

Achieving Your Indoor Air Quality Goals: Which Filtration System Works Best?

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INTRODUCTION

It is well known that outdoor air pollution can be serious enough to cause human illness. Because of this, protection of the public health has been the driving force behind the myriad laws and regulations put in place to clean up the air in and around our cities. However, this concern with ridding the outdoor air of toxic contaminants has often times failed to consider exposure to these same, and other, contaminants in indoor environments. In many cases these indoor exposures may be more harmful than those in the outdoor air.

The results of numerous scientific investigations have shown that air inside office buildings and residences is contaminated by a large variety of toxic contaminants, some of which are apparently in sufficient concentrations to adversely affect the health of those exposed. In addition to the recognition of the presence of toxic contaminants and the likelihood of relatively long exposure durations indoors, there have been numerous reported outbreaks of building-related illnesses (BRI) in office and other public access buildings. There is no doubt that indoor air pollution can cause serious public health problems.

One cannot discuss the problem of indoor air pollution without giving some attention to the role that energy conservation measures may play. To date, these efforts in the public sector have been primarily voluntary, however, federal and state facilities have been mandated to reduce their overall energy consumption. Often, this quest to reduce energy costs by "tightening" buildings and relying on less outside air has been pointed to as the main cause of IAQ problems. In support of this is the fact that, over the past fifteen years, most of the reported outbreaks of illnesses in office and other public buildings have coincided with the implementation of measures to conserve energy (Godish 1991). Commonly, when all other explanations for building-related illnesses have been dismissed, it is concluded that the problems are due to inadequate ventilation. And although this may be a contributing factor, a reduction in the amount of outside air alone cannot adequately explain the ever-increasing number of IAQ complaints.

As mentioned earlier, the protection of the public health has been the driving force behind laws designed to clean up the ambient air. This same driving force has prompted action by the Occupational Safety and Health Administration (OSHA). On March 25th of this year, OSHA announced a proposed rule that would regulate IAQ in workplaces across the country. This proposed rule addresses any and all indoor contaminants and would affect more than 4.5 million non-industrial workplaces, which, as defined by OSHA, include offices, educational facilities, commercial establishments, healthcare facilities, and offices, cafeterias, and break rooms located in manufacturing or production facilities.

The public's increased awareness towards IAQ-related issues and their demand to be able to work in a healthy environment, along with building owners' and managers' desires to keep energy consumption to a minimum, has fostered a growing need for economical and effective solutions. One of these solutions has been the use of air filtration. This mitigation measure can provide results similar to those expected through ventilation, i.e. the reduction of airborne contaminant levels. Air filtration can be applied for the reduction of particulate matter, gaseous contaminants, or both. It is the use of air filtration systems for the control of gaseous contaminants which will be the focus of the rest of this discussion. Before these gas-phase air filtration systems are described, an overview of gaseous contaminants will be presented.

Classification of Gaseous Contaminants

There are a variety of ways by which gaseous contaminants may be classified. None are definitive, but the following classifications have relevance to IAQ and HVAC systems.

Toxic Gases. A substance is said to be toxic if it exhibits the ability to cause damage to living tissue, impairment of the central nervous system, or in extreme cases, death when ingested, inhaled, or absorbed through the skin.

Corrosive Gases. Those gaseous compounds which are likely to cause deterioration or damage to the interior of a building or its contents are considered corrosive. They may also have a detrimental effect on human occupants as well.

Irritant Gases. Gaseous compounds which can be said to cause discomfort, and potentially permanent damage, to an exposed person may be considered irritating. Many of the gases considered to be irritants produce symptoms of pain or discomfort to the eyes, skin, mucous membranes, or respiratory system.

