)
R   Estimated from water solubility and vapour pressure
S   Estimated from vapour pressure and Henry's constant
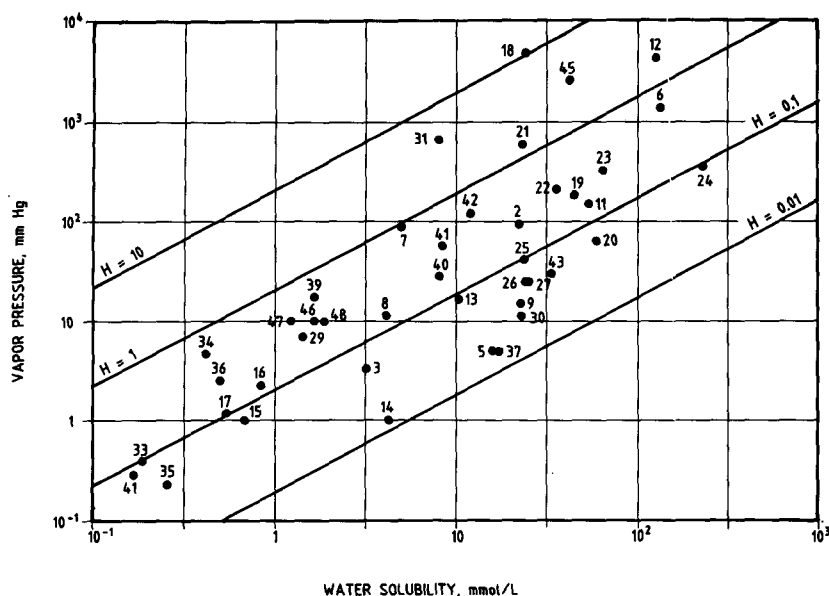T   From Lamarche and Droste (1989)

Figure 1

Water solubility, vapour pressure and dimensionless Henry's constant at 20°C for the organic drinking-water contaminants listed in Table 1 (indicated by the numerals on the figure). Not shown are compounds 1, 4, 10, 28 and 32.

which are more commonly reported. The estimated Henry's constant can then be calculated with:

$$H = 1,32 \; \frac{V\,P}{Sol \cdot R \cdot T} \tag{1}$$

with H = dimensionless Henry's constant
VP = vapour pressure in mm Hg
Sol = water solubility in mmol/L
R = 0,0821 ℓ.atm/mol. deg K (universal gas constant)
T = temperature in degrees Kelvin

Table 1 lists the vapour pressure, water solubility and Henry's constant at 20°C for 48 organic compounds currently being considered for regulation in the US. Where measured Henry's constants were available, they were selected. In the absence of measured values, they were estimated from the solubility and vapour pressure data. References were used in consistent priority for all compound properties. The reference priority was Lamarche and Droste (1989), Munz and Roberts (1987), Superfund Manual (1986), Lyman et al., (1982), Verschueren (1984), Perry's Handbook (1984), Cummins (1984), and Kavanaugh and Trussell (1980).

The solubility, vapour pressure and Henry's constant for the different contaminants are shown in Fig. 1 to show the underlying relationship between these properties. The Henry's constants, for the compounds shown, are scattered over three orders of magnitude, which represent a large spectrum of volatility.

Being an equilibrium constant, Henry's constant is affected by temperature. With the assumption that enthalpy changes are negligible over the expected temperature range, the Henry's constant at temperature T (in degrees Kelvin) can be estimated by:

$$H_T = H_{20} \left(\frac{293}{T}\right) .10^{A\left(\frac{1}{293} - \frac{1}{T}\right)} \tag{2}$$

with H_T , H_{20} = dimensionless Henry's constant
A = temperature constant in degrees Kelvin

