Respirator Cartridge Efficiency Studies: V. Effect of Solvent Vapor

G. O. NELSON and C. A. HARDER

Lawrence Livermore Laboratory, Livermore, California 94550

We have determined the service lives of organic vapor respirator cartridges for 121 solvent vapors and gases including aromatics, alcohols, acetates, alkanes, ketones, amines, and chlorinated materials. We passed the vapor and air mixtures through the cartridges and monitored the downstream concentration with a flame ionization detector (FID). Monitoring continues until the cartridge is completely saturated. We compared breakthrough times to values calculated from the adsorption isotherm and Mecklenburg equation and obtained reasonable agreement. In general, the activated carbon has greater affinity for the less volatile materials. Also, the higher the boiling point of the solvent, the greater is the weight of solvent adsorbed. Water vapor, in general, decreases the amount of solvent vapor adsorbed, especially of the more volatile solvents and those soluble in water. The effect of concentration n breakthrough time was briefly investigated and found to conform to the basic Freundlich equation.

Introduction

THIS IS THE FIFTH in a series of papers concerning respirator cartridge efficiency. The previous reports have described our program goals,[1] the testing apparatus,[2] development of a mechanical breathing simulator,[3] and a comparison of the effects of steady-state and pulsating flow.[4]

We observed no significant difference in cartridge service life between steady-state and pulsating flow. This conforms to basic adsorption theory; equilibrium between the vapor and adsorbent should be practically instantaneous.[5] We discarded the breathing simulator, therefore, and in all subsequent testing employed steady-state flow.

We also observed that the amount of solvent adsorbed at a given temperature, humidity, and concentration is essentially constant (see Figure 1) and is independent of the flow rate in the range normally associated with human breathing. Since the equilibrium rates are so rapid, the time to reach a predetermined breakthrough is inversely proportional to the flow rate. That is, doubling the flow through the cartridges will halve the effective service life if all the other test parameters remain the same.

The present investigation sought to determine how the cartridge service life varies with the type of solvent vapor adsorbed. We investigated 121 solvent vapors and gases and compared observed breakthrough times with the values calculated from the adsorption isotherm and the Mecklenburg equation. This report, in some respects, respresents an

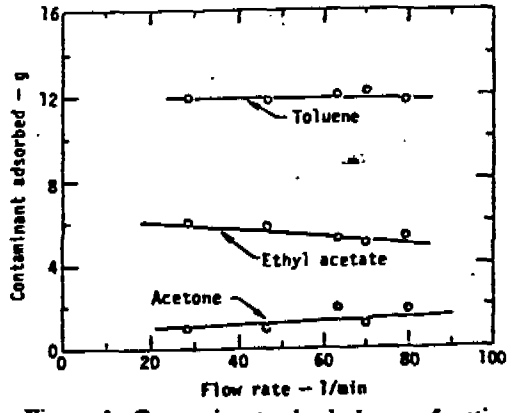


Figure 1. Contaminant adsorbed as a function of flow rate.

This work was performed under the auspices of the United States Atomic Energy Commission.

extension of the investigation by Freedman *et al.*[6]

Our standard test conditions included a solvent concentration of 1000 ppm, 50% relative humidity, and 53.3-liter/min flow, equivalent to a moderately heavy work rate of 830 kg-m/min. The solvents tested included aromatics, alcohols, actetates, alkanes, ketones, amines, and chlorinated materials. Some preliminary investigations on the effect of concentration (125 to 2000 pp) were also initiated.

Experimental Procedure

The apparatus used to generate and monitor the test concentrations is basically the same as that described in refs. 2 and 4. Several minor changes appear in Figure 2.

The humidifier now consists of a Lucite reservoir with a level switch and solenoid valve assembly to maintain a constant water volume. A 126-watt spot heater on the reservoir bottom controlled by a humidity monitor holds the humidity constant.

A 2-inch plug of glass wool added to the solvent vapor injection port aids in evaporating the solvents, especially those with higher boiling points. Maintaining the block temperature as close to the boiling point as possible avoids decomposing the solvent and plugging the needle. The activated carbon plug downstream further smooths solvent evaporation irregularities.

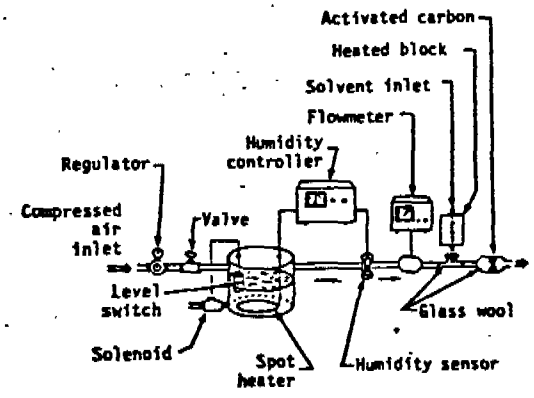


Figure 2. Schematic diagram of humidifier and solvent vaporizer.

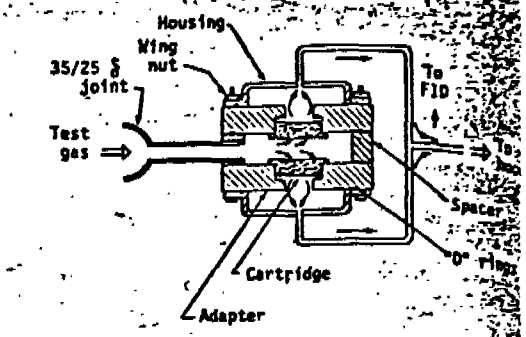


Figure 3. Schematic diagram of dual cartrid holder.

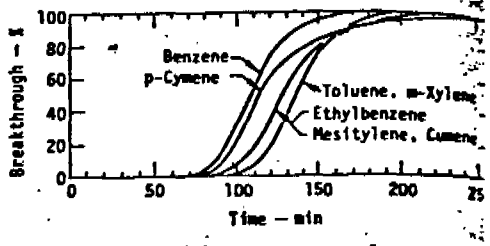


Figure 4. Breakthrough curves for aromati boiling in the range 80° to 177°C.

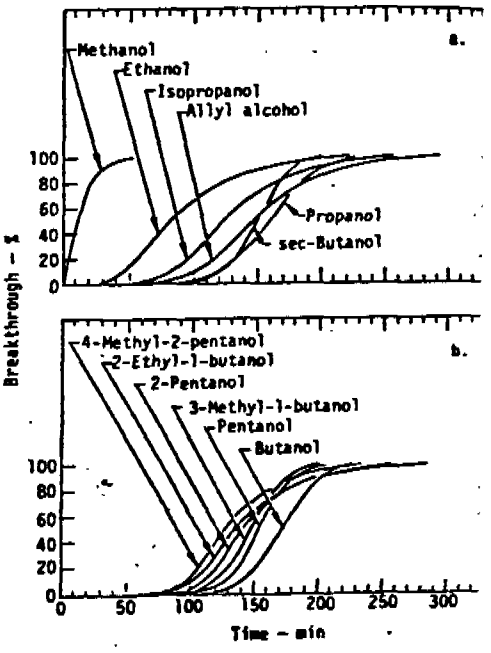
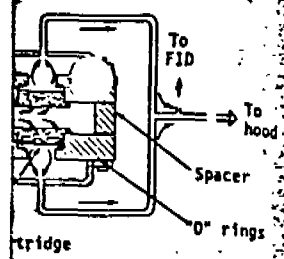
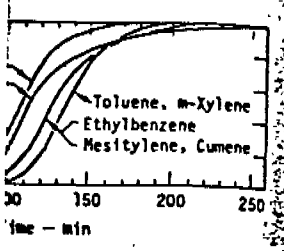


Figure 5. Breakthrough curves for alcohols bc ing in the ranges *(a)* 65° to 100°C and *(b)* 118° 147°C.

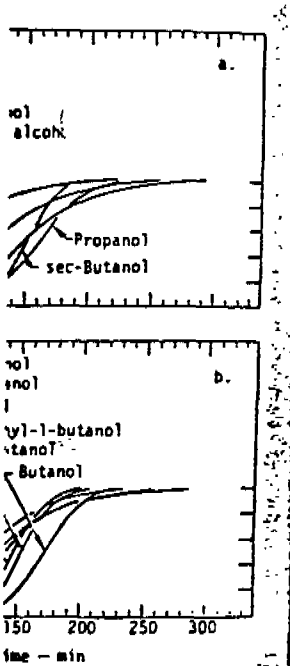


tridge

diagram of dual cartridge



ugh curves for aromatics
° to 177°C.



h curves for alcohols boil-
to 100°C and *(b)* 118° to

The cartridges were vacuum-dried and stored in a cabinet for at least 2 days at 50% relative humidity and 22°C.[4] Two cartridges were tested simultaneously in the parallel configuration shown in Figure 3.

The test gas entered through a 35/25 ground brass socket joint and passed through the cartridges held in individual polyethylene adaptors. Anodized aluminum housings, secured with wing nuts, collected the downstream gases and conducted them to the common sample outlet.

