Fabrication and Evaluation of Hematite Modified Granular Activated Carbon (GAC) Media for Arsenic Removal from Groundwater

by

Arti Jain

A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science in Technology

Approved April 2011 by the
Graduate Supervisory Committee:

Kiril Hristovski, Chair
David Madar
David Edwards
Larry Olson

ARIZONA STATE UNIVERSITY

May 2011

ABSTRACT

The goal of the study was twofold: (i) to investigate the synthesis of hematite-impregnated granular activated carbon (Fe-GAC) by hydrolysis of Fe (III) and (ii) to assess the effectiveness of the fabricated media in removal of arsenic from water. Fe-GAC was synthesized by hydrolysis of Fe(III) salts under two Fe (III) initial dosages (0.5M and 2M) and two hydrolysis periods (24 hrs and 72 hrs). The iron content of the fabricated Fe-GAC media ranged from 0.9% to 4.4% Fe/g of the dry media. Pseudo-equilibrium batch test data at pH = 7.7±0.2 in 1mM $NaHCO_3$ buffered ultrapure water and challenge groundwater representative of the Arizona Mexico border region were fitted to a Freundlich isotherm model. The findings suggested that the arsenic adsorption capacity of the metal (hydr)oxide modified GAC media is primarily controlled by the surface area of the media, while the metal content exhibited lesser effect. The adsorption capacity of the media in the model Mexican groundwater matrix was significantly lower for all adsorbent media. Continuous flow short bed adsorber tests (SBA) demonstrated that the adsorption capacity for arsenic in the challenge groundwater was reduced by a factor of 3 to 4 as a result of the mass transport effects. When compared on metal basis, the iron (hydr)oxide modified media performed comparably well as existing commercial media for treatment of arsenic. On dry mass basis, the fabricated media in this study removed less arsenic than their commercial counterparts because the metal content of the commercial media was significantly higher.

DEDICATION

I would like to dedicate my thesis to my loving parents, my father, Pravin Kumar Jain, and my mother, Meena Jain. Their ongoing support and encouragement from half way around the globe made my work possible.

ACKNOWLEDGMENTS

This thesis never would have been written without the help and supportof Dr. Kiril Hristovski whose ideas and enthusiasm guided my research. His focus, drive and attention to detail prevented me from going astray. I am a much better scientist today for having worked with him.

I would like to thank Dr. Larry Olson who supported and guided me throughout my education at Arizona State University. I would also like to thank my fellow research group members for their constant help during my research.

I am also thankful to SCERP for providing funding without which this research might not have been possible.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure Page

Figure Page

LIST OF EQUATIONS

Equation Page

LIST OF ACRONYMS

ACRONYM	DEFINITION
AC	Activated Carbon
As(III)	Arsenite
As(V)	Arsenate
AsB	Arsenobetaine
AsC	Arsenocholine
ATSDR	Agency for Toxic Substances and Disease Registry
BAT	Best Available Technology
BET	Brunauer Emmet Teller
BPP	Bulk Particle Porosity
CCA	Copper Chrome Arsenate
CDC	Center For Disease Control
CNS	Central Nervous System
DMA	Dimethylarsinic acid
DMA(III)	Dimethylarsinous acid
EBCT	Empty Bed Contact Time
FAA	Flame Atomic Adsorption
SDWA	Safe Drinking Water Act
Fe-GAC	Iron Hydroxide Impregnated Granular Activated Carbon
FeOOH	Iron (Hydr)oxide
FMO	Ferruginous Manganese Ore

GAC	Granular Activated Carbon
GFAA	Graphite Furnace Atomic Adsorption
GF/F	Glass Microfiber Filter
GFH	Granular Ferric Hydroxide
GFO	Granular Ferric Oxide
GTA	Graphite Tube Analysis
HD3000	Hydro Darco 3000
HDPE	High Density Polyethylene
HFO	Hydrous Ferric Oxide
IARC	International Agency for Research on Cancer
IEP	Isoelectric Point
IIS	Iron Impregnated Sand
IOCS	Iron Oxide Coated Sand
IUPAC	International Union of Pure and Applied Chemistry
MCL	Maximum Contaminant Level
MCLG	Maximum Contaminant Level Goal
MF	Microfiltration
MMA	Monomethylarsonic acid
MMA(III)	Methylarsonous acid
NF	Nanofiltration
NIPDWRs	National Interim Primary Drinking Water Regulations
PAC	Powdered Activated Carbon

PSD	Pore Size Distribution
RO	Reverse Osmosis
RSSCT	Rapid Small Scale Column Tests
SBA	Short Bed Adsorber
SDWAA	Safe Drinking Water Act Amendment
SEM	Scanning Electron Microscope
TMA	Trimethylarsine
TMAO	Trimethylarsine Oxide
UF	Ultrafiltration
USEPA	US Environmental Protection Agency
WHO	World Health Organization

Chapter 1

INTRODUCTION

Contamination of the environment with arsenic from both natural and anthropogenic sources has been recognized as a global problem (Smedley & Kinniburgh, 2002). Arsenic contamination of drinking water is of major concern in several countries, such as Bangladesh, Chile, Taiwan, India and several parts of the USA (Nickson et al., 1998; Nickson, McArthur, Shrestha, Myint & Lowry, 2005; McArthur, Ravenscroft, Safiulla & Thirlwall, 2001). Over the past several years, numerous toxicological and epidemiological studies have been conducted to ascertain health risks associated with low-level exposure to arsenic ingestion (Jain & Ali, 2001). Several epidemiological studies have documented the association between chronic exposure to arsenic in drinking water and skin cancer (Yoshida, Yamauchi & Sun, 2004). Various studies show that chronic arsenic exposure is related to cancer in the liver, bladder, kidney, lung, and prostate (Smith, 1992; WHO, 2003; Sams II et al., 2007; Mondal, Adamson, Nickson, & Polya, 2008; Lindberg, Rahman, Persson & Vahter, 2008). Arsenic has been classified as a Class A human carcinogen by International Agency for Research on Cancer (IARC) (USHHS, 2007; ATSDR, 2007).

In 1975, National Interim Primary Drinking Water Regulations (NIPDWRs) established the arsenic maximum contaminant level (MCL) of 0.05 mg/L (USEPA, 2006). As part of the 1996 Safe Drinking Water Act (SDWA) Amendments, the United States Environmental Protection Agency (USEPA) was directed to conduct health effects and cost/benefit research to finalize a new arsenic standard (USEPA, 2006). In 2001, the USEPA published a final rule in the Federal Register replacing the existing MCL of 0.05 mg/L with a new lower MCL of 0.01 mg/L (USEPA, 2006; WHO, 2003).

To protect consumers served by public water systems from the effects of long-term, chronic exposure to arsenic, public water systems must comply with the new standard which reduces the MCL for arsenic in drinking water from 0.05 mg/L to 0.01 mg/L (USEPA, 2004; SDWA, 2004). To comply with this regulatory level, the USEPA has identified Best Available Technologies (BATs) to remove arsenic from groundwater (USEPA, 2003). These include ion exchange, activated alumina, oxidation/filtration, reverse osmosis, electro dialysis reversal, enhanced coagulation/filtration, enhanced lime softening, etc. (USEPA 2003). A combination of these technologies works well for water treatment systems in big communities. However, small scale systems have to bear a higher cost per unit of treated water when compared to large scale water treatment systems with these technologies. Hence, there is a need to develop effective arsenic removal technology for small communities to comply with the arsenic regulatory levels.

According to the USEPA, adsorption has proven to be an effective technology for water treatment for small systems with low operating and maintenance costs, and it is fairly easy to operate. It has also been demonstrated that adsorption has also been fruitful in fulfilling the need for small community water treatment systems (USEPA, 2000; USEPA 2002a). Adsorption is the process by which a dissolved species present in liquid phase (adsorbate) is transported into a porous solid adsorbent granule and adsorbed onto the surface of the adsorbent (Crittenden et al, 2005). Dissolved species are concentrated on the surface of the adsorbent by physical attraction (van der Waals forces) or by chemical reaction (Crittenden, 2005; Reynolds & Richards, 1996). Granular activated carbon is one of the primary adsorbent materials used in the adsorption process for water treatment not only due to high surface area and porosity but also availability (Carter & Weber, 1994; Snoeyink and Summers, 1999; Vaughan et al., 1999; Zytner, 1992; Awwa, 2005). This material, however, is generally only efficient for removal of organic contaminants. Organic contaminants predominantly are found in areas affected by heavy industrial activity and enter the water stream via chemicals discharged from petroleum, chemical, textile, drug and pesticides industries apart from natural sources (Kolpin et al., 2002; Nguyen et al., 2006; Facozio et al., 2008).

Application of metal (hydr)oxides has proven to be effective for removal of arsenic from water by adsorption. It has been reported that naturally occurring arsenic species form inner-sphere bidentate ligands on the surface of metal (hydr)oxides as they undergo ligand exchange reaction with iron species and can thus be removed from natural waters. (Fuller et al., 1993; Grossl et al., 1997; Sherman & Randall, 2003; Smedley & Kinniburgh, 2002). One of the well known metal (hydr)oxides for arsenic treatment is ferric (hydr)oxide. Ferric (hydr)oxide particle generation has been extensively studied. These particles could be helpful in removing arsenic from water. The concentration of surface sites available for adsorption is determined by surface area of the metal (hydr)oxide (Wilkie & Hering, 1996). Iron (hydr)oxide nanoparticles have high surface area per mass of iron as compared to larger particles. Available literature indicates that the capacity of arsenic adsorption by iron (hyr)oxide materials can be improved if the surface area and porosity is increased (Peleanu et al., 2000). Matijevic *et al.* (1978) have demonstrated that forced hydrolysis of homogenous metal(Fe) salt can produce hematite particles in a controlled manner (Matijevic & Scheiner, 1978). Reviews by Mohan and Pittman (2007), Smedley and Kinniburgh (2002) and dissertation research by Badruzzaman (2004) show that adsorption of arsenic by iron oxides (hydroxides) has been examined by numerous authors. But the problem remains that small particles of iron (hydr)oxides cannot be used by themselves in packed bed columns. To overcome this issue support is needed for iron (hydr)oxide on which these small particles can be impregnated which could be GAC. Further, the role of iron oxides (hydroxides) for arsenic removal and GAC for organic contaminant removal suggests that a combination of the two (iron oxides and carbon) in hybrid media can be a useful technology for removing arsenic and organic pollutants from groundwater at the same time. Research has been done demonstrating metal (hydr)oxide modified carbon based technology is capable of removing arsenic in water along with organic co-contaminants (Cooper et al., 2010; Hristovski et al., 2008; Nguyen, 2008; Reed et al., 2000). However, a need to develop inexpensive and simple approaches to fabricating these Fe-GAC still exists.

Goal and Objectives

The goal of this study was to investigate if hematite - impregnated granular activated carbon (Fe-GAC) can be synthesized by hydrolysis of Fe (III) to effectively remove arsenic from water. To achieve this goal, the following task-oriented objectives were undertaken:

1) Fe-GAC media was synthesized under two Fe (III) initial dosages and two hydrolysis times;
2) Properties of the synthesized media were characterized;
3) Arsenic adsorption capacity was evaluated under equilibrium conditions in the absence of competing ions to estimate the maximum adsorption capacity of the fabricated media and in the presence of competing ions to estimate performance under realistic groundwater conditions; and
4) Short bed column tests were conducted to estimate adsorption capacity under continuous flow and constant initial concentration conditions in model groundwater.

Scope of the Study

Like any other study, the scope of this study was influenced by a number of assumptions and limitations. Only one kind of GAC, HydroDarco 3000 (HD3000), was used as a starting material which was assumed to be representative of macroporous GACs. The assumption is reasonable since the untreated media is produced under a controlled process as defined by ISO9001:2000 (Norit Americas Inc. [Norit], 2007). HD 3000 is characterized by wide pore size distribution and large pore volume which provides HD 3000 with a rapid adsorption rate and a high capacity for dissolved organics (Norit Americas Inc. [Norit], 2007). The study conducted by Cooper et al. (2010) has successfully demonstrated that selection of macroporous GAC is beneficial when making a hybrid media for arsenic and organic contaminant removal. Cooper and collaborators found that due to the macroporous structure of GAC, the organic co-contaminant removal capacity of the media is not reduced significantly when trying to remove arsenic simultaneously (Cooper et al., 2010).

The pH of the model waters used in the experiment was limited to 7.7 ± 0.2. A pH difference of ± 0.2 does not significantly affect the adsorption of arsenic, and such variation is anticipated to be found in groundwater. As(V) is the most representative form of arsenic in oxygenated waters at pH ~ 7 (Ferguson & Gavis, 1972). Arsenite when present in aerobic waters becomes oxidized to arsenate at pH values above 7.0. It is further assumed that a temperature variation of $\underline{+}2\ ^{o}$C during experiments does not affect adsorption and pseudo equilibrium during batch equilibrium experiments conducted over a period of three days.

Water buffered with 1 mM of $NaHCO_3$ is assumed to provide a good model to estimate the maximum adsorption capability of arsenic. This type of model water was previously demonstrated to be effective at preventing other species present in the water from competing with arsenate for available adsorption sites and influencing the outcome of the experiments (Hristovski et al., 2009).

It is also assumed that challenge groundwater (with competing ions) is representative of groundwater found in the Mexico-Arizona border region with a pH of 7.7± 0.25. Arsenic concentrations in the model water and challenge groundwater used in the study are limited to ~125 µg/L, a level that might be reasonably be anticipated in contaminated groundwater.

Chapter 2

LITERATURE REVIEW

Arsenic Chemistry

Arsenic (As) is a heavy metalloid that occurs naturally at low concentrations in rocks, soil, water, air, plants, and animals (USEPA, 2001; Yan-Chu, 1994; Smedley & Kinniburgh, 2001). It is also associated with certain industrial and commercial processes. Its name is derived from the Greek word “arsenikon”, meaning potent (Choong et al., 2007; Evens et al., 2004; Dilda & Hogg, 2007). Referred to as the king of poisons, arsenic is also a natural constituent of earth’s crust and ranks 20th in abundance in relation to other elements (Marcus, 2010; Nriagu, 2007).

Arsenic is unique among the heavy metalloids and oxyanion forming elements in its sensitivity to mobilize at pH values typically found in groundwaters (pH 6.5–8.5) under both oxidizing and reducing conditions (Smedley & Kinniburgh, 2001). It occurs in the environment in both organic and inorganic forms. Inorganic arsenic exists in four main chemical forms known as valency or oxidation states of (-3, 0, +3 and +5). The dominant forms are

1) Trivalent arsenic (As (III), As^{+3}), also referred to as arsenite. Representative trivalent inorganic compounds are arsenic trioxide, arsenic trichloride, arsenic trisulphide and sodium arsenite.

2) Pentavalent arsenic (As (V), As^{+5}), also referred to as arsenate. Pentavalent ones include arsenic pentoxide, arsenic acid and sodium arsenate.

Representative organic compounds are monomethyl-, dimethyl- and trimethylarsine and arsenobetaine. Some of the known arsenic compounds and species are summarized in Table 1.

Table 1.

Common arsenic compounds and species

Name	Abbreviation	Chemical Formula
Arsenous acid	As(III)	H_3AsO_3
Arsenic acid	As(V)	H_3AsO_4
Oxythioarsenic acid		H_3AsO_3S
Monomethylarsonic acid	MMA	$CH_3AsO(OH)_2$
Methylarsonous acid	MMA(III)	$CH_3As(OH)_2[CH_3AsO]_n$
Dimethylarsinic acid	DMA	$(CH_3)_2AsO(OH)$
Dimethylarsinous acid	DMA(III)	$(CH_3)_2AsOH[((CH_3)_2As)_2O]$
Trimethylarsine	TMA	$(CH_3)_3As$
Trimethylarsine oxide	TMAO	$(CH_3)_3AsO$
Tetramethylarsonium ion	Me_4As^+	$(CH_3)_4As^+$
Arsenocholine	AsC	$(CH_3)_3As^+CH_2CH_2OH$
Arsenobetaine	AsB	$(CH_3)_3As^+CH_2COO$-

(Adopted from Arsenic in Drinking Water, National Research Council, 1999).

The most commonly found inorganic arsenic compounds in groundwater are trivalent arsenite (As(III)) or pentavalent arsenate (As(V)). Arsenates are stable under aerobic or oxidizing conditions, while arsenites are stable under anaerobic or reducing conditions (Lorenzen et al., 1995). These anions have acidic characteristics, and the stability and dominance of a specific species depend on the pH of the solution. Organic arsenic forms may be produced by biological activity, mostly in water significantly impacted by industrial pollution (Smedley & Kinniburgh, 2001).

The molecular structure of arsenate and arsenite has been illustrated in Figure 1. According to Pauling, “the double bond oxygen in the arsenate molecule influences its ability to become ionized through the loss of hydrogen ions, the process is termed dissociation. A negative charge develops on the molecule when dissociation occurs and the double bond oxygen increases the capacity to delocalize that charge, easing the loss of hydrogen ions in arsenate facilitating removal of arsenic by adsorption” (Barakat & Ismat Shah, 2010)

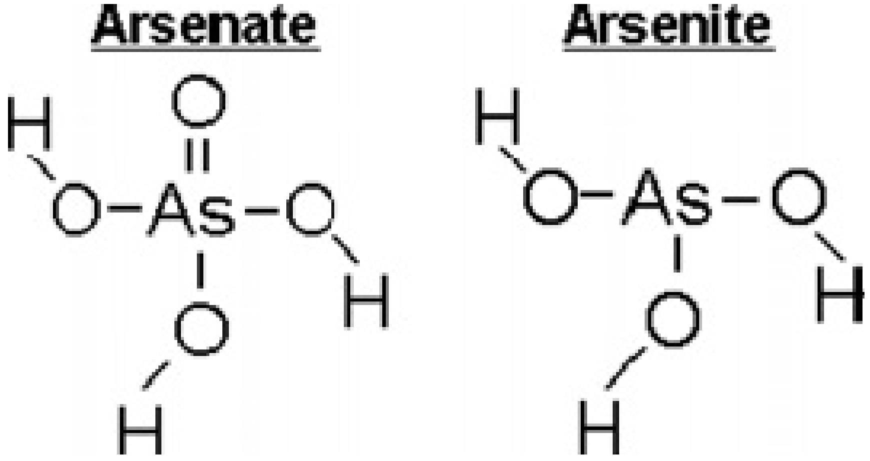

Figure 1. Difference in Molecular Configuration of Arsenate and Arsenite (Adopted from Barakat & Ismat Shah, 2010)

Both arsenite and arsenate exist as four different common species H_3AsO_3, $H_2AsO_3^-$, $HAsO_3^{-2}$, AsO_3^{-3} and H_3AsO_4, $H_2AsO_4^-$, $HAsO_4^{-2}$, AsO_4^{-3} respectively. The speciation of these species changes by dissociation and is pH dependent (Mok & Wai, 1989). The propensity for ionization is expressed by the dissociation constant, pK_a (which is a negative log of pK_a, such that a smaller number shows a greater degree of dissociation). For arsenate, the pK_a values are expressed in equation1, 2 and 3 along with figure 2.

$H_3AsO_4 \rightarrow H_2AsO_4^- + H^+$ $pK_1 = 2.2$ Equation 1

$H_2AsO_4- \rightarrow HAsO_4^{2-} + H^+$ $pK_2 = 6.95$ Equation 2

$HAsO_4^{2-} \rightarrow AsO_4^{3-} + H^+$ $pK_3 = 11.5$ Equation 3

(Barakat & Ismat-Shah, 2010)

For arsenite, the pK_a values are as follows:

$H_3AsO_3 \rightarrow H_2AsO_3^- -+ H^+$ $pK_1 = 9.20$ Equation 4

$H_2AsO_3- \rightarrow HAsO_3^{2-} + H^+$ $pK_2 = 13.5$ Equation 5

$HAsO_3^{2-} + OH \rightarrow AsO_3^{3-}$ $pK_3 = >15$ Equation 6

(Kutschera, Schmidt, Köhler, & Otto, 2007)

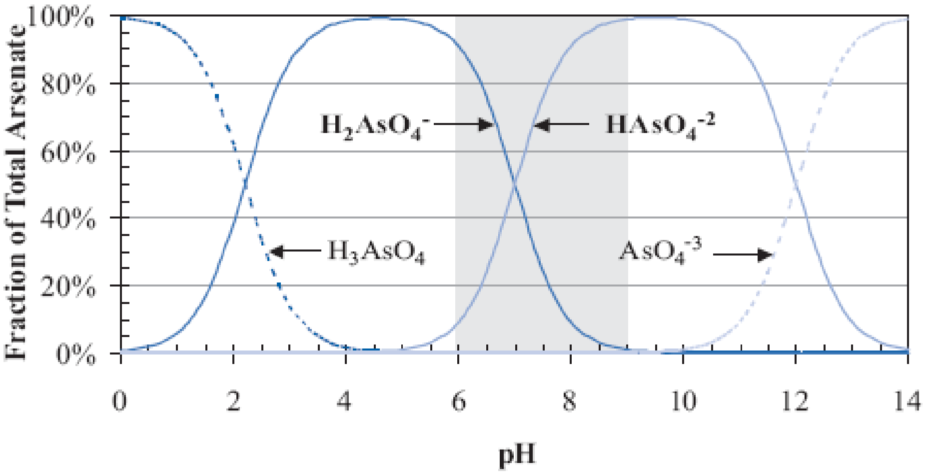

Figure 2: Speciation of arsenate with change in pH

(Adopted from Arsenic Treatment Technology Evaluation Handbook for Small Systems, USEPA, 2003)

Since the negative surface charge on arsenic facilitates removal by adsorption, the chemical speciation has a key role in arsenic treatability (USEPA, 2003). As the pH increases, the fraction of arsenate anions increases, limiting the adsorption capacity in natural pH conditions. The pH at which these ionization steps occur is significantly different between arsenate and arsenite.

Occurrence of Arsenic in the Environment

Arsenic is released into the environment via two principal pathways: (1) natural processes and (2) industrial activities (Rubio et al., 1992; Nriagu et al. 2007). Flow of arsenic in different compartments of the ecosystem is shown in Figure 3.

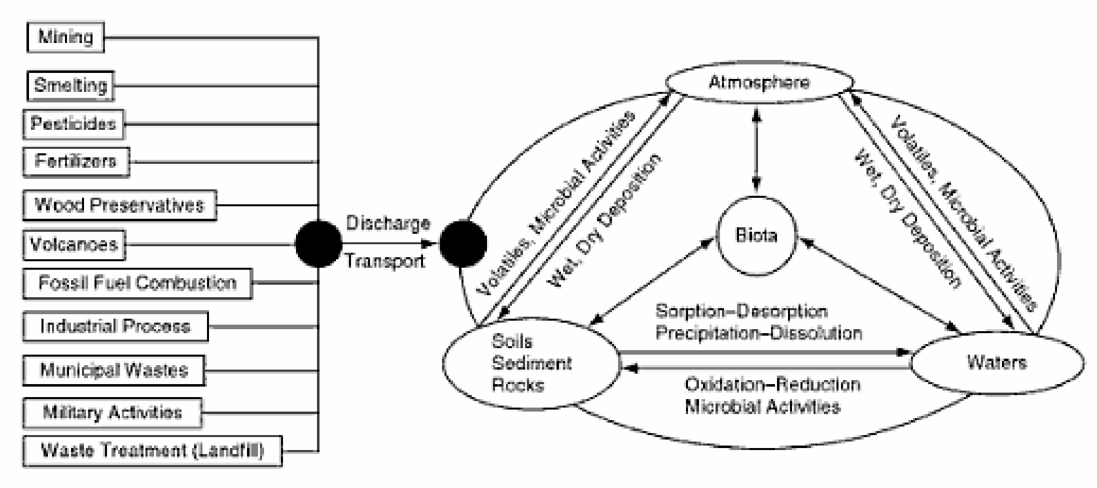

Figure 3: Sources and distribution of arsenic in the environment (Adopted from Wang and Mulligan, 2006)

Natural processes such as erosion of rocks, hydrothermal ore deposits, geothermal activities, sea salt spray and wind-blown dust release arsenic into the environment (Nriagu et al., 2007). Arsenic is also emitted into the atmosphere by certain high-temperature processes such as burning vegetation and volcanic activity (ATSDR, 2007). Natural low-temperature biomethylation and reduction to arsines also releases arsenic into the atmosphere. Arsenic is released into the atmosphere primarily as As_2O_3 and exists mainly adsorbed on particulate matter. These particles are dispersed by the wind and are returned to the earth by wet or dry deposition (WHO, 2001; USHHS, 2007).

Arsenic released through natural processes can be transported over large distances as suspended particulates to gaseous forms through water and air. Airborne arsenic either settles on the ground surface or is washed out of the air by rain, which ultimately travels to the surface or groundwater sources. As arsenic get washed out, some of it is carried along with the water while some of it settles with the sediments at the bottom of water bodies. In the process, arsenic is consumed by various aquatic animals and builds up in their tissues by biomagnification and bioaccumulation processes (ASTDR, 2007; Nriagu et al., 2007).

"The chemical character of arsenic is dominated by the fact that it is labile, readily changing oxidation state or chemical form through chemical or biological reactions that are common in the environment" (Vance, 2005, p.1). Therefore, instead of solubility equilibrium controlling the mobility of arsenic, it is usually controlled by redox conditions, pH, biological activity, and adsorption/desorption reactions (Izbicki et al., 2008; Smith, 2005; Ferguson & Davis, 1972; McArthur et al., 2001; Smedley & Kinniburgh, 2002). Arsenic in groundwater most often occurs from geogenic sources, although anthropogenic arsenic pollution does occur. Geogenic arsenic, almost exclusively exists as arsenite or arsenate. Anthropogenic arsenic may have any form of arsenic including organic arsine species. Arsenic concentrations generally exceed 10µg/L in groundwater found in acidic to intermediate volcanic rocks or in sediments derived from those kind of volcanic rocks (Vance, 2005; ATSDR, 2007).

Arsenic is introduced into drinking-water sources primarily through the dissolution of naturally occurring minerals and ores (Korte & Fernando, 1991). These contaminants originate in As rich ores like, pyrite minerals, from which inorganic arsenic leaches into ground and surface waters (Gebel, 2000).

Arsenic cannot be destroyed in the environment, but it can change its form. It may also get attached to or get separated from particles. It may change its form by reacting chemically with various molecules found in nature. It may react with oxygen or other different molecules present in air, water, soil or by action of bacteria that live in soil (Choong etal., 2007; ATSDR, 2007; USHHS, 2007). Amongst the various ways in which arsenic transformation can take place, major modes of arsenic biotransformation found to occur in the environment can be summarized under three major headings: (1) redox transformation between arsenite and arsenate, (2) the reduction and methylation of arsenic, and (3) the biosynthesis of organoarsenic compounds. There is biogeochemical cycling of compounds formed from these processes (WHO, 2001; Lindberg et al., 2008; Chauhan et al., 2009; Izbiciki et al., 2008; Kumarsean & Riyazuddin, 2001).

To a small extent, arsenic occurs in the elemental state; however, higher concentrations of arsenic principally occur in mineral complexes with metals and other elements (Welch et al., 1988). For example, arsenic is a common impurity in the sulfide ores of lead, copper, and zinc. Arsenic is released into the environment from natural processes such as the weathering and dissolution of arsenic-containing minerals and ores along with microbial activities (Yan-Chu, 1994). For example, by the reductive dissolution of FeOOH and the release of the adsorbed arsenic to the solution, arsenic is supplied to anoxic groundwater in alluvial aquifers. The most intense reduction occurs, which is driven by both within the aquifer sands and in the overlying confining units by microbial degradation of natural organic matter in peaty strata (Mc Arthur et al, 2001; Mc

Arthur et al, 2004). Arsenic is scavenged, adsorbed and transported from different sources as dispersed phases of hydrated ferric oxide (HFO) (Acharyya, 2005). Mobilization and eventual release of arsenic to groundwater is possibly caused by biomediated reductive dissolution of HFO that occurs primarily as coatings on sediment grains. It is also postulated that release of sorbed arsenic from HFO could occur by ion exchange processes involving phosphate and carbonate. HFO has great capacity to absorb or co-precipitate arsenic, which is released to groundwater during reductive dissolution (Acharyya et al., 1999; Acharyya et al., 2000; Acharyya & Shah., 2004). According to Robertson (1989) occurrence and origin of arsenic in groundwater depends on several factors such as oxidation-reduction, precipitation-dissolution, ion exchange, organic contents, biological activity and aquifer characteristics (Jain and Ali, 2000).

In addition to its release from natural sources, arsenic is released from a variety of anthropogenic sources. The anthropogenic release of arsenic by mining, wood preservation, incineration, smelting and ore processing, pesticides, fertilizers, chemical industries and thermal power plants can elevate environmental arsenic concentrations (Nriagu et al., 2007; Kumaresan & Riyazuddin, 2001; Reedy et al. 2007; Nriagu & Pacyna, 1988; Bhattacharya et al., 2002). It has been estimated that 70% of the world arsenic production is used in timber treatment as copper chrome arsenate (CCA), 22% in agricultural chemicals, and the remainder in glass, pharmaceuticals and non-ferrous alloys (WHO 2001). The major industrial processes that contribute to anthropogenic arsenic contamination of air, water and soil are mining, smelting of non-ferrous metals and burning of fossil fuels. For example, in Reichenstein, Silesia, the drinking water had been polluted with wastes from the smelting of arsenic bearing ores (Neubauer, 1947). Historically, the use of arsenic-containing pesticides has left large tracts of agricultural land contaminated, and in some developing countries arsenic containing pesticides are still being used in agricultural practices. Some of the past and current industrial uses of arsenic are listed in Table 2.

Table 2.

Summary of Current and Past Uses of Arsenic

Sector	Uses
Lumber	Wood preservatives
Agriculture	Pesticides, insecticides, defoliants, debarking agents, soil sterilant
Livestock	Feed additives, disease preventatives, animal dips, algaecides
Medicine	Antisyphilitic drugs, treatment of trypanosomiasis, amebiasis, sleeping sickness
Industry	Glassware, electro photography, catalysts, pyrotechnics, antifouling paints, dye and soaps, ceramics, pharmaceutical substances, alloys (automotive solder and radiators), battery plates, solar cells, optoelectronic devices, semiconductor applications, light emitting diodes in digital watches

Source: Azcue and Nriagu, 1994

Arsenic Toxicity

According to WHO, arsenic has not been demonstrated to be essential in humans (WHO, 2004). Worldwide, the main reason for a chronic human intoxication with arsenic is the intake of contaminated drinking water (Smedley & Kinniburgh, 2002; Ferguson & Gavis, 1972; Gebel, 2000; Sams II et al. 2007). In several parts of the world such as India, Taiwan, Bangladesh, Argentina, Hungary, China, many parts of USA and Chile, arsenic-induced diseases are a significant public health issue making arsenic a high-priority substance for screening in drinking water sources (Smedley & Kinniburgh, 2002; Nickson et al., 1998; Ravenscroft et al., 2001; Ahmed at al., 2004; Shrestha et al., 2005; Nickson et al., 2007). Human exposure to arsenic can result in a variety of chronic and acute effects (Sams II et al., 2007). It is one of the few substances shown to cause cancer in humans through consumption of drinking water. In particular, there is evidence that associates chronic arsenic ingestion at low concentrations with increased risk of skin cancer and that arsenic may cause cancers of the lung, liver, bladder, kidney, and colon (ATSDR, 1998; Jain & Ali, 2001; Schlicher & Ghosh, 1985; Morales et al. 2000; Goldsmith et al., 1972).

As discussed, arsenic is present in a variety of chemical forms in water and the specific compound present would determine its fate in the environment and its toxicity. It is generally believed that the trivalent form is the carcinogen due to the fact that trivalent inorganic arsenic has greater reactivity and toxicity than pentavalent inorganic arsenic (WHO, 2001; Morales et al., 2000). As published by WHO (2003), there is considerable uncertainty and controversy over both the mechanism of carcinogenicity and the shape of the dose–response curve at low intakes of arsenic. On the basis of sufficient evidence for carcinogenicity in humans and limited evidence for carcinogenicity in animals; IARC, the WHO's source for information on cancer has classified inorganic arsenic compounds in Group 1 (carcinogenic to humans) (WHO, 2004; ATSDR, 1998).

Non carcinogenic effects induced by arsenic include vascular disorders, skin lesions, chronic cough, peripheral neuropathy, diabetes mellitus, adverse pregnancy outcomes, impaired child development and neurotoxicity (De Wolff & Edelbroek, 1994; Mazumder et al, 2000; WHO, 2001; Chakraborti et al., 2003; Rahman et al., 2007; Wasserman et al., 2007). According to the information published on the USEPA website in July 2009, because of the human health risks associated with arsenic, USEPA regulates the level of arsenic in drinking water and designates it as a major health concern around the world (USEPA, 2009).

Arsenic Removal Technologies

The water industry is focusing on arsenic removal from water because of the increasing health concerns associated with presence of arsenic in natural waters. USEPA has summarized some of the arsenic removal technologies from water as follows: (1) Precipitation/coprecipitation, (2) Ion exchange, (3) Membrane filtration and (4) Adsorption (USEPA 2002b).

Precipitation/Coprecipitation.

According to the US Environment Protection Agency, precipitation is the process of transforming dissolved contaminants into an insoluble solid (USEPA, n.d.). In coprecipitation, however, the target contaminant may be dissolved or in colloidal or suspended form. During coprecipitation, dissolved contaminants generated do not precipitate, rather get adsorbed onto other species that are precipitated. According to USEPA (2002b, p. 17), “Colloidal or suspended contaminants are removed by processes such as coagulation/ flocculation or become enmeshed with other precipitated species. The precipitated/ coprecipitated species are then removed from the liquid phase by filtration or clarification”.

Some of the chemicals and processes used for arsenic precipitation/coprecipitation include (1) ferric salts, (2) aluminum sulfate, (3) copper sulfate, (4) lime softening, (5) ammonium sulfate, (6) pH adjustment, and (7) oxidation of As(III) to As(V) by addition of oxidizing chemicals (USEPA 2001, 1995; MSE Technology application, 1998; Garelick et al., 2005). The chemistry of precipitation/coprecipitation depends upon several factors:

- Speciation of arsenic - Presence of more soluble trivalent arsenic might reduce the removal efficiency,
- pH of the water - Arsenic removal can be maximized by pH at which the precipitated species is least soluble,
- Presence of other contaminants - Calcium or iron can increase the arsenic removal capacity in processes involving ferric chloride as coagulant but presence of sulfate can decrease arsenic removal (USEPA, 1995; USEPA, 2000e; USEPA, 2000f; USEPA, 2002b).

Precipitation/co-precipitation is an active technology treatment designed to function with routine chemical addition and sludge removal (USEPA, 2002b). The sludge generated during the process, generally requires treatment and subsequent disposal. During precipitation/co-precipitation, precipitation of other compounds, in the presence of other contaminants or metals along with arsenic in water can render the resulting sludge hazardous, which makes it important to treat the sludge before disposal (USEPA, 2005; USEPA, 2000d). Prior to discharge, the effluent may require additional treatment, such as pH adjustment.

Ion exchange.

Ion exchange is a physical and/or chemical process in which ions held electrostatically on the surface of a solid are exchanged for ions of similar charge or size in the solution. The process removes ions from the aqueous phase by exchange of cations or anions between the contaminants and the exchange medium (USEPA, 2000e; USEPA, 2000a; Murcott, 1999). The technology is sensitive to a variety of untreated water contaminants and their characteristics. This process is less frequently used as compared to precipitation/coprecipitation (USEPA, 2002b; USEPA, 2002a).

Ion exchange media used to treat arsenic generally are strong base anion exchange resins. It is proposed that ion exchange resins should be periodically regenerated to remove the adsorbed contaminants and replenish the exchanged ions. Factors affecting ion exchange performance include valence state, presence of competing ions, fouling, presence of trivalent iron and pH (USEPA, 2000b; USEPA, 2000e; USEPA, 2000c).

For ion exchange, resins used to remove arsenic from water and the spent regenerating solution may contain a high concentration of arsenic along with other adsorbed contaminants, which could be corrosive (USEPA, 2002c). This makes it important that the spent resin is treated, if required, prior to reuse and/ or disposal. The effectiveness of ion exchange is also sensitive to a variety of contaminants and characteristics in the untreated water such as suspended solids. Therefore, it is suggested that the technology be applied to groundwater which has less probability of containing fouling contaminants (USEPA, 2002a, USEPA, 2002b).

Membrane filtration.

As explained by USEPA, membrane filtration separates contaminants from water by passing it through a semi-permeable barrier or membrane. The membrane allows some constituents to pass through, while blocking others (USEPA, 2002c; USEPA, 1996; USEPA, 2000a). Despite the fact that the technology is capable of removing a wide range of contaminants from water, it is sensitive to a variety of untreated water contaminants and their characteristics (ETV, 2001). This technology tends to be more expensive than other arsenic treatment technologies as it produces a large volume of residuals which need treatment before disposal (USEPA, 2002b. USEPA, 2000d).

Membrane processes are commonly divided into four overlapping categories of increasing sensitivity: microfiltration (MF), ultrafiltration (UF), nanofiltartion (NF), and reverse osmosis (RO) or hyperfiltration. All of them are characterized by the size of particles that can pass through the membrane or by the pore size of the membrane, and are pressure driven processes (USEPA, 2000a; USEPA, 2000e; Awwa, 2007). Factors affecting membrane filtration performance are pH, temperature, oxidation state of arsenic and suspended solids, high molecular weight, dissolved solids and colloids (USEPA, 2000a; USEPA, 2000e).

Membrane technologies are capable of removing a wide range of dissolved contaminants and suspended solids. These technologies for treatment can be run in either batch or continuous mode. The effectiveness of membrane technologies is sensitive to the variety of contaminants and characteristics in the untreated water (USEPA, 2002c). Suspended solids, organics, colloids, and other contaminants can cause membrane fouling. Hence, this technology is typically applied to groundwater with less likelihood of fouling contaminants (USEPA, 2002a; USEPA, 2002b). Membrane technology is also applied as a polishing step to other water treatment technologies, when lower concentrations of the contaminant must be achieved (Awwa, 2007). USEPA has documented some other drawbacks of using membrane technologies in arsenic removal: (1) the systems are more costly than other treatment methods, (2) the discharge of concentrate could be a problem, and (3) water loss associated with concentrate stream membrane fouling and flux decline (USEPA, 2002b; Choong et al., 2007).

Reverse Osmosis and nanofiltration do not require chemical addition to ensure adequate separation of suspended solids and/or dissolved contaminants from water. Nanofiltration has high arsenic removal efficiency. However, the process comes with very high capital and operating cost along with need for preconditioning and has high water rejection rate (Groot et al., 2007). Reverse osmosis is advantageous since in some cases no toxic solid waste is produced but it is not cost-effective, as it requires high technical operation and maintenance. (USEPA, 2002a; USEPA, 2002b).

Adsorption.

Adsorption is a surface phenomenon, defined as the increase in concentration of a particular component at the surface or interface between two phases (Crittenden et al., 2005). A compound (pollutant) that sticks or adheres to the solid surface is called an adsorbate and the solid surface is known as an adsorbent. During adsorption, the solutes (i.e. the contaminants) concentrate at the surface of a sorbent, thereby reducing their concentration in the bulk liquid phase (USEPA, 2002b). The process of adsorption involves separation of a substance from one phase accompanied by its accumulation or concentration at the surface of another. According to Ali and Gupta (2006, p. 2661), "when a finely divided solid is shaken with the contaminated and/or polluted water, the pollutants adhere to the solid surface and a stage of equilibrium is established. At this stage, the concentration of pollutants adsorbed and in the water become constant."

Physical adsorption is caused by van der Waals forces and electrostatic forces between adsorbate molecules and the adsorbent surface (Crittenden et al., 2005) Therefore, adsorbents are characterized by surface properties such as surface area and polarity. Factors affecting adsorption process are (USEPA, 2000 a; USEPA, 2000b; Twidell et al. 1999; Ali and Gupta, 2006) :

1) Temperature,
2) The nature of adsorbate and adsorbent,

3) The presence of other pollutants and
4) Experimental conditions: The experimental conditions are comprised of the pH of water to be treated, arsenic oxidation state, concentration of pollutants, contact time, particle size of the adsorbent, flow rate through adsorption unit and fouling.

Types of adsorbents used to treat arsenic include activated alumina, granular ferric hydroxide, green sand filtration, surfactant coated zeolite, iron oxide coated sand, iron oxide and hydroxides, and metal oxide nanoparticles (e.g. Nanostructured ZrO_2 spheres, nanocrystalline titanium dioxide) (Huang & Vane, 1989; Viraghavan et al. 1999, 2005; Reed et al. 2000; Jiang, 2001; Vaishya & Gupta, 2003; Pena et al., 2005; Pena et al., 2006; Hristovski et al., 2007; Hristovski et al., 2008).

Activated carbon is a highly porous carbonaceous substance with a wide range of applications in gas, vapor, and liquid treatment (Parker and Hughes, 1998). The use of activated carbon dates back to 1500 BC when Egyptians used it for medicinal purposes and purifying oils (Parker and Hughes, 1998; Cameron Carbon Incorporated, 2006). In the 18 century, the adsorptive powers of carbons in experiments with gases were recognized (Parker and Hughes, 1998). During World War I, activated carbon was used in gas masks as personal protection equipment to filter out chlorine gas (Parker and Hughes, 1998; Cameron Carbon Incorporated, 2006). Today, activated carbon is being used successfully in water treatment to remove organic compounds that impart color, taste and odor to the water. Granular activated carbon is good adsorptive media due to its high surface area to volume ratio. Granular activated carbon processes are used to remove organic contaminants due to their versatility, efficiency and low operating costs (Schimmel et al., 2010). Amongst the granular activated carbons designed for water treatment applications, HydroDarco 3000 (HD3000) has been used in studies due to its macroporous nature with wide pore size distribution and large pore volume, which provide HD3000 with rapid adsorption rate (Norit, 2007).

According to available literature, Matijević and Scheiner (1978) seem to be the first ones to successfully control the production of large number of mono-dispersed sols of ferric hydrous oxide. They have studied in detail the formation of ferric hydrous oxide sols in acidic solutions, containing ferric ions and nitrate, perchlorate and chloride ions with uniform shape and narrow size distribution. These sols were prepared by aging the solutions (hydrolysis) at elevated temperatures and for different durations of time ranging from a few hours to few days or even weeks. It has been emphasized in the study that synthesis conditions like temperature, concentration of ferric ions, pH, nature of anions present and time of aging play a significant role in the formation of the sols/particles. Synthesis conditions have significant impact on the particle shape, size and uniformity, surface properties etc. (Matijevic and Scheiner, 1978). Later in 1981, Matejevic (p. 1981) pointed out “all that is necessary to generate uniform particles of different metal (hydrous) oxides by forced hydrolysis is to keep acidified solutions of metal salts at elevated temperatures for a definite period of time.” The difficulty lies with conditions like pH, nature of anion, ferric ion concentration, temperature etc. which can be very restrictive in many cases (Matijevic, 1981).

One of the aspect of the same study was that hematite is only obtained in the presence of chloride ions. He even pointed out that metal (hydrous) oxides due to their uniform size and well defined morphology are suitable adsorbents for a variety of solutes.

As mentioned by Cundy et.al. (2008), "Current applications of iron-based technologies in contaminated land or groundwater removal can be broadly divided into two (overlapping) groups, based on the chemistry involved in the remediation process: technologies which use iron as a sorbent, (co)precipitant or contaminant immobilizing agent; and those which use iron as an electron donor to breakdown or to convert contaminants into less toxic or mobile form." Iron oxides and ferromanganese oxide compounds have been widely used as sorbents to remove contaminants from groundwater (Liu & Zhang, 2008; Pajany et al., 2009). Mohan and Pittman (2007) in their review on arsenic removal from water/wastewater clearly mentioned that 'iron and iron compounds (iron oxides, oxyhydroxides and hydroxides, including amorphous hydrous ferric oxide, goethite and hematite etc.) are the most widely used adsorbents, having higher removal efficiency at lower cost versus many other adsorbents." The tendency of As to bind to iron oxides and hydroxides has been studied by several authors. The role of freshly precipitated, amorphous iron oxide as sorbent of arsenic has also been of interest to many researchers. Authors like Sarkar et al. (2007) have discussed the application of iron nanoparticle based hybrid anion exchanger media which is expensive but regenerable and at the same time generate arsenic rich sludge which upon disposal may lead to further contamination of environment with arsenic.

Many other authors have examined the adsorption of iron oxides highlighting (1) the tendency of arsenic, in both states As (III) and As (V), to strongly bind to iron oxides as monodentate or bidentate inner sphere complexes even at very low arsenic concentrations and (2) the important environmental role of amorphous, freshly precipitated iron oxides as sorbents for arsenic. Iron based arsenic removal technologies make use of the strong (geo)chemical association of arsenic with iron, removing arsenic by direct adsorption processes or coprecipitation using ferric chloride (Mohan & Pittman, 2007; Yuan et al., 2002; Sylvester et al., 2007; Meng & Korfiatis, 2001; Pajany et al., 2009; Cundy et al., 2008). Adsorption of arsenic on magnetic iron-manganese oxide in aqueous medium suggested adsorption or desorption of 60-80% of the overall uptake or desorption within 5 min (Liu & Zhang, 2008). Mamindy-Pajany et al. (2009), have studied sorption of As(V) on commercially available hematite and goethite with removal efficiency of more than 80% irrespective of the initial concentration of As in the waters. Compared to HFO, hematite has reduced surface area and therefore is less reactive and effective as a substrate (Cundy et al., 2008). Hristovski et al. (2007), found Fe_2O_3 along with TiO_2 and NiO greater than 98% efficient in removing arsenic from groundwater when comparing various commercially available metal oxide nanomaterials and aggregated nanoparticles for arsenic removal in fixed bed columns.

