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ABSTRACT

This report presents a brief review of the kinetic theory applicable to adsorption of gaseous contaminants by filter media and an algorithm for assessing the effectiveness of filtering devices. It briefly describes the selected testing technique for measuring the effectiveness of filter media and presents experimental data for adsorption of n-butane, carbon monoxide, and toluene. The selected method permits contaminant penetration measurement as a function of elapsed time on a continuous basis and can be used for filters having a flow bypass.

KEY WORDS: Adsorption; contaminant; efficiency; filter; gaseous; granular; media; method; penetration; removal; test.

NOMENCLATURE

A = media bed cross-section area (cm^2)
B = Microporocity constant for the granular carbon media
d = Diameter of media particle (cm)
D = Test canister diameter (cm)
c = $(M \cdot C/V) \cdot 10^{-6}$ = contaminant concentration (g/l)
C = Contaminant concentration (ppm)
C_b = Theoretical breakthrough concentration, or the expected value of concentration downstream of the filter (ppm)
C_d = Effective breakthrough concentration, or the measured value of concentration downstream of the filter (ppm)
C_c = $[Cd - f \cdot C_u]/[1 - f] \approx C_b$ = Corrected value of breakthrough concentration (ppm)
C_u = Challenge concentration, or the concentration upstream of the filter(ppm)
E = $1 - P_d$ = measured value of instantaneous adsorption Fraction, or contaminant removal efficiency (non-dimensional)
f = Bypass fraction of flow (non-dimensional)
K = $N/\tau = K_r \cdot c_u \cdot v_m/(W_s)$ = proportionality constant (1/min.)
K_r = adsorption rate constant (1/min.)
L = Media bed depth (cm)
M = Molecular weight (g/mole)
n_i = Molar fraction of ith component (non-dimensional)
P_o = Equilibrium partial pressure of the gaseous contaminant (kPa)
P_s = Saturation vapor pressure of the contaminant at temperature T (kPa)
P = C_b/C_u = theoretical value of instantaneous breakthrough fraction, or media penetration (non-dimensional)
P_d = C_d/C_u = measured value of instantaneous breakthrough fraction, or media penetration (non-dimensional)
P_c = C_c/C_u = corrected value of instantaneous breakthrough fraction, or media penetration (non-dimensional)
Q = Flow rate (l/min.)
R = Gas constant (1.987 cal/g-mole-°K)
Rh = Relative humidity (non-dimensional)
t = Time (min.)
t_b = Time required to obtain any desired value of the breakthrough concentration
T = Temperature (°C or °K)
U = Q/A = superficial velocity (cm/min.)
v_c = Specific volume of the liquid contaminant (cc/g)
V = Molar volume at the system temperature and pressure (l/mole) ≈ [24.1 l/mole at T= 20°C and p=1 Atmosphere]
W_m = Weight of filter media (g)
W_o = The maximum space available for adsorption (cc/g)
W_s = Adsorption capacity; weight of contaminant per unit weight of the filter media (g/g)
W_e = $W_m \cdot W_s$ = mass of contaminant adsorbed in the filter media (g)

Greek Symbols

α = $[1-P] = [(C_u-C_b)/C_u]$ = theoretical value of instantaneous contaminant adsorption fraction, or filter media contaminant removal efficiency (non-dimensional)

β = affinity coefficient of the contaminant vapor for activated carbon (non-dimensional)

$\blacksquare_m$ = Density of granular filter media (g/cc)

τ = $(W_m \cdot W_s)/(c_u \cdot Q)$ = time (min.) required to obtain 50% breakthrough; or time at which $P = \alpha = 0.5$

Subscripts

a refers to air

c refers to contaminant

d refers to downstream of the filter

m refers to filter media

u refers to upstream of the filter

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1. INTRODUCTION

Filtering devices using granular materials called filter media or sorbents (such as activated carbons, chemically treated alumina, and certain other substances) are being proposed for the removal of gaseous contaminants from indoor air. These devices can be incorporated into the heating, ventilation and air conditioning (HVAC) systems of buildings in a manner similar to filters used for particulate removal. Particulate filters can be evaluated by using the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 52-76 [1]. Over the years, attempts have been made to evaluate gaseous removal filters for some specific applications; however, no general procedures are available for evaluating the effectiveness of these devices and methods are needed to provide acceptable means for evaluation.

A research effort to develop the needed test methods was initiated at the National Institute of Standards and Technology (NIST). The objectives of the initial phase were; (1) to develop a test method suitable for measuring the single-pass effectiveness of the filter media; (2) to design and fabricate an appropriate test apparatus; (3) to develop techniques that would permit automation of all aspects of the testing scheme; and (4) to conduct preliminary experiments to demonstrate the feasibility of the testing scheme.

A progress report describing the selected test method, test apparatus, and testing scheme has been published [2]. The test apparatus described in ASTM Standard D3803, [3], utilizes a modified version of the ASTM test canister for holding the filter media and a computer controlled gas chromatograph (GC) for measuring the contaminant concentration.

The filter under test is challenged with a known gaseous contaminant introduced into the intake air at a constant concentration and the contaminant concentrations upstream of the filter media (C_u) and downstream of the filter media (C_d or the breakthrough concentrations) are measured at various elapsed times. A non-dimensional quantity (C_d/C_u) called penetration (or fractional breakthrough) is computed from the measured value of C_u and C_d. Contaminant removal efficiency is equal to one minus the penetration. The results can provide needed data, namely contaminant removal efficiency and the useful life of the filter for at least one contaminant at the operating conditions of the test.

Preliminary experiments were conducted with n-butane as the contaminant and two different coal-based carbons as filter media. After completion of the first phase of the project, a public design review meeting was held on March 8, 1988 at NIST. The purpose was to seek technical input from interested individuals and organizations. The design review meeting was attended by individuals representing industry, universities, and government laboratories. These included personnel from the Consumer Product Safety Commission (CPSC), the Association of Home Appliance Manufacturers (AHAM), the American Refrigeration Institute (ARI), and (ASHRAE), American Society of Heating, Refrigerating and Air-Conditioning Engineers.

During this design review meeting, many issues were discussed including the following: single-pass and multi-pass testing of filters and devices with air by-pass; gaseous contaminants and their challenge concentrations; test conditions (i.e. temperature and relative humidity); filter media size (i.e. cross-section and depth); and face velocity. The members of the design review panel evaluated the test method under development at NIST, and issued a report [4].

It was agreed that the gaseous contaminant removal effectiveness of filter media should be measured under laboratory conditions using the single-pass method developed by NIST. The test conditions should be consistent with typical field use insofar as possible. It was also agreed to conduct these experiments using one contaminant at a time. The gaseous contaminants recommended by the review panel for this purpose include the following: toluene (1 to 100 ppm); carbon monoxide (100 and 10 ppm); formaldehyde (1 and 0.1 ppm); NO_2 (0.3 and 0.03 ppm); Methyl isobutyl ketone (10 and 1 ppm); and butylcellosolve (100 and 10 ppm).

This diverse representation of gaseous contaminants and concentration levels of interest requires different detection schemes. For example, carbon monoxide can be detected by GC with a flame ionization detector (FID) by using a methanizer. However, the packing material used in the column becomes contaminated (poisoned) with water vapors in the test gas if the tests are conducted at high relative humidity (50%). Formaldehyde and NO_2 at the concentration levels of interest can be detected with a GC but not with a flame ionization detector. Almost all gaseous contaminants of interest can be detected with mass spectroscopy, but the test procedure becomes expensive and time consuming, and testing cannot be done in a dynamic mode or in real time.

It was decided to review the theory of gas adsorption kinetics applicable to gaseous contaminant removal filters/devices; develop algorithms for assessing the effectiveness (effective penetration and/or adsorption) of gaseous contaminant removal filters/devices with or without a flow bypass; and conduct experiments to demonstrate the applicability of the testing scheme for measuring the single-pass effectiveness of filter media. As indicated earlier, the preliminary experiments were conducted with n-butane as the contaminant and two coal-based carbons as the filter media. Additional experiments were conducted with carbon monoxide and toluene as contaminants and one coal-based carbon as the filter media. This report presents a brief review of the gas adsorption kinetics theory and algorithms for assessing the effectiveness of filtering devices with or without a flow bypass. It briefly describes the testing procedures and presents results of the experiments conducted with n-butane, carbon monoxide, and toluene.

2. THEORETICAL ANALYSIS

The simple analysis presented below follows the gas adsorption kinetics theory developed in [5-9]. When an airstream containing gaseous contaminants flows through a stationary bed of filter media (such as activated charcoal), some of the contaminant molecules are adsorbed on activated sites and others pass through the filter media bed. With the passage of time, as some of the activated sites are occupied with the adsorbed contaminant, the capacity of the media to adsorb more contaminant is reduced. Hence, the value of instantaneous adsorption fraction decreases and the value of instantaneous breakthrough fraction increase with the passage of time.

It is interesting to note that the instantaneous adsorption and breakthrough fractions also vary with the distance along the depth of the media bed. However, for the purpose of this study, the variations of adsorption and breakthrough fractions with respect to the distance along the depth of the media bed are not considered to be important. This is because we are only interested in knowing the fraction of contaminant adsorbed by the filter or the fraction of contaminant that penetrates the filter. Nonetheless, the depth of the media is an important variable as it affects the weight and the adsorption capacity of the filter media.

Let α, P, and Q respectively denote the instantaneous adsorption fraction, instantaneous breakthrough fraction, and flow rate of the contaminated air flowing through the filter media bed. Assuming that the airstream contains a single contaminant of concentration C_u, and that C_u and Q are constant, the values of α and P are given by:

$$\ln(P/\alpha) = \ln[P/(1-P)] = \ln[C_b/(C_u-C_b)] = K\cdot(t - \tau) \qquad (1)$$

$$P = 1/[1 + \exp\{K\cdot(\tau-t)\}] \qquad (2)$$

$$\alpha = 1/[1 + \exp\{-K\cdot(\tau-t)\}] \qquad (3)$$

Where the proportionality constant K, and 50% breakthrough time, τ, are experimentally determined parameters. The other symbols are defined in the nomenclature. Equation (1) may be rearranged to obtain an expression for the breakthrough time "t_b", or the time needed to obtain any desired value of breakthrough concentration (C_b):

$$t_b = \tau + \ln[C_b/(C_u - C_b)]/K \qquad (4)$$

The parameters K and τ can be related to the filter media density $\blacksquare_m$, adsorption capacity W_s, and adsorption rate constant, K_r, as:

$$K = K_r \cdot c_u/(\blacksquare_m . W_s) \qquad (5)$$

$$\tau = (W_m \cdot W_s)/(c_u \cdot Q) \qquad (6)$$

or,

$$W_s \approx c_u \cdot Q \cdot \tau / W_m \qquad (7)$$

The above expressions for α and P were derived by Yoon and Nelson [5] were shown to be consistent with experimental data. It is interesting to note that the above expressions for α and P are the special cases of gas adsorption kinetics equations derived by Bohart and Adams [6] and Wheeler and Robell [7].

The Wheeler equation, which has been commonly used in the literature to express the breakthrough time, is not the proper equation to use for this purpose. The particular simplification of the general solution is not applicable over the entire time regime. According to the authors of the paper [7], the simplification is only a good approximation when t/τ lies between 0.2 and 0.8.

In order to use Eqns. (2), (3), or (4), it is necessary to know the values of the parameters K and τ. The parameters K and τ may be determined from the experimental data. According to equation (1), the value of K can be obtained from the slope of the plot of $\ln[P/(1-P)]$ or $\ln[C_b/(C_u - C_b)]$ versus elapsed time t; and the value of τ (50% breakthrough time) as the time when $P = 0.5$ (or the time when $\ln[P/(1-P)] = 0$).

Alternatively, parameters K and τ could be computed if the adsorption rate constant K_r and adsorption capacity W_s are known or could be determined. Adsorption rate constant K_r and adsorption capacity W_s are the parameters of a particular granular carbon (media) in relationship to a particular gaseous contaminant and its concentration. Determination of these quantities is quite involved and beyond the scope of present work. For example, an expression for W_s for a single contaminant, according to Dubinin [8], is reproduced in equation (8) below. An expression for K_r for a single contaminant and for the case where the adsorption is due to mass transfer or external diffusion, according to Wheeler [9], is reproduced below as equation (9).

$$W_s = (W_o/v_c) \cdot \mathrm{Exp}[-B \cdot T^2/\beta^2 \cdot (\ln(p_s/p_o)^2] \qquad (8)$$

$$K_r \approx 10 \cdot [U/(M_a \cdot P_t \cdot d^3]^{1/2} \qquad (9)$$

Where B is the microporocity constant for the granular media, β is affinity coefficient for the contaminant vapor; d is the average diameter of media particles; p_o, p_s, and p_t are the equilibrium partial pressure of the contaminant, saturation vapor pressure of the contaminant, and total pressure respectively; T is the temperature of the contaminated air; U is the superficial velocity of the airstream; v_c is the specific volume of the contaminant when it is in liquid state; W_o is the maximum space available for adsorption; M_a is the molecular weight of contaminated air; and K_r and W_s were defined before.

