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Permeation of Polychlorinated Biphenyls and Solutions of These Substances Through Selected Protective Clothing Materials*

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Polychlorinated biphenyls (PCBs) have been used in a number of applications, particularly in the electric power industry. While these materials are no longer manufactured in the United States, they still exist in the field. Because of the hazardous nature of these compounds, effective chemical protective clothing is required. The permeation of neat PCBs, and solutions with trichlorobenzene and paraffin oil, through 11 different protective garment materials was determined. These experiments were done both with a permeation cell with water collection medium, and by periodically swiping thumb cots which contained the challenge liquids. Contamination was a continuing problem because of the resinous, nonvolatile properties of PCBs. While the results from the two methods were not identical, they did agree qualitatively. The best protection against PCBs was provided by nitrile, Viton, Viton SF and Vitrile. While the results with PVA and Teflon were also very good, these materials have other characteristics which may make their use suspect. For most of the other materials, the performance depended on the challenge liquid. The weight and volume changes which occurred when the materials were soaked in the challenge liquids were determined. The volume changes of 80 percent of those challenge/material combinations which exhibited breakthrough correlated with the breakthrough times normalized to the square of the material thickness.

Introduction

For years, polychlorinated biphenyls (PCBs) were manufactured for use in various electrical components, primarily capacitors and transformers, as fluids in heat transfer and hydraulic systems, and for plasticizer use. It has been estimated that roughly 1.25 billion pounds of PCBs have been used by United States Industry, about 60 percent of which are still in service with 290 million pounds in landfills and dumps.[1] Because of their toxic properties, these materials are no longer manufactured in the United States. However, personnel can still be exposed to them during routine maintenance, repair, disposal, or spill clean-up. Not only were the neat (not purposely diluted with another component) PCBs used, but also solutions in various diluents, notably trichlorobenzene and paraffin oil.

Both direct skin contact and inhalation of PCBs should be avoided. Because of the very low vapor pressure of these compounds,[2] skin contact could be the major route of entry into the body. This results in a need for clothing which will adequately protect the worker. To this end, experiments were conducted to determine the permeation of representative PCBs, and solutions of PCBs, through selected garment materials.

The principal PCB studied was Aroclor 1254. Aroclor is the trademark for Monsanto-produced PCBs. This material is not a single compound but a mixture of biphenyl molecules with varying numbers of chlorine atoms, as are all commercially-prepared PCBs. Aroclor 1254 is 54 weight/percent (w/o) chlorine, which would correspond to the pure pentachlorinated biphenyl. In actuality, a gas chromatograph/mass spectrometric analysis showed more than 20 components which were present in greater than 1 percent concentration, and 45 components with concentrations greater than 0.2 percent.

Pertinent properties of the Aroclor 1254 are: sticky, resinous liquid with a pour point of 10°C;[3] solubility in water, 12 - 70 μg/L;[2,4] vapor pressure at 25°C, 7.7×10^{-5} torr (1.0×10^{-2} Pa).[2] These properties make the two most common permeation test methods difficult to use. These methods utilize a permeation test cell in which the material to be tested is clamped in the center and the challenge substance is added to one side. The collection side of the cell contains either an aqueous, perspiration simulant, or a flowing gas stream. In both cases, the permeant is removed (either by dissolving in the aqueous phase or vaporizing into the gas stream) and analyzed.

A third method is to mechanically remove the permeant at periodic time intervals by wiping the membrane with a swipe moistened with a solvent in which the permeant is soluble. The swipe is then analyzed for what was removed. There are two difficulties with this approach. First, the amount of solvent which can be used is limited so as to minimize any possible interaction between the solvent and membrane. By limiting this amount, it is difficult to remove all challenge which has permeated, particularly with resinous substances. Second, breakthrough may never be detected if the analytical sensitivity is inadequate and all permeant is removed with each

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swipe, frequent swipes are taken, and the permeation rate is low. This problem can be minimized if infrequent swipes are taken. However, in any one experiment this decreases the accuracy with which breakthrough time can be defined. This latter difficulty is also true for gas collection methods in which a flowing gas stream is passed through a vapor sorbent which is then periodically analyzed.

