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Carbon tetrachloride has been used for years as the standard compound for evaluating the adsorption capacity of charcoal. The National Institute for Occupational Safety and Health is mandated under 42 CFR 84 to test organic vapor/gas cartridge and canister breakthrough characteristics against carbon tetrachloride. However, due to carbon tetrachloride's toxicity and potential lack of commercial availability, a substitute test agent is desirable. Screening tests employing ethyl acetate, pentane, *n*-hexane, and heptane have been completed and published on negative-pressure organic vapor respirator cartridges. Two test conditions (550 ppm pentane and 1000 ppm *n*-hexane) were selected for limited side-by-side testing with the 42 CFR 84 test criterion of 1000 ppm carbon tetrachloride. This article presents previously unpublished cartridge breakthrough time data on negative-pressure and powered air-purifying respirator organic vapor cartridges. The data were generated to establish a correlation between possible substitute test agents and carbon tetrachloride. Reproducibility data not previously reported are also presented. The results show that both pentane and *n*-hexane are potential replacement compounds for carbon tetrachloride. Additional work with less-adsorbent charcoals still needs to be performed. MOYER, E.S.; CALVERT, C.; WASSELL, J.T.; KULCZYCKI, G.W.: CORRELATION AND REPRODUCIBILITY DATA ON A REPLACEMENT AGENT FOR CARBON TETRACHLORIDE TESTING OF ORGANIC VAPOR. APPL. OCCUP. ENVIRON. HYG. 12(4):271–277; 1997. © 1997 AIH.

The National Institute for Occupational Safety and Health (NIOSH) has been conducting research to find a suitable replacement substance for carbon tetrachloride in evaluating organic vapor and gas cartridges[(1)] and canisters.[(2)] This research was expedited because carbon tetrachloride is required by the Environmental Protection Agency proposal to conform its stratospheric ozone protection regulations [Title 40, Code of Federal Regulations (CFR), Part 82 (40 CFR 82)] to the requirements of Title VI of the Clean Air Act Amendments of 1990 (PL 101-549). This action has affected the supplies of carbon tetrachloride by immediately limiting production and perhaps ultimately causing it to be phased out of production.

Occupational health guidelines[(3)] for various chemical substances have been prepared and published by NIOSH and the Occupational Safety and Health Administration. As part of the carbon tetrachloride guidelines, a special note indicates that the International Agency for Research on Cancer evaluated the data on carbon tetrachloride and concluded that it causes cancer. The NIOSH *Pocket Guide to Chemical Hazards*[(4)] labels carbon tetrachloride as a potential occupational carcinogen. The American Conference of Governmental Industrial Hygienists 1991–1992 booklet of threshold limit values[(5)] lists carbon tetrachloride with an A3 designation, which indicates a chemical substance that "is carcinogenic in experimental animals at a relatively high dose, by route(s) of administration, at site(s), of histologic type(s), or by mechanism(s) that are not considered relevant to worker exposure."

Availability and toxicity of carbon tetrachloride mandate the identification of a suitable replacement agent for carbon tetrachloride in evaluating organic vapor and gas cartridges and canisters. The evaluation consists of measuring the time (breakthrough time, $t_b$) that an organic vapor cartridge can maintain the downstream exit concentration below a set level when challenged with a known challenge concentration. Previous screening data[(1,2)] were reported on four potential replacement agents (ethyl acetate, pentane, *n*-hexane, and heptane) for negative-pressure air-purifying organic vapor cartridges and chin-style canisters. This article presents previously unpublished cartridge breakthrough time ($t_b$) data on negative-pressure and powered air-purifying respirator (PAPR) organic vapor cartridges. Correlation data between carbon tetrachloride and the two most promising substitute test agents (*n*-hexane and pentane) are presented. Breakthrough time is the sole critical criterion for determining equivalence of the alternative agents with carbon tetrachloride. Additional studies were conducted to determine if the test results were reproducible.

