

## Removal of Low Concentrations of Acid Gases: Issues and Solutions

Andrew J. Dallas,<sup>\*a</sup> Lefei Ding,<sup>a</sup> Jeremy Exley,<sup>a</sup> Jon Joriman,<sup>a</sup> Brian Hoang,<sup>b</sup> Jonathan Parsons<sup>b</sup>,  
Kevin Seguin<sup>b</sup>, and Dustin Zastera<sup>a</sup>

<sup>a</sup>Donaldson Co., Inc., Corporate Technology, 9301 James Ave., Bloomington, MN 55431

<sup>b</sup>Donaldson Co., Inc., High Purity Products, 9301 James Ave., Bloomington, MN 55431

### ABSTRACT

Part per billion concentrations of acid gases such as SO<sub>x</sub> and NO<sub>x</sub> have been detected in both high purity gases and CDA lines. These contaminants can have deleterious effects on a number of high purity applications such as the optics found in lithography equipment steppers, scanners, and inspection tools. In addition, acidic gases have also been shown to reduce the life of masks and reticles, decrease fuel cell output due to catalyst poisoning, and cause hard disk drive crashes due to surface contamination and corrosion. Consequently, acid gas control in these applications has become a critical part of the required filtration system.

SO<sub>x</sub> concentrations are typically used as the baseline for acid gas filter exposure guidelines and performance testing. However, this approach has been shown to provide poor filter life predictions, which has been attributed to the presence of other acidic and organic contaminants that compete with SO<sub>x</sub> for the available adsorption sites. Equally important, the type of sorbents and methods used to control acid gases can significantly affect the ability to remove SO<sub>x</sub>. In this work we will compare the performance of various sorbents, structures, and methods for the removal of SO<sub>x</sub> and NO<sub>x</sub>.

Keywords: acid gas filtration, acid gas removal, chemical filtration, airborne molecular contamination, contamination control, low pressure drop, oxides of nitrogen, NO<sub>x</sub>, oxides of sulfur, SO<sub>x</sub>

### 1. INTRODUCTION

Acid gases are ubiquitous in the environment and can pose problems for a wide range of applications that demand high purity air. For example, semiconductor processing, fuel cell operation, emissions testing, dilution air for testing and manufacturing, hard disk drives, aircraft cabins, and gas turbines all suffer deleterious effects due to exposure to acid gases. The sensitivity of these applications to the type and concentration of acid gases can vary significantly. SO<sub>x</sub>, NO<sub>x</sub>, H<sub>2</sub>S, and HCl levels can vary in the ambient environment from more than 50 ppmv to less than 1 ppbv. Reducing the working concentration of these acid gases to pptv levels is critical for semiconductor processing environments; however, ppmv-ppbv levels may be adequate for many other applications.

Designing acid gas filters to provide the specified air purity requirement imposes great demands on the choice of media and the structure of the media. Besides being able to obtain a specified purity for a given length of time, critical requirements can exist relative to the filter footprint, weight, pressure drop, and flammability. For example, in semiconductor processing, tool mount and full fab acid gas filters require excellent removal efficiency, long life, light weight, very low pressure drop, and flow reconstruction. All of these factors are difficult to achieve with a single structure and media type.

Currently, the state of the filtration industry is such that the optimum filter life and removal efficiency for acid gases is offered by granular filter beds. However, these attributes that make these packed beds extremely efficient also impart issues related to elevated filter weight and pressure drop. Low pressure drop filters, such as those designed as open-channel networks (OCN's), offer good filter life and removal efficiency, with the additional benefits of significant reductions in overall filter weight and pressure drop. Equally important for many applications, the OCN filters can reconstruct the airflow so as to enhance the operation of a tool or process.<sup>1-7</sup> For tool mount assemblies and full fan unit filters this can result in reduced fan and blower speeds, which subsequently can provide reduced vibration and energy

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\* andrewd@corptech.donaldson.com; phone 1 952 887-3318; fax 1 952 887-3937; <http://www.donaldson.com>

costs. Additionally, these low pressure drop designs can provide a cost effective way of effectively removing acid gases in full fab (or HVAC) filtration applications without significantly affecting air-handling requirements. For various types of aircrafts, these low pressure drop designs can be easily modified in order to minimize flammability concerns.

This work is directed at providing insight into our investigations of granular filters as well as low pressure drop designs for the removal of  $\text{SO}_x$ ,  $\text{NO}_x$ ,  $\text{H}_2\text{S}$ , and  $\text{HCl}$ . Several of the advantages and disadvantages of both approaches are highlighted. The granular studies compare non-impregnated and impregnated activated carbon. Contrasted with these studies are some preliminary results from our proprietary low pressure drop media designs. We note, that primarily modified fibrous networks (LPD-FN) are used to meet the pressure drop requirements of the above stated high purity applications. The design and application of these fibrous network medias and structures are currently patent pending, thereby preventing us from providing full descriptions in this report.

## 2. EXPERIMENTAL

The materials we have evaluated are contrasted using acid gas challenge breakthrough tests, pressure drop measurements, full filter weight measurements; and in the case of the open channel fibrous network filter design, the particulation of ionic contaminants is also evaluated with and without an acid gas challenge. These comparisons are made for three low pressure drop fibrous network (LPD-FN) designs, a low pressure drop coated open channel network (LPD-CN), a high surface area coconut based non-impregnated activated carbon (NIC), and a similar activated carbon impregnated for acid gas removal (AGR). The four LPD-FN's are given the non-descript designations LPD-FN1, LPD-FN2, LPD-FN3, and LPD-FN4 since these are considered proprietary materials.

### 2.1. Breakthrough Testing:

Acid gas breakthrough tests were performed on non-impregnated and impregnated granular activated carbon filters and fibrous network filters. Test were performed with  $\text{SO}_2$ ,  $\text{NO}$ ,  $\text{NO}_2$ ,  $\text{H}_2\text{S}$ , and  $\text{HCl}$ . A wide range of concentration, residence time, and humidity has been evaluated. For brevity, we will not address the affects of humidity in this work; these efforts will be the source of a future report. For some background details on some of our humidity studies with granular materials, the reader is referred to reference 8.

A general block diagram of our breakthrough test bench design is given in reference 8. Contaminants were generated from certified gas standards delivered into the test airstream through mass flow controllers (Aalborg; Orangeburg, NY; or Brooks/Emerson Process Management, Hatfield, PA). The relative humidity was controlled using a Flow-Temperature-Humidity Controller (Miller-Nelson Research, Inc.; Monterey, CA); Model HCS-401. A relative humidity of 50% RH was used for the studies presented herein. The temperature and relative humidity of the airstream upstream and downstream of the adsorbent bed were measured using calibrated temperature and humidity sensors (Vaisala; Woburn, MA; Model HMP233; or J&W Instruments, New Brighton, MN, Teledyne loop powered dew point transmitters XTR-100). The temperature of the adsorbent bed was controlled at  $25^\circ\text{C}$  using a water-jacketed sample holder and a water bath. Detection of the upstream and downstream contaminant concentration was monitored using specific detectors. A listing of the detectors used for each test are listed below:

1.  $\text{SO}_2$ , 100, 75, 50, and 25 ppm, FTIR detector (Thermo Electron Corp.; Franklin, MA; Miran 1B2).
2.  $\text{SO}_2$ , 1000 and 500 ppb, pulsed fluorescence detector, (Thermo Electron Corp.; Franklin, MA; Model 43C).
3.  $\text{NO}/\text{NO}_2/\text{NO}_x$ , 50 ppm, chemiluminescent detector (Teledyne Monitor Labs, Inc.; Englewood, CO; Model 9841AS).
4.  $\text{H}_2\text{S}$ , 10 ppm, electrochemical detector, (Interscan Corp.; Chatsworth, CA; Model 117-LD).
5.  $\text{HCl}$ , 35 ppm, FTIR detector (On-Line Technologies, Inc.; East Hartford, CT; Model 2010 Multi-Gas Analyzer).