Two independent methods were used to evaluate eleven garment materials. The first method used a permeation cell with a two-phase collection medium; water with an immiscible layer of isooctane on the surface. As in some experiments there was evidence that not all the Aroclor which permeated the membrane desorbed into the water, so a second method was adopted. This procedure utilized thumb cots, which contained the challenge liquid, the outsides of which were swiped at specified time intervals. The weight and volume changes which occurred when the materials were soaked in the challenge liquids were also determined. These tests were performed to determine whether they might be adequate for preliminary screening of protective garment materials.

Experimental

General

Seven liquids were selected to challenge 11 different protective garment materials. Table I shows the number of different garment materials which were tested with each challenge/test combination. Three neat liquids were used; trichlorobenzene (TCB), Aroclor 1254 (1254), and paraffin oil (PO). Four solutions were also tested: Aroclor 1254 with TCB, and three different concentrations of 1254 in paraffin oil. With the neat PO, only immersion tests were conducted.

Two types of permeation testing were conducted; one used a permeation cell and the other thumb cots. For all permeation tests, at least two replicate experiments were carried out. These tests lasted 24 hrs, or until breakthrough was clearly established. With the 1254/PO solutions, permeation tests were run with only those materials for which breakthrough was detected with the solution of next higher concentration. For the immersion tests no weight changes were determined with the neat Aroclor because the liquid is so resinous that the surfaces of the samples could not be cleaned of excess Aroclor after soaking. No weight or volume changes were determined for Saranex-laminated Tyvek because the Tyvek layer of the laminate (which affords little permeation resistance) soaked up the liquids, making the weight change measurements meaningless, while at the same time the laminates separated, making the volume measurements worthless. Weight and volume change experiments lasted a minimum of 24 hrs.

The 11 materials which were tested are shown in Table II. For most tests done with the permeation cell, the samples were cut from the palm or gauntlet of the glove. The Teflon samples were taken from the thumb. For the Saranex-laminated Tyvek, for which no gloves were available, pieces were cut from a sheet of the material. The thumb cots were thumbs cut off gloves, except for the Saranex-laminated Tyvek from which small bags were fabricated.

TABLE II
Materials Tested

Material	Measured Thickness (cm)	Supplier
Surgical Rubber	0.023	Los Alamos National Laboratory Stock
Butyl Rubber	0.038	Norton Company
Polyethylene	0.003	Edmont
Polyvinyl Alcohol	0.046	Edmont
Saranex-laminated Tyvek	0.015	DuPont
Neoprene	0.043	Edmont
Milled Nitrile	0.030	Surety Rubber
Viton	0.023	Norton Company
Viton SF	0.023	Norton Company
Vitrile	0.020	Norton Company
Teflon (Crumpled)	0.005	Clean Room Products

TABLE I
Number of Different Garment Materials Tested

Challenge Liquid	Permeation Tests		Immersion Tests	
	Permeation Cell	Thumb Cot	Weight	Volume
Trichlorobenzene	11		10	10
Aroclor 1254	11	11		10
58 v/o[A] Aroclor 1254 42 v/o Trichlorobenzene		11	10	10
Paraffin Oil			11	11
5000 ppm Aroclor 1254 in Paraffin Oil	11	11	10	10
2000 ppm Aroclor 1254 in Paraffin Oil		5	4	4
100 ppm Aroclor 1254 in Paraffin Oil		4	3	3

[A]v/o = volume/percent.

Permeation Tests

For tests with the permeation cell, the material samples were clamped in the middle of the cell which was then placed in a 23° C constant temperature bath. A schematic of this cell is shown in Figure 1.[5] One hundred mL of water was added to the right half of the cell and 100 mL of the challenge liquid to the left. The water was stirred with a magnetic stirrer. Because of the very low solubility of Aroclor in water, 40 mL of isooctane was floated on the surface. The purpose of this was to extract any Aroclor that permeated the sample and then dissolved in the water. A 5 mL aliquot of the isooctane was taken and analyzed at set time intervals. Samples were normally taken at 1, 3, 5, 10, 15, 30, and 45 min, and 1, 1-1/2, 2, 2-1/2, 3, 3-1/2, 4, 5, 6, 7, 8, and 24 hrs. A sample was usually taken at time zero, before the challenge was added, to check for contamination. Five mL of isooctane were added to the cell immediately after each sample was taken to maintain 40 mL in the cell. Except for the neat TCB experiments, analyses of the isooctane solutions were by gas chromatography with an electron capture detector and a 1.5 percent SP-2250/ 1.95 percent SP-2401 column. The column was operated isothermally at 250° C except for the Aroclor/ TCB solutions when it was operated at 210° C for 1 min and then heated to 250° C. The neat TCB analyses were by ultraviolet spectrophotometry using the peak at 288 nm for quantitation.