## Background

Carbon tetrachloride has been used for years as a standard material for evaluating charcoal's ability to adsorb organic materials. It has also been the standard organic compound for testing organic vapor breakthrough characteristics of respirator cartridges and canisters because it is water immiscible and shows a prominent diminished adsorption effect at high water vapor concentrations. The Code of Federal Regulations[(6)] (42 CFR 84, Subpart L, Section 84.207) mandates the use of carbon tetrachloride for testing negative-pressure air-purifying

TABLE 1. Summary of Organic Vapor Cartridge Certification Tests

| Type of Respirator | Cartridge Pretreatment[A] | Test Atmosphere Gas or Vapor | Test Atmosphere Concentration (ppm) | Test Flow Rate (L/min) | Number of Tests | Penetration (ppm) | Minimum Life[B] (min) |
|---|---|---|---|---|---|---|---|
| Chemical cartridge organic vapor | As received | $CCL_4$ | 1000 | 64 | 3 | 5 | 50 |
| Chemical cartridge organic vapor | Equilibrated 25% RH | $CCL_4$ | 1000 | 32 | 2 | 5 | 50 |
| Chemical cartridge organic vapor | Equilibrated 85% RH | $CCL_4$ | 1000 | 32 | 2 | 5 | 50 |
| Powered air-purifying tight-fitting | As received | $CCL_4$ | 1000 | 115[C] | 3 | 5 | 50 |
| Powered air-purifying tight-fitting | Equilibrated 25% RH | $CCL_4$ | 1000 | 115[C] | 2 | 5 | 25 |
| Powered air-purifying tight-fitting | Equilibrated 85% RH | $CCL_4$ | 1000 | 115[C] | 2 | 5 | 25 |
| Powered air-purifying loose-fitting hood or helmet | As received | $CCL_4$ | 1000 | 170[C] | 3 | 5 | 50 |
| Powered air-purifying loose-fitting hood or helmet | Equilibrated 25% RH | $CCL_4$ | 1000 | 170[C] | 2 | 5 | 25 |
| Powered air-purifying loose-fitting hood or helmet | Equilibrated 85% RH | $CCL_4$ | 1000 | 170[C] | 2 | 5 | 25 |

[A]The test RH is 50 percent in all cases.
[B]For cartridges designed for use against more than one type of agent, the minimum life shall be one-half of that shown above for each.
[C]Flow rate shall be the effective flow rate of the device, but not less than this flow rate.

organic vapor respirator cartridges. Organic vapor PAPR cartridges are tested with carbon tetrachloride according to 42 CFR 84, Subpart L, Section 84.207 and Subpart KK, Section 84.1156. NIOSH has tested possible substitute agents at various challenge concentrations and testing conditions to identify certain agents with breakthrough characteristics similar to carbon tetrachloride.

Negative-pressure and PAPR air-purifying organic vapor cartridges are tested according to 42 CFR 84 as received from the applicant or after preconditioning at 25 or 85 percent relative humidity (RH). Different flow rates and times are employed in the testing (Table 1). The rationale for equilibrating the cartridges at 25 and 85 percent RH, followed by testing at 50 percent RH and at a reduced flow rate, has been questioned.(7) It is thought that testing of as-received cartridges over a broader range of RHs at the higher flow rate would be more appropriate and would constitute an improved and more realistic performance standard for testing organic vapor and gas respirator cartridges.

Previously, negative-pressure organic vapor cartridges were tested against four potential replacement agents (ethyl acetate, pentane, *n*-hexane, and heptane).(1) Testing was performed using a stacked-cartridge test system.(8) This screening method identified replacement agent challenge concentrations which gave breakthrough characteristics comparable to 1000 ppm carbon tetrachloride. Breakthrough time was the critical criterion. Two test conditions (550 ppm pentane and 1000 ppm *n*-hexane) were selected for side-by-side testing with 1000 ppm carbon tetrachloride to compare the present 42 CFR 84 test methods(6) with data generated on as-received cartridges. The five test conditions were: (1) preconditioned at 25 percent RH and tested at 50 percent RH and 32 L/min, (2) preconditioned at 85 percent RH and tested at 50 percent RH and 32 L/min, (3) as-received tested at 25 percent RH and 64 L/min, (4) as-received tested at 50 percent RH and 64 L/min, and (5) as-received tested at 80 percent RH and 64 L/min. Conditions 1, 2, and 4 represent the present 42 CFR 84 carbon tetrachloride testing scheme, while conditions 3, 4, and 5 represent a testing scheme NIOSH is considering for future implementation.

The cartridge test results showed that for the most stringent test condition (as-received cartridges tested at 64 L/min and 80 percent RH) the breakthrough times were comparable for the following three test conditions: 1000 ppm carbon tetrachloride; 550 ppm pentane; and 1000 ppm *n*-hexane. Two different manufacturers' organic vapor cartridges were tested in triplicate.