Also, for a given media-gaseous contaminant combination, both of these parameters (i.e. W_s and K_r) are affected by the presence of other gaseous contaminants as well as by the presence of water vapors in the airstream. For a contaminant mixture the adsorption phenomenon is further complicated by selective adsorption; that is some contaminants may be more readily adsorbed onto the media than others. Bering, et. al., [10] suggested that equation (9) may be generalized to obtain the capacity (W_{sm}) of a media for adsorption of contaminant mixtures as shown below:

$$W_{sm} = (W_o/v_m)\cdot \mathrm{Exp}[-B\cdot(T^2/\beta_m{}^2)\cdot\{\ln(\mu)\}^2] \qquad (10)$$

where,

$$\beta_m = \Sigma n_i \cdot \beta_i \qquad (11)$$

$$v_m = \Sigma n_i \cdot v_i \qquad (12)$$

$$\mu = [\Sigma n_i \cdot \ln(p_{si}/p_{oi})] \qquad (13)$$

Where, p_{oi} and p_{si} are the equilibrium partial pressure and saturation vapor pressure of the individual contaminants.

Some researchers [8,10, and 11] have conducted studies to determine values of W_s and K_r for the adsorption of binary vapor mixtures (i.e. two gaseous contaminants) on activated charcoal. However, to use the models developed, one must either know or experimentally determine the values of B, d, and W_o, and the quantities β and K_r for the individual gaseous contaminant.

The effects of relative humidity on the adsorption characteristics of activated carbons (filter media) have been studied by several researchers [12-18]. The presence of water vapor usually degrades the performance of the filter media. For some contaminants, however, water vapor may enhance the performance of the media by acting as a catalyst, a reactant, or a solvent. Both the adsorption rate constant (K_r) and the adsorption capacity (W_s) are modified by the presence of water vapor. Pre-test humidity also affects the performance of filter media. Water vapor, once adsorbed onto the filter media, is not readily desorbed. Therefore, it is necessary to specify the value of pre-test relative humidity in any standard test procedure for testing the effectiveness of filter media. However, for values below 50%, the effect of relative humidity on the adsorption characteristics are relatively small [18].

Experimental data on the effects of adsorbed water vapor and relative humidity of airstream on the subsequent adsorption of several gaseous contaminants are available in the literature cited. Also, some empirical correlations to model the effects of relative humidity on the adsorption characteristics have been developed. However, universally applicable correlations for the dependence of K_r and W_s (or K and τ) on relative humidity are not currently available, and one needs to determine the values of parameters K and τ for each case from experimental data in accordance with equation (1).

Effect of filter media bypass: It is extremely difficult to fill a filtering device to the maximum possible packing density. For example, we filled our experimental cartridges by following the procedure outlined in the ASTM Standard D 3803 [3]. The cartridge was placed on a vibrating table to insure as optimal packing as possible. Even so, the mass of the granular media packed in the cartridge was always different (within ± 4 %). Filters for the filtering devices may/or may not be filled to the maximum filling capacity. Therefore, it is important to consider the effects of media packing on contaminant penetration.

Packing of the granular media in the filtering device has a considerable effect on contaminant penetration. When a filtering device is not filled to the maximum possible packing density, the empty spaces in the filtering device provide a path for air to bypass the media, and a fraction of the airstream leaves the filtering device without coming into contact with the adsorbing media. The airstream bypass probably occurs even with the maximum packing, but it is minimal. Hence, the contaminant concentration downstream of the filter would be different than that predicted by the theory. Let us call this the effective breakthrough concentration ,C_d, and ,C_d/C_u, the effective contaminant penetration, P_d. The flow bypass fraction, depending on the filling details of a filtering device, would be different for different devices and needs to be determined experimentally. If f is the fraction of flow bypass, then quantities C_d and P_d may be related to quantities P, C_u, C_b, and f as shown below:

$$C_d = [(1 - f)\cdot P + f]\cdot C_u \tag{14}$$

$$C_c \approx C_b = [Cd - f\cdot C_u]/[1 - f] \qquad (15)$$

$$P_d = C_d/C_u = [(1 - f)\cdot P + f] \qquad (16)$$

$$P_c = (P_d - f)/(1 - f) = C_c/C_u \approx P \qquad (17)$$

$$E = 1-P_d = (1 - f)\cdot(1 - P) \qquad (18)$$

$$t_b = \tau + \ln[(C_e - f\cdot C_u)/(C_u - C_d)]/K \qquad (19)$$

Equations (1) to (4) and (14) to (19) completely describe the behavior of a fresh bed of granular filter media. They are sufficient to determine the effectiveness of gaseous contaminant removal devices for cases when the value of C_u (i.e. challenge concentration) is constant and when the airflow is steady and constant. These equations, however, are not applicable in cases where the challenge concentration (C_u), airflow rate (Q), or both C_u and Q are variable, or when filter media are already partially contaminated. Theoretical treatment of such cases is beyond the scope of this study.

3. EXPERIMENTAL TECHNIQUES

The test apparatus for measuring the performance of filter media was described in reference 2. A schematic of the test apparatus is shown in Fig. 1. It is an open loop system consisting of four principal components: an air supply section, a test section, a contaminant generation section, and a contaminant analysis section. The contaminant analysis section consists of a computer-controlled gas chromatograph (GC) with a packed stainless steel column, a ten port automatic gas sampling valve, and a flame ionization detector (FID).

An experimental procedure to continuously measure the contaminant penetration through the filter media was developed. This method takes advantage of the fact that the elution or retention time of a given gaseous contaminant in a given column and at given operating conditions of GC (i.e. at set values of oven, injector, and detector temperature, and carrier gas flow) is constant. Hence, if the air samples from upstream of the filter and downstream of the filter are taken "■t" minutes apart for a GC run, the contaminant in the upstream and downstream air will elute out of the column at "■t" minutes apart. Interval "■t" minutes can be precisely controlled with software, when an automatic gas sampling valve is used for injecting the samples, as is the case in our GC configuration.

Experiments were conducted with n-butane, carbon monoxide, and toluene as contaminants and coal-based carbons as filter media. The test parameters for these adsorption experiments are summarized in Table 1. Carbon monoxide tests did not produce any useful data because 100% breakthrough occurred almost instantly.

3.1 Test Procedure

Primary gas standards at different contaminant concentrations in air were acquired for calibration of the GC (three standards for each gaseous contaminant). Operating conditions of the GC (i. e. oven, injector, and detector temperature and the carrier gas flow rate) were adjusted to obtain the desired retention time for the contaminant of interest. Retention time is an important parameter for conducting the filter tests and needs to be optimized. Since the detection of contaminant concentrations in the air sample upstream of the filter media (S1), as well as in the air sample downstream of the filter media (S2), is required, the retention time is of critical importance. The retention time has to be long enough to allow for complete separation of the contaminant from the air samples S1 and S2, yet short enough to permit the analysis to be completed in a reasonable time. The retention time may be optimized by varying the oven temperature, column length, and carrier gas flow or by using a column with different packing material. For example, we used stainless steel columns (2 mm in diameter and 1 m in length) packed with porapak Q, porapak P, and molecular sieve 13X for n-butane, toluene, and carbon monoxide respectively.

After the retention time was optimized, the desired time intervals for automatic sampling of the upstream and downstream air for a GC run were selected. This selected time sequence permitted sampling of the downstream air at any time "■t" minutes after that of the upstream air. The time for a complete GC run, i.e., the time required for a complete analysis of both the upstream and downstream samples, was determined. The GC was programmed to start the succeeding run at a desired time interval (greater than the GC run Time) after the previous run. Now, the GC was calibrated with one of the primary gas standards; and the other two gas standards were used to confirm the calibration.

After calibrating the GC, the test loop was checked for any leaks. The leak test consists of conducting the experiment without the filter media in the test loop (that is with the empty test canister). For each GC run during the leak tests, the contaminant concentrations upstream and downstream of the test canister should be the same since there is nothing to adsorb the contaminant.

Test canisters (experimental cartridges) were filled with the granular filter media by following the procedure outlined in the ASTM Standard D 3803 [3]. The cartridge to be filled was placed on a vibrating table to insure as optimal packing as possible. Each cartridge was weighed before and after it was filled with the filter media to determine the mass of material in the cartridge.

A cartridge containing the filter media was placed in the test loop and the experiment was started. During the experiments, the flow rate of conditioned air and the challenge contaminant concentration (C_u) in the test loop were maintained at constant levels. Fluctuations in the laboratory air line pressure did result in some variations in the air flow rate and C_u. These, however, were not precisely monitored. Fluctuations in the values of C_u were recorded along with other data for each GC run. These data included run number, time at which upstream air samples were taken, date, C_u, C_d, and dew point and airstream temperatures. Most experiments were continued until 100% breakthrough occurred, but some experiments were stopped earlier (n-butane test #5, and toluene test #6).

3.2 Data Analysis and Test results

A typical chromatogram for a complete GC run is shown in Figure 2. This chromatogram is from toluene test #2; it contains such information as the run number, time the run was started, peak times and graphs of the contaminant in the upstream air sample (Tol-1) and the downstream air sample (Tol-2), etc. In this chromatogram "B" refers to baseline, "BGN" refers to the start of the GC run, and "END" refers to the end of the GC run.

The values of P_d, and P1 were computed from the measured data for each run. Where:

$$P_d = C_d/C_u \qquad (20)$$

$$P1 = [C_d - f1 \cdot C_u]/[(1-f1) \cdot C_u] \qquad (21)$$

$$f1 = (\text{first value of } C_d)/(\text{ first value of } C_u) \qquad (22)$$

f1 is the first approximate value of the flow bypass fraction. These computed values of P_d and P1 are used to plot $\ln[P_d/1-P_d]$ and $\ln[P1/1-P1]$ as function of elapsed time. The resulting graph was examined to determine the values of K, τ and the value of flow bypass fraction ,f, which lies between zero and f1. It was indicated earlier that the parameter K is the slope of the line representing ln[P/1-P] vs elapsed time and the parameter τ is the time when ln[P/1-P] is equal to zero or when P is equal to 0.5. Once the value of K and τ are determined in accordance with equation (1), the value of the flow bypass fraction ,f, can be easily estimated. Now, this value of the flow bypass fraction is utilized to compute the corrected value of breakthrough concentrations ,C_c, and penetration, P_c, [$P_c = C_c/C_u$] in accordance with equations (15) and (17) respectively.

A graph of ln[P_e/1-P_e], ln[P1/1-P1], ln[Pd/1-Pd], and ln[P/1-P] versus elapsed time for toluene test #1 is presented in Figure 3. The value of flow bypass fraction ,f, was computed in a similar manner for all of the tests. The value of parameters N and W_s were computed by using the values of parameters K and τ determined from the experimental data. The values of parameters τ, K, W_s, N, and f, determined from the experimental data are presented in Table 2.

Typical experimental results are presented in figures 4 to 20; the test numbers listed on these figures are the numbers designated for the tests in Table 1 or 2. Figures 4 - 6 show ln(P/1-P) versus elapsed time, concentration versus elapsed time, and penetration and efficiency (effectiveness) versus elapsed time respectively for one of the n-butane tests. Figures 7 and 8 show effective penetration, P_d, and corrected penetration respectively for n-butane test #1, 2, and 3. Figures 9 and 10 show values of Pd and P_c

respectively for n-butane test #5, 6, and 7. Figures 11 to 17 show data similar to the data presented in Figures 4 to 10 for various tests with toluene.

These Figures indicate that experimental data and the theory are in good agreement. The data also shows that the values of parameters K, and W_s increase as the value of C_u is increased and the value of parameter τ decreases as the value of C_u is increased. These results are also in good qualitative agreement with the results of references 19 and 20; these references contain a large amount of data on the adsorption of various classes of gases and solvent vapors. The result also indicates that to determine parameters K, and τ, it is not necessary to continue an experiment to 100% penetration.

In order to develop an empirical correlation between τ and C_u, the values of τ computed from the toluene tests were graphed as presented in Figures 18 - 20. Figure 18 shows a graph of τ versus C_u, Figure 19 shows a graph of $\ln(\tau)$ versus $\ln(C_u)$, and Figure 20 shows a graph of $\ln[\tau$ for C_u equal to $434/\tau$ for other value of $C_u]$ versus $\ln(C_u/434)$. The purpose of the graph of Figure 20 was to see if a correlation of the type, $[C_{u1}/C_{u2}] = [\tau_2/\tau_1]^a$, could be developed as was done in reference 19; here C_u equal to 434 was selected as C_{u1}. These graphs indicate that the data are too few to develop any definitive correlation; although, one could force a line through the data of Figure 19. Hence, the value of τ for other values of C_u can not be determined by interpolation, with any degree of confidence. No such attempt was made for the n-butane data.

4. CONTAMINANT DESORPTION EXPERIMENT

In one of the experiment with toluene (toluene test #7) the value of C_u was varied. The purpose of this test was to show that a contaminant adsorbed onto the filter media would start to elute out or desorb from the filter media (even before the media has been saturated) as soon as the value of C_u become smaller than its original value. The desorption of the contaminant from the filtering device will keep polluting the air downstream of the filter for a long time.