In some of the tests with neat Aroclor 1254, a foreign, sticky substance was noted on the downstream sides of the membranes when the cells were disassembled after 24 hrs. This sometimes occurred when there was little or no Aroclor detected in the isooctane. For instance, in the case of one nitrile sample, a small spot was noted. This spot was cleaned with a Kimwipe moistened with isooctane. The Kimwipe was extracted with isooctane which was then analyzed. The results showed 100 μg of Aroclor 1254 on the swipe while the isooctane layer had contained less than 15 μg.

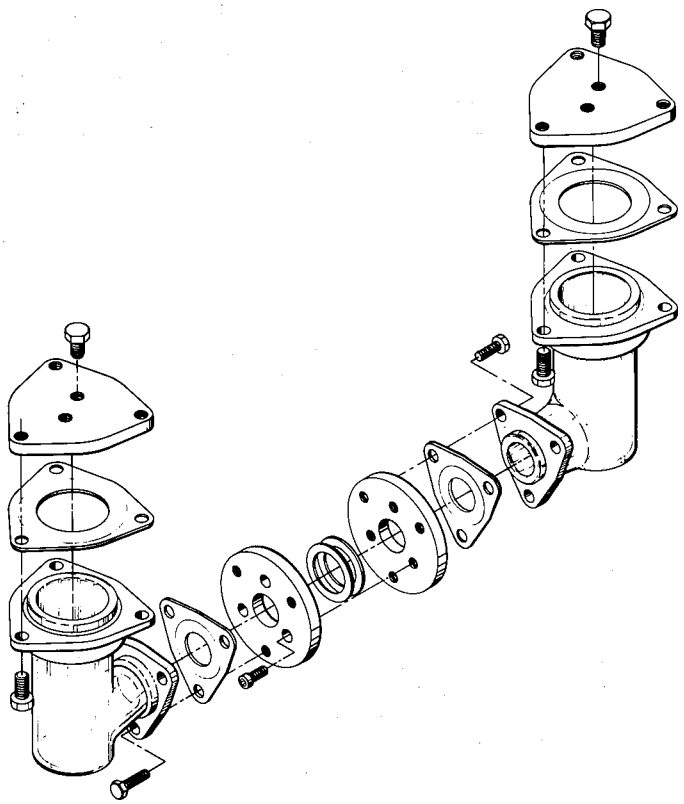

Figure 1 — Permeation test cell.

TABLE III
Permeation of Neat Aroclor 1254 Through Surgical Rubber

	mg Aroclor 1254 Permeated/m^2	
Time (Min)	Permeation Cell	Thumb Cot[A]
0	180[B]	<3
3	90	50
5	1300	
10	1800	
15	3400	
30	28 000	
45	>30 000	
60		90
180		1260
300		2100
420		5400
480		8100
1440		12 000
Approximate Permeation Rate: mg/min/m^2	1000	15

[A]Cumulative sums of successive swipes.

[B]Suspected contamination.

Because of these indications that not all the Aroclor that permeated was reaching the isooctane, a modification of an old permeation test method was adopted. Thumbs were cut off gloves, hung on a line, and a few mL of challenge liquid put in each. Periodically, the outsides were swiped with a Kimwipe moistened with isooctane which was then analyzed for what had been removed. Small pouches were fabricated from the Saranex-laminated Tyvek. Swipes were usually taken at 0 and 5 min, then hourly to 8 hrs, and a final one at 24 hrs.