The few available values for A are listed in Table 1. Where values were not available from the surveyed literature, a typical value of 1 900 K will be used in the rest of this paper for the compounds with unknown temperature constant. Henry's constant is significantly affected by temperature; a temperature constant of A = 1 900 K for example, will reduce Henry's constant by 53% if the temperature drops from 20°C to 5°C. Additional information on Henry's constant and its temperature dependence is given in **Appendices A and B.**

Diffusivity in air and water

A number of correlations are available to estimate the molecular diffusivity of a compound in air and water. For the purposes of this paper, the diffusivity of a compound in air has been calculated with the method of Wilke and Lee, which requires information on the molecular weight, the boiling point and the molar volume (at boiling point) of the compound. The diffusivity in water has been calculated with the method of Hayduk and Laudie, which requires only the molar volume of the compound at boiling point. The absolute average errors of these two correlations were reported to be 4,3% and 5,8% respectively. These methods are extensively reviewed and illustrated elsewhere (Lyman et al., 1982). Table 1 lists the estimated diffusivities at 20°C, as well as the primary compound properties from which they were calculated.

Properties of random tower packings

The tower packing serves two primary purposes in a stripping tower. Firstly, it splits the flow of water into a multitude of tiny streams which flow over the packing surfaces as thin films. Secondly, it provides the channels or flow paths through which the air can flow upward without bubbling or surging.

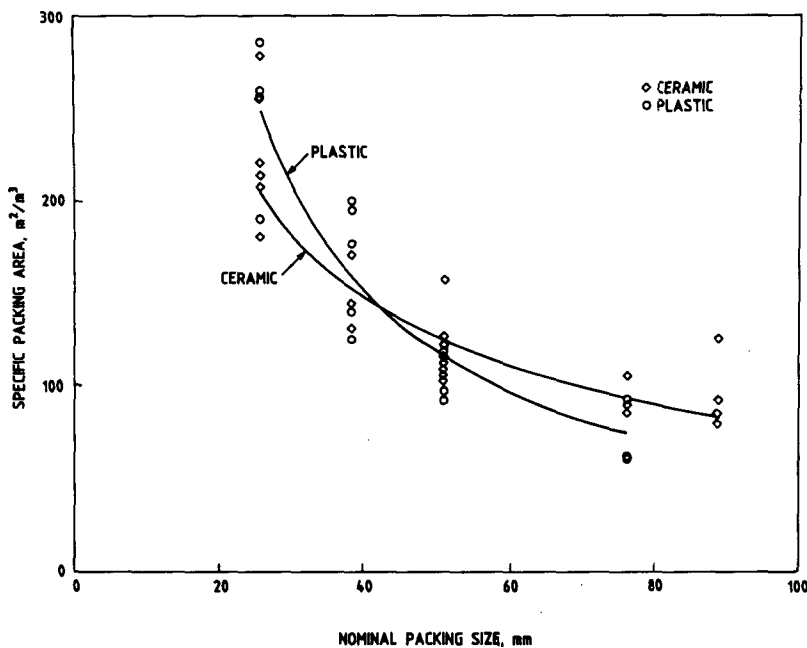*The specific packing area* defines the total surface area per

Figure 2
Specific packing area of commercial random packings. Packings include cylindrical, spherical and saddle shapes.

TABLE 2
SPECIFIC AREA AND AIR FRICTION FACTOR FOR COMMERCIAL PACKINGS

Property	Specific area (m²/m³)					Air friction factor (-)				
Nominal size (mm)	25,4	38,1	50,8	76,2	88,9	25,4	38,1	50,8	76,2	88,9
Plastic packing										
Ballast rings	213	131	105		85	52	32	25		16
Ballast saddles	213		112	92		30		20	15	
Super Intalox	207		108	89		33		21	16	
Tellerettes	180		125			40		20		
Flexirings	213	131	115		92	50	31	24		20
Tripacks	278		157		125	28		15		14
Nor-Pac	180	180	102			25	17	12		
Novalox	256	256	121	105		33	27	21	16	
Pall rings	220	220	108	85	79	52	31	25	18	16
Ceramic packing										
Intalox	256	195	118	92		92	52	40	22	
Raschig	190	125	92	62		160	95	65	36	
Novalox	256	200	121	92		97	52	40	22	
High-Flow	285	140	97	61		90	39	23	19	
Berl saddles	259	177	121			110	79	45		