The experiment was started with about 150 ppm of toluene; the value of C_u was dropped to zero after about 200 minutes and held at zero for 1100 minutes. It was then increased to about 340 ppm, dropped to about 26 ppm, and eventually dropped to zero again. Experimental data for this test are presented in Figure 21. The Figure shows values of C_u and C_d versus elapsed time.

It can be seen from these data that as soon as the value of C_u becomes lower than the previous value, some of the adsorbed contaminant starts to elute out of the media. For example, at about 1550 minutes (when the value of C_u is lowered from 320 to 25 ppm) C_d ($\approx$ 220 ppm) is higher than C_u ($\approx$ 25 ppm). About 1000 minutes after the value of C_u had been dropped to zero, the value of C_d was about 10 ppm and the toluene adsorbed onto the media was still eluting.

This phenomenon of desorption of the adsorbed contaminant suggests that the physical adsorbers are not practical for removing the gaseous contaminants from indoor air. When the contaminant source has been removed or turned off, then the room air would be polluted by the contaminant emitted from the filter. The amount of contaminant emitted from the filter is approximately equal to the amount that was adsorbed. Therefore, this type of material is only mitigating the peak exposure to the contaminant, and the total exposure is about the same. The health risks may be concentration - dependent, absent at low concentration.

Physical adsobers, however, may be useful in situations where relatively high levels of contaminants are expected to occur, as long as the user understands that the filter media is only providing a temporary storage for the contaminant.

5. CONCLUSION AND RECOMMENDATIONS

The test method developed by NIST can be used for measuring the single-pass effectiveness of gaseous contaminant removing filter media and devices under laboratory conditions when the airstream is contaminated with one gas. This method permits contaminant penetration measurement as a function of elapsed time on a continuous basis and can be used for filters having a flow bypass. We believe that this test method can also be used for contaminant mixtures. The good agreement between the experimental data and algorithms suggests that the gas adsorption theory has been successfully extended to predict the behavior of filter media with a flow bypass.

More experimental work is needed to develop correlations between τ and C_u. Experiments with contaminant mixtures are also necessary. Future experimental study should also include testing of some commercially available filtering devices. Analytical studies are also needed to develop algorithms applicable to cases where the values of challenge concentration ,C_u, and airflow rate ,Q, are varied and to cases where the filter media is already partially contaminated.

It is important to note that gaseous contaminant removal devices which utilize physical adsorbers may not be practical for cleaning indoor air. The contaminant adsorbed onto the filter slowly elutes out of the filter when the contaminant level in the upstream air drops below the previous level or drops to zero. Therefore, the future studies must also include tests with devices which utilize alternative methods of gaseous contaminant removal. Such methods might include chemically changing a contaminant to harmless compound, or media which chemically (permanently) bond gaseous contaminants.

6. ACKNOWLEDGMENT

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Table 1. Adsorption experiments test parameters

Test #	Media #	density g/cc	Surface Area / mass sq.m/g	Rh %	Temp. °C	Depth L cm	Media mass g	C_u ppm
Tests with n-butane								
1	C3	0.43	1200	20	23.6	5.1	41.16	23
2	C3	0.43	1200	20	23.5	5.1	42.45	50
3	C3	0.43	1200	20	23.3	5.1	42.30	92
4	C1	0.48	1100	20	23.6	5.1	47.40	20
5	C3	0.43	1200	20	23.5	2.54	21.78	20
6	C1	0.48	1100	20	23.6	2.54	23.79	100
7	C1	0.48	1100	20	23.5	2.54	24.23	470
Tests with carbon monoxide								
1	C3	0.43	1200	20	25.1	2.54	22.34	100
2	C1	0.48	1100	20	25.1	2.54	23.79	96
3	C3	0.43	1200	20	25.1	2.54	22.43	6.6
Tests with toluene								
1	C3	0.43	1200	50	24.8	2.54	22.63	444
2	C3	0.43	1200	50	24.8	2.54	21.85	192
3	C3	0.43	1200	10	24.8	2.54	22.54	434
4	C3	0.43	1200	10	24.8	2.54	24.04	105
5	C3	0.43	1200	9	24.8	2.54	23.73	64
6	C3	0.43	1200	9	24.8	2.54	23.96	21
7	C3	0.43	1200	10	24.8	2.54	23.96	Variable

Table 2. Adsorption experiments data

Test #	Media #	Depth L cm.	Media Wt.g	Cu ppm	T min	K	Ws g/g	N=K*T	bypass fraction f
Adsorption data for n-butant									
1	C3	5.1	41.16	23	1001	0.0046	0.0336	4.605	0.043
2	C3	5.1	42.45	50	716	0.0065	0.0506	4.654	0.040
3	C3	5.1	42.30	92	438	0.0113	0.0572	4.949	0.042
4	C1	5.1	47.40	20	919	0.0047	0.0233	4.319	0.037
5	C3	2.54	21.78	20	531	0.0087	0.0293	4.620	0.057
6	C1	2.54	23.79	100	221	0.0193	0.0558	4.265	0.053
7	C1	2.54	24.23	470	57	0.0784	0.0664	4.469	0.059
Adsorption data for carbon monoxide									
1	C3	2.54	22.34	100	almost instaneous 100% breakthrough				
2	C1	2.54	23.79	96	almost instaneous 100% breakthrough				
3	C3	2.54	22.43	6.4	about 65% instaneous breakthrough, 100% breakthrough in about 45 minutes				
Adsorption data for toluene									
1	C3	2.54	22.63	444	246	0.0229	0.4595	5.633	0.085
2	C3	2.54	21.85	192	451	0.0127	0.3773	5.728	0.095
3	C3	2.54	22.54	434	269	0.0208	0.4931	5.595	0.930
4	C3	2.54	24.04	105	871	0.0063	0.3622	5.487	0.078
5	C3	2.54	23.73	64	1336	0.0041	0.3430	5.478	0.063
6	C3	2.54	23.96	21	3926	0.0013	0.3276	5.104	0.065
7	C3	2.54	23.91	Variable	*	*	*	*	*

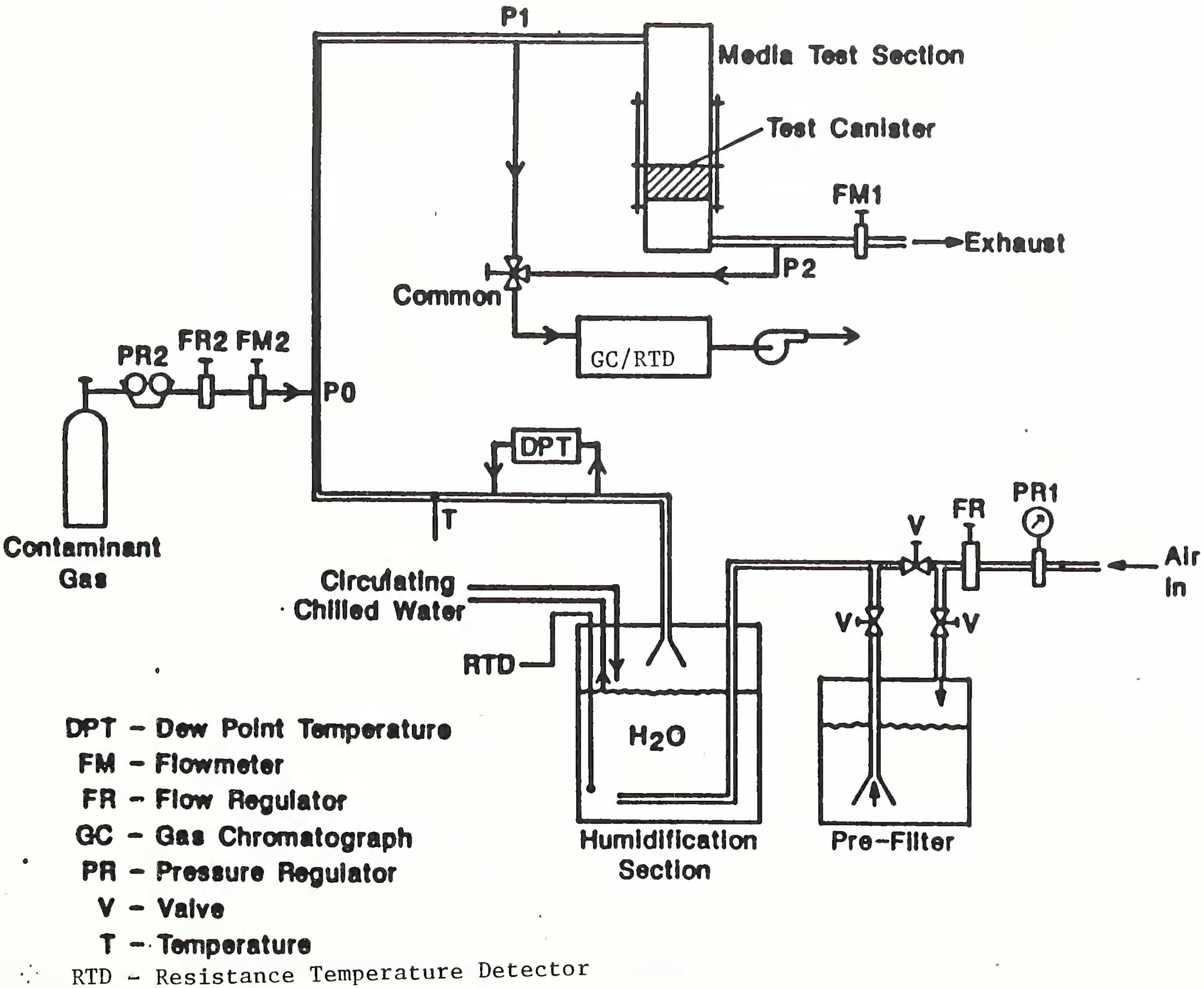

Figure 1. Schematic of test apparatus.