All testing, except  $\text{HCl}$ , was performed at 30 LPM.  $\text{HCl}$ , testing was performed at 52 LPM. Residence times were varied by changing the test bed volume.

## 2.2. Pressure Drop:

Pressure drop measurements were conducted on Donaldson's Low Flow Pressure Drop test system. The airflow was maintained using a Hoffman blower assembly. The pressure drop across the element was monitored using high precision manometers. All test filter elements were constructed so as to have a similar configuration that met the testing requirements. In the case of granular activated carbon, 1.0 inch of 12x20 mesh granules was used. The low pressure drop filter designs were tested at several filter lengths varying from 1.0 to 6.0 inches.

## 2.3. Ionic Particulation:

Our fibrous low pressure drop filters, LPD-FN's, were evaluated for their potential to contribute to ionic contamination downstream of the filter. The modified fibrous low pressure drop filters were placed in the same breakthrough test bench for SO<sub>2</sub> described above. These filters were challenged with clean air and air contaminated with 500 ppbv of SO<sub>2</sub> under the same conditions as used for the breakthrough tests. The filters were exposed for approximately three days. During this time period sampling of the air stream upstream and downstream of the filter was accomplished using two methods:

1. Bubbling a portion of the air stream through a 100 ml aqueous solution at a rate of 40 ml/min.
2. Pulling a portion of the air stream through a series of Orbo cartridges at a rate of 40 ml/min.

The aqueous samples were analyzed directly by ion chromatography for anions and cations. The cartridges were first extracted with water and subsequently analyzed using ion chromatography for anions (F<sup>-</sup>, Cl<sup>-</sup>, Br<sup>-</sup>, I<sup>-</sup>, NO<sub>2</sub><sup>-</sup>, NO<sub>3</sub><sup>-</sup>, SO<sub>4</sub><sup>-2</sup>, and PO<sub>4</sub><sup>-3</sup>) and cations (Li<sup>+</sup>, Na<sup>+</sup>, K<sup>+</sup>, NH<sub>4</sub><sup>+</sup>, Mg<sup>+2</sup>, and Ca<sup>+2</sup>). The detection limit for both of these procedures is approximately 5 pptv for each ion in air.

## 3. RESULTS AND DISCUSSION

### 3.1. Packed Bed Filter Breakthrough Testing:

Non-impregnated and impregnated activated carbons have excellent removal efficiency and life for certain acid gases. Figure 1 shows the performance of a high surface area coconut shell NIC carbon in accelerated breakthrough tests for SO<sub>2</sub>, NO<sub>2</sub>, and H<sub>2</sub>S. We note that the H<sub>2</sub>S testing was conducted at 10 ppm, whereas a 50 ppm challenge was used for the other two acid gases. These efficiency breakthrough curves show that this NIC carbon only has excellent removal efficiency for NO<sub>2</sub> at these accelerated test concentrations. However, these data also show it has good capacity for removing all three acid gases.

Although the efficiency breakthrough curve for 50 ppm NO<sub>2</sub> on this NIC carbon indicates it has excellent efficiency and life; as has been observed in previous accelerated testing with NO<sub>2</sub> on activated carbon surfaces, the carbon surface is very effective at reducing NO<sub>2</sub> to NO.<sup>9-11</sup> This mechanism can easily be observed when monitoring multiple channels (NO<sub>2</sub>, NO, and NO<sub>x</sub>) on a NO<sub>x</sub> detector during the breakthrough test. For this 50 ppm NO<sub>2</sub> breakthrough test, the multiple channel display of the raw breakthrough curves is given in Figure 2. As can be seen, the effective removal of NO<sub>2</sub> is accompanied by the "generation" of approximately 50-60% NO. Our investigations have proven that the generation of NO, upon exposure of activated carbon surfaces to these concentrations of NO<sub>2</sub>, takes place on virtually every activated carbon surface.

Packed beds of impregnated activated carbons are known to be the most effective adsorbent for the removal of acid gases. Figure 3 shows the performance of impregnated activated carbons in accelerated tests for SO<sub>2</sub>, NO<sub>2</sub>, H<sub>2</sub>S, and HCl. The AGR media we have evaluated has excellent efficiency and life for all three of the acid gases, even at these elevated test concentrations. The addition of an impregnant improves the overall performance of activated carbon media for the removal of acid gases through the addition of chemisorption sites and by increasing the water capacity of the activated carbon. The reader is referred to reference 12 for an actual comparison for SO<sub>2</sub>.

Again we note the performance of the impregnated activated carbon, AGR media, in the removal of NO<sub>2</sub>. Figure 4 shows that even after impregnation, the activated carbon surface is still very effective at "generating" NO when exposed to these test concentrations of NO<sub>2</sub>. These results suggest that the impregnation of acid gas removing compounds does

not effectively increase, or decrease, the conversion of  $\text{NO}_2$  to  $\text{NO}$  on activated carbon substrates at these elevated concentrations.<sup>13-15</sup> However, these results do not provide conclusions as to what actually takes place at exceptionally low  $\text{NO}_x$  concentrations. As discussed below, these results are very encouraging for our impregnated activated carbon acid gas removal filters.

Our experience is that at typical concentrations found in the field the phenomenon of “generating”  $\text{NO}$  from  $\text{NO}_2$  is not as significant as we have observed at elevated concentrations. Below we provide several examples of field-testing in applications with typical  $\text{NO}_2$  concentrations, performed by independent organizations, indicate that the generation of  $\text{NO}$  is not observed. The California Air Resources Board (CARB) has performed testing with our AGR and NIC medias in a Dilution Air Purification emissions test system. Significant reductions of  $\text{NO}_x$  were observed upon exposure of these medias to approximately 500 ppbv  $\text{NO}_x$ .<sup>12, 16</sup> Los Alamos National Lab (LANL) has shown that fuel cell life and power can be significantly improved using our AGR media when exposed to 5.0 ppmv of  $\text{NO}_2$ .<sup>12</sup> IMEC and DIONEX have combined to show that in 193 nm Lithography applications our AGR filters are effective at reducing  $\text{SO}_2$  levels from ~1.0 ppbv to <5.0 pptv (>99.5% efficiency),  $\text{NO}$  from ~2.0 ppbv to 25 pptv (98.5% efficiency), while maintaining  $\text{NO}_2$  levels below 10 pptv.<sup>17, 18</sup> Currently, we are working in our lab to better understand the performance of various media and substrates against low concentrations of  $\text{NO}_2$  and  $\text{NO}$ .