Odorous Gases. Those gases which affect primarily the olfactory senses are considered odorous and usually carry negative connotations. When asked to describe an "odorous compound", most would describe it in terms of unpleasant odors. However, even odors generally considered as pleasant or unobjectionable when present at normal concentrations may quickly become objectionable at higher concentrations. Because of the wide variability in the ability of people to perceive odors, there is a corresponding wide subjectivity in the determination of just what constitutes an objectionable odor. The HVAC design engineer will always have to contend with a finite portion of the general population whose ability to perceive odors is greater than the rest. The lowest concentration at which most people can detect, but not necessarily identify, an odor is referred to as the threshold level, and can vary by several orders of magnitude with different compounds. Odors can be caused by simple inorganic compounds such as hydrogen sulfide (H₂S) and ammonia (NH₃) and organic compounds such as formaldehyde (HCHO). The most common method of identifying odors has been by type, e.g. cooking odors, bathroom odors, cigarette odors. However, with increased awareness to IAQ issues, more and more problem odor identifications are being made by direct chemical analysis.

Environmental Tobacco Smoke (ETS). Environmental tobacco smoke is the term used to describe the material in indoor air which results from tobacco smoking. A lit cigarette gives off approximately 4700 chemical compounds, and some 400 of these have been quantitatively characterized. According to the EPA, at least 43 of these are carcinogenic. Some of the more significant compounds or materials associated with ETS are respirable particles, nicotine, nitrosamines, polycyclic aromatic hydrocarbons (PAH), carbon monoxide and dioxide (CO, CO₂), nitrogen oxides (NO_x), acrolein (CH₂CHCHO), formaldehyde, and hydrogen cyanide (HCN) (Guerin et al. 1992).

Not only is tobacco smoke a complex mixture of toxic gases and particulates, but it also acts synergistically with other indoor air pollutants (Guerin et al. 1992). Because cigarette smoke is essentially ubiquitous, passive exposure to it is almost unavoidable. It is paradoxical that ETS is one of the most common, best characterized, and hazardous indoor air pollutants, and yet, it is, conceptually, an easy pollutant to eliminate. The fact that ETS has not been eliminated from offices and commercial buildings is a testimonial to the wide variations in public knowledge and the perception of risk.

The indoor and outdoor environments differ significantly in both the types and levels of contaminants common to both (Brooks and Davis 1992; Gammage and Kaye 1984; Godish 1989; Godish 1991; Kay et al. 1991; National Research Council 1981; Walsh et al. 1984). Contaminants with sources predominantly outdoors include sulfur dioxide (SO₂), nitrogen dioxide (NO₂), ozone (O₃), and a number of volatile organic compounds (VOC's). Contaminants generated primarily from indoor sources include CO₂, HCHO, NH₃, acrolein, and a variety of organic chemicals.

Control Strategies

The three methods of gaseous contaminant control most commonly employed in HVAC systems are source control, ventilation control, and removal control. Source control should always be the first strategy examined. Eliminating the sources of contaminants prevents them from becoming a problem in the first place. However, the source of gaseous contaminants cannot always be readily identified and, therefore, cannot be removed. Many times the buildings themselves are the greatest sources of gaseous contaminants.

When source control is not feasible or practical, ventilation control should be the next option. Ventilation control may involve the introduction of clean dilution air into the affected space (appropriate for small, distributed sources) or by local exhaust (appropriate for strong point sources). Contaminant levels can thus be reduced below acceptable threshold levels. However, as in source control, this may not prove viable in all cases, either. Most ventilation air used for dilution would come from outside the building. The National Primary Ambient Air Quality Standards (U.S. EPA 1992) represent national goals for permissible outdoor air exposure levels. However, in many of our urban environments today, the outside air does not meet this required criteria with regards to gaseous contaminants. Therefore, if this air were to be used for ventilation control, whether via simple dilution or local exhaust, one would

simply be substituting one (group of) contaminant(s) for another and even possibly increasing the total contaminant load in the space.

If this control strategy is employed, ASHRAE Standard 62-1989, "Ventilation for Acceptable Indoor Air Quality" (ASHRAE 1989), specifies minimum ventilation rates which should provide IAQ acceptable to human occupants. This Ventilation Rate Procedure, however, provides only an indirect solution for the control of indoor contaminants. While it does allow for the use of cleaned, recirculated air, it does not allow using this air to reduce the amount of outdoor air specified.

The standard goes on to state that if the outdoor air contaminant levels exceed those listed in the National Ambient Air Quality Standards, this air must be treated to control the offending contaminants. For the removal of gases and vapors, appropriate air-cleaning systems should be used. Properly cleaned air may be used for recirculation.