Type 1 cartridges (see ref. 4 for cartridge

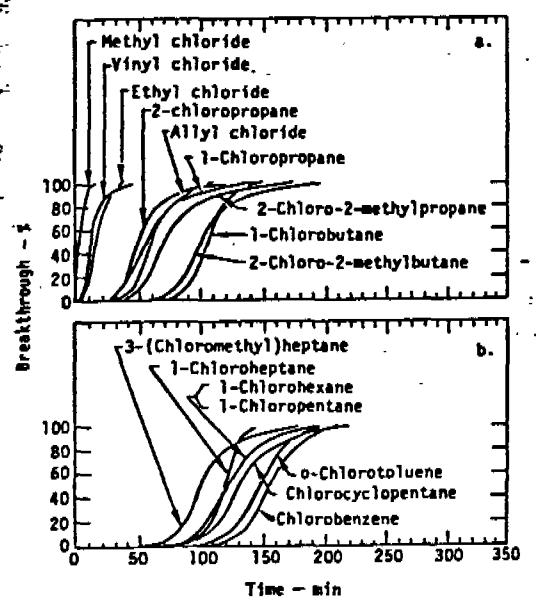


Figure 6. Breakthrough curves for monochlorides boiling in the ranges *(a)* −24° to 86°C and *(b)* 108° to 172°C.

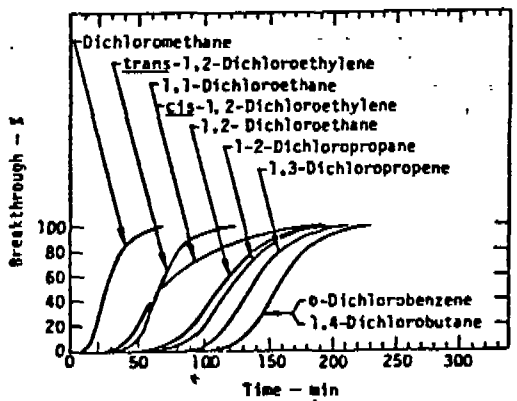


Figure 7. Breakthrough curves for dichlorides boiling in the range 40° to 180°C.

Type 1 cartridges (see ref. 4 for cartridge

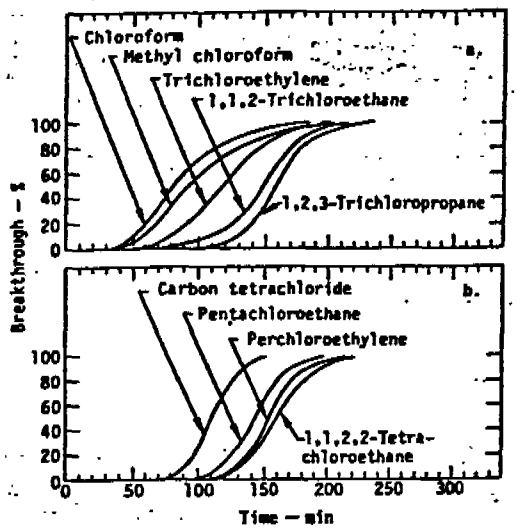


Figure 8. Breakthrough curves for *(a)* trichlorides and *(b)* tetra- and pentachlorides boiling in the ranges 61° to 156°C and 77° to 161°C, respectively.

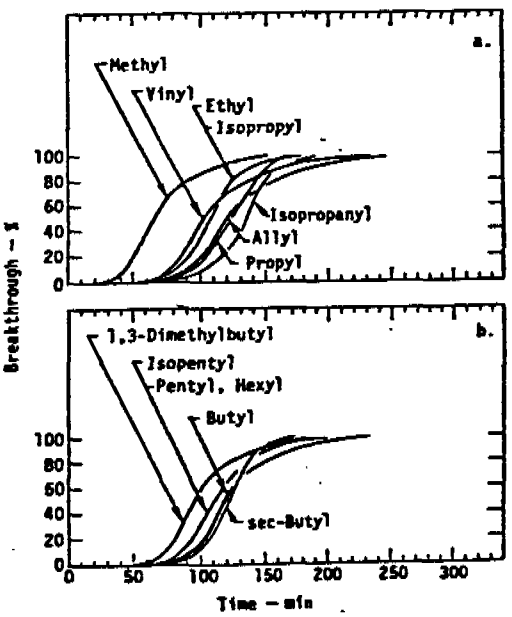


Figure 9. Breakthrough curves for acetates boiling in the ranges *(a)* 57° to 104° and *(b)* 112° to 169°C.

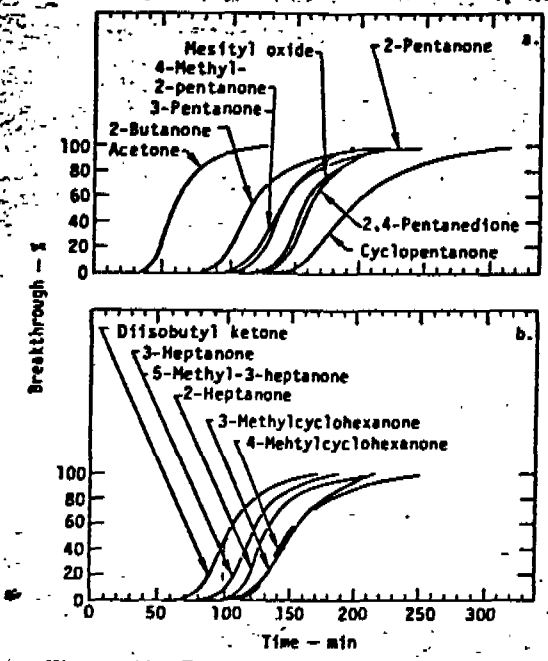


Figure 10. Breakthrough curves for ketones boiling in the ranges *(a)* 56° to 104°C and *(b)* 112° to 169°C.

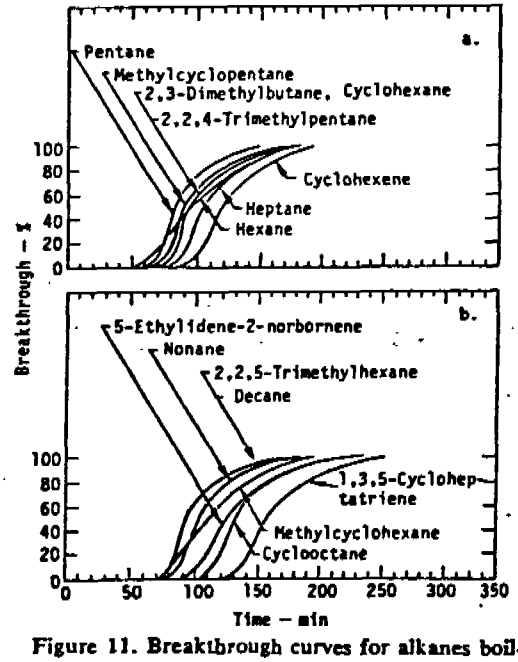


Figure 11. Breakthrough curves for alkanes boiling in the ranges *(a)* 39° to 99°C and *(b)* 101° to 174°C.

characteristics) were tested with aromatics, alcohols, esters, and chlorinated materials; type 2 cartridges were tested with ketones, alkanes, amines, and most miscellaneous compounds.

Results

Effect of Solvent Vapor

Figures 4 through 13 show how the cartridge service life varies when tested with each class of solvent vapor. The percent breakthrough (the ratio of the downstream

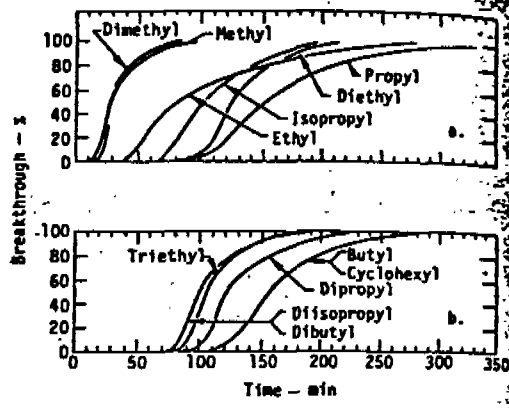


Figure 12. Breakthrough curves for amines boiling in the ranges *(a)* −7° to 56°C and *(b)* 78° to 159°C.