Hydrous ferric oxide (HFO) and granular ferric hydroxide (GFH) are important sorbents in waste water treatment and groundwater treatment respectively (Penner & Koopal, 1986). GFH has high adsorption capacity in natural waters (Badruzzaman & Westerhoff, 2004). Findings by Driehaus et al. show that granulated iron hydroxide provides greater operational reliability with the least maintenance and monitoring effects (Choong et al., 2007). Use of porous iron oxides (GFH) for arsenate removal has been validated by studies conducted by Westerhoff et al., (2005) and Badruzzaman et al., (2004). Though granular ferric hydroxide has been studied by several researchers for its effectiveness in removal of arsenic, it has its own disadvantages like quick head loss buildup due to fine particles and reduction in adsorption capacity by even 50% with larger sized media. Akaganeite-type β-FeO(OH) adsorbent was synthesized by Deliyanni and his coworker by precipitation from Fe(III)chloride and ammonium carbonate for arsenic removal which has the advantages of high surface area and narrow pore size distribution (Deliyanni & Peleka , 2001; Deliyanni et al., 2009) . A study conducted by Deliyanni et al. (2009), showed higher arsenate removal capacity by nanostructured akaganeite as compared to granular akaganeite.

Several researchers have developed hybrid adsorption media by impregnating sorbent media with various kinds of metals for arsenic removal from water. A study conducted by Reed et al. (2000), proved Fe (III) impregnation to be most effective for anionic adsorbates and recommended those to be the focus of future research. Gang et al. (2010) conducted a study on a low cost and high efficiency arsenite removal technology by using an iron impregnated chitosan sorbent. Katsoyiannis and Zouboulis (2002) have modified and studied polymeric materials like polystyrene and polyHIPE by coating their surface with appropriate adsorbing agents, i.e. iron hydroxides which has been classified as an emerging adsorptive filtration technology in the removal of inorganic arsenic anions from contaminated water sources. The modified media was found to be capable of removing arsenic from an aqueous stream, leading to residual concentration of the toxic metalloid element below 10µg/L. Iron oxide coated sand was found to be effective in removing arsenic below 5 to 10 µg/L levels compared to manganese green sand which was efficient in removing arsenic to a level below 25 µg/L (Thirunavukkarasu et al., 2005).

Arsenate adsorption has also been studied with hydrous ferric oxide incorporated onto granular activated carbon with formaldehyde resins coating (HFO-PF-coated GAC). This media has been found capable of removing 85% of the arsenate from industrial waters containing As(V) levels of about 2 mg/L within one hour (Zhuang et al., 2008). Some researchers impregnated carbon with various metal oxides such as iron oxide in order to improve arsenic adsorption (Chen et al., 2007; Hristovski et al., 2009). Iron coated pottery granules have been found effective in removing both arsenite and arsenate from drinking water (Dong et al., 2009). Iron oxide impregnated activated carbon has shown higher As(III) and As(V) removal as compared to non-impregnated carbon (Hristovski et al., 2009; Reed et al., 2000). Studies have shown that arsenic adsorption can be improved by impregnating carbon with iron hydroxide (Hristovski et al., 2008). Synthesis conditions for the media developed can dictate the arsenic adsorption capacity was clearly demonstrated by Hristovski et al. Fe-GAC developed by the permanganate/Fe(II) method had an order of magnitude greater As(V) removal capacity as compared to Fe-GAC developed by direct precipitation of Fe(III)

(Hristovski et al., 2009). Iron modified activated carbon has been synthesized on various types of bituminous, wood and lignite carbons by either precipitation or iron salt evaporation of Fe(III). This study demonstrated that the amount of arsenic removed is closely related to the amount of iron loaded and also how much is actually available for adsorption to occur (Chen et al., 2007). A recent study conducted by Cooper et al. (2010), showed that lignite based Fe-GAC has better arsenic removal capacity as compared to bituminous Fe-GAC. Not only this, an important finding of the study was that every step of hybridization process affects the performance of the media. Nguyen (2008) has also studied Fe impregnated activated carbon for arsenic removal. Adsorption is highly recommended for small community systems due to its low cost of operation and maintenance as compared to other technologies (USEPA, 2002b).

Adsorption isotherm models.

Adsorption isotherms are performed by exposing a known quantity of adsorbate in a fixed volume of liquid to various dosages of adsorbent (Crittenden, 2005). The adsorption equilibrium capacity is calculated for each sample using the mass balance expression

$$q_e = \frac{V(Co - Ce)}{m_{dry}} \qquad \text{Equation 7.}$$

Where

q_e = equilibrium adsorbent-phase concentration of adsorbate, μg adsorbate/g adsorbent

*C*o = initial aqueous-phase concentration of adsorbate, μg/L

Ce = equilibrium aqueous-phase concentration of adsorbate, μg/L

V = volume of aqueous-phase added to bottle, L

m_{dry}= mass of dry adsorbent, g

Adsorption equilibrium capacity is the relationship between the amount of adsorbate adsorbed on the surface of adsorbent and the equilibrium conditions of the adsorbate at a certain temperature and other conditions. The equilibrium data is formulated into an isotherm model (Dubey, Gopal & Bersillon, 2009).

Different isotherm models are used to describe different kinds of adsorption. The most widely used models to describe the equilibrium behaviors of adsorbate uptake are the well-known Langmuir and Freundlich sorption isotherms. According to Liu and his team, the Freundlich model was derived empirically, while the Langmuir adsorption isotherm was developed from rational considerations (Liu, Xu & Tay, 2005). To date, the Langmuir and Freundlich equations have been considered two independent models. Morel and Hering state that “there is evidence that not all adsorption data show the clear maximum of the Langmuir isotherm, while the Freundlich isotherm can accommodate adsorption data only over a range of adsorbate concentrations” (Liu et al., 2005, p. 1466).

The Freundlich adsorption isotherm is used to describe the data for heterogeneous adsorbents and was developed for liquid-phase adsorption (Maurya & Mittal, 2006). According to Goldberg (1995, p. 76), “the Langmuir adsorption isotherm equation was developed to describe the adsorption of gases onto clean solids and implies uniform adsorption sites and absence of lateral interactions.” The Langmuir adsorption isotherm is used to describe the equilibrium between surface and solution as a reversible chemical equilibrium between species

(Crittenden et al., 2005). This model is based on a few assumptions: (1) the reaction has a constant free-energy change for all sites and (2) at maximum adsorption only a monolayer is formed. (Crittenden et al., 2005).

The Brunauer, Emmett and Teller (BET) adsorption isotherm extends the Langmuir model from a monolayer to several molecular layers (Crittenden et al., 2005). It was developed by Stephen Brunauer, Paul Emmett and Edward Teller in 1938. BET theory aims to explain the physical adsorption of gas molecules on a solid surface (gas phase adsorption) and serves as the basis for an important analysis technique for the measurement of the specific surface area of a material (Muarya & Mittal, 2006). Above the monolayer, each additional layer of adsorbate molecules is assumed to equilibrate with the layer below it, and the layers of different thickness are allowed to coexist. In the BET model the site energy is the same for the first layer and equal to the free energy of precipitation for subsequent layers (Crittenden at al., 2005).

LeVan et al. (1998) demonstrated that other adsorption isotherm models in addition to the Langmuir and Freundlich models, such as Sips, Tóth, Radke–Prausnitz, and Fritz–Schluender models, have also been used to fit experimental data. As stated by Liu et al. these models are derivatives of either Langmuir or Freundlich, and they are empirical or semiempirical (Liu et al, 2005).

Evaluating media performance.

While evaluating media for its arsenic adsorption capacity, the combination of characterization, testing (batch equilibrium and column) and modeling is an easy, fast and less expensive approach compared to long duration pilot testing. Some of the techniques used for evaluating media performance are described below:

Surface charge (Zeta potential).

Surface charge of the particles depends on the nature of the particles and also the medium surrounding the particle. Particles dispersed in an aqueous medium develop a surface charge, essentially either by ionization of surface groups, or adsorption of charged species, which determines the stability of the particles (Ramachandran, 1995). The distribution of the surrounding ions is modified by these surface charges, resulting in a layer around the particle that is different than the bulk solution. If the particle moves, under Brownian motion for example, this layer moves as part of the particle. The potential at the point in this layer where it moves past the bulk solution is known as the zeta potential. This is usually called the slipping plane and the charge at this plane will be very sensitive to the concentration and type of ions in solution (Heurtault, Schuber & Frisch, 2010).

Zeta potential varies with pH. A low pH values the zeta potential is positive, as pH increases the zeta potential decreases, goes through zero at a pH called isoelectric point, (IEP, explained later in this section) and then becomes negative as the pH is further decreased (Moudgil et al., 2002). Zeta potential is considered one of the main forces that mediate interparticle interactions. Particles with a high zeta potential of the same charge sign, either positive or negative, will repel each other. Conventionally a high zeta potential can be high in a positive or negative sense, i.e. <-30mV and >+30mV would both be considered as high zeta potentials (Malvern Instruments, n.d.). For molecules and particles that are small enough, and of low enough density to remain in suspension, a high zeta potential will confer stability or in other words, the solution or dispersion will resist aggregation (ZetaSizer Nano Series, 2003).

Zeta potential is used to assess the charge stability of a disperse system and to assist in the formulation of stable products. It is important to note that zeta potential controls charge interactions, not the charge at the surface (Koetz & Kosmella, 2007).

Generally speaking, zeta potential can be detected by means of electroosmosis, electrophoresis, streaming potential measurements or sedimentation potential. Koetz and Kosmella (2007) describes that electrophoresis and sedimentation potential measurements involve the motion of charged particles in a liquid whereas streaming potential and electroosmosis involve the flow of fluid past a stationary charged surface. These phenomena also can be classified in terms of driving forces and response. In electrophoresis and electroosmosis experiments, one applies an electric field and generates particle or fluid flow. In sedimentation potential or streaming potential measurements, one imposes an external pressure gradient or an accelerated force and generates an electric potential (Brett & Brett, 1994; Koetz & Kosmella, 2007).

According to the article by Dukhins (2010), published in SciTopics website, zeta potential is measured by applying an electric field across the dispersion. When an electric field is applied to charged particles in a liquid, they begin to move (Heurtault et al., 2010). Particles with a zeta potential within the dispersion will migrate toward the electrode of opposite charge. These particles move with a velocity proportional to the magnitude of the zeta potential. This velocity is measured using the technique of laser doppler anemometry and depends on the strength of electric field i.e. dielectric constant. The frequency shift or phase shift of an incident laser beam caused by these moving particles is measured as the particle mobility. This mobility is converted to the zeta potential by inputting the dispersant viscosity, and the application of the Smoluchowski or Huckel theories (Dukhin, 2010). Smoluchowski equation used to calculate the zeta potential for particles being treated as point charges is as follows (Moudgil et al., 2002):

$$U_E = \frac{\zeta\varepsilon}{\eta} \qquad \text{Equation 8}$$

Where

U_E = Mobility under an applied potential E

ζ = Zeta potential (mV)

ε = permittivity of the electrolyte medium

η = viscosity of the medium

The measurements are influenced by factors like the conductivity, absolute temperature, concentration of electrolytes, concentration of formulation component and pH (Pansu & Gautheyrou, 2006).

The isoelectric point (IEP) is the pH at which the zeta potential is zero (Pansu & Gautheyrou, 2006). At a pH below the isoelectric point the particles are positively charged and will move towards the cathode and at a pH above the isolecetric point they are negatively charged and will move towards anode. At the isoelectric pH, the particles remain immobile (Pattabhi & Gautham, 2002).

Surface area by BET method.

The BET method is based on adsorption of gas on a surface. The amount of gas adsorbed at a given pressure allows the determination of the surface area. It is a cheap, fast and reliable method. It is very well understood and applicable in many fields.

According to the literature available on gas adsorption analysis, surface area helps determine how solids will dissolve or react with other materials. Generally, to determine surface area samples are pretreated by applying heat, vacuum or flowing gas to remove primarily water and other adsorbed contaminants on the sample. If needed all three things as mentioned above could be used for pre-treatment of the sample. The solid is then cooled, under vacuum, usually to cryogenic temperature. The pressure is ramped by introducing an additive typically nitrogen to the solid in controlled amounts and after each dose, the pressure is allowed to equilibrate and the quantity of gas adsorbed is calculated. The gas adsorbed at each pressure at a particular temperature defines an adsorption isotherm. It is from this data that the quantity of gas required to form a monolayer over the external surface of the solid and its pores is determined. With the area covered by each adsorbed gas molecule known, the surface area can be calculated by using equation 9 (Micrometrics, 2001; Holmberg, 2002).

$a_{(\mathrm{BET})} = n_m N_A \sigma$ Equation 9

Where

$a_{(\mathrm{BET})}$ = Specific BET surface area

n_m = monolayer capacity

N_A = Avogadro's Number= $6.02\text{x } 10^{-23}$ molecules/mole

σ = average area per molecule

The determined surface area comprises of the outer as well as the inner (open pores) surface area. Because the adsorbing gas molecules cannot access the closed pores, the surface area of the closed pores cannot be determined (Neikov et al., 2009).

Pore size distribution.

Gas adsorption can also be used to measure pore size distribution. According to the information available surface area determination creates conditions required to adsorb an average monolayer of gas molecules onto a sample. In order to evaluate the fine pore structure of the sample, the gas is allowed to condense in the pores for an extended period of time. As pressure increases, the gas starts condensing in the pores with the smallest dimensions first. Further, the pressure is increased until all pores are filled with liquid and saturation is reached. At this time, the adsorptive gas pressure is reduced drastically leading to the evaporation of the condensed gas from the system. Calculations are beyond the scope of the study but it is important to mention that evaluation of the adsorption and desorption of the isotherms developed by above processes and the hysteresis between them provides necessary information about the pore size, volume, area and shape. Hysteresis seen due to establishment of metastable state (a feature of adsorption than desorption). Barrett, Joyner and Halenda(BJH) procedure is applied to calculating the pore size distributions from the experimental isotherm data (Holmberg, 2002; Micrometrics, 2001).

Batch equilibrium tests and column tests.

An isotherm model is a suitable tool to assess the adsorption capabilities in batch studies. According to Maurya and Mittal (2006), the adsorption isotherm is a basic requirement for the design of any batch or fixed bed adsorption system. As described by Dubey et al (2009, p. 328). "Batch study consists of contacting an adsorbate with a definite quantity of adsorbent in batch stirring system. The mixture is agitated to facilitate the adsorption process. In column study, adsorbent is packed in column reactor and almost no movement of adsorbent takes place inside the column". Development and optimization of adsorption parameters can be carried out by batch and column processes in the laboratory. The adsorption technology is then applied at pilot and industrial scales by use of large columns. Langmuir, Freundlich and other models are well known and can describe the adsorption efficiency of a pollutant systematically (Crittenden et al., 2005).

Batch equilibrium tests are conducted to determine the adsorption capacity of arsenic onto the various adsorption media synthesized. Data can be applied to one or more of the models discussed above. Most of the reported studies for arsenic removal in the literature have been conducted in batch operation. According to Singh and Pant, (2006, p. 289), batch experimental data is often difficult to apply directly to fixed bed adsorber tests. It is so because an isotherm cannot give accurate data for scale up since a flow column is not at equilibrium. Also, isotherms are unable to predict chemical or biological changes occurring in the adsorbent. Column adsorption experiments are performed to study the adsorption dynamics. According to Singh and Pant, (2006, p. 289) “the most important criterion in the design of fixed bed adsorption systems is the prediction of column breakthrough or the shape of the adsorption wave front, which determine the operation life span of the bed and regeneration times.”

The two dominant factors that control the breakthrough in GAC columns are the adsorption capacity and the adsorption kinetics. Pilot columns utilize the same reliable predictors of breakthrough behavior in full-scale columns in terms of both capacity and rate of adsorption. However, this approach may require time consuming and expensive studies. Rapid methods to design GAC columns from small columns have been developed to reduce the study time and cost. Examples of methods using small columns are the short fixed bed, the minicolumns, the high-pressure minicolumns, the dynamic minicolumn adsorption technique, the accelerated column tests, the small-scale columns and the rapid small-scale column test (RSSCT) (Eckenfelder et al., 2009).

The objective of performing SBA test is to significantly reduce the cost and time; quickly determine the most effective treatment technology/media and design for small scale water treatment systems and for a variety of water qualities (Aragon, n.d.; Kundu and Gupta, 2005).

The advantages of small scale column testing are (Crittenden et al., 1986; Crittenden et al., 1987; Crittenden et al., 1991; Crittenden et al., 2005; Westerhoff et al., 2005)

1) It can be conducted in a fraction of the time required of pilot tests
2) Requires a fraction of water compared to pilot tests
3) Can be conducted under controlled laboratory conditions
4) Continuous flow tests allow evaluation of dynamic behavior and competition reactions that are more representative than batch tests
5) More inexpensive than full sized media pilot study (i.e. low capital and operational cost)
6) Help with comparison of media and water quality effects

Chapter 3

METHODOLOGY

This chapter describes the methodology implemented to (1) investigate the synthesis of iron-impregnated granular activated carbon by hydrolysis and (2) assess the effectiveness of fabricated media in the removal of arsenic from water. The chapter is divided into four sections

1) Glassware Cleaning Protocol;
2) Synthesis of Hybrid Adsorbent Media;
3) Characterization of Adsorbent Media; and
4) Media Evaluation for arsenic adsorption capacity under batch equilibrium and continuous flow conditions.

Glassware Cleaning Protocol

The glassware and plasticware used for this study were cleaned using the following procedure:

1) Rinsed with tap water;
2) Soaked and scrubbed with 1% Alconox solution;
3) Rinsed with tap water until no soap bubbles were seen;
4) Rinsed with ultrapure water three times;
5) Sonicated for 15 minutes while filled with 10% nitric acid;
6) Rinsed with ultrapure water minimum 4 times;
7) Allowed to dry in an oven; and
8) Sealed with parafilm to prevent contamination.

Synthesis of Hybrid Adsorbent Media

HydroDarco 3000 (HD3000), a lignite based granular activated carbon (GAC) obtained from NORIT Americas Inc. USA, was used in this study. This GAC is an acid washed carbon designed for water treatment applications and is produced through high temperature steam activation of lignite coal (Norit, 2007).

Fabrication of hybrid media.

Four types of Fe-GACs were synthesized by varying the initial iron (III) chloride concentration and hydrolysis time. This synthesis method is a modification of a study conducted by Matejevic et al. (1978) in which it was shown that hematite sols can be generated by forced hydrolysis of iron (III) chloride at elevated temperatures. A flowchart of the synthesis process is shown in Figure 4.

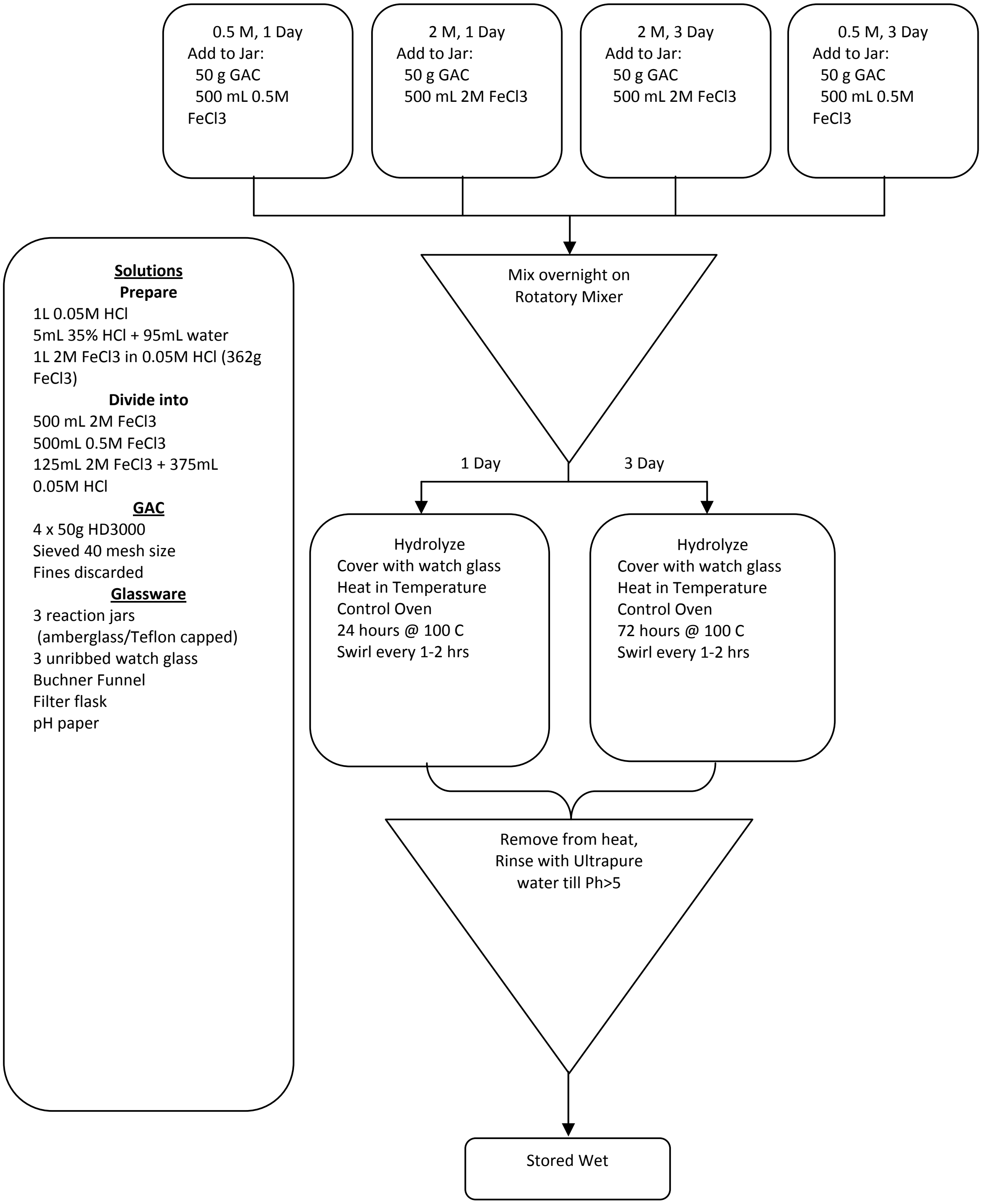

Figure 4. Schematic of Fabrication of Fe-GAC media

Preparation of iron (III) chloride solution.

Two initial concentration of iron (III) chloride i.e. 0.5 M and 2 M as illustrated in the flowchart (Figure 4) were prepared. The three steps in the preparation of different iron (III) chloride solutions are:

1) 1L of 0.05 M HCl was prepared by pipetting 5 mL of 35% HCl in a volumetric flask with water to make 1 L of the solution,

2) 2 M iron (III) chloride solution was prepared by combining 362 g of iron (III) chloride in a 1 L volumetric flask filled with 0.05 M HCl to make 1 L of the solution. Since the combination of iron (III) chloride and HCl leads to an exothermic reaction, therefore, the flask was cooled on a water bath while swirling it to dissipate heat and to ensure the salt is completely dissolved,

3) 0.05 M iron (III) chloride solution was prepared by diluting 125 mL of 2 M iron (III) chloride with 375 mL of 0.05 M HCl in a 500 mL volumetric flask.

Fabrication of media.

Two amber glass jars with teflon caps were filled with (1) 50 g of dry virgin media (HD-3000) and 500 mL of 2 M, and (2) 50 g of dry virgin media and 500 mL 0.5 M iron (III) chloride solution, respectively. The contents of the jars were mixed overnight (15 hours) on a rotary mixer at 30 rpm to ensure that the solution reaches the pore spaces available on the surface of the GAC. The following day, bottles were taken off from the mixer, teflon caps removed and bottle necks covered with watch glass. These bottles were set in temperature controlled oven for 24 hrs (1 Day) at 100 ^{0}C swirling the contents of the bottles every one to two hours. After hydrolysis, the bottles are removed from heat and filtered with the help of a vacuum pump using a buchner funnel lined by Whatman filter paper # 41. The filtrate was discarded. The pH of the filtrate was measured by using Hydrion® pH paper.

Since the adsorbent media was made in HCl, even after repeated rinsing the media could not be brought to a pH greater than 5. Hence, it was soaked in 2% $NaHCO_3$ for 24 hrs and rinsed with ultrapure water to bring the pH of the synthesized media from pH 2.5 ±0.5 to a desirable pH range (pH greater than 5) The pH of the filtrate was measured by using Hydrion® pH paper. The media synthesized is kept soaked in ultrapure water for future analysis and testing.

The other two media with initial iron (III) chloride concentration of 0.5 M and 2 M were synthesized in the same manner but the hydrolysis time was 72 hours. All four fabricated adsorbent media for water treatment are collectively called Fe-GACs. Table 3 summarizes the media synthesized and used in the study.

Table 3.

Summary of Synthesis Conditions for Media used in the Study and Designations

Sample ID	Initial Conc. of Iron(III)Chloride	Hydrolysis Time (Days)	Fabricated Media	Media Type
0.5M-24hr	0.5 M	1	0.5M, 1Day	Fabricated Fe-GAC
2M-24hr	2.0 M	1	2M, 1Day	Fabricated Fe-GAC
0.5M-72hr	0.5 M	3	0.5M, 3Days	Fabricated Fe-GAC
2M-72hr	2.0 M	3	2M, 3Days	Fabricated Fe-GAC
V	N/A	N/A	N/A	Virgin GAC (V-GAC)

Characterization of Adsorbent Media

Moisture content, bulk particle porosity, material density measurements.

The moisture content, bulk particle porosity and material density of all media used in the study was determined using a picnometer as described by Sontheimer et al. (1988). The empty picnometer was weighed and excess water from soaked media was drained out and discarded. A small portion of wet media was weighed in the picnometer and reading recorded. Then picnometer was filled up to the rim with ultrapure water and weighed again. The water was drained and picnometer kept in an oven at 105 ^{0}C for drying the media until constant mass was achieved. The dry mass of the picnometer along with media was recorded after cooling it in a desiccator. Oven-dried samples were discarded and not used in isotherm testing. The percent moisture, bulk particle porosity and material density were calculated using Equations 10, 11 and 12 respectively. Data generated generated is attached in Appendix A.

$$\%_{moisture} = \frac{m_{wet} - m_{dry}}{m_{wet}} X\ 100 \qquad \text{Equation 10.}$$

Where

$\%_{moisture}$ = Calculated % moisture for each sample (%)

m_{wet} = Mass of wet media in the picnometer (g)

m_{dry} = Net dry mass of media (g)

$$E_b = \frac{V_{wet\ media} - \left(\frac{m_{dry}}{\rho_m}\right)}{V_{wet\ media}} \qquad \text{Equation 11.}$$

Where

E_b= Bulk particle porosity

$V_{wet\ media}$ = Volume of wet media (mL)

m_{dry} = Mass of dry media (g)

ρ_m = Density of the media (g/mL)

$$\rho_m = \frac{m_{dry}}{V_{wet\ media} - (m_{wet} - m_{dry})}$$ Equation 12.

Where

ρ_m = Density of the media (g/mL)

m_{dry} = Mass of dry media (g)

$V_{wet\ media}$ = Volume of wet media (mL)

m_{wet}= Mass of wet media (g)

Iron content of the Fe-GAC media.

The iron content of dry Fe-GAC media was determined by acid digestion according to USEPA SWA 846, Method 3050B (United States Environment Protection Agency [USEPA], 1996). To determine Fe content, dry samples of fabricated media (Fe-GAC) were ground to fine powder using a mortar and pestle and dried to a constant mass in an oven at 105 ^{0}C for 24 hours to remove all moisture from the samples before they are subjected to acid digestion. Approximately 1g of dried sample was transferred to a 150 mL beaker followed by 20 mL of 1:1 conc. HNO_3 : ultrapure H_2O and heated on a hot plate covered with watch glass until the volume of the solution was reduced to 10 mL. The beaker was removed from the hot plate followed by addition of 5 mL of conc. HNO_3 and returned to heat until reflux was observed. The beaker was taken off the hot plate, cooled and slowly 3 mL 30% H_2O_2 was added to the beaker. When reaction was complete, ultrapure water was added to make a final volume of 30-40 mL. The cooled solution was gravity filtered through #41 Whatman filter and diluted to 100 mL with ultrapure water. This solution was then analyzed using Flame Atomic Adsorption Spectroscopy (FAA, Varian SpectrAA 50B Atomic

Absorption Spectrometer) to determine the Fe content for each Fe-GAC sample fabricated. The settings used for FAA analysis are listed in Table 4. The instrument was calibrated using freshly prepared Fe standards using a stock solution of 500 mg/L made from 1000 mg/L Fe standard solution with a matrix of 2% nitric acid (Fisher Chemicals). The 500 mg/L stock solution was diluted to 10, 20, 50, 100, 125 mg/L and a five point calibration curve was developed.

Table 4.

Instrument settings for Flame Atomic Adsorption analysis of Fe.

Working Conditions (Fixed)				
Lamp Current	Fuel	Support	Flame Stoichiometry	Bulb
5 Ma	Acetylene	Air	Oxidizing	Fe
Working Conditions (Variable)				
Wavelength (nm)	Slit Width (nm)	Optimum Working Range (µg/mL)		
386.0	0.2	1.5 – 200		

The Fe content of the fabricated GAC (collectively called Fe-GAC) was determined using Equation 13 and 14. Stepwise calculations have been attached in Appendix C.

$$mFe_{(GAC)} = V_{(solution)} x \;\; C_{(Fe\ in\ Fe-GAC)} \qquad \text{Equation 13.}$$

Where:

m $Fe_{(GAC)}$= Mass of Fe in fabricated media measured using FAA (µg Fe)

$V_{(solution)}$= Volume of sample prepared after digestion of sample

$C_{(\text{Fe in Fe}-\text{GAC})}$= Concentration of Fe in Fe-GAC digested.

$$\% \, Fe = 100 \times \frac{\text{m Fe}_{(\text{GAC})}}{\text{m Fe}-\text{GAC}_{(\text{digested})}} \qquad \text{Equation 14.}$$

Where:

$\text{m Fe}_{(\text{GAC})}$= Mass of Fe in fabricated media measured using FAA (mg Fe)

$\text{m Fe} - \text{GAC}_{(\text{digested})}$= Mass of dry fabricated media (mg Fe-GAC)

Iron distribution.

FEI NOVA 200 Nanolab UHR FEG-SEM/FIB equipped with a backscatter detector was used to provide high magnification micrographs of the deposited iron (hydr)oxide nanoparticles within the media pores and mapping of iron throughout the media. With the help of this backscatter detector heavier elements, like iron, and lighter elements, like carbon, nitrogen, and oxygen can be distinguished as light areas and dark areas, respectively. High resolution micrographs from this system were used to determine the iron nanoparticles' size and shape. Micrographs for 0.5M-72hr Fe-GAC media produced by using this technique are attached in Appenix D.

pH measurements.

pH measurements were measured with Mettler-Toledo 7 Multi pH Meter which includes a pH indicating electrode and conductivity indicating electrode. Before use, pH was calibrated using 4.00, 7.00, 10.00 pH buffers from VWR.

Zeta potential measurements.

Zeta-potential analysis was performed and the isoelectric point (IEP) was estimated on all Fe-GAC samples and V-GAC. The wet samples were air dried and ground to a fine powder. Approximately 2 g of the ground sample was suspended in 30 mL of 0.01 M KNO_3 solution (GAC-KNO_3). The suspension was allowed to stand for at least 2 days to ensure thorough wetting of the media surfaces. Zeta-potential was measured on the ZetaPALS (Brookhaven Instruments Corporation, Holtsville, NY) using a phase-analysis light-scattering technique.

To perform the analysis, approximately ~5 mL of the GAC-KNO_3 suspension was added to approximately 60 mL of 0.01 M KNO_3 in a 150 mL beaker and stirred on a magnetic stir plate at a speed sufficient to prevent the particles from settling. A calibrated pH meter set to continuously measure pH was placed in the solution and, after it had equilibrated, the initial pH was recorded. A small amount of this solution was used to rinse and then fill a clean, unscratched, polystyrene square cuvette (10 mm square, 4.5 mL). The zeta potential electrode was placed in the cuvette, checked for bubbles that could cause measurement error, and then placed in the chamber of the analyzer. After the measurements were taken, the cell was removed, shaken slightly to mix, checked for bubbles and then measured again. The pH of the GAC-KNO_3 stirred solution was adjusted by drop wise addition of 1 M and 0.1M acid (HNO_3) or base (KOH), and the zeta-potential was measured at the new pH. A minimum of three runs of six readings (20 measurements per reading) were taken and averaged at each selected pH interval between the pH of 2 and 11. Average zeta-potential vs. pH was plotted for each pH point measured and the isoelectric point was estimated as the point at which the graph crossed the x-axis. Two-tailed 95% confidence interval was calculated and plotted for each average zeta using the method in Equation 15 (Manly, 2001).

$$\alpha_{(2\text{-tailed})} = \frac{t_{95}\sigma}{n^2} \qquad \text{Equation 15.}$$

Where

$\alpha_{(2-tailed)}$ = Upper and lower confidence interval

t_{95} = Students t for 95% confidence interval

σ = Standard deviation of the mean

n = Number of measurements

Pore size distribution and surface area analysis.

In order to determine the surface area and pore size distribution for all Fe-GAC with change in hydrolysis time and varying initial concentration of iron (III) chloride and V-GAC, the samples were analyzed using the Brunauer Emmett and Teller (BET) model on the Micrometrics Tristar-II 3020 automated gas adsorption analyzer.

Prior to analysis, the samples were dried in an oven at 105 ºC for 24 hours to constant mass and cooled in a desiccator. A small sample (~1 g) of the media was added to a pre-weighed, dry, clean, sample tube with stopper. It was dried overnight (~8 hrs) in an inert environment at 300 ^{0}C under N_2 purge to ensure no moisture remains adhered to the Fe-GAC media and reweighed. Sample weight was calculated by subtracting the weight of the stopper and tube from the cooled weight. The surface area and pore size distribution of the samples was measured on a Tristar-II 3020 – Automated gas adsorption analyzer (Micrometrics Tristar-II 3020). Data files are attached in Appendix B.

Media Evaluation for Arsenic Adsorption Capacity under Batch Equilibrium and Continuous Flow conditions

Preparation of model water matrixes.

To assess the arsenic removal capacity of Fe-GAC, batch equilibrium tests were conducted with two types of model waters: (1) Model test water with arsenic only (no competing ions) to estimate the maximum arsenic adsorption capacity and (2) Challenge groundwater representative of groundwater at the Arizona-Mexico Border region to estimate performance under realistic conditions.

1) Model test water with arsenic only (no competing ions) to estimate the maximum arsenic adsorption capacity.

The model test water was created to contain an arsenic concentration of ~125 μg/L and 1 mM $NaHCO_3$. This was achieved by adding 1.26 g $NaHCO_3$ (Mallinckrodt Chemicals) and 2.4 mL 0.010 M solution of arsenic to 20 L plastic HDPE container to make final volume of 20 L in ultrapure water.

2) Challenge groundwater representative of groundwater at the Arizona-Mexico Border region to estimate performance under realistic conditions.

This water matrix was prepared by dissolving ionic species as summarized in Table 5. The types of ions and their concentration were similar to the study by

Westerhoff et al. (2004) and NSF 53 challenge water (Westerhoff et al., 2004; Hristovski et al., 2008).

To create the model groundwater, 100 L of ultrapure water was added to a clean 250 L HDPE tank using a calibrated 20 L plastic container. All compatible chemicals, as described in the Table 5, were dissolved in 20 L HDPE container step by step to prevent precipitation and transferred to the 250 L test tank. The contents of the test tank are checked periodically to ensure there is no precipitation and all salts remain dissolved.

In the end, 50 g of $NaHCO_3$ is added to the test tank to buffer the water and stirred to dissolve while covered with the lid to avoid contamination of model groundwater. Prior to using the challenge groundwater in isotherm testing and short bed column tests, pH of this model water is adjusted to 7.7 ± 0.25 by dropwise addition of 1M HCl solution.

Table 5

Composition of Model Challenge Groundwater Matrix

Ion Species	**Conc. of Ion (mg/L)**	**Added As**	**Conc. of Compound (mg/L)**	**Manufacturer**
N as NO_3^-	1.6	$NaNO_3$	2.193	JT Baker (Crystal)
F^-	1.1	NaF	2.431	Sigma Aldrich (min 99%)
PO_4^{3-}	0.069	$NaH_2PO_4.H_2O$	0.100	Fischer Scientific
B^-	6.6	H_3BO_3	37.73	JT Baker (Crystal)
Pb(II)	0.002	$Pb(NO_3)_2$	0.003	JT Baker (Crystal)
Cr(III)	0.001	$CrK(SO_4)_2.12H_2O$	0.010	JT Baker (Crystal)
Fe(III)	0.075	$FeCl_3.6H_2O$	0.363	Fischer Scientific
Mn(II)	0.029	$MnCl_2.4H_2O$	0.104	Malinckrodt
V(III)	0.007	Na_3VO_4	0.025	JT Baker (Powder)
Se(IV)	0.003	$SeCl_4$	0.008	Fischer Scientific (Powder)
As(V)	0.12	$Na_2HAsO_4.7H_2O$	0.500	Sigma Aldrich
Al(III)	0.046	$Al_2(SO_4)_3.18H_2O$	0.568	JT Baker (Crystal)
Cu(II)	0.031	$CuSO_4.5H_2O$	0.194	EM Scientific (Crystal)
Zn(II)	0.101	$ZnSO_4.7H_2O$	0.444	JT Baker (Crystal)
Mo(VI)	0.007	$Na_2MoO_4.2H_2O$	0.018	JT Baker
SiO_2	20	$Na_2SiO_3.9H_2O$	94.59	Aldrich
Mg^{2+}	12	$MgSO_4.7H_2O$	626.0	Sigma Aldrich (98+% ACS)
SO_4^{2-}	196.56	$MgSO_4.7H_2O$	626.0	Sigma Aldrich (98+% ACS)
Ca^{2+}	40	$CaCl_2$	110.8	Sigma Aldrich (Powder)

Assessment of arsenic adsorption capacity under batch equilibrium conditions.

Batch equilibrium tests were conducted to evaluate the arsenic adsorption capacity of synthesized Fe-GAC media. Virgin media was also tested for comparison to assess the role of hematite in arsenic adsorption capacity. Two sets of eight sample bottles were prepared for each of the 5 media shown in Table 3. Of the eight samples for each Fe-GAC experiment, six samples contained different dry GAC dosages in the range from 0.12 g/L to 5.6 g/L and one of the GAC dosage level was used to prepare a triplicate samples. A set of 6 control samples were also prepared. To one set, 100 mL of the test water (no competing ions) was added and challenge groundwater (with competing ions) was added to the other set. The pH of the challenge groundwater was adjusted by dropwise addition of 1M HCl so that the final pH is 7.7± 0.15.

These samples were then set on the shaker table for 72 hrs until pseudo equilibrium was achieved. After three days, sample bottles were removed from the shaker table and the media was allowed to settle. The supernatant was filtered in 60mL plastic bottles using binder free Glass Microfiber Filter (GF/F). The syringe was rinsed 3 times with ultrapure water and the filter removed and replaced after each sample to avoid contamination. A calibrated pH meter was used to measure and record the pH of the solution remaining in the test bottle. The probe was washed thoroughly with ultrapure water between readings. The filtered sample was saved in a refrigerator at temperature of less than 25 ºC for later analysis using a graphite furnace atomic absorption spectrophotometer (Varian Zeeman Spectra 400).

The same procedure was repeated for challenge groundwater. The pH of the water was adjusted by drop wise addition of 1 M HCl before the samples were placed on the shaker table so that the final pH is 7.5± 0.15.

Filtered water samples were analyzed for arsenic using a graphite furnace atomic absorption (GFAA) spectrophotometer (Varian Zeeman Spectra 400). The settings used for GFAA analysis are listed in Table 6. The instrument was calibrated with freshly prepared arsenic standards using a stock solution of 500 µg/L made from 1000 mg/L arsenic standard solution with a matrix of 2% KOH (from Arcos Chemicals). The 500 µg/L stock solution was diluted to reach the operating range for the instrument i.e. 2, 5, 10, 20, 30µg/L. A five point calibration curve was developed. Water samples were analyzed by the GFAA using the standard five point calibration curve. Arsenic adsorption data and charts are presented in Appendix E.

Table 6

Instrument Settings for Graphite Furnace Atomic Absorption spectrophotometer

Category	**Setting**
Solution Matrix	0.1% HNO_3
Atomizer	Pyrolytic coated partitioned graphite tube
Temperature range	85-2600 ^{o}C
Lamp Current	10 Ma
Spectral Bandwidth	0.2 nm
Matrix Modifier	Nickel (1000 mg/L)
Wavelength (λ)	193.7 nm
Max Absorbance	0.95
MSR	86%

Isotherms were developed for arsenic adsorption and modeled using Freundlich adsorption isotherm model (Equation 16).

$$q_e = K_a \, x \, C_e^{1/n} \qquad \text{Equation 16.}$$

Where

q_e = Equilibrium adsorption capacity (µg Adsorbate / g dry Adsorbent **)**

K_a = Freundlich adsorption capacity parameter (µg Adsorbate/g dry Adsorbent)(µg Adsorbate /L)$^{-1/n}$

C_e = Equilibrium concentration adsorbate in solution (µg Adsorbate/L Solution)

$1/n$ = Freundlich adsorption intensity parameter (unitless)

The freundlich isotherm equation is used to describe adsorption on the surface of heterogeneous adsorbents: where the forces governing physical adsorption dominate, resulting in multi-layer adsorption of the contaminant on the adsorbent surface. The freundlich isotherm equation relates the concentration of solute adsorbed onto the surface of an adsorbent to the concentration of the solute remaining in the liquid phase of the solution. The constants K_a and 1/n are determined by linear regression of the log of q_e plotted against the log of C_e. The constant log K_a is the intercept and the indication of the adsorptive capacity of the media in the system, while the constant 1/n indicates adsorption intensity. Both these parameters help to explain how effective a media is in removing arsenic from groundwater (Crittenden et al, 2005).

Assessment of arsenic adsorption capacity under continuous flow conditions.

In order to compare the maximum adsorption capacity of the media synthesized under continuous flow conditions, short bed column tests were conducted. Glass columns of length 30 cm and internal diameter of 1.1 cm (Ace Glass) were packed with 4 cm deep synthesized Fe-GAC adsorbent media bed. The adsorbent media was packed on top of quartz sand and a metal support screen supported on hydrated glasswool in the glass column. Glass beads were placed above and below the media to provide evenly distributed flow. Table 7 summarizes the column operation conditions. To assess the effectiveness of media in natural waters found in the environment, all SBA tests were conducted using challenge groundwater matrix at a surface loading rate of 5313.6 L/day/m^2. Such high loading rates have been used because similar rates are used out in the field.

The samples were collected in 60 mL plastic bottles every 5, 10, 15, 30, 60 and 120 minutes until 720 minutes. Immediately after collection, each sample was tested for pH and the details written on the sample bottle. Control samples were taken at the very beginning of the experiment and at the end of the experiment. The samples were analyzed for arsenic using the graphite furnace atomic absorption (GFAA) spectrophotometer (Varian Zeeman Spectra 400) as described earlier.

Table 7

Continuous Flow Column Operation Conditions

Column Experiment	Adsorbent media used	Column Depth (cm)	Mass of Media (g)	Flow rate (mL/min)	EBCT (min)	Total Bed Volumes processed	Flow rate (mL/min.)
C 1	0.5M-24hr	4	1.46	39	0.0974	7392.197	39
C 2	2M-24hr	4.1	1.63	39	0.0998	7214.428	39.06
C 3	0.5M-72hr	4	1.55	39.1	0.0972	7407.407	39.06
C 4	2M-72hr	3.9	1.45	39.5	0.0937	7684.098	39.47

The maximum adsorption capacity for each media (Fe-GAC and V-GAC) in continuous flow conditions were calculated using Equation 17 and 18.

$$\int_0^{m_{max}} m_{As} = Q \int_0^t (C_o - C_{ef})(t)dt \qquad \text{Equation 17}$$

Where:

m_{As} = Mass of arsenic adsorbed(µg)

C_o= Initial Concentration of arsenic in challenge groundwater (µg/L)

C_{ef} = Concentration of Arsenic in effluent challenge groundwater (µg/L)

Q = Flow rate of challenge groundwater (L/min.)

t= Time at which the sample was collected (minutes)

$$q_{max} = \frac{m_{As}}{m_{dry\ media}} \qquad \text{Equation 18}$$

Where:

q_{max} = Maximum adsorption capacity of that particular Fe-GAC media (µg As/g Fe-GAC)

$m_{dry\ media}$ = Mass of dry Fe-GAC used in the column (g)

Chapter 4

RESULTS & DISCUSSION

Media Characterization

Iron content.

Figure 5 shows the relationship between the initial iron (III) chloride concentration, duration of hydrolysis and percentage of Fe in various fabricated Fe-GAC media after acid digestion. Analysis in triplicate was done only for 0.5M-72hr Fe-GAC media. The iron content of the untreated GAC was < 0.002% of Fe per dry weight of the adsorbent. The iron content of the Fe-GAC fabricated by 1 day hydrolysis at 0.5 M concentration of iron (III) chloride was 0.9% and 2 M concentration of iron (III) chloride was 1.7% Fe per dry adsorbent weight. The iron content for Fe-GAC fabricated by hydrolysis for 3 days at 2 M initial concentration of iron (III) chloride increased to 2.2% per dry adsorbent weight. A maximum of 4.4% per dry adsorbent weight was reached for 0.5M-3days Fe-GAC. (Figure 5). We see that iron content of the synthesized Fe-GAC increased with the increase in hydrolysis time irrespective of the initial $FeCl_3$ concentration.