### 3.2. Low Pressure Drop Filter Breakthrough Testing:

Although packed beds of acid gas removal substrates offer the optimum efficiency and life for a given filter volume, there are many applications where the filter pressure drop and weight can be an issue. Hence, demanding that lightweight, low pressure drop chemical filters be developed. However, the primary issue associated with most low pressure drop chemical filters is that they cannot achieve the removal efficiency and life that well designed packed bed filters and therefore cannot meet the performance demands of many critical, high purity applications. Through extensive investigations directed at better understanding these issues, we have developed LPD-FN and LPD-CN chemical filter designs that overcome most of the typical limitations.

Figure 5 shows the relative performance of several of the LPD-FN and LPD-CN chemical filters for the removal of 50 ppm  $\text{SO}_2$ . The 90% efficiency time is plotted as a function of filter thickness, or in other words, as a function of increasing residence time. We note that the data for LPD-FN3 are very preliminary and should be interpreted with caution at this time.

In all cases, the 1.0 inch deep LPD-FN and LPD-CN acid gas filters did not perform as well as 1.0 inch of the packed bed AGR chemical filter. In fact, for LPD-FN1 and LPD-CN, there appears to be very little perceptible performance benefit. These observations are a result of the flow dynamics in the LPD-FN and LPD-CN designs relative to packed bed structures. As the LPD-FN and LPD-CN acid gas chemical filters increase in thickness, or the residence time of the contaminant is increased in the chemical filter, the relative performance to that of a packed bed increases non-linearly. For comparative purposes, we provide the raw breakthrough curves for three different thicknesses of LPD-FN2 and 1.0 inch of packed bed AGR when challenged against 50 ppm  $\text{SO}_2$  in Figure 6. The non-linearity of the 90% efficiency time is evident in this figure, revealing the additional benefits offered by deeper beds.

From Figure 5, it is interesting to note the performance relationships observed between 1.0 inch of packed bed AGR media and LPD-FN3. From an  $\text{SO}_2$  90% efficiency/life expectancy perspective, 2.0 inches of LPD-FN3 would be predicted to outperform 2.0 inches of the packed bed AGR media by a factor of two. Conversely, the results for 1.0 inch of each media show that 1.0 inch of packed bed AGR media will outperform LPD-FN3 by almost a factor of two. Amazingly, to equal the  $\text{SO}_2$  removal performance of 3.0 inches of LPD-FN3, it would require more than 4.0 inches of packed bed AGR.

The above testing of LPD-FN's, LPD-CN, and packed beds were primarily carried out at an acid gas challenge concentration of 50 ppm. As chemical filter efficiency is a strong function of residence time, its capacity and life are strongly dependent on contaminant concentration. Figure 7 shows the relationship between the 90% efficiency time, in hours, as a function of the  $\text{SO}_2$  concentration for three separate LPD-FN2 chemical filter thicknesses, relative to that of 1.0 inch of a packed bed of AGR. The lowest concentration tested was 500 ppbv  $\text{SO}_2$ . Even at this very high test concentration, 3.0 inches of LPD-FN2 will provide greater than 99.5% removal efficiency for the most of its life and will provide greater than a 90% efficiency for approximately 1.0 year.

It is clear that from an efficiency and life standpoint, the LPD-FN and LPD-CN acid gas chemical filter designs offer great promise in exceeding the requirements of applications that demand high purity air from a low pressure drop and lightweight chemical filter. Ongoing research is directed at applying these LPD-FN and LPD-CN designs to lower concentrations and other acid gases.

### 3.3. Pressure Drop and Weight Comparison:

Besides performance, two of the most critical features of a chemical filter are filter pressure drop and overall weight. In addition to being able to provide excellent performance, the proprietary LPD-FN's and LPD-CN's discussed herein, also provide a significant reduction in filter pressure drop and weight relative to similar sized packed bed filters.

Figure 8 provides a comparison of the pressure drop curves for LPD-FN2 with NIC carbon. We note that in order to better show the differences between the two filters, the Y-axis is plotted as the logarithm of the pressure drop, in inches of water. All of LPD-FN's and LPD-CN's we have designed in this work have very similar pressure drop curves which are greater than a factor of 100 lower pressure drop than a 1.0 inch packed bed of 12x20 mesh activated carbon.

However, a comparison based on the same depth of filter isn't quite fair since, as has been shown above, the filtration performance between the two filters is not the same. Therefore, we have also measured the pressure drop as function of LDP-FN layers (1.0 inch thickness per layer). These results are presented in Figure 9. As indicated above, depending on the LPD-FN or LPD-CN design, approximately three layers (3.0 inches) are required to meet, or exceed, the performance of 1.0 inch of a packed bed of AGR media for the removal of SO<sub>2</sub>. The pressure drop for 3.0 inches of LPD-FN2 is approximately 50 times lower than that for a 1.0 inch packed bed of AGR media, with at least the same performance. Figure 9 indicates that the performance for SO<sub>2</sub> life would be at approximately 40% longer for 3.0 inches of LPD-FN2. Put another way, it would take approximately 140 layers (140 inches) of LPD-FN2 to achieve the same pressure drop as a 1.0 inch packed bed of AGR media.

In addition to the reduction in pressure drop, these LPD-FN's and LPD-CN's offer a significant reduction in overall filter weight. Table 1 provides the filter weight for an acid gas chemical filter design that incorporates 1.0 inch of impregnated activated carbon or a depth of either the LPD-FN or LPD-CN structure that provides similar performance for SO<sub>2</sub>. These results assume that the same facial area and operating conditions are used for each filter design. The depth of the LPD-FN or LPD-CN acid gas filter required was obtained by determining where the performance curves given in Figure 5 for the LPD-FN and LPD-CN media cross the 1.0 inch packed bed line. We note that the performance comparisons used in Figure 5 are based on results obtained at SO<sub>2</sub> concentrations that far exceed those in typical field applications, but are used here in order to provide an indication of the potential filter weight reduction that may be realized. We must also state that although these are full filter weight ratios, they do not take into account the added weight reduction benefits that would be realized by the ability to use lightweight frames and the ability to remove potting compounds and sealants from the structure.

**Table 1:** Comparison of acid gas chemical filter weight.

Chemical Filter Material	Filter Depth <sup>a</sup>	Weight Ratio <sup>b</sup>
Packed Bed AGR	1.00	1.00
LPD-FN1	2.92	0.58
LPD-FN2	2.48	0.77
LPD-FN3	1.39	0.35
LPD-CN	3.60	1.33

a. Required acid gas filter depth to obtain the same performance as 1.0 inch packed bed of AGR media against a challenge of 50 ppm SO<sub>2</sub>, at 50% RH, 25°C, and 30 LPM. b. Ratio of the required total chemical filter weight to the total weight of 1.0 inch packed bed AGR media.