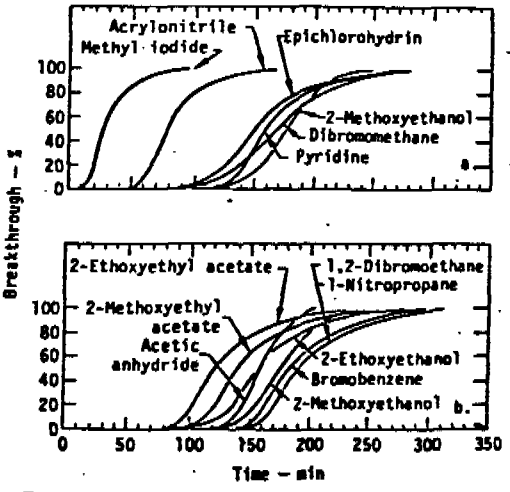
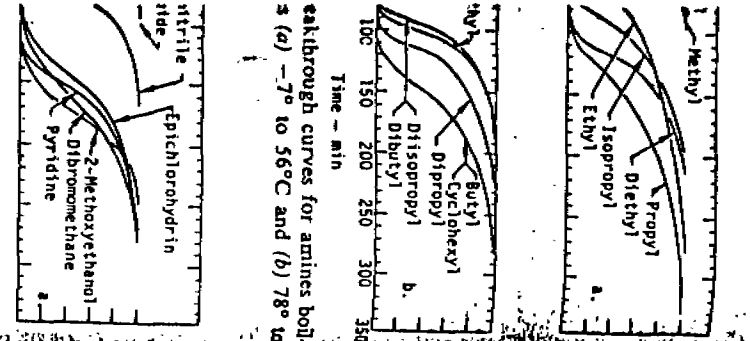


Figure 13. Breakthrough curves for miscellaneous solvents boiling in the ranges *(a)* 42° to 124°C and *(b)* 132° to 156°C.

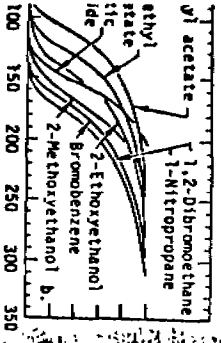
...were tested with aromatic...
...rs, and chlorinated materials...
...dges were tested with ketones...
...nes, ( ) most miscellaneous...

...ent Vapor

...through 13 show how the ca...
...life varies when tested wi...
...f solvent vapor. The percen...
...(the ratio of the downstream...



...akthrough curves for amines boil...
...s (*a*) −7° to 56°C and (*b*) 78° to...



...akthrough curves for miscellane...
...ng in the ranges (*a*) 42° to 124°C...
...156°C.

TABLE I

Solvent	BP (C°)	Vapor pressure at 20°C (Torr)	Diffusion coefficient at 25°C (cm^2/sec)	Volume charcoal (ml)[a]	Weight charcoal (g)[b]	Experimental breakthrough times $t_{1\%}$ (min)	$t_{10\%}$ (min)	$t_{99\%}$ (min)	Wt. solvent adsorbed per wt. of carbon $t_{1\%}$[c] (g/g)	$t_{10\%}$[d] (g/g)	$t_{100\%}$[e] (g/g)	Water adsorbed at $t_{100\%}$ per wt. carbon[f] (g/g)
Aromatics[g]												
Benzene	80.1	72.4	0.0932	146	59.1	73.3	88.6	170	0.214	0.249	0.327	0.035
Toluene	110.6	21.8	0.0849	144	57.5	94.5	114	196	0.334	0.397	0.473	-
Ethyl benzene	136.2	7.08	0.0755	148	55.9	83.7	105	223	0.352	0.432	0.573	0.021
m-Xylene	138.4	6.16	0.0670	148	59.7	98.7	116	193	0.388	0.450	0.536	-
Cumene	152.4	3.34	0.0677	146	60.0	81.2	103	153	0.359	0.447	0.538	0.022
Mesitylene	164.7	1.73	0.0663	147	59.5	85.5	105	189	0.382	0.460	0.565	-
p-Cymene	176.7	1.28	0.0630	148	56.9	75.6	92.9	253	0.394	0.476	0.594	-
Alcohols[g]												
Methanol	64.7	96.8	0.1520	148	55.4	0.2	3.2	47.0	0.0003	0.004	0.018	0.091
Ethanol	78.4	43.6	0.1181	146	55.5	28.0	45.3	207	0.051	0.079	0.168	0.135
Isopropanol	82.3	32.4	0.1013	145	55.7	54.5	81.8	247	0.129	0.188	0.314	0.133
Allyl alcohol	97.0	21.4	0.1021	145	55.4	65.5	105	280	0.152	0.234	0.362	0.117
Propanol	97.1	14.4	0.0993	144	55.7	70.4	111	250	0.168	0.255	0.384	0.065
sec-Butanol	99.5	12.6	0.0891	144	55.9	96.0	121	196	0.281	0.347	0.438	0.050
Butanol	117.7	5.65	0.0861	143	55.5	115	141	235	0.340	0.409	0.512	0.016
2-Pentanol	119.9	4.36	0.0728	147	56.7	86.8	111	277	0.298	0.373	0.517	0.020
3-Methyl-1-butanol	131.2	2.4	0.0709[h]	147	55.0	97.0	121	195	0.344	0.421	0.525	0.047
4-Methyl-2-pentanol	131.8	3.9	0.0653[h]	148	55.7	75.4	96.1	243	0.306	0.382	0.545	0.041
Pentanol	137.9	1.82	0.0716	148	55.0	102	130	208	0.362	0.451	0.552	0.019
2-Ethyl-1-butanol	146.8	1.56	0.0653[h]	150	55.7	76.5	101	257	0.310	0.400	0.582	0.030

TABLE I (Continued)

Solvent	BP (C°)	Vapor pressure at 20°C (Torr)	Diffusion coefficient at 25°C (cm^2/sec)	Volume charcoal (ml)[a]	Weight charcoal (g)[b]	Experimental breakthrough times $t_{1\%}$ (min)	$t_{10\%}$ (min)	$t_{99\%}$ (min)	Wt. solvent adsorbed per wt. of carbon $t_{1\%}$[c] (g/g)	$t_{10\%}$[d] (g/g)	$t_{100\%}$[e] (g/g)	Weight water adsorbed at $t_{100\%}$ per wt. carbon[f] (g/g)
Nonchlorides[g]												
Methyl chloride	-24.2	3460	0.1140[h]	148	55.7	0.05	0.7	14.6	0.0001	0.001	0.008	0.074
Vinyl chloride	-13.9	2310	0.0995[h]	147	55.7	3.8	6.6	46.3	0.009	0.016	0.038	0.070
Ethyl chloride	12.3	1110	0.0950[h]	148	56.1	5.6	10.7	38.7	0.014	0.026	0.048	0.096
2-Chloropropane	35.2	430	0.0819[h]	148	56.8	26.1	35.9	109	0.080	0.107	0.167	0.018
Allyl chloride	44.5	300	0.0975	141	55.5	30.5	44.6	108	0.093	0.132	0.194	0.040
1-Chloropropane	46.7	277	0.0829[h]	146	55.8	24.5	34.8	141	0.076	0.105	0.196	0.080
2-Chloro-2-methylpropane	50.8	240	0.0737[h]	147	57.0	37.4	52.3	168	0.134	0.183	0.279	0.010
1-Chlorobutane	77.5	80.0	0.0745[h]	145	55.8	73.3	88.1	145	0.265	0.317	0.391	0.008
2-Chloro-2-methylbutane	85.7	60.3	0.0675[h]	148	57.0	58.8	79.3	194	0.243	0.320	0.439	-
1-Chloropentane	108.4	23.9	0.0681[h]	147	56.8	74.7	96.6	197	0.310	0.392	0.505	-
Chlorocyclopentane	113	-	0.0718	146	55.6	77.5	106	211	0.322	0.429	0.562	0.050
Chlorobenzene	132	9.11	0.0747	146	55.8	107	131	205	0.478	0.574	0.688	-
1-Chlorohexane	134.5	7.15	0.0631[h]	150	55.8	77.3	95.8	189	0.370	0.449	0.591	0.013
o-Chlorotoluene	159.2	2.66	0.0688	146	55.5	102	122	192	0.514	0.605	0.741	0.005
1-Chloroheptane	159.2	2.2	0.0591[h]	150	55.5	81.5	101	143	0.437	0.533	0.625	0.013
3-(Chloromethyl) heptane	172.	-	0.0557[h]	148	55.7	63.4	80.5	183	0.374	0.485	0.613	0.013

Chlorocyclopentane	113	-	0.0718	146	55.6	77.5	106	211	0.322	0.429	0.562	0.050
Chlorobenzene	132	9.11	0.0747	146	55.8	107	131	205	0.478	0.574	0.688	-
1-Chlorohexane	134.5	7.15	0.0631[h]	150	55.8	77.3	95.8	189	0.370	0.449	0.591	0.015
o-Chlorotoluene	159.2	2.66	0.0688	146	55.5	102	122	192	0.514	0.605	0.741	0.005
1-Chloroheptane	159.2	2.2	0.0591[h]	150	55.5	81.5	101	143	0.437	0.531	0.625	0.013
3-(Chloromethyl) heptane	172.	-	0.0557[h]	148	55.7	63.4	80.5	183	0.374	0.465	0.614	0.032

TABLE I (Continued)