The size and shape of particles obtained by aging of ferric salt solution at elevated temperatures depends strongly on ferric ion concentration. Increasing the iron(III) chloride concentration at the same temperature (100 ºC) and time (24 hr), resulted in 2 times increase in deposition of iron for 2M-24hr Fe-GAC compared to 0.5M-24hr Fe-GAC. Matijevic et al. (1978), showed a similar behavior when they demonstrated that larger hematite particles formed under prolonged duration of hydrolysis at higher concentration of iron (III) chloride.

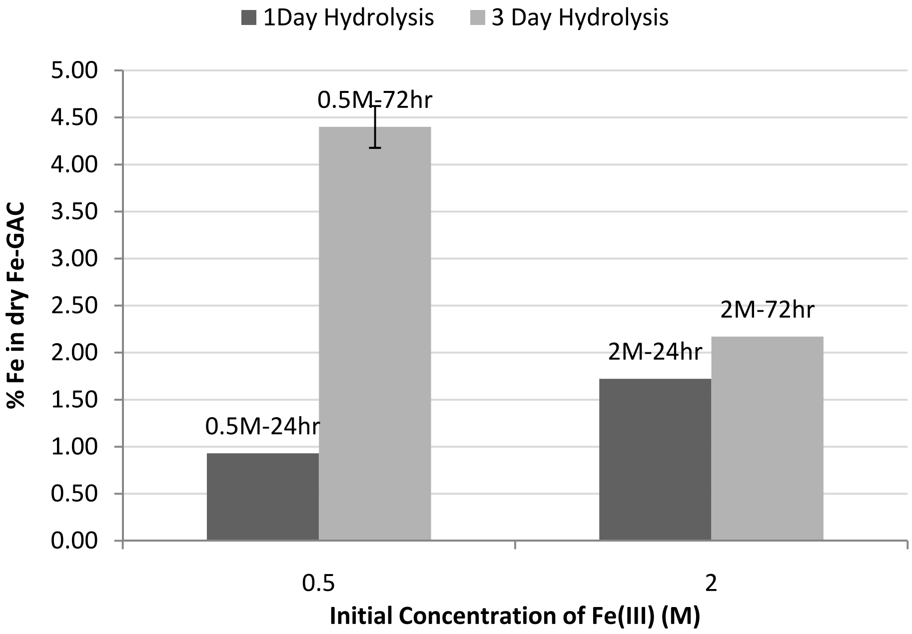

Figure 5. Iron content after acid digestion of Fe-GAC media. (percentage Fe per dry weight). Error bar represent upper and lower 95% confidence interval.

Hydrolysis is a process where sol/particle formation takes place slowly as they agglomerate and cling to each other around central nuclei. Therefore, an increase in hydrolysis time from 1 day to 3 days for 0.5 M iron(III) chloride resulted in an increase of concentration of iron in Fe-GAC media by a factor of ~5. A similar trend was seen for 2 M iron (III) chloride, although the iron loading increase is less compared to 0.5 M iron (III) chloride concentration. So, 0.5M-72hr media would be used if higher concentration of iron is needed. This reveals that time plays an important role in iron hydr(oxide) formation and longer hydrolysis time at lower concentration could yield better and less expensive Fe-

GAC media as less iron (III) chloride is being used for the generation of the media.

Surface area and pore size distribution.

Surface area of the adsorbent media plays an important role in the adsorption of arsenic by the media. Figure 7 shows the relationship between surface area and the iron content in virgin and fabricated Fe-GAC media. The surface area increased for 0.5M-24hr Fe-GAC confirming that iron deposition is taking place on the virgin GAC and indicating generation of new surface area. Further increase in concentration to 2 M showed a decrease in surface area. As previously explained, an increase in initial concentration of iron(III) chloride leads to the formation of large hematite particles which here are blocking the pores of the GAC resulting in lower surface area.

For 0.5M-72hr and 2M-72hr media with iron content of 4.4% and 2.2% respectively, the surface area is not significantly affected by the % Fe content. This is because the distribution pattern of iron deposition determines the surface area available. In the case of 0.5M-72hr Fe-GAC, even though surface area is decreasing slightly, we know that iron deposition (4.4%) is taking place which means that due to prolonged hydrolysis time (72hr) iron deposition has taken place in the pores of GAC and is well distributed.

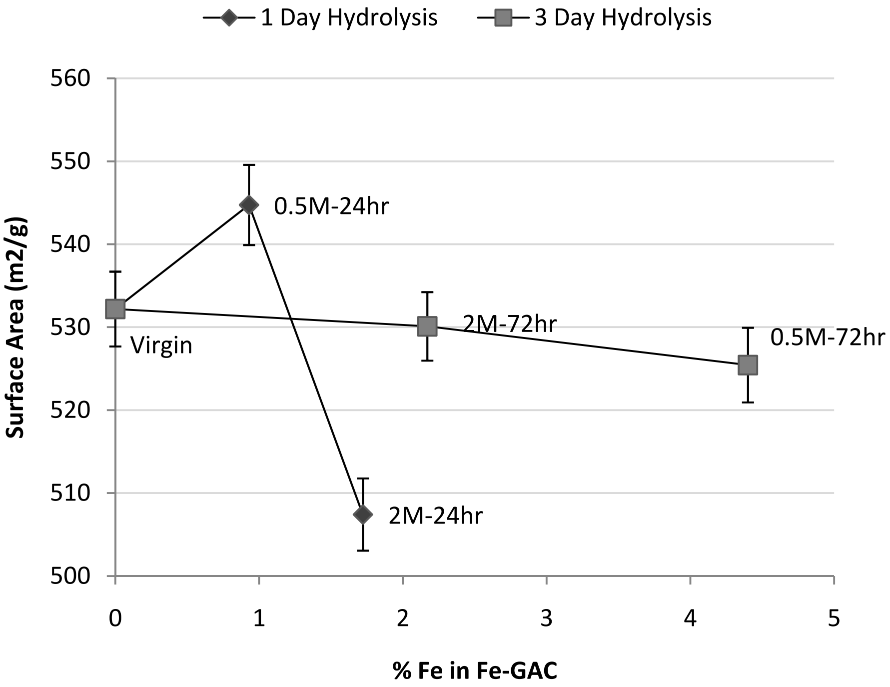

Figure 6: Relation between the surface area and percentage iron on Virgin and Fe-GAC. Error bars represent upper and lower 95% confidence intervals

Also, the pore size distribution analysis reveals that new pores/surface is generated in macroporous region for 0.5M-72hr media, but a significant decrease in pore volume is seen in microporous and mesoporous region due to saturation of media pores with iron deposition for the rest of the media which would mean large particles are blocking the pores.

Fe-GAC media at high ferric ion concentration (2 M) was hydrolyzed for a longer time (72 hrs) because of which large hematite particles deposit and block the pores of this Fe-GAC during the synthesis process as explained by Matijevic and co-workers (1978). The blocking of pores is confirmed by pore size distribution analysis which shows decrease in pore volume of this Fe-GAC compared to virgin GAC. This could further be explained by the dissolution effect.

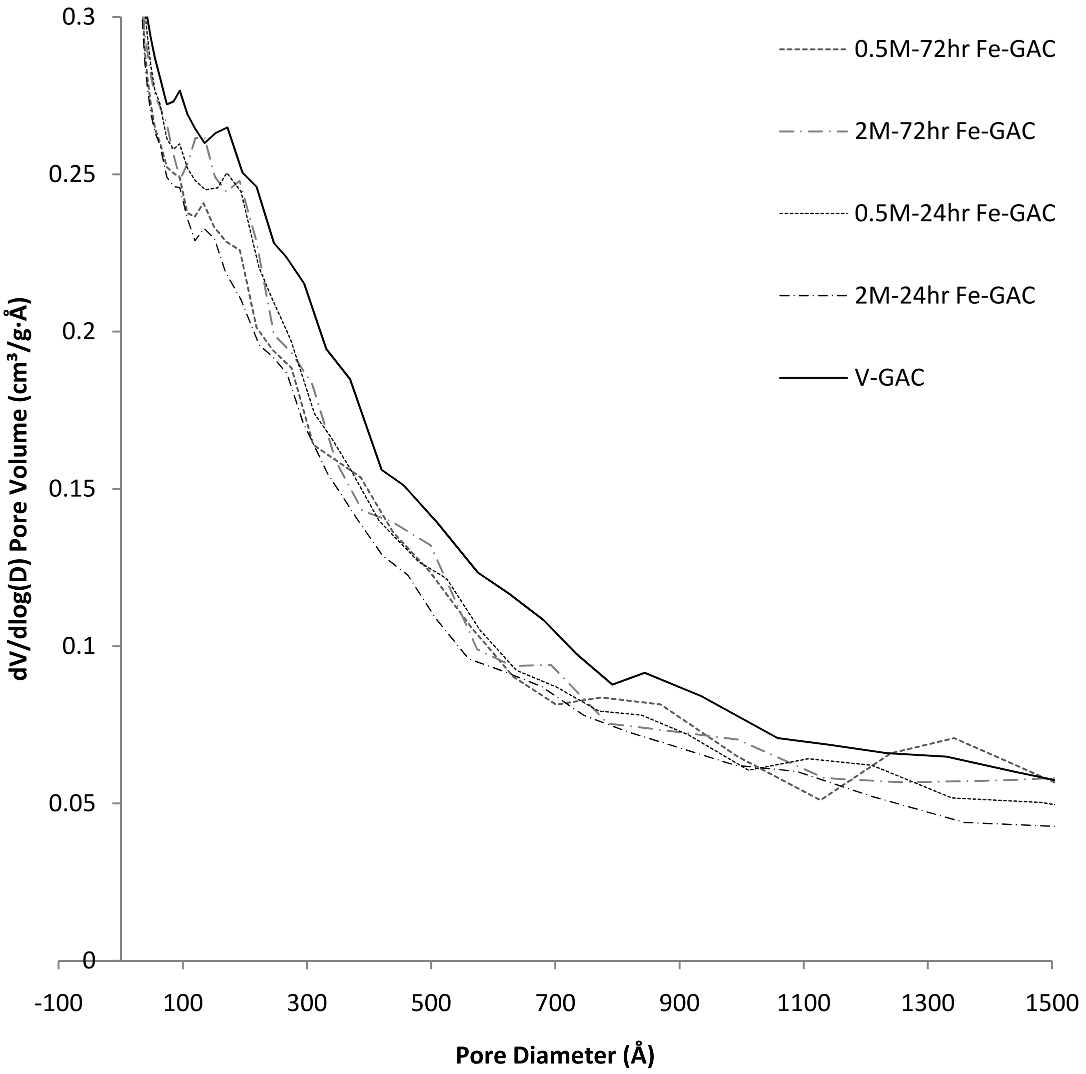

Figure 7. Pore size distribution in media before & after Fe impregnation

Matijevic and coworkers (1978) had clearly demonstrated that hydrolysis time along with other parameters like pH are crucial in hydrolysis of iron hydr(oxides). It is possible that with initial concentration of 2 M iron (III) chloride large particles are formed first and then decrease in iron loading occurs due to dissolution in the acidic environment. The dissolution process leading to decrease in iron loading could be explained by Equation 19.

$2Fe^{3+} + 3\ H_2O \Rightarrow Fe_2O_3 + 6H^+$ Equation 19.

Since, the media is hydrolyzed for a long time, after dissolution reprecipitation occurs, not leading to significant decrease in surface area as compared to virgin GAC.

Both surface area and iron content play an important role in determining arsenic removal performance of the media, surface area may contribute more to the sorbent's ability to perform better because most of the iron could be in the form of larger iron(hydr)oxide particles. Large iron(hydr)oxide particles have a smaller specific surface area per mass of iron which might not be able to adsorb as many contaminants as smaller ferric (hydr)oxide particles which would be more evenly distributed inside the Fe-GAC media.

Zeta potential.

The zeta potential analysis of each of the Fe-GAC and virgin media helped estimate the isoelectric point (IEP) for each media. Figure 8 and 9 show the relationship between the pH and the zeta potential at that particular pH.

The IEP for virgin media is at pH ~3.25. The IEP for 0.5M-24 hr, 2M-24 hr and 2M-72 hr Fe-GACs does not vary from the IEP of virgin media i.e. for Fe-GAC with iron deposition less than 2% there is no change in IEP. A lower isoelectric point could be because it is a lignite base GAC which are rich in oxidized surfaces and oxygen rich functional groups. For the 0.5M-72hr sample with iron deposition of ~4.4%, a change in IEP of ~5.2 was observed which was more than 2 pH units higher than other Fe-GAC media synthesized (Figure 9). This was expected, since, hematite has a high IEP of 8-8.9 (He, Wan & Tokunaga, 2007). Since the IEP defines the pH below which the particles are net positively charged and above which they are net negatively charged; this property is essential in considering the interactions of the media with other particles present in the surrounding environment. The negatively charged surface of GAC is counterbalanced by the positively charged surface of ferric (hydr)oxide due to increase in iron content. High IEP is a favorable characteristic helping in the removal of anions like arsenic as the electrostatic repulsive forces between the GAC surface and negatively charged particles is minimized in a pH range found ingroundwater. .

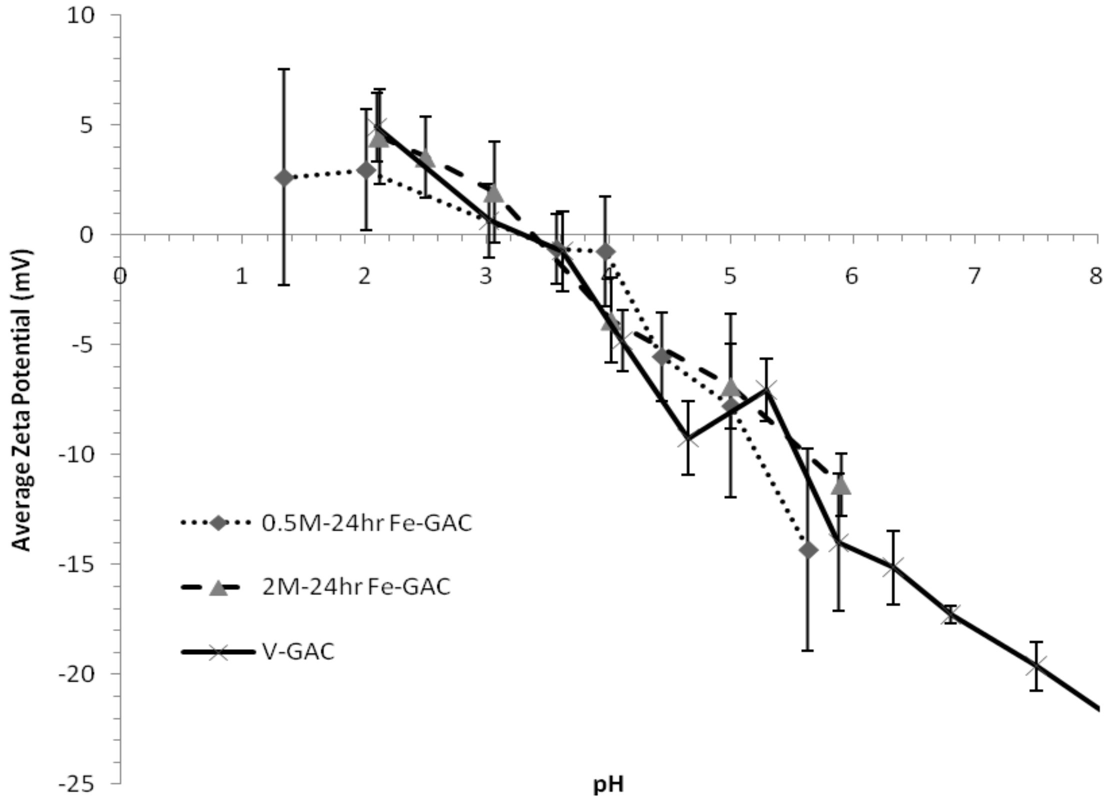

Figure 8. Variation of Zeta Potential over pH for 1 day Fe-GAC and Virgin media.

Error bars represent upper and lower 95% confidence intervals. Background solution-10mM KNO_3

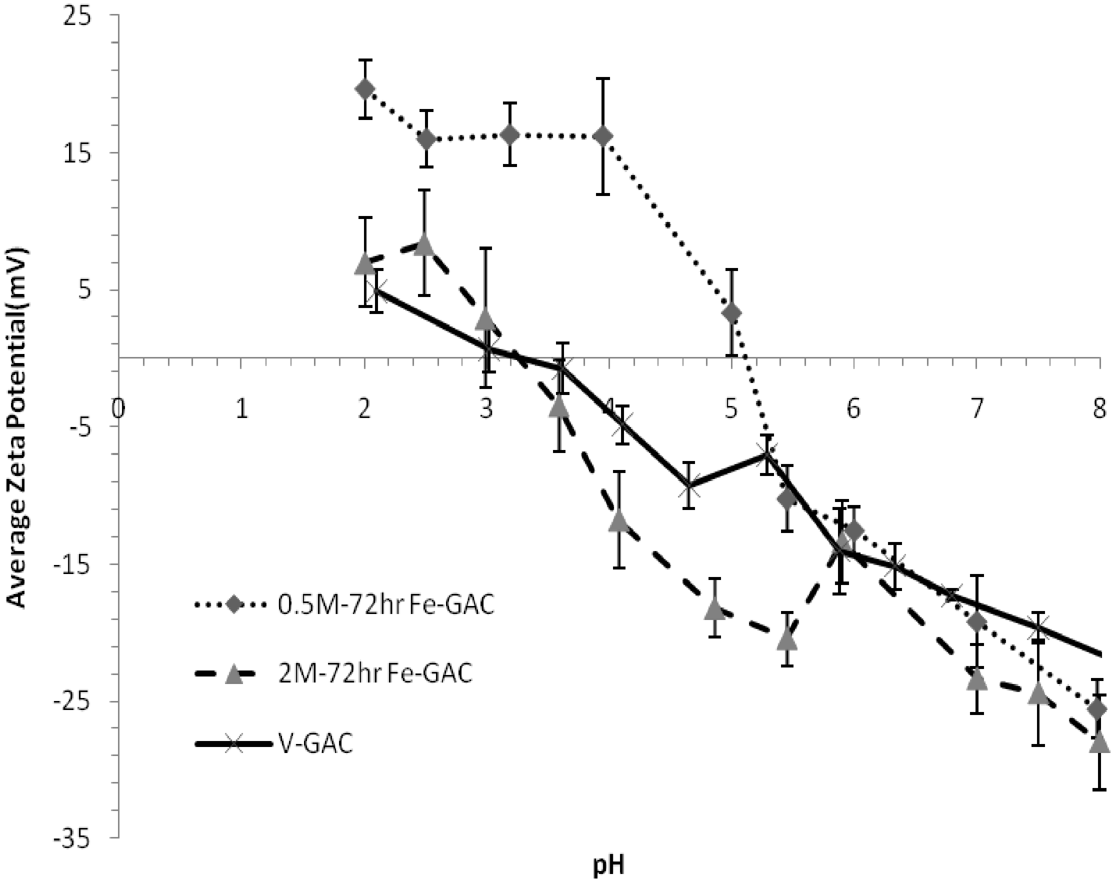

Figure 9. Variation of Zeta Potential over pH for 3 day Fe-GAC and virgin media.

Error bars represent upper and lower 95% confidence intervals. Background solution-10mM KNO_3

SEM/FIB imaging.

SEM was done to verify formation of nanoparticles on the surface of GAC and to study the effects of particle size and surface area available for adsorption. All images are attached in Appendix D. Figure 10 shows that nanoparticles are being formed, and they are coating the surface of GAC. The deposition of iron inside the pores of GAC can be seen in Figure 11. Formation of small nanoparticles as seen in Figure 12, helps to increase the surface area of the media. In Figure 13 we see the formation of larger particles which may be blocking some of the meso and the micropores which would result in a decrease in some of the original surface area. Thus the SEM images clearly show that though the nanoparticles are formed within the pores of GAC media the size of the particles formed play an important role in determining the surface area available. Formation of smaller particles helps to increase surface area where as larger particles reduce the surface area available for arsenic adsorption by blocking the pores.

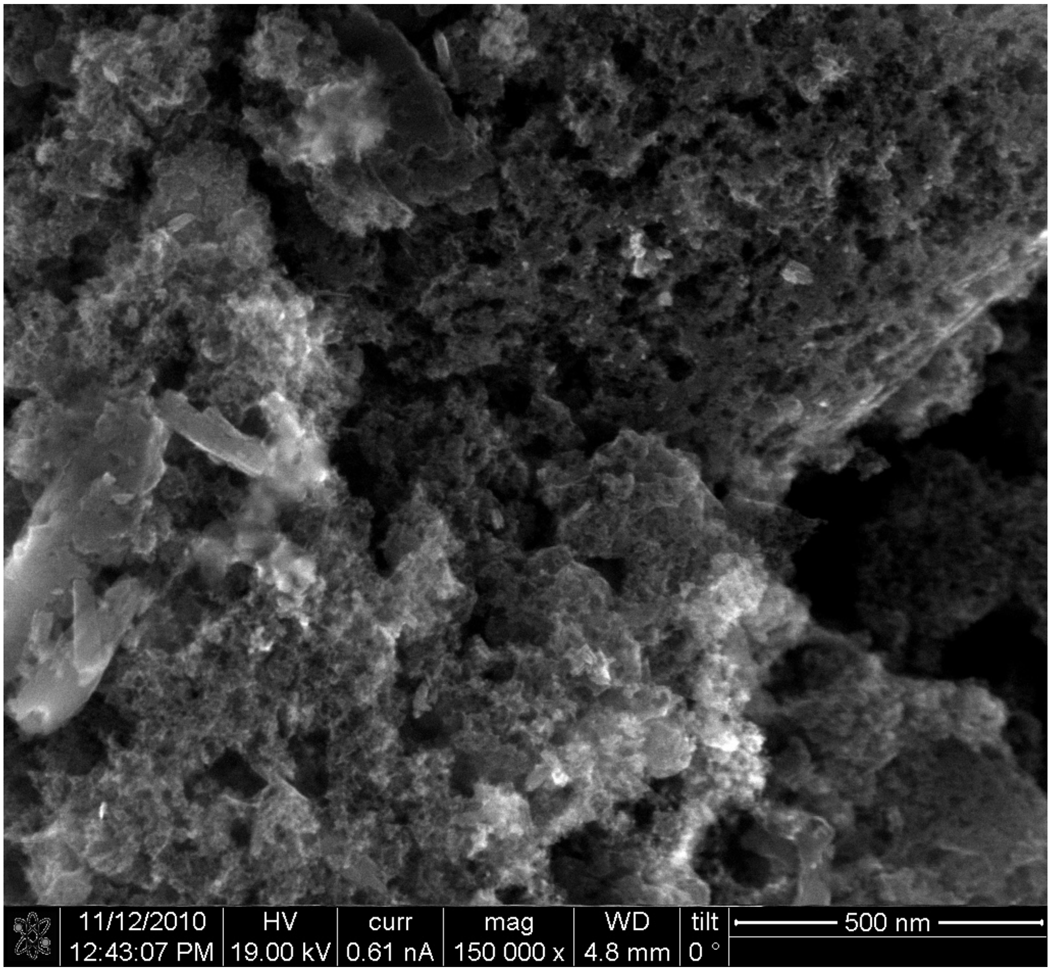

Figure 10. SEM image of 0.5 M-72hr Fe-GAC

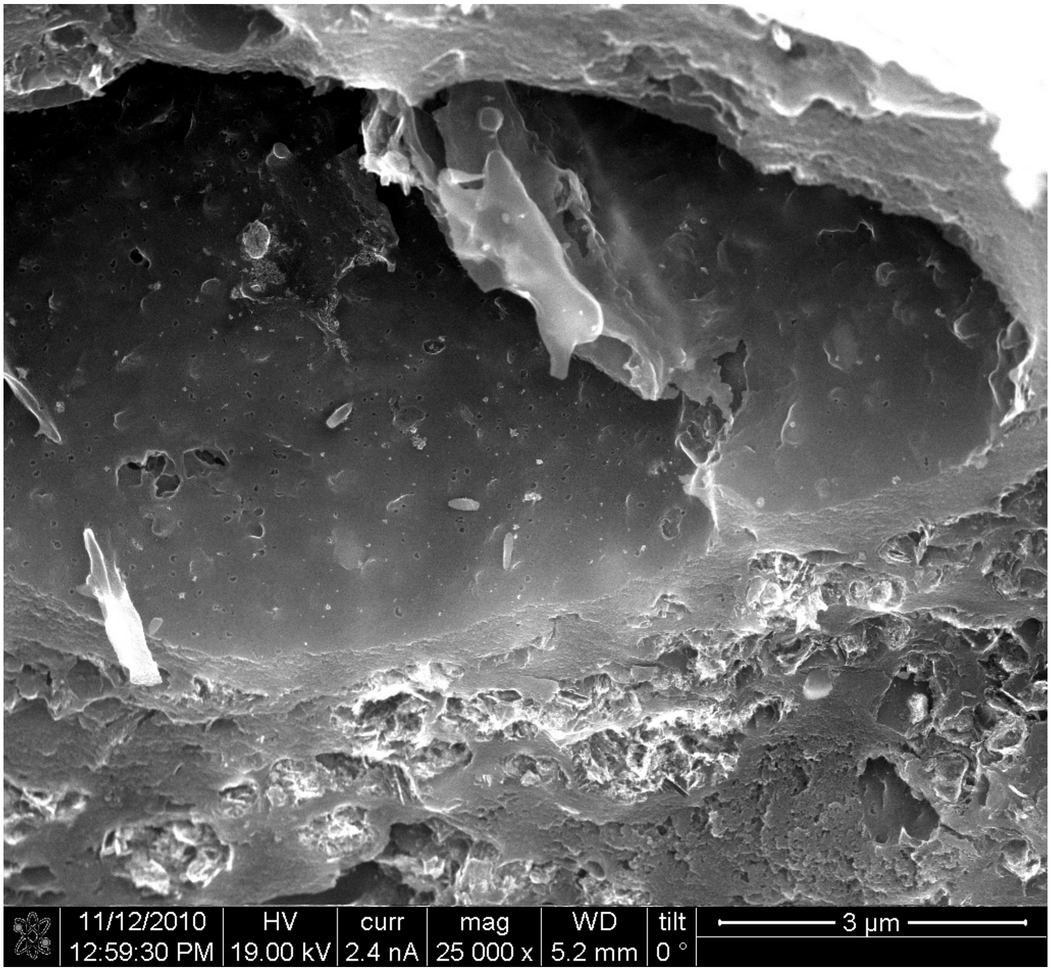

Figure 11. SEM image of 0.5 M-72hr Fe-GAC

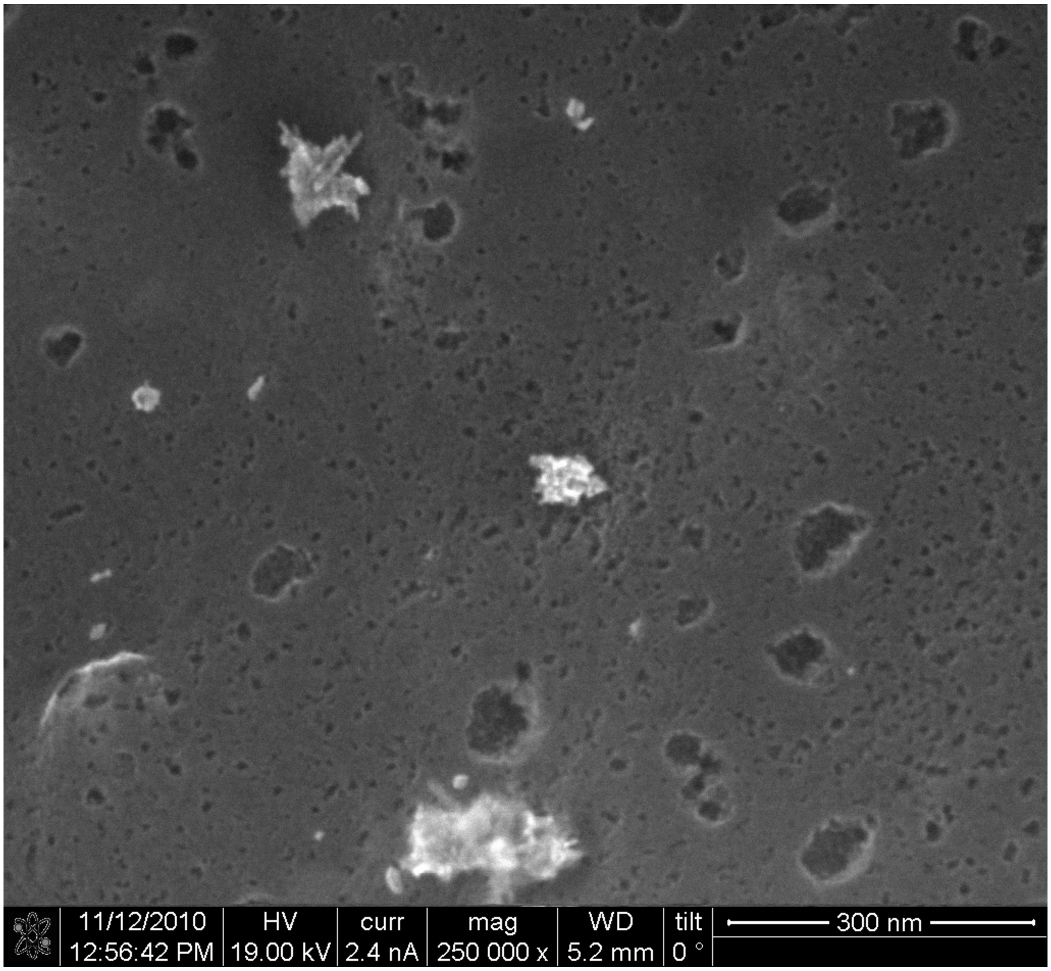

Figure 12. SEM image of 0.5 M-72hr Fe-GAC

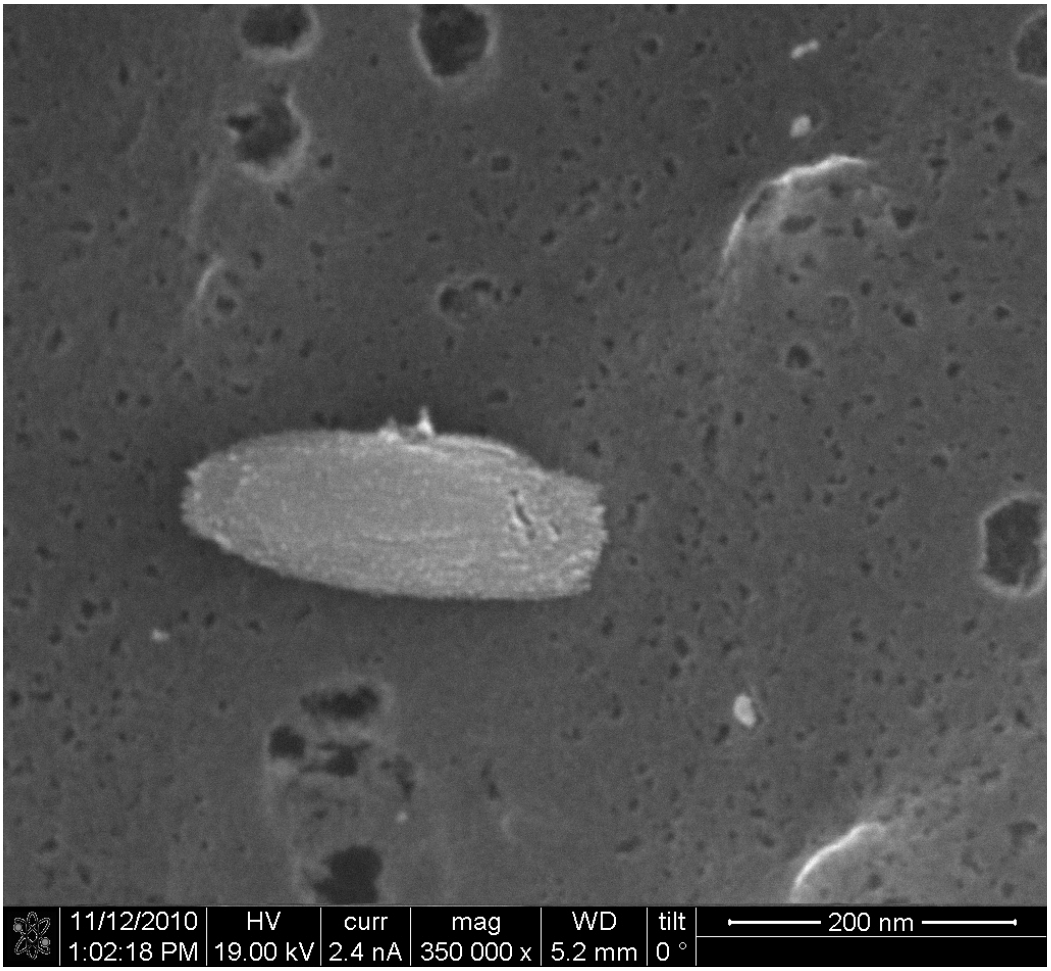

Figure 13. SEM image of 0.5 M-72hr Fe-GAC

Though the iron content for 0.5M-72hr media is significantly larger than the 0.5M-24hr media, it is due to the formation of larger hematite nanoparticles which block the micropores and the mesopores of the GAC ultimately resulting in the lower surface area available for adsorption. In 0.5M-24hr media small nanoparticles are being formed which are well distributed inside the pores of GAC. Small nanoparticle formation increases the surface area for this media which is an important characteristic for arsenic adsorption. The formation of large hematite particles could be the cause for the jump in the IEP for 0.5M-72hr media.

Thus, a significantly high IEP alone cannot be the indicator for the performance of the media. Though high iron content and high IEP are important indicators for a good adsorbing media the distribution of iron particles and surface area may be more important in determining the performance of the media. Large iron (hydr)oxide particles have small specific surface area per mass of iron which might not be able to adsorb as many contaminants as smaller ferric (hydr)oxide particles which would be more evenly distributed inside the Fe-GAC media.

Media Evaluation for Arsenic Adsorption

Arsenic adsorption isotherm experiments were conducted to study and compare the adsorption capacities between the media obtained in two water matrixes, 1 mM $NaHCO_3$ and the challenge groundwater. The experiments were conducted at pH value of 7.7±0.2, since most of the natural waters exhibit the pH values in this range. The adsorption capacity parameters (K) and Freundlich intensity parameters (1/n) for all fabricated media are given in Table 8. Freundlich intensity parameter (1/n) is an important parameter indicating the energy required for adsorption to occur suggesting favorable or unfavorable adsorption. Low 1/n values ($1/n<1$) indicate lower energy is required for adsorption to occur, possibly due to minimized electrostatic repulsion between the surface of the media and the negatively charged contaminant which indicates favorable adsorption. Fe-GAC media synthesized with 0.5 M iron(III) chloride solution when analyzed in model water without competing ions (1mM $NaHCO_3$ water matrix) exhibited a Freundlich intensity parameter (1/n) less than 1. This implies that less energy is required for arsenic to get adsorbed on the surface of the Fe-GAC hence arsenic would easily be pulled out of the groundwater. However, in challenge groundwater the Freundlich intensity parameter of GAC hydrolysed for 24 hrs with 0.5 M iron(III) chloride increased from 0.86 to 1.32. This indicates that higher energy is required to adsorb arsenic suggesting competition for adsorption sites by competing ions in model challenge groundwater. Competing ions like phosphate, silica, vanadium etc. can saturate the available adsorption sites resulting in unfavorable absorption of arsenic (Naeem et al., 2007; Meng at al., 2000). For 0.5M-72hr Fe-GAC the 1/n value is less than 1 (0.47) even in challenge groundwater due to high iron content of the media and high IEP (indicating increase in number of positively charged sites which would help in removal of arsenate, a negatively charged oxy-anion) suggesting this media should be able to perform well at low arsenic concentrations in ground water.

The 1/n values for Fe-GAC media synthesized with 2 M iron(III) chloride remained greater than 1 in both model water and challenge ground water indicating unfavorable adsorption. This indicates that higher energy is required to adsorb arsenic, suggesting that due to synthesis conditions (high initial concentration of ferric ion) 2M-24hr and 2M-72hr samples lead to larger iron particle deposition poorly distributed on the surface of GAC. The surface area created by iron deposition was inaccessible to arsenic, hence less surface area is available for adsorption of arsenic resulting in unfavourable adsorption. But these media may perform well in water matrixes in which arsenic concentration is comparatively high.

Table 8.

Adsorption capacity parameters (K) and Freundlich adsorption intensity parameters (1/n) for fabricated Fe-GAC media in two model water matrixes

	% Fe in	1mM $NaHCO_3$ Matrix				Challenge Groundwater			
Sample ID	Fe-GAC	K	K*	1/n	R^2	K	K*	1/n	R^2
0.5M-24hr	0.93	2.53	272.04	0.86	0.82	0.23	24.73	1.32	0.94
2M-24hr	1.72	1.85	107.55	1.10	0.95	0.28	16.28	1.11	0.91
0.5M-72hr	4.4	6.83	155.23	0.65	0.94	7.97	181.14	0.47	0.97
2M-72hr	2.17	2.42	111.43	1.11	0.97	0.11	5.06	1.48	0.9

Contact time= 3 days; initial As(V) concentration~ 120ug/L

$$K = \frac{\mu As/g_{Dry\ Fe-GAC}}{(\mu As/L)^{1/n}}$$

$$K* = \frac{\mu As/g_{Fe}}{(\mu As/L)^{1/n}}$$

It is clear from the table 8 that as the Freundlich intensity parameter increases, the adsorption capacity parameter per gram of Fe-GAC decreases for the Fe-GAC media synthesized. That means if less energy is required for arsenic to bind with iron on the media and/or more adsorption sites are available, more arsenic is sorbed and better the media performs. This observation supports our argument above and that distribution of iron plays an important role in media performance as an adsorber.

When comparing the arsenic adsorption capacity of the Fe-GAC in 1mM $NaHCO_3$ model water and challenge groundwater Figure 14 and 15 in conjunction with Table 8 clearly show that arsenic adsorption capacity of the Fe-GAC is significantly reduced in the challenge groundwater as compared to the 1 mM $NaHCO_3$ model water. The decrease in adsorption capacity with change in water matrix to that of challenge groundwater was expected due to competition of arsenate with other negatively charged ions like phosphorus, silica, vanadium etc. in the model groundwater, which is representative of the natural waters found in the Arizona Mexico border region. It has been shown that adsorption of silica on Fe-GAC increases the electrostatic repulsion for the arsenic anions and reduces the concentration of the surface sites available for arsenic (Meng et al, 2000). Studies have shown that phosphate and molybdate also compete strongly with arsenic along with silicate for sorption sites. (Meng et al, 2000; Su & Puls, 2001, Katsoyiannis & Zouboulis, 2002).

Further, the K and K* for 0.5M-72hr Fe-GAC does not decrease with change in test water even in presence of competing ions suggests that there are enough binding sites for arsenic even in the presence of competing ions. It is also important to recall that the same iron GAC has the highest iron content and due to increase in pore volume, number of sites available for arsenic to attach has increased, possibly leading to bidentate ligand formation rather than monodentate making it favorable for arsenic to bind to iron.

This clearly shows that synthesis of media under controlled conditions like hydrolysis time at elevated temperature on a macroporous base medium governs the iron distribution and surface area available; ultimately affect the performance of the media (metal hydroxide) in removing inorganic contaminants from groundwater.

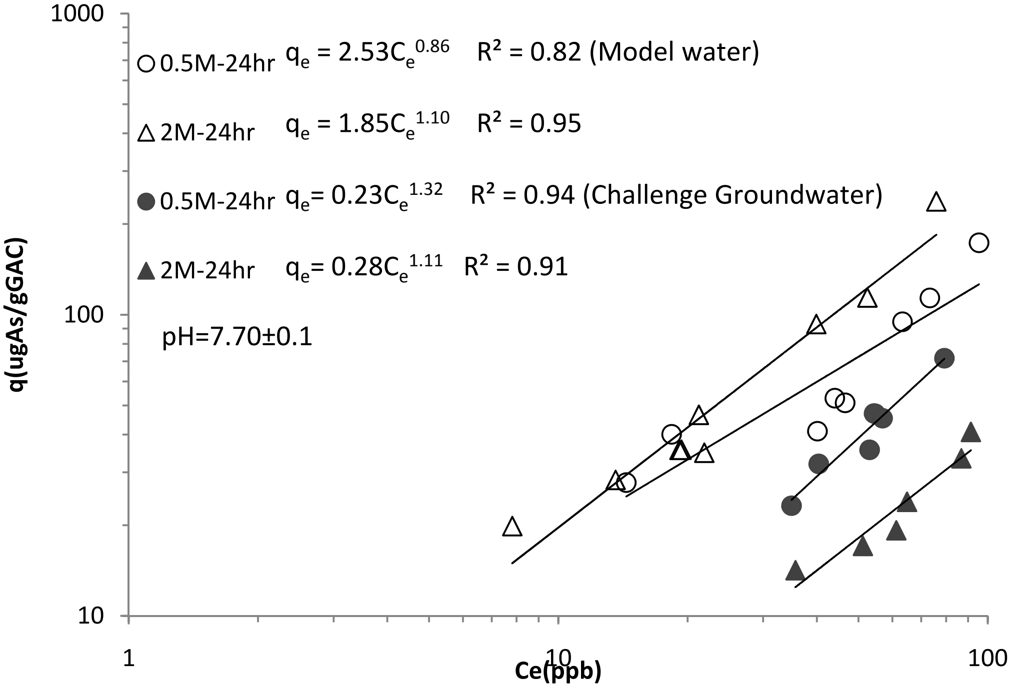

Figure 14. Arsenic adsorption isotherms for 1 day Fe-GAC in 1mM $NaHCO_3$ buffered nanopure water (Initial arsenic conc. ~120ug/L) and challenge groundwater matrices (Contact time= 3 Days).

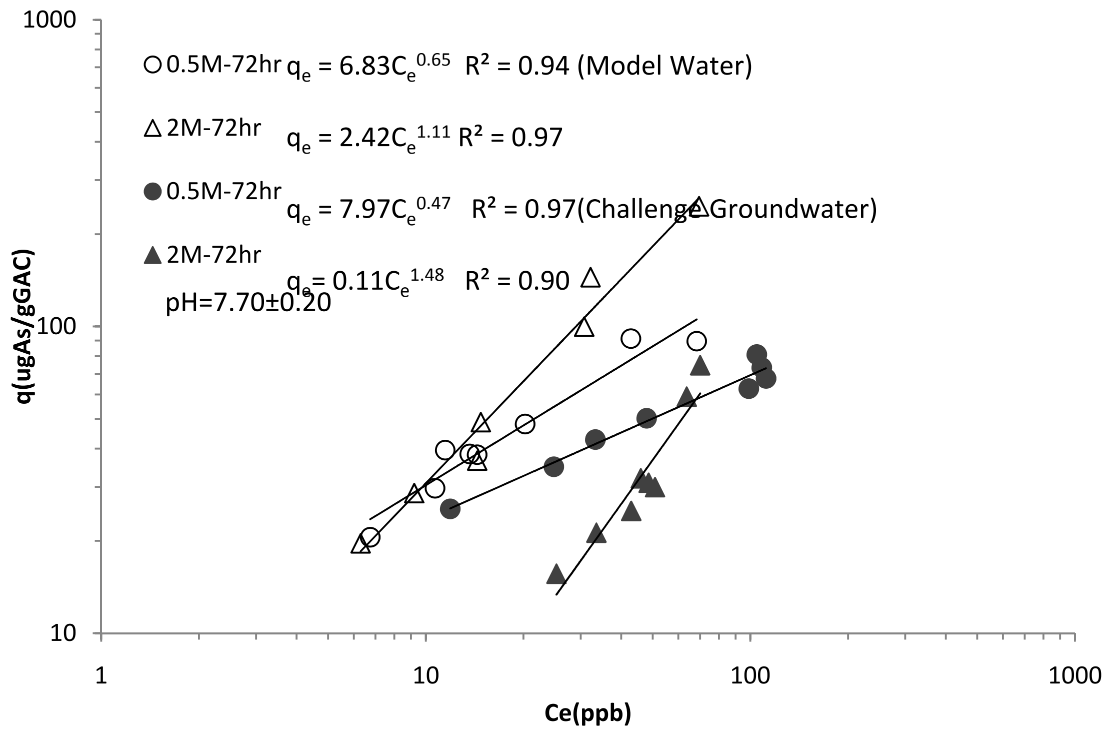

Figure15. Arsenic adsorption isotherms for 3 day Fe-GAC in 1mM NaHCO$_3$ buffered nanopure water (Initial arsenic conc. ~120ug/L) and challenge groundwater matrices (Contact time= 3 Days).