If it is clear that neither source nor ventilation control will effectively reduce the level of gaseous contaminants in the affected space, removal control should be employed. Most interest and research over the last few years regarding the control of gaseous contaminants has been to the processes involved in removing these contaminants from airstreams. Removal control, as employed as part of an HVAC system, is usually accomplished through the use of various dry, granular, gas-phase (dry-scrubbing) air filtration media.

Standard 62-89 also describes an IAQ Procedure which provides a direct solution for reducing and controlling the concentrations of contaminants, through air cleaning, to specified acceptable levels. This procedure allows for both quantitative and subjective evaluation of the effectiveness of the air cleaning method(s) employed. The standard acknowledges that air-cleaning, along with recirculation, is an effective means for controlling contaminants when using the IAQ Procedure. Employing this procedure allows the amount of outside ventilation air to be reduced below standard levels if it can be demonstrated that the resulting air quality meets the required criteria.

GAS-PHASE AIR FILTRATION

Dry-Scrubbing Air Filtration Media

As will be described in the following section on equipment designs, dry-scrubbing media can be applied in a number of different configurations. These media, regardless of how installed, utilize two main processes used to remove airborne gaseous contaminants. One, is a reversible physical process known as adsorption. The other, which involves adsorption and irreversible chemical reaction(s), is termed chemisorption. Each of these processes will be described briefly below.

Adsorption. By definition, adsorption is the process by which one substance is attracted to and held on the surface of another. The terms *adsorbent* and *adsorbate* refer to the solid and its captured molecules. Adsorption can occur wherever a material has sufficient attractive force to overcome the kinetic energy of a gas molecule. This is evident by the adsorption of cigarette smoke on the interior of an automobile or on a person's clothing.

Adsorption is viewed as a surface phenomenon, and it is well to understand the significance of this statement. The removal capacity of an adsorbent is directly related to its total surface area, and in a porous solid adsorbent, the surface extends well into the interior of the solid. Therefore, it is important to develop as large an accessible surface area per unit volume as possible. Granular activated carbons (GAC's) are the most common materials which fulfill this requirement. A variety of materials are used in their preparation. Each imparts its own special characteristics to the GAC which, in turn, may make it the preferred product for a specific application. Other commonly used sorbents include activated aluminas.

Because of the relatively weak forces involved, adsorption is (essentially) totally reversible (Hassler 1974). Thus the net rate of adsorption depends on the rate at which adsorbate molecules reach the surface of the adsorbent, the percent of those making contact which are adsorbed, and the rate of desorption. However, many other factors can affect removal of gaseous contaminants by physical adsorption. Among these are the type of adsorbent, the resistance to airflow (ΔP), the adsorbent bed depth, the gas velocity, the concentration and characteristics of the contaminant(s) in the space around the adsorbent, and the temperature and relative humidity of the gas stream.

Chemisorption. Adsorbent materials do not adsorb all contaminant gases equally. One way to improve the effectiveness of sorbents for these materials is by the use of various chemical impregnants which react with these "less-adsorbable" gases. These impregnates react (essentially) spontaneously and irreversibly with these gases

forming stable chemical compounds which are bound to the media as organic or inorganic salts or released into the air as CO₂, water vapor, or some material more readily adsorbed by other adsorbents. Therefore, it is not uncommon to have a gas-phase air filtration system which uses a combination of unimpregnated and chemically-impregnated adsorbent medias.

In contrast to the reversible process of physical adsorption, chemical adsorption, or chemisorption, is the result of chemical reactions on the surface of the adsorbent. Chemisorption is specific and depends on the chemical nature of both the adsorbent and the adsorbate. It is actually a two-stage process. First the adsorbates are physically adsorbed onto the adsorbent. Once adsorbed, they react chemically with the adsorbent. The chemical impregnant added to the adsorbent makes it more or less specific for a contaminant or group of contaminants. Many of the same factors which affect the removal of gases by physical adsorption also affect their removal by chemisorption.

One of the more broad-spectrum chemical impregnants in common use is potassium permanganate (KMnO₄), and it is typically used as an impregnant on activated alumina. Potassium permanganate-impregnated alumina (PIA) is often used in conjunction with GAC to provide a very broad-spectrum gas-phase air filtration system. However, this dual-media approach continues to be the exception rather than the rule.

