

The Effect of Challenge Concentration on the Gas Life of Respirator Filters

C. John Littleton and John R. Feeney

Protector Safety Limited, Pimbo Rd, West Pimbo, Skelmersdale, Lancashire, England.
WN8 9RA

Abstract

Performance standards call for filters to be tested against certain test agents at specified concentrations. However, the majority of workplace situations will have a significantly lower concentration of contaminants. This leads to the question "how long will a filter remain effective in service?" The commonly used approximation is to assume that the filter life doubles when the concentration is halved. This may not be a good assumption. A variety of test agents have been used to test filters at concentrations ranging from 0.05 to 1.0%. These data indicate that for chlorine and sulphur dioxide the time to breakthrough more than doubled when the concentration was halved, whereas for the organic species studied, the breakthrough times were often significantly less than double when the concentration was halved.

Introduction

Gas respirator filters are used to remove toxic gases and vapours from otherwise breathable air. However, the filter life is often difficult to predict. The most widely used criterion for changing the filter is to rely on the olfactory sense of the wearer to detect breakthrough. This is not ideal as (a) it relies on the sensitivity of the olfactory system, which may vary within the population and (b) the exposure at the point of breakthrough may be hazardous to health. Thus, a method of estimating the life expectancy of filters in workplace situations is desirable. The whole philosophy behind the use of gas filters, and the problems associated with their use, has been reviewed by Nelson and coworkers.¹

The question "how long will a gas filter remain effective in service?" is often asked; this

question is addressed here. Performance standards, such as EN141, specify breakthrough times for gas filters under specified conditions.² These standards are used both for type approval and quality control by the manufacturer. However, only a few test agents (at a few concentrations, under defined conditions) are specified. Each filter manufacturer will test filters against these test agents at the concentrations indicated in the standards. The concentrations are usually selected to be at or in excess of any likely workplace concentration and also to give a destructive test that can be completed within two hours, but preferably much less. A large amount of data have therefore been collected at these concentrations and there is a wide tendency to try to use the data in predicting life expectancy of filters in service. The majority of workplace situations where gas filters are used,

will have significantly lower concentrations of contaminants than the test atmospheres called for in the standards. Additionally, the toxic contaminant will almost always be other than one of the test agents specified in the standards, yet the quality control data are still used to give a prediction of filter performance. The commonly used rule of thumb being is the breakthrough time will double when the influent concentration is halved. This may not be a good assumption.

There remains very little published experimental data on the breakthrough times for gas filters. Nelson et al. has attempted to generate test data to investigate filter performance.^{1,3-9} A mechanical breathing simulator was constructed⁴ but tests indicated that there was no significant difference between steady and pulsating flow rate modes.⁵ This has since been confirmed by Reidiger¹⁰ and consequently the work reported here has been performed at steady-state flow rates.

Nelson also investigated the service life of respirators against over 100 different organic solvent vapours.⁶ This work served to give a ranking order for solvents and the following general conclusions were made: Gas filters have a longer service life against (1) higher boiling point compounds and (2) compounds of low polarity. This data was obtained at 1000 parts per million (ppm) influent concentration using organic vapour cartridges that had been preconditioned at 50% RH and 22°C, with test air similarly conditioned. The effect of both changing the preconditioning and the test conditions was also investigated.⁶ The authors found that the performance of filters against some of the agents tested decreased markedly when the relative humidity exceeded 65%.

Lardeaux¹¹ attempted to reinterpret Nelson's data and postulated that if the behaviour of a filter towards carbon tetrachloride was **known—under a given set of conditions**—then a fairly accurate idea of its behaviour with respect to any given contaminant could be gained. The assumption that must be made in order for this theory to hold true is that the ratio of breakthrough times for carbon tetrachloride and a given contaminant at any given set of conditions is a constant. Some of the data presented here appears to contradict this theory (see later under discussion) and indeed Nelson's own data⁷ indicate that when the concentration of the contaminant is changed then the ratio of breakthrough times may also change. This is indicated, both here and in Nelson's work, by the $\log(\text{breakthrough time})$ against $\log(\text{concentration})$ plots. The graphs all show reasonable linearity, but they are not necessarily parallel, which indicates that comparisons of the type proposed by Lardeaux hold true only at the concentrations under which the filters were actually tested. This in turn indicates that the filters need to be tested at low concentrations of the specific contaminant.

