Effects of Thermal Regeneration of Activated Carbon Fibers on Adsorption Characteristics for Toluene

by

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ABSTRACT

Respiratory protective equipment is recommended as one method to diminish exposure to airborne pollutants, including volatile organic compounds (VOCs)**.** Activated carbon fiber (ACF) has a potential use as an alternative adsorbent in respirators for VOCs. The advantages of ACF as an alternative absorbent include larger surface areas, higher adsorption capacities, thinner critical bed depth, higher number of micropores, faster heat and mass transfer properties, and its fabric form. When its saturation capacity is reached, the adsorbent is no longer effective for removing pollutants. To recover the ability to capture gaseous pollutants, carbon adsorbents typically are regenerated. The ACF's ability to be regenerated makes it a more cost effective, energy efficient and environmentally sustainable option to aid in certain purification processes. The purpose of this study was to investigate the effects of thermal regeneration on the adsorption characteristics of activated carbon fiber (ACF) in respirator cartridges for toluene and also to investigate the extent to which regeneration decreased the ACF's adsorption capacity and breakthrough time (BT). Results showed that the 10% and 50% BTs for the two tested ACF types (ACF 210 and ACF 605) were not significantly different ($P = 0.06$). However, the differences in 10% and 50% BT between the two toluene concentrations (200 and 500 ppm) were significant ($P < 0.01$) but the differences in 10% and 50% BT among the regeneration

events were not statistically significant ($P = 1.00$). Consequently, ACF performed consistently well in adsorbing toluene to its full capacity even after multiple regenerations. The ACF's performance in this study displays its potential to serve as an alternative adsorbent to granular activated carbon (GAC) in respirators. Effective adsorbents in respirators need to consistently adsorb VOCs to their full capacity even after multiple regenerations. Additionally, they must have no loss in breakthrough times regardless of the concentration exposures to VOCs. These particular requirements allow ACF to be a potentially effective adsorbent in respirators.

Effects of Thermal Regeneration of Activated Carbon Fibers on Adsorption Characteristics for Toluene

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I. INTRODUCTION

Exposure to volatile organic compounds (VOCs) can lead to serious effects on public health. Studies have shown an increase in a person's risk of developing respiratory diseases, such as asthma, lung cancer, bronchitis, and chronic obstructive pulmonary disease when exposed to VOCs, in general (Fukakusa *et al*., 2011). In today's society, the use of respirators is important in certain work environments due to increased use of VOCs, which could be detrimental to the health and safety of workers in these specific work fields. Respiratory protective equipment is recommended as one method to diminish the risk of exposure to airborne pollutants. However, many studies have shown that workers, in many cases, are not compliant with respiratory protection guidelines, especially with the use of respirators as protection (Baig *et al*., 2008; Fukakusa *et al*., 2011). One of the reasons behind this trend is that respirators can be heavy, causing discomfort for the workers (Baig *et al*., 2008). Most respirators are designed to use granular activated carbon (GAC) and, while it has various advantages, the GAC's properties contribute to the respirator's bulkiness. Research is being conducted to find alternatives to reduce discomfort for workers required to use respirators, and one of the breakthroughs is the possibility of replacing GAC with a different form of adsorbent, which is the activated carbon fiber (ACF) (Balanay *et al*., 2016).

II. LITERATURE REVIEW

Volatile Organic Compounds

Volatile organic compounds (VOCs) are pollutants frequently encountered in the workplace and common sources are building materials, office equipment, graphics and craft materials including glues and adhesives (U.S. Environmental Protection Agency [EPA], 2017). Common VOCs encountered in the workplace include toluene, benzene, and tetrachloroethylene. VOCs have the potential to cause health problems ranging from eye, nose, and throat irritation to more serious health effects such as mutations in humans, which can lead to oncogenesis (EPA, 2017). Workers chronically exposed to higher concentrations of VOCs have higher risks of chronic respiratory symptoms (Jang *et al*., 2007). Such VOC exposure includes emissions from chemical manufacturing plants, associated with increased rates of chronic respiratory symptoms that are characteristic of reactive airways (Jang *et al*., 2007). Ways to reduce exposure to VOCs include increasing ventilation when using products that emit VOCs, as well as the use of respirators. A common method for removing VOCs in respirators is by adsorption onto GAC.

Toluene as a VOC

A common VOC found in the workplace is toluene. Toluene is an organic solvent found in commercially available products such as gasoline, paint, adhesives, glue, and various industrial solvents (Yoon *et al*., 2016). Toluene can become distributed throughout the body, accumulating in tissues with high lipid content and affecting organs such as the liver, lungs, kidneys, and brain (Yoon *et al*., 2016). The central nervous system (CNS) is the primary target organ for toluene toxicity in both humans and animals for acute (short-term) and chronic (long-term) exposures. Symptoms frequently observed in humans acutely exposed to elevated airborne levels of toluene are fatigue, sleepiness, headaches, and nausea. Chronic inhalation exposure of humans to toluene also causes irritation of the upper respiratory tract and eyes, sore throat, dizziness, and headache (EPA, 2012). Occupational exposures to toluene can be found in industrial and construction workplaces. Workers using toluene-containing products (e.g., paints, varnishes, glues and adhesives, rust preventives or industrial solvents) may be exposed to toluene. Toluene may enter a person's body by inhalation, ingestion, or contact via skin or eyes. The recommended level of toluene a person breathes over a work day is determined by the concentrations in the air, also known as permissible exposure limits (PELs) (Occupational Safety and Health Administration [OSHA] 2014). Workers tolerate concentrations ranging up to 200 ppm for 6 to 8 hours daily with no demonstrable ill effects; concentrations between 200 to 500 ppm for 6 to 8 hours will cause clinical symptoms in workers; concentrations greater than 500 ppm for 1 to 3 hours can cause serious acute damage to worker health due to high concentration exposure (OSHA, 2014).

VOC Adsorption on Activated Carbon

Adsorption is the adhesion of molecules (e.g., gases, solutes, or liquids) to the surfaces of solids or liquids with which it comes into contact. In adsorption, gaseous pollutants are removed from an air stream by transferring the pollutants to the solid surface of an adsorbent (EPA, 2017). The two basic forms of adsorption are physical and chemical adsorption. Chemical adsorption occurs when there is a formation of chemical bonds between the adsorbate and the adsorbent. This process requires activation energy and results in unimolecular layer. This process is considered to be irreversible. In contrast, physical adsorption, or physisorption, involves attractive forces between the adsorbent surface and adsorbate molecules that are relatively weak and is governed by van der Waals' and electrostatic forces (Ramaswamy *et al*., 2013). Hence, it is also called van der Waals' adsorption. Low temperature promotes physical adsorption, while high temperatures decrease the rate of adsorption. This process is considered reversible, is exothermic, and requires no activation energy.

Activated carbon is the most commonly used adsorbent, although zeolites, polymers, and other adsorbents may be used. Limitations exist in the amount the adsorbent can collect. When the limit is reached, the adsorbent is no longer effective in removing pollutants. To recover the ability to capture gaseous pollutants, adsorbents typically are regenerated. The maximum capacity the adsorbent can hold is the saturation capacity. However, before reaching saturation capacity, there is a breakthrough capacity. Breakthrough capacity is the amount of pollutant that can be adsorbed before a significant pollutant concentration exits, or breaks through, the bed. Heel capacity is the amount of pollutant that remains in the bed after it has been regenerated. Working capacity is the difference between breakthrough capacity and heel capacity, and represents the amount of material that can be adsorbed in each working cycle (EPA, 2017).

Granular Activated Carbon (GAC) vs Activated Carbon Fiber (ACF)

The usual method of purifying VOCs from breathed air in the workplace involves using respirators that adsorb the VOCs onto granular activated carbon (GAC). GAC is currently the most common adsorbent used in respirators for protection against gas phase contaminants, such as the VOCs. However, the use of GAC has its drawbacks. For example, using GAC requires the use of a cartridge or canister to contain the granules, which can present issues with increasing weight and bulkiness of respirators, contributing to discomfort of the wearer and lowering the probability of respirator use (Balanay *et al*., 2016). Other drawbacks of GAC include the attrition of the granular material and particle entrainment (Pang *et al.*, 2005).

ACF is an alternative carbon adsorbent that can overcome some of the drawbacks of

GAC. ACF is attained from the carbonization and activation of polymeric fibers from various precursors, such as viscose rayon, phenolic resin, polyacrylonitrile, and pitch (Suzuki, 1994). The unimodal narrow pore size distribution of the ACF is due to its small diameter which allows for the homogeneous activation of the fibers (Feng *et al*., 2005). Two of the current applications for ACF, other than in respirators, include air pollution control (Lorimier *et al*., 2005) and wastewater treatment (Wang *et al.*, 2007). ACF has been used in air pollution control and wastewater treatment to remove acidic gases (ACID), benzene, butanol, toluene, undecane, and other harmful gases and chemicals (EPA, 2017).