Compiled from technical literature supplied by the following US companies:

Glitsch
Norton Chemical Processes Products Division
Ceilcote Company
Koch Engineering
Jaeger Products

bulk volume of randomly dumped tower packing. The larger the specific packing area, the more interfacial area will be available for the transfer of the contaminant from the water to the air.

The air friction factor, also called the packing factor, is a dimensionless coefficient which determines the air pressure gradient across the stripping tower. It is used in a standard graphical procedure for obtaining the air pressure gradient (Treybal, 1973).

Although the air friction factor does not influence the contaminant removal in the stripping tower, it is of great importance to the overall economy of the stripping operation. The lower the air friction factor, the lower the air pressure gradient and, hence, the blower operating cost.

The nominal packing size defines the overall diameter of an individual packing piece. It is not a precise measure and is normally
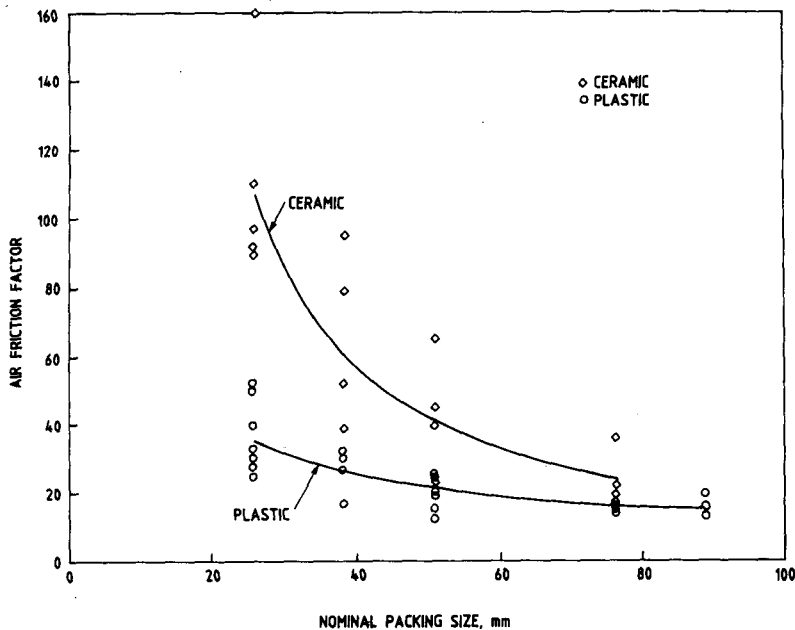
Figure 3
Air friction factor of commercial random pack-
ings. Packings include cylindrical, spherical
and saddle shapes.

derived from the manufacturer's specification. Small nominal packing sizes will result in a large specific packing area, as well as a large air friction factor.

The practical choice of the **packing material** for drinking-water treatment is limited to either plastic or ceramic. The surface properties of the two materials are such that ceramic will allow water to spread more evenly over its surface. For packings of equal specific packing area, the ceramic packing will lead to a larger wetted area than the plastic packing. The wetted area is the true interfacial area which contributes to the mass transfer rate. For example, if the wetted area of plastic packing is 70% of the specific packing area, the calculated wetted fraction (Onda *et al.*, 1968) for similar ceramic packing under identical conditions will be 85%.