There is an almost infinite number of substances but limited time available for testing, thus a quick method of determining approximate life expectancy must be found. The work reported here follows the example of Nelson et al. and attempts to generate linear plots for empirical functions of time/concentration, which can then be extrapolated to even lower (workplace) concentrations.

Experimental

Steady flow rate gas filter test rigs are essentially simple in construction. The filter performance is assessed by drawing a known (influent) concentration of test agent at a known flow rate through the filter and monitoring the downstream (effluent) air for the test agent. The breakthrough time is the time at which a predetermined concentration of the test agent is detected in the effluent air. The apparatus is shown schematically in Figure 1. Laboratory air was drawn through a humidifying unit to generate test air of a known relative humidity which was measured by a wet and dry bulb hygrometer. The humidity was

maintained at $70 \pm 2\%$ RH in accordance with EN 141. The test agent was metered into the flow of conditioned air either by using a peristaltic pump for liquid test agents or by a calibrated flowmeter for gaseous test agents. A heater positioned inside the mixing chamber ensured that the liquid test agents were completely vaporized. The influent concentration was calculated from mass loss calculations based on the test agent reservoir for both liquid and gaseous test agents. Filters were tested in pairs with the bulk air flow through each filter being regulated to 30 cubic decimeter per minute ($\text{dm}^3\text{min}^{-1}$). A Miran 1B2 variable-

pathlength infrared spectrometer was used to monitor the effluent air streams. The breakthrough times were recorded when the effluent concentration reached 10 ppm, the breakthrough concentration for the carbon tetrachloride test given in EN141. An electronic switching unit allowed each stream to be sampled alternately on a two-minute cycle time, allowing breakthrough times to be recorded for both filters tested. All the individual times (not the averages) were used in the calculations. A diaphragm pump was used to pull the $30 \text{ dm}^3 \text{ min}^{-1}$ air flow through each of the filters.

Class 2 filters are defined in EN141 as being medium capacity gas/vapour filters and are tested

at 5000 ppm influent concentration and $30 \text{ dm}^3 \text{ min}^{-1}$. Four basic types of filter are defined:

- A**—for use against organic vapours with a boiling point greater than 65°C .
- B**—for use against inorganic gases.
- E**—for use against acidic gases.
- K**—for use against ammonia and ammonia derivatives.

Class 2 filters defined above were tested against a number of different toxic substances. The specific type of filter used in each case being dependent on the nature of the substance. The filters tested and the specific substances against which they were tested are given in Table 1.

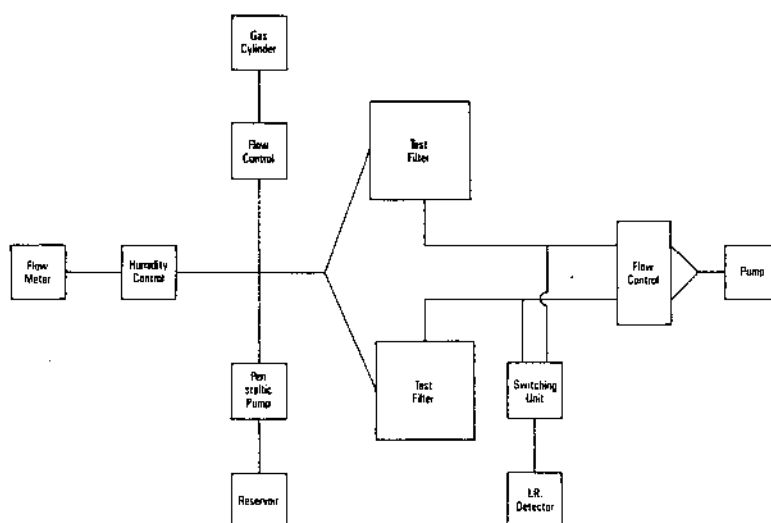


Figure 1. Schematic diagram of the filter testing system.

Results and Discussion

The often used *assumption* that if the concentration is halved then the gas life of a filter will double can be expressed mathematically by:

$$t_b = a/C \quad (t_b = aC^{-1}) \quad (1)$$

where t_b is the breakthrough time, C is the influent concentration, and a is a constant.