Some of the advantages of ACF as an adsorbent over GAC include larger surface area, higher adsorption capacity, thinner critical bed depth, higher number of micropores, and faster heat and mass transfer properties (Tsai *et al*., 2008; Balanay *et al.,* 2011). A study by Balanay *et al*. (2011) found that ACF, both in cloth and felt forms, with similar or greater surface area (1,500 – 2,000 m^2/g) than the GAC has higher adsorption capacity for toluene and, thus, may provide greater protection against toluene when used in a respirator. Another advantage is that ACF can be manufactured in fabric forms (e.g., cloth, felt), making it more versatile to use compared to the GAC (Lorimier *et al*., 2005). ACFs are a more affordable and versatile option for the adsorption of VOCs in respirators (Wang *et al*., 2007). These advantages make the ACF a great candidate to serve as an alternative adsorbent to GAC in the design of a respirator that is thinner and lighter, and provides efficient protection against exposure to VOCs (Balanay *et al*., 2011).

Adsorption Capacity of Activated Carbon Fibers for Toluene

Others have investigated the adsorption capacity of ACF for various VOCs. Tsai *et al.* (2008) showed that the ACF's high surface area and smaller fiber diameter increased the adsorption capacity compared to other ACF forms and sludge-derived adsorbent for VOCs. Previous studies also investigated the adsorption capacity of various ACF forms, such as cloth and felt, for VOCs. These two ACF forms are distinct in terms of physical characteristics. For example, the ACF cloth is composed of woven bunch of twisted fibers while the ACF felt is composed of non-woven, randomly distributed fibers (Balanay *et al.*, 2014). Consequently, this makes a single layer of ACF cloth thinner and denser than a layer of ACF felt, which is spongier in nature (Balanay *et al.*, 2011). Balanay *et al.* (2011) found ACFs to be good adsorbents for toluene, with ACF in cloth form with 2000 m^2/g surface area having the highest adsorption capacity (595-878 mg/g) for toluene compared to the ACF in felt form (221-616 mg/g). In a study conducted by Lorimier *et al.* (2005), the adsorption capacity of toluene onto ACF cloth and felt was investigated. Findings showed no major differences between adsorption capacities at saturation (and breakthrough time) between either forms at low toluene concentration (10 ppm), but appeared to be slightly higher for felts (616 and 430 mg/g) than for cloths (549 and 270 mg/g) at a higher toluene concentration (80 ppm). Additionally, the toluene concentration influenced the adsorption capacity at saturation which was found to be greater for felts than for cloths (Lorimier *et al*., 2005). Another study analyzed the behavior and kinetics of toluene adsorption and desorption on activated carbons with varying pore structures (Yang *et al*., 2017). The same study showed that adsorption force, the force required to release the adsorbate from the surface, increased as pore size decreased. This leads to adsorption occurring first in the micropores, where the adsorption was high. It was also found that when the relative pressure was low, the adsorption capacity increased, and slowed in the increase at its neared saturation. In a study conducted by Lin *et al*. (2013), the oxidation and adsorption of toluene onto ACFs at high concentration and adsorption temperatures was investigated. Results indicated that the breakthrough time decreased with an increase in toluene concentrations, and the adsorption capacity of toluene increased when the concentration of toluene increased. Additionally, the data showed a decrease in breakthrough time and adsorption capacity with increasing adsorption temperature (Lin *et al*., 2013). In a study that investigated the effects of composition of fibrous filter on toluene adsorption, it was concluded that composition of fibrous filters strongly influenced the structural and mechanical properties (Rochereau *et al*., 2008). The ACF ratio and beating of cellulose fiber as parameters compromise the adsorption and filtration performances done on the ACF (Rochereau *et al*., 2008). Beating, or refining, of cellulose fibers is the mechanical action that causes fibers to become more flexible and conformable and their specific surface area to increase, but it makes fiber surfaces to become frayed and fibers to be shortened and swell (Rochereau *et al*., 2008).

Pressure Drop across ACF Respirators Cartridges

The difference in static pressure between two pressure points located before and after an air-cleaning media, which is a function of flow rate and face velocity, is defined as pressure drop (Balanay *et al*., 2016). The National Institute for Occupational Safety and Health (NIOSH) has standard testing procedures (STPs) that set maximum resistances in mmH_2O for air-purifying respirators. The maximum allowable resistance requirement for chemical cartridge respirators other than single-use vinyl chloride respirators is 20 mmH_2O for exhalation resistance (NIOSH, 2014a), and 40 mmH_2O for inhalation resistance (NIOSH, 2014b). It is important that respirators have a low pressure drop so workers do not experience any negative effects in work performance (Baig *et al*, 2008). When there is an increase in inhalation and exhalation resistances across respirators, workers experience decreased performance.

A study conducted by Balanay *et al.* (2016) demonstrated that ACF can be configured in respirator cartridges to have acceptable pressure drop based on the NIOSH maximum inhalation resistance of 40 mmH_2O (NIOSH, 2014b). In the same study, pressure drop measurements were conducted across ACF cartridges containing various types and combinations of ACF forms (e.g., 100% ACF cloth, 100% ACF felt, combination of ACF cloth and felt). Results showed that cartridges filled with 100% ACF cloth had unacceptable pressure drop of 85.47 mmH_2O (i.e., more than twice the NIOSH limit) while those filled with 100% ACF felt had acceptable values (23.71 – 39.93 mmH_2O), which is likely attributed to the difference in fiber organization (woven vs. non-woven) between the ACF cloth and felt (Balanay *et al.*, 2016). Therefore, although shown to have higher adsorption capacity than the ACF felt in previous studies, the ACF cloth was not recommended for use in respirators if used by itself due to its unacceptably high pressure drop (Balanay *et al.*, 2016). Thus, the current study focuses on only the use of ACF felt forms in respirator cartridge in investigating their adsorption characteristics.

Regeneration of Activated Carbon

Regeneration is the process of desorbing accumulated adsorbates and restoring the original porous structure with little or no damage (Ramaswamy *et al*., 2013). Activated carbon (AC) can be regenerated via thermal regeneration, which can be done by using steam, microwaves, embedded heaters, and heated nitrogen (Yue et al., 2017). Thermal regeneration is more practical when VOC have lower vapor pressures. To maximize solvent recovery, and elimination of contamination of VOCs by steam, a vacuum regeneration system may be used. Vacuum regeneration uses a vacuum pump to lower the pressure in the adsorbent below the vapor pressure of the adsorbed VOC, which causes the VOC to boil off at the temperature that is ambient within the adsorbent (Ramaswamy *et al*., 2013).

Thermal regeneration involves the processes of drying, vaporization, pyrolysis, and selective oxidation of the pyrolyzed residue. Drying eliminates the highly volatile adsorbates;

vaporization of volatile adsorbates and decomposition of unstable adsorbates form volatile fragments; pyrolysis of non-volatile adsorbates causes deposition of carbonaceous residue on the surface of activated carbon; and selective oxidation of the pyrolyzed residue is conducted by steam, carbon dioxide, and other oxidizing agents (Yue *et al*., 2017). The regeneration of activated carbon is important because it is a more cost effective, energy efficient, and environmentally sustainable option to aid in processes, such as wastewater treatments and air pollution controls (Yue *et al*., 2017). Yue *et al.* (2017) conducted a study on electrochemical regeneration, which is considered a promising technology to regenerate exhausted ACFs. They found this to be important due to the high cost of raw materials for activated carbon (AC) and high energy consumption. This method would save in the cost for transporting ACs between water treatment facilities and AC regeneration units, and decreases the energy consumption associated with high temperature operation of thermal regeneration. The study also found that regenerated ACFs can effectively remove various VOCs from the air, but the average diameter of the spun fibers of the ACF was reduced to ∼10 μm (with most fibers originally with 7-15 μm diameter) (Yue *et al*., 2017). In a study using Joule heating regeneration technique, ACF cloth was rapid and efficient in removing the low initial loading of toluene. Additionally, after continuous adsorption/regeneration cycles (over 300 heating and cooling cycles), the ACF cloth showed excellent durability and adsorption capacity (Yao *et al.*, 2009). Johnsen and Rood (2012) conducted a study on temperature control during regeneration of ACF cloth and any resistance feedback that could be experienced. ACF cloth resistance that was modeled based on its physical properties was within 10.5% of the measured resistance values during electrothermal heating. After 2 min of heating, the temperature of the adsorbent with isobutane was 13% less than the adsorbent without isobutene, and it decreased to 2.1% in difference after 9 min of heating, showing desorption of isobutane. An ACF cloth cartridge was heated to 175 °C for 900 cycles.

Its resistance and adsorption capacity values were within 3% and 2%, respectively. The study demonstrated that the electrothermal heating method provides a simple, cost-efficient, and long-term regeneration technique for electrothermal swing adsorption (ESA) systems (Johnsen and Rood, 2012).

Knowledge Gap in Thermal Regeneration of ACF

Since physical adsorption occurs between the activated carbon (adsorbent) and VOCs (adsorbate), activated carbon can be regenerated via thermal, vacuum or electrochemical regeneration, making it a more cost effective, energy efficient and environmentally sustainable option to aid in certain purification processes (e.g., wastewater treatment, air pollution control) (Lorimier *et al*., 2005). However, additional studies should investigate the effects of thermal regeneration on the adsorption characteristics of the ACF used in respirator cartridges. A study found that the regeneration process reduces the average diameter of the ACF's spun fibers (Yue *et al*., 2017). Is it possible that such fiber diameter reduction occurs and happens to the same extent every time the ACF is regenerated? Will this result to the decrease in the ACF's adsorption capacity and breakthrough time when used in a respirator cartridge? Another factor that needs to be studied is if the breakthrough time would decrease at a higher concentrations of VOCs overtime after several regeneration cycles. There are significant gaps in the knowledge of the ACF's capability to be regenerated for long-term use. There is insufficient data available at the present time to answer these questions, warranting additional studies to address these issues.