Traditionally, which of these two types of dry-scrubbing was recommended for a particular application usually depended on to whom one was talking. Most of the GAC manufacturers/suppliers did not recommend the use of PIA and vice-versa. However, a single-media approach to solving IAQ problems is proving inadequate simply due to the vast numbers of chemical contaminants which have been identified in indoor environments. Therefore, it was desired to show, through testing, that a dual-media approach, either as a blended media product or contained in separate filter beds, can be more effective than a single media for the control of gaseous contaminants important to IAQ.

EXPERIMENTAL METHODS

General

For the testing to be performed, a draft ASTM Standard Test Method for the determination of the accelerated hydrogen sulfide (H₂S) breakthrough capacity of GAC was used (ASTM 1993). This method is intended for the evaluation of gas-phase (dry-scrubbing) air filtration media by determining its hydrogen sulfide breakthrough capacity when treated with a humidified H₂S-laden air stream (1% vol/vol, 10,000 ppm). This breakthrough capacity is defined as the grams of hydrogen sulfide removed from the gas stream per unit volume (cubic centimeter) of media at a predefined removal efficiency (99.5%). Although this test method was originally developed to compare the performance of various dry-scrubbing media used in gas-phase air filtration systems against hydrogen sulfide, it can also be used to compare media performance against other gases. The gas concentration specified was originally a source of some concern, however, testing performed at Research Triangle Institute has indicated that a correlation can be made between accelerated testing and media performance at lower gas challenge concentrations.

In the test procedure, a calibrated adsorption tube is filled with a known volume of a representative media sample. The weight of the media sample is determined by weighing the adsorption tube both before and after the sample has been introduced. The filled adsorption tube is then placed into the test apparatus shown in Figure 1. The challenge gas/air flow and a detection timer are started, and continued until a challenge gas breakthrough of 50 ppm is indicated. At this point the challenge gas/air flow is discontinued, and the time from test start noted and recorded. This 50 ppm breakthrough time is used to calculate the breakthrough capacity. The formula used for this calculation is presented in the **RESULTS** section.

Samples of coconut shell GAC, PIA, and a 50/50 mixture (by volume) of these two media were obtained and subjected for testing against a number of contaminant gases using the above procedure. One additional test involved "layering" of the two media in the test apparatus to simulate results expected when using a dual filter bed, or "two-pass," arrangement for the media.

Selection of Challenge Gases

It was desired to test the media against more than one contaminant gas, and against gases with somewhat more relevance to IAQ than hydrogen sulfide. ASHRAE uses the National Primary Ambient Air Quality Standards for determining the acceptability of outside air used for ventilation. Numerous scientific investigations have provided

insight as to some of the more commonly encountered indoor air pollutants (Epstein and Singh 1987; Sheldon et al. 1988; Wallace et al. 1988; Wallace et al. 1991). Therefore, the additional contaminant gases of chlorine (Cl₂), nitric oxide (NO), nitrogen dioxide (NO₂), sulfur dioxide (SO₂), formaldehyde (HCHO), and toluene were selected.