No PAPRs were tested in conjunction with these earlier NIOSH studies, so studies at the five conditions stated above were performed to identify the most severe experimental test conditions for PAPRs. Test data at various test conditions, including preconditioned and as-received cartridges, were collected for comparison and to identify the test condition which was most severe for testing PAPR cartridges.

## Experimental

The testing was done using the certification testing system(1) as shown in Figure 1. Numerous manufacturers' cartridges were tested for both nonpowered and PAPR cartridges. As can be seen from Figure 1, the conditioned air stream (50 or 80% RH at 25°C) containing the challenge agent was pushed through a single cartridge or cartridge pair mounted on a holder as employed on the respirator. The challenge concentration was determined gravimetrically (time-weighted average) over the entire test run. The breakthrough time was determined at a 5-ppm breakthrough concentration. In the case of pentane, a

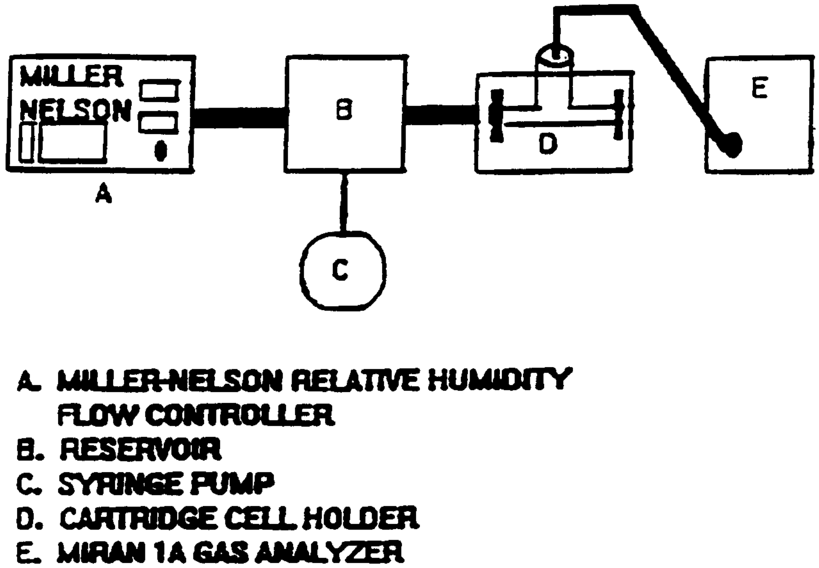


FIGURE 1. Carbon tetrachloride certification test system.



Teflon® needle resting on heated glass beads was used during vapor generation to prevent solvent solidification.

The downstream breakthrough concentration was continually monitored by means of a Miran 1A (Foxboro, Massachusetts) general purpose, infrared gas analyzer equipped with a variable path length gas cell. The analytical wavelength and minimum detectable limits as specified by the manufacturer, with a 20-m cell for the test agents, were as follows: carbon tetrachloride, 12.6 μm and 1.1 ppm; pentane, 3.4 μm and 0.2 ppm; and *n*-hexane, 3.4 μm and 0.2 ppm.

The flow rates employed were those stipulated in 42 CFR 84: 64 L/min for as-received negative-pressure organic vapor cartridges; 115 L/min for PAPRs with tight-fitting facepieces; and 170 L/min for PAPRs with loose-fitting facepieces (Table 1).

The test agents evaluated were as follows: (1) carbon tetrachloride [Fisher Scientific, Pittsburgh, Pennsylvania, certified American Chemical Society (ACS) spectranalyzed, or Aldrich Chemical Company, Milwaukee, Wisconsin, ACS reagent 99%]; (2) *n*-pentane [Fisher Scientific, high pressure liquid chromatography (HPLC) grade]; and (3) *n*-hexane (either Fisher Scientific, certified ACS 99 Mol% pure, or J.T. Baker Chemical Company, Phillipsburg, New Jersey, HPLC 97%). House air, which was passed through a dryer/sorbent system to remove contaminants, was used as the carrier stream.