Immersion Tests

For the weight and volume change tests, material samples were placed in 100 mL beakers with sufficient liquid to com-

TABLE IV
Permeation of Aroclor 1254 from 5000 ppm Solution in Paraffin Oil Through Surgical Rubber

	mg Aroclor 1254 Permeated/m^2	
Time (Min)	Permeation Cell	Thumb Cot[A]
0	<15	<3
5	<15	<3
30	<15	
60	<15	3
180	<15	30
300	<15	60
420		170
480	<15	210
1440	<15	290

[A]Cumulative sums of successive swipes.

pletely cover them. For the weight change tests, either the material from a single glove or the maximum amount which would conveniently fit in the beaker was used. These samples, weighed to the closest 0.1 gm, ranged from 3 gms of polyethylene to greater than 10 gms. After a specified length of time, usually 1, 2, and 7 days, the specimens were removed, patted dry, and reweighed. For the volume change tests, 1.00 ± 0.02 in. (2.54 ± 0.05 cm) squares were cut. The thickness was measured to the nearest 0.001 in. (0.003 cm). These samples were removed and remeasured at 1, 4, 24, and 48 hrs.

Results and Discussion

Permeation Test Results

As examples of the results, Tables III and IV show the data for surgical rubber with the neat 1254 and the 5000 ppm solution of 1254 in PO. Data from both the permeation cells and thumb cots are included. These data are shown only to illustrate the problems which were encountered; contamination and differences in the results from the two test methods. The results are the calculated total amounts of the 1254 which would have permeated 1 m^2 of the material at the times shown. For the permeation cell, these values are readily calculated from the concentrations found in the isooctane, corrected for the dilution which takes place when the 5 mL of isooctane which is sampled is replaced. With the thumb cots, it is assumed that all the Aroclor is removed with each swipe so that the total amount which had permeated is the cumulative sum of all swipes taken to that time.

The numbers noted in the first row (time 0) are the results of the analyses of either the isooctane or swipe taken before the challenge was added. The value listed for the permeation cell in Table III was due to contamination. Because of the very viscous, resinous nature of this PCB, it is exceedingly difficult to remove all traces from anything with which it has come into contact. Any spill invariably leaves some behind, even after vigorous cleaning attempts. Finally, even though the vapor pressure is low, it still appears in all sorts of unlikely places. After trying a number of different cleaning procedures, the final method adopted was: rinse the glassware in very hot water, scrub twice with RBS (a proprietary, basic detergent from Pierce Chemical Co.), each followed by a water rinse, an isooctane rinse, and finally heating to 400°C overnight. However, even with this cleaning procedure, it was these contamination problems which dictated our lower reported level, rather than the analytical sensitivity. In general, concentrations of 0.1 - 0.2 ppm (v) in the actual solutions analyzed were considered to be contamination.

Previous work from this laboratory[6] indicated that for many materials, Aroclor breakthroughs were more rapid than we report here. We believe this discrepancy is primarily due to the unsuspected presence of contamination in the earlier work. Another possible reason for the discrepant results is that ultraviolet spectrophotometry was the analytical method used in the earlier work. This method has lower sensitivity and cannot differentiate between the Aroclor and TCB as well as the gas chromatography method used in this study.

Referring again to Table III, while breakthrough had occurred by 5 minutes in both tests, the rates of permeation were considerably different. This difference may be due to the difficulty of removing all the 1254 with a swipe. In Table IV, which shows the permeation data for the 1254 from the 5000 ppm solution in PO, the breakthrough results are quite different. In this case the cell showed no breakthrough in 24 hrs while the thumb cots exhibited breakthrough in 60 minutes. This may be explained by the 1254 not desorbing from the membrane.

Based on these data it appears that reliable permeation rates could not be obtained from either test method, nor could breakthrough always be seen with the permeation cell. However, breakthrough should have been detected with the thumb cots even though all the 1254 which had permeated might not have been removed with each swipe. Therefore, it