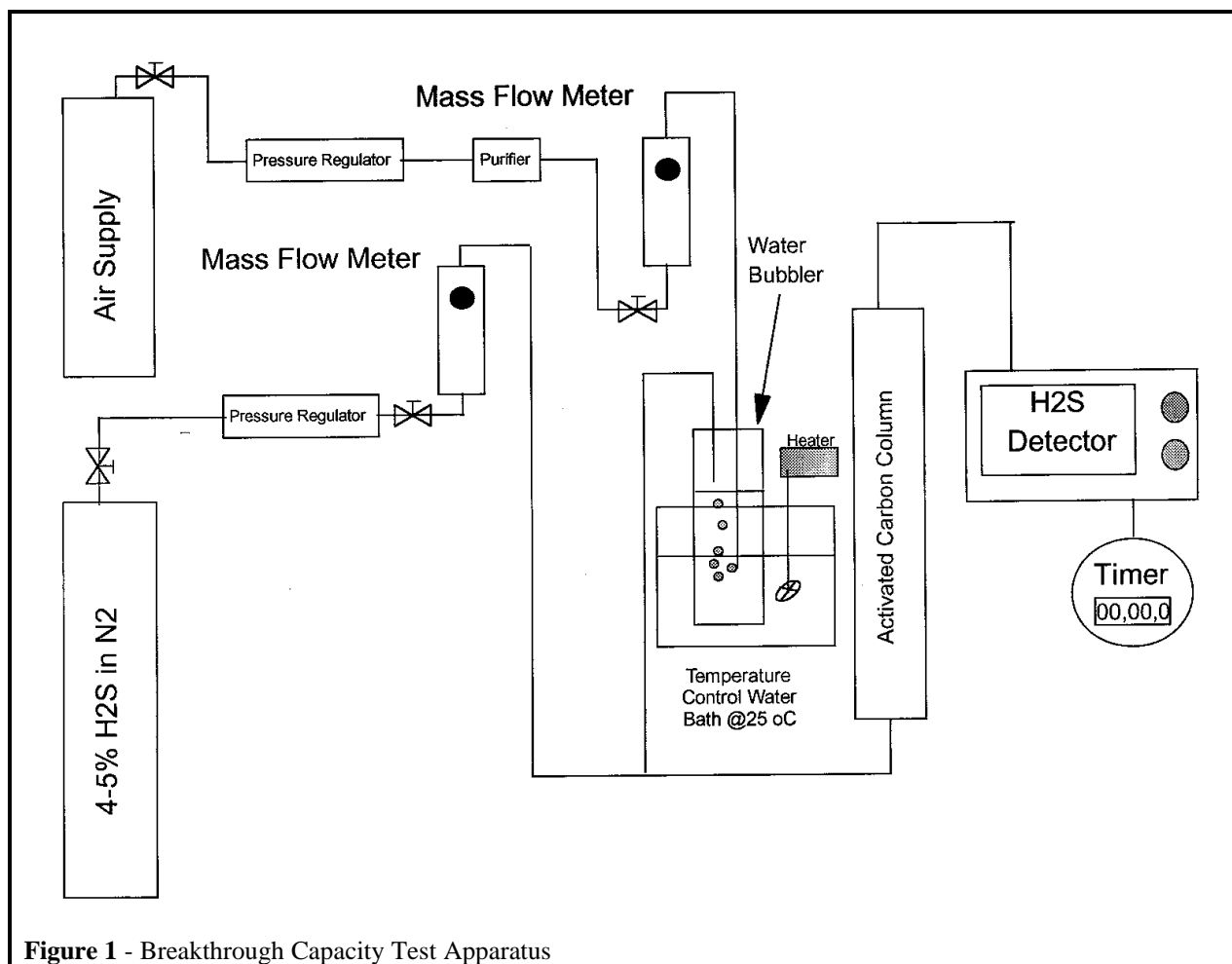


Figure 1 - Breakthrough Capacity Test Apparatus

RESULTS

The equation used to calculate the hydrogen sulfide (H₂S) breakthrough capacity is shown below.

$$H_2S \text{ Capacity, g/cc} = 4 \frac{(1.52 \times 10^{-5})(C)(F)(T)}{V}$$

Where: C = concentration of H₂S in air stream, volume %
 F = total H₂S/air stream flow rate, cm³/min
 T = time to 50 ppmv breakthrough, min
 V = volume of the adsorption tube media bed, cm³.

The constant value, 1.52 x 10⁻⁵, used in the above calculation, is related to the molecular weight and is valid only for hydrogen sulfide. Constant values for the other test gases have been derived (Purafil, Inc. 1990) and can be used to calculate the corresponding breakthrough capacity results when following the procedure as for H₂S. The