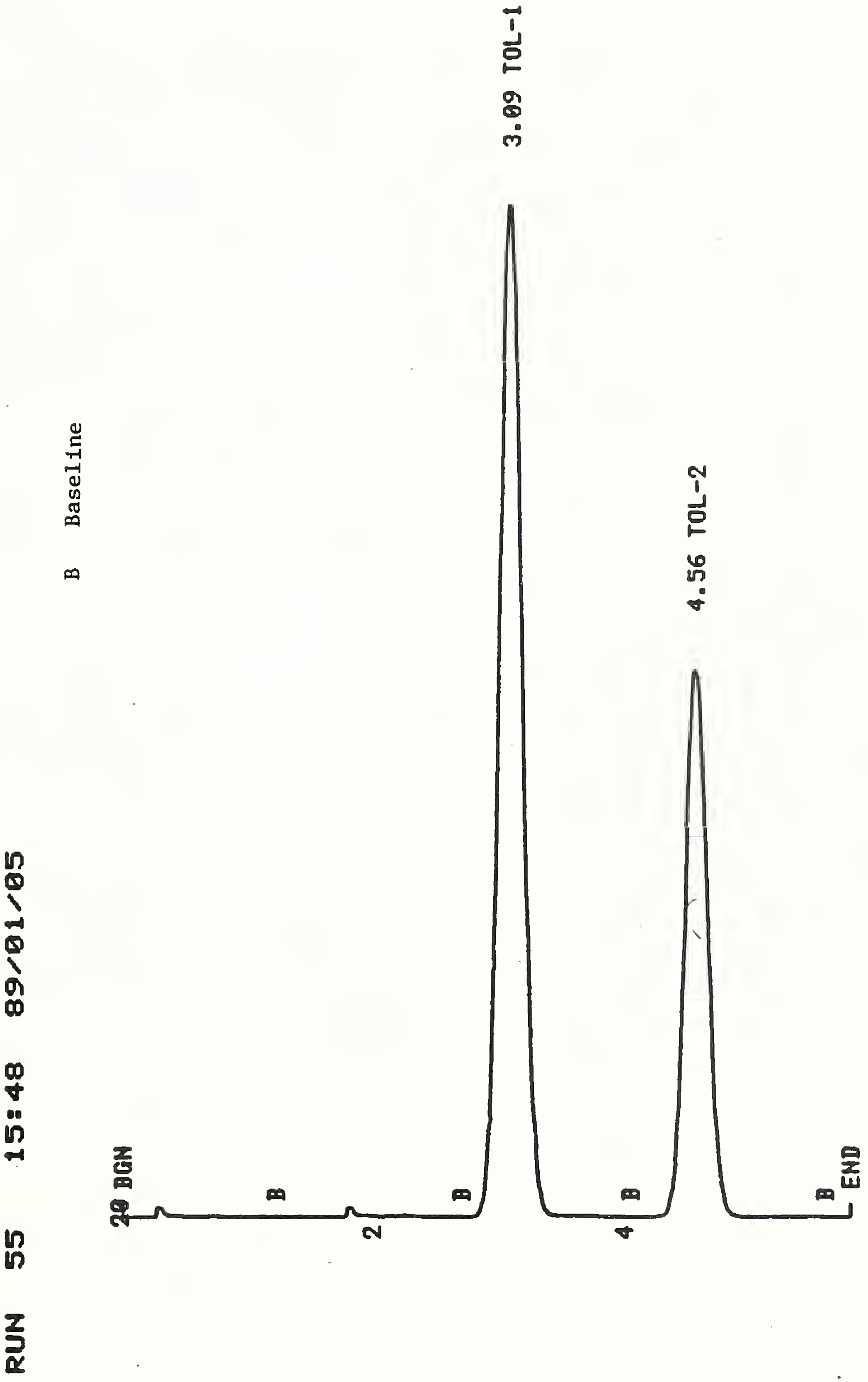

FIGURE 2. A TYPICAL CHROMATOGRAM

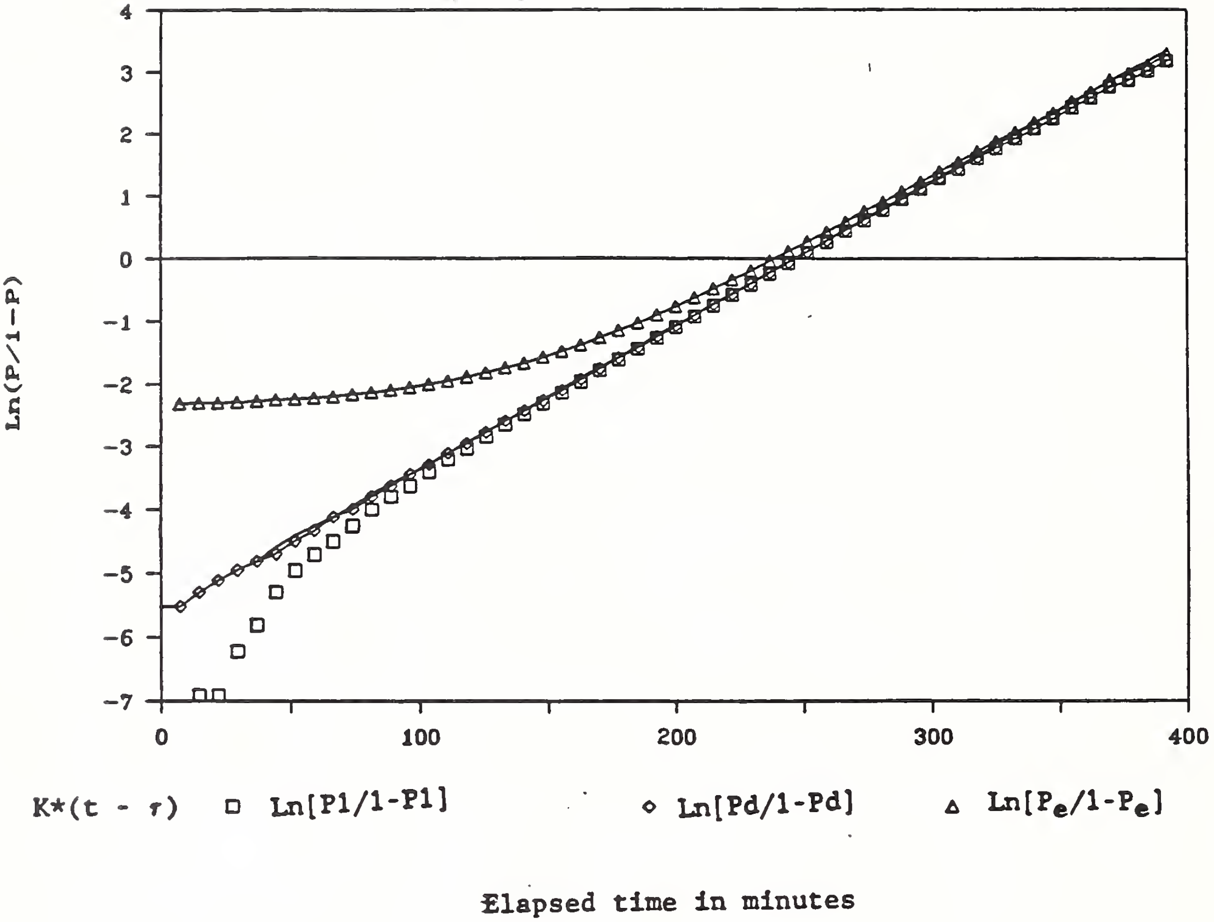

Figure 3. ln (P/1-P) vs elapsed time for toluene
Test #1; Rh=50%; T=24.8; Cu=443 ppm

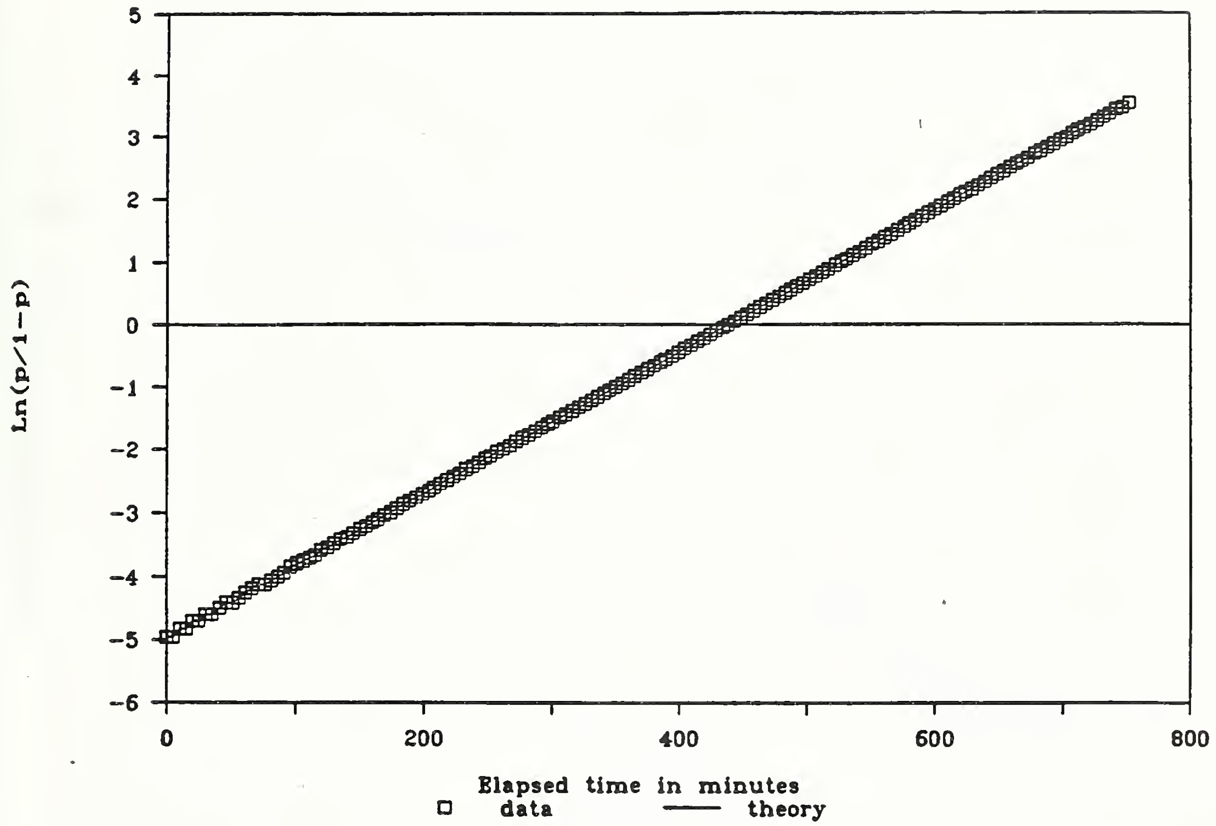

Figure 4. ln(P/1-P) vs elapsed time for N-butane
Test #3; Rh=20%; T=23.6; Cu=92 ppm

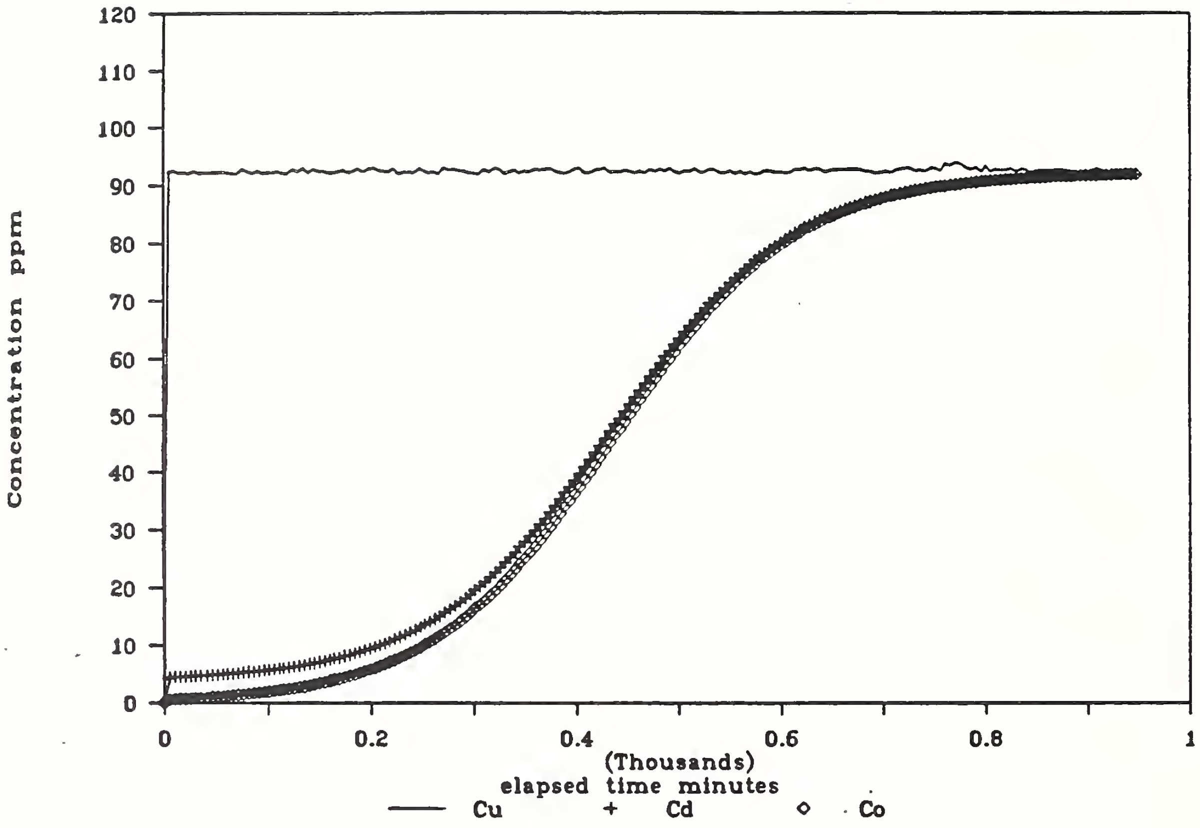

Figure 5. N-butane concentration vs elapsed time

Test #3; Rh=20%; T=23.6; Cu=92 ppm

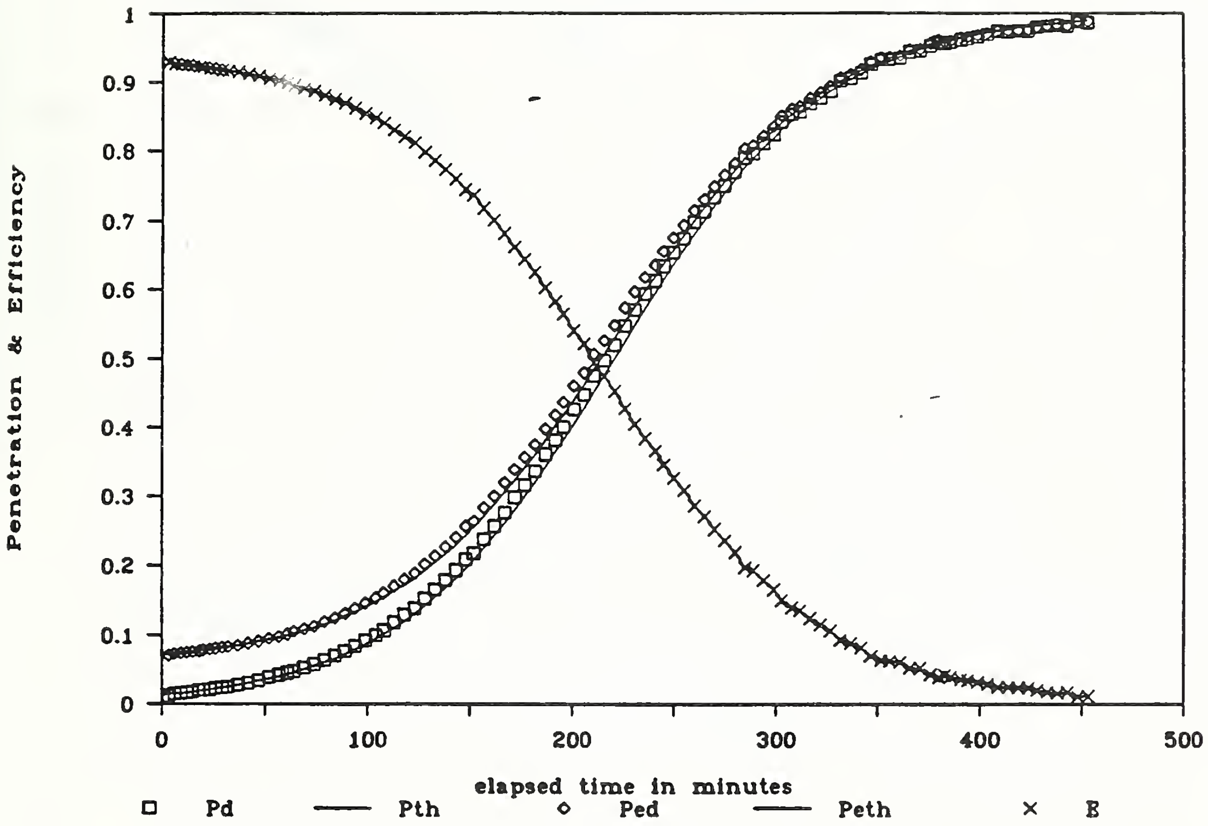

Figure 6. Penetration/efficiency vs elapsed time for N-butane Test #6; Rh=20% T=23.3; Cu=100