The work of Nelson et.al. indicated that a modification is required and a logarithmic expression of the form:

$$t_b = aC^{-n} \quad (\text{or } \text{Log } t_b = \text{Log } a - n \text{Log } C) \quad (2)$$

holds true for the species studied to date, where n is a constant. A plot of $\text{Log}(\text{breakthrough time})$ against $\text{Log}(\text{concentration})$ should yield a straight line of gradient equal to n if Eq (2) holds true.

For situations where n exceeds 1, the gas life will more than double when the concentration is halved, thus the assumption expressed in Eq (1) errs on the side of safety. However, when n is less than 1, the assumption will overstate the gas life of a filter with the overstatement increasing as n tends towards zero.

Table 1 Values of n calculated for the different test agents.

Test agent	Filter type	This work n	Nelson n
Chlorine(*C12)	2B	1.16	
Sulphur dioxide (*SO2)	2E	1.35	
Ammonia (*NH2)	2K	0.85	
Pentane (C2H12)	2A	0.86	
Hexane (C6H14)	2A	0.95	0.94/0.91
Heptane (C7H16)	2A	0.94	
Octane (C8H18)	2A	0.92	
Trichloroethylene (C2HC13)	2A	0.85	
Carbon tetrachloride (*CCl4)	2A	0.92	0.67
Chloroform(CHC13)	2A	0.84	
Dichloromethane (CH2C12)	2A	0.59	0.39
Acetone (C3H6O)	2A	0.67	0.45/0.62
Ethylacetate (C4H8O2)	2A	0.91	
Diethylamine (C4H11N)			0.73
Benzene (C6H6)			0.74
Methylacetate (C3H6O2)			0.54
Isopropanol (C3H8O)			0.60
Vinyl chloride (C2H3C1)			0.39

NOTES

n is defined in Equation 2 and is the gradient of the lines plotted in Figures 2 and 4.

Those marked with an asterisk are EN141 test agents. Other test agents were selected on the basis of customers requesting information.

Chlorine, sulphur dioxide and ammonia can be removed from air using gas filters of type B (inorganic gases), E (acidic gases), and K (ammonia and ammonia derivatives), respectively. These filters generally function by the process of chemisorption, which means that they chemically (irreversibly) bind the species to the charcoal filtering media. Chlorine, sulphur dioxide, and ammonia were used to test B, E, and K filters, respectively, at a range of concentrations. The data are plotted in Figure 2 and a regression analysis reveals that the data are described by Eq (2). The calculated values for n are given in Table 1.

The values of n obtained for both chlorine and sulphur dioxide are greater than 1, and therefore these species do not create a problem when trying to extrapolate down to workplace concentrations (under the conditions employed during these tests). That is to say, assuming the wearer breathes 70% RH air at a rate of 30 dm³min⁻¹ in an atmosphere that contains a known and constant level of either chlorine or sulphur dioxide (and no other contaminant), then

the simplifying assumption expressed in Eq (1) should err on the side of safety.

The figure of 0.85 found for ammonia poses a problem. Since ammonia is chemisorbed onto an impregnated charcoal, it could be expected to behave in a similar manner to chlorine and sulphur dioxide. However, it does not, and this apparent anomaly may be related to the high moisture content of the K2 type of filters tested here. Clearly, further work is required to try to understand this system.

Chemisorbed species could be expected to have values for n greater than 1 from the application of the principles laid down by Grubner and Burgess,¹² who used normal distribution curves to indicate a concentration gradient within the carbon bed. Grubner and Burgess used this to explain the nature of breakthrough curves. Here the principles are used to explain values of n that are greater than 1. A diagram showing a schematic representation of the system is given in Figure 3. Increasing the concentration will in-