Table 9 shows the maximum adsorption capacities for fabricated Fe-GAC's in challenge groundwater under equilibrium (q_o) and continuous flow conditions ($q_{\text{max column}}$). Breakthrough curves were obtained by the continuous adsorption experiment (SBA test) using all media synthesized as the adsorbent (Appendix F). It is observed that the maximum adsorption capacity under continuous flow conditions decreases ~2 to ~4.5 times as compared to equilibrium conditions for same initial concentration of arsenic in the challenge groundwater. This suggests that mass transport has an effect on contaminants competition for the available adsorption sites. Available literature shows that contaminant species with higher liquid diffusivity (D_l) exhibit lower film and intraparticle resistance. Because of high diffusivity they can diffuse much faster inside the pores of the particle than arsenate. This allows them to reach unoccupied adsorption sites before the arsenic does; making it difficult for arsenic to be adsorbed on the surface of Fe-GAC (Sontheimer et al., 1998). This effect is favorable for oxo-anions with higher liquid diffusivities than arsenate ($D_{l\text{–Arsenate}} \approx 0.905 \text{ x } 10^{-5}$ cm^2/s), such as silica ($D_{l\text{–Silica}} \approx 1.170 \text{ x } 10^{-5}$ cm^2/s), phosphate ($_{\text{Dihydrogen phosphate}} \approx$ $0.959 \text{ x } 10^{-5}$ cm^2/s), or selenate ($D_{l\text{–Selenate}} \approx 1.008 \text{ x } 10^{-5}$ cm^2/s) (Rebrenau et al., 2008; Lide, 2006). Considering that these oxo-anions also form strong inner-sphere complexes, it is very difficult for arsenate to displace them once they adsorb onto the metal (hydr)oxide surfaces. This competetion effect eventually results in reduction of adsorption capacity for arsenic, which was shown by the lower $q_{\text{max-column}}$ values.

Table 9.

Maximum adsorption capacity for Fe-GAC's in challenge groundwater under equilibrium and continuous flow conditions.

Sample ID	Co (μg/L)	q_0 (μg As/g Fe-GAC)	q^*_0(mgAs/g Fe)	$q_{\text{max column}}$ (μg As/g Fe-GAC)	$q^*_{\text{max column}}$ (mgAs/g Fe)
0.5M-24hr	130	141.9	15.26	77.4	8.33
2M-24hr	130	62.17	3.61	19.35	1.12
0.5M-72hr	130	78.5	1.78	29.57	0.64
2M-72hr	130	147.9	6.82	25.08	1.16

** Additional data and breakthrough curves on column tests in continuous flow system are attached in Appendix F

Table 10.

Maximum adsorption capacity for Fe-GAC's in 1mM $NaHCO_3$ model water under equilibrium conditions.

Sample ID	% Fe in Fe-GAC	1mM $NaHCO_3$ Matrix		
		Co	qo (ugAs/g Fe-GAC)	qo* (mgAs/g Fe)
0.5M-24hr	0.93	130	166.38	17.89
2M-24hr	1.72	130	391.30	22.749
0.5M-72hr	4.4	130	161.62	34.906
2M-72hr	2.17	130	537.39	24.764

Table 9 also summarizes the maximum equilibrium adsorption capacities (q_0) per gram of Fe-GAC and on basis of metal content that were estimated from the isotherm data at C_0 = 130 µg As/L in model challenge groundwater matrix. In model water matrix without competing ions, the Fe-GAC media synthesized with 2.0 M $FeCl_3$ had slightly higher adsorption capacity than the Fe-GAC media synthesized via 24 hour hydrolysis with 0.5 M $FeCl_3$ (Table 10). However, in the model challenge groundwater, the 0.5M-24 hr Fe-GAC media exhibited similar maximum arsenic adsorption capacity (ugAs/g Fe-GAC) as the media obtained by 72 hour hydrolysis with 2.0 M $FeCl_3$. These two media exhibited highest specific surface areas suggesting that specific surface areas may be the most critical factor when fabricating media to remove arsenic from the waters present in the Arizona-Mexico border region. Further, when compared on the basis of metal content in the model challenge groundwater matrix, the 0.5M-24hr Fe-GAC media performed two times better than 2M-72hr Fe-GAC. The 0.5M-24hr Fe-GAC media removed ~ 15.3 mg As/g Fe, while the second ranking Fe-GAC media, synthesized by 72 hour hydrolysis with 2.0 M $FeCl_3$, removed ~ 7 mg As/g Fe, suggesting that the higher specific surface area is the essential factor contributing to the high arsenic removal capacity in water matrices with competing ions such as the model Mexican groundwater matrix.

Table 9 also summarizes the continuous flow maximum adsorption capacities ($q_{\text{max-column}}$) for all Fe-GAC media. The Fe-GAC synthesized by 24 hour hydrolysis with 0.5 M $FeCl_3$ exhibited maximum adsorption capacity of ~77 µg As/gFe-GAC and ~ 8.3 mg As/g Fe, which was more than 2.5 times and 5 times greater than the rest of the media respectively. When compared with arsenic sorbents studies by other researchers the best performing Fe-GAC media (0.5M-24hr) exhibited better arsenic removal capacities. Amy et al. (2004) and Westerhoff et al. (2005) have extensively studied commercially available commercially available adsorbents for arsenic removal. They have reported adsorption capacities in the range of ~ 2.5 to 3.5 mg As/g Fe.

The findings of the study clearly suggest that 0.5M-24hr Fe-GAC is the best performing media in challenge groundwater. Also, we can conclude that surface area is a key factor for adsorption of arsenic when the Fe-GAC media is modified with hematite nanoparticles and not always high iron content is important for determining the performance of the media.

Chapter 5

CONCLUSIONS & RECOMMENDATIONS

Successful generation of ferric (hydr)oxide particles by hydrolysis of iron salts solutions by Matijevic and his co-workers (1978); and research demonstrating arsenic and organic co-contaminant removal by use of metal (hydr)oxide modified activated carbon, led to the study that hematite impregnated granular activated carbon (Fe-GAC) could be synthesized by hydrolysis of Fe(III) on GAC. Characterization of the Fe-GAC media revealed that the iron content of the synthesized Fe-GAC media increased with increase in hydrolysis time regardless of the initial ferric chloride concentrations. However, this increase in iron content was greater for the 0.5 M hydrolysis conditions. Prolonged hydrolysis at lower concentrations and longer hydrolysis times could yield better and less expensive Fe-GAC media because lower amounts of ferric salts would be needed for the fabrication of this type of media. The GAC hydrolyzed with 0.5M initial concentration of iron (III) chloride for 3 days gave the highest iron loading of ~4.4% and highest isoelectric point of ~5.3 as compared to other media fabricated.

The adsorption capacity for all media synthesized decreased significantly in model challenge groundwater due to competition with other oxo-anions for adsorption sites. Despite high iron content, 0.5M-72hr Fe-GAC fails to perform as the best media for arsenic removal at initial arsenic concentration of ~130 µg/L under continuous flow conditions, as seen by conducting Short Bed Adsorber (SBA) column tests. This tells us that high iron content is not necessary for effective removal of arsenate from groundwater. Findings suggest that high surface area and iron distribution are critical factors in determining performance of the media (arsenic removal capacity) in water matrixes with competing ions like the challenge groundwater.

It can be concluded based on the findings of this study that hematite impregnated granular activated carbon (Fe-GAC) can be synthesized by hydrolysis of Fe(III) to remove arsenic from groundwater. However, it was beyond the scope of the study to evaluate removal of organic contaminants, which can be found along with arsenic in groundwater and whether the simultaneous removal of both the contaminants affects the arsenic removal capacity of the hybrid media. It would also be interesting to study the arsenic removal capacity of the synthesized Fe-GAC for pH values other than the range examined in the study. It is also important to study if the spent Fe-GAC can be successfully regenerated and how efficient it is in removing arsenic from the contaminated groundwater. It might be of interest from industrial standpoint to study if regeneration of the spent media is a cost effective option or production of new media.

REFERENCES

Acharyya, S.K. & Shah, B. A. (2004). Risk of arsenic contamination in groundwater affecting Ganga Alluvial Plain, India? . *Environment Health Perspective, 112*, 19-20.

Acharyya, S.K. (2005). Arsenic levels in groundwater from quaternary alluvium in the Ganga plain and the Bengal basin, Indian subcontinent: insights into influence of stratigraphy. *Gondwana Research, 8 (1*), 55-66.

Acharyya, S.K., Chakraborty, P., Lahiri, S., Raymahashay, B. C., Guha, S. & Bhaowmik, A. (1999). Arsenic poisoning in the Ganges Delta. *Nature., 401*, 545.

Acharyya, S.K., Lahiri, S., Raymahashay, B. C., & Bhowmik, A. (2000). Arsenic toxicity in groundwater in parts of Bengal Basin in India and Bangladesh: role of Qauternary stratigraphy and Holocene sea-level fluctuation. *Env. Geol., 39*, 1127-1137.

Agency for Toxic Substances and Disease Registry.(2007). Arsenic. Retrieved from www.atsdr.cdc.gov

Ahmed, K. M., Bhattacharya, P., Hasan, M. A., Akhtar, S. M., Alam, S. M. M., Bhuyian, M. A. H., … Sracek, O. (2004). Arsenic enrichment in groundwater of the alluvial aquifers in Bangladesh: an overview. *Applied Geochemistry, 19*, 181-200. doi:10.1016/j.apgeochem.2003.09.006.

Ali, A., & Gupta, V. K. (2006). Advances in water treatment by adsorption technology. *Nature Protocols, 1(6),* 2661- 2667. doi:10.1038/nprot.2006.370

Aposhian, H. V., & Aposhian, M. M. (2006). Arsenic Toxicology: Five Questions. *Chemical Research in Toxicology, 19*(1), 1-15. doi: 10.1021/tx050106d

Aragon, A. (n.d.). Rapid small-scale column tests in support of the arsenic water technology partnership's – pilot demonstration project. Retrieved from http://www.sandia.gov/water/docs/AragonACS-1-24-06.pdf

Aragon, A.,Thomson, B., & Chwirka, J. (2002). *Rapid Small-Scale Column Testing for Arsenic Adsorption media*. Retrieved from http://ipec.utulsa.edu/Conf2002/aragon_thomson_chwirka_50.pdf

AWWA Research Foundation (2007). *Advancing the science of water: AwwaRF and Membrane processes*. Retrieved from http://www.waterrf.org/Research/ResearchTopics/StateOfTheScienceReports/MembranesResearch.pdf

AWWA WQTC62547 (2005) - *RSSCT: A Quick Tool for Arsenic Treatment Technology Verification When Time is Running Short for Compliance*. Retrieved from http://www.industrycodes.com/products/10fc53/awwa-wqtc62547-rssct-quick-tool-arsenic-treatment

Badruzzaman, M. (2005). *Mass transport scaling and the role of silica on arsenic adsorption onto porous iron oxide (hydroxide)*. Dissertation work at Arizona State University.

Badruzzaman, M., Westerhoff, P. K. & Knappe, D. R. U. (2004). Intraparticle diffusion and adsorption of arsenate onto granular ferric hydroxide (GFH). *Water Research*, *38*(18), 4002-4012.

Barakat, M.A., Ismat-Shah, S. (2010).Utilization of anion exchange resin Spectra/Gel for separation of arsenic from water. *Arabian Journal of Chemistry.* doi:10.1016/j.arabjc.2010.10.011

Baruth, E.E. (2005) American Water Works Association, and American Society of Civil Engineers. Water Treatment Plant Design. Fourth ed. New York: McGraw-Hill Handbooks.

Brett, C.M.A. & Brett, A.M.O. (1994). *Electrochemistry : Principles, Methods and Applications* (reprint). New York: Oxford University Press.

Cameron Carbon Incoporated (2006). *Activated Carbon: Manufacture, structure and properties*. Retrieved from http://www.cameroncarbon.com/documents/carbon_structure.pdf

Carter, M. C., & Weber, W. J. (1994). Modeling adsorption of TCE by activated carbon preloaded by background organic matter. *Environmental Science and Technology, 28* (4), 614-623. doi: 10.1021/es00053a013

Chakraborti, D., Mukherjee, S.C., Pati, S., Sengupta, M. K., Rahman, M. M., Chowdhury, U. K., … Basu, G. K. (2003). Arsenic groundwater contamination in middle Ganga plain, Bihar, India: A future danger?. *Environmental Health Prospectives, 111 (9),* 1194-1201.

Chauhan, V. S., Nickson, R.T., Chauhan, D., Iyengar, L., & Sankararamakrishnan, N. (2009). Groundwater geochemistry of Bhallia district, Uttar Pradesh, India and mechanism of arsenic release. *Chemosphere, 75*, 83-91. doi: 10.1016/j.chemosphere.2008.11.065

Chen, W., Parette, R., Sheehan, W., Cannon, F. S., Dempsey, B.A. (2010). *Arsenic removal with Iron-tailored activated carbon plus zero-valent iron*. Retrived from http://www.waterrf.org/ProjectsReports/PublicReportLibrary/4158.pdf

Chen, W., Parette, R., Zou, J., Cannon, F. S. & Dempsey, B.A. (2007). Arsenic removal by iron-modified activated carbon. *Water Research*, *41,* 1851-1858.

Choong, T. S. Y., Chuah, T. G., Robiah, Y., Koay, F. L. G., & Azni, I. (2007). Arsenic toxicity, health hazards and removal techniques from water: an overview. *Desalination, 217*, 139-166. doi: 10.1016/j.desal.2007.01.015.

Column Testing for Arsenic Adsorption Media. Proc., 9th Annual International Petroleum Environmental Conference, Albuquerque, NM, October 2002.

Cooper, A.M., Hristovski, K.D., Moller, T., Westerhoff, P., & Sylvester, P. (2010). The effect of carbon type on arsenic and tricholoroethylene removal capabilities of iron (hydr)oxide nanoparticle-impregnated activated carbons. *Journal of Hazardous Materials, 183*, 381-388.

Crittenden, J. C., Trussell, R. R., Hand, D. W., Howe, K. J., & Tchobanoglous, G. (2005). *Water treatment: Principles and practice* (2nd ed.). Hoboken, NJ: John Wiley and Sons.

Crittenden, J.C., Berrigan, J.K., & Hand, D.W. (1986). Design of rapid fixed-bed adsorption tests for constant diffusivities. *Journal of Water Pollution Control Federation, 58* (4), 243- 259.

Crittenden, J.C., Berrigan, J.K., Hand, D.W., & Lykins, B. (1987). Design of rapid fixed-bed adsorption tests for nonconstant diffusivities. *Journal of Environmental Engineering, 113* (2), 243- 259.

Crittenden, J.C., Reddy, P.S., Arora, H., Trynoski, J., Hand, D.W., Perram, D.L., & Summers, R.S. (1991). Predicting GAC performance with rapid small-scale column tests. *Journal AWWA Research and Technology,* 77-87.

Cundy, A.B., Hopkinson, L. & Whitby, R. L.D. (2008). Use of iron-based technologies in contaminated land and groundwater remediation: A review. Science of the total *Total Environment, 400,* 42-51. doi: 10.1016/j.scitotenv.2008.07.002.

De Wolff, F. A., & Edelbroek, P. M. (1994). Neurotoxicity of arsenic and its compounds. *Handbook Clin. Neurol, 20,* 283-291.

Deliyanni, E. A. & Peleka, E. N. (2001). Nanohybrid anionic surfactant-akaganeite: preparation, structural analysis & cation sorption. *International Journal of Environmental Technology & Management, 12 (2-4)*, 369-380.

Deliyanni, E. A., Peleka, E. N., & Matis, K.A. (2009). Modelling the sorption of metal ions from aqueous solution by iron-based adsorbents. *Journal of Hazardous Materials, 172 (2-3)*, 550-558. doi: 10.1016/j.hazmat.2009.07.130

Dennis, R. (2006). *Testing Method Enables Rapid Scale-up for Arsenic Treatment Systems*. Retrieved from <www.severntrentservices.com/enews/vol12/arsenic.html>

Dilda, P. J., & Hogg, P. J. (2007). Arsenical-based cancer drugs. *Cancer Treatment Reviews, 33,* 542-564. doi:10.1016/j.ctrv.2007.05.001
doi: 10.1016/j.jhazmat.2010.07.036
doi:10.1016/j.scitotenv.2008.02.021

Dong, L.J., Zinin, P. V., Cowen, J.P., & Ming , L.C. (2009). Iron coated pottery granules for arsenic removal from drinking water. *Journal of hazardous material, 168*, 626-632.

Driehaus, W., Jekel M. & Hildebrandt, U. (1998). Granular ferric hydroxide – a new adsorbent for the removal of arsenic from natural water. *J. Water Supply: Res. Technol.–AQUA, 47* (1998) 30–35.

Dubey, S. P., Gopal, K., & Bersillon, J.L. (2009). Utility of adsorbents in the purification of drinking water: A review of characterization, efficiency and safety evaluation of various adsorbents. *Journal of Environmental Biology, 30 (3),* 327-332.

Dukhin, A. (2010). *Zeta Potential*. Retrieved from www.scitopics.com/zeta_potential.html

Eckenfelder,W.W., Ford, D., & Englande, A.J. (2009). *Adsorption*. Industrial Water Quality. New York: McGraw-Hill. Retrieved from www.knovel.com

Environment Technology Verification Program. (2001). *Reverse Osmosis membrane filtration used in packaged drinking water treatment systems*. Retrieved from http://www.membranes.com

Evens, A. M., Tallman, M. S., & Gartenhaus, R. B. (2004). The potential of arsenic trioxide in the treatment of malignant diseases: past, present and future. *Leukemia Research, 28*, 891-900. doi:10.1016/j.leukres.2004.01.011

Ferguson, J. F. & Gavis, J. (1972). A review of the arsenic cycle in natural waters. *Water Research, 6*, 1259-1274.

Focazio, M. J., Kolpin, D. W., Barnes, K. K., Furlong, E. T., Meyer, M. T., Zaugg, S. D., Barber, L. B., & Thurman, M. E. (2008). A national Reconnaissance for pharmaceuticals and other organic waste water contaminants in the United States- II) Untreated drinking water sources. *Science of the total Environment, 402*(2-3), 201-216.

Fuller, C.C., Davis, J. A., Waychunas, G.A., 1993. Surface chemistry of ferrihydrite: Part 2. Kinetics of arsenate adsorption and coprecipitation. *Geochimica et Cosmochimica Acta, 57*, 2271-2282.

Gang, D. D., Deng, B., & Lin, L. (2010). As(III) removal using an iron-impregnated chitosan sorbent. *Journal of Hazardous Materials, 182*, 156-161. doi: 10.1016/j.jhazmat.2010.06.008

Garelick, H., Dybowska, A., Eugenia, V. –J., & Priest, N. D. (2005). Remedial technologies for arsenic contaminated drinking waters. *Journal of Soils and Sediments, 5(3),* 182-190.

Gebel, T. (2000). Confounding variables in the environment toxicology of arsenic. *Toxicology, 144,* 155-162.

Goldberg, S. (1995). Adsorption Models incorporated into chemical equilibrium models. *Chemical Equilibrium and Reaction Models, SSSA, 42,* 75-95.

Goldsmith, J. R., Deane, M., Thome, J. & Gentry, G. (1972). Evaluation of health implications of elevated arsenic in well water. *Water Research, 6,* 1133-1136.

Groot, W., Sarkhel, S., & Hobbes, M. (2007). *Delivery of Subterranean Arsenic removal in West Bengal*. Report in the framework of the TIPOT project sponsored by EU. Retrieved from https://openaccess.leidenuniv.nl/bitstream/1887/12294/1/cml+report+176_delivery_subterranean_arsenic_removal_West_Bengal.pdf

Grossl, P. R., Eick, M., Sparks, D. L., Goldberg, S., & Ainworth, C. C.(1997). Arsenate and chromate retension mechanisms on goethite – Kinetic evaluation using a pressure-jump relaxation technique. *Environmental Science and Technology, 31* (2). 321-326.

He, Y. T., Wan, J., & Tokunaga, T. (2007). Kinetic stability of hematite nanoparticles: the effect of particle sizes. *Journal of nanoparticle research.* doi: 10.1007/s11051-007-9255-1

Heurtault. B., Schuber,F., & Frisch, B. (2010). Pharmaceutical Applications of Nanoparticle Carriers. In P. Boisseau, P. Houdy, M., Lahmani (Eds.), *Nanoscience- Nanotechnology and Nanobiology*. Retrieved from www.knovel.com

Holmberg, K. (2002). *Handbook of Applied surface and colloid chemistry.*John Wiley and sons. Retrieved from www.knovel.com

Hristovski, K. D., Baumgardner, A., & Westerhoff, P. K. (2007). Selecting metal oxide nanomaterials for arsenic removal in fixed-bed columns: From nanopowders to aggregated nanoparticle media. *Journal of Hazardous Materials*, *147*, 265-274. doi: 10.1016/j.hazmat.2007.01.017

Hristovski, K. D., Ngyuen, H. P., & Westerhoff, P. K. (2009). Removal of arsenate and 17 a-ethinyl estradiol (EE2) by iron (hydr)oxide modified activated carbon fibers. *Journal of Environmental Science and Health Part A*, *44*, 354-361. doi: 10.1080/10934520802659695

Hristovski, K. D., Westerhoff, P. K., Crittenden, J., & Olson, L. (2008). Arsenate removal by iron (hydr)oxide modified granulated activated carbon: Modeling arsenate breakthrough with the pore surface diffusion model. *Separation Science and Technology*, *43*, 3154-3167.

Hristovski, K. D., Westerhoff, P. K., Crittenden, J., & Olson, L. (2008). Arsenate removal by nanostructured ZrO2 spheres. *Environmental Science and Technology*, *42(10)*, 3786-3790.

Hristovski, K. D., Westerhoff, P. K., Moller, T., & Sylvester, P. (2009). Effect of synthesis conditions on nano-iron (hydr)oxide impregnated granular activated carbon. *Chemical Engineering Journal*, *146*, 237-243. doi:10.1016/j.cej.2008

Hristovski, K., Westerhoff, P., & Crittenden, J. (2008). An approach for evaluating nanomaterials for use as packed bed adsorber media: A case study of arsenate removal by titanate nanofibers. *Journal of Hazardous Materials*, *156*, 604 - 611.

Hristovski, K., Westerhoff, P., Moller, T., Sylvester, P., Condit, W., & Mash, H. (2008). Simultaneous removal of perchlorate and arsenate by ion-exchange media modified with nanostructured iron (hydr)oxide. *Journal of Hazardous Materials*, *152*, 397 - 406.

http://www.nap.edu/catalog.php?record_id=6444

Huand, C. P., & Vane, L. M. (1989). Enhancing As 5+ removal by a Fe 2+ - treated activated carbon. *Journal of Water Pollution Control Federation, 61* (9), 1596-1603.

Izbicki, J. A., Stamos, C. L., Metzger, L. F., Halford, K. J., Kulp, T. R., & Bennett, G. L. (2008*). Source, distribution and management of arsenic in water from wells, eastern San Joaguin groundwater subbasin, California*. USGS open file report 2008-1272. Retrived from USGS website: http://pubs.usgs.gov/of/2008/1272/

Jain, C. K., & Ali, I. (2000). Arsenic: occurrence, toxicity and speciation techniques. *Water Research, 34 (17*), 4304- 4312.

Katsoyiannis, I. A., & Zouboulis, A. I. (2002). Removal of arsenic from contaminated water sources by sorption onto iron-oxide-coated polymeric materials. *Water Research*, *36*, 5141-5155.

Koetz, J., & Kosmella, S.(2007). *Polyelectrolytes and nanoparticles*. New York: Springer. doi: 10.1007/978-3-540-46382-5

Kolpin, D. W., Furlong, E. T., Meyer, M. T., Thurman, E. M., Zuagg, S. D., Barber, L. B., & Buxton, H. T. (2002). Pharmaceuticals, Hormones, and other Organic Wastewater Contaminants in U.S. Streams, 1999-2000: A National Reconnaissance. *Environmental Science and Technology, 36,* 1201-1211. doi: 10.1021/es011055j

Korte, N. E., and Fernando, Q. (1991). A review of arsenic (III) in groundwater. Critical Review. *Environ. Control*. 21, 1–39.

Kumareasan, M., & Riyazuddin, P. (2001). Overview of speciation chemistry of arsenic. *Current Science, 80* (7), 837-845.

Kundu, S., & Gupta, A.K. (2005). Analysis and modeling of fixed bed column operations on As (V) removal by adsorption onto iron oxide-coated cement (IOCC). *Journal of colloidal and Interface Science, 290*, 52-60. doi: 10.1016/j.jcis.2005.04.006

Kutschera, K., Schmidt, A., Köhler, S. & Otto, M. (2007). CZE for the speciation of arsenic in aqueous soil extracts. *Electrophoresis, 28* (19), 3466-3476. doi: 10.1002/elps.200700107

Lide, D. (2006). *CRC Handbook of Chemistry and Physics*. Baco Raton, FL: Taylor and Francis Group.

Lindberg, A. –L., Rahman, M., Persson, L. –Å., & Vahter,M. (2008). The risk of arsenic induced skin lesions in Bangladeshi men and women is affected by arsenic metabolism and the age at first exposure. *Toxicology and Applied Pharmacology, 230*, 9-16. doi: 10.1016/j.taap.2008.02.001

Liu, G. & Zhang, H. (2008). The adsorption of arsenic on magnetic iron-manganese oxide in aqueous medium. *Proceedings of the International MultiConference of Engineers and Computer Scientists (IMCES), 2*.

Liu, Y., Xu, H., & Tay, Joo-Hwa. (2005). Derivation of a General Adsorption Isotherm Model. *Journal of Environmental Engineering, 131*(10), 1466-1468. doi: 10.1016/(ASCE)0733-9372(2005)131:10(1466)

Lorenzen, L., Van Deventer, J. S., & Landi, W. M. (1995). Factors affecting the mechanism of the adsorption of arsenic species on activated carbon. *Mineral Engineering*, *8*(4/5), 557-569.

Malvern Instruments (2003). *Zetasizer nano series*. MAN0317. Retrieved from http://macro.lsu.edu/psrgroup/Instrument%20Manuals/MalvernZetaMAN0317-1.0(NANO).pdf

Malvern Instruments. *Zeta Potential Measurements*. Retrieved from http://www.malvern.com/LabEng/technology/zeta_potential/zeta_potential_LDE.htm

Malvern Instruments. *Zeta Potential: Introduction in 30 minutes*.Technical notes. Retrieved from Zeta%20potential%20-%20An%20introduction%20in%2030%20minutes

Mamindy-Pajany, Y., Hurel, C., Marmier, N., & Roméo, M. (2009*). C. R. Chimie, 12*, 876-881. doi: 10.1016/j.crci.2008.10.012.

Manly, B. F. (2001). *Statistics for environmental science and management*. Boca Raton, FL: CRC Press.

Matijević, E., & Scheiner, P. (1978). Ferric hydrous oxide sols III. Preparation of uniform particles by hydrolysis of Fe(III)-chloride, -nitrate, and –perchlorate solutions. *Journal of Colloid and Interface Science, 63 (3),* 509- 524.

Matijević, E., (1981). Monodispersed metal (hydrous) oxides- A fascinating field of colloidal science. *American Chemical Society, 14,* 22-29.

Maurya, N.S., & Mittal, A.K. (2006). Applicability of equilibrium isotherm models for the biosorptive uptakes in comparison to activated carbon based adsorption. *Journal of Environmental Engineering, 132* (12), 1589-1599. doi: 10.1061/(ASCE)0733-9372(2006)132:12(1589)

Mazumder, D. N., Haque, R., Ghosh, N., De, B. K., Santra, A., Chakraborti, D., & Smith, A. H. (2000). Arsenic in drinking water and the prevalence of respiratory effects in West Bengal, India. International Journal of Epidemiology, 29, 1047-1052.

McArthur, J. M., Banerjee, D. M., Hudson-Edwards, K. A., Mishra, R., Purohit, R., Ravenscroft P.,Chadha, D.K. (2004). Natural organic matter in sedimentary basins and its relation to arsenic in anoxic groundwater: the example of West Bengal and its worldwide implications. *Applied Geochemistry, 19*, 1255-1293. doi: 10.1016/j.apgeochem.2004.02.001

McArthur, J.M., Ravenscroft, P., Safiulla, S., & Thirlwall, M. F. (2001). Arsenic in groundwater: Testing pollution mechanisms for sedimentary aquifers in Bangladesh. *Water Resources Research, 37 (1*), 109-117. McGraw-Hill Handbooks.

Meng, X., Bang, S., & Korfiatis, G. P. (2000). Effects of silica, sulfate, and carbonate on arsenic removal by ferric chloride. *Water Research, 34 (4),* 1255-1261.

Micromeritics (2001). *Gas sorption Analysis*. Retrieved from http://www.micromeritics.com/Repository/Files/Gas_Sorption.pdf

Mohan, D., & Pittman, C. U., Jr. (2007). Arsenic removal from water/wastewater using adsorbents - A critical review. *Journal of Hazardous Materials*, *142*(1-2), 1-53.

Mok, W. M., & Wai, C. M. (1989). Distribution and mobilization of arsenic species in the creeks around the Blackbird mining district, Idaho. *Water Research, 23 (1),* 7-13.

Mondal, D., Adamson, G. C. D., Nickson, R., & Polya, D.A. (2008). A comparison of two techniques for calculating groundwater arsenic-related lung, bladder and liver cancer disease burden using data from Chadhka block, West Bengal. *Applied Geochemistry, 23*, 2999-3009. doi: 10.1016/j.apgeochem.2008.06.009

Morales, K. H., Ryan, L., Kuo, T. L., Wu, M. M., & Chen, C. J. (2000). Risk of internal cancers from arsenic in drinking water. *Environmental Health Perspstives, 108*, 655-661.

Morel, F. M. M., & Hering, J. P. (1993). *Principles and applications of aquatic Chemistry.* New York: Wiley

Moudgil, B. M., Singh, P. K., & Adler, J. J. (2002). Surface Chemistry in dispersion, flocculation and flotation. In K. Holmberg (Ed.), Handbook of Applied Surface and Colloidal Chemistry. Retrived from www.knovel.com

MSE Technology Applications, Inc. *Arsenic oxidation demonstration project-Final report.*(1998). Retrieved from http://www.arsenic.org/PDF%20Files/Mwtp-84.pdf

Murcott, S. (1999). *Appropriate remediation technologies for arsenic-contaminated wells in Bangladesh*. Massachusetts Institute of Technology. Retrieved from http://web.mit.edu/civenv/html/people/faculty/murcott.html

Naeem, A., Westerhoff, P., & Mustafa, S. (2007). Vanadium removal by metal (hydr)oxide adsorbents. *Water Research, 41*, 1596- 1602. doi:10.1016/j.watres.2007.01.002.

Nanosizer Zeta Series. *Zeta Potential Theory*. Retrieved from Zetapotential_16.pdf

National Research Council. (1999). *Arsenic in Drinking Water*. Washington DC: National Academy Press, ISBN-10: 0-309-06333-7.

Neikov, O.D., Naboychenko, S., Murashova, I., Gopienka, V.G., Frishberg, I.V., & Lotsko, D.V. (2009). *Handbook of Non-Ferrous metal powders-Technologies and Applications.* Elsevier. Retrieved from www.knovel.com

Neubauer, O. (1947). Arsenical cancer: a review. *Br. J. Cancer* **1**, 192–251. Retrieved from http://www.nature.com/bjc/journal/v1/n2/pdf/bjc194722a.pdf

Nguyen, T.V., Vigneswaran, S., Ngo, H. H., Pokhrel, D., & Viraraghavan, T. (2006). Specific Treatment Technologies for Removing Arsenic from Water. *Engineering in Life Sciences, 6*(1), 86-90. doi:10.1002/elsc.200620120

Nickson, R. T., McArthur, J. M., Shrestha, B., Kyaw-Myint, T. O., & Lowry, D. (2005). Arsenic and other drinking water quality issues, Muzaffargarh district, Pakistan. *Applied Geochemistry, 20,* 55-68. doi:10.1016/j.apgeochem.2004.06.004

Nickson, R., McArthur, J., Burgess, W., Ahmed, K. M., Ravenscroft, P., & Rahman, M. (1998). Arsenic poisoning of Bangladesh groundwater. *Nature, 395*, 338.

Nickson, R., Sengupta, C., Mitra, P., Dave, S. N., Banerjee, A. K., Bhattacharya, A., Deverill, P. (2007). Current knowledge on the distribution of arsenic in groundwater in five states of India. *Journal of Environmental Science and Health Part A, 42,* 1707- 1718. doi:10.1080/10934520701564194.

Norit Americas, Inc. (2007). *Datasheet HydroDarco 3000 GAC* [Fact sheet]. Retrieved from www.norit-americas.com

Nriagu, J. O., & Azcue, J. M. (1994). Part I: Cycling and characterization. In J. O. Nriagu (Ed.), *Arsenic in the environment* (pp. 1-15). New York: John Wiley and Sons.

Nriagu, J. O., & Pacyna, J. M. (1988). Quantitative assessment of worldwide contamination of air, water and soils with trace metals. *Nature, 333,*134-139.

Nriagu, J. O., Bhattacharya, P., Mukherjee, A. B., Bundschuh, J., Zevenhoven, R., & Loeppert, R. H. (2007). Arsenic in soil and groundwater: an overview. *Trace metals and other Contaminants in the Environment, 9*, 3-60. doi: 10.1016/ S0927-5215(06)09001-1

Pajany, Y. M., Hurel, C., Marmier, N., & Roméo, M. (2009). Arsenic adsorption onto hematite and goethite. *Comptes Rendus Chimie,12*, 876-881. Doi: 10.1016/j.crci.2008.10.012

Pan,G., & Liss, P.S. (1998). Metastable-Equilibrium Theory I. Theoretical. *Journal of Colloid and interface science, 201*, 71-76.

Pansu. M., & Gautheyrou, J. (2006). Handbook of soil analysis: mineralogical, organic and inorganic methods. Berlin, New York: Springer. pp 55, 22-24, 649-650.

Parker, I., & Hughes, D. (1998). *Water Treatment Primer: Activated Carbon*. Retrieved from http://www.cee.vt.edu/ewr/environmental/teach/wtprimer/actcarbon/actcarbon.html

Pattabhi, V., & Gautham, N. (2002). *Biophysics*. New York: Kluwer Academic Publishers.

Peleanu,I., Zaharescu, M., Rau, I., Crisan, M., Jitianu, A. and Meghea, A. (2000). Composite SiO2—Iron Oxide Materials for Magnetically Intensified

Adsorption. *Journal of Radioanalytical and Nuclear Chemistry, 246* (3), 557-563. doi: 10.1023/A:1006788806079

Pena, M. E., Korfiatis, G. P., Patel, M., Lippincott, L., & Meng, X. (2005). Adsorption of As(V) and As(III) by nanocrystalline titanium dioxide. *Water Research, 39*, 2327-2337. doi: 10.1016/j.watres.2005.04.006.

Pena, M., Meng, X., Korfiatis, G. P., & Jing, C. (2006). Adsorption mechanism of arsenic on nanocrystalline titanium dioxide. *Environmental Science and Technology, 40*, 1257-1262.

Penners, N.H.G., & Koopal, L.K. (1986). Preparation and optical properties of homosphere haematite hydrosols. *Colloids and Surfaces, 19*, 337-349.

Rahman, A., Vahter,M., Ekstrom, E. C., Rahman, M., Golam Mustafa, A. H., Wahed, M. A., Yunus, M., & Persson, L. A. (2007). Association of arsenic exposure during pregnancy with fetal loss and infant death: a cohort study in Bangladesh. *American Journal of Epidemiology, 165*, 1389-1396.

Ramachandran, V. S. (1995). *Concrete admixtures Handbook-Properties, Science and Technology.* Williams Andrew publishing. Retrieved from www.knovel.com

Ravenscroft, P., McArthur, J. M., Hoque, B. A. (2001). Geochemical and palaeohydrological controls on pollution of groundwater by arsenic. In *Arsenic Exposure and Health Ef*fects IV. Chapell WR, Abernathy CO, Calderon R (Eds). Pp 53-78.

Rebrenau,L., Vanderborght,J., & Chou,L. (2008). The diffusion coefficient of dissolved silica revisited. *Marine Chemistry, 112*, 230-233

Reed, B. E., & Nonavinakere, S. K. (1992). Metal removal by activated carbon: Effects of complexing ligands, competing adsorbates, ionic strength, and background electrolyte. *Separation Science and Technology*, *27*(14), 1985-2000.

Reed, B. E., Vaughan, R., & Jiang, L. (2000). As(III), As(V), Hg and Pb removal by Fe-oxide impregnated activated carbon. *Journal of Environmental Engineering*, *126*(9), 869-873.

Reedy, R. C., Scanlon, B. R., Nicot, J. –P., & Tachovsky, J. A. (2007). Unsaturated zone arsenic distribution and implications for groundwater contamination. *Environmental Science and Technology, 41 (20),* 6914-6919.

Reynolds, T. D., & Richards, P. A. (2nd ed.).(1996). *Unit Operations and Processes in Environmental Engineering* (pp. 25, 350, 749). PWS Publishing Co.

Riyazuddin, P., & Kumaresan, M. (2001). Overview of speciation chemistry of arsenic. *Current Science, 80 (7),* 837-846.

Robertson, F.N. (1989). Arsenic in groundwater under oxidizing conditions, south-west United States. *Environmental Geochemistry and Health, 11*, 171-176.

Sams II, R., Wolf, D. C., Ramasamy, S., Ohanian, E., Chen, J., & Lowit, A. (2007). Workshop overview: Arsenic research and risk assessment. *Toxicology and Applied Pharmacology, 222*, 245-251. doi:10.1016/j.taap.2007.01.007

Sarkar, S., Blaney, L. M., Gupta , A., Ghosh, D., & SenGupta, A.K. (2007). Use of ArsenX^{np}, a hybrid anion exchanger, for arsenic removal in remote villages in the Indian subcontinent. *Reactive and Functional Polymers, 67* (12), 1599-1611. doi:10.1016/j.reactfunctpolym.2007.07.047

Saxena, V. K., Kumar, S., & Singh, V. S. (2004). Occurrence, behavior and speciation of arsenic in groundwater. *Current Science, 86 (2),* 281- 284.

Schimmel,D., Fagnani, K. C., Oliveira dos Santos, J. B., Barros, M. A. S. D., & Antonio da Silva, E. (2010). Adsorption of Turquoise blue QG reactive dye on commercial activated carbon in batch reactor: Kinetic and equilibrium studies. *Brazilian journal of Chemical Engineering, 27* (2), 289-298.

Schlicher, R.J., Ghosh, M.M. (1985). Removal of arsenic from water by physical–chemical processes. In: Peters, R.W., Kim, B.M. (Eds.). Separation of Metals and Other Trace Contaminants, New York. AIChE Symp. Ser. 81 (243), 152–164.

Sherman, D.M. & Randall, S. R. (2003). Surface complexation of arsenic (V) to iron (III) hydr(oxides): structure mechanism from ab initio molecular geometries and EXAFS spectroscopy. *Geochim. Cosmochim. Acta, 67*, 4223-4230.

Singh, T.S. & Pant, K. K. (2006). Experimental and modelling studies on fixed bed adsorption of As (III) ions from aqueous solution. *Seperation Purification Technology, 48*, 288-296. doi: 10.1016/j.seppur.2005.07.035

Smedley, P. L. & Kinniburgh, D. G. (2002). A review of the source, behavior and distribution of arsenic in natural waters. *Applied Geochemistry, 17,* 517-568.

Smith. S. J. (2005). Naturally occurring arsenic in groundwater, Norman, Oklahoma, 2004, and remediation options for produced water. USGS factsheet 2005-3111. Retrived from USGS website: http://pubs.usgs.gov/fs/2005/3111/

Snoeyink, V. L.; Summers, R. S. (1999). Adsorption of Organic Compounds. In *Water Quality and Treatment. A Handbook of Community Water Supplies* (Letterman, R. D., Ed.). New York: McGraw-Hill, pp 13.1-13.82.

Su, C., & Puls, R.W. (2001). Arsenate and arsenite removal by zerovalent iron: effects of phosphate, silicate, carbonate, borate, sulfate, chromate, molybdate, and nitrate, relative to chloride. *Environmental Science and Technology*, 35 (22), 4562-4568.

Thirunavukkarasu, O. S., Viraraghavan, T., Subramanian, K. S., & Tanjore, S. (2002). Organic arsenic removal from drinking water. *Urban Water*, *4*, 415-421.

Thirunavukkarasu, O. S., Viraraghavan, T., Subramanian, K. S., Chaalal, O., & Islam, M. R. (2005). Arsenic removal in drinking water- impacts and novel removal technologies. *Energy Resources, 27*, 209-219. doi: 10.1080/00908310490448271

Torrens, K.D. (1999). Evaluating arsenic removal technologies. *Pollution Engineering, 31 (7)*, 25-27.

Twidwell, L. G. (1999). Technologies and potential technologies for removing arsenic from process and mine waste water. REWAS. Retrieved from http://www.mtech.edu/metallurgy/arsenic/REWASAS%20for%20proceedings99%20in%20word.pdf

United States Department of Health and Human Services (Ed) (2007). *Toxicological profile for arsenic*. Washington, DC: US Department of Health and Human Services.

United States Environmental Protection Agency (2000d). *Arsenic in drinking water rule: Economic assessment* (EPA 815-R-00-026). Washington, DC: U.S. Government Printing Office.

United States Environmental Protection Agency (2002b). *Proven alternatives for aboveground treatment of arsenic in groundwater* (EPA 542-S-02-002). Washington, DC: U.S. Government Printing Office.

United States Environmental Protection Agency (2009). *Drinking water and wells*. Retrieved from http://www.epa.gov/oecaagct/tdri.html

United States Environmental Protection Agency(2002c). Arsenic *Treatment Technologies for soil, waste and water.* (EPA-542-R-02-004). Retrieved from http://www.epa.gov/tio/download/remed/542r02004/arsenic_report.pdf

United States Environmental Protection Agency(2005). *Treatment Technologies for arsenic removal.* (EPA/600/S-05/006). Retrieved from http://www.epa.gov/nrmrl/pubs/600s05006/600s05006.pdf

United States Environmental Protection Agency. (2003). *Arsenic Treatment Technology Evaluation Handbook for Small Systems.* (EPA-816-R-03-014). Retrieved from http://cfpub.epa.gov/safewater/arsenic/arsenictradeshow/Pubs/handbook_arsenic_treatment-tech.pdf

United States Environmental Protection Agency. (1995). *Contaminants and remedial options at selected- metal contaminated sites* (EPA/540/R-95/512). Retrived from http://search.epa.gov/s97is.vts

United States Environmental Protection Agency. (1996).*Background document for spent potliners from primary alumina reduction-K088.* (EPA-530-R-96-015). Retrieved from http://www.epa.gov/ncepi/Catalog/EPA530R96015.html

United States Environmental Protection Agency. (2000a). *Regulations on the disposal of arsenic residuals from drinking water treatment plants.* (EPA-600-R-00-025). Retrieved from http://www.epa.gov/ORD/WebPubs/residuals/index.htm

United States Environmental Protection Agency. (2000b). *Arsenic removal from drinking water by Ion Exchnage and Activatde alumina plants.* (EPA-600-R-00-088). Retrieved from http://www.epa.gov/ORD/WebPubs/exchange/EPA600R00088.pdf

United States Environmental Protection Agency. (2000e). *Technologies and costs for removal of arsenic from drinking water* (EPA 815-R-00-028). Washington, DC: U.S. Government Printing Office.

United States Environmental Protection Agency. (2000f). *Aresnic removal from drinking water by coagulation/filtration and lime softening plants.* (EPA/600/R-00/063). Retrived from http://www.epa.gov/ncepi/Catalog/EPA600R00063.html

United States Environmental Protection Agency. (2002). *Arsenic treatment technology design manual for small systems.* Retrieved from http://www.epa.gov/safewater/smallsys/arsenicdesignmanualpeerreviewed draft.pdf

United States Environmental Protection Agency. (2006). *EPA National primary drinking water standards* [Fact sheet]. Retrieved from http://www.epa.gov/safewater/contaminants/index.html#1

United States Environmental Protection Agency. (n.d). Small system treatment technologies- Chemical contaminant removal. Retrieved from http://www.epa.gov/nrmrl/wswrd/dw/smallsystems/ccr.html

Vaishya, R. C., & Gupta, S. K. (2003). Arsenic removal from ground water by iron impregnated sand. *Journal of Environmental Engineering, 129* (1), 89-92.

Vance, D.B. (2005). Arsenic- chemical behavior and treatment. *National Environment Journal, 5* (3). Retrieved from http://2the4.net/arsenicart.htm

Vaughan, R. L., Jr., Reed, B. E., Viadero, R. C., Jr., Jamil, M., & Berg, M. (1999). Simultaneous removal of organic and heavy metal contaminants by granular activated carbon (GAC) columns. *Advances in Environmental Research; an international journal of research in environmental science, engineering and technology*, *3*(3), 229-242.

Wang, S., & Mulligan, C. N. (2006). Occurrence of arsenic contamination in Canada: sources, behavior and distribution. *Science of the Total Environment, 366,* 701-721.

Wasserman, G. A., Liu, X., Parvez, F., Ahsan, H., Factor-Litvak, P., Kline, J., … Graziano, J. H. (2007). Water arsenic exposure and intellectual function in 6-year-old children in Araihazar, Bangladesh. *Environmental Health Perspectives, 115,* 285-289.

Welch, A.H.; Lico, M. & Hughes, J. (1988). Arsenic in ground water of the western United States. *Ground water*, *26*(3): 333-347.

Westerhoff, P. (2004). *Rapid small-scale column test(RSSCT)- Procedures for arsenic studies and application of results*. Retrieved from http://www.epa.gov/nrmrl/wswrd/dw/arsenic/tech/pubs/rssctAsteststudy.pdf

Westerhoff, P., Highfield, D., Badruzzaman, M., & Yoon, Y. (2005). Rapid small-scale column tests for arsenate removal in iron oxide packed bed column. *Journal of Environmental Engineering, 131* (2), 262- 271. doi: 10.1016/(ASCE)0733-9372(2005)131:2(262)

Westerhoff, P.; Highfield, D.; Badruzzaman,M & Yoon, Y. (2005). Rapid Small-Scale Column Tests for Arsenate Removal in Iron Oxide Packed Bed Columns. *Journal of Environmental Engineering, 131 (*2), 262-271. doi: 10.1061/(ASCE)0733-9372(2005)131:2(262)

Wilkie, J.A., & Hering, J. G. (1996). Adsorption of arsenic onto hydrous ferric oxide: effects of adsorbate/adsorbent ratios and co-occurring solutes. *Colloidals and surfaces A: Physicochemical and Engineering Aspects, 107*, 97-110.