Table 2 and Figs. 2 and 3 present the basic properties of a number of commercial packings, as gleaned from manufacturer's specifications and technical literature. These packings represent a wide range of different shapes such as cylindrical, saddle-shaped, and spherical. A number of conclusions follow from these data. Firstly, there are considerable differences between the properties of different packings, even though they may have the same nominal packing size and are made of the same material. While the generalised curves may be useful for approximate calculations, final designs should consider the properties of the specific packing selected. Secondly, the specific packing area decreases quite sharply as nominal packing size increases, with little difference between plastic and ceramic packings. Thirdly, the air friction factor also decreases with an increase in nominal packing size, but much less so for plastic than for ceramic packings. Plastic packing offer much less resistance to air flow than ceramic packings, especially for smaller nominal packing sizes.

The final packing choice should reflect an optimum combination of the different packing properties and, of course, the packing cost. With some water sources, the water quality will also play an important role. If it contains high concentrations of reduced iron, a precipitate will be formed in the stripping tower due to oxidation by the oxygen in the air. Smaller packings will be more likely to clog than large packings. It requires the evaluation of a range of packings and sound engineering judgment to obtain a site-specific optimum choice.

Stripping tower design considerations

The stripping tower designer has great flexibility in fixing the final tower design. Apart from the water temperature and the contaminant(s) to be removed, which are specific to the source treated, the following parameters are under the designer's control:

● water loading rate;
● volumetric air/water (A/W) ratio, which implicitly determines the air loading rate;
● packing material, size and type; and
● packing depth.

Each of the design parameters can be adjusted to obtain maximum air stripping efficiency on the one hand, or to reduce air stripping costs on the other. A lower water loading rate will spread the same quantity of water over a larger area of tower packing. A higher A/W ratio will remove the stripped contaminant more rapidly out of the tower (which will improve the stripping of less volatile contaminants), but will increase blower operating costs. Smaller packing will increase the interfacial surface area, but will also increase the resistance to air flow and the danger of clogging. An increased packing depth will improve the contaminant removal, but will require more packing as well as a higher loss of hydraulic head through the stripping tower.

The practical ranges of these design parameters are listed in Table 3. For each parameter, the value that will lead to maximum contaminant removal is placed under the "maximum stripping" column, and *vice versa*. The two tower designs shown in the two columns, therefore, represent two practical ends of the design spectrum for full-scale installations. The "maximum" stripping tower will achieve the highest contaminant removal that can reasonably be expected, while the "minimum" stripping tower will be the least efficient, but cheapest tower option. For contaminants of very high volatility, the "minimum" tower may be adequate; for contaminants of very low volatility, even the "maximum" tower may be grossly inadequate.

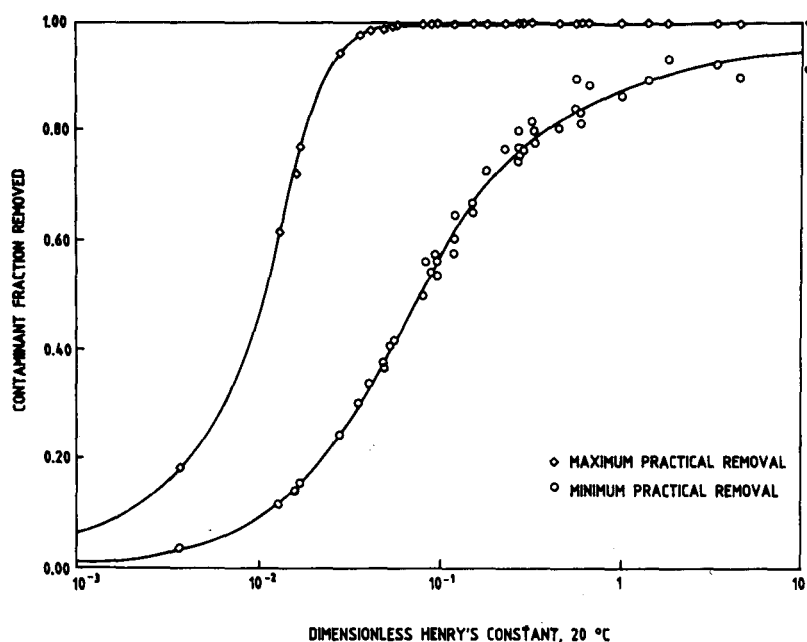It goes without saying that the selected maxima and minima

Figure 4
Contaminant removal of organic drinking-water contaminants by air stripping at 20°C. Maximum and minimum stripping conditions based on the tower designs shown in Table 3.