## Statistical Analysis

Several different statistical models for failure time data were investigated for the cartridge test data. Initially we fit a separate Weibull distribution for each of the challenge agents. The Weibull distribution is suitable for analysis of failure time data with increasing hazard, such as exhibited by the cartridge breakthrough time data. The Weibull distribution assumes that the probability of failure before some time, t, can be expressed as $P\ (T \leq t) = \exp\ (-\lambda t^{\eta})$, with $\lambda$ as the location parameter and $\eta > 1$ as a scale parameter indicating an increasing failure rate. It was then determined that the data for all three challenge agents could be combined for greater precision by expressing the location parameter as a function of covariates $\lambda = \exp\ (\beta_0 + \beta_1 Z_1 + \beta_2 Z_2)$ and assuming a common value for the shape parameter $\eta$. The covariates were defined so that $Z_1 = 1$ for pentane and $Z_2 = 1$ for hexane; otherwise, the covariates were zero. To determine an equivalent breakthrough time for pentane consistent with the 50-minute breakthrough time for carbon tetrachloride for negative-pressure air-purifying organic vapor respirator cartridges (42 CFR 84), we solved the following equation:

$$P_c\ (50) = (P_p\ t_p)$$

where subscripts indicate the challenge agents (c for carbon tetrachloride and p for pentane). The same method was used to estimate an equivalent breakthrough time for hexane. Estimates of the standard errors derived from the Weibull regression model were used to obtain 95 percent confidence intervals for the equivalent breakthrough times.

Additional statistical analyses of an exploratory nature have been done to assess the effects of different manufacturing processes or materials used in the construction of cartridges. Manufacturing effects were modeled as both fixed effects (Weibull regression and Cox proportional hazard regression) and as random effects (Gamma and Stable frailty models). The equivalent breakthrough times based on these models are presented here for comparison, although details of these analyses are presented elsewhere.[9,10]

## Results and Discussion

### *Nonpowered Negative-Pressure Organic Vapor Cartridge*

The preliminary screening study[1] identified two test agents worthy of further study: (1) 550 ppm pentane and (2) 1000 ppm *n*-hexane. Additional work was conducted to determine breakthrough times of these alternative challenge agents consistent with 1000 ppm carbon tetrachloride at 50 percent RH negative-pressure cartridges (the most severe test condition

TABLE 2. Carbon Tetrachloride Breakthrough Time Correlation with Pentane

| Manufacturer | Type | Lot | Run | 1000 ppm Carbon Tetrachloride (64 L/min, 50% RH, 25°C): $t_b$ at 5 ppm (min) | 550 ppm Pentane (64 L/min, 80% RH, 25°C): $t_b$ at 5 ppm (min) |
|---|---|---|---|---|---|
| A | Pair | A | 1 | 83.8 | 72.0 |
| | | | 2 | 90.0 | 71.6 |
| B | Pair | A | 1 | 117.8 | 99.8 |
| | | | 2 | 119.9 | 95.9 |
| C | Pair | A | 1 | 102.8 | 102.1 |
| | | | 2 | 123.6 | 89.5 |
| D | Pair | A | 1 | 114.2 | 91.1 |
| | | | 2 | 117.1 | 93.0 |
| E | Pair | A | 1 | 76.1 | 60.5 |
| | | | 2 | 69.7 | 58.6 |
| F | Pair | A | 1 | 96.3 | 79.8 |
| | | | 2 | 98.7 | 71.6 |
| G | Pair | A | 1 | 86.5 | 70.2 |
| | | | 2 | 86.3 | 69.3 |
| | Pair | B | 1 | 55.3 | 49.2 |
| | | | 2 | 59.9 | 49.2 |
| | | | 3 | 58.0 | |
| | Pair | C | 1 | 61.2 | |
| | | | 2 | 64.4 | |
| H | Pair | A | 1 | 94.6 | 73.9 |
| | | | 2 | 97.3 | 77.6 |
| | | B | 1 | 100.6 | 77.5 |
| | | | 2 | 94.8 | 74.6 |
| | | C | 1 | 92.7 | |
| I | Pair | A | 1 | 95.0 | 86.6 |
| | | | 2 | 106.8 | 69.7 |
| I | Single | A | 1 | 103.8 | 70.2 |
| | | | 2 | 101.3 | 64.7 |
| | | | 3 | 101.6 | 71.5 |
| | | | 4 | 97.0 | 68.7 |

specified under 42 CFR 84). Testing was conducted with 550 ppm pentane for as-received cartridges tested at 64 L/min and 80 percent RH, which was the most severe new test condition evaluated for the certified negative-pressure organic vapor cartridges. Also, test data were obtained for *n*-hexane: 1000 ppm, as-received cartridges, 64 L/min, and 80 percent RH.