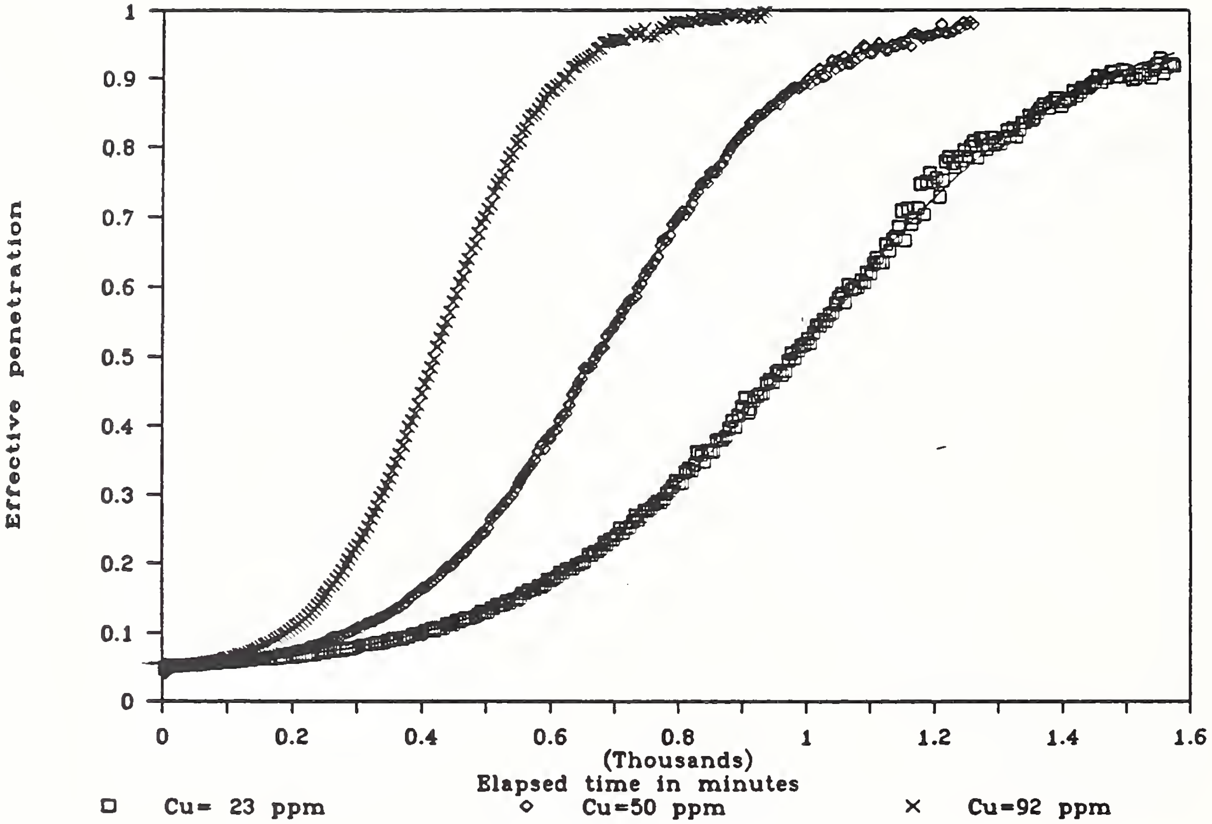

Figure 7. Effective penetration vs elapsed time for N-butane Test # 1, 2, and 3

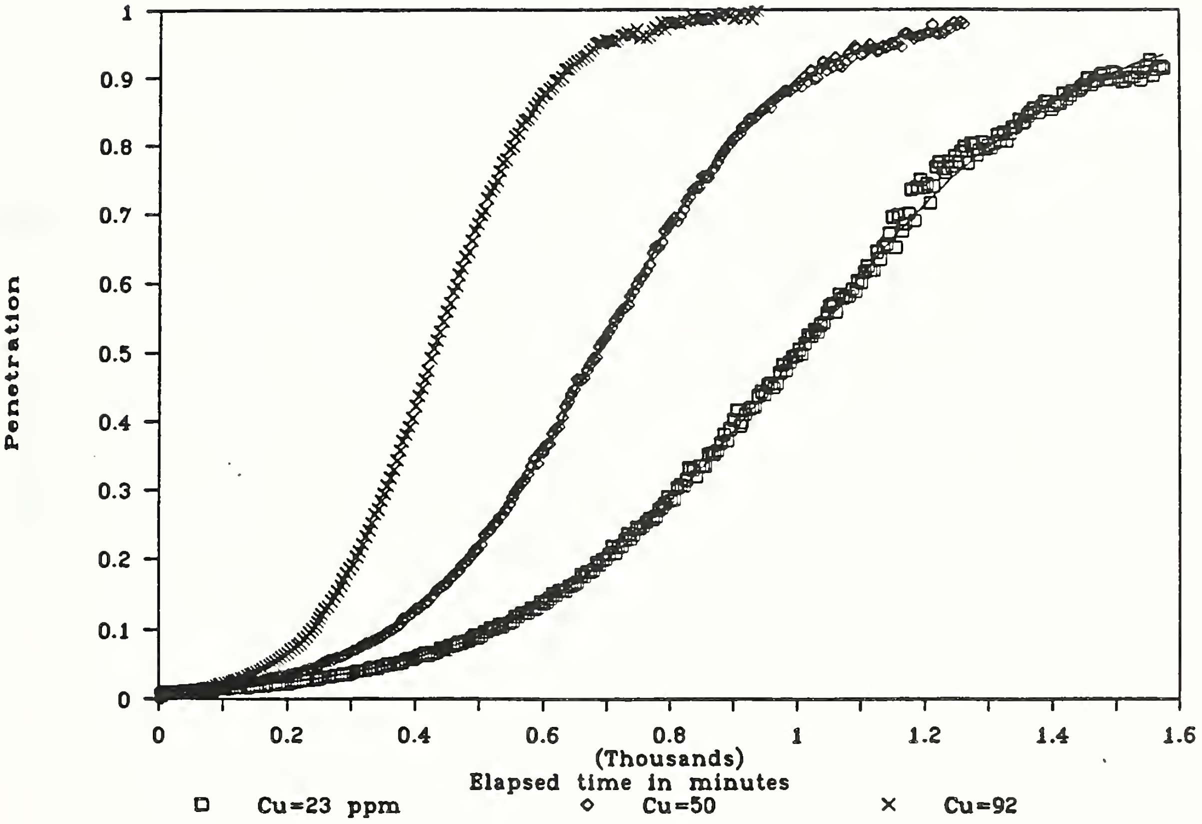

Figure 8. Penetration vs elapsed time for n-butane Test # 1, 2, and 3

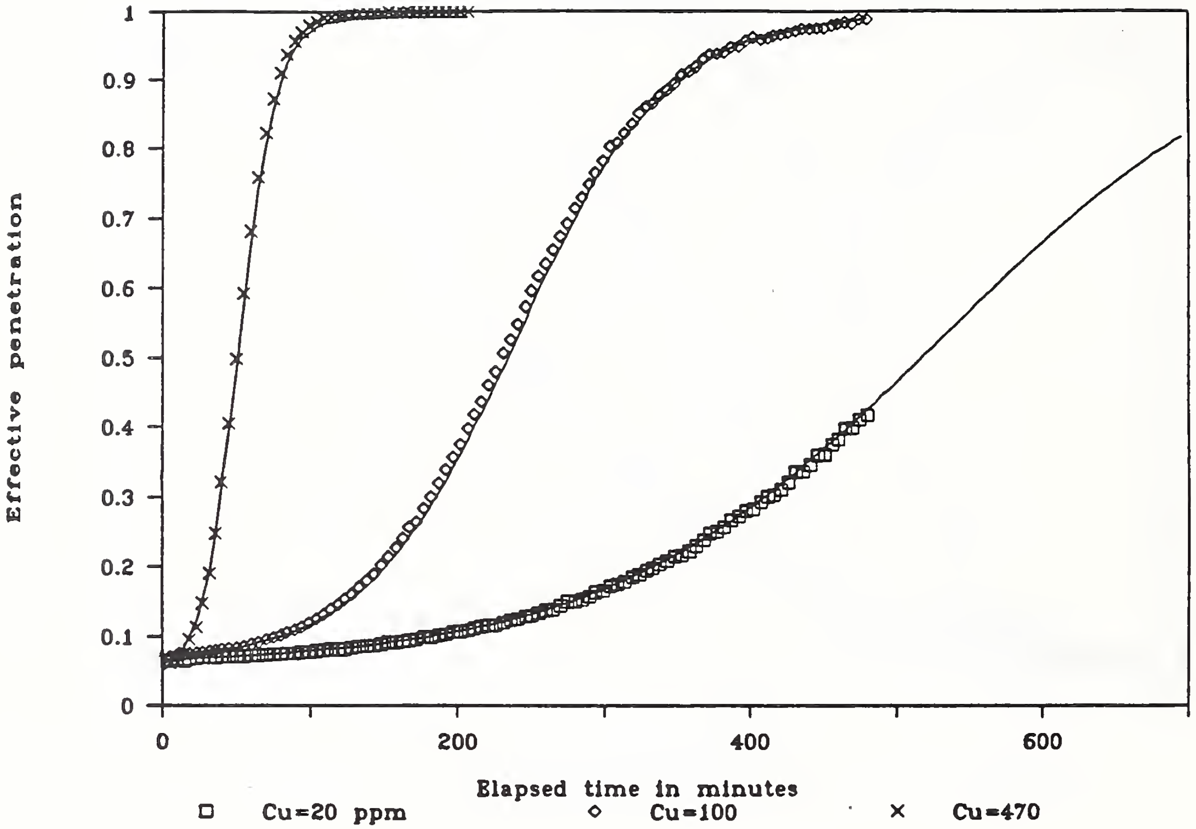

Figure 9. Effective penetration vs elapsed time for n-butane Test # 5, 6 and 7

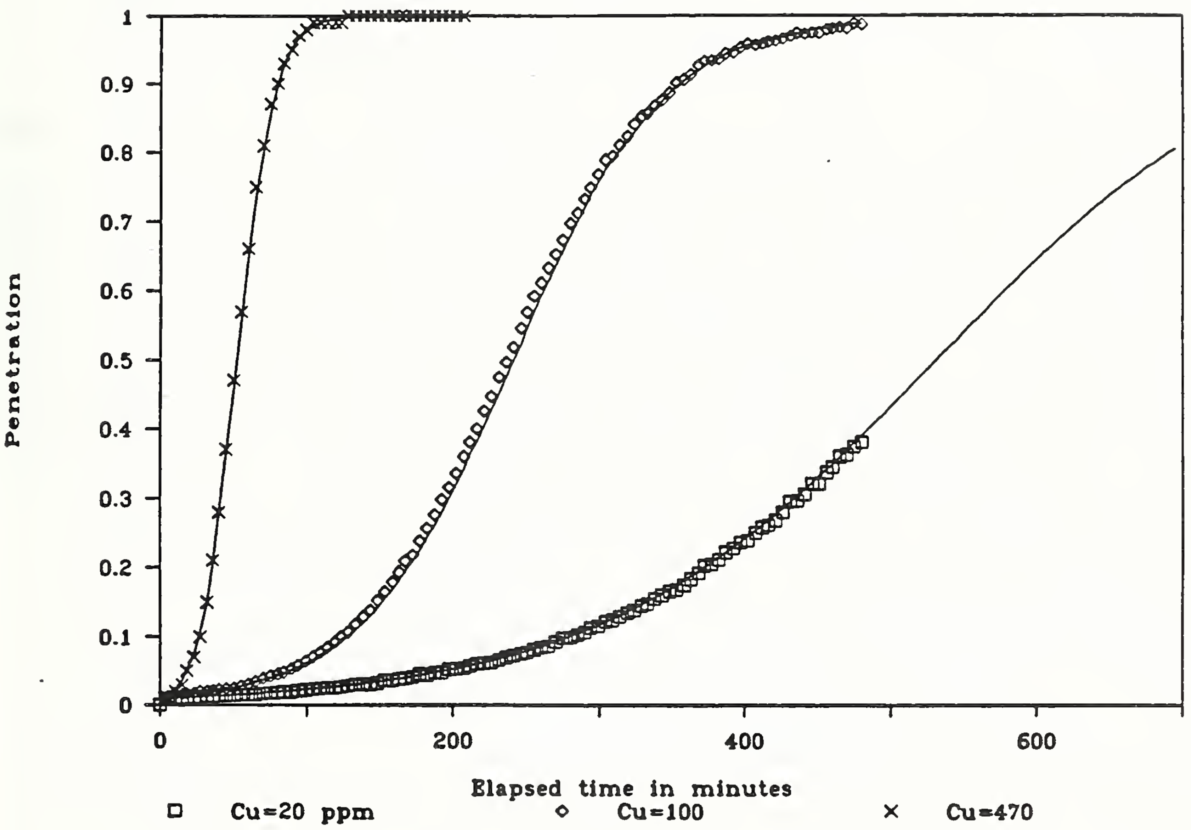