III. SPECIFIC AIMS OF THE STUDY

The main objective of this study is to investigate the effects of thermal regeneration on the adsorption characteristics of ACF in respirator cartridges for toluene. The specific aims of the study are to:

1. Compare the breakthrough times of toluene across ACF respirator cartridges by toluene concentration (200 and 500 ppm)
2. Compare the breakthrough times of toluene across ACF respirator cartridges by ACF felt type based on density and layer thickness
3. Compare the breakthrough times of toluene across ACF respirator cartridges by number of thermal regeneration events.

IV. HYPOTHESES

Hypothesis 1: The percent reduction in breakthrough times of toluene across the ACF respirator cartridge after consecutive regeneration events will be greater in a higher toluene concentration (500 ppm) compared to a lower toluene concentration (200 ppm).

Justification 1: Previous studies have demonstrated that breakthrough times of toluene decrease as the toluene concentration increases. In a study conducted by Lin *et al*. (2013), the oxidation and adsorption of toluene onto ACFs at high concentration and adsorption temperatures was investigated, and results indicated that the breakthrough time decreased with an increase in toluene concentrations, and the adsorption capacity of toluene increased when the inlet concentration of toluene increased. I hypothesize that regenerated ACFs that are exposed to a higher toluene concentration (compared to a lower toluene concentration) will have a bigger reduction in breakthrough times after consecutive regenerations because of higher heel capacity, which is the amount of adsorbate that remains in the ACF adsorbent after it has been regenerated.

Hypothesis 2: The percent reduction in breakthrough times of toluene across the ACF respirator cartridge after consecutive regeneration events will be lower for thicker and denser ACF materials compared to a thinner and less dense ACF materials.

Justification 2: In a study that investigated the effects of composition of fibrous filter on toluene adsorption, it was concluded that composition of fibrous filters strongly influences the structural and mechanical properties. I hypothesize that thicker and denser ACF, after regeneration, will undergo a lesser extent of degradation (e.g., reduction in fiber diameter) and structural modification compared to thinner and less dense ACF, and thus resulting in lower reduction in breakthrough times.

Hypothesis 3: The breakthrough time of toluene across the ACF respirator cartridge will be reduced as the number of thermal regeneration events is increased.

Justification 3: Breakthrough time decreases with continuous adsorption/ regeneration cycles. In a study conducted by Yao *et al*. (2009), a single-layer of ACF cloth was tested for the adsorption and regenerative properties using toluene as the indoor contaminant for filtration of air pollution. It was tested for breakthrough times and its effectiveness after regeneration for adsorption of VOCs. Results showed that ACF cloth had excellent durability and adsorption capacity. However, after numerous regenerations, the breakthrough time for the ACF decreased. This finding was deduced due to the reduction in the thickness of fibers, resulting in less adsorbent mass and surface area to which adsorbates may be collected.

V. SIGNIFICANCE OF THE STUDY

In today's society, the use of respirators is important in certain work environments due to increased use of volatile organic compounds (VOCs), which could be detrimental to the health and safety of the workers. Respiratory protection may help diminish the risk of exposure to gaseous contaminants in the workplace. However, breakthroughs in finding an alternative adsorbent (e.g., ACF) for GAC, due to its recognized disadvantages, can be a promising option to improving respiratory protection and compliance in its use in the future. Advantages that come with the use of ACF as an alternative absorbent include larger surface areas, higher adsorption capacities, thinner critical bed depth, higher number of micropores, faster heat and mass transfer properties, and its fabric form which allow for the fabric form to heat more quickly; due to its higher number of microspores at its surface area. This makes ACF a great candidate to serve as an alternative adsorbent to GAC in the design of a thinner, lighter, and efficient respirator for protection against exposure to VOCs.

The regeneration of carbonaceous materials is common, and its practice allows for the reuse of these materials. The regeneration of AC is important because it is a cost-effective, energy efficient, and environmentally sustainable option to aid in processes, such as wastewater treatments and air pollution controls (Yue *et al*., 2017). Hence, it is important to investigate the effects of thermal regeneration on the effectiveness of ACF as an adsorbent for VOCs in respirators. It is essential to know if regeneration decreases the ACF's adsorption capacity and breakthrough time, and to know the extent for such decrease, if at all present. Another factor that will be investigated in this study is the effect of toluene concentration on ACF's adsorption characteristics after regeneration. If thermal regeneration has insignificant effects on ACF's adsorption characteristics, ACF will have a greater promise on the design of a regenerable, thinner, lighter and more efficient respirator than is currently on the market. However, there are

\currently significant gaps in the knowledge of the ACF's capability to be regenerated for long-term use. This study contributes significant knowledge on an under-investigated topic on ACF regeneration for respiratory protection application. There is insufficient data available at the present time to answer these questions, warranting for further research to help provide data on this gap to encourage further investigations into the effectiveness and durability of ACF after regeneration.

VI. METHODOLOGY

Materials

Two types of ACF felt materials (American Technical Trading, Inc., Pleasantville, NY) with varying thickness and density were tested (Table 1). Three-inch diameter ACF discs (Figure 1) that were previously exposed to toluene were treated overnight in a laboratory oven at 200°C, and then placed in a desiccator cabinet to cool down the ACF while preventing moisture adsorption. The ACF discs were then placed, layer by layer, on top of each other and sealed in a typical respirator cartridge (3-inch [7.62 cm] internal diameter, 1-inch [2.54 cm] bed depth) (Figure 2). Cartridges were filled with 100% of each ACF felt type with pressure drop values of <40 mm H_2O based on previous study findings on pressure drop (Balanay *et al.*, 2016). Polypropylene sheets (Pall Life Sciences, Port Washington, NY) were cut into 3-inch diameter discs and placed on both sides such that the ACF disc bed would be sandwiched between the polypropylene sheets to prevent the inhalation of carbon particulates from the ACF cartridge when used in a respirator.

Table 1. Activated Carbon Fiber (ACF) Structural Properties by ACF Type

ACF Type	Thickness (cm)*	Density (g/cm^3)	Number of Layers per Cartridge
ACF 210	0.24	0.043	10
ACF 605	0.50	0.070	5

Figure 1. Activated carbon fiber (ACF) felt discs: ACF 210 (left) and ACF 605 (right)

Figure 2. Respirator cartridge with 3-inch internal diameter and 1-inch bed depth: a) uncovered showing the ACF discs; b) covered

Breakthrough Determination

ACF respirator cartridges were challenged with 2 concentrations (200 and 500 ppm) of toluene in a customized cylindrical test chamber. Using an Aladdin-1000 programmable syringe pump (World Precision Instruments, Sarasota, FL), liquid toluene was injected continuously at a specific rate into pre-conditioned air at constant temperature (25°C), relative humidity (50%) and air flow (32 LPM) creating the desired challenge concentration of toluene in vapor form. Dry, oil-free air was supplied by an air compressor equipped with air filtering units and pre-conditioned using a Miller-Nelson Model HCS-501-100 instrument (Assay Technology, Livermore, CA). The temperature and relative humidity in the test chamber were monitored using a HOBO Model U14-002 temperature and relative humidity data logger (Onset Computer Corp., Pocasset, MA). Breakthrough curves were obtained for each ACF cartridge configuration at different toluene concentrations by continuous monitoring of the effluent (i.e., downstream of the ACF cartridge) using a VOC-TRAQ II photoionization detector (PID) (MOCON Baseline Series, Lyons, CO). The influent (i.e., upstream of the ACF cartridge) was also monitored continuously in the same manner using another PID to confirm the influent gas concentration. The exposure system was calibrated before and after every exposure run while using the PID monitors in the same manner as the breakthrough experiments. The time in minutes when $C_x/C_0 = 0.1$ (referred as the 10% breakthrough time) and $C_x/C_0 = 0.5$ (50% breakthrough time), were determined for each breakthrough curve, and compared for each ACF cartridges tested. Repeat measurements (n=2) were performed to characterize variability of results. The ACF materials were thermally treated in a Precision Compact Model 665 oven (Thermo Scientific, Marietta, OH) at 200°C overnight prior to testing to desorb any volatile impurities and remove excess moisture on the adsorbent materials. This was done to regenerate the material for the next sequence of testing for the breakthrough determination of regenerated ACF. Each ACF disc was placed on the oven rack as single layers during regeneration to facilitate efficient desorption of toluene. The ACF materials underwent 4 regeneration/exposure events to determine its effects on adsorption characteristics. Figure 3 shows the schematic diagram of the experimental setup for breakthrough determination.