The equivalence study data for 550 ppm pentane and 1000 ppm carbon tetrachloride are presented in Table 2. The 1000 ppm carbon tetrachloride breakthrough times (64 L/min, 50% RH, and 25°C according to 42 CFR 84) were compared with the 550 ppm pentane (64 L/min, 80% RH, and 25°C) breakthrough times. The required breakthrough time for carbon tetrachloride according to 42 CFR 84 is 50 minutes ($t_b = 50$). An estimate of the equivalent breakthrough time for pentane was found to be 39.75 minutes [95% confidence interval (CI) 35.32, 44.73].

The equivalency data between 1000 ppm *n*-hexane and 1000 ppm carbon tetrachloride are presented in Table 3. The estimate of the corresponding breakthrough time of *n*-hexane was found to be 36.96 minutes (95% CI, 32.82, 41.61).

If a Weibull regression model is used employing fixed effects to account for differences among manufacturers, the results are not significantly different. This approach yields an estimate for pentane of 39.37 minutes (95% CI 35.16, 44.09) and an estimate for hexane of 37.24 minutes (95% CI 33.25, 41.70). Other models were examined and are described elsewhere.[10] A summary of that data is shown in Table 4. Different types of random effects (frailty) models have been investigated for these

TABLE 3. Carbon Tetrachloride Breakthrough Time Correlation with n-Hexane

| Manufacturer | Type | Lot | Run | 1000 ppm Carbon Tetrachloride (64 L/min, 50% RH, 25°C): $t_b$ at 5 ppm (min) | 1000 ppm *n*-Hexane (64 L/min, 80% RH, 25°C): $t_b$ at 5 ppm (min) |
|---|---|---|---|---|---|
| A | Pair | A | 1 | 83.8 | 71.4 |
| | | | 2 | 90.0 | 66.6 |
| B | Pair | A | 1 | 117.8 | 81.3 |
| | | | 2 | 119.9 | 74.6 |
| C | Pair | A | 1 | 102.8 | 106.0 |
| | | | 2 | 123.6 | 83.0 |
| D | Pair | A | 1 | 114.2 | 81.6 |
| | | | 2 | 117.1 | 73.1 |
| E | Pair | A | 1 | 76.1 | 51.2 |
| | | | 2 | 69.7 | 49.0 |
| F | Pair | A | 1 | 96.3 | 61.9 |
| | | | 2 | 98.7 | 67.7 |
| G | Pair | A | 1 | 86.5 | 64.7 |
| | | | 2 | 86.3 | 68.6 |
| | Pair | B | 1 | 55.3 | 49.6 |
| | | | 2 | 59.9 | 44.8 |
| | | | 3 | 58.0 | |
| | Pair | C | 1 | 61.2 | |
| | | | 2 | 64.4 | |
| H | Pair | A | 1 | 94.6 | 73.0 |
| | | | 2 | 97.3 | 72.7 |
| | | B | 1 | 100.6 | 73.8 |
| | | | 2 | 94.8 | 72.7 |
| | | C | 1 | 92.7 | 67.5 |
| | | | 2 | | 68.0 |
| I | Pair | A | 1 | 95.0 | |
| | | | 2 | 106.8 | |
| I | Single | A | 1 | 103.8 | 74.3 |
| | | | 2 | 101.3 | 76.8 |
| | | | 3 | 101.6 | 69.6 |
| | | | 4 | 97.0 | 61.0 |
| | | | 5 | | 70.2 |
| | | | 6 | | 71.9 |

data.[9,10] The estimates of the equivalence time are fairly robust to the model assumptions.

Reproducibility experiments were conducted on manufacturer I organic vapor cartridges with a challenge of 550 ppm pentane at 80 or 50 percent RH on as-received cartridges. The 80 percent RH data are presented in Table 5 and the 50 percent RH data are presented in Table 6. The methods reproducibility is good, with the 80 percent RH pentane data giving a mean of 73.2 minutes with a standard deviation of 3.4 minutes. The 50 percent RH pentane data produced a mean of 113.5 minutes with a standard deviation of 3.4 minutes. Similar data were obtained for the 1000 ppm *n*-hexane challenge at 80 and 50 percent RH on as-received cartridges. The 80