TABLE 3
TYPICAL RANGE OF STRIPPING TOWER PARAMETERS

	For maximum stripping	For minimum stripping
Design parameters		
Liquid loading (kg/m².s)	10	30
Volumetric A/W ratio(-)	50	10
Packing depth (m)	6	3
Nominal packing size (mm)	25	75
Packing properties for average plastic packing		
Specific packing area (m²/m³)	250	75
Air friction factor (-)	36	17
At 20°C		
Air pressure gradient (Pa/m)	56	<50
Wetted area (m²/m³)	106	55
At 5°C		
Air pressure gradient (Pa/m)	59	<50
Wetted area (m²/m³)	100	53

have nothing magical about them. They simply bracket the authors' perception of the ranges of values commonly reported in the literature and encountered in practice. As more practical experience is gained with air stripping towers in drinking-water treatment, common design values may evolve into new ranges. Designers can of course use, or already may have used, other values successfully under the appropriate conditions.

Practical removal ranges for air stripping

For each of the organic contaminants listed in Table 1, the removal was calculated for both the stripping towers specified in Table 3. The calculations were based throughout on the Onda cor-

relations (Onda et al., 1968).

Fig. 4 shows the calculated removal at 20°C as a function of Henry's constant. The observed scatter about the best-fit lines is due to the different diffusivities of the contaminants, which clearly have much less effect than Henry's constant, or the differences between the two stripping towers evaluated.

Fig. 5 shows the calculated removal at 5°C, but once again as a function of Henry's constant at 20°C for ease of comparison with Fig. 4. Henry's constant was corrected to 5°C for the calculation of the data points. The observed scatter about the best-fit lines, in this case, reflects the differences in temperature dependence as well as in diffusivities. Once again, the scatter in the data is small compared to the effects of Henry's constant and the stripping
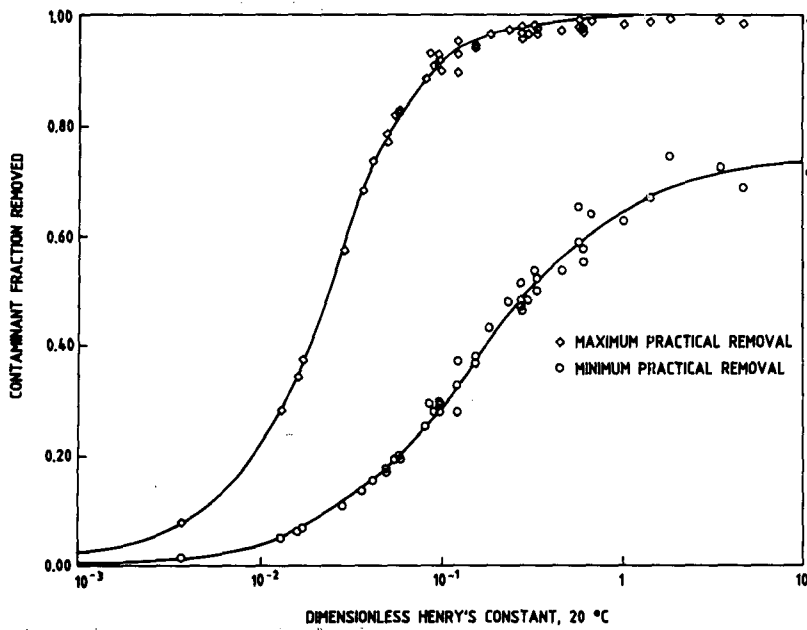
Figure 5
Contaminant removal of organic drinking-water contaminants by air stripping at 5°C. Removal fraction for each contaminant plotted against its dimensionless Henry's constant at 20°C. Maximum and minimum stripping conditions based on the tower designs shown in Table 3.
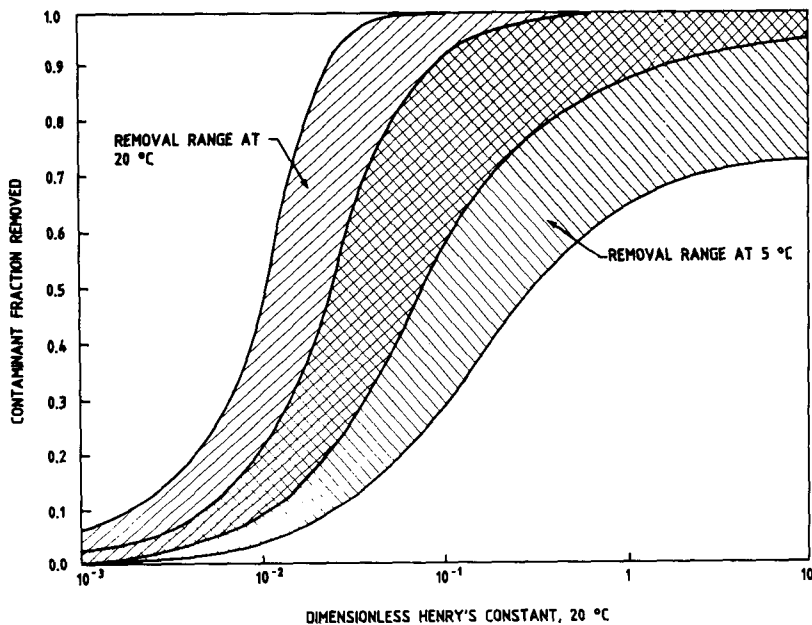