TABLE V
Breakthrough Times for Neat 1254, TCB, and 1254/TCB Solutions

Material	Measured Thickness (cm)	Challenge Liquids Breakthrough Time - min. Neat 1254[A]	Neat TCB[B]	58% 1254/42% TCB 1254[A]	58% 1254/42% TCB TCB[A]
Surgical Rubber	0.023	5, 60	5, 5	5, 5	5, 5
Butyl Rubber	0.038	1440, N	5, 5	360, 420	180, 240
Polyethylene	0.003	60, 60	10, 10	5, 5	5, 5
Polyvinyl Alcohol	0.046	N, N	60, 60	N, N	N, N
Saranex-laminated Tyvek	0.015	360, 420, 420	60, 60	420, 420	180, 360
Neoprene	0.043	1440, 1440, N, N	60, 60(?)	240, 300	120, 180
Milled Nitrile	0.030	N, N, N, N	240, 300	N, N	480(?), N
Viton	0.023	N, N, N	10, 10	N, N	420(?), N
Viton SF	0.023	N, N, N	1440, 1440	N, N	N, N
Vitrile	0.020	N, N	N, N	1440, N	N, N
Teflon (Flexed)	0.005	N, N, N	60, 480	N, N	N, N

[A]Thumb cot experiments. Gas chromatography analysis with lower detectable limit of 6 mg/m^2.

[B]Permeation cell experiments. Ultraviolet spectrophotometry analysis with lower detectable limit of 150 mg/m^2.

(?) Breakthrough indication not definite.

is primarily the thumb cot breakthrough time data which are discussed in the remainder of the article. These times are listed in Tables V and VI. Data for the neat TCB, obtained from permeation cell experiments, are also shown in Table V. "N" signifies no breakthrough was detected in 24 hrs. A question mark following a time denotes there is a question as to whether or not breakthrough actually occurred because the small amounts of 1254 measured could have been due to contamination.

Most of the materials studied would have provided protection against the neat 1254 for a number of hours (Table V). Only two of the 11 exhibited breakthrough in less than 6 hrs. The data for the 1254/TCB solution show that the TCB appears to promote the 1254 permeation in some cases (surgical and butyl rubber, polyethylene, and neoprene) while there is no evidence for any permeation inhibition. In light of the neat TCB data which show rapid permeation (only two materials with breakthrough times greater than 5 hrs), this may not be surprising. We believe that the markedly different results with the two Teflon samples were due to physical defects rather than a chemical property of the material. These defects were caused by flexing the material samples before testing, as might happen when a garment is worn.

Because of the apparent effect of TCB on 1254 permeation, application of these data to select a garment material for use with a 1254/TCB solution should be restricted to cases in which the TCB concentrations are less than about 42 percent.

A similar comparison of the effect of PO on 1254 permeation is not as straightforward. Table VI shows the breakthrough times for the 1254 from the three PO solutions and the neat 1254. At first glance, it appears the PO decreased the permeation and increased the breakthrough time. In all cases these times were longer with the solutions than with the neat liqud and increased, if anything, as the solutions became more dilute. However, even the most concentrated of these solutions, 5000 ppm (0.5 percent), is still quite dilute. In general, the rate of permeation of any component of a solution will decrease as the concentration of that substance decreases, although this is not always the case.[7] While another component may enhance this permeation, when the solution becomes sufficiently dilute, the rate will be less than for the neat component. Because of this, even though the PO may enhance the permeation of the 1254, it is impossible to differentiate between the dilution factor and any effects which might be caused by the PO.

Weight and Volume Screening Tests

Because permeation follows the absorption of a challenge in a polymer, there should be a correlation between the amount absorbed and the breakthrough time. The percentage weight gain a polymer exhibits when it is soaked in the liquid is a measure of this absorption. Also, because polymers usually swell during this process, the percent increase in volume is also a measure of the absorption, albeit not as direct as weight gain. Theoretically,[8] breakthrough time is inversely proportional to the square of the membrane thickness for challenge/polymer systems which exhibit constant diffusion coefficients. Thus there is the possibility for a simple screening test to determine the relative breakthrough times for different materials with the same challenge liquid.