It is clear from these estimates, that the weight reduction for a similar performing filtration system can be significant. However, in the case of LPD-CN, the final filter weight for similar performance is actually larger than that of the packed bed filter. This results from the aluminum structure and the relatively poor performance necessitating the use of a much thicker filter bed. Nonetheless, this structure still has several benefits desired by specific applications demanding low pressure drop, good multi-pass performance, and non-flammability.

A factor of 50 reduction in chemical filter pressure drop and a significant reduction in overall filter weight allows for LPD-FN and LPD-CN filter designs to significantly enhance the contributions offered by tool mounted chemical filters, full fab chemical filters, and fan filter assembly chemical filters in semiconductor applications. These improvements result by allowing for lower blower, or fan, speeds to be used in order to maintain the same operating conditions. A reduction in the energy output from these devices usually results in reduced energy cost and vibration. These benefits can be realized without significantly affecting chemical filter performance. Similar benefits can be realized for use of LPD-FN chemical filters in fuel cells, HVAC, gas turbine, and industrial processing applications.

### 3.4. Ionic Particulation

In high purity applications, the removal of acid gases to very low levels is critical. Acid gas chemical filters must be able to remove acid gases without contributing to ionic contamination downstream. Equally important, the chemical filter cannot shed or off-gas contaminants downstream of the filter that contribute to crystal growth, particle growth, or hazing of surfaces, that ultimately destroy the quality of a process the filter is designed to protect. Examples where problems have been reported are HVAC, gas turbines, hard disk drives, photolithography exposure tool lens, reticles and pellicles.<sup>20-24</sup>

In relatively high humidity environments, modified fibrous networks, such as those designed here, can adsorb large amounts of water, thereby providing the potential for deliquescence of the added compounds. Through capillary action under flow, it is possible that these liquefied materials could migrate through the fibrous network and concentrate at the filter exit. It has been hypothesized that these resulting ionic crystalline materials can be removed from fibrous filters through particulation processes and subsequently, ionic contaminants are found downstream of the filter. In order to evaluate that this does not occur with the LPD-FN designs evaluated in this work, we have performed the testing described above.

In both cases, exposure of the LPD-FN-2 filters to pure air and 500 ppbv SO<sub>2</sub> at ambient temperature and 50% RH, all ion concentrations in the airstream were found to be less than 5 pptv. These concentrations were consistent between the aqueous solution and adsorbent tube sampling approaches. This indicates that ionic particulation via deliquescence and transport through the filter medium is not a mechanism of concern for these filter designs.

## 4. SUMMARY

The optimum chemical filter design is application specific, but it generally has high removal efficiency and long life for the contaminants of interest, in addition it has low pressure drop and is lightweight. For a wide range of acid gases, impregnated packed bed chemical filters have proven to come close, but can suffer from high-pressure drop and excessive weight. In our search for the optimum acid gas chemical filter, lightweight, low pressure drop acid gas filters have been developed that can compete with impregnated packed bed designs. These new acid gas chemical filters are referred to as low pressure drop fibrous network acid gas filters. Preliminary results have proven that they are effective at removing sulfur dioxide over a wide range of test conditions and they do not suffer from issues associated with deliquescence and transport of surface modifiers and contaminants through the filter.

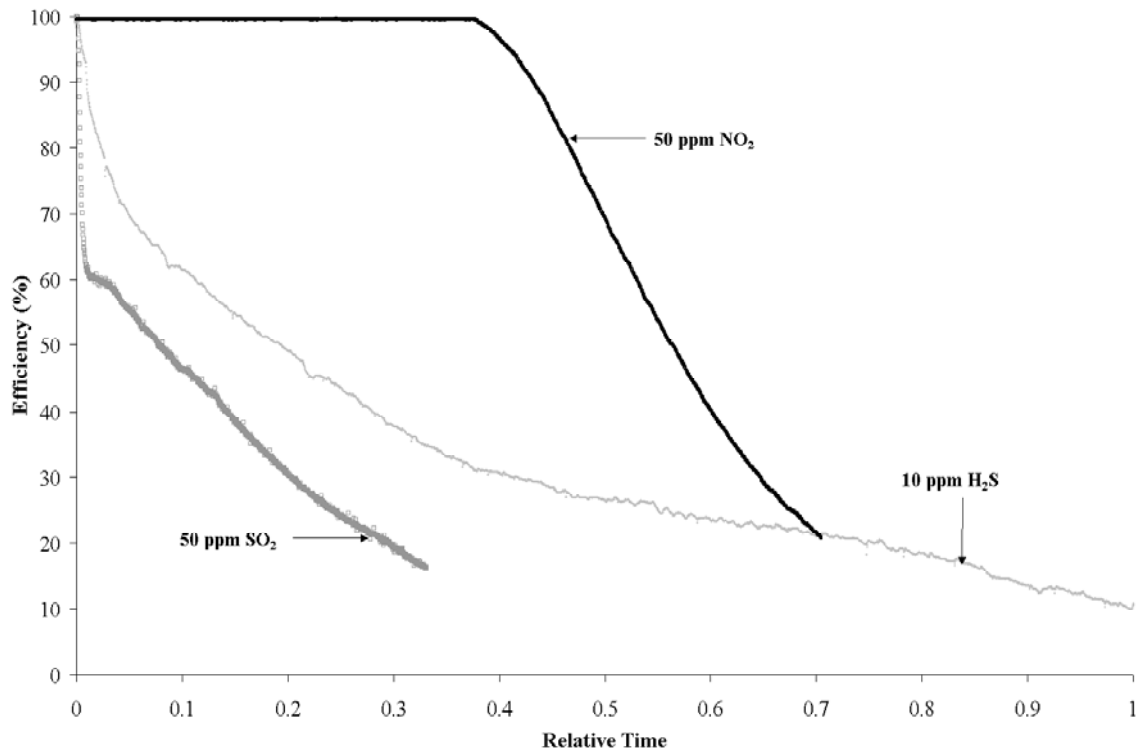
Although not reported here, our efforts to development low pressure drop fibrous network designs for the removal of NO<sub>x</sub> is being met with some success. Besides addressing the issues of pressure drop and weight of the packed bed filters, these efforts address the issue demonstrated in this work for NO<sub>x</sub> contaminants. Impregnated activated carbon packed bed acid gas chemical filters have been established as being effective at removing NO<sub>x</sub> gases, but at high concentrations of NO<sub>2</sub> they can liberate NO downstream of the filter. Yet, our field application results from independent investigations of these chemical filters being exposed to NO<sub>x</sub> levels significantly below 1.0 ppmv, demonstrate that this issue appears to be minimized, or non-existent, at lower concentrations. For the removal of SO<sub>2</sub>, H<sub>2</sub>S and HCl, at high and low concentrations, it has been proven that impregnated activated carbon beds are very effective. In addition to NO<sub>x</sub> contaminants, it is our goal to expand the understanding for low pressure drop fibrous networks to these other acid gases and their range of application.