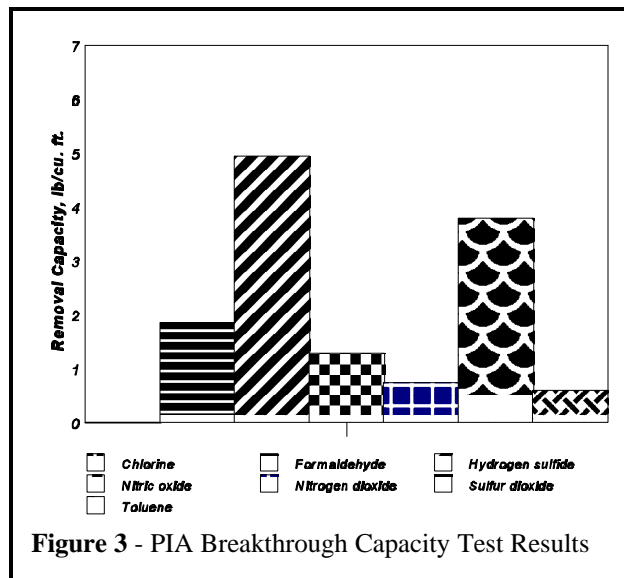
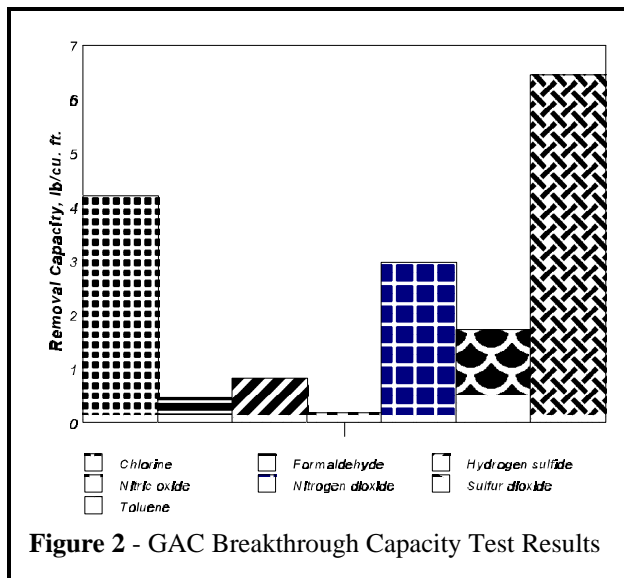
constant values used are as follows: chlorine, 3.17×10^{-5} ; formaldehyde, 1.34×10^{-5} ; nitric oxide, 1.34×10^{-5} ; nitrogen dioxide, 2.05×10^{-5} ; toluene, 4.11×10^{-5} ; and sulfur dioxide, 2.86×10^{-5} .

The breakthrough capacity test results for the GAC and the PIA are shown in Table 1, and are represented graphically in Figures 2 and 3. For the gases tested, GAC performed better against chlorine, nitrogen dioxide, and toluene. The PIA was more effective against the formaldehyde, hydrogen sulfide, nitric oxide, and sulfur dioxide.

TABLE 1 - Breakthrough Capacity Test Results							
Contaminant	Sample Weight, g	Sample Density		Breakthrough Time, min	Breakthrough Capacity		
		g/cc	lb/ft ³		g/cc	wt %	lb/ft ³
Granular Activated Carbon (GAC) Results							
Chlorine	38.20	0.5090	31.78	110	0.0674	13.24	4.21
Formaldehyde	36.36	0.4848	30.27	29	0.0074	1.55	0.47
Hydrogen sulfide	38.28	0.5100	31.83	45	0.0132	2.59	0.83
Nitric oxide	33.79	0.4505	28.12	12	0.0032	0.69	0.19
Nitrogen dioxide	38.98	0.5200	32.46	120	0.0476	9.15	2.97
Sulfur dioxide	38.80	0.5170	32.28	50	0.0276	5.35	1.73
Toluene	36.97	0.4929	30.77	130	0.1033	20.96	6.45
Potassium Permanganate-Impregnated Alumina (PIA) Results							
Chlorine	54.17	0.7428	46.37	0	0.0000	0.00	0.00
Formaldehyde	55.56	0.7408	46.25	115	0.0298	4.02	1.86
Hydrogen sulfide	53.65	0.7150	44.64	270	0.0793	11.10	4.95
Nitric oxide	55.05	0.7340	45.82	80	0.0209	2.82	1.29
Nitrogen dioxide	57.00	0.7600	47.45	30	0.0119	1.56	0.74
Sulfur dioxide	56.50	0.7533	47.03	110	0.0608	8.07	3.80
Toluene	56.41	0.7522	46.96	12	0.0095	1.27	0.60
GAC/PIA Media Blend Results							
Chlorine	45.66	0.6080	37.96	45	0.0276	4.54	1.72
Formaldehyde	47.33	0.6310	39.39	65	0.0168	2.67	1.05
Hydrogen sulfide	47.20	0.6290	39.27	150	0.0441	7.01	2.75
Nitric oxide	46.00	0.6133	38.29	45	0.0115	1.90	0.73
Nitrogen dioxide	47.45	0.6300	39.33	85	0.0337	5.35	2.10
Sulfur dioxide	42.34	0.5650	35.27	70	0.0387	6.85	2.42
Toluene	45.95	0.6127	38.25	80	0.0636	10.38	3.97
GAC/PIA "Layered" Results							
Hydrogen sulfide	46.95	0.6260	39.08	145	0.0426	6.81	2.66