Solvent	BP (C°)	Vapor pressure at 20°C (Torr)	Diffusion coefficient at 25°C (cm^2/sec)	Volume charcoal (ml)[a]	Weight charcoal (g)[b]	Experimental breakthrough times $t_{1\%}$ (min)	$t_{10\%}$ (min)	$t_{99\%}$ (min)	Wt. solvent adsorbed per wt. of carbon $t_{1\%}$[c] (g/g)	$t_{10\%}$[d] (g/g)	t_{100}[e] (g/g)	Weight water adsorbed at $t_{100\%}$ per wt. carbon[f] (g/g)
Dichlorides[g]												
Dichloromethane	40.2	346	0.1037	144	55.4	10.1	15.8	63.7	0.034	0.052	0.101	0.132
trans-1,2-Dichloroethylene	49	263	0.0828[h]	145	55.7	33.0	50.3	124	0.127	0.187	0.268	0.065
1,1-Dichloroethane	56.5	158	0.0919	143	55.5	23.3	40.1	225	0.092	0.152	0.327	0.034
cis-1,2-Dichloroethylene	59.8	142	0.0828[h]	144	55.3	29.8	42.6	165	0.116	0.160	0.298	0.063
1,2-Dichloroethane	83.5	60.2	0.0907	144	55.3	54.0	79.7	186	0.214	0.305	0.456	0.036
1,2-Dichloropropane	96.4	42.3	0.0794	145	55.8	65.0	90.3	200	0.291	0.393	0.554	0.034
cis,trans-1,3-Dichloropropene	108	-	0.0763[h]	147	56.7	85.5	110	208	0.319	0.402	0.606	0.036
1,4-Dichlorobutane	162	3.10	0.0666[h]	146	55.6	108	129	215	0.505	0.637	0.755	-
o-Dichlorobenzene	180.4	0.86	0.0646[h]	146	57.3	109	132	239	0.618	0.736	0.911	-
Trichlorides[g]												
Chloroform	61.2	159.3	0.0888	144	55.6	33.2	52.4	174	0.158	0.240	0.415	0.050
Methyl chloroform	74	105	0.0794	144	56.2	40.4	58.9	197	0.212	0.299	0.530	0.036
Trichloroethylene	86.5	58.6	0.0875	145	54.8	55.3	83.0	195	0.293	0.428	0.625	0.038
1,1,2-Trichloroethane	113.6	17.5	0.0792	145	56.1	71.8	112	206	0.377	0.568	0.773	0.043
1,2,3-Trichloropropane	156	2.1	0.0672[h]	147	56.2	111	132	223	0.643	0.754	0.915	-

TABLE I (continued)

Solvent	BP (C°)	Vapor pressure at 20°C (Torr)	Diffusion coefficient at 25°C (cm^2/sec)	Volume charcoal (ml)[a]	Weight charcoal (g)[b]	Experimental breakthrough times $t_{1\%}$ (min)	$t_{10\%}$ (min)	$t_{99\%}$ (min)	Wt. solvent adsorbed per wt. of carbon $t_{1\%}$[c] (g/g)	$t_{10\%}$[d] (g/g)	$t_{100\%}$[e] (g/g)	Weight water adsorbed at $t_{100\%}$ per wt. carbon[f] (g/g)
Tetrachlorides[g]												
Carbon tetrachloride	76.8	92.1	0.0828	144	55.4	77.0	90.0	147	0.473	0.545	0.617	
Perchloroethylene	121.2	14.0	0.0797	146	55.7	107	129	209	0.704	0.835	1.01	
1,1,2,2-Tetrachloroethane	146	4.73	0.0722	146	55.3	104	131	216	0.809	0.861	1.07	
Pentachlorides[g]												
Pentachloroethane	161	-	0.0673	145	56.1	93.0	117	187	0.742	0.914	1.13	
Acetates[g]												
Methyl acetate	57.5	170.2	0.0978	146	55.6	32.8	46.5	143.8	0.097	0.135	0.214	0.071
Vinyl acetate	72.5	91.2	0.0793[h]	148	55.6	55.0	81.1	235	0.188	0.269	0.391	0.006
Ethyl acetate	72.2	74.4	0.0861	145	60.6	66.8	84.7	172	0.215	0.267	0.350	0.008
Isopropyl acetate	87.5	47.3	0.0770	146	55.6	64.5	85.6	166	0.262	0.339	0.453	0.036
Isopropenyl acetate	96	30.0	0.0718[h]	145	57.1	80.6	106	193	0.323	0.409	0.507	
Propyl acetate	101.3	24.9	0.0768	145	55.9	78.8	99.0	184	0.318	0.392	0.507	0.020
Allyl acetate	103.5	-	0.0718[h]	148	56.1	75.8	95.6	246	0.299	0.369	0.517	0.043
sec-Butyl acetate	111.5	-	0.0648	145	55.9	82.8	101	164	0.381	0.456	0.537	
Butyl acetate	126.1	8.0	0.0672	148	55.0	77.3	96.9	228	0.361	0.443	0.595	0.025
Isopentyl acetate	141.5	3.6	0.0603[h]	148	55.8	70.8	88.3	177	0.368	0.447	0.542	0.020

[illegible]	[illegible]	[illegible]	[illegible]	145	60.6	66.8	84.7	172	0.215	0.267	0.350	[illegible]
Isopropyl acetate	87.5	47.3	0.0770	146	55.6	64.5	85.6	166	0.262	0.339	0.453	0.036
Isopropenyl acetate	96	30.0	0.0718[h]	145	57.1	80.6	106	193	0.323	0.409	0.507	
Propyl acetate	101.3	24.9	0.0768	145	55.9	78.8	99.0	164	0.318	0.392	0.507	0.020
Allyl acetate	103.5	-	0.0718[h]	148	56.1	75.8	95.6	246	0.299	0.369	0.517	0.043
sec-Butyl acetate	111.5	-	0.0648	145	55.9	82.8	101	164	0.381	0.456	0.537	-
Butyl acetate	126.1	8.0	0.0672	148	55.0	77.3	96.9	228	0.361	0.443	0.595	0.023
Isopentyl acetate	141.5	3.8	0.0603[h]	148	55.8	70.9	88.3	177	0.366	0.447	0.584	0.020

TABLE I (continued)

Solvent	BP (C°)	Vapor pressure at 20°C (Torr)	Diffusion coefficient at 25°C (cm^2/sec)	Volume charcoal (ml)[a]	Weight charcoal (g)[b]	Experimental breakthrough times $t_{1\%}$ (min)	$t_{10\%}$ (min)	$t_{99\%}$ (min)	Wt. solvent adsorbed per wt. of carbon $t_{1\%}$[c] (g/g)	$t_{10\%}$[d] (g/g)	$t_{100\%}$[e] (g/g)	Weight water adsorbed at $t_{100\%}$ per wt. carbon[f] (g/g)
Acetates[g] Cont.												
1,3-Dimethylbutyl acetate	146.2	4	0.0567[h]	149	55.8	60.6	76.0	188	0.346	0.426	0.588	0.025
Pentyl acetate	148.4	2.95	0.0610	148	55.7	72.6	87.3	225	0.375	0.444	0.616	0.014
Hexyl acetate	169	-	0.0567[h]	148	55.5	67.0	85.3	202	0.385	0.480	0.658	-
Ketones[i]												
Acetone	56.2	307	0.1049	164	60.8	37.1	46.0	119	0.078	0.095	0.135	0.109
2-Butanone	79.6	70.6	0.0903	160	66.0	81.9	94.4	239	0.198	0.225	0.295	0.056
2-Pentanone	102.3	30.5	0.0793	159	58.0	104	121	231	0.341	0.392	0.483	0.016
3-Pentanone	102.7	26.8	0.0740[h]	162	58.4	93.5	114	175	0.305	0.365	0.449	0.055
4-Methyl-2-pentanone	115.5	16	0.0677[h]	160	58.1	96.1	111	211	0.367	0.418	0.511	0.007
Mesityl oxide	129.7	7.8	0.0760	169	60.2	122	139	224	0.440	0.495	0.578	-
Cyclopentanone	130.7	-	0.0796[h]	167	64.3	141	161	308	0.408	0.460	0.585	-
2,4-Pentanedione	140.4	6.5	0.0727[h]	176	70.6	130	144	214	0.408	0.447	0.527	0.009
3-Heptanone	147.3	-	0.0628[h]	160	58.1	91.0	105	186	0.396	0.451	0.548	0.014
2-Heptanone	151.2	2.8	0.0628[h]	187	61.9	101	114	237	0.412	0.460	0.560	0.005
Cyclohexanone	155.6	3.4	0.0720[h]	166	64.7	126	144	249	0.423	0.477	0.585	0.003
5-Methyl-3-heptanone	159.5	-	0.0588[h]	165	62.8	86.4	99.3	183	0.389	0.443	0.550	0.024

TABLE I (Continued)