## ACKNOWLEDGEMENTS

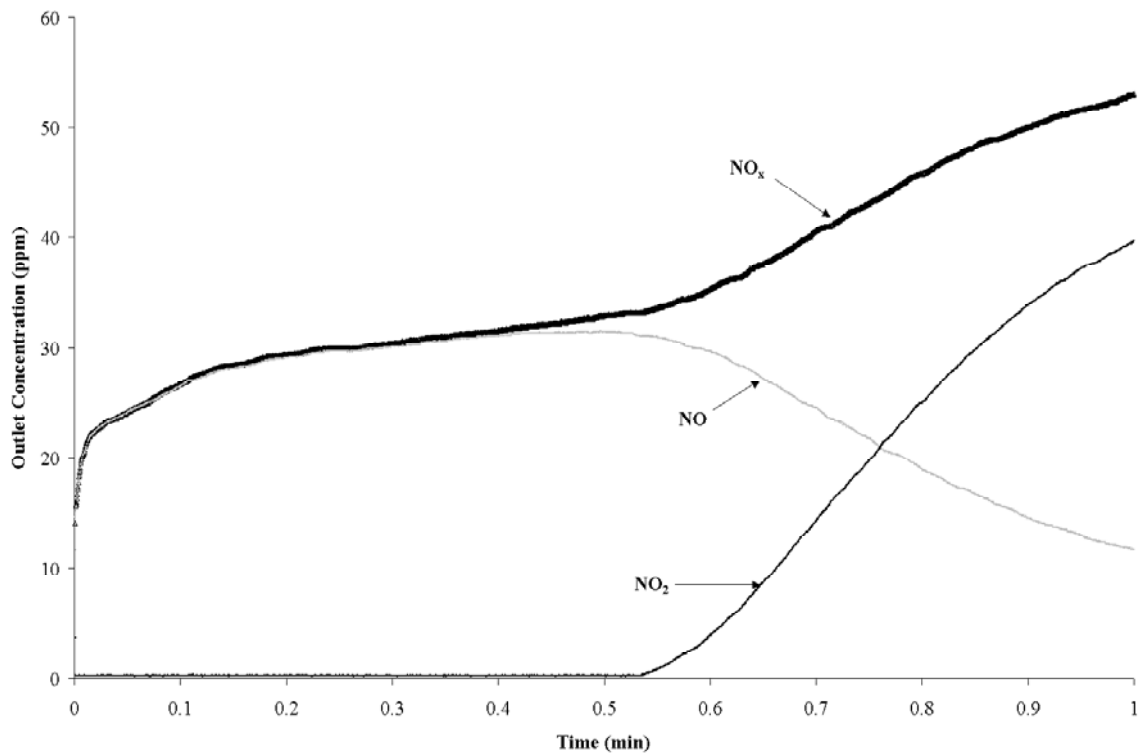
The authors would like to acknowledge the contributions made by Roel Gronheid of IMEC and Rida Al-Horr of DIONEX for their evaluation of the Donaldson Co. Inc. chemical filters for Lithographic tools. We would also like to thank Ed Sun and Wayne McMahon of California Air Resources Board for their evaluation of the Donaldson Co. Inc. chemical filters for DAPS systems and Los Alamos National Laboratories for their evaluation of Donaldson Company, Inc. chemical filters for fuel cells.

## REFERENCES

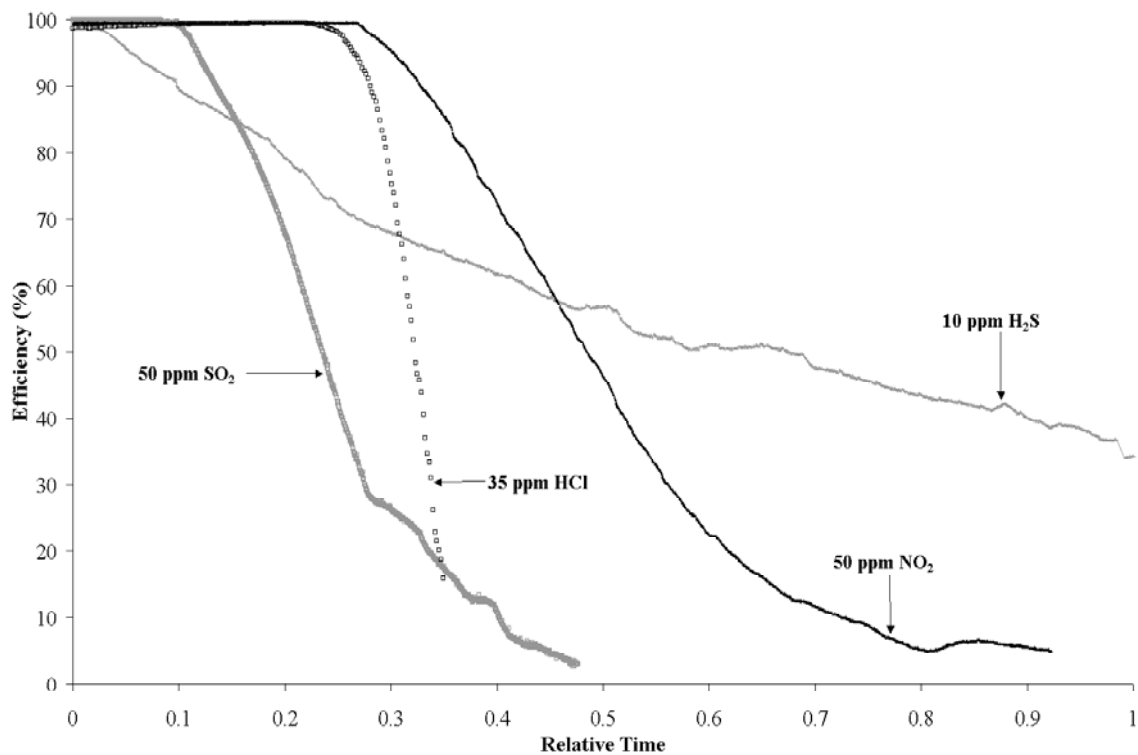
1. U.S. Patent No. 3,925,021.
2. U.S. Patent No. 3,992,412.
3. U.S. Patent No. 4,289,513.
4. U.S. Patent No. 4,992,319.
5. U.S. Patent No. 6,071,479.
6. U.S. Patent No. 6,413,303.
7. U.S. Patent No. 6,645,271.
8. A. J. Dallas, W. Ding, B. Hoang, J. Joriman, J. Parsons, and K. Seguin, "New Concerns with the Design of Filters for the Protection of Lithography Optics," *SPIE Proceedings*, Vol. 5040, pp. 1712-1728, 2003.
9. N. Shirahama, S. H. Moon, K-H. Choi, T. Enjoji, S. Kawano, Y. Korai, M. Tanoura, and I. Mochida, "Mechanistic Study on Adsorption and Reduction of NO<sub>2</sub> Over Activated Carbon Fibers," *Carbon*, Vol. 40, pp. 2605-2611, 2002.
10. Y.W. Lee, D.-K. Choi, and J.-W. Park, "Characteristics of NO<sub>x</sub> Adsorption and Surface Chemistry on Impregnated Activated Carbon," *Separation Science and Technology*, Vol. 37(4). Pp. 937-956, 2002.
11. Y.-W Lee, J.-W Park, S.-J. Jun, D.-K. Choi, and J.-E. Yie, "NO<sub>x</sub> Adsorption-Temperature Programmed Desorption and Surface Molecular Ions Distribution by Activated Carbon with Chemical Modification," *Carbon*, Vol. 42, pp. 59-69, 2004.
12. A. J. Dallas, L. Ding, J. Joriman, B. Hoang, J. Parsons, and K. Seguin, "Are Ambient SO<sub>2</sub> Levels a Valid Indicator of Projected Acid Gas Filter Life?" *SPIE Proceedings*, Vol. 5375, pp. 807-818, 2004.
13. Y.-W. Lee and D.-K. Choi, "Surface Chemical Characterization Using AES/SAM and ToF-SIMS on KOH-Impregnated Activated Carbon by Selective Adsorption of NO<sub>x</sub>," *Ind. Eng. Chem. Res.*, Vol. 40, pp. 3337-3345, 2001.
14. Y.-W. Lee, H.-J. Kim, J.-W. Park, B.-U. Choi, D.-K. Choi, and J.-W. Park, "Adsorption and Reaction Behavior for the Simultaneous Adsorption of NO-NO<sub>2</sub> and SO<sub>2</sub> on Activated Carbon Impregnated with KOH," *Carbon*, Vol. 41, pp. 1881-1888, 2003.
15. Y.-W. Lee, D.-K. Choi, and J.-W. Park, "Performance of Fixed-Bed KOH Impregnated Activated Carbon Adsorber for NO and NO<sub>2</sub> Removal in the Presence of Oxygen," *Carbon*, Vol. 40, pp. 1409-1417, 2002.
16. E. I. Sun, W. N. McMahon, D. Peterson, J. Wong, E. Stenersen, and A. J. Dallas, "Evaluation of an Enhanced Constant Volume Sampling System and a Bag Mini Diluter for Near Zero Exhaust Emission Sampling," *Proceedings of the SAE 2005 World Congress and Exhibition*, in preparation 2005-01-0684, April, 2005.
17. R. Gronheid, *personal communication*.
18. R. Gronheid and R. Al-Horr, "In-Line Monitoring of Airborne Acid and Base Contaminants at Low ppt-Levels for 193nm Lithography," *SPIE Proceedings*, in preparation 5754-176, 2005.
19. M. Camenzind, "Airborne Molecular Contamination in Semiconductor and Disk Drive Cleanrooms," *Cleanrooms West 99*, pp. 29-90, 1999.
20. U.S. Patent No. 6,123,751.
21. U.S. Patent No. 6,368,386.
22. S. Barzaghi, A. Pilenga, G. Vergani, and S. Guadagnuolo, "Purged Gas Purification for Contamination Control of DUV Stepper Lens," *Solid State Technology*, pp. 99-104, September, 2001.
23. B. Grenon, "Reticle Surface Contaminants and their Relationship to Sub-Pellicle Particle Formation," presented at BACUS Symposium on Photomask Technology, 2003.
24. D. E. Fowler, R. Duque, T. Anokin, and J. Zhou, "Protecting the Head/Disk Interface from the Chemical Environment with Disk Drive Filtration," *TMRC*, pp. 1-7, 2002.