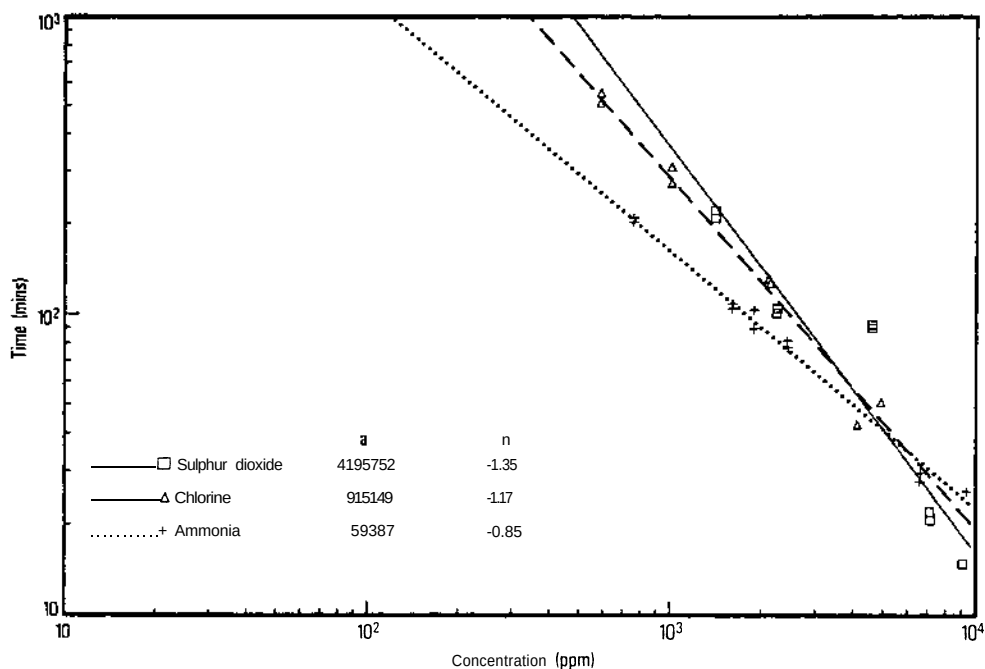


Figure 2. Breakthrough times as a function of the influent concentration of the chemisorbed species.

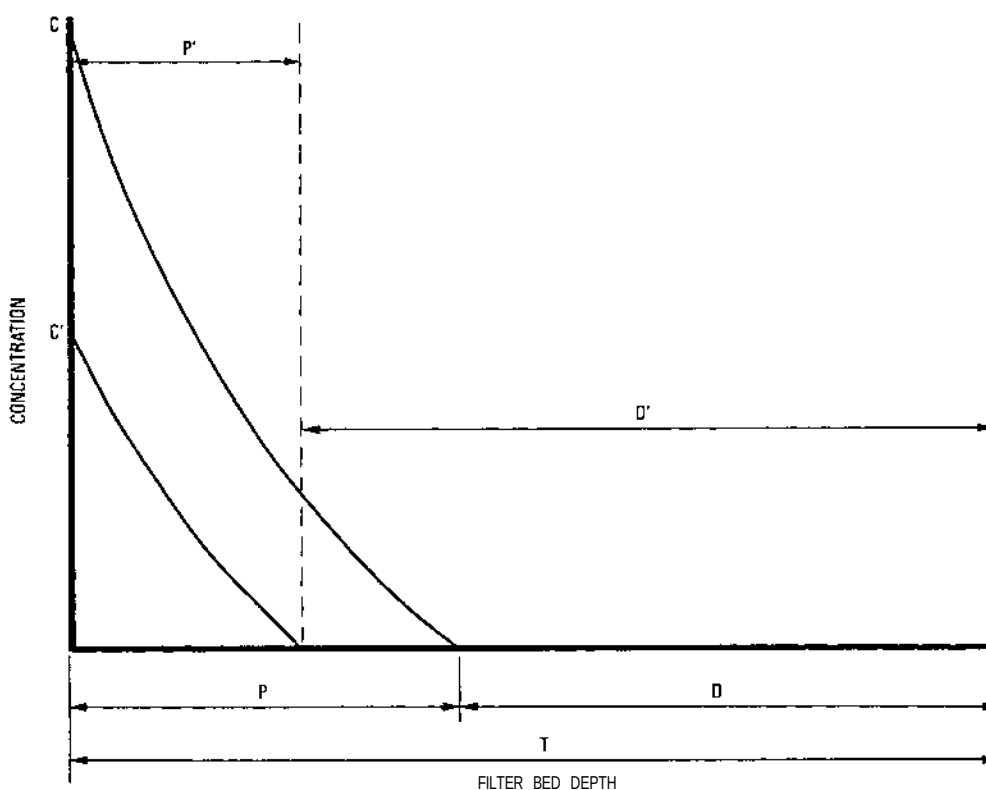


Figure 3. Schematic representation showing the effective bed depth decreasing as the influent concentration is increased. T = Total carbon bed depth within the filter; P = Depth of penetration of a substance at a concentration of C ; D = Effective bed depth of the filter at a concentration of C ; P' = Depth of penetration of a substance at a concentration of C' ; D' = Effective bed depth of the filter at a concentration of C' .

crease the penetration of a species into the carbon bed initially (distance represented by P in Figure 3). As a consequence, the effective bed depth (distance represented by D in Figure 3) decreases and hence a shorter breakthrough time is predicted than would be predicted from Eq (1).