TABLE 4. Summary of Data for Other Models

| Model | Pentane Equivalent $t_b$ (min) | Hexane Equivalent $t_b$ (min) |
|---|---|---|
| Weibull regression with separate shapes | 39.75 | 36.96 |
| Weibull regression with common shape | 39.37 | 37.24 |
| Weibull regression with fixed effects | 39.32 | 38.67 |
| Gamma frailty | 41.79 | 39.20 |
| Stable frailty | 32.93 | 31.01 |

TABLE 5. Reproducibility Study of Cartridge Breakthrough Times Against 550 ppm Pentane for As-Received Manufacturer I Organic Vapor Cartridges

| Sample Number | Weight of Cartridges (g) | | | | | Breakthrough Time $t_b$ at 5 ppm (min)* |
|---|---|---|---|---|---|---|
| | Initial | Final | ΔW | Case | Sorbent | |
| 1 | 172.2 | 190.2 | 18.0 | 60.9 | 111.3 | 77.3 |
| 2 | 169.2 | 186.1 | 16.9 | 60.1 | 109.1 | 77.2 |
| 3 | 172.0 | 190.0 | 18.0 | 60.3 | 111.7 | 72.3 |
| 4 | 172.1 | 190.0 | 17.9 | 60.4 | 111.7 | 68.8 |
| 5 | 171.1 | 189.8 | 18.7 | 60.6 | 110.5 | 77.3 |
| 6 | 168.2 | 186.1 | 17.9 | 60.8 | 107.4 | 73.6 |
| 7 | 172.0 | 190.1 | 18.1 | 60.8 | 111.2 | 68.8 |
| 8 | 172.1 | 189.5 | 17.4 | 61.1 | 111.0 | 70.4 |
| 9 | 173.1 | 191.2 | 18.0 | 61.3 | 111.9 | 71.6 |
| 10 | 171.0 | 191.2 | 20.2 | 60.8 | 110.2 | 74.5 |

*Test flow rate of 64 L/min and test RH of 80 percent.

percent RH *n*-hexane data gave a mean of 70.3 minutes with a standard deviation of 3.2 minutes. The 50 percent RH *n*-hexane data gave a mean of 86.7 minutes with a standard deviation of 1.8 minutes. These results are consistent with data published previously for organic vapor chin-style canisters.[2]

### Powered Air-Purifying Organic Vapor Cartridges

PAPR cartridges were evaluated as part of this study. The data collected on PAPRs consisted of: (1) carbon tetrachloride control on 85 percent preconditioned cartridges tested at 1000 ppm, 50 percent RH, and 25°C ($t_b \geq 25$ minutes); (2) carbon tetrachloride control on as-received cartridges tested at 1000 ppm, 50 percent RH, and 25°C ($t_b \geq 50$ minutes); (3) pentane on as-received cartridges tested at 550 ppm, 80 percent RH, and 25°C; and (4) *n*-hexane on as-received cartridges tested at 1000 ppm, 80 percent RH, and 25°C.

The test results (Table 7) show that the most severe PAPR organic vapor cartridge test condition under the requirements of 42 CFR 84.207 and 84.1156 is the 85 percent RH preconditioned cartridges with carbon tetrachloride testing performed at 1000 ppm, 50 percent RH, 25°C, and a flow rate of 115 L/min for tight-fitting facepieces or 170 L/min for loose-fitting hoods or helmets. The minimum breakthrough time requirement is 25 minutes at a 5-ppm breakthrough concentration.

Laboratory testing has been conducted to match the 85 percent preconditioned cartridge results against carbon tetrachloride with pentane results on as-received cartridges tested at 550 ppm, 80 percent RH, 25°C, and a flow rate of 115 L/min for tight-fitting facepieces or 170 L/min for loose-fitting hoods or helmets. The pentane data are presented in Table 7. Similarly, *n*-hexane data on as-received cartridges tested at 1000 ppm, 80 percent RH, 25°C, and the flow rate indicated earlier are presented in Table 7. From the model (Weibull regression) the point estimates for pentane and *n*-hexane were determined using the carbon tetrachloride breakthrough data for the 85 percent RH preconditioned cartridges tested at 1000 ppm, 50 percent RH, 25°C, designated flow rate, and $t_b \geq 25$ minutes as the control criteria. The pentane point estimate was 50.02 minutes (95% CI 37.27, 67.13). The *n*-hexane point estimate was 51.77 minutes (95% CI 37.16, 72.11).