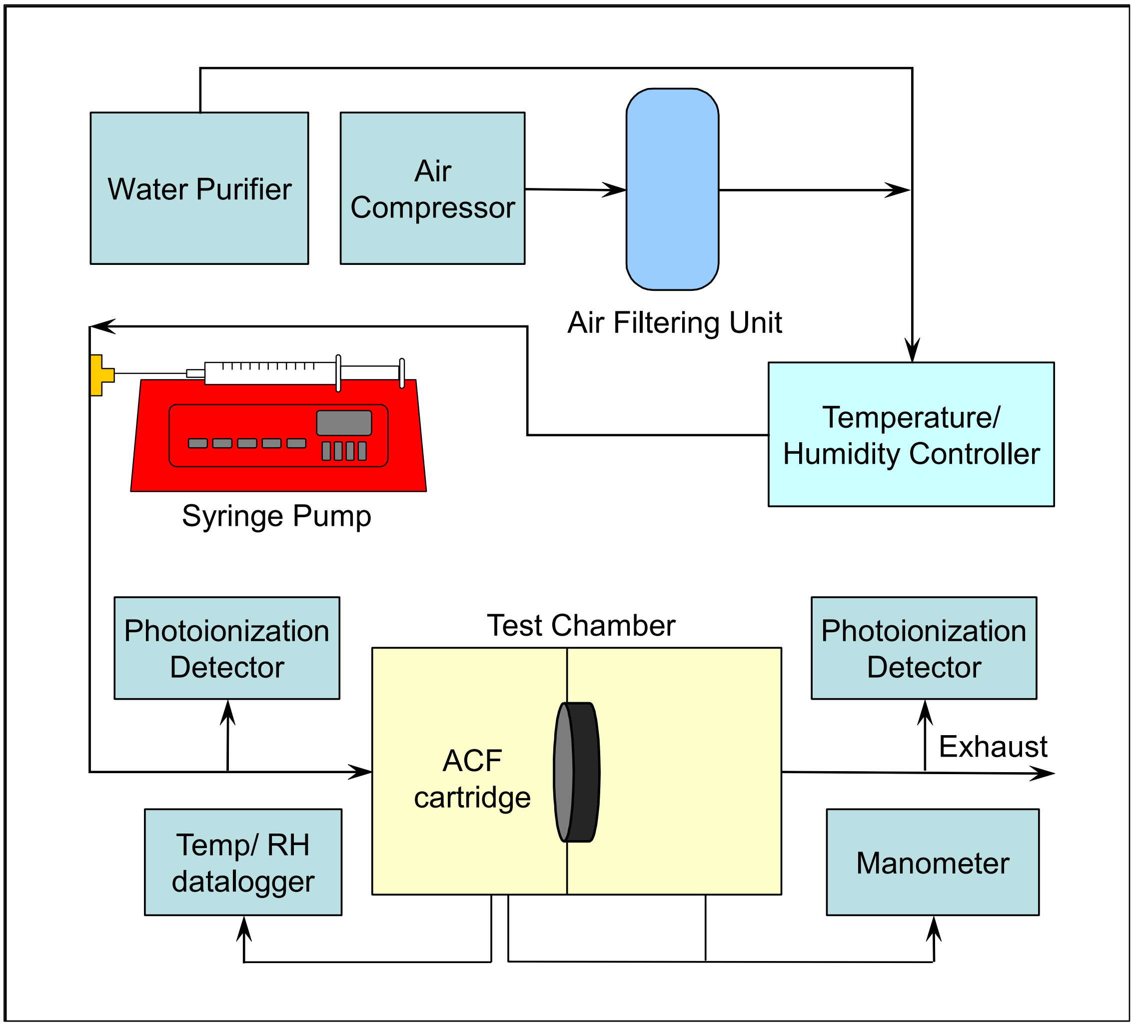


Figure 3. Experimental setup for breakthrough determination

Data Analysis

Line graphs were created to visualize breakthrough curves using Microsoft Excel. Means and standard deviations for breakthrough times (10% and 50%) were determined and organized in tables. Percent reductions in breakthrough times, which is defined as the percent change in toluene breakthrough times by comparing the breakthrough times for new (i.e., never used) ACF with those for regenerated (i.e., previously used) ACF, were calculated using the following equation:

$$Percent\ change\ (\%) = \frac{\text{"Never used" ACF BT } - \text{"Regenerated" ACF BT}}{\text{"Never used" ACF BT}} \times 100$$

The purpose of the percent reduction calculation is to demonstrate the extent of the change in breakthrough times of toluene across the ACF respirator cartridges as the effect of consecutive regeneration events. The Statistical Package for the Social Sciences (SPSS version 20, IBM, New York, NY) was used to analyze the data. One-way analysis of variance (ANOVA) was used to evaluate differences in 10% breakthrough times by ACF type, toluene concentration, and number of regeneration. $P < 0.05$ were considered statistically significant.

VII. RESULTS

The main objective of this study was to investigate the effects of thermal regeneration on the adsorption characteristics of activated carbon fiber (ACF) in respirator cartridges for toluene. Two types of ACF materials underwent 4 regeneration/exposure events (R1 to R4) at 2 toluene concentrations, resulting in a total of 32 regenerations and chemical challenges (Table 2). The average baking time for regeneration was 18 hours and 1 minute ± (standard deviation [SD] = 10.8 minutes) (range: 17 hours and 30 minutes to 18 hours and 22 minutes).

Table 2. Number of Breakthrough Runs by ACF Type, Toluene Concentration and Number of Regenerations (N = 32)

ACF Type	Toluene Concentration							
	200 ppm				500 ppm			
	R1	R2	R3	R4	R1	R2	R3	R4
ACF 210	2	2	2	2	2	2	2	2
ACF 605	2	2	2	2	2	2	2	2

R1 – R4 – 1st to 4th regeneration

Effect of Toluene Concentration on Breakthrough Time

The 1st specific aim of the study was to compare the breakthrough times (BT) of toluene across ACF respirator cartridges between 200 and 500 ppm as toluene challenge concentrations to which the ACF cartridges were exposed. Table 3 shows the average 10% BT and 50% BT for 2 ACF types (ACF 210 and ACF 605) at 2 toluene concentrations (200 and 500 ppm). Results show that differences in 10% BT and 50% BT between the two concentrations (200 ppm and 500 ppm) were significant ($P < 0.01$) (Appendix B1). The average 10% BT for 200 ppm toluene concentration (91.4 ± 15.7 min) was significantly higher ($F = 196.8$, $P < 0.01$) than that for 500 ppm concentration (37.2 ± 4.9 min). On the other hand, the 50% BT for 200 ppm toluene concentration (106.4 ± 16.8 min) was significantly higher (F = 218.7, $P < 0.01$) than that for 500 ppm concentration (43.1 ± 6.9 min) (Table 3). Figure 4 compares the breakthrough curves between 200 and 500 ppm toluene concentrations for ACF 210 (Figure 4A) and ACF 605 (Figure 4B), showing that breakthrough times occurred at a later time at a lower concentration (i.e., 200 ppm) for both ACF types.

In relation to the BT comparison between toluene concentration, the 1st hypothesis of this study states that the percent reduction in breakthrough times after regeneration will be greater at a higher toluene concentration (500 ppm) compared to a lower one (200 ppm). Figure 5 shows the trend in percent reduction in 10% (Figure 5A) and 50% (Figure 5B) BT after regeneration events by toluene concentration and ACF type. As the number of regenerations increases, the percent reductions in either 10% or 50% BT times fluctuate and does not seem to have either a decreasing or increasing trend. Table 4 shows the percent reduction in 10% and 50% BTs of toluene across the ACF respirator cartridge after consecutive regeneration events by toluene concentration. The average percent reduction in 10% BT for 200 ppm toluene concentration (-3.7 ± 9.4 %) was not significantly different ($F = 0.21$, $P = 0.65$) from that of the 500 ppm concentration (-2.1 ± 2.5 %). Similarly, the 50% BT for the 200 ppm toluene concentration (0.6 ± 4.5 %) was not significantly different, though marginally, ($F = 4.44$, $P = 0.05$) from that of the 500 ppm concentration (-3.2 ± 2.4 %) (Table 4, Appendix B4).

Effect of ACF Type on Breakthrough Time

The 2nd specific aim of the study was to compare the breakthrough times of toluene across ACF respirator cartridges between ACF 210 and ACF 605 as ACF felt types with different density and layer thickness. Table 3 shows that both the 10% BT and 50% BT for ACF 605 (73.4 ± 32.8 and 85.5 ± 37.5 min, respectively) are higher (p = 0.07 and 0.06, respectively) than those for ACF 210 (55.2 ± 23.9 and 62.0 ± 28.5 min, respectively) (Appendix B2). Figure 6 compares the breakthrough curves between ACF 210 and ACF 605 for 200 ppm (Figure 6A) and 500 ppm (Figure 6B) toluene concentrations, showing that the BTs occur later for ACF 605 for both toluene concentrations.

In relation to the BT comparison between ACF types, the 2nd hypothesis of this study states that the percent reduction in BTs after regeneration will be lower for thicker and denser ACF 605 compared to thinner and less dense ACF 210. Table 5 shows the percent reduction in 10% and 50% breakthrough times of toluene across the ACF respirator cartridge after consecutive regeneration events by ACF type to compare if there was a difference between thicker and denser ACF materials (ACF 605) and a thinner and less dense ACF materials (ACF 210). There were slight changes in percent reduction but these differences were very small after each regeneration of either material. Consequently, thick/dense ACF and thin/less dense ACF performed within the same level of adsorption, regardless of the number of regenerations. The average percent reduction in 10% BT for ACF 605 (0.0 ± 4.1 %) was not significantly different (F = 3.42, p = 0.09) from that of ACF 210 (-5.8 ± 7.8 %). Moreover, the 50% BT for ACF 605 (-0.5 ± 4.8 %) was not significantly different (F = 3.79, p = 0.07) from that of ACF 210 (-3.1 ± 2.0 %) (Table 5, Appendix B5).