The breakthrough capacity test results for the GAC/PIA blend (50/50 by volume), are also shown in Table 1 and represented graphically in Figure 4. Overall, the capacity values obtained were ~98% of the average of the GAC and PIA results.

An additional test was performed with H₂S where the GAC and PIA media were "layered" to simulate a two-pass arrangement. One-half of the media sample test volume was used and the PIA was placed downstream of the GAC in the test apparatus. The breakthrough capacities obtained were 92% of the GAC/PIA blend average and 97% of the blended media result. These results, too, are shown in Table 1.



DISCUSSION

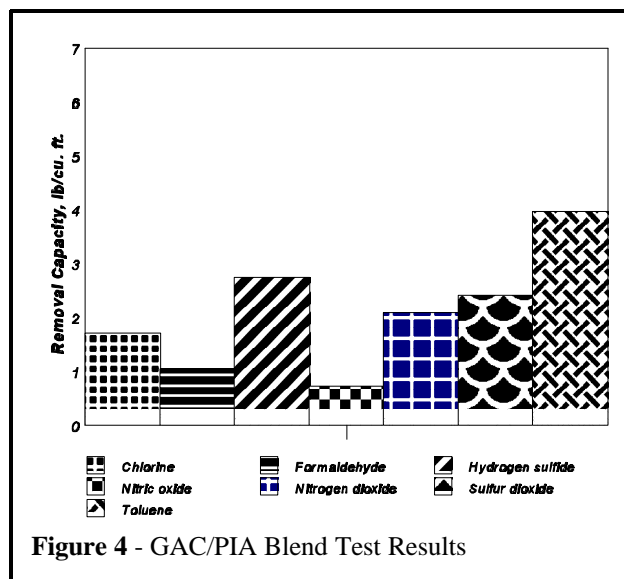
The number and types of dry-scrubbing air filtration media available today are an indication that no single media is going to be effective in all gas-phase air filtration applications. Some of these media are fairly specific inasmuch as they will be effective only against a particular contaminant or group of contaminants. However, it would be impractical, not to mention extremely costly, to target each contaminant individually.

GAC does a very good job in removing most hydrocarbons, many aldehydes and organic acids, and nitrogen dioxide due (in part) to its high surface area to volume ratio. It is not particularly effective against oxides of sulfur, formaldehyde, nitric oxide, hydrogen sulfide or lower molecular weight aldehydes and organic acids. However, PIA is effective against these latter contaminants.

This should make it apparent that more than one dry-scrubbing media is required to adequately control the majority ambient gaseous contaminants. It is a gas-phase system employing plain (unimpregnated) activated carbon and potassium permanganate-impregnated activated alumina in individual filter beds which offers the best effectiveness against the broadest range of chemical contaminants. The results of testing shown in Table 1 illustrates this well.

The testing described above was expected to accomplish two things. First, was to confirm which media would be more effective against each of the seven gases before proceeding to the blended media testing. From the results of previous testing (Muller 1993; Purafil 1991; Vosteen and Bakker 1992), we had anticipated the GAC would perform best against the Cl_2 , NO_2 , and toluene and the PIA would perform better against the rest. This was confirmed.