Table VII compares the average normalized breakthrough times from the thumb cot experiments with the 24-hr percent weight changes for the neat 1254, and the weight and volume changes for the 1254/TCB and PO solutions. The normalized breakthrough time is the observed breakthrough time divided by the square of the polymer thickness. Only those materials are shown which exhibited either breakthrough, or weight or volume changes exceeding 2 percent. As noted earlier, weight and volume change experiments were not conducted with the Saranex-laminated Tyvek. From this tabulation it can be seen that, in general, as the weight or volume changes decrease, the breakthrough times increase. This correlation is more clearly seen in Figure 2 which is the log of the normalized breakthrough time (t_B/l^2) plotted

TABLE VI
Breakthrough Times for Neat 1254 and Paraffin Oil Solutions — Thumb Cots

Material	Measured Thickness (cm)	Challenge Liquids Breakthrough Time - Min. Neat 1254	5000 ppm 1254	2000 ppm 1254	100 ppm
Surgical Rubber	0.023	5, 60	120, 120	180, 240	1440(?), N
Butyl Rubber	0.038	N, 1440	N, N	N, N	N, N
Polyethylene	0.003	60, 60	360(?), 360(?)	1440(?), N	N, N, N
Polyvinyl Alcohol	0.046	N, N	N, N	N, N	N, N
Saranex-laminated Tyvek	0.015	360, 420, 420	1440, 1440	1440(?), N	N, N, N
Neoprene	0.043	1440, 1440, N, N	N, N	N, N	N.R
Milled Nitrile	0.030	N, N, N, N	N, N	N, N	N.R
Viton	0.023	N, N, N	N, N	N.R	N.R
Viton SF	0.023	N, N, N	N, N	N.R	N.R
Vitrile	0.020	N, N	N, N	N.R	N.R
Teflon (Flexed)	0.005	N, N, N	N, N	N.R	N.R

N - Less than or equal to 6 mg/m^2 at 1440 min.

? - Breakthrough indication not definite.

N.R - Experiment not conducted because no breakthrough was detected at next higher concentration.

TABLE VII
Comparison of Breakthrough Times and 24-Hour Weight and Volume Changes (Thumb Cots)

Material	Nominal Thickness (cm)	Breakthrough Time		Change at 24 Hrs	
		min	Normalized min/cm^2	Weight Percent	Volume Percent
Neat Aroclor 1254[A]					
Surgical Rubber	(0.023)	30	6×10^4		200
Neoprene	(0.043)	1440	8×10^5		10
Polyethylene	(0.003)	60	9×10^6		35
Butyl Rubber	(0.038)				14
Polyvinyl Alcohol	(0.046)				4
1254/TCB Solution					
Surgical Rubber	(0.023)	5	1×10^4	480	460
Neoprene	(0.043)	270	1×10^5	330	270
Butyl Rubber	(0.038)	300	2×10^5	75	110
Polyethylene	(0.003)	5	8×10^5	7	6
Vitrile	(0.020)	1440	3×10^6	30	50
Nitrile	(0.038)			80	110
5000 ppm Aroclor 1254 in Paraffin Oil					
Surgical Rubber	(0.023)	120	2×10^5	170	140
Polyethylene	(0.003)	360	6×10^7	15	35
Butyl Rubber	(0.038)			25	25
Neoprene	(0.043)			5	0
2000 ppm Aroclor 1254 in Paraffin Oil					
Surgical Rubber	(0.023)	180	3×10^5	150	190
Polyethylene	(0.003)	1440	2×10^8	7	6
Butyl Rubber	(0.038)			22	30
Nitrile	(0.030)			<2	4
100 ppm Aroclor 1254 in Paraffin Oil					
Surgical Rubber	(0.023)			144	190
Polyethylene	(0.003)			23	33
Butyl Rubber	(0.038)			7	6

[A]No weight change data with neat Aroclor 1254.

against the log of the percent volume change for those tests in which breakthrough occurred. As can be seen, a moderately good correlation exists for 80 percent of the data points. Only the neoprene/1254 and polyethylene/(1254/TCB) data points are exceptions. With the dilute PO solution, the weight and volume changes are caused primarily by the PO, so it is not surprising that detectable breakthrough does not always occur in such cases. These data indicate that weight and volume change screening tests can be useful when choosing appropriate garment materials. Although they should be used only for preliminary screening, they will usually detect materials with poor permeation resistance for a given challenge. In a number of cases no breakthrough was detected, although measurable weight and/or volume changes were measured. While this might cause a prospective garment to be removed from further consideration, this would at least err on the safe side.