Wilkin, R.T., Acree, S.D., Ross, R. R., Beak, D. G., & Lee, T.R. (2009). Performance of a zerovalent iron reactive barrier for the treatment of arsenic in groundwater:Part 1. Hydrogeochemical studies. *Journal of Contaminant Hydrology, 106*, 1-14. doi: 10.1016/j.jconhyd.2008.12.002

World Health Organisation (2001). *EHC 224 Arsenic and arsenic compounds. Environment Health Criteria*. Geneva.

World Health Organisation (2003). *Arsenic in drinking water. Background document for preparation of WHO guidelines for drinking water quality.* (WHO/SDE/WSH/03.04/75). World Health Organisation, Geneva.

World Health Organisation (2004). *Guidelined for drinking water quality: Recommendations.*Geneva

Yan-Chu, H. (1994). Arsenic Distribution in Soils. Chapter 2 in Nriagu, J.O., Ed., *Arsenic in the Environment Part I: Cycling and Characterization.* New York: John Wiley & Sons, Inc. pp 17-49.

Yoshida, T., Yamauchi, H., & Sun, G. F. (2004). Chronic health effects in people exposed to arsenic via the drinking water: dose response relationships in review. *Toxicology and Applied Pharmacology, 198*, 243-252. doi:10.1016/j.taap.2003.10.022.

Zhuang, J. M., Hobenshield, E., & Walsh, T. (2007). Arsenate sorption by hydrous ferric oxide incorporated onto granular activated carbon with phenol formaldehyde resins coating. *Environmental Technology, 29*, 401-411.

Zytner, R. G. (1992). Adsorption-desorption of tricholoroethylene in granular media. *Water, air and soil pollution, 65*(3-4), 245- 255. doi: 10.1007/BF00479890

APPENDIX A

DATA ON MOISTURE CONTENT, MATERIAL DENSITY AND PARTICLE POROSITY

Table A 1. Percent Moisture, Material Density and Particle Porosity of all Fe-GAC

Fe-GAC Media	Mass					% Moisture	Material Density (g/ml)	Particle Porosity
	Picmt (g)	Wet media + Picmt. (g)	Wet media + Picmt. +water (g)	Dry media + Picmt. (g)	Dry Media (g)			
0.5M- 24 hr	31.98	33.29	62.57	32.49	0.51	61.07	0.98	0.61
2M-24hr	31.96	37.35	63.34	34.04	2.08	61.35	1.59	0.71
0.5M-72hr	29.98	31.74	63.11	30.69	0.71	59.58	1.12	0.62
2M-72hr	31.99	34.41	62.74	32.85	0.86	64.59	1.22	0.69

Note: Picmt. = Picnometre

APPENDIX B

ADDITIONAL DATA ON SURFACE AREA AND PORE SIZE DISTRIBUTION

Sample:	0.5M,1DAY		
Operator:	ARTI		
File:	C:\...\ARTI\000-184.SMP		
Started:	5/4/2010 9:59:28AM	Analysis Adsorptive:	N2
Completed:	5/5/2010 4:13:56AM	Analysis Bath Temp.:	77.300 K
Report Time:	5/5/2010 4:13:56AM	Sample Mass:	0.8646 g
Warm Free Space:	10.3179 cm³ Measured	Cold Free Space:	26.8919 cm³ Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm³	Automatic Degas:	No

Summary Report

Surface Area

BET Surface Area:	544.7371 m²/g
t-Plot Micropore Area:	241.2829 m²/g
t-Plot External Surface Area:	303.4543 m²/g
BJH Adsorption cumulative surface area of pores between 17.000 Å and 3000.000 Å diameter:	263.010 m²/g

Pore Volume

Single point adsorption total pore volume of pores less than 3597.735 Å diameter at P/Po = 0.994613428:	0.528290 cm³/g
t-Plot micropore volume:	0.113286 cm³/g
BJH Adsorption cumulative volume of pores between 17.000 Å and 3000.000 Å diameter:	0.401242 cm³/g

Pore Size

Adsorption average pore width (4V/A by BET):	38.7923 Å
BJH Adsorption average pore diameter (4V/A):	61.023 Å

TriStar II 3020 V1.02 Unit 1 Port 1 Serial #: 204 Page 1

Sample:	0.5M,1DAY		
Operator:	ARTI		
Submitter:			
File:	C:\...\ARTI\000-184.SMP		
Started:	5/4/2010 9:59:28AM	Analysis Adsorptive:	N2
Completed:	5/5/2010 4:13:56AM	Analysis Bath Temp.:	77.300 K
Report Time:	5/5/2010 4:13:56AM	Sample Mass:	0.8646 g
Warm Free Space:	10.3179 cm^3 Measured	Cold Free Space:	26.8919 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

Isotherm Tabular Report

Relative Pressure (P/Po)	Absolute Pressure (mmHg)	Quantity Adsorbed (cm^3/g STP)	Elapsed Time (h:min)	Saturation Pressure (mmHg)
			00:54	731.5276
0.009608	6.980631	116.8542	05:41	726.5648
0.026025	18.88892	127.4468	06:17	725.8035
0.02867	20.80092	128.6056	06:30	725.5375
0.042227	30.62891	133.158	06:43	725.3389
0.057504	41.69542	137.1154	06:55	725.0828
0.059953	43.46572	137.7104	07:03	724.9951
0.078538	56.92236	141.5266	07:14	724.7769
0.079765	57.80059	141.8016	07:20	724.6389
0.095874	69.45944	144.6475	07:30	724.4866
0.100295	72.64585	145.4209	07:39	724.3244
0.114061	82.60188	147.5887	07:48	724.189
0.121667	88.09959	148.7549	07:56	724.1037
0.132332	95.81461	150.3154	08:05	724.0462
0.14315	103.6445	151.8435	08:14	724.0251
0.150815	109.1597	152.8854	08:21	723.796
0.16441	118.9881	154.6737	08:30	723.7301
0.182409	131.9785	156.9475	08:39	723.5313
0.2049	148.2229	159.6651	08:48	723.3909
0.22443	162.3293	161.9641	08:57	723.2946
0.242169	175.1614	164.0091	09:05	723.3027
0.259617	187.759	165.9762	09:14	723.2165
0.306838	221.8895	171.1725	09:26	723.1484
0.361328	261.2448	177.0804	09:37	723.0136
0.394095	284.8789	180.6521	09:47	722.8689

0.449091	324.5939	186.6706	10:01	722.7792
0.497543	359.5504	192.1756	10:14	722.6513
0.547815	395.8453	198.2253	10:28	722.5898
0.596546	431.0276	204.5232	10:42	722.5383
0.645371	466.2596	211.4867	10:56	722.4677
0.694843	501.9696	219.4659	11:11	722.4211
0.738924	533.7307	227.4666	11:28	722.3085
0.764016	551.7469	232.7879	11:39	722.1671
0.793841	573.1696	239.8632	11:51	722.0209
0.81512	588.4769	245.4708	12:03	721.9508
0.834737	602.5612	251.2805	12:14	721.8575
0.861134	621.4241	260.2091	12:35	721.6342
0.872762	629.715	264.8789	12:46	721.5198
0.884767	638.2983	270.2697	12:56	721.4307
0.903619	651.7875	279.2969	13:15	721.3082
0.911699	657.5884	283.5385	13:25	721.2779
0.919509	663.1306	287.8092	13:35	721.1788
0.932191	672.171	295.0634	13:55	721.0661
0.93763	675.9861	298.3372	14:04	720.9522
0.942855	679.6416	301.6851	14:14	720.8334
0.947552	682.9515	304.7208	14:23	720.7532
0.9563	688.9806	310.3417	14:40	720.4647
0.959992	691.5388	313.0377	14:48	720.359
0.963824	694.1509	315.861	14:57	720.2049
0.967206	696.4677	318.1814	15:05	720.0823
0.970342	698.6717	320.4055	15:13	720.0262
0.973051	700.4941	322.436	15:20	719.8945
0.975468	702.1665	324.1807	15:27	719.8251
0.977318	703.3828	325.859	15:34	719.7072
0.979558	704.9548	327.4577	15:41	719.6664
0.98148	706.249	328.9919	15:47	719.5756
0.98298	707.2621	330.4724	15:53	719.5084
0.984581	708.3956	331.8915	16:00	719.4891
0.986162	709.5009	333.2565	16:06	719.4564
0.987456	710.3452	334.5755	16:12	719.3693
0.988963	711.414	335.8398	16:18	719.3533
0.990189	712.2648	337.0569	16:23	719.3218
0.991331	713.012	338.2374	16:29	719.2474
0.992348	713.6978	339.3774	16:34	719.2008
0.993406	714.4014	340.4789	16:40	719.1434
0.994613	715.2247	341.5372	16:45	719.0981
0.994898	715.3781	342.584	16:52	719.0464
0.995114	715.4054	343.6267	17:03	718.918

Sample:	0.5M,1DAY		
Operator:	ARTI		
Submitter:			
File:	C:\...\ARTI\000-184.SMP		
Started:	5/4/2010 9:59:28AM	Analysis Adsorptive:	N2
Completed:	5/5/2010 4:13:56AM	Analysis Bath Temp.:	77.300 K
Report Time:	5/5/2010 4:13:56AM	Sample Mass:	0.8646 g
Warm Free Space:	10.3179 cm³ Measured	Cold Free Space:	26.8919 cm³ Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm³	Automatic Degas:	No

Isotherm Linear Plot

0.5M,1DAY – Adsorption

Relative Pressure (P/Po)	Quantity Adsorbed (cm³/g STP)
0.009608	116.8542
0.026025	127.4468
0.02867	128.6056
0.042227	133.158
0.057504	137.1154
0.059953	137.7104
0.078538	141.5266
0.079765	141.8016
0.095874	144.6475
0.100295	145.4209
0.114061	147.5887
0.121667	148.7549
0.132332	150.3154
0.14315	151.8435
0.150815	152.8854
0.16441	154.6737
0.182409	156.9475
0.2049	159.6651
0.22443	161.9641
0.242169	164.0091
0.259617	165.9762
0.306838	171.1725
0.361328	177.0804
0.394095	180.6521
0.449091	186.6706

0.497543	192.1756
0.547815	198.2253
0.596546	204.5232
0.645371	211.4867
0.694843	219.4659
0.738924	227.4666
0.764016	232.7879
0.793841	239.8632
0.81512	245.4708
0.834737	251.2805
0.861134	260.2091
0.872762	264.8789
0.884767	270.2697
0.903619	279.2969
0.911699	283.5385
0.919509	287.8092
0.932191	295.0634
0.93763	298.3372
0.942855	301.6851
0.947552	304.7208
0.9563	310.3417
0.959992	313.0377
0.963824	315.861
0.967206	318.1814
0.970342	320.4055
0.973051	322.436
0.975468	324.1807
0.977318	325.859
0.979558	327.4577
0.98148	328.9919
0.98298	330.4724
0.984581	331.8915
0.986162	333.2565
0.987456	334.5755
0.988963	335.8398
0.990189	337.0569
0.991331	338.2374
0.992348	339.3774
0.993406	340.4789
0.994613	341.5372
0.994898	342.584
0.995114	343.6267

Goldwater Environmental Lab

TriStar II 3020 V1.02	Unit 1 Port 1	Serial #: 204	Page 1

Sample:	0.5M,1DAY		
Operator:	ARTI		
Submitter:			
File:	C:\...\ARTI\000-184.SMP		
Started:	5/4/2010 9:59:28AM	Analysis Adsorptive:	N2
Completed:	5/5/2010 4:13:56AM	Analysis Bath Temp.:	77.300 K
Report Time:	5/5/2010 4:13:56AM	Sample Mass:	0.8646 g
Warm Free Space:	10.3179 cm^3 Measured	Cold Free Space:	26.8919 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

Isotherm Log Plot

0.5M,1DAY – Adsorption

Relative Pressure (P/Po)	Quantity Adsorbed (cm^3/g STP)
0.009608	116.8542
0.026025	127.4468
0.02867	128.6056
0.042227	133.158
0.057504	137.1154
0.059953	137.7104
0.078538	141.5266
0.079765	141.8016
0.095874	144.6475
0.100295	145.4209
0.114061	147.5887
0.121667	148.7549
0.132332	150.3154
0.14315	151.8435
0.150815	152.8854
0.16441	154.6737
0.182409	156.9475
0.2049	159.6651
0.22443	161.9641
0.242169	164.0091
0.259617	165.9762
0.306838	171.1725
0.361328	177.0804
0.394095	180.6521
0.449091	186.6706

0.497543	192.1756
0.547815	198.2253
0.596546	204.5232
0.645371	211.4867
0.694843	219.4659
0.738924	227.4666
0.764016	232.7879
0.793841	239.8632
0.81512	245.4708
0.834737	251.2805
0.861134	260.2091
0.872762	264.8789
0.884767	270.2697
0.903619	279.2969
0.911699	283.5385
0.919509	287.8092
0.932191	295.0634
0.93763	298.3372
0.942855	301.6851
0.947552	304.7208
0.9563	310.3417
0.959992	313.0377
0.963824	315.861
0.967206	318.1814
0.970342	320.4055
0.973051	322.436
0.975468	324.1807
0.977318	325.859
0.979558	327.4577
0.98148	328.9919
0.98298	330.4724
0.984581	331.8915
0.986162	333.2565
0.987456	334.5755
0.988963	335.8398
0.990189	337.0569
0.991331	338.2374
0.992348	339.3774
0.993406	340.4789
0.994613	341.5372
0.994898	342.584
0.995114	343.6267

Sample:	0.5M,1DAY
Operator:	ARTI
Submitter:	
File:	C:\...\ARTI\000-184.SMP

Started:	5/4/2010 9:59:28AM	Analysis Adsorptive:	N2
Completed:	5/5/2010 4:13:56AM	Analysis Bath Temp.:	77.300 K
Report Time:	5/5/2010 4:13:56AM	Sample Mass:	0.8646 g
Warm Free Space:	10.3179 cm^3 Measured	Cold Free Space:	26.8919 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

BET Surface Area Report

BET Surface Area:	544.7371 ± 4.8311 m^2/g
Slope:	0.008014 ± 0.000070 g/cm^3 STP
Y-Intercept:	-0.000022 ± 0.000010 g/cm^3 STP
C:	-355.328581
Qm:	125.1349 cm^3/g STP
Correlation Coefficient:	0.9992720
Molecular Cross-Sectional Area:	0.1620 nm^2

Relative Pressure (P/Po)	Quantity Adsorbed (cm^3/g STP)	1/[Q(Po/P - 1)]
0.009608	116.8542	8.3E-05
0.026025	127.4468	0.00021
0.02867	128.6056	0.00023
0.042227	133.158	0.000331
0.057504	137.1154	0.000445
0.059953	137.7104	0.000463
0.078538	141.5266	0.000602
0.079765	141.8016	0.000611
0.095874	144.6475	0.000733
0.100295	145.4209	0.000767
0.114061	147.5887	0.000872
0.121667	148.7549	0.000931
0.132332	150.3154	0.001015
0.14315	151.8435	0.0011
0.150815	152.8854	0.001162
0.16441	154.6737	0.001272

0.182409	156.9475	0.001422
0.2049	159.6651	0.001614
0.22443	161.9641	0.001787
0.242169	164.0091	0.001948
0.259617	165.9762	0.002113

Goldwater Environmental Lab

TriStar II 3020 V1.02 Unit 1 Port 1 Serial #: 204 Page 1

Sample:	0.5M,1DAY		
Operator:	ARTI		
Submitter:			
File:	C:\...\ARTI\000-184.SMP		
Started:	5/4/2010 9:59:28AM	Analysis Adsorptive:	N2
Completed:	5/5/2010 4:13:56AM	Analysis Bath Temp.:	77.300 K
Report Time:	5/5/2010 4:13:56AM	Sample Mass:	0.8646 g
Warm Free Space:	10.3179 cm³ Measured	Cold Free Space:	26.8919 cm³ Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm³	Automatic Degas:	No

BET Surface Area Plot

0.5M,1DAY

Relative Pressure (P/Po)	1/[Q(Po/P - 1)]
0.009608	8.3E-05
0.026025	0.00021
0.02867	0.00023
0.042227	0.000331
0.057504	0.000445
0.059953	0.000463
0.078538	0.000602
0.079765	0.000611
0.095874	0.000733
0.100295	0.000767
0.114061	0.000872
0.121667	0.000931
0.132332	0.001015
0.14315	0.0011
0.150815	0.001162
0.16441	0.001272
0.182409	0.001422
0.2049	0.001614
0.22443	0.001787
0.242169	0.001948
0.259617	0.002113

Goldwater Environmental Lab

TriStar II 3020 V1.02 Unit 1 Port 1 Serial #: 204 Page 1

Sample:	0.5M,1DAY
Operator:	ARTI
Submitter:	
File:	C:\...\ARTI\000-184.SMP

Started:	5/4/2010 9:59:28AM	Analysis Adsorptive:	N2
Completed:	5/5/2010 4:13:56AM	Analysis Bath Temp.:	77.300 K
Report Time:	5/5/2010 4:13:56AM	Sample Mass:	0.8646 g
Warm Free Space:	10.3179 cm^3 Measured	Cold Free Space:	26.8919 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

BJH Adsorption Pore Distribution Report

Faas Correction Halsey

$t = 3.54 [-5 / \ln(P/Po)] ^\wedge 0.333$

Diameter Range:	17.000 Å to 3000.000 Å
Adsorbate Property Factor:	9.53000 Å
Density Conversion Factor:	0.0015468
Fraction of Pores Open at Both Ends:	0.00

Pore Diameter Range (Å)	Average Diameter (Å)	Incremental Pore Volume (cm^3/g)	Cumulative Pore Volume (cm^3/g)	Incremental Pore Area (m^2/g)	Cumulative Pore Area (m^2/g)
2945.3 - 2542.7	2714.215	0.001774	0.001774	0.026149	0.026149
2542.7 - 2247.7	2376.823	0.001843	0.003617	0.031018	0.057167
2247.7 - 1989.6	2102.719	0.001914	0.005531	0.036409	0.093576
1989.6 - 1771.6	1867.765	0.00198	0.007511	0.042397	0.135974
1771.6 - 1561.7	1653.243	0.002062	0.009573	0.049881	0.185855
1561.7 - 1418.1	1482.842	0.002164	0.011737	0.058386	0.244241
1418.1 - 1275.0	1338.809	0.002245	0.013982	0.067062	0.311302
1275.0 - 1157.1	1210.244	0.002345	0.016326	0.077495	0.388798
1157.1 - 1065.1	1107.222	0.00246	0.018786	0.088861	0.477658
1065.1 - 966.9	1011.119	0.002552	0.021338	0.100961	0.578619
966.9 - 873.3	915.1837	0.002668	0.024007	0.116629	0.695249
873.3 - 808.8	838.4951	0.002828	0.026835	0.13491	0.830158

808.8 - 737.8	769.951	0.002942	0.029777	0.152841	0.982999
737.8 - 671.9	701.6941	0.003448	0.033225	0.19655	1.179549
671.9 - 609.2	637.3667	0.003797	0.037022	0.238311	1.41786
609.2 - 553.6	578.6319	0.003987	0.041009	0.275621	1.693481
553.6 - 501.9	525.1245	0.004898	0.045907	0.373061	2.066542
501.9 - 460.6	479.4175	0.00471	0.050617	0.393014	2.459556
460.6 - 385.8	416.3266	0.009914	0.060531	0.952484	3.412041
385.8 - 355.0	369.0503	0.005418	0.065948	0.587185	3.999226
355.0 - 326.1	339.2662	0.006026	0.071975	0.710512	4.709738
326.1 - 300.7	312.3442	0.005933	0.077907	0.759798	5.469536
300.7 - 254.7	273.7158	0.013339	0.091246	1.949306	7.418841
254.7 - 232.9	242.7858	0.007958	0.099204	1.311052	8.729894
232.9 - 214.0	222.5957	0.007985	0.107189	1.434864	10.16476
214.0 - 180.0	193.8672	0.017286	0.124475	3.56665	13.73141
180.0 - 163.6	170.9352	0.010496	0.134971	2.456019	16.18743
163.6 - 150.3	156.2989	0.009166	0.144136	2.345672	18.5331
150.3 - 126.9	136.4271	0.017777	0.161913	5.212139	23.74524
126.9 - 113.8	119.5391	0.011756	0.17367	3.933867	27.6791
113.8 - 102.3	107.3322	0.011504	0.185174	4.287266	31.96637
102.3 - 89.5	94.95053	0.014822	0.199996	6.244166	38.21054
89.5 - 81.0	84.78827	0.011336	0.211332	5.347755	43.55829
81.0 - 69.3	74.09666	0.017356	0.228687	9.369315	52.92761
69.3 - 59.5	63.48917	0.017882	0.246569	11.26623	64.19384
59.5 - 52.0	55.1114	0.016	0.26257	11.61301	75.80685
52.0 - 46.0	48.543	0.014825	0.277395	12.2159	88.02275
46.0 - 40.9	43.10719	0.014636	0.29203	13.58057	101.6033
40.9 - 36.8	38.61882	0.013649	0.305679	14.13711	115.7404
36.8 - 32.9	34.55931	0.015369	0.321048	17.78812	133.5285
32.9 - 30.8	31.71503	0.009366	0.330414	11.81318	145.3417
30.8 - 27.6	28.93845	0.015913	0.346327	21.99501	167.3367
27.6 - 25.1	26.17472	0.014346	0.360673	21.92339	189.2601
25.1 - 24.2	24.6281	0.005498	0.366171	8.929703	198.1898
24.2 - 23.3	23.75475	0.005789	0.37196	9.747796	207.9376
23.3 - 22.4	22.84537	0.006557	0.378517	11.48109	219.4187
22.4 - 21.3	21.83471	0.00779	0.386307	14.27055	233.6893
21.3 - 20.5	20.89384	0.006608	0.392914	12.64979	246.3391
20.5 - 19.9	20.16474	0.005247	0.398161	10.40754	256.7466
19.9 - 19.5	19.67748	0.003081	0.401242	6.262999	263.0096

Goldwater Environmental Lab

TriStar II 3020 V1.02 Unit 1 Port 1 Serial #: 204 Page 1

Sample:	0.5M,1DAY		
Operator:	ARTI		
Submitter:			
File:	C:\...\ARTI\000-184.SMP		
Started:	5/4/2010 9:59:28AM	Analysis Adsorptive:	N2
Completed:	5/5/2010 4:13:56AM	Analysis Bath Temp.:	77.300 K
Report Time:	5/5/2010 4:13:56AM	Sample Mass:	0.8646 g
Warm Free Space:	10.3179 cm³ Measured	Cold Free Space:	26.8919 cm³ Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm³	Automatic Degas:	No

BJH Adsorption Cumulative Pore Volume
Halsey : Faas Correction

0.5M,1DAY

Pore Diameter (Å)	Pore Volume (cm³/g)
2542.689	0.001774
2247.706	0.003617
1989.586	0.005531
1771.587	0.007511
1561.735	0.009573
1418.064	0.011737
1275.045	0.013982
1157.127	0.016326
1065.121	0.018786
966.8601	0.021338
873.2802	0.024007
808.801	0.026835
737.8183	0.029777
671.9318	0.033225
609.1677	0.037022
553.6066	0.041009
501.9108	0.045907
460.6216	0.050617
385.8019	0.060531
354.9962	0.065948
326.1214	0.071975
300.7441	0.077907

254.7493	0.091246
232.9155	0.099204
213.9981	0.107189
180.0315	0.124475
163.5601	0.134971
150.2717	0.144136
126.9076	0.161913
113.7696	0.17367
102.271	0.185174
89.54345	0.199996
81.01247	0.211332
69.29287	0.228687
59.45243	0.246569
51.97205	0.26257
46.0001	0.277395
40.94241	0.29203
36.8399	0.305679
32.85996	0.321048
30.75212	0.330414
27.57955	0.346327
25.087	0.360673
24.21167	0.366171
23.34162	0.37196
22.40256	0.378517
21.33916	0.386307
20.49645	0.392914
19.86145	0.398161
19.50285	0.401242

Goldwater Environmental Lab

TriStar II 3020 V1.02	Unit 1 Port 1	Serial #: 204	Page 1

Sample:	0.5M,1DAY		
Operator:	ARTI		
Submitter:			
File:	C:\...\ARTI\000-184.SMP		
Started:	5/4/2010 9:59:28AM	Analysis Adsorptive:	N2
Completed:	5/5/2010 4:13:56AM	Analysis Bath Temp.:	77.300 K
Report Time:	5/5/2010 4:13:56AM	Sample Mass:	0.8646 g
Warm Free Space:	10.3179 cm³ Measured	Cold Free Space:	26.8919 cm³ Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm³	Automatic Degas:	No

BJH Adsorption dV/dlog(D) Pore Volume
Halsey : Faas Correction

Pore Diameter (Å)	0.5M,1DAY dV/dlog(D) Pore Volume (cm³/g·Å)
2714.215	0.030566
2376.823	0.035791
2102.719	0.037792
1867.765	0.0382
1653.243	0.04463
1482.842	0.050326
1338.809	0.051729
1210.244	0.06214
1107.222	0.064237
1011.119	0.060552
915.1837	0.071772
838.4951	0.078098
769.951	0.079386
701.6941	0.087023
637.3667	0.092303
578.6319	0.105148
525.1245	0.121459
479.4175	0.126915
416.3266	0.139821
369.0503	0.156635
339.2662	0.166215
312.3442	0.173829

273.7158	0.197459
242.7858	0.210954
222.5957	0.220418
193.8672	0.24449
170.9352	0.250457
156.2989	0.245693
136.4271	0.245028
119.5391	0.248098
107.3322	0.25203
94.95053	0.259637
84.78827	0.257949
74.09666	0.26145
63.48917	0.272232
55.1114	0.276546
48.543	0.28445
43.10719	0.293733
38.61882	0.302985
34.55931	0.319073
31.71503	0.32929
28.93845	0.343006
26.17472	0.355199
24.6281	0.359757
23.75475	0.363965
22.84537	0.368814
21.83471	0.374882
20.89384	0.373391
20.16474	0.382645
19.67748	0.382645

Goldwater Environmental Lab

TriStar II 3020 V1.02 Unit 1 Port 1 Serial #: 204 Page 1

Sample:	0.5M,1DAY		
Operator:	ARTI		
Submitter:			
File:	C:\...\ARTI\000-184.SMP		
Started:	5/4/2010 9:59:28AM	Analysis Adsorptive:	N2
Completed:	5/5/2010 4:13:56AM	Analysis Bath Temp.:	77.300 K
Report Time:	5/5/2010 4:13:56AM	Sample Mass:	0.8646 g
Warm Free Space:	10.3179 cm³ Measured	Cold Free Space:	26.8919 cm³ Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm³	Automatic Degas:	No

BJH Adsorption Cumulative Pore Area

Halsey : Faas Correction

0.5M,1DAY

Pore Diameter (Å)	Pore Area (m²/g)
2542.689	0.026149
2247.706	0.057167
1989.586	0.093576
1771.587	0.135974
1561.735	0.185855
1418.064	0.244241
1275.045	0.311302
1157.127	0.388798
1065.121	0.477658
966.8601	0.578619
873.2802	0.695249
808.801	0.830158
737.8183	0.982999
671.9318	1.179549
609.1677	1.41786
553.6066	1.693481
501.9108	2.066542
460.6216	2.459556
385.8019	3.412041
354.9962	3.999226
326.1214	4.709738
300.7441	5.469536

254.7493	7.418841
232.9155	8.729894
213.9981	10.16476
180.0315	13.73141
163.5601	16.18743
150.2717	18.5331
126.9076	23.74524
113.7696	27.6791
102.271	31.96637
89.54345	38.21054
81.01247	43.55829
69.29287	52.92761
59.45243	64.19384
51.97205	75.80685
46.0001	88.02275
40.94241	101.6033
36.8399	115.7404
32.85996	133.5285
30.75212	145.3417
27.57955	167.3367
25.087	189.2601
24.21167	198.1898
23.34162	207.9376
22.40256	219.4187
21.33916	233.6893
20.49645	246.3391
19.86145	256.7466
19.50285	263.0096

Goldwater Environmental Lab

TriStar II 3020 V1.02 Unit 1 Port 1 Serial #: 204 Page 1

Sample:	0.5M,1DAY		
Operator:	ARTI		
Submitter:			
File:	C:\...\ARTI\000-184.SMP		
Started:	5/4/2010 9:59:28AM	Analysis Adsorptive:	N2
Completed:	5/5/2010 4:13:56AM	Analysis Bath Temp.:	77.300 K
Report Time:	5/5/2010 4:13:56AM	Sample Mass:	0.8646 g
Warm Free Space:	10.3179 cm³ Measured	Cold Free Space:	26.8919 cm³ Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm³	Automatic Degas:	No

BJH Adsorption dA/dlog(D) Pore Area
Halsey : Faas Correction

	0.5M,1DAY
Pore Diameter (Å)	dA/dlog(D) Pore Area (m²/g·Å)
2714.215	0.477924
2376.823	0.640872
2102.719	0.76992
1867.765	0.852855
1653.243	1.16693
1482.842	1.427975
1338.809	1.618201
1210.244	2.181024
1107.222	2.42626
1011.119	2.473563
915.1837	3.36146
838.4951	3.891538
769.951	4.310364
701.6941	5.224488
637.3667	6.094125
578.6319	7.667377
525.1245	9.723936
479.4175	11.10869
416.3266	14.66179
369.0503	17.75516
339.2662	20.47323
312.3442	23.38198

273.7158	31.18333
242.7858	36.41278
222.5957	41.61012
193.8672	54.70454
170.9352	61.56161
156.2989	66.10493
136.4271	77.6341
119.5391	87.81201
107.3322	99.50302
94.95053	116.6883
84.78827	128.6186
74.09666	152.1295
63.48917	185.4414
55.1114	214.6577
48.543	249.5478
43.10719	288.8648
38.61882	332.0817
34.55931	390.6283
31.71503	430.7996
28.93845	501.0818
26.17472	568.8832
24.6281	596.364
23.75475	625.5146
22.84537	660.3787
21.83471	704.4614
20.89384	724.4155
20.16474	752.3851
19.67748	753.5223

Goldwater Environmental Lab

TriStar II 3020
V1.02 Unit 1 Port 1 Serial #: 204 Page 1

Sample:	0.5M, 3DAY		
Operator:	ARTI		
File:	C:\...\ARTI\000-119.SMP		
Started:	3/3/2010 10:38:52AM	Analysis Adsorptive:	N2
Completed:	3/3/2010 10:23:26PM	Analysis Bath Temp.:	77.300 K
Report Time:	3/3/2010 10:23:26PM	Sample Mass:	0.3025 g
Warm Free Space:	10.3506 cm³ Measured	Cold Free Space:	24.7405 cm³ Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm³	Automatic Degas:	No

Summary Report

Surface Area

BET Surface Area: 525.4306 m²/g

t-Plot Micropore Area: 233.6551 m²/g

t-Plot External Surface Area: 291.7755 m²/g

BJH Adsorption cumulative surface area of pores between 17.000 Å and 3000.000 Å diameter: 253.198 m²/g

Pore Volume

Single point adsorption total pore volume of pores less than 5269.377 Å diameter at P/Po = 0.996335057: 0.516109 cm³/g

t-Plot micropore volume: 0.109090 cm³/g

BJH Adsorption cumulative volume of pores between 17.000 Å and 3000.000 Å diameter: 0.388207 cm³/g

Pore Size

Adsorption average pore width (4V/A by BET): 39.2904 Å

BJH Adsorption average pore diameter (4V/A): 61.329 Å

Goldwater Environmental Lab

TriStar II 3020			
V1.02	Unit 1 Port 1	Serial #: 204	Page 1
Sample:	0.5M, 3DAY		
Operator:	ARTI		
File:	C:\...\ARTI\000-119.SMP		
Started:	3/3/2010 10:38:52AM	Analysis Adsorptive:	N2
Completed:	3/3/2010 10:23:26PM	Analysis Bath Temp.:	77.300 K
Report Time:	3/3/2010 10:23:26PM	Sample Mass:	0.3025 g
Warm Free Space:	10.3506 cm^3 Measured	Cold Free Space:	24.7405 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

Isotherm Tabular Report

Relative Pressure (P/Po)	Absolute Pressure (mmHg)	Quantity Adsorbed (cm^3/g STP)	Elapsed Time (h:min)	Saturation Pressure (mmHg)
			00:56	732.0768
0.009582	7.003015	112.3892	02:46	730.8635
0.025823	18.86489	122.5502	03:14	730.5441
0.029165	21.30078	123.9439	03:24	730.3644
0.042255	30.85275	128.1741	03:39	730.1487
0.058158	42.45713	132.1215	03:51	730.0364
0.060436	44.11979	132.671	03:58	730.0298
0.079081	57.72142	136.289	04:05	729.8998
0.079772	58.22276	136.4556	04:09	729.8652
0.095736	69.87157	139.1641	04:17	729.8339
0.100053	73.01518	139.8813	04:22	729.7678
0.113613	82.90572	141.9386	04:29	729.7177
0.121298	88.50875	143.0679	04:34	729.6786
0.131631	96.034	144.521	04:40	729.5703
0.142311	103.8223	145.947	04:45	729.5435
0.149915	109.3695	146.9563	04:50	729.542
0.163079	118.9608	148.6195	04:55	729.4663
0.167051	121.8505	149.1394	05:00	729.4211
0.183391	133.7671	151.0944	05:06	729.4102
0.202223	147.4938	153.2879	05:11	729.3638
0.222023	161.9299	155.5258	05:17	729.3396
0.239211	174.4665	157.4326	05:22	729.3427
0.25649	187.0558	159.3015	05:28	729.2919

0.304946	222.3717	164.4356	05:36	729.2171
0.356302	259.8124	169.7959	05:43	729.1923
0.39468	287.7621	173.7936	05:49	729.1032
0.449307	327.5581	179.5488	06:00	729.0289
0.493197	359.5274	184.2961	06:07	728.9728
0.547782	399.2656	190.5622	06:16	728.8765
0.598323	436.0281	196.8182	06:25	728.7504
0.648164	472.3274	203.6546	06:35	728.7162
0.697307	508.098	211.2788	06:44	728.6572
0.739046	538.4728	218.6923	06:55	728.6057
0.764469	556.9225	223.8806	07:03	728.509
0.79346	577.9709	230.4542	07:12	728.4184
0.814967	593.6103	235.7494	07:20	728.3857
0.833708	607.2137	241.124	07:28	728.3289
0.853573	621.6486	247.5349	07:36	728.2899
0.870414	633.8316	253.5073	07:44	728.1956
0.88505	644.467	259.4636	07:53	728.1703
0.900526	655.7708	266.3138	08:01	728.2087
0.91185	664.0768	271.5415	08:09	728.2745
0.921101	670.7666	276.4361	08:17	728.2228
0.930949	677.8563	281.8214	08:25	728.1351
0.93808	682.9922	285.8172	08:32	728.0743
0.944382	687.5643	289.8746	08:39	728.0571
0.951336	692.5016	294.4137	08:46	727.9258
0.957139	696.6577	298.4111	08:54	727.8544
0.962542	700.6194	302.1751	09:01	727.8845
0.966835	703.7162	305.1045	09:08	727.8555
0.970253	706.1888	307.3919	09:13	727.84
0.973129	708.3216	309.4043	09:18	727.8804
0.975697	710.2114	311.6382	09:24	727.9017
0.978993	712.5926	314.2848	09:30	727.8831
0.981373	714.3289	316.1475	09:35	727.8872
0.983842	716.0899	317.7642	09:39	727.8506
0.984456	716.4853	318.9113	09:44	727.7985
0.986423	717.9945	320.9818	09:48	727.8768
0.988567	719.4742	323.1664	09:53	727.7949
0.989763	720.4365	324.569	09:58	727.8877
0.990738	721.1446	325.6962	10:02	727.8865
0.992639	722.5085	326.957	10:07	727.8663
0.994136	723.613	328.997	10:12	727.8812
0.994812	724.1165	330.7626	10:18	727.8928
0.996162	725.0859	333.1414	10:29	727.8798
0.996335	725.2025	333.6627	10:39	727.8701
0.998337	726.6288	335.9774	10:50	727.8391
0.999291	727.3732	338.0932	11:01	727.889

Goldwater Environmental Lab

TriStar II 3020 V1.02	Unit 1 Port 1	Serial #: 204	Page 1
Sample:	0.5M, 3DAY		
Operator:	ARTI		
File:	C:\...\ARTI\000-119.SMP		
Started:	3/3/2010 10:38:52AM	Analysis Adsorptive:	N2
Completed:	3/3/2010 10:23:26PM	Analysis Bath Temp.:	77.300 K
Report Time:	3/3/2010 10:23:26PM	Sample Mass:	0.3025 g
Warm Free Space:	10.3506 cm^3 Measured	Cold Free Space:	24.7405 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

Isotherm Linear Plot

Relative Pressure (P/Po)	Quantity Adsorbed (cm^3/g STP)
0.009582	112.3892
0.025823	122.5502
0.029165	123.9439
0.042255	128.1741
0.058158	132.1215
0.060436	132.671
0.079081	136.289
0.079772	136.4556
0.095736	139.1641
0.100053	139.8813
0.113613	141.9386
0.121298	143.0679
0.131631	144.521
0.142311	145.947
0.149915	146.9563
0.163079	148.6195
0.167051	149.1394
0.183391	151.0944
0.202223	153.2879
0.222023	155.5258
0.239211	157.4326
0.25649	159.3015
0.304946	164.4356

0.356302	169.7959
0.39468	173.7936
0.449307	179.5488
0.493197	184.2961
0.547782	190.5622
0.598323	196.8182
0.648164	203.6546
0.697307	211.2788
0.739046	218.6923
0.764469	223.8806
0.79346	230.4542
0.814967	235.7494
0.833708	241.124
0.853573	247.5349
0.870414	253.5073
0.88505	259.4636
0.900526	266.3138
0.91185	271.5415
0.921101	276.4361
0.930949	281.8214
0.93808	285.8172
0.944382	289.8746
0.951336	294.4137
0.957139	298.4111
0.962542	302.1751
0.966835	305.1045
0.970253	307.3919
0.973129	309.4043
0.975697	311.6382
0.978993	314.2848
0.981373	316.1475
0.983842	317.7642
0.984456	318.9113
0.986423	320.9818
0.988567	323.1664
0.989763	324.569
0.990738	325.6962
0.992639	326.957
0.994136	328.997
0.994812	330.7626
0.996162	333.1414
0.996335	333.6627
0.998337	335.9774
0.999291	338.0932

Goldwater Environmental Lab

TriStar II 3020			
V1.02	Unit 1 Port 1	Serial #: 204	Page 1

Sample:	0.5M, 3DAY		
Operator:	ARTI		
File:	C:\...\ARTI\000-119.SMP		
Started:	3/3/2010 10:38:52AM	Analysis Adsorptive:	N2
Completed:	3/3/2010 10:23:26PM	Analysis Bath Temp.:	77.300 K
Report Time:	3/3/2010 10:23:26PM	Sample Mass:	0.3025 g
Warm Free Space:	10.3506 cm^3 Measured	Cold Free Space:	24.7405 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

Isotherm Log Plot

Relative Pressure (P/Po)	Quantity Adsorbed (cm^3/g STP)
0.009582	112.3892
0.025823	122.5502
0.029165	123.9439
0.042255	128.1741
0.058158	132.1215
0.060436	132.671
0.079081	136.289
0.079772	136.4556
0.095736	139.1641
0.100053	139.8813
0.113613	141.9386
0.121298	143.0679
0.131631	144.521
0.142311	145.947
0.149915	146.9563
0.163079	148.6195
0.167051	149.1394
0.183391	151.0944
0.202223	153.2879
0.222023	155.5258
0.239211	157.4326
0.25649	159.3015

0.304946	164.4356
0.356302	169.7959
0.39468	173.7936
0.449307	179.5488
0.493197	184.2961
0.547782	190.5622
0.598323	196.8182
0.648164	203.6546
0.697307	211.2788
0.739046	218.6923
0.764469	223.8806
0.79346	230.4542
0.814967	235.7494
0.833708	241.124
0.853573	247.5349
0.870414	253.5073
0.88505	259.4636
0.900526	266.3138
0.91185	271.5415
0.921101	276.4361
0.930949	281.8214
0.93808	285.8172
0.944382	289.8746
0.951336	294.4137
0.957139	298.4111
0.962542	302.1751
0.966835	305.1045
0.970253	307.3919
0.973129	309.4043
0.975697	311.6382
0.978993	314.2848
0.981373	316.1475
0.983842	317.7642
0.984456	318.9113
0.986423	320.9818
0.988567	323.1664
0.989763	324.569
0.990738	325.6962
0.992639	326.957
0.994136	328.997
0.994812	330.7626
0.996162	333.1414
0.996335	333.6627
0.998337	335.9774
0.999291	338.0932

Goldwater Environmental Lab

TriStar II 3020 V1.02	Unit 1 Port 1	Serial #: 204	Page 1

Sample:	0.5M, 3DAY
Operator:	ARTI
Submitter:	
File:	C:\...\ARTI\000-119.SMP

Started:	3/3/2010 10:38:52AM	Analysis Adsorptive:	N2
Completed:	3/3/2010 10:23:26PM	Analysis Bath Temp.:	77.300 K
Report Time:	3/3/2010 10:23:26PM	Sample Mass:	0.3025 g
Warm Free Space:	10.3506 cm^3 Measured	Cold Free Space:	24.7405 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

BET Surface Area Report

BET Surface Area:	525.4306 ± 4.4985 m^2/g
Slope:	0.008307 ± 0.000070 g/cm^3 STP
Y-Intercept:	-0.000022 ± 0.000010 g/cm^3 STP
C:	-371.770711
Qm:	120.6999 cm^3/g STP
Correlation Coefficient:	0.9992857
Molecular Cross-Sectional Area:	0.1620 nm^2

Relative Pressure (P/Po)	Quantity Adsorbed (cm^3/g STP)	1/[Q(Po/P - 1)]
0.009582	112.3892	8.61E-05
0.025823	122.5502	0.000216
0.029165	123.9439	0.000242
0.042255	128.1741	0.000344
0.058158	132.1215	0.000467
0.060436	132.671	0.000485
0.079081	136.289	0.00063
0.079772	136.4556	0.000635
0.095736	139.1641	0.000761
0.100053	139.8813	0.000795
0.113613	141.9386	0.000903

0.121298	143.0679	0.000965
0.131631	144.521	0.001049
0.142311	145.947	0.001137
0.149915	146.9563	0.0012
0.163079	148.6195	0.001311
0.167051	149.1394	0.001345
0.183391	151.0944	0.001486
0.202223	153.2879	0.001654
0.222023	155.5258	0.001835
0.239211	157.4326	0.001997
0.25649	159.3015	0.002166

Goldwater Environmental Lab

TriStar II 3020 V1.02	Unit 1 Port 1	Serial #: 204	Page 1

Sample:	0.5M, 3DAY
Operator:	ARTI
Submitter:	
File:	C:\...\ARTI\000-119.SMP

Started:	3/3/2010 10:38:52AM	Analysis Adsorptive:	N2
Completed:	3/3/2010 10:23:26PM	Analysis Bath Temp.:	77.300 K
Report Time:	3/3/2010 10:23:26PM	Sample Mass:	0.3025 g
Warm Free Space:	10.3506 cm³ Measured	Cold Free Space:	24.7405 cm³ Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm³	Automatic Degas:	No

BET Surface Area Plot

Relative Pressure (P/Po)	1/[Q(Po/P - 1)]
0.009582	8.61E-05
0.025823	0.000216
0.029165	0.000242
0.042255	0.000344
0.058158	0.000467
0.060436	0.000485
0.079081	0.00063
0.079772	0.000635
0.095736	0.000761
0.100053	0.000795
0.113613	0.000903
0.121298	0.000965
0.131631	0.001049
0.142311	0.001137
0.149915	0.0012
0.163079	0.001311
0.167051	0.001345
0.183391	0.001486
0.202223	0.001654
0.222023	0.001835
0.239211	0.001997
0.25649	0.002166

Goldwater Environmental Lab

TriStar II 3020

V1.02 Unit 1 Port 1 Serial #: 204 Page 1

Sample:	0.5M, 3DAY		
Operator:	ARTI		
Submitter:			
File:	C:\...\ARTI\000-119.SMP		
Started:	3/3/2010 10:38:52AM	Analysis Adsorptive:	N_2
Completed:	3/3/2010 10:23:26PM	Analysis Bath Temp.:	77.300 K
Report Time:	3/3/2010 10:23:26PM	Sample Mass:	0.3025 g
Warm Free Space:	10.3506 cm^3 Measured	Cold Free Space:	24.7405 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

BJH Adsorption Pore Distribution Report

Faas Correction Halsey

$$t = 3.54 [-5 / \ln(P/Po)] ^ {0.333}$$

Diameter Range:	17.000 Å to 3000.000 Å
Adsorbate Property Factor:	9.53000 Å
Density Conversion Factor:	0.0015468
Fraction of Pores Open at Both Ends:	0.00