Solvent	BP (C°)	Vapor pressure at 20°C (Torr)	Diffusion coefficient at 25°C (cm^2/sec)	Volume charcoal (ml)[a]	Weight charcoal (g)[b]	Experimental breakthrough times $t_{1\%}$ (min)	$t_{10\%}$ (min)	$t_{99\%}$ (min)	Wt. solvent adsorbed per wt. of carbon $t_{1\%}$[c] (g/g)	$t_{10\%}$[d] (g/g)	$t_{100\%}$[e] (g/g)	Weight water adsorbed at $t_{100\%}$ per wt. carbon[f] (g/g)
Ketones[i] Cont.												
3-Methyl-cyclohexanone	168	-	0.0669[h]	162	63.5	101	123	216	0.395	0.472	0.595	--
Diisobutyl ketone	169.4	-	0.0554[h]	162	60.4	70.8	83.3	171	0.369	0.427	0.556	0.005
4-Methylcyclo-hexanone	171.3	-	0.0669[h]	172	67.9	111	126	245	0.463	0.520	0.580	0.009
Alkanes[i]												
Pentane	36.1	424	0.0842	166	62.6	60.7	71.3	147	0.155	0.179	0.228	0.020
2,3-Dimethylbutane	58.0	191	0.0689[h]	167	63.5	72.0	81.1	192	0.216	0.241	0.300	0.021
Hexane	68.7	121	0.0732[h]	160	55.0	52.3	64.6	178	0.181	0.220	0.334	0.036
Methylcyclopentane	71.8	110	0.0734[h]	164	66.7	62.2	76.1	174	0.174	0.209	0.278	0.036
Cyclohexene	80.7	77.5	0.0743[h]	161	59.3	68.7	82.3	179	0.216	0.254	0.337	0.024
Cyclohexene	83.3	70.4	0.0765[h]	159	57.3	85.8	100	193	0.272	0.313	0.401	--
2,2,4-Trimethyl-pentane	96.5	38.6	0.0594[h]	161	57.5	68.3	80.4	166	0.300	0.348	0.440	0.019
Heptane	98.5	35.4	0.0636[h]	160	57.9	78.2	89.8	188	0.299	0.339	0.432	0.019
Methylcyclohexane	100.9	36.2	0.0679[h]	160	57.5	68.5	80.5	191	0.259	0.300	0.440	0.045

Solvent	BP (C°)	Vapor pressure at 20°C (Torr)	Diffusion coefficient at 25°C (cm^2/sec)	Volume charcoal (ml)[a]	Weight charcoal (g)[b]	Experimental breakthrough times $t_{1\%}$ (min)	$t_{10\%}$ (min)	$t_{99\%}$ (min)	Wt. solvent adsorbed per wt. of carbon $t_{1\%}$[c] (g/g)	$t_{10\%}$[d] (g/g)	$t_{100\%}$[e] (g/g)	Weight water adsorbed at $t_{100\%}$ per wt. carbon[f] (g/g)
Cyclohexane	80.7	77.5	0.0743[h]	161	59.3	68.7	82.3	179	0.216	0.254	0.337	0.024
Cyclohexene	83.5	70.4	0.0765[h]	159	57.3	85.8	100	193	0.272	0.313	0.	-
2,2,4-Trimethyl-pentane	96.5	38.6	0.0594[h]	161	57.5	68.3	80.4	166	0.300	0.348	0.440	0.019
Heptane	98.5	35.4	0.0636[h]	160	57.9	78.2	89.8	188	0.299	0.339	0.432	0.019
Methylcyclohexane	100.9	36.2	0.0679[h]	160	57.5	68.5	80.5	191	0.259	0.300	0.440	0.045

TABLE I (Continued)

Solvent	BP (C°)	Vapor pressure at 20°C (Torr)	Diffusion coefficient at 25°C (cm^2/sec)	Volume charcoal (ml)[a]	Weight charcoal (g)[b]	Experimental breakthrough times $t_{1\%}$ (min)	$t_{10\%}$ (min)	$t_{99\%}$ (min)	Wt. solvent adsorbed per wt. of carbon $t_{1\%}$[c] (g/g)	$t_{10\%}$[d] (g/g)	$t_{100\%}$[e] (g/g)	Weight water adsorbed at $t_{100\%}$ per wt. carbon[f] (g/g)
Alkanes[i] Cont.												
1,3,5-Cycloheptatriene	115.5	-	0.0742[h]	168	63.4	121	137	246	0.389	0.435	0.536	0.003
2,2,5-Trimethylhexane	124.5	12.5	0.0559[h]	166	64.2	67.6	80.0	168	0.266	0.310	0.444	0.001
5-Ethylidene-2-norbornene	147.5	4.2	0.0644[h]	165	67.4	86.5	101	221	0.341	0.393	0.526	0.007
Cyclooctane	150	-	0.0639[h]	172	70.5	96.8	113	220	0.345	0.397	0.497	0.027
Nonane	150	3.15	0.0559[h]	168	63.5	76.2	89.3	198	0.340	0.393	0.490	
Decane	174	0.96	0.0530[h]	164	57.7	70.8	81.5	158	0.386	0.439	0.553	0.017
Amines[i]												
Methylamine	-6.7	2160	0.1300[h]	161	58.5	12.4	17.9	91.5	0.015	0.020	0.041	0.150
Dimethylamine	6.7	1285	0.1023[h]	164	70.0	17.1	21.7	94	0.024	0.030	0.050	0.291
Ethylamine	16.6	872	0.1032[h]	161	59.8	40.5	49.7	270	0.068	0.081	0.179	0.268
Isopropylamine	31.5	478	0.0879[h]	160	60.4	65.6	75.8	194	0.142	0.162	0.275	0.136
Propylamine	47.8	247	0.0879[h]	172	65.5	90.0	111	330	0.180	0.217	0.335	0.252
Diethylamine	55.5	188	0.0993	160	62.1	88.0	105	213	0.229	0.269	0.351	0.100
Butylamine	77.5	75	0.0872	162	63.9	110	125	278	0.278	0.312	0.429	0.031
Triethylamine	89.4	46.2	0.0754	160	59.1	81.1	91.0	174	0.307	0.341	0.426	0.032
Dipropylamine	110	18.2	0.0647[h]	170	68.2	93.0	105	226	0.305	0.340	0.439	0.060
Diisopropylamine	110.5	-	0.0647[h]	171	67.0	77.0	87.1	185	0.257	0.289	0.370	0.069

TABLE I (continued)

Solvent	BP (C°)	Vapor pressure at 20°C (Torr)	Diffusion coefficient at 25°C (cm^2/sec)	Volume charcoal (ml)[a]	Weight charcoal (g)[b]	Experimental breakthrough times $t_{1\%}$ (min)	$t_{10\%}$ (min)	$t_{99\%}$ (min)	Wt. solvent adsorbed per wt. of carbon $t_{1\%}$[c] (g/g)	$t_{10\%}$[d] (g/g)	$t_{100\%}$[e] (g/g)	Weight water adsorbed at $t_{100\%}$ per wt. carbon[f] (g/g)
Amines[i] Cont.												
Cyclohexylamine	134	-	0.0664[h]	169	64.3	112	128	279	0.382	0.431	0.564	0.141
Dibutylamine	159	1.61	0.0567[h]	164	64.6	75.5	84.8	186	0.335	0.372	0.480	0.009
Miscellaneous												
Methyl iodide[i]	42.4	336	0.0900[h]	160	58.2	11.6	17.7	94.5	0.063	0.092	0.187	0.223
Acrylonitrile[i]	77.3	67.8	0.1059	160	58.0	48.5	61.1	168	0.098	0.121	0.174	0.016
Dibromomethene[i]	98.6	33	0.0826	160	62.8	82	121	279	0.502	0.717	1.06	0.006
Pyridine[i]	115.2	15.4	0.0824[h]	160	64.3	119	134	292	0.324	0.360	0.460	0.016
Epichlorohydrin[g]	116.9	12.5	0.0821[h]	146	56.9	85.5	110	288	0.308	0.387	0.566	0.014
2-Methoxyethanol[g]	124.4	9.0	0.0884	146	55.5	116	145	249	0.352	0.431	0.540	0.096
1,2-Dibromoethane[i]	131.5	8.6	0.0840[h]	161	61.9	141	165	303	0.946	1.09	1.336	-
1-Nitropropane[i]	131.6	7.2	0.0781[h]	160	63.2	143	164	322	0.443	0.504	0.638	-
2-Ethoxyethanol[g]	135.5	-	0.0788	148	55.4	77.0	133	283	0.277	0.426	0.593	0.011
Acetic anhydride	139.6	3.7	0.0755[h]	161	61.0	124	138	290	0.459	0.506	0.593	0.070

2-Methoxyethanol[a]	124.4	9.0	0.0884	146	55.5	116	143	249	0.352	0.431	0.5[illegible]	[illegible]
1,2-Dibromoethane[i]	131.5	8.6	0.0840[h]	161	61.9	141	165	303	0.946	1.09	1.336	
1-Nitropropane[i]	131.6	7.2	0.0781[h]	160	63.2	143	164	322	0.443	0.504	0.6[illegible]	-
2-Ethoxyethanol[g]	135.5	-	0.0788	148	55.4	77.0	123	283	0.277	0.426	0.593	0.011
Acetic anhydride	139.6	3.7	0.0755[h]	161	61.0	124	138	200	0.459	0.506	0.592	0.070

TABLE I (Continued)

Solvent	BP (C°)	Vapor pressure at 20°C (Torr)	Diffusion coefficient at 25°C (cm^2/sec)	Volume charcoal (ml)[a]	Weight charcoal (g)[b]	Experimental breakthrough times $t_{1\%}$ (min)	$t_{10\%}$ (min)	$t_{99\%}$ (min)	Wt. solvent adsorbed per wt. of carbon $t_{1\%}$[c] (g/g)	$t_{10\%}$[d] (g/g)	$t_{100\%}$[e] (g/g)	Weight water adsorbed at $t_{100\%}$ per wt. carbon[f] (g/g)
Miscellaneous Cont.												
2-Methoxyethyl-acetate[g]	144.5	3.6	0.0666[h]	150	55.7	93.3	113.2	303	0.438	0.521	0.707	-
Bromobenzene[i]	156	3.0	0.0661[h]	160	58.1	142	159	297	0.849	0.940	1.126	-
2-Ethoxyethyl acetate[g]	156.3	2.0	0.0619[h]	148	55.8	79.5	96.5	248	0.417	0.497	0.689	0.010

[a]Average volumes for a cartridge pair are 146.3 ± 1.9 ml for the Type 1 and 163.8 ± 4.3 ml for the Type 2.