### Conclusions

Data are presented correlating the present 42 CFR 84 organic vapor cartridge tests to a test criterion which proposes a new test scheme using only as-received cartridges and a new test

TABLE 6. Reproducibility Study of Cartridge Breakthrough Times Against 550 ppm Pentane for As-Received Manufacturer I Organic Vapor Cartridges

| Sample Number | Weight of Cartridges (g) | | | | | Breakthrough Time $t_b$ at 5 ppm (min)* |
|---|---|---|---|---|---|---|
| | Initial | Final | ΔW | Case | Sorbent | |
| 1 | 172.0 | 181.2 | 9.2 | 59.8 | 112.2 | 117.1 |
| 2 | 172.0 | 181.9 | 9.9 | 61.1 | 110.9 | 116.5 |
| 3 | 167.8 | 177.8 | 10.0 | 60.3 | 107.5 | 111.3 |
| 4 | 168.1 | 178.0 | 9.9 | 60.5 | 107.6 | 112.3 |
| 5 | 169.5 | 179.5 | 10.0 | 60.2 | 109.3 | 118.4 |
| 6 | 169.0 | 179.0 | 10.0 | 60.7 | 108.3 | 110.8 |
| 7 | 172.1 | 183.1 | 11.0 | 60.9 | 111.2 | 108.0 |
| 8 | 173.5 | 183.9 | 10.4 | 61.4 | 112.1 | 111.5 |
| 9 | 169.0 | 178.9 | 9.9 | 60.2 | 108.8 | 112.7 |
| 10 | 170.5 | 180.5 | 10.0 | 60.4 | 110.1 | 116.7 |

*Test flow rate of 64 L/min and test RH of 50 percent.

TABLE 7. PAPR Breakthrough Time Data

| Manufacturer | $t_b$ (min) Carbon Tetrachloride 1000 ppm, 50% RH, 25°C: 85% RH Preconditioned Cartridges | $t_b$ (min) Carbon Tetrachloride 1000 ppm, 50% RH, 25°C: As-Received Cartridges | $t_b$ (min) Pentane 550 ppm, 80% RH, 25°C As-Received Cartridges | $t_b$ (min) *n*-Hexane 1000 ppm, 80% RH, 25°C As-Received Cartridges |
|---|---|---|---|---|
| V | 33.0 | 141.9 | 123.8 | 87.7 |
| | 30.9 | 149.3 | 121.2 | 100.2 |
| | 40.6 | | | |
| | 33.2 | | | |
| | 29.2 | | | |
| W | 70.1 | 178.2 | 141.1 | 131.0 |
| | 94.6 | 186.6 | 128.3 | 127.3 |
| X | 78.5 | 147.5 | 133.4 | 96.8 |
| | 60.4 | 139.0 | 132.5 | 97.0 |
| Y | 92.1 | 184.4 | 146.0 | 126.3 |
| | 64.2 | 181.3 | 142.6 | 113.9 |
| | | | | 98.9 |
| Z | 39.8 | 175.4 | 113.5 | 111.8 |
| | 38.2 | 158.5 | 121.3 | 111.1 |
| | | 169.7 | 110.9 | |

agent (pentane) to replace carbon tetrachloride. The new test shows good reproducibility. The point estimates for both pentane and *n*-hexane for negative-pressure air-purifying organic vapor respirator cartridges and PAPR organic vapor respirator cartridges are given in Results and Discussion. A variety of Weibull regression models using both fixed and random effects were employed to determine the point estimate correlations which are fairly robust as to choice of model.

It must first be pointed out that all cartridges tested in this study were NIOSH-certified cartridges. Cartridges made with less-adsorbent charcoals have thus been excluded. How these less-adsorbent charcoals would perform under these test conditions still needs to be determined and is a critical issue. This is an especially important issue for the nonpowered negative-pressure organic vapor cartridges where the 50 percent RH test on as-received cartridges at 64 L/min and 25°C gave shorter breakthrough times than the 85 percent RH preconditioned cartridges. Added to this concern is the fact that all other cartridges (PAPR) and canisters (chin, back mounted/front mounted) tested confirmed that the 85 percent RH preconditioned test condition was the most severe. Thus, NIOSH will continue to use carbon tetrachloride as the certification test agent as long as it is available or until studies of less-adsorbent charcoals are completed and the results used to improve the certification regulations as part of a future module.

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