Pore Diameter Range (Å)	Average Diameter (Å)	Incremental Pore Volume (cm^3/g)	Cumulative Pore Volume (cm^3/g)	Incremental Pore Area (m^2/g)	Cumulative Pore Area (m^2/g)
3307.8 - 2641.8	2900.227	0.003268	0.003268	0.045069	0.045069
2641.8 - 2105.7	2313.063	0.002015	0.005282	0.034838	0.079906
2105.7 - 1907.9	1996.917	0.001826	0.007109	0.036584	0.116491
1907.9 - 1711.1	1798.657	0.002281	0.00939	0.05073	0.16722
1711.1 - 1444.8	1555.219	0.003567	0.012957	0.091735	0.258955
1444.8 - 1264.9	1342.701	0.003403	0.016359	0.101373	0.360329
1264.9 - 1217.7	1240.383	0.001904	0.018263	0.061387	0.421716
1217.7 - 1059.1	1127.148	0.002653	0.020916	0.094145	0.515861
1059.1 - 941.4	993.1727	0.003092	0.024008	0.124544	0.640405
941.4 - 816.2	869.6889	0.004431	0.028439	0.203799	0.844205
816.2 - 739.9	774.2182	0.003773	0.032212	0.194934	1.039139
739.9 - 670.0	701.3548	0.003404	0.035616	0.194127	1.233266

670.0 - 602.5	632.5488	0.003895	0.039511	0.246278	1.479544
602.5 - 535.1	564.6956	0.005035	0.044546	0.356687	1.836231
535.1 - 469.4	497.7851	0.006543	0.051089	0.525754	2.361985
469.4 - 414.9	438.6281	0.007024	0.058113	0.640564	3.002549
414.9 - 364.4	386.2456	0.00806	0.066174	0.834752	3.837302
364.4 - 328.4	344.46	0.007288	0.073461	0.846257	4.683559
328.4 - 295.5	310.1247	0.007222	0.080683	0.931469	5.615027
295.5 - 259.7	275.1638	0.009872	0.090555	1.435071	7.050098
259.7 - 233.3	244.997	0.009098	0.099653	1.485458	8.535556
233.3 - 207.6	218.8149	0.009806	0.109459	1.792524	10.32808
207.6 - 180.5	191.9666	0.013096	0.122555	2.72875	13.05683
180.5 - 160.7	169.3265	0.011572	0.134127	2.733629	15.79046
160.7 - 142.7	150.5496	0.01174	0.145867	3.119287	18.90975
142.7 - 126.1	133.3097	0.012827	0.158694	3.848928	22.75867
126.1 - 113.7	119.1877	0.010902	0.169597	3.658865	26.41754
113.7 - 102.1	107.1818	0.010834	0.180431	4.043364	30.4609
102.1 - 89.7	94.99547	0.013774	0.194205	5.799849	36.26075
89.7 - 81.1	84.8776	0.011066	0.205271	5.215108	41.47586
81.1 - 69.9	74.49716	0.016127	0.221398	8.659031	50.13489
69.9 - 59.9	64.00991	0.017048	0.238446	10.65365	60.78854
59.9 - 52.2	55.44089	0.015691	0.254137	11.32064	72.10918
52.2 - 46.0	48.62678	0.01472	0.268857	12.10826	84.21744
46.0 - 40.5	42.84722	0.015187	0.284043	14.17742	98.39486
40.5 - 36.9	38.4801	0.011754	0.295798	12.21864	110.6135
36.9 - 32.9	34.59088	0.014733	0.31053	17.03639	127.6499
32.9 - 30.4	31.54721	0.010496	0.321027	13.30862	140.9585
30.4 - 27.5	28.75873	0.014494	0.33552	20.15935	161.1179
27.5 - 24.9	26.03558	0.014229	0.34975	21.86139	182.9793
24.9 - 24.1	24.4761	0.005223	0.354973	8.535446	191.5147
24.1 - 23.2	23.6245	0.005408	0.360381	9.156355	200.6711
23.2 - 22.3	22.72247	0.006381	0.366761	11.23252	211.9036
22.3 - 21.4	21.80481	0.00631	0.373071	11.57452	223.4781
21.4 - 20.6	20.9829	0.005629	0.3787	10.73127	234.2094
20.6 - 20.4	20.5259	0.001601	0.380301	3.119931	237.3293
20.4 - 19.8	20.11347	0.004873	0.385174	9.690928	247.0202
19.8 - 19.5	19.63684	0.003033	0.388207	6.177351	253.1976

Goldwater Environmental Lab

TriStar II 3020 V1.02	Unit 1 Port 1	Serial #: 204	Page 1

Sample:	0.5M, 3DAY		
Operator:	ARTI		
Submitter:			
File:	C:\...\ARTI\000-119.SMP		
Started:	3/3/2010 10:38:52AM	Analysis Adsorptive:	N2
Completed:	3/3/2010 10:23:26PM	Analysis Bath Temp.:	77.300 K
Report Time:	3/3/2010 10:23:26PM	Sample Mass:	0.3025 g
Warm Free Space:	10.3506 cm^3 Measured	Cold Free Space:	24.7405 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

BJH Adsorption Cumulative Pore Volume
Halsey : Faas Correction

Pore Diameter (Å)	Pore Volume (cm^3/g)
2641.823	0.003268
2105.685	0.005282
1907.928	0.007109
1711.126	0.00939
1444.835	0.012957
1264.896	0.016359
1217.706	0.018263
1059.13	0.020916
941.4059	0.024008
816.243	0.028439
739.9104	0.032212
669.9662	0.035616
602.5284	0.039511
535.1414	0.044546
469.3807	0.051089
414.8886	0.058113
364.4465	0.066174
328.4226	0.073461
295.5034	0.080683
259.7212	0.090555
233.2999	0.099653

207.5584	0.109459
180.4596	0.122555
160.6889	0.134127
142.7392	0.145867
126.1437	0.158694
113.6774	0.169597
102.0862	0.180431
89.71359	0.194205
81.05018	0.205271
69.86205	0.221398
59.93851	0.238446
52.21467	0.254137
45.99652	0.268857
40.54689	0.284043
36.85683	0.295798
32.89918	0.31053
30.44336	0.321027
27.47563	0.33552
24.92854	0.34975
24.06527	0.354973
23.22487	0.360381
22.27509	0.366761
21.38529	0.373071
20.61988	0.3787
20.43431	0.380301
19.81938	0.385174
19.46354	0.388207

Goldwater Environmental Lab

TriStar II 3020
V1.02 Unit 1 Port 1 Serial #: 204 Page 1

Sample:	0.5M, 3DAY		
Operator:	ARTI		
Submitter:			
File:	C:\...\ARTI\000-119.SMP		
Started:	3/3/2010 10:38:52AM	Analysis Adsorptive:	N2
Completed:	3/3/2010 10:23:26PM	Analysis Bath Temp.:	77.300 K
Report Time:	3/3/2010 10:23:26PM	Sample Mass:	0.3025 g
Warm Free Space:	10.3506 cm³ Measured	Cold Free Space:	24.7405 cm³ Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm³	Automatic Degas:	No

BJH Adsorption dV/dlog(D) Pore Volume
Halsey : Faas Correction

Pore Diameter (Å)	dV/dlog(D) Pore Volume (cm³/g·Å)
2900.227	0.027772
2313.063	0.032709
1996.917	0.045807
1798.657	0.048374
1555.219	0.052242
1342.701	0.0708
1240.383	0.065964
1127.148	0.05106
993.1727	0.064973
869.6889	0.081446
774.2182	0.083718
701.3548	0.081412
632.5488	0.090269
564.6956	0.105948
497.7851	0.12368
438.6281	0.136286
386.2456	0.153733
344.46	0.159363
310.1247	0.164009
275.1638	0.188391
244.997	0.194076

218.8149	0.201308
191.9666	0.225825
169.3265	0.228649
150.5496	0.233259
133.3097	0.240819
119.1877	0.236453
107.1818	0.237713
94.99547	0.249047
84.8776	0.250387
74.49716	0.252224
64.00991	0.259566
55.44089	0.264373
48.62678	0.272339
42.84722	0.280959
38.4801	0.290404
34.59088	0.306476
31.54721	0.317597
28.75873	0.331486
26.03558	0.341742
24.4761	0.345557
23.6245	0.349454
22.72247	0.355004
21.80481	0.361431
20.9829	0.362008
20.5259	0.362385
20.11347	0.371571
19.63684	0.371571

Goldwater Environmental Lab

TriStar II 3020
V1.02 Unit 1 Port 1 Serial #: 204 Page 1

Sample:	0.5M, 3DAY		
Operator:	ARTI		
Submitter:			
File:	C:\...\ARTI\000-119.SMP		
Started:	3/3/2010 10:38:52AM	Analysis Adsorptive:	N2
Completed:	3/3/2010 10:23:26PM	Analysis Bath Temp.:	77.300 K
Report Time:	3/3/2010 10:23:26PM	Sample Mass:	0.3025 g
Warm Free Space:	10.3506 cm^3 Measured	Cold Free Space:	24.7405 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

BJH Adsorption Cumulative Pore Area
Halsey : Faas Correction

Pore Diameter (Å)	Pore Area (m^2/g)
2641.823	0.045069
2105.685	0.079906
1907.928	0.116491
1711.126	0.16722
1444.835	0.258955
1264.896	0.360329
1217.706	0.421716
1059.13	0.515861
941.4059	0.640405
816.243	0.844205
739.9104	1.039139
669.9662	1.233266
602.5284	1.479544
535.1414	1.836231
469.3807	2.361985
414.8886	3.002549
364.4465	3.837302
328.4226	4.683559
295.5034	5.615027
259.7212	7.050098
233.2999	8.535556

207.5584	10.32808
180.4596	13.05683
160.6889	15.79046
142.7392	18.90975
126.1437	22.75867
113.6774	26.41754
102.0862	30.4609
89.71359	36.26075
81.05018	41.47586
69.86205	50.13489
59.93851	60.78854
52.21467	72.10918
45.99652	84.21744
40.54689	98.39486
36.85683	110.6135
32.89918	127.6499
30.44336	140.9585
27.47563	161.1179
24.92854	182.9793
24.06527	191.5147
23.22487	200.6711
22.27509	211.9036
21.38529	223.4781
20.61988	234.2094
20.43431	237.3293
19.81938	247.0202
19.46354	253.1976

Goldwater Environmental Lab

TriStar II 3020 V1.02	Unit 1 Port 1	Serial #: 204	Page 1

Sample:	0.5M, 3DAY		
Operator:	ARTI		
Submitter:			
File:	C:\...\ARTI\000-119.SMP		
Started:	3/3/2010 10:38:52AM	Analysis Adsorptive:	N2
Completed:	3/3/2010 10:23:26PM	Analysis Bath Temp.:	77.300 K
Report Time:	3/3/2010 10:23:26PM	Sample Mass:	0.3025 g
Warm Free Space:	10.3506 cm^3 Measured	Cold Free Space:	24.7405 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

BJH Adsorption dA/dlog(D) Pore Area
Halsey : Faas Correction

Pore Diameter (Å)	dA/dlog(D) Pore Area (m^2/g·Å)
2900.227	0.410138
2313.063	0.609058
1996.917	0.974239
1798.657	1.146037
1555.219	1.448167
1342.701	2.273366
1240.383	2.176531
1127.148	1.936067
993.1727	2.729396
869.6889	4.091692
774.2182	4.537786
701.3548	4.868318
632.5488	6.06349
564.6956	7.994446
497.7851	10.62602
438.6281	13.2335
386.2456	17.03169
344.46	19.51394
310.1247	22.37826
275.1638	29.24226

244.997	33.47612
218.8149	39.20656
191.9666	50.39269
169.3265	57.32077
150.5496	65.73884
133.3097	77.0948
119.1877	83.58536
107.1818	93.77457
94.99547	112.0389
84.8776	124.7144
74.49716	145.9617
64.00991	175.1307
55.44089	204.2821
48.62678	239.421
42.84722	278.8553
38.4801	318.0395
34.59088	374.6951
31.54721	419.7131
28.75873	486.2516
26.03558	550.7242
24.4761	576.4721
23.6245	603.3466
22.72247	639.2789
21.80481	677.9021
20.9829	699.8454
20.5259	704.3806
20.11347	732.0225
19.63684	732.701

Goldwater Environmental Lab

TriStar II 3020			
V1.02	Unit 1 Port 3	Serial #: 204	Page 1

Sample:	2M,1DAY		
Operator:	ARTI		
File:	C:\...\ARTI\000-186.SMP		
Started:	5/4/2010 9:59:28AM	Analysis Adsorptive:	N2
Completed:	5/5/2010 4:13:56AM	Analysis Bath Temp.:	77.300 K
Report Time:	5/5/2010 4:13:57AM	Sample Mass:	0.8907 g
Warm Free Space:	10.6163 cm^3 Measured	Cold Free Space:	27.5716 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

Summary Report

Surface Area

BET Surface Area:	507.4122 m^2/g
t-Plot Micropore Area:	223.8474 m^2/g
t-Plot External Surface Area:	283.5648 m^2/g
BJH Adsorption cumulative surface area of pores between 17.000 Å and 3000.000 Å diameter:	246.640 m^2/g

Pore Volume

Single point adsorption total pore volume of pores less than 3678.941 Å diameter at P/Po = 0.994733518:	0.492026 cm^3/g
t-Plot micropore volume:	0.104756 cm^3/g
BJH Adsorption cumulative volume of pores between 17.000 Å and 3000.000 Å diameter:	0.374762 cm^3/g

Pore Size

Adsorption average pore width (4V/A by BET):	38.7871 Å
BJH Adsorption average pore diameter (4V/A):	60.779 Å

Goldwater Environmental Lab

TriStar II 3020			
V1.02	Unit 1 Port 3	Serial #: 204	Page 1
Sample:	2M,1DAY		
Operator:	ARTI		
File:	C:\...\ARTI\000-186.SMP		
Started:	5/4/2010 9:59:28AM	Analysis Adsorptive:	N2
Completed:	5/5/2010 4:13:56AM	Analysis Bath Temp.:	77.300 K
Report Time:	5/5/2010 4:13:57AM	Sample Mass:	0.8907 g
Warm Free Space:	10.6163 cm^3 Measured	Cold Free Space:	27.5716 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

Isotherm Tabular Report

Relative Pressure (P/Po)	Absolute Pressure (mmHg)	Quantity Adsorbed (cm^3/g STP)	Elapsed Time (h:min)	Saturation Pressure (mmHg)
			00:54	731.5276
0.009605	6.965879	108.6301	06:52	725.2464
0.026128	18.92655	118.5325	07:36	724.3717
0.028839	20.88364	119.6445	07:51	724.138
0.042782	30.97744	123.9305	08:08	724.0833
0.057084	41.32082	127.368	08:24	723.855
0.059679	43.19214	127.9813	08:34	723.7373
0.079523	57.53152	131.7151	08:45	723.4601
0.079763	57.70388	131.8027	08:51	723.4435
0.095753	69.25496	134.4198	09:01	723.263
0.100186	72.45779	135.1416	09:09	723.2355
0.113574	82.13755	137.1129	09:18	723.2099
0.121219	87.65059	138.2104	09:27	723.0739
0.131833	95.31515	139.6566	09:35	723.0011
0.142995	103.3641	141.1137	09:44	722.8499
0.150183	108.5611	142.0455	09:52	722.8585
0.163972	118.5158	143.7356	10:01	722.7795
0.167313	120.9425	144.1592	10:06	722.8537
0.184915	133.6338	146.2077	10:15	722.6783
0.205056	148.1744	148.4878	10:24	722.6047
0.223405	161.4318	150.4975	10:32	722.5967
0.240731	173.9333	152.3649	10:41	722.5209
0.25865	186.8676	154.256	10:49	722.4717
0.305761	220.8951	159.0912	11:00	722.4438

0.360448	260.3951	164.6419	11:11	722.4211
0.394205	284.7524	168.0964	11:20	722.3467
0.448985	324.2794	173.7464	11:35	722.2498
0.497811	359.4709	178.9777	11:48	722.1038
0.547452	395.236	184.6083	12:01	721.9553
0.597002	430.9483	190.6664	12:14	721.8539
0.64612	466.2884	197.3269	12:27	721.6747
0.696309	502.4224	204.9881	12:42	721.5508
0.739375	533.3735	212.4945	12:58	721.3843
0.764968	551.8001	217.6126	13:09	721.3375
0.793594	572.4011	224.0343	13:21	721.2769
0.815571	588.1816	229.385	13:32	721.1899
0.834734	601.9904	234.6251	13:43	721.1765
0.854069	615.8491	240.8082	13:54	721.0761
0.870622	627.6581	246.5123	14:06	720.9306
0.884302	637.3911	251.7453	14:17	720.7847
0.903544	651.101	259.8066	14:35	720.608
0.912305	657.2319	263.9318	14:44	720.4083
0.920322	662.8492	268.0488	14:54	720.2364
0.92727	667.6993	271.8506	15:04	720.0703
0.934064	672.5438	275.4489	15:13	720.0192
0.944969	680.1734	281.7281	15:31	719.7841
0.949933	683.6472	284.7119	15:40	719.6797
0.954614	686.9072	287.6432	15:48	719.5652
0.958505	689.6694	290.2476	15:57	719.526
0.962625	692.5761	292.7227	16:05	719.4658
0.966109	694.9929	295.0141	16:12	719.3734
0.969299	697.2456	297.179	16:20	719.3297
0.972106	699.1976	299.2297	16:27	719.2606
0.974756	701.0269	300.9783	16:34	719.182
0.976849	702.477	302.6548	16:41	719.1257
0.979179	704.1009	304.2554	16:47	719.0731
0.980999	705.3906	305.7844	16:53	719.0533
0.982882	706.6585	307.2503	17:00	718.9661
0.984654	707.853	308.6573	17:06	718.885
0.986565	709.1037	309.9976	17:12	718.7603
0.987913	710.0433	311.2847	17:17	718.7307
0.989265	710.926	312.5213	17:23	718.6406
0.990496	711.7813	313.7151	17:28	718.6113
0.991631	712.5591	314.8678	17:34	718.573
0.992934	713.3844	315.9799	17:40	718.4608
0.993953	714.058	317.0522	17:46	718.4019
0.994734	714.5601	318.0931	17:52	718.3433
0.994874	714.6189	319.1268	18:02	718.3007
0.995758	715.1829	320.1325	18:13	718.2297

Goldwater Environmental Lab

TriStar II 3020 V1.02	Unit 1 Port 3	Serial #: 204	Page 1
Sample:	2M,1DAY		
Operator:	ARTI		
File:	C:\...\ARTI\000-186.SMP		
Started:	5/4/2010 9:59:28AM	Analysis Adsorptive:	N2
Completed:	5/5/2010 4:13:56AM	Analysis Bath Temp.:	77.300 K
Report Time:	5/5/2010 4:13:57AM	Sample Mass:	0.8907 g
Warm Free Space:	10.6163 cm³ Measured	Cold Free Space:	27.5716 cm³ Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm³	Automatic Degas:	No

Isotherm Linear Plot

2M,1DAY - Adsorption

Relative Pressure (P/Po)	Quantity Adsorbed (cm³/g STP)
0.009605	108.6301
0.026128	118.5325
0.028839	119.6445
0.042782	123.9305
0.057084	127.368
0.059679	127.9813
0.079523	131.7151
0.079763	131.8027
0.095753	134.4198
0.100186	135.1416
0.113574	137.1129
0.121219	138.2104
0.131833	139.6566
0.142995	141.1137
0.150183	142.0455
0.163972	143.7356
0.167313	144.1592
0.184915	146.2077
0.205056	148.4878
0.223405	150.4975
0.240731	152.3649
0.25865	154.256
0.305761	159.0912

0.360448	164.6419
0.394205	168.0964
0.448985	173.7464
0.497811	178.9777
0.547452	184.6083
0.597002	190.6664
0.64612	197.3269
0.696309	204.9881
0.739375	212.4945
0.764968	217.6126
0.793594	224.0343
0.815571	229.385
0.834734	234.6251
0.854069	240.8082
0.870622	246.5123
0.884302	251.7453
0.903544	259.8066
0.912305	263.9318
0.920322	268.0488
0.92727	271.8506
0.934064	275.4489
0.944969	281.7281
0.949933	284.7119
0.954614	287.6432
0.958505	290.2476
0.962625	292.7227
0.966109	295.0141
0.969299	297.179
0.972106	299.2297
0.974756	300.9783
0.976849	302.6548
0.979179	304.2554
0.980999	305.7844
0.982882	307.2503
0.984654	308.6573
0.986565	309.9976
0.987913	311.2847
0.989265	312.5213
0.990496	313.7151
0.991631	314.8678
0.992934	315.9799
0.993953	317.0522
0.994734	318.0931
0.994874	319.1268
0.995758	320.1325

Goldwater Environmental Lab

TriStar II 3020			
V1.02	Unit 1 Port 3	Serial #: 204	Page 1
Sample:	2M,1DAY		
Operator:	ARTI		
File:	C:\...\ARTI\000-186.SMP		
Started:	5/4/2010 9:59:28AM	Analysis Adsorptive:	N2
Completed:	5/5/2010 4:13:56AM	Analysis Bath Temp.:	77.300 K
Report Time:	5/5/2010 4:13:57AM	Sample Mass:	0.8907 g
Warm Free Space:	10.6163 cm^3 Measured	Cold Free Space:	27.5716 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

Isotherm Log Plot

Relative Pressure (P/Po)	Quantity Adsorbed (cm^3/g STP)
0.009605	108.6301
0.026128	118.5325
0.028839	119.6445
0.042782	123.9305
0.057084	127.368
0.059679	127.9813
0.079523	131.7151
0.079763	131.8027
0.095753	134.4198
0.100186	135.1416
0.113574	137.1129
0.121219	138.2104
0.131833	139.6566
0.142995	141.1137
0.150183	142.0455
0.163972	143.7356
0.167313	144.1592
0.184915	146.2077
0.205056	148.4878
0.223405	150.4975
0.240731	152.3649
0.25865	154.256
0.305761	159.0912
0.360448	164.6419

0.394205	168.0964
0.448985	173.7464
0.497811	178.9777
0.547452	184.6083
0.597002	190.6664
0.64612	197.3269
0.696309	204.9881
0.739375	212.4945
0.764968	217.6126
0.793594	224.0343
0.815571	229.385
0.834734	234.6251
0.854069	240.8082
0.870622	246.5123
0.884302	251.7453
0.903544	259.8066
0.912305	263.9318
0.920322	268.0488
0.92727	271.8506
0.934064	275.4489
0.944969	281.7281
0.949933	284.7119
0.954614	287.6432
0.958505	290.2476
0.962625	292.7227
0.966109	295.0141
0.969299	297.179
0.972106	299.2297
0.974756	300.9783
0.976849	302.6548
0.979179	304.2554
0.980999	305.7844
0.982882	307.2503
0.984654	308.6573
0.986565	309.9976
0.987913	311.2847
0.989265	312.5213
0.990496	313.7151
0.991631	314.8678
0.992934	315.9799
0.993953	317.0522
0.994734	318.0931
0.994874	319.1268
0.995758	320.1325

Goldwater Environmental Lab

TriStar II 3020

V1.02	Unit 1 Port 3	Serial #: 204	Page 1

Sample:	2M,1DAY		
Operator:	ARTI		
Submitter:			
File:	C:\...\ARTI\000-186.SMP		
Started:	5/4/2010 9:59:28AM	Analysis Adsorptive:	N_2
Completed:	5/5/2010 4:13:56AM	Analysis Bath Temp.:	77.300 K
Report Time:	5/5/2010 4:13:57AM	Sample Mass:	0.8907 g
Warm Free Space:	10.6163 cm^3 Measured	Cold Free Space:	27.5716 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

BET Surface Area Report

BET Surface Area:	507.4122 ± 4.3547 m^2/g
Slope:	0.008603 ± 0.000073 g/cm^3 STP
Y-Intercept:	-0.000023 ± 0.000010 g/cm^3 STP
C:	-367.397894
Qm:	116.5608 cm^3/g STP
Correlation Coefficient:	0.9992825
Molecular Cross-Sectional Area:	0.1620 nm^2

Relative Pressure (P/Po)	Quantity Adsorbed (cm^3/g STP)	1/[Q(Po/P - 1)]
0.009605	108.6301	8.93E-05
0.026128	118.5325	0.000226
0.028839	119.6445	0.000248
0.042782	123.9305	0.000361
0.057084	127.368	0.000475
0.059679	127.9813	0.000496
0.079523	131.7151	0.000656
0.079763	131.8027	0.000658
0.095753	134.4198	0.000788
0.100186	135.1416	0.000824
0.113574	137.1129	0.000934

0.121219	138.2104	0.000998
0.131833	139.6566	0.001087
0.142995	141.1137	0.001182
0.150183	142.0455	0.001244
0.163972	143.7356	0.001365
0.167313	144.1592	0.001394
0.184915	146.2077	0.001552
0.205056	148.4878	0.001737
0.223405	150.4975	0.001911
0.240731	152.3649	0.002081
0.25865	154.256	0.002262

Goldwater Environmental Lab

TriStar II 3020

V1.02	Unit 1 Port 3	Serial #: 204	Page 1

Sample:	2M,1DAY		
Operator:	ARTI		
Submitter:			
File:	C:\...\ARTI\000-186.SMP		
Started:	5/4/2010 9:59:28AM	Analysis Adsorptive:	N2
Completed:	5/5/2010 4:13:56AM	Analysis Bath Temp.:	77.300 K
Report Time:	5/5/2010 4:13:57AM	Sample Mass:	0.8907 g
Warm Free Space:	10.6163 cm³ Measured	Cold Free Space:	27.5716 cm³ Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm³	Automatic Degas:	No

BET Surface Area Plot

Relative Pressure (P/Po)	1/[Q(Po/P - 1)]
0.009605	8.93E-05
0.026128	0.000226
0.028839	0.000248
0.042782	0.000361
0.057084	0.000475
0.059679	0.000496
0.079523	0.000656
0.079763	0.000658
0.095753	0.000788
0.100186	0.000824
0.113574	0.000934
0.121219	0.000998
0.131833	0.001087
0.142995	0.001182
0.150183	0.001244
0.163972	0.001365
0.167313	0.001394
0.184915	0.001552
0.205056	0.001737
0.223405	0.001911
0.240731	0.002081
0.25865	0.002262

Goldwater Environmental Lab

TriStar II 3020			
V1.02	Unit 1 Port 3	Serial #: 204	Page 1
Sample:	2M,1DAY		
Operator:	ARTI		
Submitter:			
File:	C:\...\ARTI\000-186.SMP		
Started:	5/4/2010 9:59:28AM	Analysis Adsorptive:	N2
Completed:	5/5/2010 4:13:56AM	Analysis Bath Temp.:	77.300 K
Report Time:	5/5/2010 4:13:57AM	Sample Mass:	0.8907 g
Warm Free Space:	10.6163 cm^3 Measured	Cold Free Space:	27.5716 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

BJH Adsorption Pore Distribution Report

Faas Correction Halsey

$t = 3.54 [-5 / \ln(P/Po)] ^ 0.333$

Diameter Range:	17.000 Å to 3000.000 Å
Adsorbate Property Factor:	9.53000 Å
Density Conversion Factor:	0.0015468
Fraction of Pores Open at Both Ends:	0.00

Pore Diameter Range (Å)	Average Diameter (Å)	Incremental Pore Volume (cm^3/g)	Cumulative Pore Volume (cm^3/g)	Incremental Pore Area (m^2/g)	Cumulative Pore Area (m^2/g)
3208.9 - 2750.9	2944.456	0.001723	0.001723	0.023402	0.023402
2750.9 - 2327.3	2503.472	0.001791	0.003514	0.02862	0.052022
2327.3 - 2052.8	2172.602	0.001867	0.005381	0.03437	0.086392
2052.8 - 1820.6	1922.589	0.00194	0.00732	0.040358	0.12675
1820.6 - 1619.9	1708.346	0.002016	0.009337	0.047205	0.173955
1619.9 - 1459.8	1531.389	0.002108	0.011444	0.055059	0.229014
1459.8 - 1281.0	1358.518	0.002197	0.013641	0.06468	0.293694
1281.0 - 1150.6	1208.65	0.002323	0.015964	0.076879	0.370573
1150.6 - 1038.7	1088.792	0.002432	0.018396	0.089335	0.459908
1038.7 - 949.6	990.0544	0.002552	0.020948	0.103093	0.563002

949.6 - 856.0	897.7907	0.002676	0.023623	0.119216	0.682217
856.0 - 786.5	818.1891	0.002826	0.02645	0.138171	0.820388
786.5 - 713.4	746.2632	0.002953	0.029403	0.158281	0.978669
713.4 - 649.6	678.4377	0.003493	0.032896	0.205968	1.184637
649.6 - 589.9	616.8119	0.003706	0.036602	0.240342	1.424978
589.9 - 536.3	560.4684	0.003948	0.04055	0.281792	1.70677
536.3 - 484.4	507.6088	0.004289	0.044839	0.337951	2.04472
484.4 - 444.0	462.3529	0.004564	0.049403	0.394847	2.439568
444.0 - 403.6	421.7706	0.005169	0.054572	0.490219	2.929787
403.6 - 368.2	384.1985	0.005302	0.059875	0.552052	3.481838
368.2 - 309.0	333.1854	0.011316	0.071191	1.358568	4.840407
309.0 - 281.0	293.6066	0.006554	0.077745	0.892958	5.733365
281.0 - 257.3	268.0227	0.007016	0.084761	1.047022	6.780387
257.3 - 234.5	244.737	0.007666	0.092427	1.252952	8.033339
234.5 - 213.8	223.1341	0.007748	0.100175	1.388922	9.422261
213.8 - 179.3	193.3287	0.015393	0.115568	3.184909	12.60717
179.3 - 160.9	169.0514	0.01016	0.125729	2.404087	15.01126
160.9 - 143.2	150.9415	0.011229	0.136958	2.97569	17.98695
143.2 - 126.9	133.9703	0.012403	0.149361	3.703325	21.69027
126.9 - 114.0	119.7072	0.010612	0.159973	3.546143	25.23641
114.0 - 102.2	107.3611	0.010991	0.170964	4.094942	29.33136
102.2 - 89.9	95.14103	0.013505	0.184469	5.677876	35.00923
89.9 - 81.2	85.01344	0.010938	0.195407	5.14643	40.15566
81.2 - 69.6	74.37378	0.016385	0.211792	8.812254	48.96792
69.6 - 59.6	63.68901	0.01722	0.229012	10.81489	59.78281
59.6 - 52.0	55.19757	0.015375	0.244387	11.14209	70.92489
52.0 - 46.0	48.53894	0.014313	0.2587	11.79506	82.71996
46.0 - 41.0	43.10853	0.013648	0.272349	12.66401	95.38397
41.0 - 36.8	38.62263	0.012998	0.285347	13.46199	108.846
36.8 - 32.9	34.5611	0.014452	0.299799	16.72679	125.5728
32.9 - 30.7	31.68608	0.009059	0.308858	11.43585	137.0086
30.7 - 27.5	28.88047	0.014927	0.323786	20.67442	157.683
27.5 - 25.0	26.1215	0.013291	0.337077	20.35262	178.0356
25.0 - 24.1	24.56682	0.005276	0.342353	8.5912	186.6268
24.1 - 23.3	23.69526	0.005271	0.347624	8.897161	195.524
23.3 - 22.4	22.82733	0.005694	0.353317	9.976907	205.5009
22.4 - 21.5	21.90451	0.006541	0.359858	11.94485	217.4458
21.5 - 20.6	21.02172	0.005881	0.365739	11.19027	228.636
20.6 - 20.5	20.55323	0.001295	0.367035	2.520837	231.1569
20.5 - 19.8	20.13931	0.004924	0.371959	9.780801	240.9377
19.8 - 19.5	19.65962	0.002803	0.374762	5.702466	246.6401

Goldwater Environmental Lab

TriStar II 3020
V1.02 Unit 1 Port 3 Serial #: 204 Page 1

Sample:	2M,1DAY		
Operator:	ARTI		
Submitter:			
File:	C:\...\ARTI\000-186.SMP		
Started:	5/4/2010 9:59:28AM	Analysis Adsorptive:	N2
Completed:	5/5/2010 4:13:56AM	Analysis Bath Temp.:	77.300 K
Report Time:	5/5/2010 4:13:57AM	Sample Mass:	0.8907 g
Warm Free Space:	10.6163 cm^3 Measured	Cold Free Space:	27.5716 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

BJH Adsorption Cumulative Pore Volume
Halsey : Faas Correction

Pore Diameter (Å)	Pore Volume (cm^3/g)
2750.916	0.001723
2327.261	0.003514
2052.772	0.005381
1820.626	0.00732
1619.867	0.009337
1459.841	0.011444
1280.965	0.013641
1150.61	0.015964
1038.687	0.018396
949.6103	0.020948
855.9506	0.023623
786.4807	0.02645
713.3923	0.029403
649.6471	0.032896
589.9367	0.036602
536.3056	0.04055
484.4069	0.044839
443.978	0.049403
403.5941	0.054572
368.2122	0.059875
309.0166	0.071191

281.017	0.077745
257.263	0.084761
234.4716	0.092427
213.8379	0.100175
179.3299	0.115568
160.9392	0.125729
143.2103	0.136958
126.9051	0.149361
114.0408	0.159973
102.1512	0.170964
89.90163	0.184469
81.15203	0.195407
69.6304	0.211792
59.58208	0.229012
52.03409	0.244387
45.96006	0.2587
40.96691	0.272349
36.83158	0.285347
32.86732	0.299799
30.69781	0.308858
27.52035	0.323786
25.03796	0.337077
24.14046	0.342353
23.29187	0.347624
22.40999	0.353317
21.45693	0.359858
20.63211	0.365739
20.47602	0.367035
19.83189	0.371959
19.49558	0.374762

Goldwater Environmental Lab

TriStar II 3020 V1.02	Unit 1 Port 3	Serial #: 204	Page 1
Sample:	2M,1DAY		
Operator:	ARTI		
Submitter:			
File:	C:\...\ARTI\000-186.SMP		
Started:	5/4/2010 9:59:28AM	Analysis Adsorptive:	N2
Completed:	5/5/2010 4:13:56AM	Analysis Bath Temp.:	77.300 K
Report Time:	5/5/2010 4:13:57AM	Sample Mass:	0.8907 g
Warm Free Space:	10.6163 cm^3 Measured	Cold Free Space:	27.5716 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

BJH Adsorption dV/dlog(D) Pore Volume
Halsey : Faas Correction

Pore Diameter (Å)	dV/dlog(D) Pore Volume (cm^3/g·Å)
2944.456	0.025047
2503.472	0.028995
2172.602	0.036448
1922.589	0.038342
1708.346	0.043372
1531.389	0.042491
1358.518	0.043968
1208.65	0.052326
1088.792	0.060207
990.0544	0.062143
897.7907	0.067806
818.1891	0.072664
746.2632	0.077959
678.4377	0.087122
616.8119	0.092006
560.4684	0.095964
507.6088	0.108763
462.3529	0.122551
421.7706	0.128798
384.1985	0.139438
333.1854	0.154862
293.6066	0.171227

268.0227	0.186586
244.737	0.19197
223.1341	0.195678
193.3287	0.210347
169.0514	0.218728
150.9415	0.229535
133.9703	0.232805
119.7072	0.22888
107.3611	0.236051
95.14103	0.24575
85.01344	0.246101
74.37378	0.249121
63.68901	0.258871
55.19757	0.263461
48.53894	0.269233
43.10853	0.2774
38.62263	0.286306
34.5611	0.300213
31.68608	0.308859
28.88047	0.319365
26.1215	0.330217
24.56682	0.334729
23.69526	0.338938
22.82733	0.343598
21.90451	0.349798
21.02172	0.350789
20.55323	0.351071
20.13931	0.359759
19.65962	0.359759

Goldwater Environmental Lab

TriStar II 3020
V1.02 Unit 1 Port 3 Serial #: 204 Page 1

Sample:	2M,1DAY		
Operator:	ARTI		
Submitter:			
File:	C:\...\ARTI\000-186.SMP		
Started:	5/4/2010 9:59:28AM	Analysis Adsorptive:	N2
Completed:	5/5/2010 4:13:56AM	Analysis Bath Temp.:	77.300 K
Report Time:	5/5/2010 4:13:57AM	Sample Mass:	0.8907 g
Warm Free Space:	10.6163 cm^3 Measured	Cold Free Space:	27.5716 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

BJH Adsorption Cumulative Pore Area
Halsey : Faas Correction

Pore Diameter (Å)	Pore Area (m^2/g)
2750.916	0.023402
2327.261	0.052022
2052.772	0.086392
1820.626	0.12675
1619.867	0.173955
1459.841	0.229014
1280.965	0.293694
1150.61	0.370573
1038.687	0.459908
949.6103	0.563002
855.9506	0.682217
786.4807	0.820388
713.3923	0.978669
649.6471	1.184637
589.9367	1.424978
536.3056	1.70677
484.4069	2.04472
443.978	2.439568
403.5941	2.929787
368.2122	3.481838
309.0166	4.840407

281.017	5.733365
257.263	6.780387
234.4716	8.033339
213.8379	9.422261
179.3299	12.60717
160.9392	15.01126
143.2103	17.98695
126.9051	21.69027
114.0408	25.23641
102.1512	29.33136
89.90163	35.00923
81.15203	40.15566
69.6304	48.96792
59.58208	59.78281
52.03409	70.92489
45.96006	82.71996
40.96691	95.38397
36.83158	108.846
32.86732	125.5728
30.69781	137.0086
27.52035	157.683
25.03796	178.0356
24.14046	186.6268
23.29187	195.524
22.40999	205.5009
21.45693	217.4458
20.63211	228.636
20.47602	231.1569
19.83189	240.9377
19.49558	246.6401

Goldwater Environmental Lab

TriStar II 3020 V1.02	Unit 1 Port 3	Serial #: 204	Page 1

Sample:	2M,1DAY		
Operator:	ARTI		
Submitter:			
File:	C:\...\ARTI\000-186.SMP		
Started:	5/4/2010 9:59:28AM	Analysis Adsorptive:	N2
Completed:	5/5/2010 4:13:56AM	Analysis Bath Temp.:	77.300 K
Report Time:	5/5/2010 4:13:57AM	Sample Mass:	0.8907 g
Warm Free Space:	10.6163 cm^3 Measured	Cold Free Space:	27.5716 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

BJH Adsorption dA/dlog(D) Pore Area
Halsey : Faas Correction

Pore Diameter (Å)	dA/dlog(D) Pore Area (m^2/g·Å)
2944.456	0.359855
2503.472	0.504666
2172.602	0.717528
1922.589	0.83911
1708.346	1.090619
1531.389	1.177035
1358.518	1.369553
1208.65	1.825134
1088.792	2.359552
990.0544	2.634211
897.7907	3.187465
818.1891	3.730283
746.2632	4.362219
678.4377	5.417965
616.8119	6.274564
560.4684	7.18054
507.6088	9.075093
462.3529	11.10696
421.7706	12.82679
384.1985	15.35748
333.1854	20.14734
293.6066	24.5515

268.0227	29.18133
244.737	32.88372
223.1341	37.03416
193.3287	47.2267
169.0514	54.62511
150.9415	64.71906
133.9703	73.8699
119.7072	80.50021
107.3611	93.42959
95.14103	109.9473
85.01344	122.3115
74.37378	144.9185
63.68901	175.532
55.19757	204.3832
48.53894	236.3632
43.10853	272.6791
38.62263	313.8339
34.5611	367.4771
31.68608	404.8585
28.88047	467.4726
26.1215	529.8953
24.56682	556.7953
23.69526	583.594
22.82733	614.9175
21.90451	654.0183
21.02172	677.6382
20.55323	681.2656
20.13931	708.2604
19.65962	708.5164

TriStar II 3020			
V1.02	Unit 1 Port 3	Serial #: 204	Page 1

Sample:	2M,3DAY		
Operator:	ARTI		
File:	C:\...\ARTI\000-121.SMP		
Started:	3/3/2010 10:38:52AM	Analysis Adsorptive:	N2
Completed:	3/3/2010 10:23:26PM	Analysis Bath Temp.:	77.300 K
Report Time:	3/3/2010 10:23:27PM	Sample Mass:	0.2935 g
Warm Free Space:	10.2589 cm³ Measured	Cold Free Space:	24.4298 cm³ Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm³	Automatic Degas:	No

Summary Report

Surface Area

BET Surface Area:	530.0958 m²/g
t-Plot Micropore Area:	232.6539 m²/g
t-Plot External Surface Area:	297.4420 m²/g
BJH Adsorption cumulative surface area of pores between 17.000 Å and 3000.000 Å diameter:	259.443 m²/g

Pore Volume

Single point adsorption total pore volume of pores less than 5697.616 Å diameter at P/Po = 0.996612628:	0.527092 cm³/g
t-Plot micropore volume:	0.108176 cm³/g
BJH Adsorption cumulative volume of pores between 17.000 Å and 3000.000 Å diameter:	0.399606 cm³/g

Pore Size

Adsorption average pore width (4V/A by BET):	39.7734 Å
BJH Adsorption average pore diameter (4V/A):	61.610 Å

Goldwater Environmental Lab

TriStar II 3020

V1.02	Unit 1 Port 3	Serial #: 204	Page 1
Sample:	2M,3DAY		
Operator:	ARTI		
Submitter:			
File:	C:\...\ARTI\000-121.SMP		
Started:	3/3/2010 10:38:52AM	Analysis Adsorptive:	N2
Completed:	3/3/2010 10:23:26PM	Analysis Bath Temp.:	77.300 K
Report Time:	3/3/2010 10:23:27PM	Sample Mass:	0.2935 g
Warm Free Space:	10.2589 cm^3 Measured	Cold Free Space:	24.4298 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

Isotherm Tabular Report

Relative Pressure (P/Po)	Absolute Pressure (mmHg)	Quantity Adsorbed (cm^3/g STP)	Elapsed Time (h:min)	Saturation Pressure (mmHg)
			00:56	732.0768
0.009588	7.002427	112.8959	03:26	730.3567
0.025838	18.86202	123.094	03:56	730.0216
0.029147	21.27315	124.5185	04:10	729.8604
0.043441	31.70378	129.0765	04:22	729.8047
0.05729	41.79939	132.5841	04:37	729.6104
0.060133	43.87205	133.2553	04:43	729.5779
0.078646	57.37314	136.9237	04:52	729.5087
0.079737	58.16533	137.1733	04:57	729.4667
0.095469	69.63673	139.8628	05:03	729.4138
0.100017	72.94871	140.6374	05:09	729.365
0.113412	82.71687	142.6965	05:15	729.3491
0.120635	87.98363	143.795	05:21	729.3351
0.131128	95.62712	145.2739	05:27	729.2646
0.141686	103.3202	146.7236	05:33	729.2171
0.14911	108.7311	147.7366	05:38	729.199
0.161766	117.9575	149.3671	05:44	729.186
0.166388	121.3187	149.9658	05:48	729.1312
0.181679	132.4569	151.8212	05:53	729.0699
0.199838	145.6888	153.9841	05:59	729.0361

0.202994	147.989	154.3829	06:03	729.0317
0.218977	159.6234	156.2215	06:09	728.9509
0.235979	171.994	158.1308	06:14	728.8524
0.253473	184.7439	160.0713	06:20	728.8512
0.302515	220.4557	165.3344	06:27	728.7433
0.35564	259.1629	170.9508	06:34	728.7231
0.394324	287.356	175.1181	06:41	728.7299
0.444025	323.5299	180.4342	06:48	728.6302
0.497709	362.6091	186.433	06:57	728.5567
0.549073	400.0052	192.5584	07:07	728.5099
0.599816	436.903	199.1156	07:18	728.395
0.648858	472.5966	206.1595	07:28	728.3518
0.698015	508.3763	214.179	07:38	728.3167
0.733283	534.0236	220.7123	07:46	728.264
0.764191	556.4371	227.0112	07:53	728.1387
0.799916	582.5001	235.35	08:05	728.2012
0.816091	594.284	239.8831	08:12	728.2084
0.835857	608.626	246.1101	08:20	728.1463
0.855012	622.5569	252.8693	08:29	728.1266
0.871274	634.2705	259.0139	08:37	727.9803
0.885155	644.3445	265.1524	08:45	727.9457
0.899633	654.8199	272.3445	08:54	727.8743
0.912527	664.1894	278.7659	09:02	727.8575
0.921751	670.8972	283.6992	09:09	727.8511
0.930265	677.1627	288.7211	09:16	727.9247
0.938079	682.8858	293.4635	09:24	727.9615
0.94532	688.0752	297.7833	09:31	727.8755
0.951082	692.3057	301.5017	09:37	727.9137
0.956895	696.4738	305.7041	09:44	727.848
0.963101	700.9503	310.173	09:51	727.8059
0.967516	704.2077	312.9231	09:57	727.8516
0.969217	705.4456	314.3678	10:02	727.8511
0.97366	708.6859	317.5737	10:09	727.8574
0.975804	710.267	319.1265	10:13	727.8786
0.978781	712.4478	321.5925	10:19	727.8931
0.981683	714.5164	323.9845	10:24	727.8481
0.983661	715.9972	325.636	10:28	727.8903
0.985283	717.1636	327.1906	10:32	727.8758
0.987188	718.5599	329.2582	10:38	727.8857
0.989319	720.0895	330.9819	10:42	727.8636
0.988594	719.5446	331.0414	10:44	727.8461
0.991129	721.4175	333.1529	10:49	727.8743
0.993288	722.9953	335.4269	10:53	727.8807
0.9942	723.6762	336.3956	10:57	727.8981
0.994303	723.7432	337.1746	11:01	727.8901

0.994859	724.1762	338.5088	11:11	727.9183
0.996613	725.4611	340.7631	11:22	727.9269
0.996578	725.3821	340.8683	11:32	727.8729
0.998144	726.5197	343.0811	11:43	727.8705