The same phenomenon will also occur when organic gases and vapours are adsorbed onto type A filters, although the filters operate by (reversible) physisorption. Data relating to organic gases and vapours are plotted in Figure 4. In each case, the values for n have been calculated from Eq (2) and are included in Table 1. Interestingly, all the values for n are less than one, indicating that a second mechanism must be in operation. There exists the possibility for desorption to occur when filters that rely on physisorption only are used. All the organic species studied to date have shown a value for n less than 1, thus all these species must show some degree of desorption in order to overcome the mechanism, which would tend to increase the numerical value of n to be greater than one.

The actual values for n that were obtained during this study are also of interest. Clearly, as the physisorption becomes stronger then the value for n will increase towards 1. Conversely, species yielding a low value for n show more pronounced desorption characteristics. Traditionally, low-boiling-point organic compounds (boiling point below 65°C) are expected to show the highest levels of desorption and hence be the most difficult to predict the life expectancy of a filter. However, this work indicates that the chemical nature of the species is also important in determining the value for n . Acetone is a good example of this (Figure 4). At about 5000 ppm, influent concentration the filter shows similar efficacy against both acetone and ethylacetate, values of about 45 minutes being typical for both compounds. Acetone has a boiling point of 56°C but a value for n of only 0.67. Whereas ethylacetate has a boiling point of 77°C and a value for n of 0.91. It is likely that the low value of n obtained from acetone is due to the polar nature of the molecule. Similarly, other polar molecules would be expected to show low values for n . This comparison shows the danger of assuming that all chemicals behave the same with respect to concentration. Predictions of filter performance at low concentrations (say 100 ppm), based only on testing at 5000 ppm, would indicate that the filter life against acetone would be equal to that obtained against ethylacetate. Calculations based on