Table 3. Average (±SD) 10% and 50% Breakthrough Times (BT, minutes) by ACF Type and Toluene Concentration

ACF Type	10% BT			50% BT		
	200 ppm	**500 ppm**	**Average by ACF Type**	**200 ppm**	**500 ppm**	**Average by ACF Type**
ACF 210	77.7 (±8.6)	32.8 (±1.5)	55.2 (±23.9)	91.3 (±6.3)	36.7 (±1.0)	62.0 (±28.5)
ACF 605	105.1 (±4.8)	41.7 (±1.9)	73.4 (±32.8)	121.6 (±6.9)	49.4 (±3.0)	85.5 (±37.5)
Average by Concentration	91.4 (±15.7)	37.2 (±4.9)	---	106.4 (±16.8)	43.1 (±6.9)	---

SD – Standard Deviation

Table 4. Percent Reduction in 10% and 50% Breakthrough Times by Toluene Concentration										
10% BT										
ACF Type	**200 ppm**					**500 ppm**				
	R0	**R1**	**R2**	**R3**	**R4**	**R0**	**R1**	**R2**	**R3**	**R4**
ACF 210	0	-22.7	-5.8	-5.2	-9.9	0	1.5	1.5	-3.0	-3.0
ACF 605	0	5.9	2.9	0.5	4.4	0	-1.2	-3.5	-4.7	-4.7
Mean	---	-3.7 ± 9.4				---	-2.1 ± 2.5			
50% BT										
ACF Type	**200 ppm**					**500 ppm**				
	R0	**R1**	**R2**	**R3**	**R4**	**R0**	**R1**	**R2**	**R3**	**R4**
ACF 210	0	.5	-5.3	-3.2	-4.8	0	-2.6	-2.	-5.3	-1.3
ACF 605	0	3.0	6.0	4.3	4.3	0	-1.0	-7.8	-3.9	-1.0
Mean.	---	0.6 ± 4.5				---	-3.2 ± 2.4			

R0 – no regeneration; R1-R4 – 1st to 4th regeneration

Table 5. Percent Reduction in 10% and 50% Breakthrough Times by ACF Type										
10% BT										
Toluene Concentration	**ACF 210**					**ACF 605**				
	R0	**R1**	**R2**	**R3**	**R4**	**R0**	**R1**	**R2**	**R3**	**R4**
200 ppm	0	-22.7	-5.8	-5.2	-9.9	0	5.9	2.9	0.5	4.4
500 ppm	0	1.5	1.5	-3.0	-3.0	0	-1.2	-3.5	-4.7	-4.7
Mean	---	-5.8 ± 7.8				---	0.0 ± 4.1			
50% BT										
Toluene Concentration	**ACF 210**					**ACF 605**				
	R0	**R1**	**R2**	**R3**	**R4**	**R0**	**R1**	**R2**	**R3**	**R4**
200 ppm	0	.5	-5.3	-3.2	-4.8	0	3.0	6.0	4.3	4.3
500 ppm	0	-2.6	-2.6	-5.3	-1.3	0	-1.0	-7.8	-3.9	-1.0
Mean	---	-3.1 ± 2.0				---	0.5 ± 4.8			

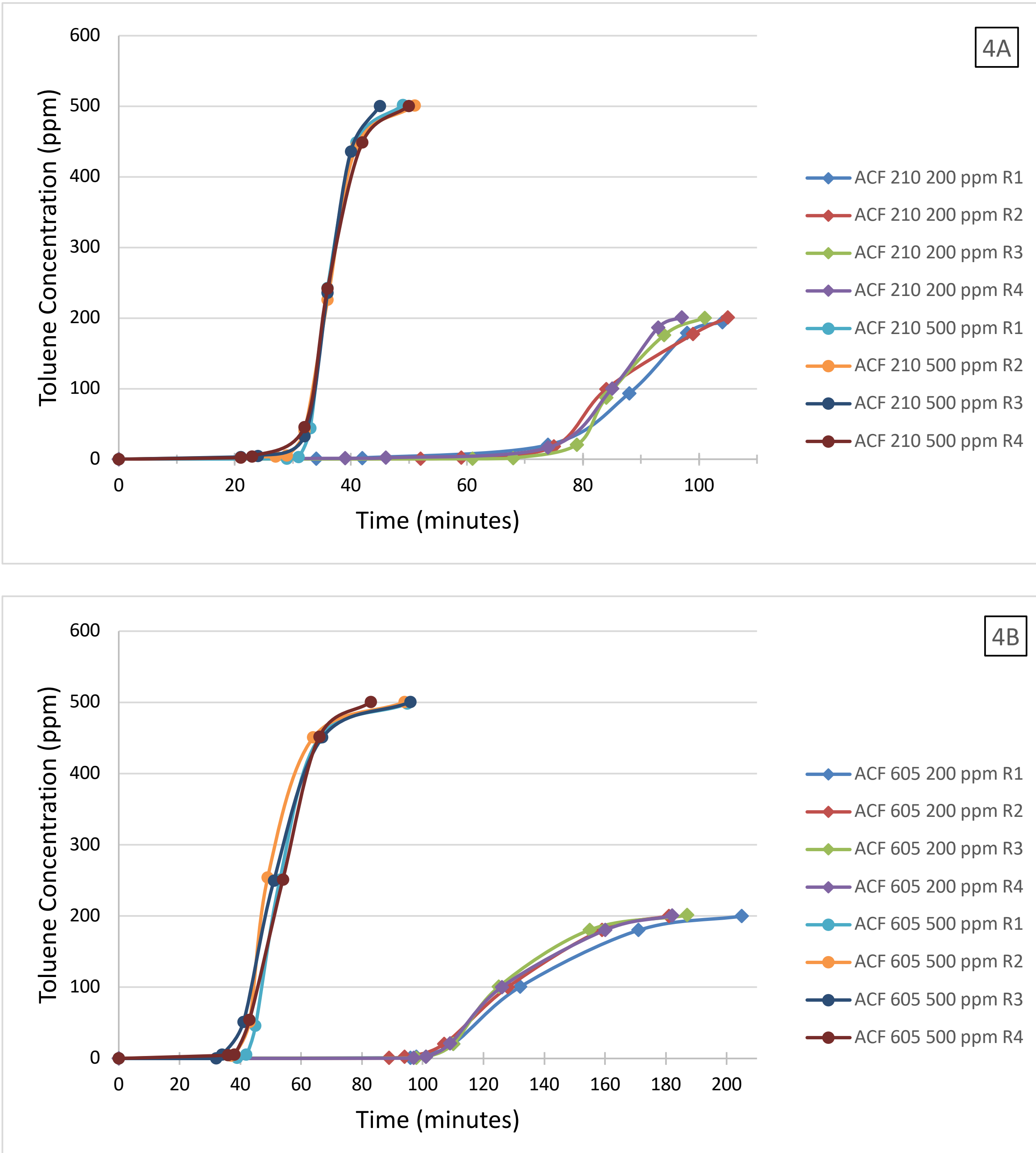


Figure 4. Comparison of Toluene Breakthrough Curves for ACF 210 (4A) and ACF 605 (4B) by Toluene Concentration and Number of Regenerations