Goldwater Environmental Lab

TriStar II 3020 V1.02	Unit 1 Port 3	Serial #: 204	Page 1

Sample:	2M,3DAY		
Operator:	ARTI		
File:	C:\...\ARTI\000-121.SMP		
Started:	3/3/2010 10:38:52AM	Analysis Adsorptive:	N2
Completed:	3/3/2010 10:23:26PM	Analysis Bath Temp.:	77.300 K
Report Time:	3/3/2010 10:23:27PM	Sample Mass:	0.2935 g
Warm Free Space:	10.2589 cm^3 Measured	Cold Free Space:	24.4298 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

Isotherm Linear Plot

000-121 - Adsorption

Relative Pressure (P/Po)	Quantity Adsorbed (cm^3/g STP)
0.009588	112.8959
0.025838	123.094
0.029147	124.5185
0.043441	129.0765
0.05729	132.5841
0.060133	133.2553
0.078646	136.9237
0.079737	137.1733
0.095469	139.8628
0.100017	140.6374
0.113412	142.6965
0.120635	143.795
0.131128	145.2739
0.141686	146.7236
0.14911	147.7366
0.161766	149.3671
0.166388	149.9658
0.181679	151.8212
0.199838	153.9841
0.202994	154.3829
0.218977	156.2215
0.235979	158.1308
0.253473	160.0713

0.302515	165.3344
0.35564	170.9508
0.394324	175.1181
0.444025	180.4342
0.497709	186.433
0.549073	192.5584
0.599816	199.1156
0.648858	206.1595
0.698015	214.179
0.733283	220.7123
0.764191	227.0112
0.799916	235.35
0.816091	239.8831
0.835857	246.1101
0.855012	252.8693
0.871274	259.0139
0.885155	265.1524
0.899633	272.3445
0.912527	278.7659
0.921751	283.6992
0.930265	288.7211
0.938079	293.4635
0.94532	297.7833
0.951082	301.5017
0.956895	305.7041
0.963101	310.173
0.967516	312.9231
0.969217	314.3678
0.97366	317.5737
0.975804	319.1265
0.978781	321.5925
0.981683	323.9845
0.983661	325.636
0.985283	327.1906
0.987188	329.2582
0.989319	330.9819
0.988594	331.0414
0.991129	333.1529
0.993288	335.4269
0.9942	336.3956
0.994303	337.1746
0.994859	338.5088
0.996613	340.7631
0.996578	340.8683
0.998144	343.0811

Goldwater Environmental Lab

TriStar II 3020
V1.02 Unit 1 Port 3 Serial #: 204 Page 1

Sample:	2M,3DAY		
Operator:	ARTI		
File:	C:\...\ARTI\000-121.SMP		
Started:	3/3/2010 10:38:52AM	Analysis Adsorptive:	N2
Completed:	3/3/2010 10:23:26PM	Analysis Bath Temp.:	77.300 K
Report Time:	3/3/2010 10:23:27PM	Sample Mass:	0.2935 g
Warm Free Space:	10.2589 cm^3 Measured	Cold Free Space:	24.4298 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

Isotherm Log Plot

Relative Pressure (P/Po)	Quantity Adsorbed (cm^3/g STP)
0.009588	112.8959
0.025838	123.094
0.029147	124.5185
0.043441	129.0765
0.05729	132.5841
0.060133	133.2553
0.078646	136.9237
0.079737	137.1733
0.095469	139.8628
0.100017	140.6374
0.113412	142.6965
0.120635	143.795
0.131128	145.2739
0.141686	146.7236
0.14911	147.7366
0.161766	149.3671
0.166388	149.9658
0.181679	151.8212
0.199838	153.9841
0.202994	154.3829
0.218977	156.2215
0.235979	158.1308
0.253473	160.0713

0.302515	165.3344
0.35564	170.9508
0.394324	175.1181
0.444025	180.4342
0.497709	186.433
0.549073	192.5584
0.599816	199.1156
0.648858	206.1595
0.698015	214.179
0.733283	220.7123
0.764191	227.0112
0.799916	235.35
0.816091	239.8831
0.835857	246.1101
0.855012	252.8693
0.871274	259.0139
0.885155	265.1524
0.899633	272.3445
0.912527	278.7659
0.921751	283.6992
0.930265	288.7211
0.938079	293.4635
0.94532	297.7833
0.951082	301.5017
0.956895	305.7041
0.963101	310.173
0.967516	312.9231
0.969217	314.3678
0.97366	317.5737
0.975804	319.1265
0.978781	321.5925
0.981683	323.9845
0.983661	325.636
0.985283	327.1906
0.987188	329.2582
0.989319	330.9819
0.988594	331.0414
0.991129	333.1529
0.993288	335.4269
0.9942	336.3956
0.994303	337.1746
0.994859	338.5088
0.996613	340.7631
0.996578	340.8683
0.998144	343.0811

Goldwater Environmental Lab

TriStar II 3020 V1.02	Unit 1 Port 3	Serial #: 204	Page 1

Sample:	2M,3DAY
Operator:	ARTI
Submitter:	
File:	C:\...\ARTI\000-121.SMP

Started:	3/3/2010 10:38:52AM	Analysis Adsorptive:	N_2
Completed:	3/3/2010 10:23:26PM	Analysis Bath Temp.:	77.300 K
Report Time:	3/3/2010 10:23:27PM	Sample Mass:	0.2935 g
Warm Free Space:	10.2589 cm^3 Measured	Cold Free Space:	24.4298 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

BET Surface Area Report

BET Surface Area:	530.0958 ± 4.1284 m^2/g
Slope:	0.008232 ± 0.000063 g/cm^3 STP
Y-Intercept:	-0.000020 ± 0.000009 g/cm^3 STP
C:	-416.037995
Qm:	121.7716 cm^3/g STP
Correlation Coefficient:	0.9993793
Molecular Cross-Sectional Area:	0.1620 nm^2

Relative Pressure (P/Po)	Quantity Adsorbed (cm^3/g STP)	1/[Q(Po/P - 1)]
0.009588	112.8959	8.57E-05
0.025838	123.094	0.000215
0.029147	124.5185	0.000241
0.043441	129.0765	0.000352
0.05729	132.5841	0.000458
0.060133	133.2553	0.00048
0.078646	136.9237	0.000623
0.079737	137.1733	0.000632
0.095469	139.8628	0.000755
0.100017	140.6374	0.00079
0.113412	142.6965	0.000896

0.120635	143.795	0.000954
0.131128	145.2739	0.001039
0.141686	146.7236	0.001125
0.14911	147.7366	0.001186
0.161766	149.3671	0.001292
0.166388	149.9658	0.001331
0.181679	151.8212	0.001462
0.199838	153.9841	0.001622
0.202994	154.3829	0.00165
0.218977	156.2215	0.001795
0.235979	158.1308	0.001953
0.253473	160.0713	0.002121

Goldwater Environmental Lab

TriStar II 3020 V1.02	Unit 1 Port 3	Serial #: 204	Page 1

Sample:	2M,3DAY		
Operator:	ARTI		
File:	C:\...\ARTI\000-121.SMP		
Started:	3/3/2010 10:38:52AM	Analysis Adsorptive:	N2
Completed:	3/3/2010 10:23:26PM	Analysis Bath Temp.:	77.300 K
Report Time:	3/3/2010 10:23:27PM	Sample Mass:	0.2935 g
Warm Free Space:	10.2589 cm³ Measured	Cold Free Space:	24.4298 cm³ Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm³	Automatic Degas:	No

BET Surface Area Plot

Relative Pressure (P/Po)	1/[Q(Po/P - 1)]
0.009588	8.57E-05
0.025838	0.000215
0.029147	0.000241
0.043441	0.000352
0.05729	0.000458
0.060133	0.00048
0.078646	0.000623
0.079737	0.000632
0.095469	0.000755
0.100017	0.00079
0.113412	0.000896
0.120635	0.000954
0.131128	0.001039
0.141686	0.001125
0.14911	0.001186
0.161766	0.001292
0.166388	0.001331
0.181679	0.001462
0.199838	0.001622
0.202994	0.00165
0.218977	0.001795
0.235979	0.001953
0.253473	0.002121

Goldwater Environmental Lab

TriStar II 3020

V1.02	Unit 1 Port 3	Serial #: 204	Page 1
Sample:	2M,3DAY		
Operator:	ARTI		
Submitter:			
File:	C:\...\ARTI\000-121.SMP		
Started:	3/3/2010 10:38:52AM	Analysis Adsorptive:	N2
Completed:	3/3/2010 10:23:26PM	Analysis Bath Temp.:	77.300 K
Report Time:	3/3/2010 10:23:27PM	Sample Mass:	0.2935 g
Warm Free Space:	10.2589 cm^3 Measured	Cold Free Space:	24.4298 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

BJH Adsorption Pore Distribution Report

Faas Correction Halsey

$t = 3.54 [-5 / \ln(P/Po)] ^ 0.333$

Diameter Range:	17.000 Å to 3000.000 Å
Adsorbate Property Factor:	9.53000 Å
Density Conversion Factor:	0.0015468
Fraction of Pores Open at Both Ends:	0.00

Pore Diameter Range (Å)	Average Diameter (Å)	Incremental Pore Volume (cm^3/g)	Cumulative Pore Volume (cm^3/g)	Incremental Pore Area (m^2/g)	Cumulative Pore Area (m^2/g)
2894.2 - 2197.4	2450.825	0.003657	0.003657	0.059688	0.059688
2197.4 - 1715.1	1896.687	0.003416	0.007073	0.072044	0.131731
1715.1 - 1529.6	1611.595	0.002917	0.00999	0.072406	0.204137
1529.6 - 1334.7	1418.689	0.003393	0.013383	0.095663	0.2998
1334.7 - 1204.5	1262.766	0.002559	0.015942	0.081064	0.380864
1204.5 - 1076.7	1133.277	0.002727	0.018669	0.096251	0.477114
1076.7 - 932.2	993.8154	0.003977	0.022646	0.160064	0.637179
932.2 - 819.8	868.5807	0.004132	0.026779	0.190299	0.827478
819.8 - 754.5	784.3465	0.002611	0.029389	0.133136	0.960614

754.5 - 648.0	692.8951	0.005436	0.034825	0.313834	1.274448
648.0 - 614.8	630.4923	0.002475	0.037301	0.157042	1.43149
614.8 - 543.0	574.3164	0.004709	0.042009	0.327938	1.759428
543.0 - 466.8	498.9387	0.007776	0.049785	0.623386	2.382814
466.8 - 412.8	436.3362	0.007398	0.057183	0.678176	3.06099
412.8 - 370.5	389.2575	0.006592	0.063775	0.677433	3.738422
370.5 - 328.4	346.7939	0.007731	0.071506	0.891689	4.630112
328.4 - 292.7	308.3837	0.008609	0.080115	1.1166	5.746712
292.7 - 261.8	275.4231	0.009231	0.089346	1.340636	7.087348
261.8 - 235.0	246.8873	0.009157	0.098502	1.483533	8.57088
235.0 - 205.8	218.3243	0.01209	0.110593	2.215143	10.78602
205.8 - 180.6	191.427	0.013826	0.124419	2.888991	13.67501
180.6 - 161.7	170.0388	0.011947	0.136365	2.810357	16.48537
161.7 - 144.1	151.8089	0.01207	0.148435	3.180238	19.66561
144.1 - 127.7	134.8438	0.013536	0.161971	4.015302	23.68091
127.7 - 114.4	120.2267	0.012657	0.174628	4.210972	27.89188
114.4 - 105.3	109.4151	0.009303	0.183931	3.40105	31.29293
105.3 - 89.6	96.0336	0.017331	0.201262	7.218622	38.51156
89.6 - 79.3	83.73764	0.013361	0.214623	6.382335	44.89389
79.3 - 70.0	73.99823	0.014211	0.228834	7.681823	52.57571
70.0 - 60.1	64.1479	0.017916	0.246749	11.17137	63.74709
60.1 - 52.4	55.62013	0.016125	0.262874	11.59644	75.34352
52.4 - 46.1	48.79335	0.015376	0.27825	12.60484	87.94837
46.1 - 41.0	43.16726	0.01474	0.29299	13.65804	101.6064
41.0 - 36.4	38.3711	0.014806	0.307795	15.43423	117.0406
36.4 - 32.9	34.42511	0.013439	0.321234	15.61554	132.6562
32.9 - 30.4	31.51327	0.010912	0.332146	13.85018	146.5064
30.4 - 27.3	28.65865	0.014975	0.347121	20.90126	167.4076
27.3 - 24.8	25.8894	0.014384	0.361505	22.22331	189.6309
24.8 - 23.9	24.31985	0.005396	0.3669	8.874588	198.5055
23.9 - 23.1	23.47165	0.005329	0.37223	9.081678	207.5872
23.1 - 22.3	22.67675	0.005186	0.377415	9.147033	216.7342
22.3 - 22.2	22.23608	0.001207	0.378622	2.171405	218.9056
22.2 - 21.3	21.70968	0.00617	0.384792	11.36839	230.274
21.3 - 20.6	20.92962	0.005259	0.390052	10.05129	240.3253
20.6 - 20.4	20.47932	0.001777	0.391829	3.471739	243.7971
20.4 - 19.8	20.06496	0.004733	0.396562	9.435301	253.2324
19.8 - 19.4	19.60359	0.003044	0.399606	6.21032	259.4427

Sample:	2M,3DAY		
Operator:	ARTI		
Submitter:			
File:	C:\...\ARTI\000-121.SMP		
Started:	3/3/2010 10:38:52AM	Analysis Adsorptive:	N2
Completed:	3/3/2010 10:23:26PM	Analysis Bath Temp.:	77.300 K
Report Time:	3/3/2010 10:23:27PM	Sample Mass:	0.2935 g
Warm Free Space:	10.2589 cm³ Measured	Cold Free Space:	24.4298 cm³ Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm³	Automatic Degas:	No

BJH Adsorption Cumulative Pore Volume
Halsey : Faas Correction

Pore Diameter (Å)	Pore Volume (cm³/g)
2197.366	0.003657
1715.122	0.007073
1529.631	0.00999
1334.724	0.013383
1204.455	0.015942
1076.721	0.018669
932.1741	0.022646
819.7836	0.026779
754.4929	0.029389
647.9554	0.034825
614.832	0.037301
543.0285	0.042009
466.7954	0.049785
412.8008	0.057183
370.5071	0.063775
328.4177	0.071506
292.6964	0.080115
261.8082	0.089346
235.0468	0.098502
205.7726	0.110593
180.6191	0.124419

161.7291	0.136365
144.1134	0.148435
127.7497	0.161971
114.3552	0.174628
105.3122	0.183931
89.60924	0.201262
79.30702	0.214623
70.02729	0.228834
60.06039	0.246749
52.4201	0.262874
46.13956	0.27825
40.95758	0.29299
36.44624	0.307795
32.87535	0.321234
30.40296	0.332146
27.34267	0.347121
24.77635	0.361505
23.90598	0.3669
23.07761	0.37223
22.31179	0.377415
22.16178	0.378622
21.3049	0.384792
20.5889	0.390052
20.37297	0.391829
19.78175	0.396562
19.43425	0.399606

Goldwater Environmental Lab

TriStar II 3020
V1.02 Unit 1 Port 3 Serial #: 204 Page 1

Sample:	2M,3DAY
Operator:	ARTI
Submitter:	
File:	C:\...\ARTI\000-121.SMP

Started:	3/3/2010 10:38:52AM	Analysis Adsorptive:	N2
Completed:	3/3/2010 10:23:26PM	Analysis Bath Temp.:	77.300 K
Report Time:	3/3/2010 10:23:27PM	Sample Mass:	0.2935 g
Warm Free Space:	10.2589 cm^3 Measured	Cold Free Space:	24.4298 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

BJH Adsorption dV/dlog(D) Pore Volume
Halsey : Faas Correction

Pore Diameter (Å)	dV/dlog(D) Pore Volume (cm^3/g·Å)
2450.825	0.029549
1896.687	0.047441
1611.595	0.059019
1418.689	0.05735
1262.766	0.056697
1133.277	0.058086
993.8154	0.070328
868.5807	0.073452
784.3465	0.075407
692.8951	0.094012
630.4923	0.093735
574.3164	0.098968
498.9387	0.132064
436.3362	0.139638
389.2575	0.14305
346.7939	0.158689
308.3837	0.183285
275.4231	0.193231
246.8873	0.198983
218.3243	0.228982
191.427	0.247905

170.0388	0.244432
151.8089	0.249183
134.8438	0.261688
120.2267	0.261454
109.4151	0.254205
96.0336	0.248323
83.73764	0.257145
73.99823	0.266228
64.1479	0.270895
55.62013	0.274996
48.79335	0.281062
43.16726	0.288748
38.3711	0.295512
34.42511	0.31159
31.51327	0.322483
28.65865	0.329974
25.8894	0.343207
24.31985	0.349568
23.47165	0.354049
22.67675	0.357831
22.23608	0.358604
21.70968	0.364901
20.92962	0.365722
20.47932	0.365786
20.06496	0.373518
19.60359	0.373518

Goldwater Environmental Lab

TriStar II 3020 V1.02	Unit 1 Port 3	Serial #: 204	Page 1
Sample:	2M,3DAY		
Operator:	ARTI		
Submitter:			
File:	C:\...\ARTI\000-121.SMP		
Started:	3/3/2010 10:38:52AM	Analysis Adsorptive:	N2
Completed:	3/3/2010 10:23:26PM	Analysis Bath Temp.:	77.300 K
Report Time:	3/3/2010 10:23:27PM	Sample Mass:	0.2935 g
Warm Free Space:	10.2589 cm^3 Measured	Cold Free Space:	24.4298 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

BJH Adsorption Cumulative Pore Area
Halsey : Faas Correction

Pore Diameter (Å)	Pore Area (m^2/g)
2197.366	0.059688
1715.122	0.131731
1529.631	0.204137
1334.724	0.2998
1204.455	0.380864
1076.721	0.477114
932.1741	0.637179
819.7836	0.827478
754.4929	0.960614
647.9554	1.274448
614.832	1.43149
543.0285	1.759428
466.7954	2.382814
412.8008	3.06099
370.5071	3.738422
328.4177	4.630112
292.6964	5.746712
261.8082	7.087348
235.0468	8.57088
205.7726	10.78602
180.6191	13.67501

161.7291	16.48537
144.1134	19.66561
127.7497	23.68091
114.3552	27.89188
105.3122	31.29293
89.60924	38.51156
79.30702	44.89389
70.02729	52.57571
60.06039	63.74709
52.4201	75.34352
46.13956	87.94837
40.95758	101.6064
36.44624	117.0406
32.87535	132.6562
30.40296	146.5064
27.34267	167.4076
24.77635	189.6309
23.90598	198.5055
23.07761	207.5872
22.31179	216.7342
22.16178	218.9056
21.3049	230.274
20.5889	240.3253
20.37297	243.7971
19.78175	253.2324
19.43425	259.4427

Goldwater Environmental Lab

TriStar II 3020 V1.02	Unit 1 Port 3	Serial #: 204	Page 1

Sample:	2M,3DAY		
Operator:	ARTI		
Submitter:			
File:	C:\...\ARTI\000-121.SMP		
Started:	3/3/2010 10:38:52AM	Analysis Adsorptive:	N2
Completed:	3/3/2010 10:23:26PM	Analysis Bath Temp.:	77.300 K
Report Time:	3/3/2010 10:23:27PM	Sample Mass:	0.2935 g
Warm Free Space:	10.2589 cm^3 Measured	Cold Free Space:	24.4298 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

BJH Adsorption dA/dlog(D) Pore Area
Halsey : Faas Correction

Pore Diameter (Å)	dA/dlog(D) Pore Area (m^2/g·Å)
2450.825	0.502236
1896.687	1.141807
1611.595	1.560299
1418.689	1.722798
1262.766	1.891314
1133.277	2.168509
993.8154	3.061005
868.5807	3.592167
784.3465	3.97931
692.8951	5.930943
630.4923	6.227616
574.3164	7.241578
498.9387	11.47903
436.3362	13.65126
389.2575	15.53236
346.7939	19.51847
308.3837	25.21657
275.4231	29.72989
246.8873	34.20606
218.3243	44.62007
191.427	55.67301

170.0388	60.77414
151.8089	69.40345
134.8438	82.86355
120.2267	91.8127
109.4151	97.73462
96.0336	111.2049
83.73764	131.0642
73.99823	153.7199
64.1479	182.1852
55.62013	211.8583
48.79335	245.7273
43.16726	284.4018
38.3711	326.8936
34.42511	381.3637
31.51327	426.7047
28.65865	486.3811
25.8894	556.4509
24.31985	586.8716
23.47165	615.3932
22.67675	643.0853
22.23608	648.9194
21.70968	686.8026
20.92962	708.5757
20.47932	713.1723
20.06496	737.4687
19.60359	738.3331

Goldwater Environmental Lab

TriStar II 3020

V1.02	Unit 1 Port 2	Serial #: 204	Page 1

Sample:	hd3000		
Operator:	ARTI		
File:	C:\...\ARTI\000-210.SMP		
Started:	6/3/2010 9:53:40AM	Analysis Adsorptive:	N2
Completed:	6/4/2010 2:26:44AM	Analysis Bath Temp.:	77.300 K
Report Time:	6/4/2010 2:26:44AM	Sample Mass:	0.9753 g
Warm Free Space:	10.3769 cm³ Measured	Cold Free Space:	27.9486 cm³ Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm³	Automatic Degas:	No

Summary Report

Surface Area

BET Surface Area:	532.1932 m²/g
t-Plot Micropore Area:	226.4249 m²/g
t-Plot External Surface Area:	305.7683 m²/g
BJH Adsorption cumulative surface area of pores between 17.000 Å and 3000.000 Å diameter:	268.475 m²/g

Pore Volume

Single point adsorption total pore volume of pores less than 2391.720 Å diameter at P/Po = 0.991859193:	0.540843 cm³/g
t-Plot micropore volume:	0.106202 cm³/g
BJH Adsorption cumulative volume of pores between 17.000 Å and 3000.000 Å diameter:	0.427555 cm³/g

Pore Size

Adsorption average pore width (4V/A by BET):	40.6501 Å
BJH Adsorption average pore diameter (4V/A):	63.701 Å

Goldwater Environmental Lab

TriStar II 3020 V1.02	Unit 1 Port 2	Serial #: 204	Page 1
Sample:	hd3000		
Operator:	ARTI		
File:	C:\...\ARTI\000-210.SMP		
Started:	6/3/2010 9:53:40AM	Analysis Adsorptive:	N2
Completed:	6/4/2010 2:26:44AM	Analysis Bath Temp.:	77.300 K
Report Time:	6/4/2010 2:26:44AM	Sample Mass:	0.9753 g
Warm Free Space:	10.3769 cm^3 Measured	Cold Free Space:	27.9486 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

Isotherm Tabular Report

Relative Pressure (P/Po)	Absolute Pressure (mmHg)	Quantity Adsorbed (cm^3/g STP)	Elapsed Time (h:min)	Saturation Pressure (mmHg)
			01:22	727.2888
0.009556	6.932704	112.6216	04:25	725.4529
0.02589	18.76737	123.2551	05:02	724.8874
0.028824	20.8889	124.5555	05:16	724.7004
0.042107	30.50597	129.025	05:31	724.4911
0.05729	41.49472	132.9874	05:46	724.291
0.059745	43.26794	133.6108	05:55	724.2103
0.079204	57.34145	137.5939	06:07	723.9736
0.079751	57.73689	137.7455	06:13	723.967
0.09561	69.20165	140.5696	06:24	723.7911
0.100383	72.64658	141.4021	06:33	723.6935
0.113925	82.43452	143.5628	06:43	723.5878
0.121513	87.913	144.7319	06:52	723.4839
0.132185	95.62225	146.2975	07:01	723.3964
0.14301	103.4336	147.8289	07:10	723.2601
0.15051	108.8414	148.8694	07:18	723.1495
0.164336	118.8225	150.7041	07:28	723.0475
0.182939	132.2644	153.0656	07:38	722.999
0.206182	149.0511	155.8924	07:48	722.9092
0.224235	162.0896	158.0354	07:57	722.8551
0.241843	174.7941	160.0853	08:06	722.7584
0.259492	187.5275	162.109	08:15	722.6729
0.30681	221.6776	167.3704	08:27	722.5242

0.36212	261.6374	173.4543	08:38	722.515
0.394042	284.6612	177.0358	08:49	722.4126
0.450564	325.4812	183.3765	09:06	722.3867
0.497894	359.673	188.9205	09:20	722.389
0.547248	395.2623	195.0569	09:34	722.2726
0.596687	430.9597	201.7274	09:49	722.2538
0.646389	466.8282	209.1195	10:04	722.209
0.695725	502.3978	217.4229	10:20	722.1215
0.739666	534.1512	225.8752	10:37	722.152
0.764492	552.0811	231.499	10:49	722.1545
0.793971	573.4061	239.0259	11:02	722.2004
0.815601	589.0739	245.0769	11:14	722.257
0.834432	602.6646	251.1147	11:26	722.2454
0.857793	619.59	259.2618	11:45	722.3074
0.869886	628.3549	264.5175	11:56	722.342
0.890304	643.1276	273.9115	12:16	722.3681
0.899045	649.4421	278.4796	12:26	722.3689
0.913787	660.1533	286.8469	12:45	722.4368
0.920238	664.6563	290.7812	12:55	722.2656
0.926354	669.068	294.865	13:06	722.2592
0.936373	676.3288	301.6645	13:23	722.2856
0.941008	679.6317	305.0841	13:33	722.2377
0.950126	686.1758	311.7426	13:52	722.1947
0.953973	688.8907	314.6616	14:01	722.1281
0.957769	691.5267	317.7834	14:10	722.0185
0.964025	696.0311	322.6049	14:26	722.0051
0.966528	697.8003	324.9242	14:34	721.9658
0.969823	700.197	327.5724	14:42	721.9844
0.971752	701.551	329.6196	14:50	721.9443
0.974159	703.1689	331.2826	14:57	721.8212
0.975767	704.3132	332.8851	15:04	721.8044
0.977305	705.4005	334.4384	15:11	721.781
0.980663	707.7703	337.3803	15:23	721.7261
0.982095	708.8436	338.7762	15:29	721.7668
0.983455	709.8328	340.1276	15:35	721.7745
0.984702	710.7064	341.4399	15:41	721.7476
0.985803	711.5281	342.7141	15:47	721.7754
0.986995	712.3876	343.9502	15:53	721.7742
0.988035	713.1583	345.1519	15:58	721.7947
0.98898	713.7899	346.3259	16:04	721.7434
0.990114	714.5652	347.4634	16:10	721.6997
0.99097	715.21	348.5711	16:15	721.7272
0.991859	715.8351	349.6528	16:20	721.7104
0.992491	716.2844	350.7141	16:26	721.7034
0.993599	717.0989	351.7421	16:31	721.7187

Goldwater Environmental Lab

TriStar II 3020 V1.02	Unit 1 Port 2	Serial #: 204	Page 1

Sample:	hd3000		
Operator:	ARTI		
File:	C:\...\ARTI\000-210.SMP		
Started:	6/3/2010 9:53:40AM	Analysis Adsorptive:	N2
Completed:	6/4/2010 2:26:44AM	Analysis Bath Temp.:	77.300 K
Report Time:	6/4/2010 2:26:44AM	Sample Mass:	0.9753 g
Warm Free Space:	10.3769 cm³ Measured	Cold Free Space:	27.9486 cm³ Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm³	Automatic Degas:	No

Isotherm Linear Plot

hd3000 - Adsorption

Relative Pressure (P/Po)	Quantity Adsorbed (cm³/g STP)
0.009556	112.6216
0.02589	123.2551
0.028824	124.5555
0.042107	129.025
0.05729	132.9874
0.059745	133.6108
0.079204	137.5939
0.079751	137.7455
0.09561	140.5696
0.100383	141.4021
0.113925	143.5628
0.121513	144.7319
0.132185	146.2975
0.14301	147.8289
0.15051	148.8694
0.164336	150.7041
0.182939	153.0656
0.206182	155.8924
0.224235	158.0354
0.241843	160.0853
0.259492	162.109
0.30681	167.3704

0.36212	173.4543
0.394042	177.0358
0.450564	183.3765
0.497894	188.9205
0.547248	195.0569
0.596687	201.7274
0.646389	209.1195
0.695725	217.4229
0.739666	225.8752
0.764492	231.499
0.793971	239.0259
0.815601	245.0769
0.834432	251.1147
0.857793	259.2618
0.869886	264.5175
0.890304	273.9115
0.899045	278.4796
0.913787	286.8469
0.920238	290.7812
0.926354	294.865
0.936373	301.6645
0.941008	305.0841
0.950126	311.7426
0.953973	314.6616
0.957769	317.7834
0.964025	322.6049
0.966528	324.9242
0.969823	327.5724
0.971752	329.6196
0.974159	331.2826
0.975767	332.8851
0.977305	334.4384
0.980663	337.3803
0.982095	338.7762
0.983455	340.1276
0.984702	341.4399
0.985803	342.7141
0.986995	343.9502
0.988035	345.1519
0.98898	346.3259
0.990114	347.4634
0.99097	348.5711
0.991859	349.6528
0.992491	350.7141
0.993599	351.7421

Goldwater Environmental Lab

TriStar II 3020

V1.02	Unit 1 Port 2	Serial #: 204	Page 1

Sample:	hd3000		
Operator:	ARTI		
File:	C:\...\ARTI\000-210.SMP		
Started:	6/3/2010 9:53:40AM	Analysis Adsorptive:	N2
Completed:	6/4/2010 2:26:44AM	Analysis Bath Temp.:	77.300 K
Report Time:	6/4/2010 2:26:44AM	Sample Mass:	0.9753 g
Warm Free Space:	10.3769 cm^3 Measured	Cold Free Space:	27.9486 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

Isotherm Log Plot

hd3000 - Adsorption

Relative Pressure (P/Po)	Quantity Adsorbed (cm^3/g STP)
0.009556	112.6216
0.02589	123.2551
0.028824	124.5555
0.042107	129.025
0.05729	132.9874
0.059745	133.6108
0.079204	137.5939
0.079751	137.7455
0.09561	140.5696
0.100383	141.4021
0.113925	143.5628
0.121513	144.7319
0.132185	146.2975
0.14301	147.8289
0.15051	148.8694
0.164336	150.7041
0.182939	153.0656
0.206182	155.8924
0.224235	158.0354
0.241843	160.0853
0.259492	162.109
0.30681	167.3704

0.36212	173.4543
0.394042	177.0358
0.450564	183.3765
0.497894	188.9205
0.547248	195.0569
0.596687	201.7274
0.646389	209.1195
0.695725	217.4229
0.739666	225.8752
0.764492	231.499
0.793971	239.0259
0.815601	245.0769
0.834432	251.1147
0.857793	259.2618
0.869886	264.5175
0.890304	273.9115
0.899045	278.4796
0.913787	286.8469
0.920238	290.7812
0.926354	294.865
0.936373	301.6645
0.941008	305.0841
0.950126	311.7426
0.953973	314.6616
0.957769	317.7834
0.964025	322.6049
0.966528	324.9242
0.969823	327.5724
0.971752	329.6196
0.974159	331.2826
0.975767	332.8851
0.977305	334.4384
0.980663	337.3803
0.982095	338.7762
0.983455	340.1276
0.984702	341.4399
0.985803	342.7141
0.986995	343.9502
0.988035	345.1519
0.98898	346.3259
0.990114	347.4634
0.99097	348.5711
0.991859	349.6528
0.992491	350.7141
0.993599	351.7421

Goldwater Environmental Lab

TriStar II 3020 V1.02	Unit 1 Port 2	Serial #: 204	Page 1

Sample:	hd3000		
Operator:	ARTI		
File:	C:\...\ARTI\000-210.SMP		
Started:	6/3/2010 9:53:40AM	Analysis Adsorptive:	N2
Completed:	6/4/2010 2:26:44AM	Analysis Bath Temp.:	77.300 K
Report Time:	6/4/2010 2:26:44AM	Sample Mass:	0.9753 g
Warm Free Space:	10.3769 cm³ Measured	Cold Free Space:	27.9486 cm³ Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm³	Automatic Degas:	No

BET Surface Area Report

BET Surface Area:	532.1932 ± 4.5096 m²/g
Slope:	0.008199 ± 0.000069 g/cm³ STP
Y-Intercept:	-0.000020 ± 0.000010 g/cm³ STP
C:	-415.212140
Qm:	122.2534 cm³/g STP
Correlation Coefficient:	0.9993348
Molecular Cross-Sectional Area:	0.1620 nm²

Relative Pressure (P/Po)	Quantity Adsorbed (cm³/g STP)	1/[Q(Po/P - 1)]
0.009556	112.6216	8.57E-05
0.02589	123.2551	0.000216
0.028824	124.5555	0.000238
0.042107	129.025	0.000341
0.05729	132.9874	0.000457
0.059745	133.6108	0.000476
0.079204	137.5939	0.000625
0.079751	137.7455	0.000629
0.09561	140.5696	0.000752
0.100383	141.4021	0.000789
0.113925	143.5628	0.000896

0.121513	144.7319	0.000956
0.132185	146.2975	0.001041
0.14301	147.8289	0.001129
0.15051	148.8694	0.00119
0.164336	150.7041	0.001305
0.182939	153.0656	0.001463
0.206182	155.8924	0.001666
0.224235	158.0354	0.001829
0.241843	160.0853	0.001993
0.259492	162.109	0.002162

Goldwater Environmental Lab

TriStar II 3020 V1.02	Unit 1 Port 2	Serial #: 204	Page 1

Sample:	hd3000
Operator:	ARTI
File:	C:\...\ARTI\000-210.SMP

Started:	6/3/2010 9:53:40AM	Analysis Adsorptive:	N2
Completed:	6/4/2010 2:26:44AM	Analysis Bath Temp.:	77.300 K
Report Time:	6/4/2010 2:26:44AM	Sample Mass:	0.9753 g
Warm Free Space:	10.3769 cm³ Measured	Cold Free Space:	27.9486 cm³ Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm³	Automatic Degas:	No

BET Surface Area Plot

Relative Pressure (P/Po)	1/[Q(Po/P - 1)]
0.009556	8.57E-05
0.02589	0.000216
0.028824	0.000238
0.042107	0.000341
0.05729	0.000457
0.059745	0.000476
0.079204	0.000625
0.079751	0.000629
0.09561	0.000752
0.100383	0.000789
0.113925	0.000896
0.121513	0.000956
0.132185	0.001041
0.14301	0.001129
0.15051	0.00119
0.164336	0.001305
0.182939	0.001463
0.206182	0.001666
0.224235	0.001829
0.241843	0.001993
0.259492	0.002162

Goldwater Environmental Lab

TriStar II 3020
V1.02 Unit 1 Port 2 Serial #: 204 Page 1

Sample:	hd3000		
Operator:	ARTI		
File:	C:\...\ARTI\000-210.SMP		
Started:	6/3/2010 9:53:40AM	Analysis Adsorptive:	N2
Completed:	6/4/2010 2:26:44AM	Analysis Bath Temp.:	77.300 K
Report Time:	6/4/2010 2:26:44AM	Sample Mass:	0.9753 g
Warm Free Space:	10.3769 cm^3 Measured	Cold Free Space:	27.9486 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

BJH Adsorption Pore Distribution Report

Faas Correction Hasley

$t = 3.54 [-5 / \ln(P/Po)] ^{0.333}$

Diameter Range:	17.000 Å to 3000.000 Å
Adsorbate Property Factor:	9.53000 Å
Density Conversion Factor:	0.0015468
Fraction of Pores Open at Both Ends:	0.00

Pore Diameter Range (Å)	Average Diameter (Å)	Incremental Pore Volume (cm^3/g)	Cumulative Pore Volume (cm^3/g)	Incremental Pore Area (m^2/g)	Cumulative Pore Area (m^2/g)
3033.1 - 2590.5	2776.695	0.001663	0.001663	0.023959	0.023959
2590.5 - 2391.7	2483.078	0.001722	0.003385	0.027739	0.051697
2391.7 - 2159.1	2263.373	0.001757	0.005142	0.031046	0.082744
2159.1 - 1974.7	2058.561	0.001803	0.006945	0.035043	0.117787
1974.7 - 1774.2	1863.589	0.001854	0.0088	0.039802	0.157588
1774.2 - 1636.1	1699.496	0.001922	0.010722	0.045236	0.202824
1636.1 - 1507.3	1566.344	0.001971	0.012693	0.050342	0.253166
1507.3 - 1382.7	1439.549	0.002032	0.014725	0.056457	0.309623
1382.7 - 1284.9	1330.17	0.002103	0.016828	0.063243	0.372867
1284.9 - 1189.7	1233.594	0.00217	0.018998	0.07037	0.443237
1189.7 - 1101.0	1141.854	0.002241	0.021239	0.078496	0.521733

1101.0 - 1021.0	1057.913	0.002322	0.023561	0.087806	0.609538
1021.0 - 872.8	935.0474	0.004918	0.028479	0.210389	0.819927
872.8 - 818.6	843.8924	0.002617	0.031097	0.124067	0.943994
818.6 - 768.7	792.032	0.00271	0.033806	0.136838	1.080832
768.7 - 704.7	733.8195	0.002803	0.036609	0.152798	1.23363
704.7 - 660.6	681.1874	0.0035	0.04011	0.20555	1.43918
660.6 - 597.1	625.576	0.004528	0.044638	0.289521	1.728702
597.1 - 556.6	575.401	0.004003	0.048641	0.278302	2.007003
556.6 - 476.2	509.9079	0.008365	0.057006	0.656194	2.663198
476.2 - 438.0	455.4059	0.005478	0.062484	0.481163	3.144361
438.0 - 405.1	420.1971	0.005147	0.067631	0.489933	3.634295
405.1 - 344.2	369.4818	0.011881	0.079512	1.286197	4.920492
344.2 - 319.9	331.1019	0.006173	0.085685	0.745759	5.666251
319.9 - 277.6	295.5984	0.012399	0.098084	1.677826	7.344077
277.6 - 257.0	266.4691	0.007536	0.10562	1.131241	8.475318
257.0 - 238.4	246.9359	0.007301	0.112921	1.182724	9.658042
238.4 - 204.6	218.7369	0.015754	0.128675	2.880906	12.53895
204.6 - 188.8	196.0289	0.008702	0.137378	1.775757	14.31471
188.8 - 160.1	171.8695	0.018169	0.155546	4.228478	18.54318
160.1 - 146.8	152.827	0.010345	0.165891	2.707693	21.25088
146.8 - 126.7	135.1257	0.016138	0.18203	4.777325	26.0282
126.7 - 114.1	119.6318	0.012202	0.194232	4.079882	30.10808
114.1 - 102.3	107.4827	0.012364	0.206596	4.601431	34.70951
102.3 - 89.7	95.08995	0.015739	0.222336	6.620738	41.33025
89.7 - 81.2	84.99955	0.011939	0.234275	5.618482	46.94873
81.2 - 69.5	74.31124	0.018241	0.252516	9.818805	56.76754
69.5 - 59.6	63.67685	0.01845	0.270966	11.59	68.35754
59.6 - 52.0	55.18507	0.016856	0.287822	12.21754	80.57508
52.0 - 45.9	48.50896	0.015606	0.303428	12.86872	93.4438
45.9 - 41.0	43.10527	0.014694	0.318122	13.63541	107.0792
41.0 - 37.0	38.70413	0.013584	0.331706	14.03913	121.1183
37.0 - 32.9	34.59835	0.015979	0.347686	18.47419	139.5925
32.9 - 30.8	31.74233	0.009296	0.356982	11.71451	151.307
30.8 - 27.6	28.95515	0.016093	0.373075	22.2323	173.5393
27.6 - 25.1	26.17014	0.014239	0.387315	21.76381	195.3031
25.1 - 24.2	24.61636	0.005576	0.392891	9.061106	204.3643
24.2 - 23.3	23.74225	0.00569	0.39858	9.585719	213.95
23.3 - 22.5	22.8751	0.00599	0.40457	10.47402	224.424
22.5 - 21.4	21.87531	0.007936	0.412506	14.51051	238.9345
21.4 - 20.5	20.90294	0.006709	0.419215	12.83906	251.7736
20.5 - 19.8	20.15538	0.005282	0.424497	10.48286	262.2564
19.8 - 19.5	19.66726	0.003057	0.427555	6.2181	268.4745

Goldwater Environmental Lab

TriStar II 3020 V1.02	Unit 1 Port 2	Serial #: 204	Page 1
Sample:	hd3000		
Operator:	ARTI		
File:	C:\...\ARTI\000-210.SMP		
Started:	6/3/2010 9:53:40AM	Analysis Adsorptive:	N2
Completed:	6/4/2010 2:26:44AM	Analysis Bath Temp.:	77.300 K
Report Time:	6/4/2010 2:26:44AM	Sample Mass:	0.9753 g
Warm Free Space:	10.3769 cm³ Measured	Cold Free Space:	27.9486 cm³ Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm³	Automatic Degas:	No

BJH Adsorption Cumulative Pore Volume
Halsey : Faas Correction

Pore Diameter (Å)	Pore Volume (cm³/g)
2590.513	0.001663
2391.72	0.003385
2159.121	0.005142
1974.704	0.006945
1774.241	0.0088
1636.136	0.010722
1507.31	0.012693
1382.739	0.014725
1284.928	0.016828
1189.748	0.018998
1101.001	0.021239
1021.009	0.023561
872.8015	0.028479
818.5666	0.031097
768.7263	0.033806
704.6636	0.036609
660.6486	0.04011
597.1433	0.044638
556.6173	0.048641
476.1872	0.057006
437.9662	0.062484

405.1127	0.067631
344.2121	0.079512
319.8778	0.085685
277.6354	0.098084
257.0018	0.10562
238.3703	0.112921
204.6124	0.128675
188.8184	0.137378
160.0567	0.155546
146.8462	0.165891
126.6801	0.18203
114.0592	0.194232
102.3343	0.206596
89.72212	0.222336
81.2422	0.234275
69.49544	0.252516
59.62885	0.270966
51.99123	0.287822
45.93754	0.303428
40.97455	0.318122
36.95543	0.331706
32.85644	0.347686
30.80115	0.356982
27.57801	0.373075
25.08065	0.387315
24.19552	0.392891
23.33215	0.39858
22.4637	0.40457
21.36405	0.412506
20.493	0.419215
19.84719	0.424497
19.49629	0.427555

Goldwater Environmental Lab

TriStar II 3020 V1.02	Unit 1 Port 2	Serial #: 204	Page 1
Sample:	hd3000		
Operator:	ARTI		
File:	C:\...\ARTI\000-210.SMP		
Started:	6/3/2010 9:53:40AM	Analysis Adsorptive:	N2
Completed:	6/4/2010 2:26:44AM	Analysis Bath Temp.:	77.300 K
Report Time:	6/4/2010 2:26:44AM	Sample Mass:	0.9753 g
Warm Free Space:	10.3769 cm³ Measured	Cold Free Space:	27.9486 cm³ Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm³	Automatic Degas:	No

BJH Adsorption dV/dlog(D) Pore Volume
Halsey : Faas Correction

Pore Diameter (Å)	dV/dlog(D) Pore Volume (cm³/g·Å)
2776.695	0.036223
2483.078	0.043527
2263.373	0.04294
2058.561	0.042487
1863.589	0.047517
1699.496	0.054613
1566.344	0.054911
1439.549	0.060111
1330.17	0.064874
1233.594	0.066019
1141.854	0.068659
1057.913	0.070762
935.0474	0.084109
843.8924	0.091559
792.032	0.087765
733.8195	0.097606
681.1874	0.108271
625.576	0.116686
575.401	0.123389
509.9079	0.139283
455.4059	0.151165
420.1971	0.156034

369.4818	0.184835
331.1019	0.194487
295.5984	0.215246
266.4691	0.223761
246.9359	0.228122
218.7369	0.245984
196.0289	0.250529
171.8695	0.264862
152.827	0.263101
135.1257	0.259872
119.6318	0.264602
107.4827	0.269032
95.08995	0.276581
84.99955	0.273107
74.31124	0.272229
63.67685	0.280451
55.18507	0.28681
48.50896	0.293276
43.10527	0.299491
38.70413	0.306793
34.59835	0.323743
31.74233	0.331989
28.95515	0.340077
26.17014	0.352941
24.61636	0.357549
23.74225	0.361005
22.8751	0.364252
21.87531	0.370564
20.90294	0.370449
20.15538	0.379919
19.66726	0.379919

Goldwater Environmental Lab

TriStar II 3020

V1.02	Unit 1 Port 2	Serial #: 204	Page 1

Sample:	hd3000		
Operator:	ARTI		
File:	C:\...\ARTI\000-210.SMP		
Started:	6/3/2010 9:53:40AM	Analysis Adsorptive:	N2
Completed:	6/4/2010 2:26:44AM	Analysis Bath Temp.:	77.300 K
Report Time:	6/4/2010 2:26:44AM	Sample Mass:	0.9753 g
Warm Free Space:	10.3769 cm^3 Measured	Cold Free Space:	27.9486 cm^3 Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm^3	Automatic Degas:	No

BJH Adsorption Cumulative Pore Area
Halsey : Faas Correction

Pore Diameter (Å)	Pore Area (m^2/g)
2590.513	0.023959
2391.72	0.051697
2159.121	0.082744
1974.704	0.117787
1774.241	0.157588
1636.136	0.202824
1507.31	0.253166
1382.739	0.309623
1284.928	0.372867
1189.748	0.443237
1101.001	0.521733
1021.009	0.609538
872.8015	0.819927
818.5666	0.943994
768.7263	1.080832
704.6636	1.23363
660.6486	1.43918
597.1433	1.728702
556.6173	2.007003
476.1872	2.663198
437.9662	3.144361
405.1127	3.634295

344.2121	4.920492
319.8778	5.666251
277.6354	7.344077
257.0018	8.475318
238.3703	9.658042
204.6124	12.53895
188.8184	14.31471
160.0567	18.54318
146.8462	21.25088
126.6801	26.0282
114.0592	30.10808
102.3343	34.70951
89.72212	41.33025
81.2422	46.94873
69.49544	56.76754
59.62885	68.35754
51.99123	80.57508
45.93754	93.4438
40.97455	107.0792
36.95543	121.1183
32.85644	139.5925
30.80115	151.307
27.57801	173.5393
25.08065	195.3031
24.19552	204.3643
23.33215	213.95
22.4637	224.424
21.36405	238.9345
20.493	251.7736
19.84719	262.2564
19.49629	268.4745

Goldwater Environmental Lab

TriStar II 3020 V1.02	Unit 1 Port 2	Serial #: 204	Page 1

Sample:	hd3000
Operator:	ARTI
File:	C:\...\ARTI\000-210.SMP

Started:	6/3/2010 9:53:40AM	Analysis Adsorptive:	N2
Completed:	6/4/2010 2:26:44AM	Analysis Bath Temp.:	77.300 K
Report Time:	6/4/2010 2:26:44AM	Sample Mass:	0.9753 g
Warm Free Space:	10.3769 cm³ Measured	Cold Free Space:	27.9486 cm³ Measured
Equilibration Interval:	10 s	Low Pressure Dose:	None
Sample Density:	1.000 g/cm³	Automatic Degas:	No

BJH Adsorption dA/dlog(D) Pore Area
Halsey : Faas Correction

Pore Diameter (Å)	dA/dlog(D) Pore Area (m²/g·Å)
2776.695	0.562932
2483.078	0.727961
2263.373	0.802994
2058.561	0.87263
1863.589	1.071402
1699.496	1.340845
1566.344	1.463522
1439.549	1.752186
1330.17	2.028594
1233.594	2.227761
1141.854	2.501894
1057.913	2.768644
935.0474	3.926326
843.8924	4.500085
792.032	4.535964
733.8195	5.625974
681.1874	6.604721
625.576	7.892485
575.401	9.085462
509.9079	11.59438
455.4059	13.86816
420.1971	15.64417

369.4818	21.54875
331.1019	24.55323
295.5984	31.12769
266.4691	34.96885
246.9359	38.7646
218.7369	48.19834
196.0289	52.92393
171.8695	67.55106
152.827	72.90135
135.1257	81.75158
119.6318	93.7725
107.4827	105.6674
95.08995	124.5057
84.99955	135.7656
74.31124	157.8648
63.67685	190.5273
55.18507	222.7023
48.50896	257.5271
43.10527	294.2747
38.70413	335.3698
34.59835	396.4153
31.74233	433.5233
28.95515	496.6744
26.17014	565.4056
24.61636	592.9823
23.74225	620.5631
22.8751	650.2559
21.87531	695.6607
20.90294	718.9845
20.15538	747.4209
19.66726	748.4014

APPENDIX C

IRON CONTENT DATA FOR ALL FE-GAC

Table C 2. Iron Content Data for all Fe-GAC

Fe-GAC Media	Absorbance	Conc. Fe Measured (ug/ml)	Dilution Factor	Conc. Fe Actual (ug/mL)	Total Fe (ug)	Total Fe (mg)	Wt.GAC digested (mg)	%Fe	Final % Fe	SD
0.5M-24hr	0.04	31.41	1.00	31.41	3140.72	3.14	337.90	0.93	0.93	0
2M-24hr	0.08	58.79	1.00	58.79	5879.10	5.88	341.40	1.72	1.72	0
0.5M-72hr	0.13	96.72	2.00	193.43	19343.36	19.34	455.10	4.25	4.4	0.23%
0.5M-72hr	0.15	113.60	2.00	227.20	22720.38	22.72	500.40	4.54		
0.5M-72hr	0.14	102.59	2.00	205.18	20517.97	20.52	499.80	4.11		
0.5M-72hr	0.08	57.39	4.00	229.55	22954.69	22.95	500.80	4.58		
2M-72hr	0.15	108.64	1.00	108.64	10864.36	10.86	500.60	2.17	2.17	0

Note: 0.5 m, 3 Day Fe-GAC was analyzed 4 times.