[b]Average weights for a cartridge pair are 56.1 ± 1.2 g for the Type 1 and 62.2 ± 3.9 g for the Type 2.

[c]Calculated from $W_{1\%} = t_{1\%}$ MQC/24.1 10^6 W_c.

[d]Estimated from $W_{10\%} = [t_{1\%} + 0.9\ (t_{10\%} - t_{1\%})]$ [MQC]/24.1 10^6 W_c.

[e]See Ref. 4, "Data Processing," calculation of W_s.

[f]Calculated from $W_{H_2O} = W_{total} - W_s$.

[g]Used Type 1 cartridges.

[h]Calculated from Gilliland's equation $D_{25} = [0.0043T^{1.5}(1/M_{air} + 1/M_{vap})^{0.5}]/(v_{air}^{0.33} + v_{vap}^{0.33})^2 P$, where v_{air} is 29.9 ml/mol and v_{vap} is calculated from the LeBas approximation (see Ref. 7).

[i]Used Type 2 cartridges.

to the upstream concentration) for each solvent is shown as a function of time. These figures yield the complete adsorption history from initial breakthrough to total cartridge saturation for each of the solvents and gases tested.

Table I helps summarize the data shown in Figs. 4 through 13. Here solvents are arranged by classes, and within classes by boiling point, with the most volatile compound shown first. The times to reach 1%, 10%, and 99% breakthrough and the respective weights adsorbed are shown for each solvent.

This table shows that, within each class of solvent, the most volatile solvent breaks through first. As the boiling points of the solvents within a class increase, however, the trend eventually reverses. At some point the breakthrough time actually *decreases* with rising solvent boiling points. This occurs for each class of solvent.

Table I also illustrates how the weight of solvent adsorbed varies with the vapor pressure as well as the boiling point. Within each solvent class the weight adsorbed is both an increasing function of the boiling point and a decreasing function of the vapor pressure—the two being interrelated. This is shown to be the case for 1%, 10%, and 100% breakthrough. These data can be used, therefore, to approximate the weight adsorbed of an untested solvent once its class and boiling point or vapor pressure are known.

Table I also gives the diffusion coefficients and the activated carbon weights and volumes needed in the theoretical calculation of the breakthrough times. It also shows the weights of water adsorbed. Note the relatively large amount of water adsorbed in connection with more volatile solvents, especially those that are miscible with water.

Calculation of Breakthrough Times

The ability to predict the cartridge breakthrough mathematically for any solvent that may be encountered would be useful. Initial cartridge breakthrough can be calculated from

$$t_b = \frac{10^6 V_m w W_c}{MQC} \quad (1)$$

where t_b = initial cartridge breakthrough time (min).
V_m = molar volume at the system temperature and pressure (24.1 liters/mole at 20°C, 760 torr).
w = weight of solvent adsorbed per gram of activated carbon (gm/gm).
W_c = weight of activated carbon (gm).
M = molecular weight of the contaminant (gm/mole).
Q = airflow rate (liters/min).
C = upstream gas concentration (ppm).

All the terms can be measured or calculated except w. The weight of solvent adsorbed is extremely difficult to predict, since it is a complex function of the nature of the adsorbent and solvent vapor. Therefore, equation 1 is useful only if the weight is determined experimentally. Estimations of the breakthrough time can be calculated, however, from the adsorption isotherm and the Mecklenburg equation.

The adsorption isotherm for microporous adsorbents yields the maximum weight of solvent adsorbed at total carbon saturation and can be calculated by

$$w_s = \rho W_0 \exp\left\{\frac{-BT^2}{\beta^2}[\log (p_s/p)]^2\right\}. \quad (2)$$

where w_s = equilibrium static adsorptive capacity per unit weight carbon (gm/gm).
ρ = density of solvent (gm/cm³).
W_0 = total volume of adsorption space (cm³/gm).
B = microporosity constant for the carbon.
T = temperature (°K).
β = affinity coefficient of solvent vapor for the activated carbon.

an be calculated

(1)

cartridge breakthrough
min).
volume at the system
ature and pressure (24.1
nole at 20°C, 760 torr).
of solvent adsorbed per
of activated carbon
m).
of activated carbon

lar weight of the con-
nt (gm/mole).
rate (liters/min).
im gas concentration

n be measured or calcu-
ie weight of solvent ad-
difficult to predict, since
:tion of the nature of the
vent vapor. Therefore,
il only if the weight is
ientally. Estimations of
time can be calculated,
adsor-ion isotherm and
quati
sotherm for microporous
he maximum weight of
t total carbon saturation
ted by

$$\frac{BT^2}{\beta^2}[\log (p_s/p)]^2 \Big\} \quad (2)$$

rium static adsorptive ca-
per unit weight carbon
n).
of solvent (gm/cm³).
olume of adsorption
cm³/gm).
orosity constant for the

ature (°K).
coefficient of solvent va-
the activated carbon.

p_s = saturated vapor pressure (torr) for the solvent at temperature T.
p = equilibrium partial pressure of the solvent vapor (torr).

This adsorption isotherm holds for any microporous adsorbent and is valid only at temperatures below the critical temperature of the vapor. The W_0 and B terms are interrelated and depend only on the nature of the adsorbent. The affinity coefficient β characterizes the adsorption of a given vapor with respect to another vapor selected as a standard. Generally benzene is chosen; its β becomes 1.00 by definition. The affinity coefficient is independent of the temperature and practically independent of the porosity.

The β term can be determined experimentally or approximated by

$$\beta \sim \frac{P}{P_s} \sim \frac{v}{v_s} = \frac{\rho_s M}{M_s \rho} \quad (3)$$

where v, v_s = molar volume for the unknown and standard solvent (cm/mole).
P, P_s = parachors for the unknown

TABLE II
Cartridge Characteristics and Test Conditions Used for Calculating Weight of Solvent Adsorbed, w'_s, from Adsorption Isotherm

Parameter	Cartridge type 1	Cartridge type 2
Density, ρ (gm/cm³)	[a]	[a]
Maximum adsorption space, W_0 (cm³/gm)	0.65	0.61
Degree of porosity, B	1.0×10^{-6}	0.95×10^{-6}
Temperature, T (°K)	293	293
Affinity coefficient, β	See Tables IV and V	
Saturated vapor pressure, p_s (torr)	See Table I	
Solvent vapor pressure at 1000 ppm, p (torr)	0.76	0.76

[a]Obtained experimentally from weight and volume measurements.

TABLE III
Cartridge Characteristics and Test Conditions Used for Breakthrough Time Calculations[a] from Mecklenburg Equation

Parameter	Cartridge Type 1	Cartridge Type 2
Weight of solvent adsorbed (w'_s) per weight of activated carbon (gm/gm)	See Table I	
Carbon density, ρc (gm/cm³)	0.375	0.389
Cross-sectional area of carbon, A (cm²)	32.1	39.6
Number of cartridges tested, n	2	2
Flow rate, Q (liters/min)	53.3	53.3
External surface, a_c (cm²/gm)	45	77
Diameter of granule, d (cm)	0.165	0.117
Viscosity of air–vapor stream, η (gm/cm-sec)	1.83×10^{-4}	1.83×10^{-4}
Density of air–vapor stream, ρa (gm/cm³)	1.2×10^{-3}	1.2×10^{-3}
Breakthrough concentration, C_b (ppm)	10	10
Inlet concentration, C_I (ppm)	1000	1000
Molecular weight, M (gm/mole)	[b]	[b]
Void volume, V_v (cm³/gm)	0.42	0.38
Cartridge volume, V (cm³)	70	80
Diffusion coefficient at 25°C, D (cm²/sec)	See Table I	

[a]At 20°C and 760 torr.
[b]Obtained from the *Handbook of Chemistry and Physics.*

and standard solvent (calculated from Sugden's equation).

p, p_s = solvent density for the unknown and standard solvent (gm/cm³).