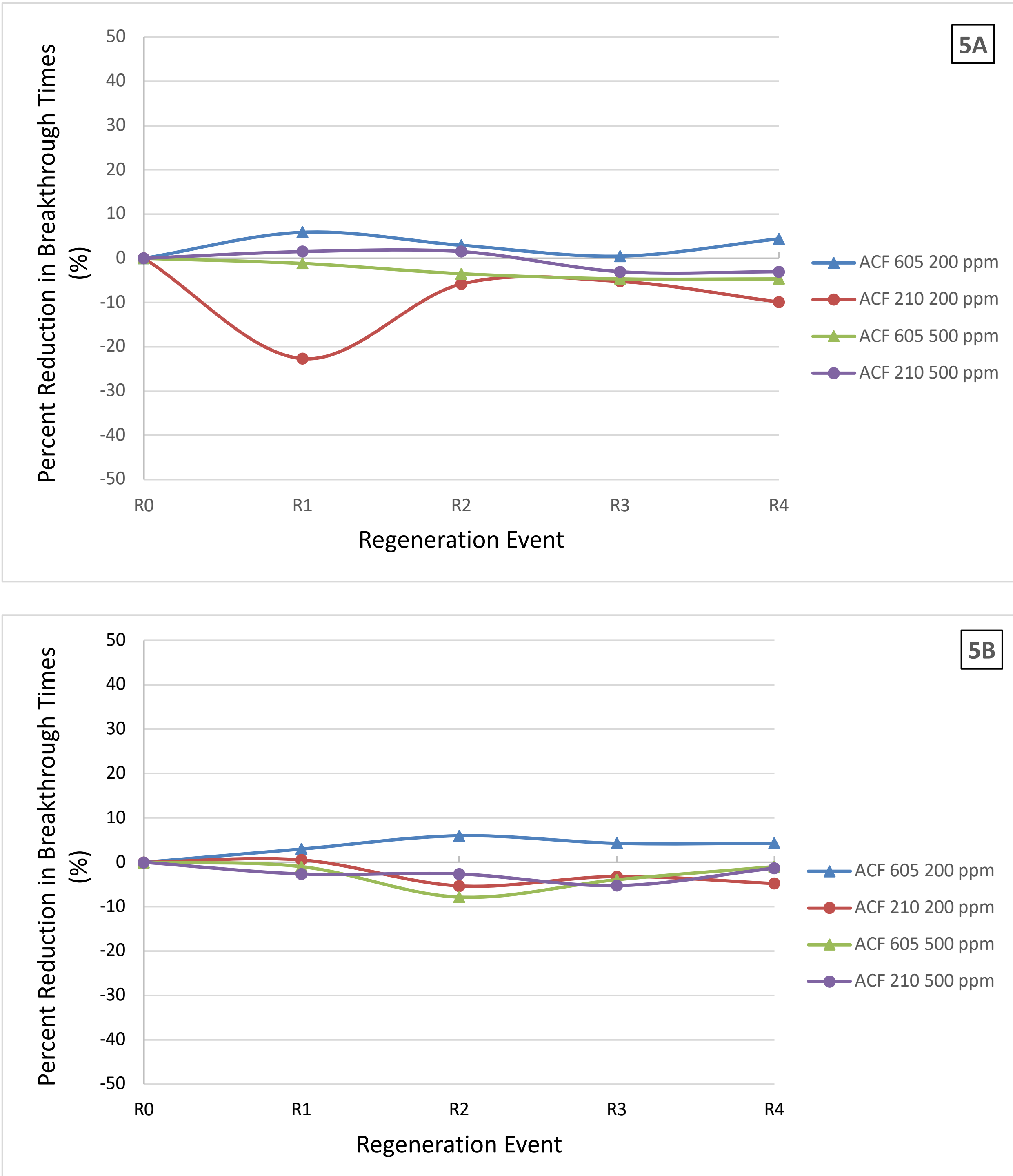
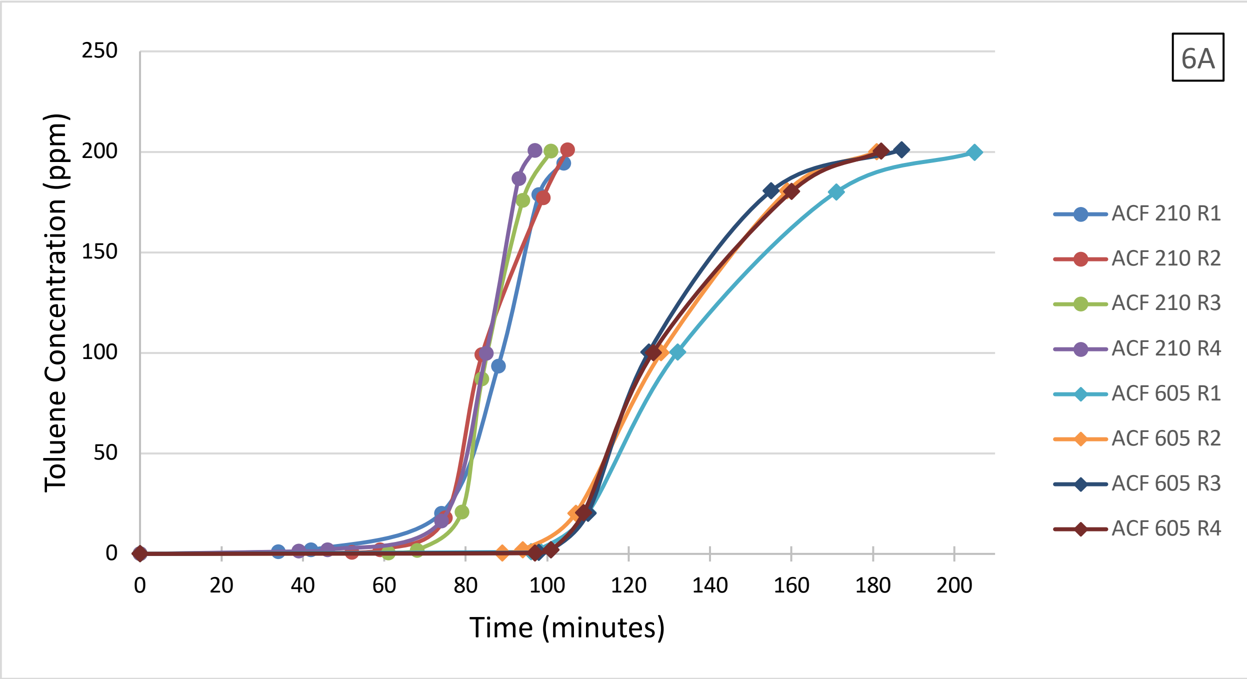


Figure 5. Percent Reduction in 10% (5A) and 50% (5B) Breakthrough Times After Thermal Regeneration by Toluene Concentration and ACF Type



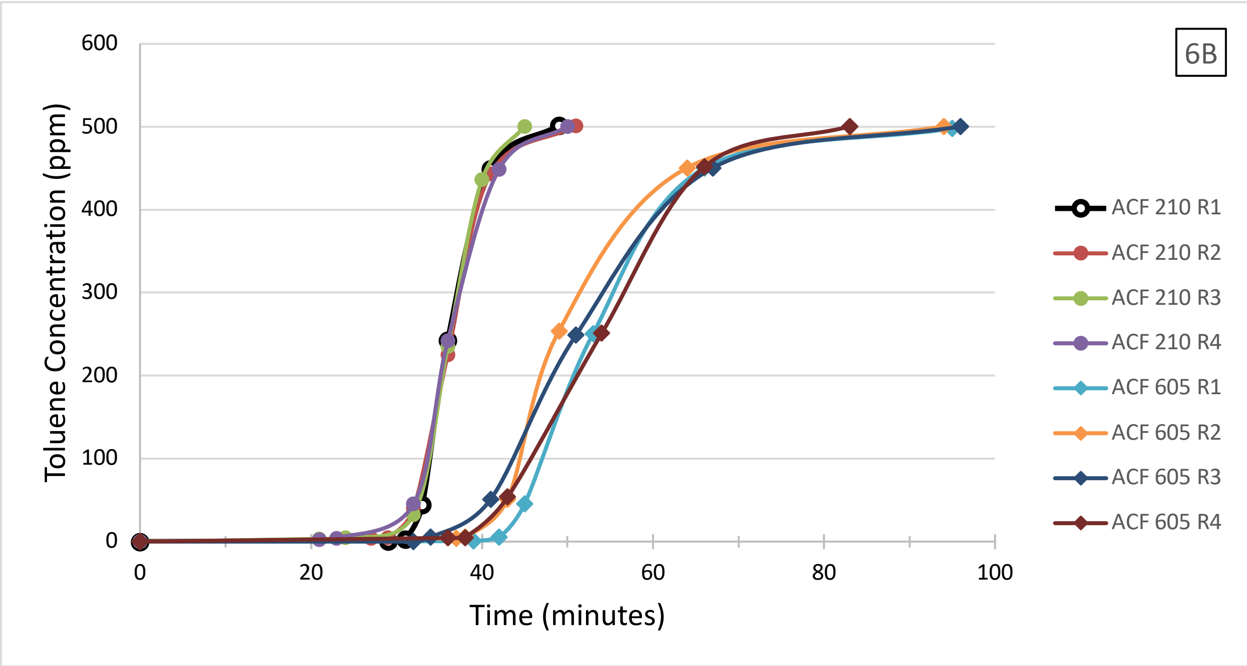


Figure 6. Comparison of Toluene Breakthrough Curves for 2 ACF Types at 200 ppm (6A) and 500 ppm (6B) Toluene Concentrations

Effect of Regeneration on Breakthrough Time

The 3rd specific aim of the study, which is also addressed by the 3rd hypothesis, was to compare the BTs of toluene across ACF respirator cartridges by the number of thermal regeneration events. Figures 4 and 5 show that the breakthrough curves after 4 consecutive regeneration events, regardless of the toluene concentration and/or ACF type, remained the same. The breakthrough curves were consistent throughout regenerations in terms of breakthrough times. Comparing the 10% and 50% BTs by number of regenerations, the differences in either 10% BT or 50% BT were not statistically significant (P = 1.0) (Appendix B3).

VIII. DISCUSSION

Toluene Concentration Effects on Breakthrough Times

The first aim of this study was to compare the BTs of toluene across ACF respirator cartridges by toluene concentration (200 and 500 ppm). It was found that the average 10% and 50% BT for 200 ppm toluene was significantly higher than the 10% and 50% for 500 ppm. This could be because lower concentrations require more time to saturate the ACF than higher concentrations, potentially leading to higher BTs. Previous studies have demonstrated that BTs of toluene decreased as the toluene concentration increased, which supports the results of this study. In a study conducted by Lin *et al*. (2013), the oxidation and adsorption of toluene onto ACFs at high concentration and adsorption temperatures was investigated, and results indicated that BT decreased with an increase in toluene concentrations, and the adsorption capacity of toluene increased when the inlet concentration of toluene increased.