However, the main goal of this testing was to measure the performance of a blended media product relative to the single medias. Experience with gas-phase air filtration had led us to hypothesize that a single bed of this GAC/PIA blend should have a removal capacity and breakthrough time approximately one-half that of two single beds of each media. This was fairly intuitive inasmuch as the latter configuration contains twice as much media. It was further believed that the GAC/PIA blend may not have been as efficient as the two-bed arrangement because of the fact that the gases entering the media had a reduced chance of contacting the appropriate media.



Averaging the individual media breakthrough capacities for the GAC and the PIA, adding these two values together, and comparing this to the average of the individual GAC/PIA blend breakthrough capacities, suggests that a single filter bed of the GAC/PIA blend would be expected to have a breakthrough capacity ~47% that of a two-bed system. If the average of the breakthrough capacities for the three gases for which the GAC performed better and the four for which the PIA performed better was used, the expected capacity for the GAC/PIA blend would be somewhat higher - ~56% that of a two-bed system. Using the average values of the individual media tests was done because testing the GAC and PIA individually and comparing it to the GAC/PIA blend was analogous comparing a two-bed to a single-bed system. This testing supported our hypothesis that a single filter bed of the blend would have a removal capacity approximately one-half that of a two-bed system.

In order to double-check this hypothesis, a "layered" test was performed. Because the test procedure called for using a constant volume of media, it was felt that this would simulate testing a two-bed system employing the media in discreet beds against a two-bed system employing the GAC/PIA blend in each bed. If this were correct, the breakthrough capacities and times would be similar. This, indeed, was the case as the breakthrough capacities and the breakthrough times were each within ~3% of each other - as expected due to testing media beds of (essentially) equal depths. Also, that fact that the endpoint for each test was fixed, i.e., 99.5% removal efficiency or 0.5% breakthrough, dispelled our concerns that the GAC/PIA blend may not have been as efficient. If this were the case we would have observed significantly shorter breakthrough times.

The service life, or in this case, the breakthrough time, of dry-scrubbing air filtration media is directly proportional to the removal capacity and the weight of the media. It is inversely proportional to the removal efficiency and airflow of the system, and the molecular weight and concentration of the target contaminant (Godish 1989; Nelson and Correia 1976; Stern, 1977; Turk et al. 1969). As each of these parameters would be constant throughout the testing except for the individual removal capacities, our beliefs that the GAC/PIA blend would have a service life one-half that of the individual medias was correct. The average breakthrough time for the GAC/PIA blend was ~48% that of the individual media average.

CONCLUSIONS

Based on the results of testing performed, it has been shown that a single dry-scrubbing air filtration media may not be sufficient to adequately control multiple contaminants. The types and numbers of gaseous contaminants one would expect to encounter in outdoor and indoor air make it likely that gas-phase air filtration systems, used as part of an overall contaminant control and/or energy conservation program, need to be equipped with at least two dry-scrubbing media - granular activated carbon and potassium permanganate-impregnated alumina.

The preferred system would contain these media in two discreet filter beds in the order GAC-PIA. This arrangement would be analogous to the roughing and polishing filters in particulate control applications. GAC is generally recognized as being a very broad-spectrum, non-specific adsorbent and PIA, due to its chemical-impregnation, is somewhat more specific as to the types of contaminants against which it will act. If, due to system size, pressure drop, or other physical constraints, a two-pass system cannot be used, these media may be employed as a blended media product (50/50 by volume). This does not appear to affect the media's ability to remove gaseous contaminants except for the fact that the two-pass configuration would exhibit a media service life twice as long due to the greater amount of media contained in the system.

Although the need for consideration of a multiple-media approach has been demonstrated for IAQ applications, it is not always feasible to incorporate a gas-phase air filtration system with two or more filter beds. Retrofit applications in particular present challenges to the HVAC engineer. Once the need for gas-phase air filtration is acknowledged, and the need for multiple media confirmed, one is often limited by lack of physical space for the system, sufficient static pressure in the air handling system, or budgetary constraints. In these cases, blended media in a single filter bed can be successfully used. The trade-offs one would be making would not be in terms of decreased system contaminant removal capacities or efficiencies, but rather in a decreased service life of the media.

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