M, M_s = molecular weights for the unknown and standard solvent (gm/mole).

All the parameters needed to solve the adsorption isotherm are given in Tables I through V. Comparison of the actual experimental values of w_s are also shown in Tables IV and V. Note that the more volatile materials show the greatest deviation from the calculated values. This is due primarily to the preferential adsorption of the water vapor present. In theory, the adsorption isotherm described by equation 2 is valid only for a single vapor in air; it neglects competing adsorption by water or any other vapors. Even by expanding the adsorption isotherm to include multiple vapor systems, it is still difficult to predict to what extent highly polar materials such as

TABLE IV
Comparison of Calculated and Observed Adsorption Capacity of Type 1 Cartridges for Several Solvents[a]

Solvent	Affinity Coefficient, β	Adsorptive Capacity, w_s: Observed (gm/gm)	Adsorptive Capacity, w_s: Calculated from Equation 2 (gm/gm)	Deviation from Observed (%)
Benzene	1.00[b]	0.327	0.408	+ 25
Toluene	1.33[b]	0.473	0.507	+ 7.2
m-Xylene	1.38[c]	0.536	0.540	+ 0.7
Methanol	0.40[b]	0.018	0.048	+167
Ethanol	0.61[b]	0.168	0.251	+ 49
Propanol	0.84[d]	0.384	0.429	+ 12
n-Butanol	1.02[d]	0.512	0.495	− 3.3
n-Pentanol	1.22[d]	0.552	0.525	− 4.9
Methyl chloride	0.56[b]	0.008	0.016	+100
Ethyl chloride	0.76[b]	0.048	0.129	+169
1-Chloropropane	0.91[c]	0.196	0.293	+ 49
1-Chlorobutane	1.09[c]	0.391	0.426	+ 9.0
Chlorobenzene	1.18[c]	0.562	0.669	+ 19
Dichloromethane	0.66[b]	0.101	0.216	+114
1,2-Dichloroethane	0.90[c]	0.456	0.555	+ 22
1,4-Dichlorobutane	1.28[c]	0.755	0.720	− 4.6
o-Dichlorobenzene	1.36[c]	0.911	0.851	− 6.6
Chloroform	0.86[b]	0.415	0.518	+ 25
1,1,2-Trichloroethane	1.08[c]	0.773	0.822	+ 6.3
Carbon tetrachloride	0.96[b]	0.677	0.690	+ 1.9
Perchloroethylene	1.21[c]	1.01	0.965	− 4.5
Methyl acetate	0.89[d]	0.214	0.333	+ 56
Ethyl acetate	1.10[d]	0.350	0.442	+ 26
Propyl acetate	1.30[d]	0.507	0.513	+ 1.2
Butyl acetate	1.48[d]	0.584	0.550	− 5.8
Pentyl acetate	1.63[d]	0.616	0.577	− 6.3

[a]The equilibrium partial pressure, p, at 1000 ppm is 0.76 torr. The saturated vapor pressure, p_s, is taken from Table I.

[b]Experimental values taken from ref. 6.

[c]Calculated from parachors using Sugden's equation.

[d]Calculated from equation 3 using molar volumes.

... are also shown in ... ote that the more vola... w the greatest deviation ... ed ... es. This is due pri... efere...al adsorption of the ... esent. In theory, the ad... n described by equation 2 ... r a single vapor in air; it ... ng adsorption by water or ... s. Even by expanding the ... rm to include multiple va... still difficult to predict to ... ly polar materials such as ...

Capacity

Deviation from Observed (%)
+ 25
+ 7.2
+ 0.7
+167
+ 49
+ 12
− 3.3
− 4.9
)
+.09
+ 49
+ 9.0
+ 19
+114
+ 22
− 4.6
− 6.6
+ 25
+ 6.3
+ 1.9
− 4.5
+ 56
+ 26
+ 1.2
− 5.8
− 6.3

...orr. The satu-

water will interfere with the normal adsorption processes of organic vapors. Currently there is no satisfactory method of correction for this interference.[6,8]

As was previously mentioned, w_s is the weight adsorbed at *total* saturation—that is, at 100% breakthrough. Initial breakthrough, however, occurs long before the equilibrium adsorptive capacity is established. Nevertheless, such breakthrough times can be estimated from the Mecklenburg equation once w_s has been determined.

The Mecklenburg equation states that

$$t_b = \frac{w_s \rho_c A n}{Q C_0}\left[z + \frac{1}{a_c \rho_c}\left(\frac{dG}{n}\right)^{0.41}\left(\frac{n}{\rho_a D_{20}}\right)^{0.67} \ln(C_b/C_1)\right] \quad (4)$$

where

$$C_0 = \frac{MC_1}{24.1 \times 10^6}$$

$$G = \frac{1000 \rho_a Q V_v \rho_c}{60 A n}$$

$$z = V/A$$

$$D_{20} = 0.967 D_{25}$$

and ρ_c = carbon density (gm/cm³).
A = cross-sectional area of the adsorbent bed (cm²).
V = carbon volume (cm³).
n = number of cartridges tested.
C_0 = assault concentration (gm/liter).
z = bed depth (cm).
a_c = specific surface area (cm²/gm).
d = diameter of granule (cm).
G = mass velocity through cartridge (gm/cm²-sec).
n = viscosity of the air–gas stream (gm/cm-sec).

ρ_a = density of air-vapor stream (gm/cm³).
D = diffusion coefficient (cm²/sec).
C_b = breakthrough concentration (ppm).
C_1 = assault concentration (ppm).
V_v = void volume (cm³/gm).

Equation 4 is generally useful only for $C_b/C_1 < 0.2$—that is, for breakthroughs

TABLE V
Comparison of Calculated and Observed Adsorption Capacity of Type 2 Cartridges for Several Solvents[a]

Solvent	Affinity Coefficient, β	Adsorptive Capacity, w_s Observed (gm/gm)	Calculated from Equation 2 (gm/gm)	Deviation from Observed (%)
Acetone	0.88[b]	0.135	0.236	+75
2-Butanone	1.10[c]	0.295	0.360	+22
2-Pentanone	1.19[c]	0.483	0.427	−12
2-Heptanone	1.57[c]	0.560	0.493	−12
Pentane	1.08[b]	0.228	0.225	− 1.3
Hexane	1.295[b]	0.334	0.319	− 4.5
Heptane	1.46[b]	0.432	0.375	−13
Nonane	1.85[d]	0.490	0.434	−11
Decane	2.05[d]	0.553	0.442	−20
Methylamine	0.72[d]	0.041	0.061	+49
Ethylamine	0.91[d]	0.179	0.166	− 7.3
Butylamine	1.29[d]	0.429	0.371	−14
Dibutylamine	1.25[d]	0.480	0.466	− 2.9

[a]The equilibrium partial pressure, p, at 1000 ppm is 0.76 torr. The saturated vapor pressure, p_s, is taken from Table I.
[b]Experimental values taken from ref. 6.
[c]Calculated from equation 3 using molar volumes.
[d]Calculated from parachors using Sugden's equation.

less than 20%.

The predicted and actual breakthrough times are compared in Table VI and VII. In general, the predicted times are somewhat more optimistic than those determined experimentally. This again can be explained by water's tendency to occupy the available adsorption sites.

Tables VI and VII show conclusively that approximate breakthrough times can indeed be calculated, but only if the activiated carbon is well characterized. Approximately twenty-five variables must be known, however, before such calculations can be initiated.

There have been attempts to simplify these calculations by relating the breakthrough time or weight adsorbed directly to a single property of the solvent such as boiling point, molecular weight, vapor pressure or diffusion coefficient. These oversimplifications generally fail, however, since so many interrelated variables play a role in adsorption.

Effect of Concentration

In a preliminary investigation we varied the concentration, from 125 to 2000 ppm for

TABLE VI
Comparison of Predicted and Actual 1% Breakthrough Times, Type 1 Cartridges[a]

Material	Time Measured (min)	Calculated from Mecklenburg Equation: Using Experimental Weight Adsorbed (min)	Calculated from Mecklenburg Equation: Using Calculated Weight Adsorbed from Adsorption Isotherm (min)
Benzene	73.3	74.2	92.6
Toluene	94.3	89.1	95.5
m-Xylene	98.7	82.0	82.6
Methanol	0.2	10.9	29.1
Ethanol	28.0	67.6	101
n-Propanol	70.4	115	128
n-Butanol	115	120	116
n-Pentanol	102	104	99.2
Methyl chloride	0.05	3.0	5.9
Ethyl chloride	5.6	13.2	35.6
1-Chloropropane	24.5	43.0	64.3
1-Chlorobutane	72.3	70.8	77.1
Chlorobenzene	107	83.8	99.7
Dichloromethane	10.6	21.6	46.2
1,2-Dichloroethane	54.0	81.2	98.8
1,4-Dichlorobutane	108	96.4	91.9
o-Dichlorobenzene	109	99.6	93.0
Chloroform	33.2	61.0	76.1
1,1,2-Trichloroethane	71.8	98.7	105
Carbon tetrachloride	77.0	75.8	77.3
Perchloroethylene	107	104	99.3
Methyl acetate	32.8	51.7	80.5
Ethyl acetate	66.8	69.1	87.3
n-Propyl acetate	78.8	83.9	84.9
n-Butyl acetate	77.3	81.8	77.0
n-Pentyl acetate	72.6	74.5	69.8

[a]Test conditions; 53.3 liters/min, 50% relative humidity, and 20°C. Cartridge characteristics are summarized in Tables II and III.