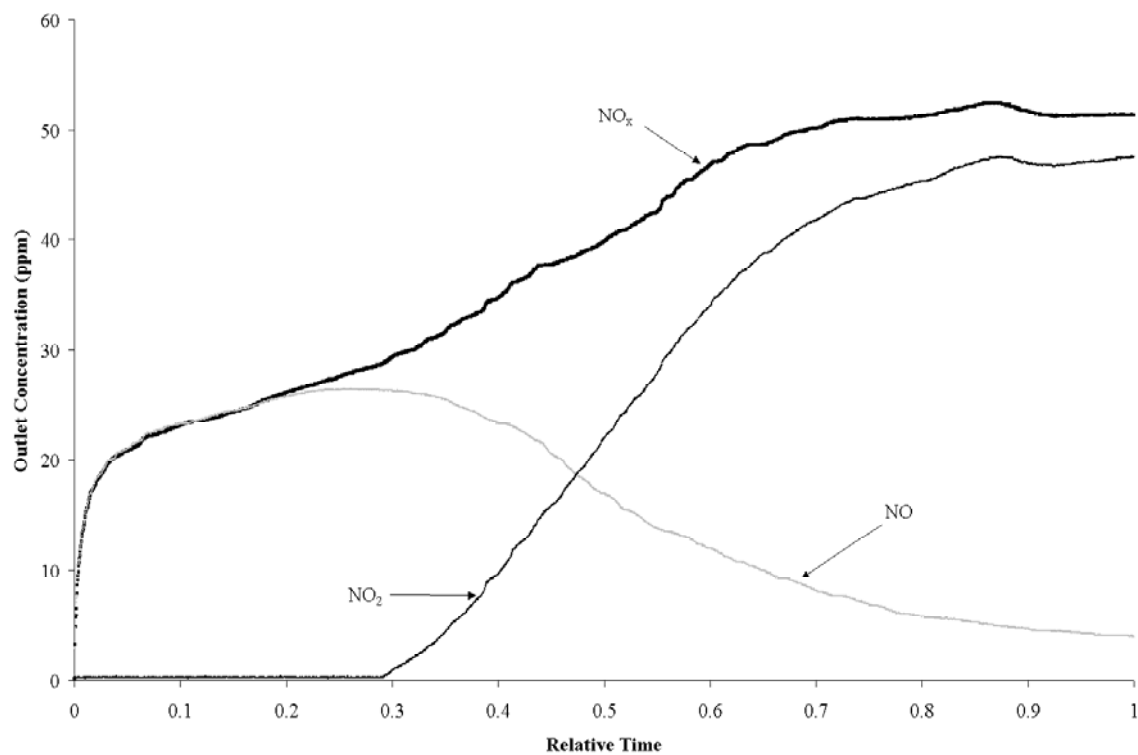
**Figure 1:** Efficiency breakthrough curves for acid gases on a NIC carbon. All three tests were performed at 50% RH, 25°C, and 30 LPM.