Conclusions

Three problems, all associated with the Aroclor 1254, were encountered in this work: (1) very low solubility in water, (2) resinous consistency making its removal with a swipe difficult, and (3) low level contamination. Because of the low water solubility with the permeation cell, breakthrough may not always have been detected and calculated permeation rates are suspect. With the thumb cots, breakthrough should have been noted; but, if all the 1254 was not removed with each swipe, again accurate rates cannot be calculated. Because of these problems, we have discussed primarily data on the thumb cot breakthrough times. The contamination placed a lower limit of about 6 mg/m^2 on the sensitivity of the breakthrough determination.

Inspection of the results indicate the materials can be divided into three categories. The first, "best," category are those materials which exhibited no breakthrough at 8 hrs and should provide adequate protection for at least half a normal work day, assuming no physical damage to the garment. At the other extreme is the "poor" category, those materials which probably should not be used with a given challenge. In this category, breakthrough times of 3 hrs or less were noted. The remaining category, "good," includes those which broke through between 3 and 8 hrs. These

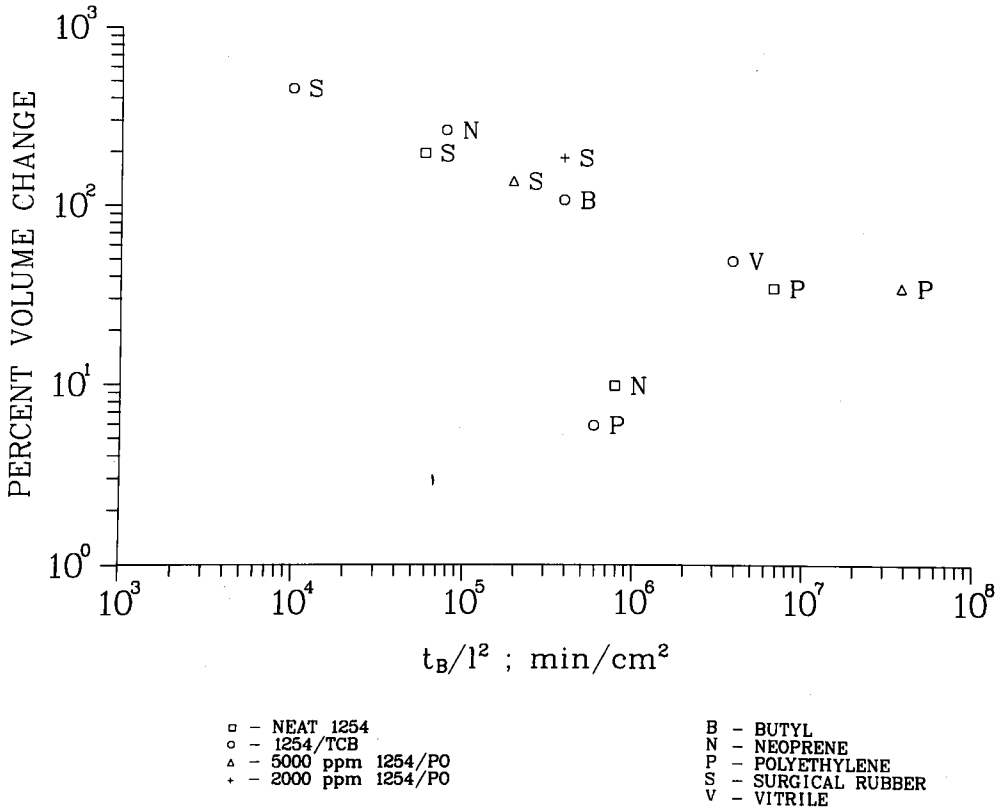

Figure 2 — Percent volume change versus normalized breakthrough time.

materials might be used for short periods but should be discarded after no more than 3 hrs use. Once PCBs come in contact with a material, they will stay there for considerable periods of time because of their low vapor pressures. As permeation can take place anytime the liquid is in contact, the times noted above are from first contact with the challenge. Cleaning and reuse of gloves is not recommended because of the very great difficulty of removing the PCBs from any surface.