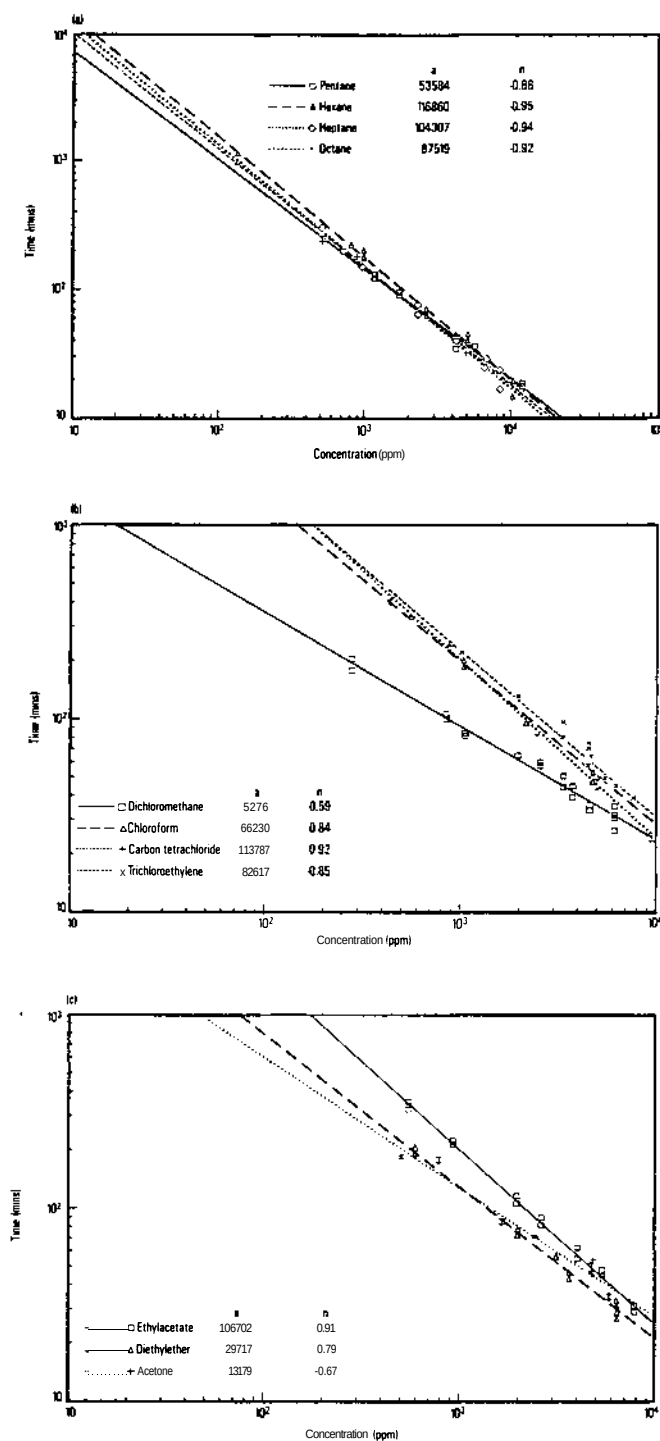


Figure 4 Breakthrough times as a function of the influent concentration of the physisorbed (organic) compounds. a) alkanes, b) chlorinated and c) miscellaneous compounds.

three different approaches demonstrate the dangers:

**Expected life of filters
at 100 ppm acetone**

1. Assuming Eq (1) is adequate	2250 mins
2. Assuming acetone behaves in the same manner as ethylacetate (n=0.91 for acetone)	1600 mins
3. Prediction based on the data obtained for acetone in this study (n=0.67)	650 mins

The second approach is similar to that adopted by Lardeaux¹¹ but it overstates the likely life expectancy by about 250%, and for many applications this would not be acceptable. An even worse prediction is produced (350% overestimation) when the Eq (1) approximation is used. Thus, the best way to gain a true reflection of filter life is to gas test at a number of different concentrations in order to generate a specific value of n for each substance. The expected breakthrough time at a given concentration can then be calculated from:

$$t_b = t_b' (C'/C)^n \quad (3)$$

where t_b is the expected breakthrough time at a workplace concentration of C, t_b' is the breakthrough time measured at a concentration of C' , and n is a constant determined by testing at a number of different concentrations.

Finally, a comparison of the values obtained in this study using Class 2 Protector Safety Ltd filters with those obtained by Nelson using the equivalent of the Class 1 filters defined in EN 141 yields some interesting differences. The data is summarized in Table 1. In each case where a comparison can be made, the values for n in the work reported here are higher than those reported by Nelson. This could be due to one or more of a number of factors. Firstly, the filters used here contain much more carbon, and secondly Nelson preconditioned the filters prior to use. The preconditioning involved equilibrating the filters with moist air before testing. This has been shown to have an adverse affect on organic cartridge filter performance at 1000 ppm and may account for the differences observed here.⁸ Finally, Nelson reported breakthrough times at typically 10% of the influent concentration, leading to breakthrough concentrations between 5 and 200 ppm (depending on the influent concentration), whereas in the work reported here the breakthrough concentration was always 10 ppm. Again this may go some way toward explaining the observed differences.

Conclusions

This work was initiated to give us a greater understanding of how filters behave in service. We have assumed that the filters will be used as received, in atmospheres of constant contaminant levels and 70% relative humidity. In addition, we have assumed that the wearer is breathing at 30 dm³min⁻¹, that there is only one contaminant present, and that the filter is used continuously. Clearly, some or all of these conditions may not be met in practice and so the data generated here must only be used as a guide to filter performance.

For two of the three chemisorbed species (chlorine and sulphur dioxide), the experimental values for n were found to be greater than one; hence for these species it would appear reasonable to assume that halving the concentration doubles the time to breakthrough. The situation with ammonia is in some doubt, and further work is required to assess this apparent anomaly. For the physisorbed species (organics) the value of n was

always less than 1, but there was quite a large range (0.59 to 0.95). To be able to predict filter life accurately, testing must be carried out at two or more different concentrations. Generally, concentrations in the range 500 to 5000 ppm should be used to simplify the experimental procedures.

In future work, we aim to test at 1000 and 5000 ppm only and extrapolate down to low (workplace) concentrations. The next stage will be to modify the existing gas-test rig such that these very low concentrations can be achieved to test the data produced by extrapolating from only two concentrations. The work will be performed at a variety of initial carbon moisture contents to test whether this aspect **affects** the experimentally determined value for n. In addition, we intend to start trials on partially used filters to test for residual life. These trials, if successful, could yield the optimum method for determining filter life expectancy in an individual application.

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