Figure 10. Penetration vs elapsed time for n-butane Test # 5, 6 and 7

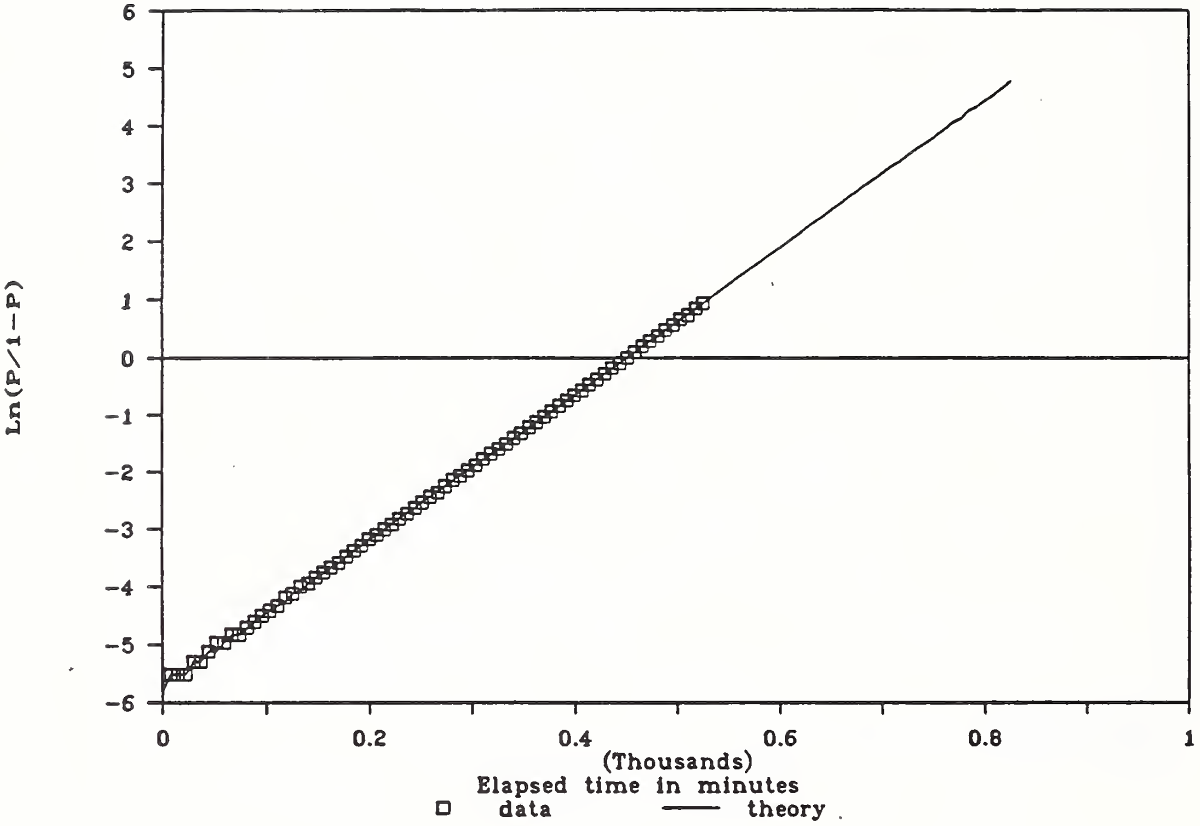

Figure 11. (ln (P/1-P) vs elapsed time for toluene)
Test #2; Rh=9%; T= 24.8; Cu=435 ppm

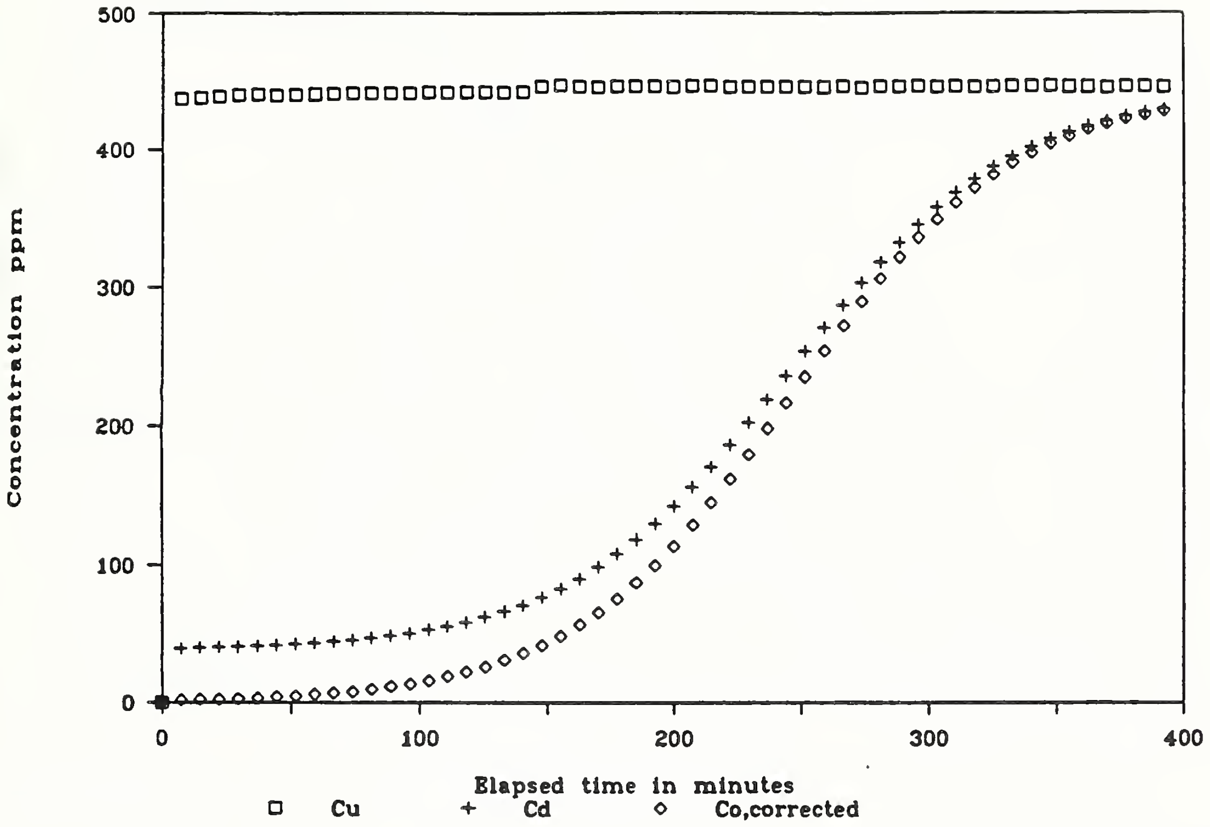

Figure 12. Toluene concentration vs elapsed time
Test #1; Rh =50%; T=24.8; Cu=444 ppm

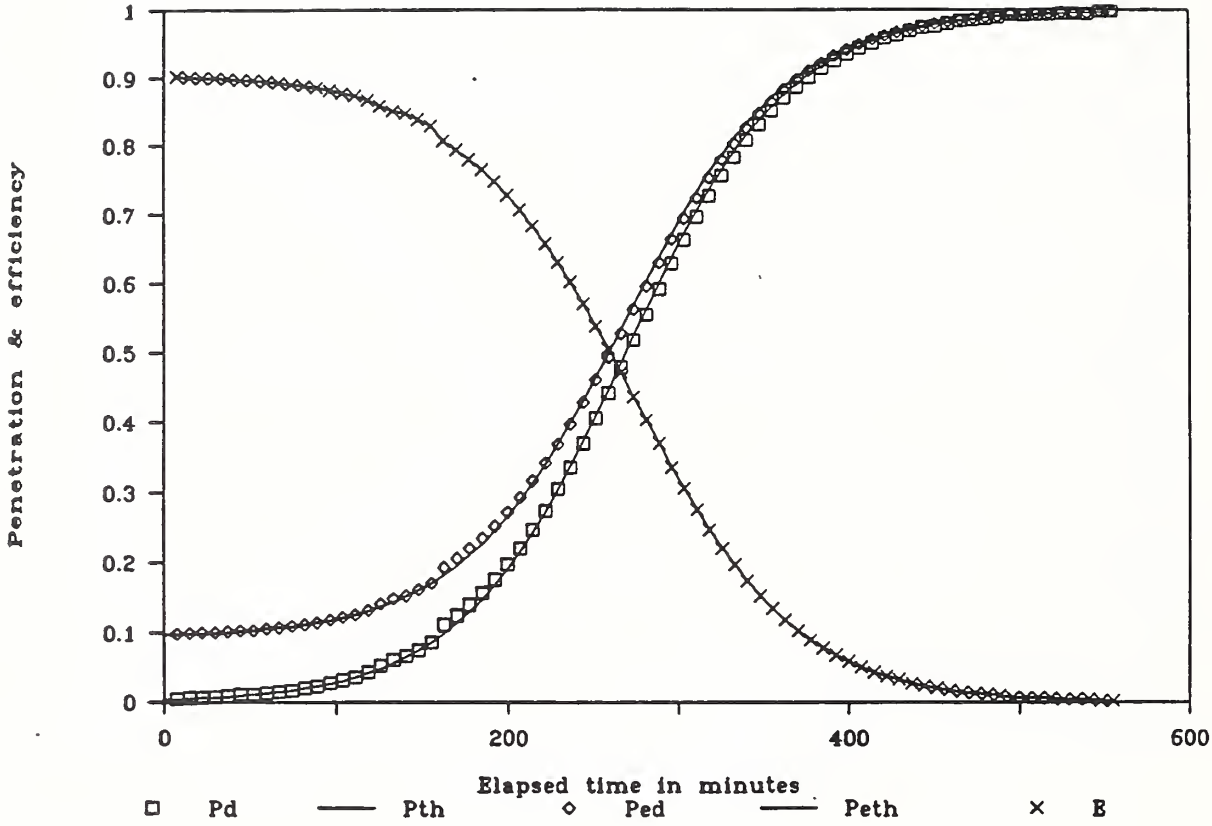

Figure 13. Penetration/efficiency vs elapsed time for toluene
Test #3; Rh=9%; T=24.8; Cu=434