Comparison of Percent Reduction between Toluene Concentrations

The initial hypothesis was that the percent reductions in BTs of toluene across the ACF respirator cartridge after consecutive regeneration events would be greater in a higher toluene concentration (500 ppm) compared to a lower toluene concentration (200 ppm) because of higher heel capacity. Heel capacity is the amount of pollutant that remains in the bed after it has been regenerated (EPA, 2017). The higher the toluene concentration, the higher the amount of pollutant will be left on the ACF after each regeneration cycle (Lin *et al*., 2013). This implies that the ACF exposed to 500 ppm toluene would have higher heel capacities compared to 200 ppm toluene concentrations and, thus, resulting to a less available surface area for VOC adsorption and a shorter BT. However, the results showed that the percent reductions in both 10% and 50% BT of toluene across the ACF respirator cartridge after consecutive regeneration events are not significantly different between the 2 toluene concentrations. A possible explanation for this is that the heel capacity may have ended to be equal and insignificant in amount for both concentrations due to the relatively long regeneration time, allowing all previously adsorbed toluene to effectively desorb and consequently freeing all possible adsorption sites. Thus, this resulted in no significant differences in percent reductions in BTs. However, heel capacity was not directly measured in this study and may be investigated in future studies.

ACF Type Effects on Breakthrough Times

The second aim of this study was to compare the BTs of toluene across ACF respirator cartridges by ACF felt type based on density and layer thickness. The study found that the average 10% and 50% BTs between ACF 210 and ACF 605 were not significantly different. These findings contradict those in some other published studies. For example, in a study conducted by Yao *et al*. (2009), a single-layer of ACF cloth was tested for the adsorption and regenerative properties using toluene as the indoor contaminant for filtration of air pollution. It was tested for BTs and its effectiveness after regeneration for adsorption of VOCs. The same study showed that ACF cloth had excellent durability and adsorption capacity. However, after numerous regenerations, the BT for the ACF decreased. This finding was deduced due to the reduction in the thickness of fibers, resulting in less adsorbent mass and surface area to which adsorbates may be collected. The reason for this contradiction in findings could be due to the thicker and denser ACF after regeneration that did not undergo any loss in surface area or thickness of fibers resulting in no significantly different averages in the 10% and 50% BTs between ACF 210 and ACF 605. The changes in fiber morphology and surface characteristics may be further investigated and confirmed in future studies by examining the adsorbent material under a scanning electron microscope (SEM) and/or analyzing the surface area using a physisorption analyzer.

Comparison of Percent Reduction between ACF Types

The second hypothesis made was that the percent reduction in BTs of toluene across the ACF respirator cartridge after consecutive regeneration events would be lower for thicker and denser ACF materials compared to a thinner and less dense ACF materials. However, this study found that the percent reductions in both 10% and 50% BT of toluene across the ACF respirator cartridge after consecutive regeneration events are not significantly different between ACF 210 and ACF 605. This found the hypothesis made to be incorrect. These findings were contradicted by another study that investigated the effects of composition of fibrous filter on toluene adsorption (Rochereau *et al*., 2008). The study concluded that composition of fibrous filters strongly influences the structural and mechanical properties. The ACF ratio and beating of cellulose fiber parameters compromise the adsorption and filtration performances done on the ACF (Rochereau *et al*., 2008). The same study indicated that thicker and denser ACF after regeneration would undergo a lesser extent of degradation (e.g., reduction in fiber diameter) and structural modification compared to thinner and less dense ACF, and thus resulting to lower reduction in BTs. However, this was not the case in the current study. This is likely due to thicker and denser ACF not undergoing less degradation (e.g., reduction in fiber diameter) and structural modification compared to thinner and less dense ACF after regeneration. Thus, this resulted in no differences in reduction percentages in BTs. A reason for observing no degradation in the ACF in the current study was possibly due to the way the ACF was handled, with consistent baking times and consistent temperature for approximately an average of 18 hours, compared to a high temperature for short periods of time in previous studies (Yao *et al*., 2009), affecting both the thick and thin ACF equally. Additionally, the way that the material was oriented in the oven, as well as it being laid individually instead of stacked could have contributed to these different findings.

Comparison of Breakthrough Times after Consecutive Regenerations

The third aim of this study was to compare the BTs of toluene across ACF respirator cartridges by the number of thermal regeneration events. Specifically, the aim was to determine the extent to which BTs of toluene across the ACF respirator cartridges would be reduced as the number of thermal regeneration events increased. This study found that the average 10% and 50% BTs among regeneration events were not significantly different, regardless of toluene concentration and ACF type. This contradicted the findings of others that BTs decreased with continuous adsorption/ regeneration cycles. For example, in a study conducted by Yao *et al*. (2009), a single-layer of ACF cloth was tested for the adsorption and regenerative properties using toluene, after numerous regenerations, the BTs for the ACF decreased. Investigators of the same study hypothesized this occurred due to a reduction in the thickness of fibers, resulting in less adsorbent mass and surface area. The baking temperature and time used in Yao *et al*. (2009) experiment was 200°C for 5 hours while 200°C for an average of 18 hours 1 min was used in the current study. This could have contributed to differences in results, due to our study having more baking time to allow for more VOCs to be desorbed from the ACF compared to those in the Yao *et al*. (2009) experiment. It may be possible that the ACF fibers may have reduced thickness but the longer regeneration time may have also created more pores for more adsorption sites (e.g., by pyrolizing residues in previously unavailable pores, by creating new micropores on the fiber surface). However, this was not confirmed by further analysis in this study.

In the current study, there were no significant differences in the average 10% and 50% BTs among regeneration events, regardless of toluene concentration and ACF type. This could be due to ACF's ability to effectively be saturated to its full capacity, even as the regeneration of the ACF increased. This finding is significant due to the ACF's potential to be used in respirators as an alternative form of adsorbent for VOCs. When using a respirator in the workplace, the amount of regenerations for which an adsorbent experiences should not affect its ability to be saturated completely by VOCs. If it does, it could potentially compromise the worker's safety. For example, if a worker uses a respirator utilizing a regenerated adsorbent that provides shorter BT and lower adsorption capacity, this could leave a worker exposed to inhaling harmful VOCs which have the potential to cause health problems ranging from eye, nose, and throat irritation to more serious health effects such as mutations in humans, which can lead to oncogenesis (EPA, 2017). These findings showcase the ACF's potential as a good adsorbent. Also, results showing that there were no significant differences in BTs in relation to concentrations (high or low) also supports ACF's potential as a good adsorbent of VOCs, because VOC concentrations in the workplace can vary and the ability to use a respirator that can absorb at different concentrations is very important for worker safety.

Strengths and Limitations

A strength found in this study was providing more knowledge on the effectiveness of ACF as an alternative VOC adsorbent in respirators, specifically after multiple regenerations. This information was of particular importance due to its link to ACF's potential to become an alternative form of adsorbent in respirators, which is understudied, leaving a gap in knowledge for its potential. The current study provided essential information to the knowledge of regeneration and the ACF's BT, finding no statistically significant decrease in BTs and also showing that thermal regeneration had statistically insignificant effects on its adsorption characteristics of ACF after regeneration. Both of these key parameters add significant information to an under-investigated topic. This adds knowledge to ACF's potential promise on a design of a regenerable, thinner, lighter and efficient respirator, which would help workers reduce complaints related to wearing respirators in the workplace.

Limitations that were found throughout the collection of data was the inability to examine the ACF materials under a high power microscope (e.g. SEM) to visually determine if degradation of the fibers of the ACF materials occurred. This study is limited to the drawing of conclusions based on differences in BTs and percent reduction in BTs after consecutive regeneration events, leaving some gray area in reference to the ACF's adsorption characteristics based on mass and surface area. Another possible limitation was not allowing the toluene to remain saturated on the material for an extended period of time before thermal regeneration, which could have resulted to the lack of difference in BT reductions or percent reductions between each regeneration. Due to these limitations, findings from this study may have differed from other studies that found a small extent of material degradation and reduction in BT.

IX. CONCLUSION

Exposure to VOCs can lead to serious effects on a person's health. Studies have shown an increase in a person's risk of developing respiratory diseases, such as asthma, lung cancer, bronchitis, and chronic obstructive pulmonary disease when exposed to VOCs, in general (Fukakusa *et al*., 2011). In today's society, the use of respirators is important in certain work environments due to increased use of VOCs, which could be detrimental to the health and safety of the workers in these specific work fields. Respiratory protective equipment is recommended as one method to diminish the risk of exposure to airborne pollutants. The usual method of purifying VOCs from breathed air in the workplace involves using respirators that adsorb the VOCs onto GAC, but ACF is an alternative carbon adsorbent due to its advantages over GAC. Results of this study showed that ACF has performed consistently well in adsorbing toluene to its full capacity even after multiple regenerations. This implies that ACF is excellent in durability even after being exposed to toluene and consequently regenerated multiple times. No decrease in BTs after each regeneration was found, regardless of the toluene concentration the ACF was exposed to after each regeneration. For both ACF types, the BTs remained consistent, and did not decrease regardless of the concentration, indicating the ACF's capability to adsorb toluene and potentially other VOCs consistently. It was demonstrated that thermal regeneration has insignificant effects on the ACF's adsorption characteristics under the conditions of the current study, indicating ACF may have promise in being an alternative form of adsorbent for VOCs and in being used to design a regenerable, thinner, lighter and efficient respirator. There are still significant gaps in the knowledge of the ACF's capability to be regenerated for long-term use. More studies should be conducted to help determine the ACF's regeneration capabilities and limitations as applied to respiratory protection.