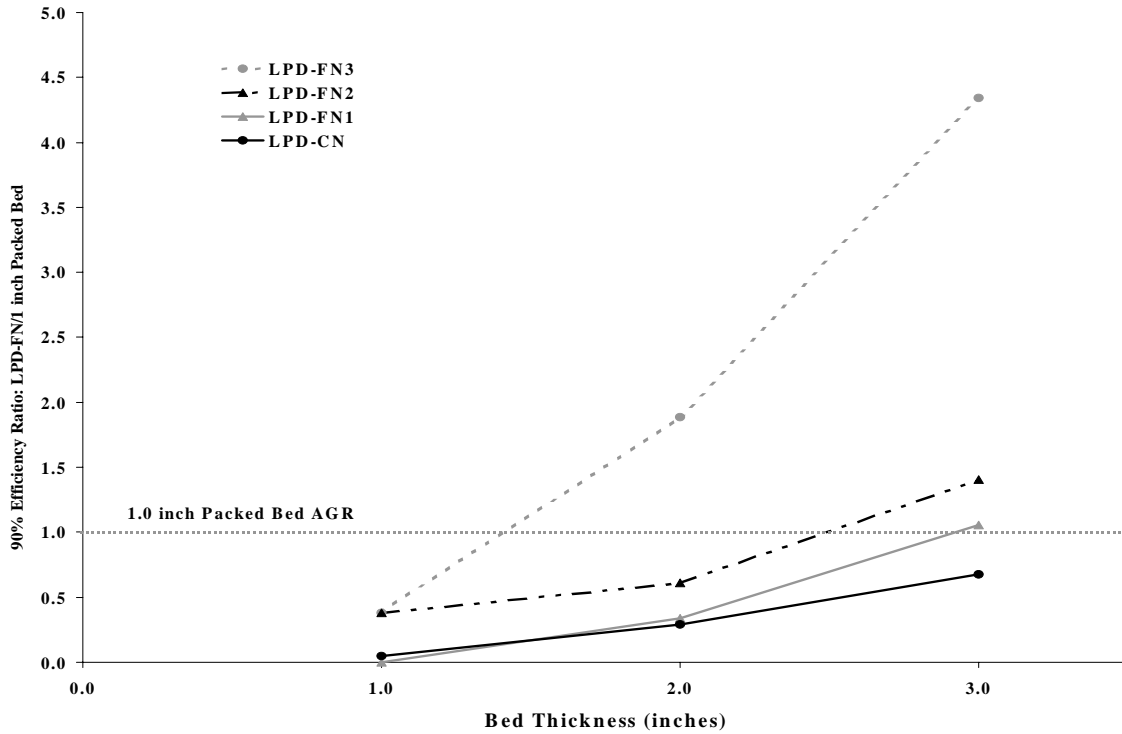
**Figure 2:** Breakthrough curves for multiple detector channels for 50 ppm NO<sub>2</sub> on a NIC carbon. Testing was performed at 50% RH, 25°C, and 30 LPM.



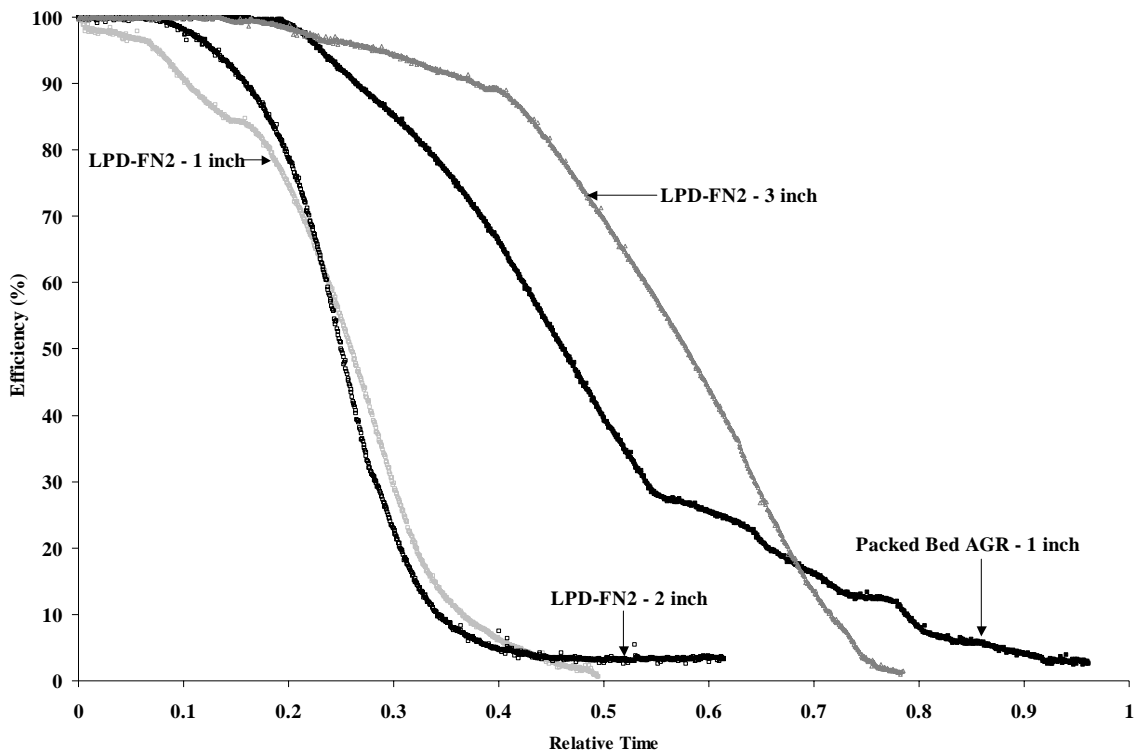
**Figure 3:** Breakthrough curves for acid gases on impregnated activated carbon, AGR. Testing was performed at 50% RH, 25°C, 30 LPM for all acid gases except HCl which was tested at 52 LPM.



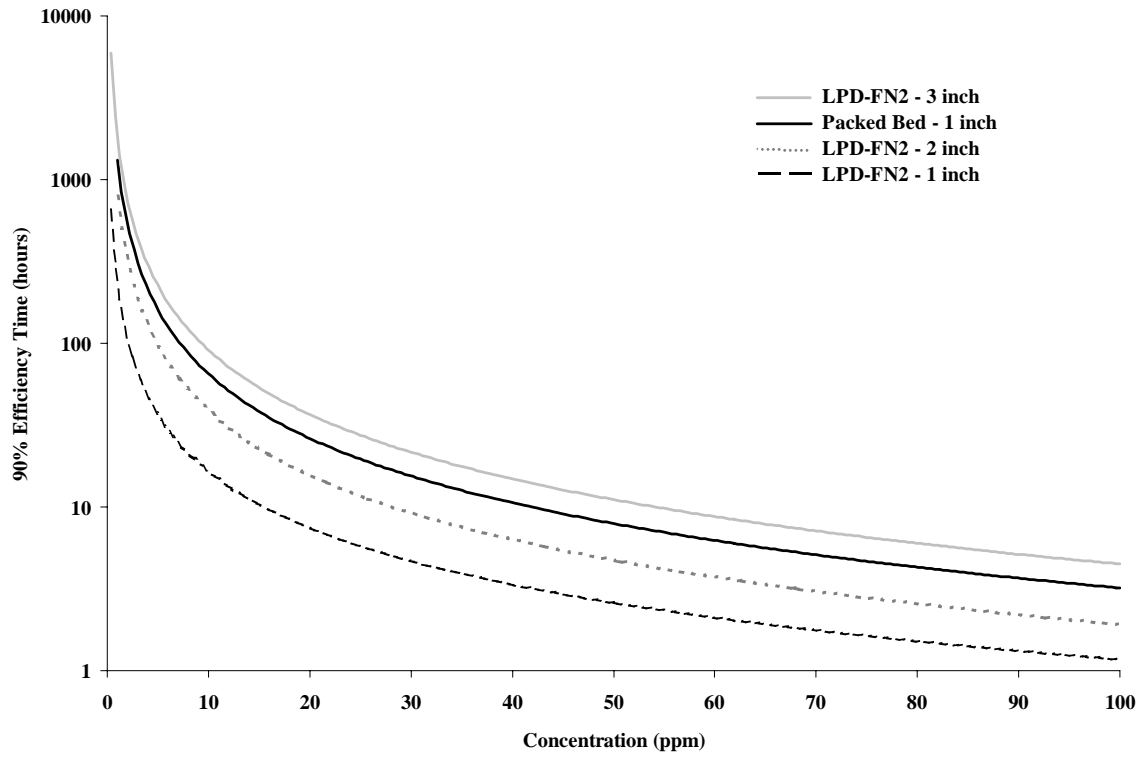
**Figure 4:** Breakthrough curves for multiple detector channels for 50 ppm NO<sub>2</sub> on impregnated activated carbon. Testing was performed at 50% RH, 25°C, and 30 LPM.