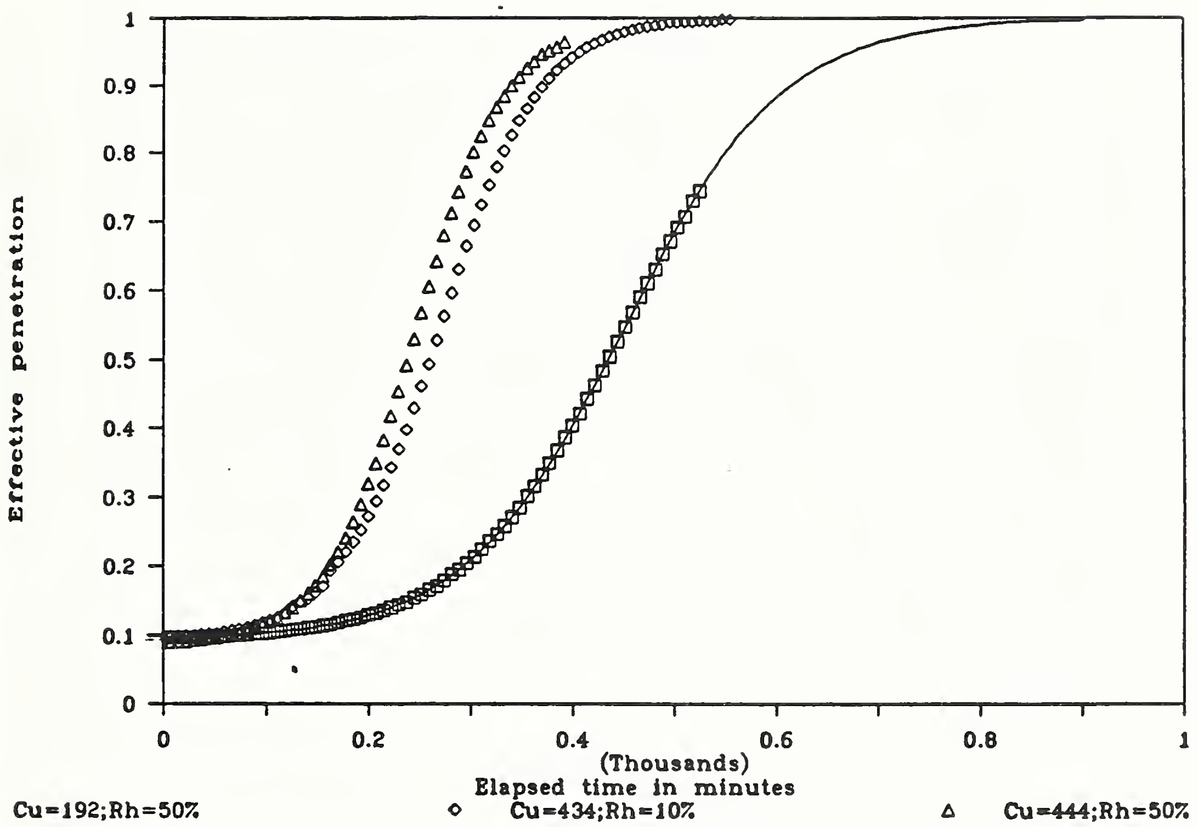

Figure 14. Effective penetration vs elapsed time for toluene Tests # 1, 2, and 3

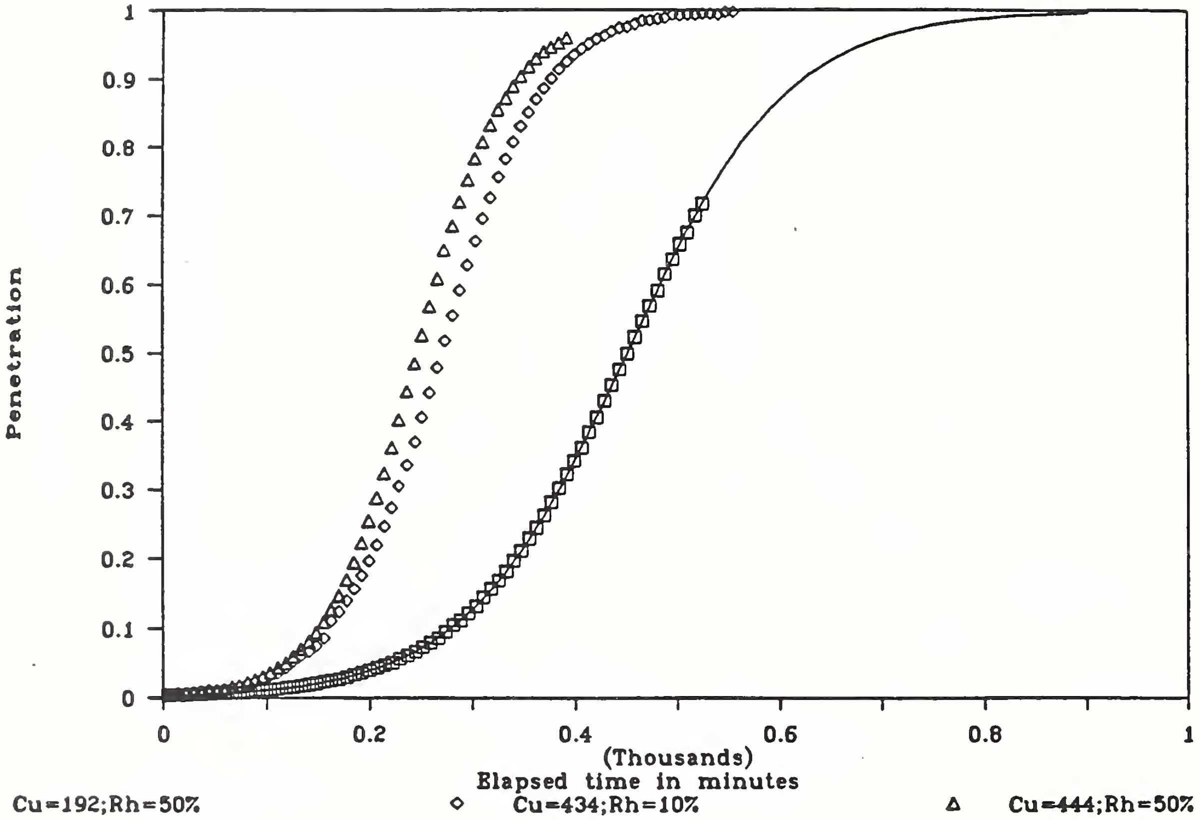

Figure 15. Penetration vs elapsed time for toluene
Tests # 1, 2 and 3

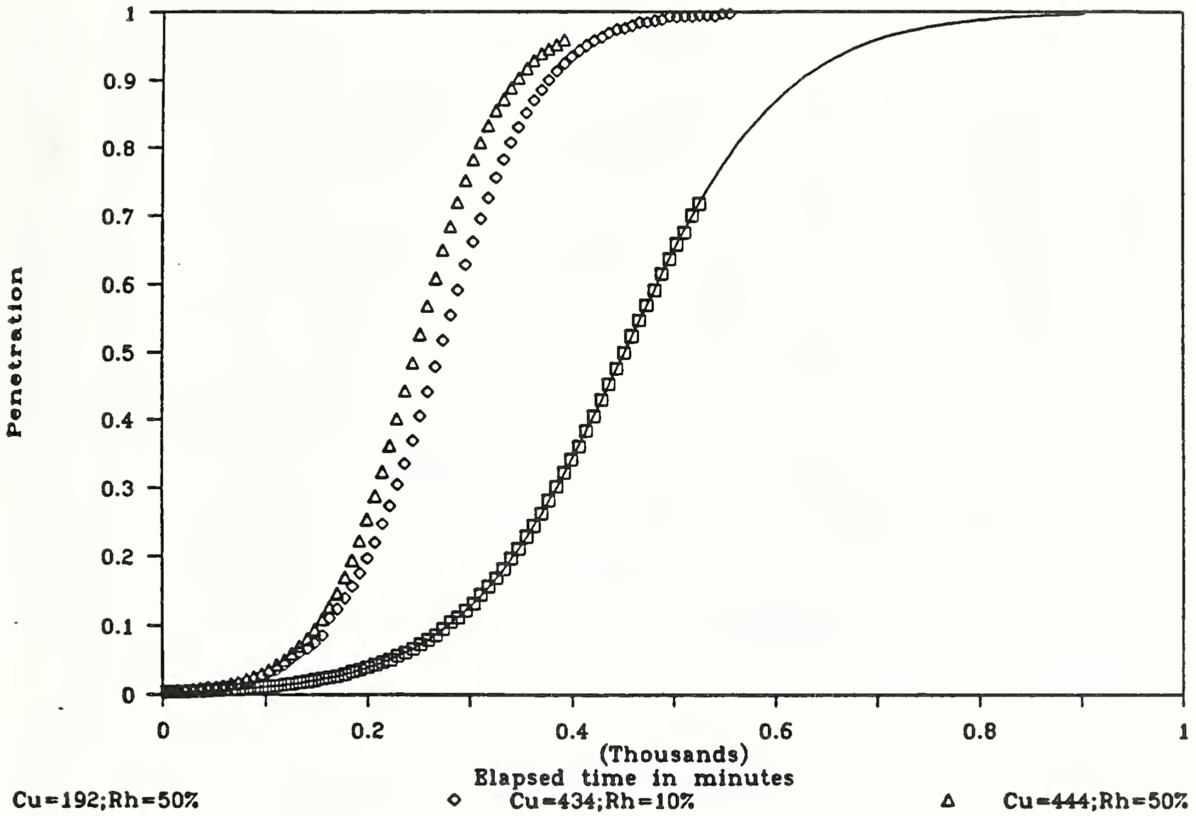

Figure 16. Effective penetration vs elapsed time for toluene Tests #3, 4, 5 and 6