These material categories are shown in Table VIII. Viton, Viton SF, Vitrile, and nitrile appear in the "best" category for all challenges. Although Teflon exhibited negligible breakthrough, it is not in this category because when it is flexed, as it would be when worn, permeation sometimes takes place. We believe this is due primarily to physical defects which flexing produces rather than a chemical property of Teflon itself. Polyvinyl alcohol (PVA) is in the "poor" category because in some cases it appears the permeation resistance is degraded by contact with water, such as the perspiration which occurs in gloves. It might be practical to wear PVA over another material impervious to water, possibly surgical rubber, to protect the PVA from this moisture. Butyl rubber is not suggested for use with 1254/TCB solutions because in permeation cell tests it exhibited breakthrough in less than 30 min. In the thumb cot experiments, breakthrough was first detected at 6 hrs.

Although the categories of Table VIII are listed only for Aroclor 1254, 58 percent 1254/42 percent TCB, and the 5000 ppm 1254 in paraffin oil solution, they should apply to higher molecular weight PCBs because permeation should decrease with increasing weight. They may also be applicable to slightly lower weight PCBs, although we have no data to prove this. These categories should also be valid for TCB solutions of higher PCB concentrations and paraffin oil solutions of lower PCB concentration.

A caveat concerning these recommendations needs to be explicitly stated. They are based on the results obtained with specific materials. As breakthrough time is theoretically proportional to the square of the material thickness, thinner materials will afford less protection. Also, materials from different manufacturers, and even different batches from the same manufacturer, may exhibit different permeation behavior even though they are nominally the same material. Finally, these recommendations are independent of possible defects in the materials. For instance, we noticed what we believed to be defects with both butyl and Saranex-laminated Tyvek, and possibly nitrile. Also, in one Teflon and one polyethylene thumb cot, penetration appeared to occur through a seam.

While materials with the longest breakthrough times are listed in the "Best" category, garments of these materials may not necessarily be the most appropriate for a given use situation. The data on which these categories are based were obtained under the most severe challenge conditions — continuous exposure. If protection against accidental exposure only is required, materials with shorter breakthrough times could be used. The garments would then be discarded after the exposure occurred. Garments which would not be expected to give protection for a full work period might be considered if they were replaced at safe time intervals during

TABLE VIII
Material Selection Guide Based on Thumb Cot Breakthrough Times

Challenge Liquid	Aroclor 1254	58% Aroclor 1254 42% Trichlorobenzene	5000 ppm Aroclor 1254 in Paraffin Oil
Best	Vitrile Viton Viton SF Butyl Nitrile Neoprene	Viton Viton SF Nitrile Vitrile	Vitrile Neoprene Viton Viton SF Nitrile Saranex-laminated Tyvek Butyl
Good	Saranex-laminated Tyvek Teflon	Neoprene Saranex-laminated Tyvek Teflon	Polyethylene Teflon
Poor	Polyvinyl Alcohol Polyethylene Surgical Rubber	Polyvinyl Alcohol Butyl[A] Polyethlene Surgical Rubber	Polyvinyl Alcohol Surgical Rubber

[A]Based on permeation cell experiments.

that period. Mechanical properties, such as strength, tear resistance, or flexibility, may also be important factors.

The weight and volume change measurements appear to offer credible preliminary screening tests. Although the correlations with breakthrough times were not perfect, those materials with large increases usually exhibited little protection. Conversely, those which increased little or not at all showed good protection. Either weight or volume measurements could be used for this screening. As a practical matter, weight measurements are easier to make, but nonvolatile, resinous liquids, such as Aroclor 1254, are difficult to remove. For example, a 7-gm Teflon sample, which was only briefly dipped in 1254, apparently gained 10 gms even after vigorous cleaning attempts. For such challenges, volume change measurements should be made. Finally, both these tests are only for preliminary screening. Materials which show large increases can probably be ignored for further testing. Those which show little or no change should undergo further testing before a firm recommendation is made.

While the results from these permeation cell and thumb cot experiments agree qualitatively, neither method supplies quantitative results. We believe these same problems are likely to occur in any permeation testing with nonvolatile, sparingly water soluble compounds. In many cases a method which collects the permeant vapor can be used. However, the maximum permeation rate which can be determined is limited by the rate at which the permeant vaporizes. Thus, if the vaporization rate is low, only low permeation rates can be obtained. Since protection is needed against materials with these characteristics, different testing or analytical methods are needed for these cases.

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