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XI. APPENDICES

Appendix A: Master Table of Breakthrough Times by Toluene Concentration, ACF Type and Number of Regeneration

Appendix B: Statistical Analysis Output Using ANOVA Tests

B1: Comparison of 10% and 50% Breakthrough Times by Toluene Concentration

B2: Comparison of 10% and 50% Breakthrough Times by ACF Type

B3: Comparison of 10% and 50% Breakthrough Times by Number of Regeneration

B4: Comparison of Percent Reductions in 10% and 50% Breakthrough Times by Toluene Concentration

B5: Comparison of Percent Reductions in 10% and 50% Breakthrough Times by ACF Type

B6: Comparison of Percent Reduction in 10% and 50% Breakthrough Times by Number of Regeneration

Appendix A: Master Table of Breakthrough Times by Toluene Concentration, ACF Type and Number of Regeneration

Table A1. Breakthrough Times (min) at 200 ppm Toluene Concentration by ACF Type and Number of Regeneration

ACF Type	R0	Set 1					Set 2					Average of 2 sets (n=2)					Overall Ave.
		R1	R2	R3	R4	Ave.	R1	R2	R3	R4	Ave.	R1	R2	R3	R4	Ave.	
10% Breakthrough Times																	
ACF 210	86	74	75	79	74	75.5	59	87	84	81	77.8	66.5	81.0	81.5	77.5	76.6	77.7
ACF 605	102	106	103	95	104	102.0	110	107	110	109	109.0	108.0	105.0	107.0	106.5	105.5	105.1
Ave.	94.0	90.0	89.0	87.0	89.0	88.8	84.5	97.0	97.0	95.0	93.4	87.3	93.0	94.3	92.0	91.1	91.4
50% Breakthrough Times																	
ACF 210	94	88	84	84	85	85.3	101	94	98	94	96.8	94.5	89.0	91.0	89.5	91.0	91.3
ACF 605	117	109	120	119	118	116.5	132	128	125	126	127.8	120.5	124.0	122.0	122.0	122.1	121.6
Ave.	105.5	98.5	102.0	101.5	101.5	100.9	116.5	111.0	111.5	110.0	112.3	107.5	106.5	106.5	105.8	106.6	106.4

Table A2. Breakthrough Times (min) at 500 ppm Toluene Concentration by ACF Type and Number of Regeneration

ACF Type	R0	Set 1					Set 2					Average of 2 sets (n=2)					Overall Ave.
		R1	R2	R3	R4	Ave.	R1	R2	R3	R4	Ave.	R1	R2	R3	R4	Ave.	
10% Breakthrough Times																	
ACF 210	33	33	32	32	34	32.8	34	35	32	30	32.8	33.5	33.5	32.0	32.0	32.8	32.8
ACF 605	43	40	40	41	39	40.0	45	43	41	43	43.0	42.5	41.5	40.0	41.0	41.5	41.7
Ave.	38.0	36.5	36	36.5	36.5	36.4	39.5	39.0	36.5	36.5	37.9	38.0	37.5	36.0	36.5	37.1	37.2
50% Breakthrough Times																	
ACF 210	38	36	36	36	36	36.0	38	38	36	36	37.0	37.0	37.0	36.0	36.0	36.5	36.7
ACF 605	51	48	45	47	47	46.8	53	49	51	54	51.8	50.5	47.0	49.0	50.5	49.3	49.4
Ave.	44.5	42.0	40.5	41.5	41.5	41.4	45.5	43.5	43.5	45.0	44.4	43.8	42.0	42.5	43.3	42.9	43.1

Appendix B: Statistical Analysis Output Using ANOVA Tests

Appendix B1. Comparison of 10% and 50% Breakthrough Times by Toluene Concentration

Report II

Conc		10%BT	50%BT
200	Mean	91.39	106.44
	N	18	18
	Std. Deviation	15.655	16.822
500	Mean	37.22	43.22
	N	18	18
	Std. Deviation	4.870	6.778
Total	Mean	64.31	74.83
	N	36	36
	Std. Deviation	29.749	34.461

ANOVA Table II

			Sum of Squares	df	Mean Square	F	Sig.
10%BT * Conc	Between Groups	(Combined)	26406.250	1	26406.250	196.484	.000
	Within Groups		4569.389	34	134.394		
	Total		30975.639	35			
50%BT * Conc	Between Groups	(Combined)	35973.444	1	35973.444	218.740	.000
	Within Groups		5591.556	34	164.458		
	Total		41565.000	35			

Appendix B: Statistical Analysis Output Using ANOVA Tests

Appendix B2. Comparison of 10% and 50% Breakthrough Times by ACF Type

Report I

ACFtype		10%BT	50%BT
210	Mean	55.22	64.17
	N	18	18
	Std. Deviation	23.859	28.299
605	Mean	73.39	85.50
	N	18	18
	Std. Deviation	32.835	37.459
Total	Mean	64.19	74.83
	N	36	36
	Std. Deviation	29.749	34.461

ANOVA Table I

			Sum of Squares	df	Mean Square	F	Sig.
10%BT * ACFtype	Between Groups	(Combined)	2970.250	1	2970.250	3.606	.066
	Within Groups		28005.389	34	823.688		
	Total		30975..639	35			
50%BT * ACFtype	Between Groups	(Combined)	4096.000	1	4096.000	3.717	.062
	Within Groups		37469.000	34	1102.029		
	Total		41565.000	35			

Appendix B: Statistical Analysis Output Using ANOVA Tests

Appendix B3. Comparison of 10% and 50% Breakthrough Times by Number of Regeneration

Report III

Regeneration		10%BT	50%BT
0	Mean	66.00	75.00
	N	4	4
	Std. Deviation	33.237	36.833
1	Mean	62.62	75.63
	N	8	8
	Std. Deviation	31.140	36.547
2	Mean	65.25	74.25
	N	8	8
	Std. Deviation	31.372	37.297
3	Mean	64.25	74.50
	N	8	8
	Std. Deviation	31.185	36.735
4	Mean	64.25	74.88
	N	8	8
	Std. Deviation	31.927	35.763
Total	Mean	64.31	74.83
	N	36	36
	Std. Deviation	29.749	34.461

ANOVA Table III

			Sum of Squares	df	Mean Square	F	Sig.
10%BT * Regeneration	Between Groups	(Combined)	41.264	4	10.316	.010	1.000
	Within Groups		30934.375	31	997.883		
	Total		30975.639	35			
50%BT * Regeneration	Between Groups	(Combined)	8.750	4	2.188	.002	1.000
	Within Groups		41556.250	31	1340.524		
	Total		41565.000	35			

Appendix B: Statistical Analysis Output Using ANOVA Tests

Appendix B4. Comparison of Percent Reductions in 10% and 50% Breakthrough Times by Toluene Concentration

Report IV

Conc		10%BT	50%BT
200	Mean	-3.74	.60
	N	8	8
	Std. Deviation	9.450	4.484
500	Mean	-2.14	-3.19
	N	8	8
	Std. Deviation	2.502	2.393
Total	Mean	-2.94	-1.29
	N	16	16
	Std. Deviation	6.729	3.985

ANOVA Table IV

			Sum of Squares	df	Mean Square	F	Sig.
10%BT * Conc	Between Groups	(Combined)	10.240	1	10.240	.214	.651
	Within Groups		668.878	14	47.777		
	Total		679.118	15			
50%BT * Conc	Between Groups	(Combined)	57.381	1	57.381	4.443	.054
	Within Groups		180.789	14	12.913		
	Total		238.169	15			

Appendix B: Statistical Analysis Output Using ANOVA Tests

Appendix B5. Comparison of Percent Reductions in 10% and 50% Breakthrough Times by ACF Type

Report V

ACFtype		10%BT	50%BT
210	Mean	-5.82	-3.07
	N	8	8
	Std. Deviation	7.792	2.045
605	Mean	-.05	.49
	N	8	8
	Std. Deviation	4.152	4.753
Total	Mean	-2.94	-1.29
	N	16	16
	Std. Deviation	6.729	3.985

ANOVA Table V

			Sum of Squares	df	Mean Square	F	Sig.
10%BT * ACFtype	Between Groups	(Combined)	133.402	1	133.402	3.422	.086
	Within Groups		545.715	14	38.980		
	Total		679.117	15			
50%BT * ACFtype	Between Groups	(Combined)	50.766	1	50.766	3.792	.072
	Within Groups		187.404	14	13.386		
	Total		238.169	15			

Appendix B: Statistical Analysis Output Using ANOVA Tests

Appendix B6. Comparison of Percent Reduction in 10% and 50% Breakthrough Times by Number of Regeneration

Report VI

Regeneration		10%BT	50%BT
1	Mean	-4.13	-.03
	N	4	4
	Std. Deviation	12.724	2.381
2	Mean	-1.23	-2.43
	N	4	4
	Std. Deviation	4.105	6.005
3	Mean	-3.10	-2.03
	N	4	4
	Std. Deviation	2.578	4.306
4	Mean	-3.30	-.70
	N	4	4
	Std. Deviation	5.913	3.753
Total	Mean	-2.94	-1.29
	N	16	16
	Std. Deviation	6.729	3.985

ANOVA Table VI

			Sum of Squares	df	Mean Square	F	Sig.
10%BT * Regeneration	Between Groups	(Combined)	18.003	3	6.001	.109	.953
	Within Groups		661.115	12	55.093		
	Total		679.118	15			
50%BT * Regeneration	Between Groups	(Combined)	15.107	3	5.036	.271	.845
	Within Groups		223.063	12	18.589		
	Total		238.169	15			