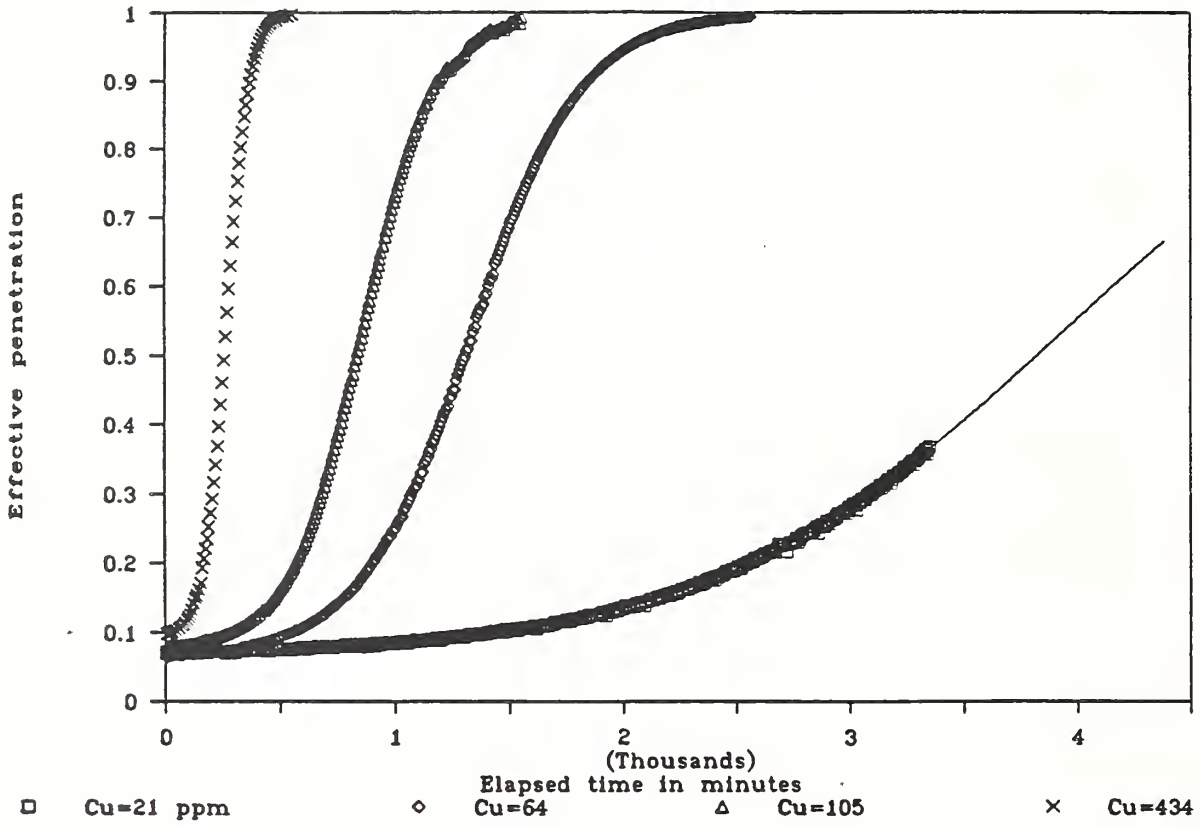

Figure 17. Penetration vs elapsed time for toluene
Tests # 3, 4, 5 and 6

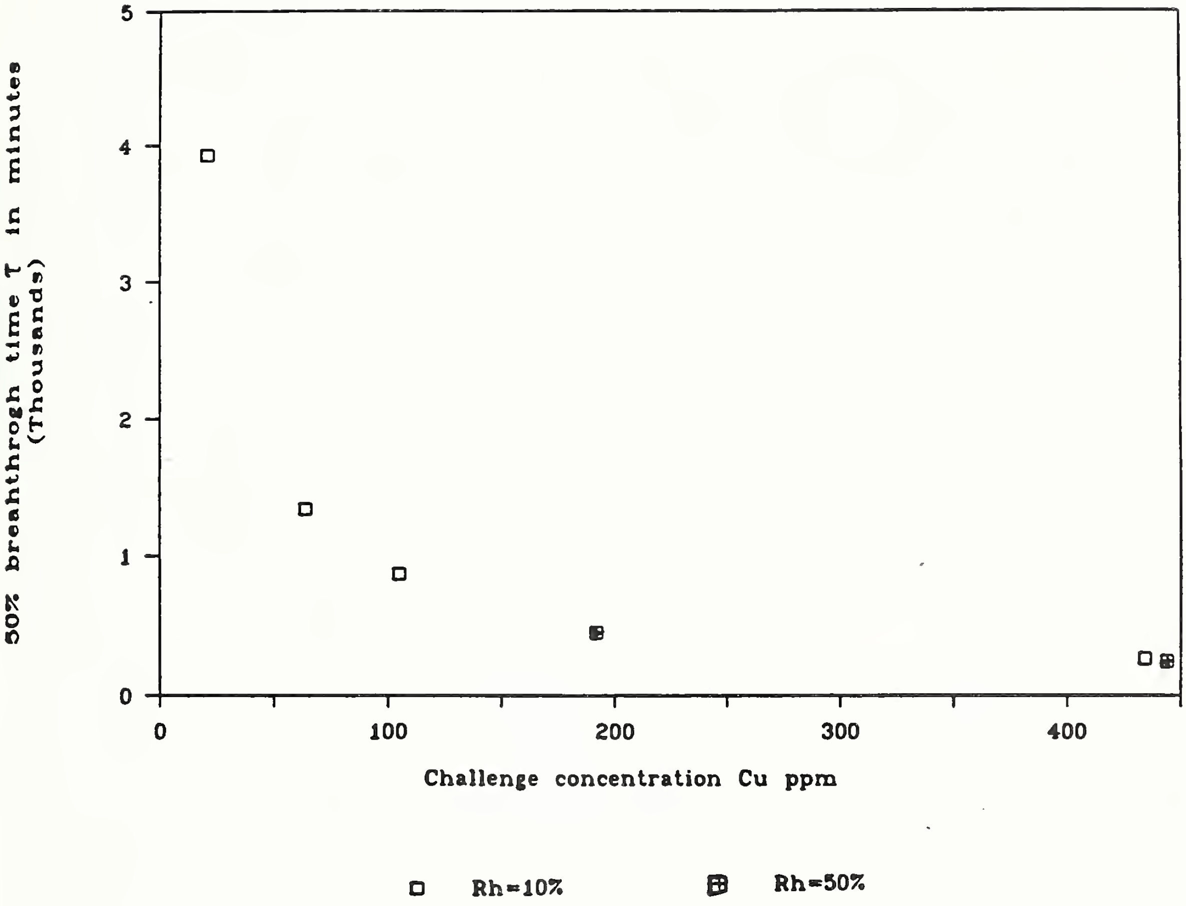

Figure 18. τ vs C_u for toluene

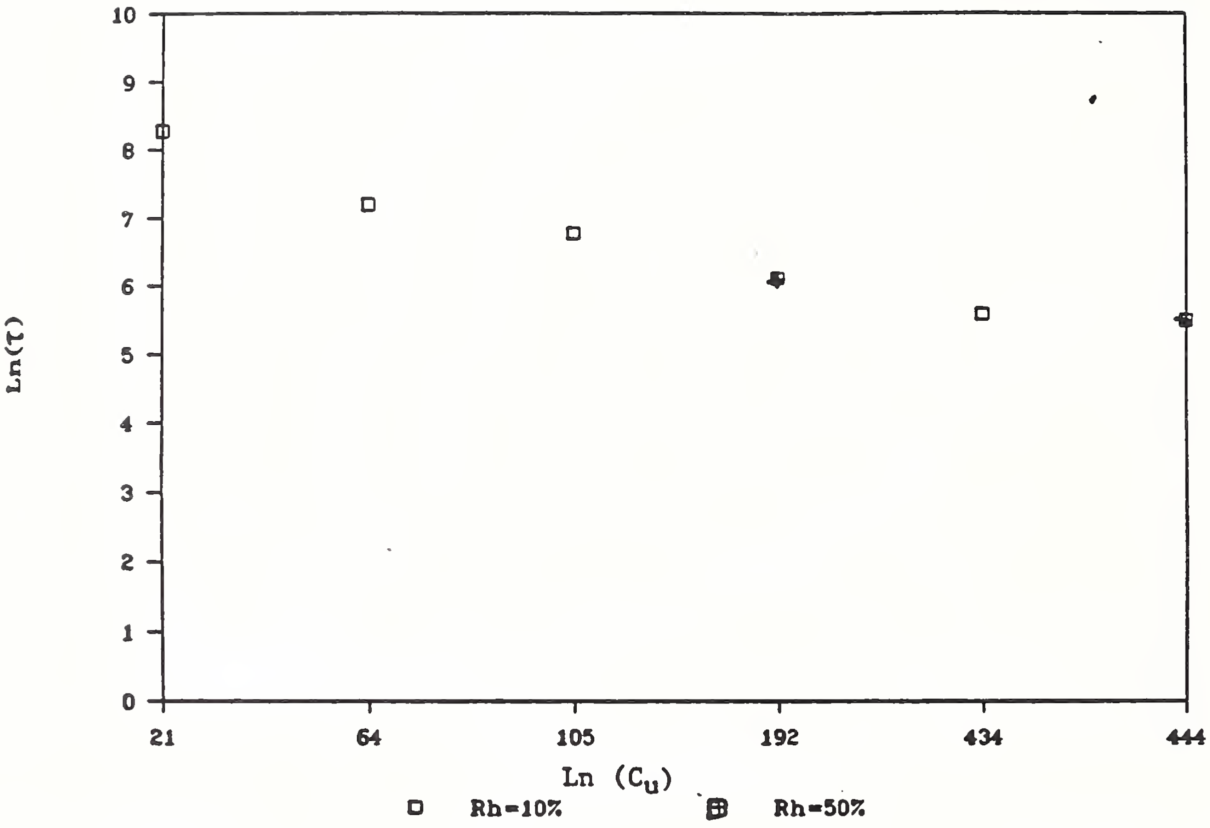

Figure 19. Ln (τ) vs Ln (C_u) for toluene

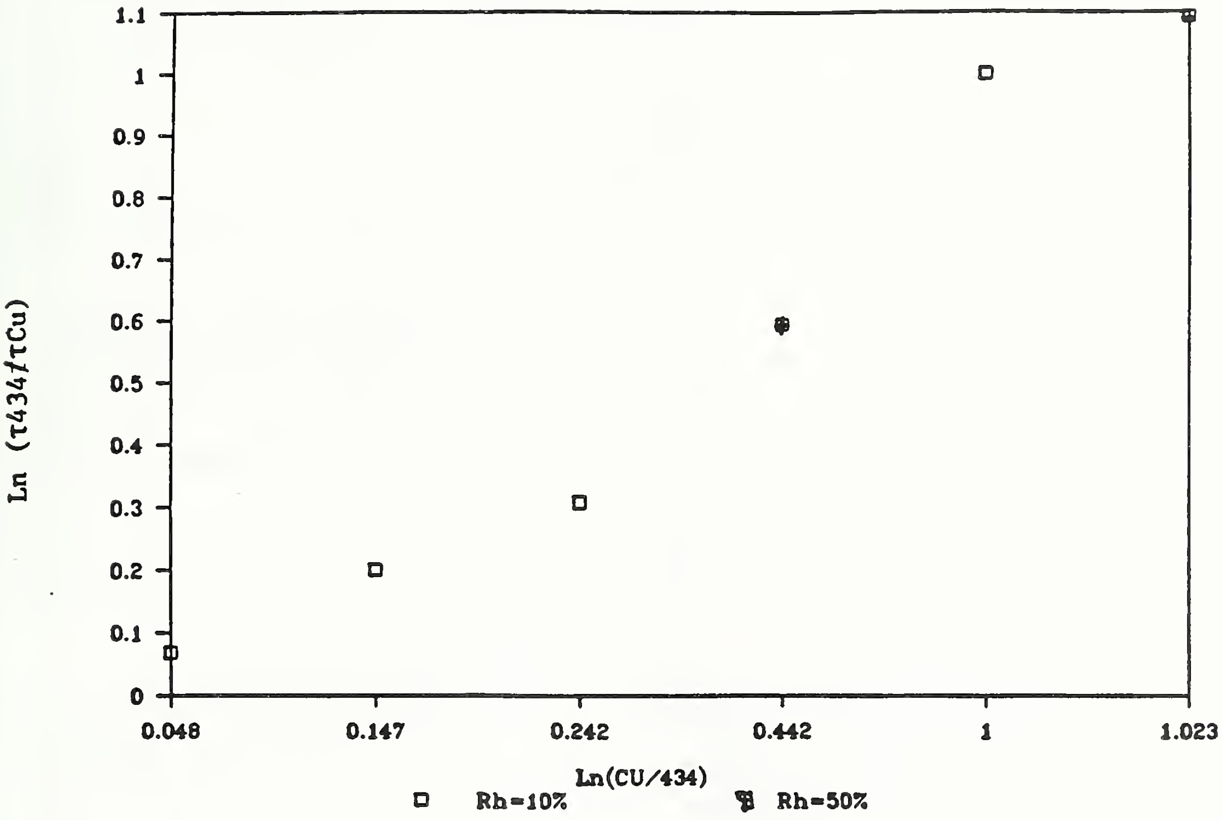

Figure 20. Ln (τ434/τcu) vs Ln (Cu/434) for toluene

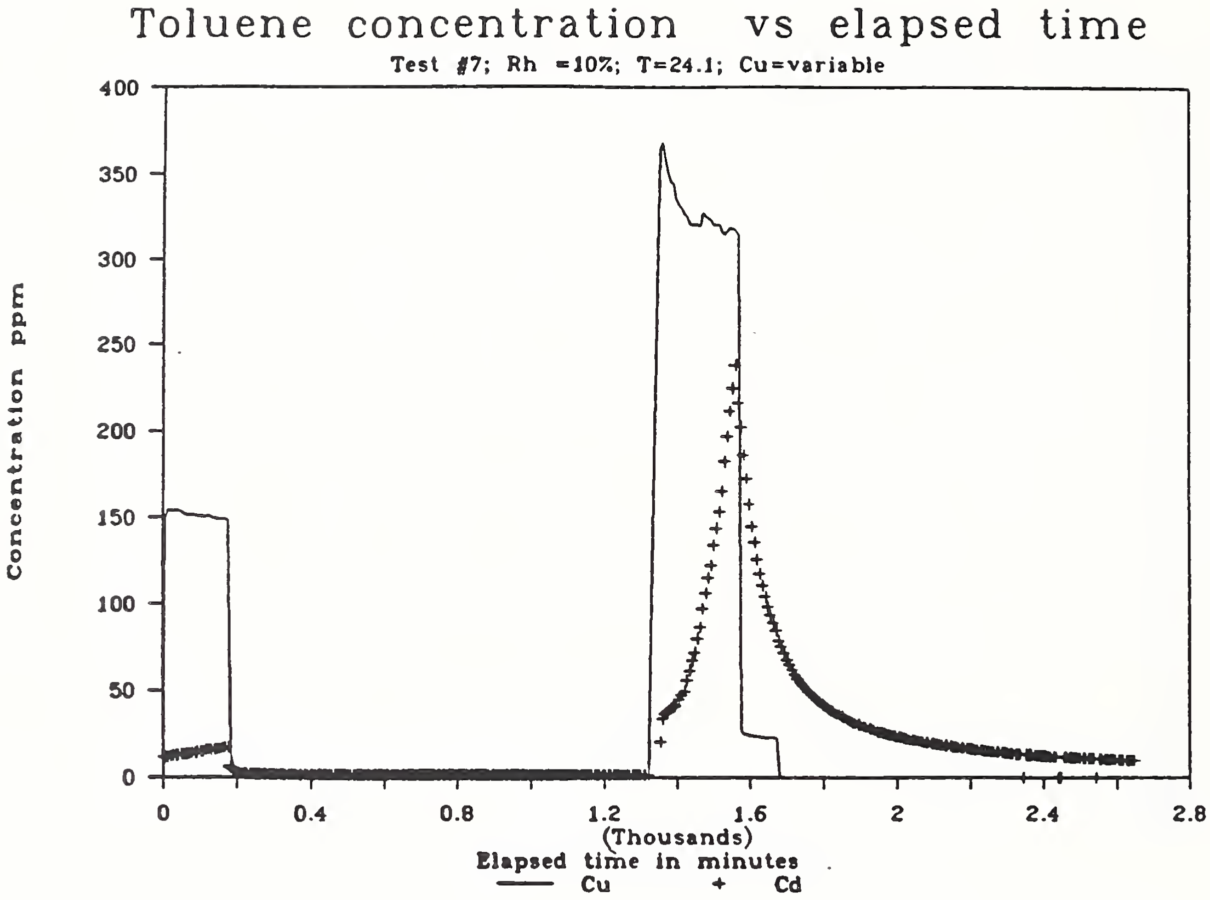

Figure 21. Toluene concentration vs elapsed time
Test #7; Rh =10%; T=24.1; Cu=variable

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A research effort to develop test methods for measuring the effectiveness of gaseous contaminant removal devices is underway. The objectives of the research effort were to devise or select a practical test method, design a test apparatus suitable for this purpose, and conduct preliminary experiments to demonstrate the feasibility of the testing scheme. This report presents a brief review of the gas adsorption kinetics theory applicable to adsorption of gaseous contaminants by filter media, and an algorithm for assessing the effectiveness of filtering devices with flow bypass. It briefly describes the selected testing technique for measuring the effectiveness of filter media, and presents experimental data for adsorption of n-butane, toluene, and carbon monoxide.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

Adsorption; contaminant; efficiency; filter; gaseous; granular; media; method; penetration; removal; test.

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