Figure 6
Generalised removal range of practical air stripping at 20°C and 5°C. Maximum and minimum stripping conditions based on the tower designs shown in Table 3.

tower differences.

The areas between the best-fit lines in Figs. 4 and 5 indicate the practical range of removal that can be achieved by air stripping; Fig. 6 presents these ranges more lucidly. The following points are noted:

● For highly volatile contaminants $(H > 1)$, air stripping will definitely remove the major part of the contaminant, even if very cheap designs are used. Complete removal can be achieved fairly easily for these contaminants. Six out of the 48 contaminants listed in Table 1 fall in this category.

● For contaminants of very low volatility $(H < 0,01)$, air stripping will remove only a minor fraction of the contaminant, even if the design parameters are pushed to their practical limits. Two of the 48 contaminants in Table 1 fall in this category.

● For contaminants with a Henry's constant in the range $0,1 < H < 1$, complete or practically complete removal can be achieved by air stripping, provided that the stripping tower is optimally designed. In Table 1, 22 out of the 48 contaminants fall in this category.

● For contaminants with a Henry's constant in the range $0,01 < H < 0,1$, complete removal by air stripping is not possible, but a significant fraction of the contaminant can be removed, depending on the specific design of the stripping tower.

According to the above analysis, air stripping appears to be a **technically** feasible process for the complete removal of 28 out of the 48, or 58% of the organic drinking-water contaminants considered in this survey. Whether air stripping would be **economically** feasible for these 28 contaminants, should be considered for each specific application, although there are some

mathematical cost models available for the economic analysis of air stripping installations (Nirmalakhandan *et al.*, 1987).

One is struck by the wide performance range of air stripping towers. The designer, by controlling a number of crucial design parameters, indeed has unusual control over the efficiency of the tower. For H = 0,05 and T = 20°C, for example, the proper choice of design parameters can achieve 98% removal of the contaminant, or could result in removal as low as 40%. This wide performance range is compelling reason for the designer to explore the many combinations of design parameters carefully for each individual application.