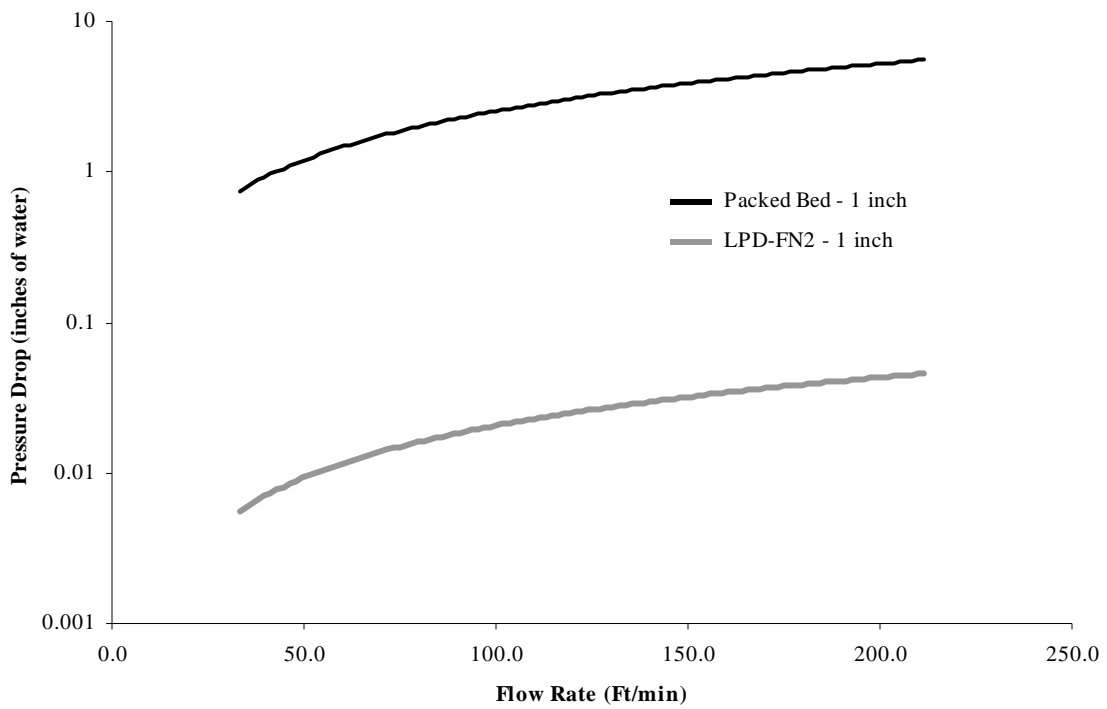
**Figure 5:** Comparison of the 90% efficiency time for LPD-FN and LPD-CN designs relative to 1.0 inch of a packed bed of impregnated activated carbon, AGR. Testing was performed at 50 ppm SO<sub>2</sub>, 50% RH, 25°C, and 30 LPM.



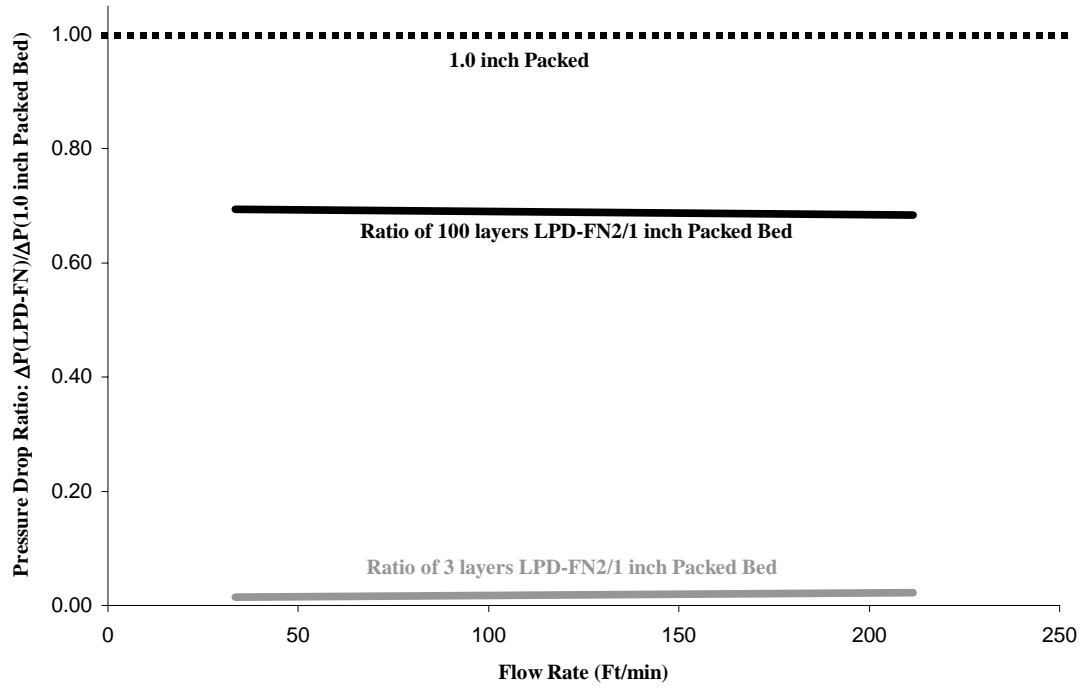
**Figure 6:** Breakthrough curves for the LPD-FN2 design compared with a 1.0 inch packed bed of impregnated activated carbon, AGR. Testing was performed at 50 ppm SO<sub>2</sub>, 50% RH, 25°C, and 30 LPM



**Figure 7:** Effect of SO<sub>2</sub> concentration on the capacity and life of LPD-FN2 compared with 1.0 inch of a packed bed of AGR. Testing was performed at 50% RH, 25°C, and 30 LPM.



**Figure 8:** Pressure drop comparison for 1.0 inch of a packed bed of non-impregnated carbon and LPD-FN2.



**Figure 9:** Pressure drop of multiple layers of LPD-FN2 relative to 1.0 inch of a packed bed of non-impregnated carbon.