...n attempts to simplify ...s by relating the break- ...wet adsorbed directly to ...y of the solvent such as boil- ...ular weight, vapor pressure, ...efficient. These oversimpli- ...lly fail, however, since so ...ed variables play a role in ...

...tration

...ary investigation we varied ..., from 125 to 2000 ppm for ...

...rough

...nburg Equation Using Calculated Weight Adsorbed from Adsorption Isotherm (min)
92.6
95.5
82.6
29.1
10*
12
116
99.2
5.9
35.6
64.3
77.1
99.7
46.2
98.8
91.9
93.0
76.1
105
77.3
99.3
80.5
87.3
84.9
77.0
69.8

...y, and 20°C. ...II.

TABLE VII
Comparison of Predicted and Actual 1% Breakthrough Times, Type 2 Cartridges

Material	Time Measured (min)	Calculated from Mecklenburg Equation: Using Experimental Weight Adsorbed (min)	Calculated from Mecklenburg Equation: Using Calculated Weight Adsorbed from Adsorption Isotherm (min)
Acetone	37.1	58.3	102
2-Butanone	81.9	101	123
2-Pentanone	104	137	121
2-Heptanone	101	116	102
n-Pentane	60.7	77.6	76.6
n-Hexane	52.3	93.7	89.5
n-Heptane	78.2	103	89.1
n-Nonane	76.2	89.4	79.2
n-Decane	70.8	90.3	72.2
Methylamine	12.4	33.6	50.0
Ethylamine	40.5	99.3	92.1
n-Butylamine	110	145	125
Di-*n*-butlyamine	75.5	86.9	84.4

*Test conditions; 53.3 liters/min, 50% relative humidity, and 20°C. Cartridge characteristics are summarized in Tables II and III.

benzene and from 50 to 2000 ppm for acetone, and measured the effect on service life. The characteristic S-shaped breakthrough curves for these solvents appear in Figures 14 and 15. Although the time to reach a given breakthrough increases as the concentration diminishes, the breakthrough time–concentration relationship is not inversely proportional as one might intuitively suspect. However, a logarithmic plot of the breakthrough time (for example, at 10%) as a function of the concentration yields the linear relationship shown in Figure 16. The resultant empirical equations for the straight lines are:

$$t_{10\ \text{percent}} = 1.4 \times 10^4 \times C_l^{-0.76} \quad \text{for benzene}$$

$$t_{10\ \text{percent}} = 1.1 \times 10^5 \times C_l^{-0.46} \quad \text{for acetone}$$

where $t_{10\ \text{percent}}$ is the time in minutes to achieve a 10% breakthrough, and C_l is the upstream assault concentration in parts per million. These results conform to the basic Freundlich equation and have been demonstrated previously by Fraust and Hermann.[9]

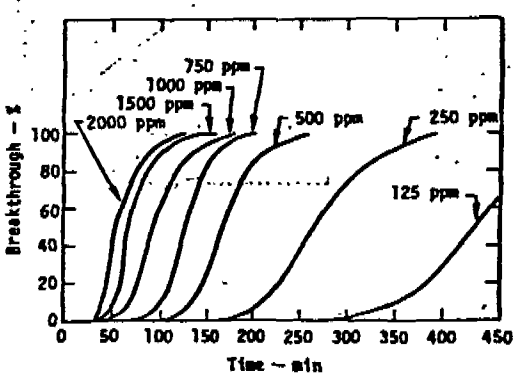


Figure 14. Breakthrough curves for type 1 cartridges, at various concentations of benzene. Each cartridge pair contained 56.6 ± 1.5 gm of activated carbon and was tested at a flow rate of 53.3 liters/min and 50% relative humidity.

Summary

We have examined the service lives of organic vapor respirator cartridges exposed to aromatics, alcohols, acetates, alkanes, ketones, amines, and chlorinated materials. We assaulted the cartridges under standardized conditions and monitored the downstream concentration to cartridge saturation. The standard test conditions included a sol-

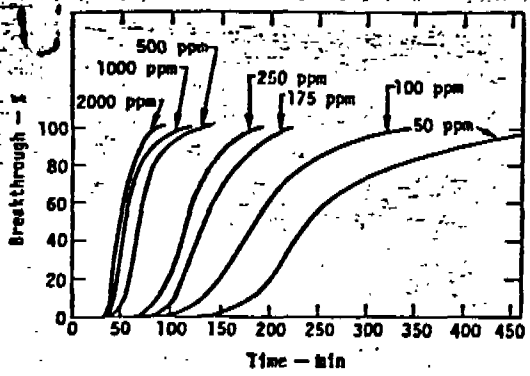


Figure 15. Breakthrough curves for type 2 cartridges at various concentrations of acetone. Each cartridge pair contained 60.5 ± 2.9 gm of activated carbon and was tested at a flow rate of 53.3 liters/min and 50% relative humidity.

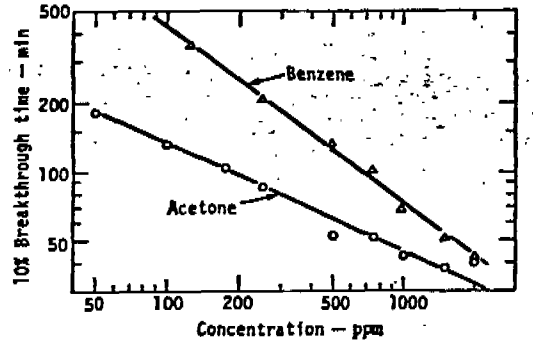


Figure 16. The 10% breakthrough time as a function of concentration for benzene and acetone.

vent concentration of 1000 ppm, 50% relative humidity, and a flow of 53.3 liters/min.

Measured breakthrough times agreed reasonably with calculated values obtained from the adsorption isotherm and Mecklenburg equation. In general, the activated carbon has a greater affinity for the less volatile materials.

The relative humidity greatly influences the amount of solvent vapor adsorbed, significantly decreasing the activated carbon's affinity for volatile or water-soluble solvents.

A brief investigation showed that the effect of concentration on breakthrough time conforms to the basic Freundlich equation.

References

1. Ruch, W. E., G. O. Nelson, C. L. Lindeken, R. E. Johnsen, and D. J. Hodgkins: Respirator Cartridge Efficiency Studies: I. Experimental Design, *Amer. Ind. Hyg. Ass. J. 33:* 105 (1972).
2. Nelson, G. O., and D. H. Hodgkins: Respirator Cartridge Efficiency Studies: II. Preparation of Test Atmospheres. *Amer. Ind. Hyg. Ass. J. 33:*110 (1972).
3. Nelson, G. O., R. E. Johnsen, C. L. Lindeken, and R. D. Taylor: Respirator Cartridge Efficiency Studies: III. A Mechanical Breathing Machine to Simulate Human Respiration. *Amer. Ind. Hyg. Ass. J. 33:745* (1972).
4. Nelson, G. O., and C. A. Harder: Respirator Cartridge Efficiency Studies: IV. Effects of Steady-State and Pulsating Flow. *Amer. Ind. Hyg. Ass. J. 33:*797 (1972).
5. Smisek, M., and S. Cerny: *Active Carbon*, pp. 133-135, Elsevier, New York (1970).
6. Freedman, R. W., B. I. Ferber, and A. M. Hartstein: Service Lives of Respirator Cartridges Versus Several Classes of Organic Vapors. *Amer. Ind. Hyg. Ass. J. 34:*55 (1973).
7. Perry, J. H.-(ed.): *Chemical Engineers' Handbook*, 3rd ed. pp. 538-539, McGraw-Hill, New York (1950).
8. Walker, P. L. (ed.): *Chemistry and Physics of Carbon*, pp. 115-116, Dekker, New York (1966).
9. Fraust, C. L., and E. R. Hermann: The Adsorption of Aliphatic Acetate Vapors onto Activated Carbon. *Amer. Ind. Hyg. Ass. J. 30:* 494 (1969).

Short Course

The annual *Short Course in Fundamentals of Industrial Hygiene* will be presented at the Kettering Laboratory, University of Cincinnati, from October 14-27, 1974. The course, half lecture-half laboratory, will be conducted by the graduate faculty of the Department of Environmental Health. The class will be limited to 20 participants, and the course fee is $600. For information contact Howard Ayer, Kettering Laboratory, 3223 Eden Avenue, Cincinnati, Ohio 45219. (513) 872-5708.