Summary of findings

● Air stripping towers, with a judicious but practical choice of design parameters, are capable of practically complete removal of 58% of the 48 organic drinking-water contaminants considered in this paper. These 48 compounds have all been targeted by the 1986 US SDWA Amendments.

● Air stripping is a very flexible process and the designer can attain a wide range of removal efficiencies by the proper selection of design variables.

● Henry's constant is by far the most important contaminant property to be considered. Differences in the molecular diffusivity of the contaminant, in contrast, are relatively small and have much less effect on the stripping tower efficiency.

● A compilation of commercial packing properties demonstrated some clear trends, and the generalised curves are useful for preliminary designs. The properties of some packings, however, deviate considerably from the generalised curves, and designs should be adjusted once the final packing material has been selected.

Acknowledgments

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Appendix A

Alternative formulation of Henry's constant

The dimensionless form of Henry's constant is conveniently used in engineering applications as:

$$G = H \cdot L \qquad \ldots\ldots\ldots(A1)$$

with G and L the gas and liquid concentrations in g/m^3. In physical chemistry, however, Henry's constant is traditionally used with pressure units, i.e.:

$$p = H_a \cdot x \qquad \ldots\ldots\ldots(A2)$$

with p = vapour pressure in atmospheres

H_a = Henry's constant in atmospheres

x = mole fraction in liquid

The vapour pressure p is related to the gas concentration G by:

$$p = \frac{G \cdot R \cdot T}{mol. \ mass} \qquad \ldots\ldots\ldots(A3)$$

with R = universal gas constant
T = absolute temperature
mol. mass = molecular mass

The liquid mole fraction x is related to the liquid concentration L by:

$$x = \frac{L}{C_0 \cdot mol.mass} \qquad \ldots\ldots\ldots(A4)$$

with C_0 = molar concentration of water

By substituting (A3) and (A4) into (A2), and equating with (A1), the relationship between the two forms of Henry's constant is found:

$$H = \frac{H_a}{C_o.R.T.} \qquad \text{..........(A5)}$$

Upon substitution of $C_o = 55,5$ kmol/m³ and $R = 0,08206$ atm.m³/kmol.K, the simplified relationship becomes:

$$H = 0,219 \frac{H_a}{T} \qquad \text{..........(A6)}$$

Appendix B

Temperature dependence of Henry's constant

The following expression for Henry's constant follows from first thermodynamical principles (Krynauw, 1989):

$$\ln H_a = -\frac{\Delta H^\circ}{RT} + \frac{\Delta S^\circ}{R} \qquad \text{..........(B1)}$$

This derivation is for the process where a compound goes **from** the liquid to the gas phase. The enthalpy change in question is, therefore, the opposite of the heat of solution.

Other reported temperature correlations take the same form, i.e.:

$$\log H_a = \frac{A}{T} + Y \qquad \text{..........(B2)}$$

or

$$\ln H_a = \frac{B}{T} + Z \qquad \text{......(B3)}$$

These expressions can be manipulated to express the Henry's constant at any temperature in terms of one known temperature, i.e.:

$$H_{a2} = H_{a1} . 10^{A (1/T_1 - 1/T_2)} \qquad \text{..........(B4)}$$

$$H_{a2} = H_{a1} . e^{B (1/T_1 - 1/T_2)} \qquad \text{..........(B5)}$$

As both these forms must lead to the same answer, it follows that:

$$B = 2,303 . A \qquad \text{..........(B6)}$$

Equations (B4) and (B5) are valid if Henry's constant H_a is expressed in atmospheres. To transpose (B4), for example, to the case where Henry's constant is available in the dimensionless form H, (A6) must be substituted into both sides of (B4), which yields:

$$H_2 = H_1 \left(\frac{T_1}{T_2} \right) . 10^{A(1/T_1 - 1/T_2)} \qquad \text{..........(B7)}$$

which is identical to Eq. (2) in the paper.