APPENDIX D

ADDITIONAL SEM IMAGES OF 0.5M-72HR FE-GAC

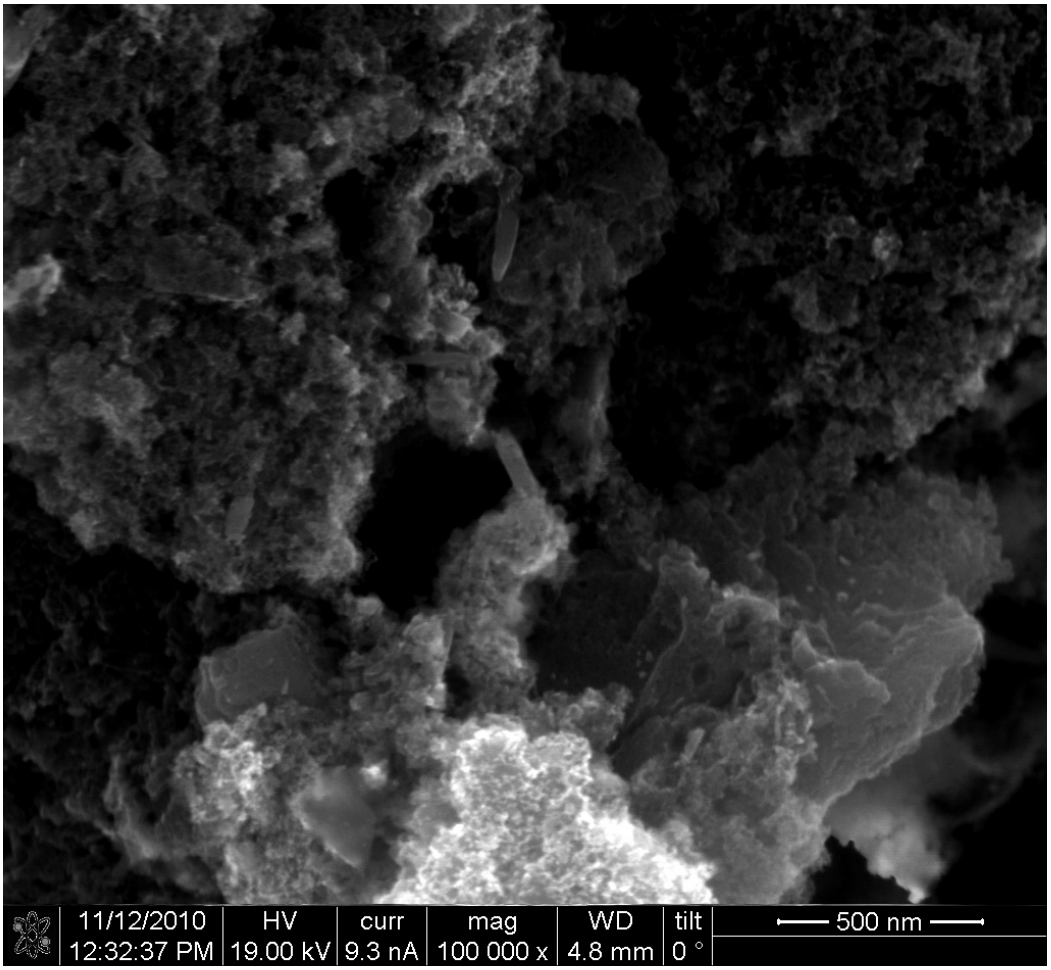

Figure D 1: SEM image of 0.5 M-72hr Fe-GAC

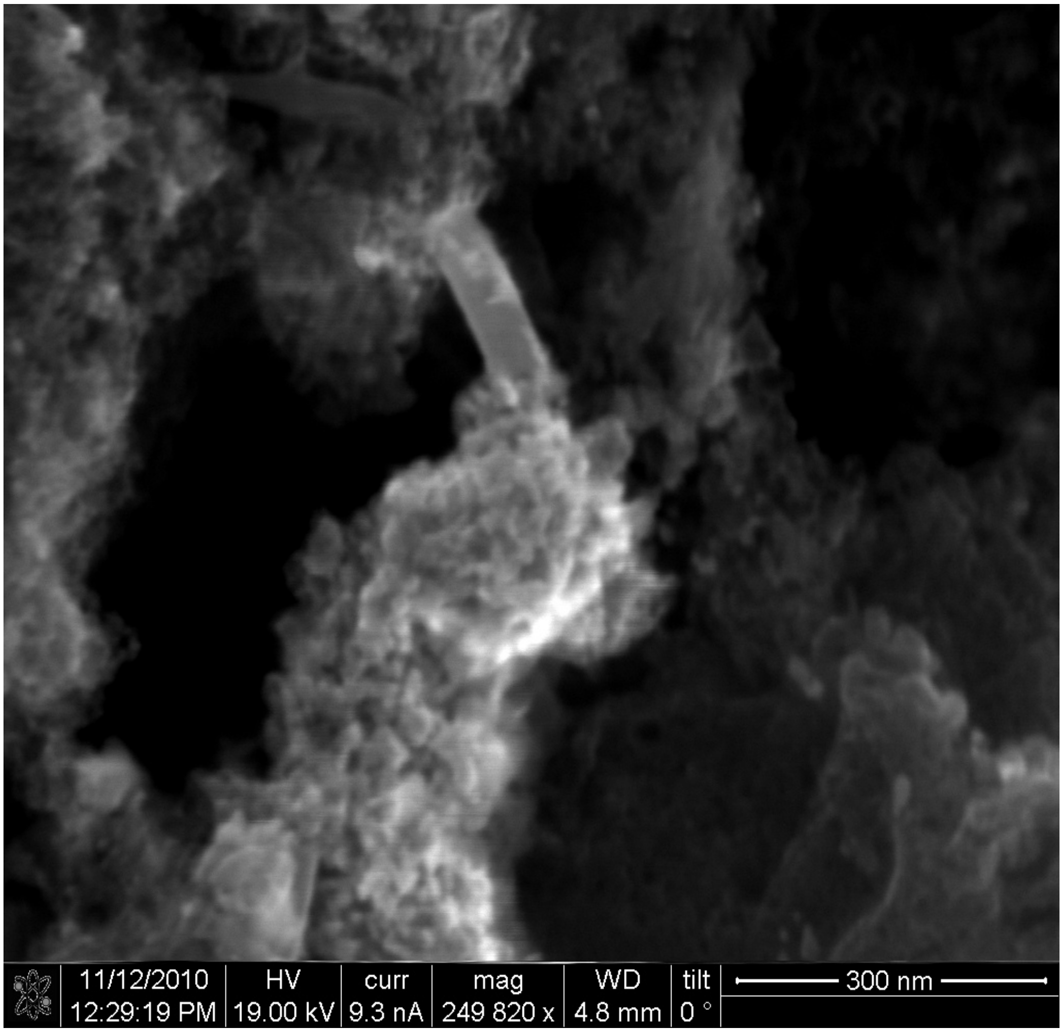

Figure D 2. SEM image of 0.5 M-72hr Fe-GAC

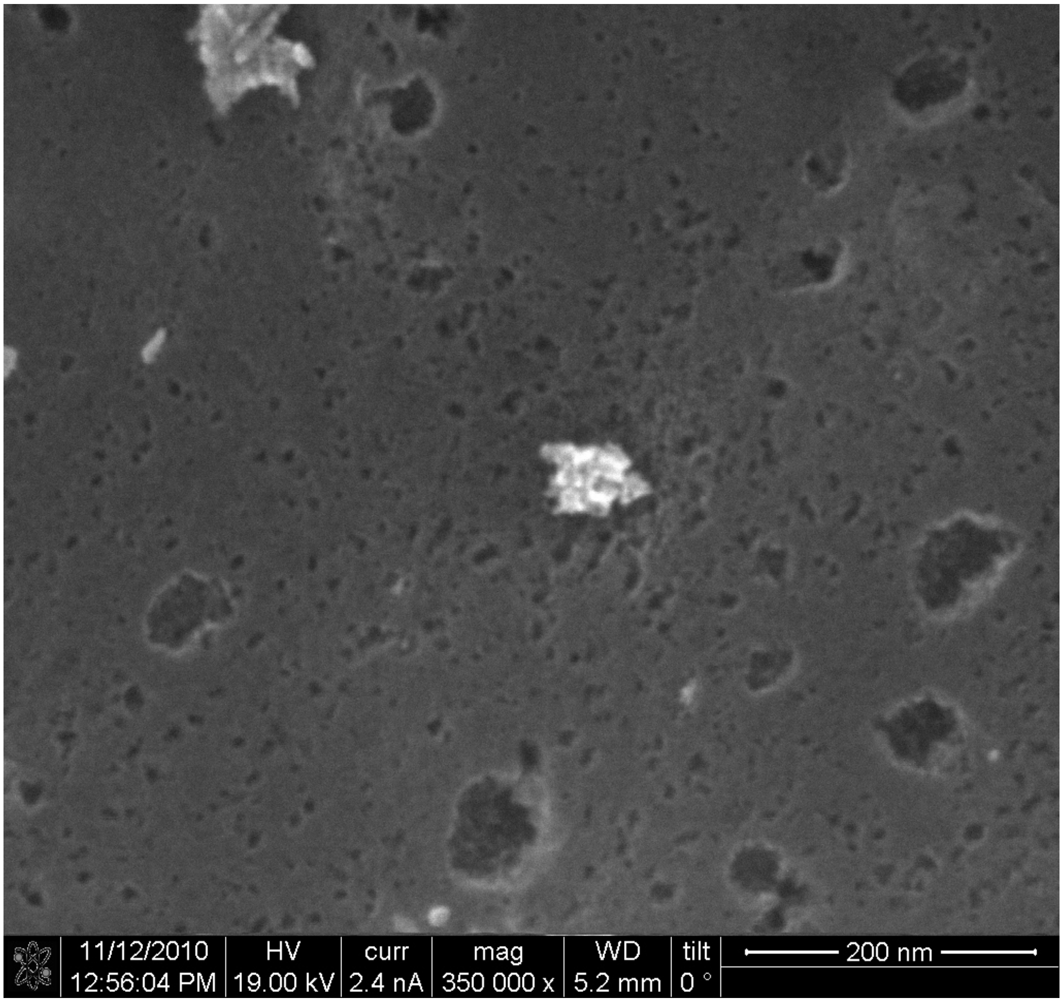

Figure D 3. SEM image of 0.5 M-72hr Fe-GAC

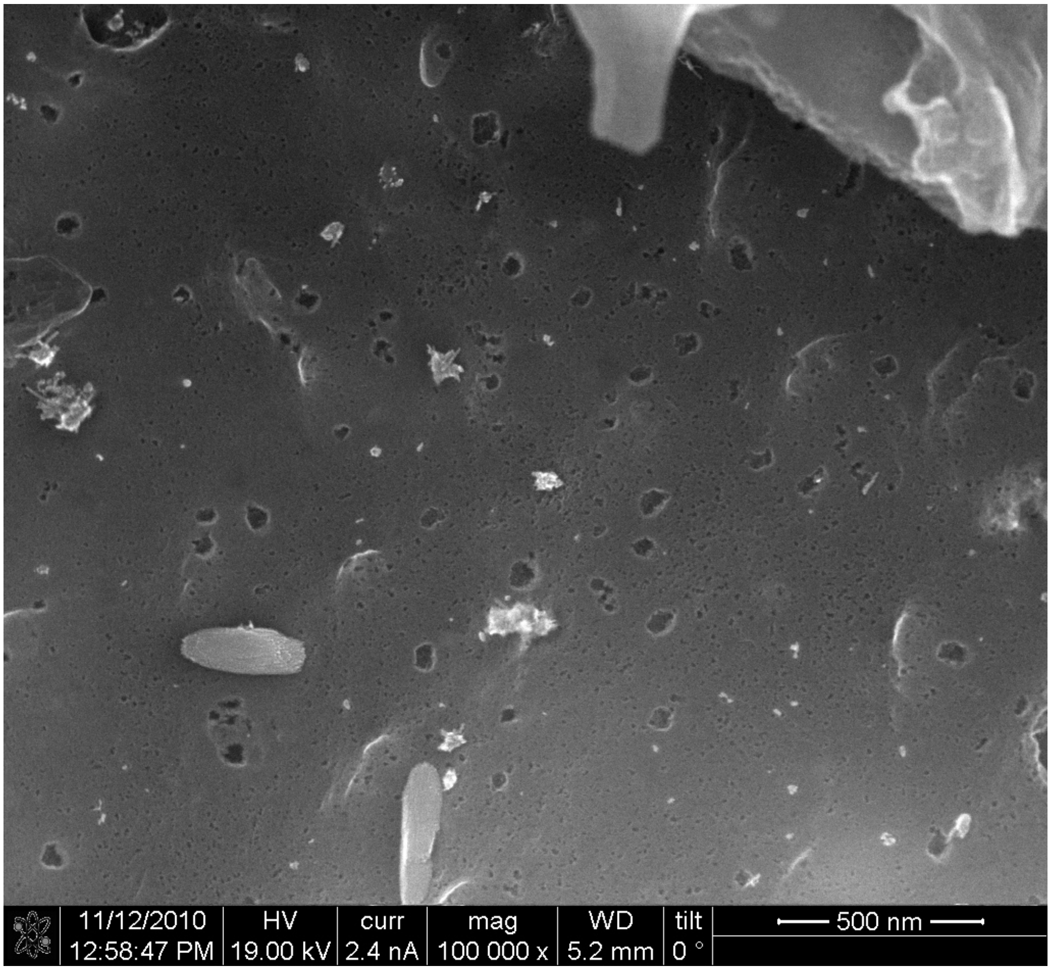

Figure D 4. SEM image of 0.5 M-72hr Fe-GAC

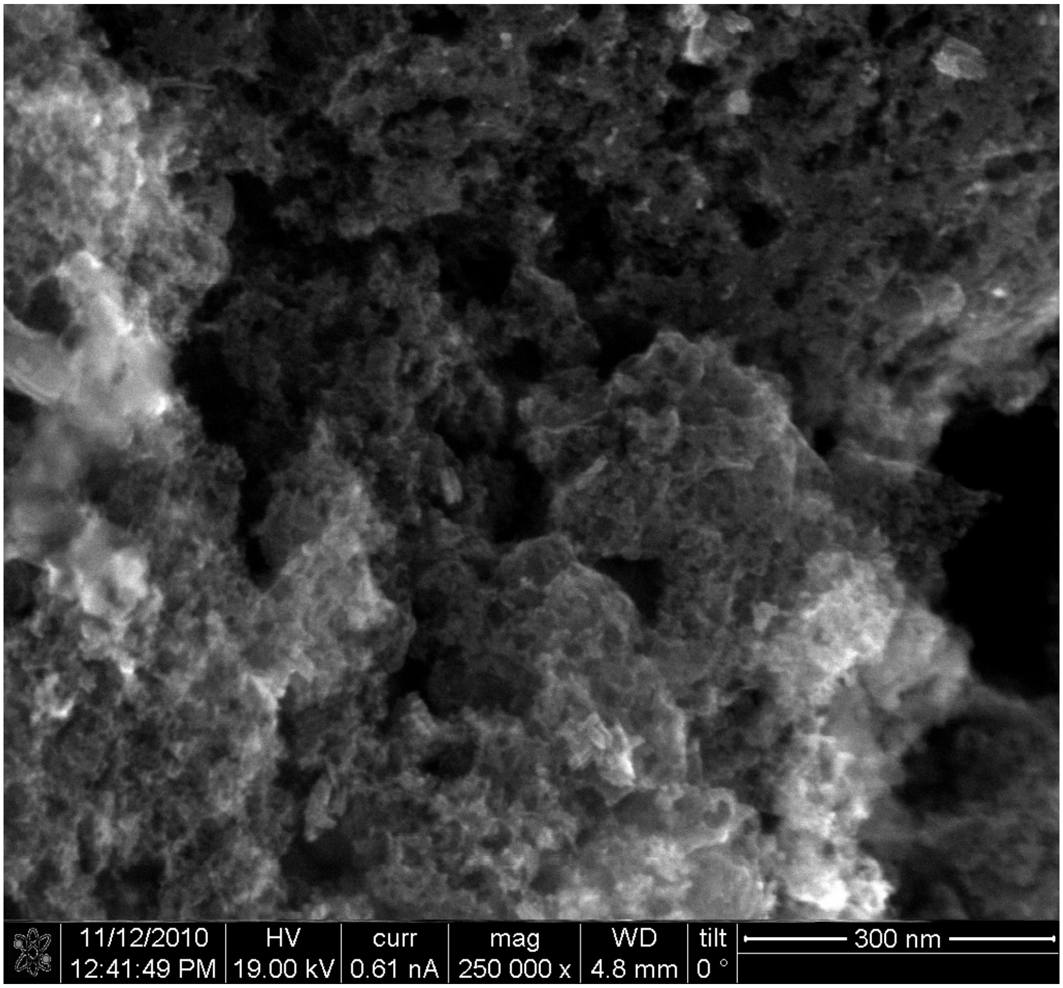

Figure D 5. SEM image of 0.5 M-72hr Fe-GAC

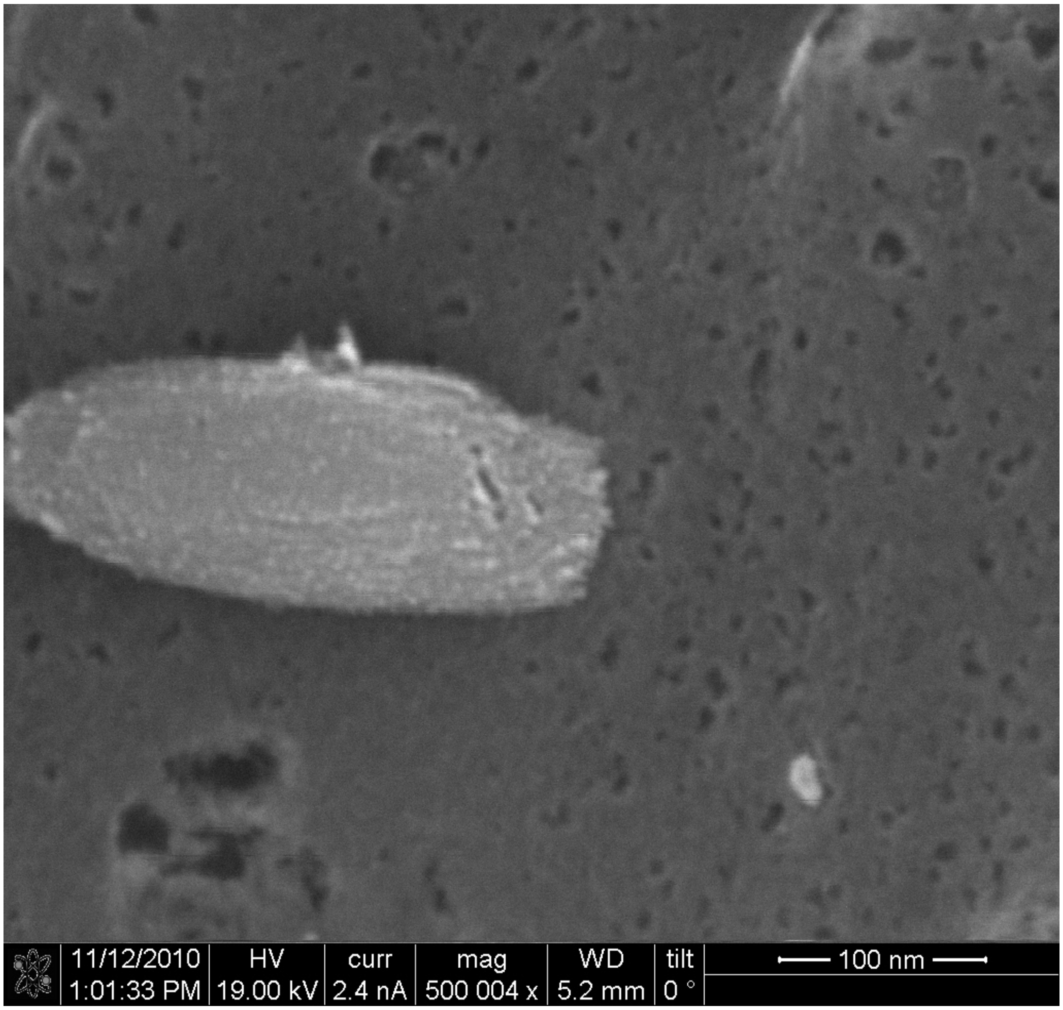

Figure D 6. SEM image of 0.5 M-72hr Fe-GAC

APPENDIX E

ARSENIC ADSORPTION ISOTHERM DATA AND CHARTS

Table E 3. Arsenic adsorption data for 0.5M-24hr Fe-GAC

					% Fe = 0.93	
Dry mass (g Fe-GAC)	Volume (L)	Dosage (g-FeGAC/L)	Ce (ugAs/L)	qe (ugAs/g Fe-GAC)	Dose* (g-Fe/L)	qe* (μg As/g-Fe)
0.37	0.10	3.70	14.40	27.72	0.03	2981.92
0.25	0.10	2.46	18.36	40.07	0.02	4311.50
0.19	0.10	1.87	40.13	41.05	0.02	4416.92
0.06	0.10	0.57	63.32	94.79	0.01	10198.37
0.04	0.10	0.38	73.31	113.72	0.00	12235.00
0.01	0.10	0.12	95.44	173.35	0.00	18649.75
0.14	0.10	1.38	46.55	51.01	0.01	5488.29
0.14	0.10	1.38	44.05	52.82	0.01	5683.05

Conditions: ph= 7.85 ± 0.09; Model water; Co As= 117 μAs/L

Table E 2. Arsenic adsorption data for 0.5M-24hr Fe-GAC

					% Fe = 0.93	
Dry mass (g Fe-GAC)	Volume (L)	Dosage (g-FeGAC/L)	Ce (ugAs/L)	qe (ugAs/g Fe-GAC)	Dose* (g-Fe/L)	qe* (µg As/g-Fe)
0.37	0.10	3.66	34.92	23.22	0.03	2498.13
0.25	0.10	2.49	40.41	31.98	0.02	3440.86
0.19	0.10	1.88	53.09	35.59	0.02	3829.07
0.14	0.10	1.40	54.35	47.01	0.01	5057.75
0.06	0.10	0.57	79.28	71.71	0.01	7715.57
0.14	0.10	1.39	54.78	46.87	0.01	5042.94
0.14	0.10	1.39	56.89	45.32	0.01	4875.33

Conditions: ph= 7.7 ± 0.1; Challenge Groundwater; Co As= 120 µAs/L

Table E 3. Arsenic adsorption data for 0.5M-72hr Fe-GAC

					% Fe = 4.4	
Dry mass (g Fe-GAC)	Volume (L)	Dosage (g-FeGAC/L)	Ce (ugAs/L)	qe (ugAs/g Fe-GAC)	Dose* (g-Fe/L)	qe* (µg As/g-Fe)
0.54	0.10	5.41	6.74	20.56	0.23	478.11
0.36	0.10	3.61	10.68	29.71	0.16	690.81
0.27	0.10	2.71	14.39	38.20	0.12	888.41
0.20	0.10	2.03	20.23	48.08	0.09	1118.17
0.08	0.10	0.82	42.83	91.33	0.04	2123.85
0.06	0.10	0.55	68.35	89.58	0.02	2083.18
0.02	0.10	0.18	82.57	198.36	0.01	4612.97
0.27	0.10	2.69	11.48	39.54	0.12	919.51
0.27	0.10	2.72	13.66	38.42	0.12	893.48

Conditions: ph= 7.67 ± 0.17; Model water; Co As= 118 µAs/L

Table E 4. Arsenic adsorption data for 0.5M-72hr Fe-GAC

					% Fe = 4.4	
Dry mass (g Fe-GAC)	Volume (L)	Dosage (g-FeGAC/L)	Ce (ugAs/L)	qe (ugAs/g Fe-GAC)	Dose* (g-Fe/L)	qe* (µg As/g-Fe)
0.54	0.10	5.43	11.89	25.42	0.23	591.20
0.36	0.10	3.59	24.80	34.89	0.15	811.33
0.27	0.10	2.73	33.30	42.79	0.12	995.11
0.20	0.10	2.03	47.91	50.19	0.09	1167.32
0.08	0.10	0.82	98.87	62.74	0.04	1459.00
0.06	0.10	0.56	111.78	67.70	0.02	1574.36
0.06	0.10	0.57	108.38	73.48	0.02	1708.87
0.06	0.10	0.56	104.64	81.04	0.02	1884.73

Conditions: ph= 7.67 ± 0.2; Challenge Groundwater; Co As= 150 µAs/L

Table E 5. Arsenic adsorption data for 2M-24hr Fe-GAC

					% Fe = 1.72	
Dry mass (g Fe-GAC)	Volume (L)	Dosage (g-FeGAC/L)	Ce (ugAs/L)	qe (ugAs/g Fe-GAC)	Dose* (g-Fe/L)	qe* (µg As/g-Fe)
0.56	0.10	5.60	7.81	19.86	0.10	1153.27
0.37	0.10	3.73	13.60	28.28	0.06	1642.36
0.28	0.10	2.81	19.16	35.59	0.05	2066.63
0.21	0.10	2.10	21.25	46.54	0.04	2702.44
0.08	0.10	0.85	39.90	93.14	0.01	5408.79
0.06	0.10	0.58	52.48	114.13	0.01	6627.38
0.02	0.10	0.18	75.95	238.08	0.00	13825.14
0.28	0.10	2.80	19.36	35.63	0.05	2068.81
0.28	0.10	2.79	21.88	34.81	0.05	2021.62

Conditions: ph= 7.7 ± 0.1; Model water; Co As= 119 µAs/L

Table E 6. Arsenic adsorption data for 2M-24hr Fe-GAC

					% Fe = 1.72	
Dry mass (g Fe-GAC)	Volume (L)	Dosage (g-FeGAC/L)	Ce (ugAs/L)	qe (ugAs/g Fe-GAC)	Dose* (g-Fe/L)	qe* (µg As/g-Fe)
0.56	0.10	5.60	35.67	14.18	0.10	823.32
0.37	0.10	3.74	51.19	17.08	0.06	991.90
0.28	0.10	2.79	61.24	19.24	0.05	1117.47
0.21	0.10	2.09	64.89	23.93	0.04	1389.75
0.08	0.10	0.85	86.80	33.37	0.01	1937.92
0.06	0.10	0.58	91.37	40.84	0.01	2371.72

Conditions: ph= 7.78 ± 0.17; Challenge Groundwater; Co As= 115 µAs/L

Table E 7. Arsenic adsorption data for 2M-72hr Fe-GAC

					% Fe = 2.17	
Dry mass (g Fe-GAC)	Volume (L)	Dosage (g-FeGAC/L)	Ce (ugAs/L)	qe (ugAs/g Fe-GAC)	Dose* (g-Fe/L)	qe* (μg As/g-Fe)
0.57	0.10	5.74	6.30	19.63	0.12	904.71
0.38	0.10	3.84	9.21	28.62	0.08	1318.84
0.29	0.10	2.86	14.40	36.53	0.06	1683.36
0.21	0.10	2.14	14.78	48.79	0.05	2247.93
0.09	0.10	0.88	30.77	99.93	0.02	4604.47
0.06	0.10	0.60	32.19	144.85	0.01	6674.47
0.02	0.10	0.20	69.52	246.73	0.00	11368.49

Conditions: ph= 7.7 ± 0.13; Model water; Co As= 119 μAs/L

Table E 8. Arsenic adsorption data for 2M-72hr Fe-GAC

					% Fe = 2.17	
Dry mass (g Fe-GAC)	Volume (L)	Dosage (g-FeGAC/L)	Ce (ugAs/L)	qe (ugAs/g Fe-GAC)	Dose* (g-Fe/L)	qe* (µg As/g-Fe)
0.57	0.10	5.74	25.27	15.63	0.12	720.07
0.38	0.10	3.83	33.55	21.25	0.08	979.37
0.29	0.10	2.88	42.97	25.05	0.06	1154.07
0.21	0.10	2.14	48.62	30.96	0.05	1426.38
0.09	0.10	0.87	63.68	59.05	0.02	2721.07
0.06	0.10	0.60	70.08	74.78	0.01	3445.63
0.22	0.10	2.16	45.98	31.99	0.05	1473.83
0.21	0.10	2.14	50.88	29.94	0.05	1379.37

Conditions: ph= 7.73 ± 0.13; Challenge Groundwater; Co As= 115 µAs/L

Table E 9. Arsenic adsorption data for Virgin Fe-GAC

Dry mass (g Fe-GAC)	Volume (L)	Dosage (g-FeGAC/L)	Ce (ugAs/L)	qe (ugAs/g Fe-GAC)	% Fe = nil Dose* (g-Fe/L)	qe* (µg As/g-Fe)
0.46	0.10	4.59	41.59	16.63	---	---
0.31	0.10	3.07	53.30	21.07	---	---
0.23	0.10	2.31	84.00	14.74	---	---
0.17	0.10	1.70	78.27	23.34	---	---
0.07	0.10	0.69	94.26	34.23	---	---
0.05	0.10	0.47	98.94	40.34	---	---
0.02	0.10	0.15	107.00	72.92	---	---
0.07	0.10	0.69	102.85	21.95	---	---
0.07	0.10	0.68	102.06	23.30	---	---

Conditions: ph= 7.66 ± 0.2; Model water; Co As= 118 µAs/L

Note: Virgin GAC did not exhibit any arsenic adsorption capacity and so dose* and qe* were not calculated.

Table E 10. Arsenic adsorption data for Virgin Fe-GAC

					% Fe = nil	
Dry mass (g Fe-GAC)	Volume (L)	Dosage (g-FeGAC/L)	Ce (ugAs/L)	qe (ugAs/g Fe-GAC)	Dose* (g-Fe/L)	qe* (µg As/g-Fe)
0.46	0.10	4.57	98.12	11.34	---	---
0.31	0.10	3.07	122.38	8.99	---	---
0.23	0.10	2.28	132.27	7.76	---	---
0.17	0.10	1.71	139.54	6.13	---	---
0.07	0.10	0.69	142.93	10.20	---	---
0.05	0.10	0.47	147.57	5.13	---	---
0.01	0.10	0.15	149.12	6.00	---	---
0.01	0.10	0.15	146.64	22.53	---	---
0.02	0.10	0.15	143.55	42.63	---	---

Conditions: ph= 7.67 ± 0.14; Challenge Groundwater; Co As= 150 µAs/L

Note: Virgin GAC did not exhibit any arsenic adsorption capacity and so dose* and qe* were not calculated

APPENDIX F

ADDITIONAL DATA AND GRAPHS ON BREAKTHROUGH CURVES

Table F 1. Data on breakthrough curves of 0.5 M-24hr Fe-GAC

Empty bed contact time	Time	Bed Volumes	Ce	C/Co	Δ BV	Δ C adsorbed	Δ M	L passed
0.0974	5	51.33	85.69	0.61	51.33	54.55	10.64	0.20
0.0974	10	102.67	86.14	0.61	51.33	54.10	10.55	0.20
0.0974	15	154.00	100.39	0.72	51.33	39.85	7.77	0.20
0.0974	20	205.34	117.35	0.84	51.33	22.88	4.46	0.20
0.0974	30	308.01	125.27	0.89	102.67	14.96	5.84	0.39
0.0974	40	410.68	131.53	0.94	102.67	8.71	3.40	0.39
0.0974	50	513.35	129.28	0.92	102.67	10.95	4.27	0.39
0.0974	60	616.02	131.53	0.94	102.67	8.71	3.40	0.39
0.0974	75	770.02	135.96	0.97	154.00	4.27	2.50	0.59
0.0974	90	924.02	135.86	0.97	154.00	4.38	2.56	0.59
0.0974	105	1078.03	135.90	0.97	154.00	4.33	2.54	0.59
0.0974	120	1232.03	134.96	0.96	154.00	5.27	3.09	0.59
0.0974	150	1540.04	135.53	0.97	308.01	4.71	5.51	1.17
0.0974	180	1848.05	139.08	0.99	308.01	1.16	1.35	1.17
0.0974	210	2156.06	134.58	0.96	308.01	5.66	6.62	1.17
0.0974	240	2464.07	139.89	1.00	308.01	0.35	0.41	1.17
0.0974	300	3080.08	137.60	0.98	616.02	2.64	6.17	2.34
0.0974	360	3696.10	136.76	0.98	616.02	3.48	8.15	2.34
0.0974	480	4928.13	139.78	1.00	616.02	0.46	1.07	2.34
0.0974	600	6160.16	137.02	0.98	1232.03	3.22	15.08	4.68
0.0974	720	7392.20	138.66	0.99	1232.03	1.57	7.37	4.68

Conditions: Challenge groundwater; Co = 140.24 µAs/L

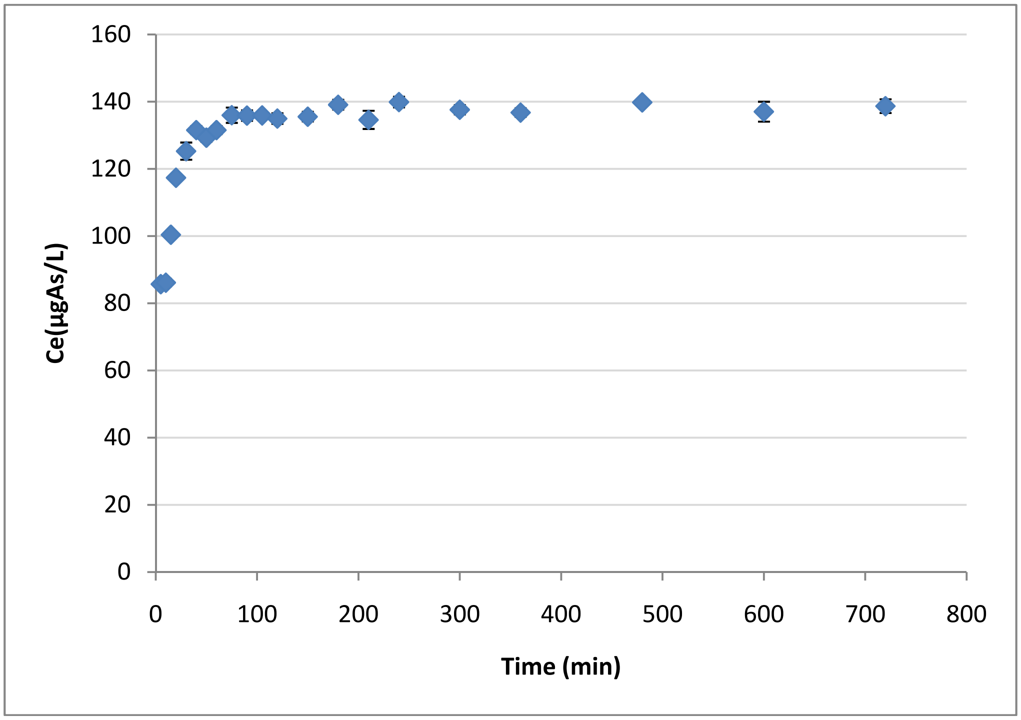

Figure F 1. Breakthrough curve for 0.5M-24hr Fe-GAC. Error bars represent upper and lower 95% confidence intervals.

Table F 2. Data on breakthrough curves of 0.5 M-72hr Fe-GAC

Empty bed contact time	Time	Bed Volumes	Ce	C/Co	Δ BV	Δ C adsorbed	ΔM	L passed
0.0972	5	51.44	105.37	0.86	51.44	17.44	3.41	0.20
0.0972	10	102.88	107.11	0.87	51.44	15.70	3.07	0.20
0.0972	15	154.32	111.17	0.91	51.44	11.64	2.28	0.20
0.0972	20	205.76	112.29	0.91	51.44	10.53	2.06	0.20
0.0972	30	308.64	113.48	0.92	102.88	9.33	3.65	0.39
0.0972	40	411.52	114.47	0.93	102.88	8.34	3.26	0.39
0.0972	60	617.28	116.04	0.94	102.88	6.77	2.65	0.39
0.0972	75	771.60	118.50	0.96	154.32	4.31	2.53	0.59
0.0972	90	925.93	120.35	0.98	925.93	2.46	8.66	3.52
0.0972	105	1080.25	121.52	0.99	154.32	1.29	0.76	0.59
0.0972	120	1234.57	121.63	0.99	154.32	1.18	0.69	0.59
0.0972	150	1543.21	118.65	0.97	308.64	4.16	4.88	1.17
0.0972	180	1851.85	122.26	1.00	308.64	0.55	0.64	1.17
0.0972	210	2160.49	122.47	1.00	308.64	0.34	0.40	1.17
0.0972	240	2469.14	122.08	0.99	308.64	0.73	0.86	1.17
0.0972	300	3086.42	122.22	1.00	617.28	0.59	1.38	2.35
0.0972	360	3703.70	122.04	0.99	617.28	0.77	1.81	2.35
0.0972	420	4320.99	122.19	0.99	617.28	0.62	1.46	2.35
0.0972	480	4938.27	122.15	0.99	617.28	0.66	1.54	2.35
0.0972	600	6172.84	122.34	1.00	1234.57	0.47	2.20	4.69

Conditions: Challenge groundwater; Co = 122.8µAs/L

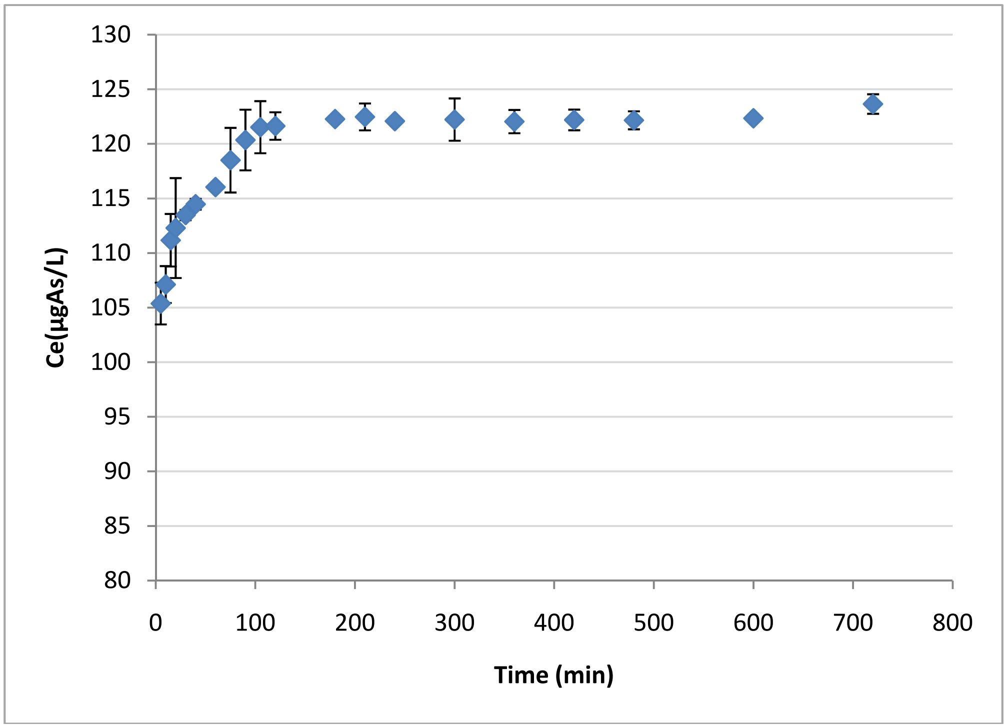

Figure F 2. Breakthrough curve for 0.5M-72hr Fe-GAC. Error bars represent upper and lower 95% confidence intervals.

Table F 3. Data on breakthrough curves of 2 M-24hr Fe-GAC

Empty bed contact time	time	Bed Volumes	Ce	C/Co	Δ BV	Δ C adsorbed	ΔM	L passed
0.0998	5	50.10	107.01	0.84	50.10	20.05	3.82	0.19
0.0998	10	100.20	109.90	0.86	50.10	17.17	3.27	0.19
0.0998	15	150.30	113.56	0.89	50.10	13.50	2.57	0.19
0.0998	20	200.40	114.49	0.90	50.10	12.57	2.39	0.19
0.0998	30	300.60	119.28	0.94	100.20	7.78	2.96	0.38
0.0998	40	400.80	119.76	0.94	100.20	7.31	2.78	0.38
0.0998	50	501.00	120.65	0.95	100.20	6.41	2.44	0.38
0.0998	60	601.20	120.84	0.95	100.20	6.22	2.37	0.38
0.0998	75	751.50	122.73	0.97	150.30	4.33	2.47	0.57
0.0998	90	901.80	125.05	0.98	150.30	2.01	1.15	0.57
0.0998	105	1052.10	125.54	0.99	150.30	1.52	0.87	0.57
0.0998	120	1202.40	126.99	1.00	150.30	0.08	0.04	0.57
0.0998	150	1503.01	126.94	1.00	300.60	0.12	0.14	1.14
0.0998	210	2104.21	126.37	0.99	300.60	0.69	0.79	1.14
0.0998	240	2404.81	126.73	1.00	300.60	0.33	0.38	1.14
0.0998	300	3006.01	126.75	1.00	601.20	0.31	0.72	2.28
0.0998	420	4208.42	126.76	1.00	601.20	0.30	0.69	2.28
0.0998	480	4809.62	126.76	1.00	601.20	0.30	0.70	2.28
0.0998	600	6012.02	126.91	1.00	1202.40	0.15	0.70	4.57
0.0998	720	7214.43	126.98	1.00	1202.40	0.08	0.37	4.57

Conditions: Challenge groundwater; Co = 127.06µAs/L

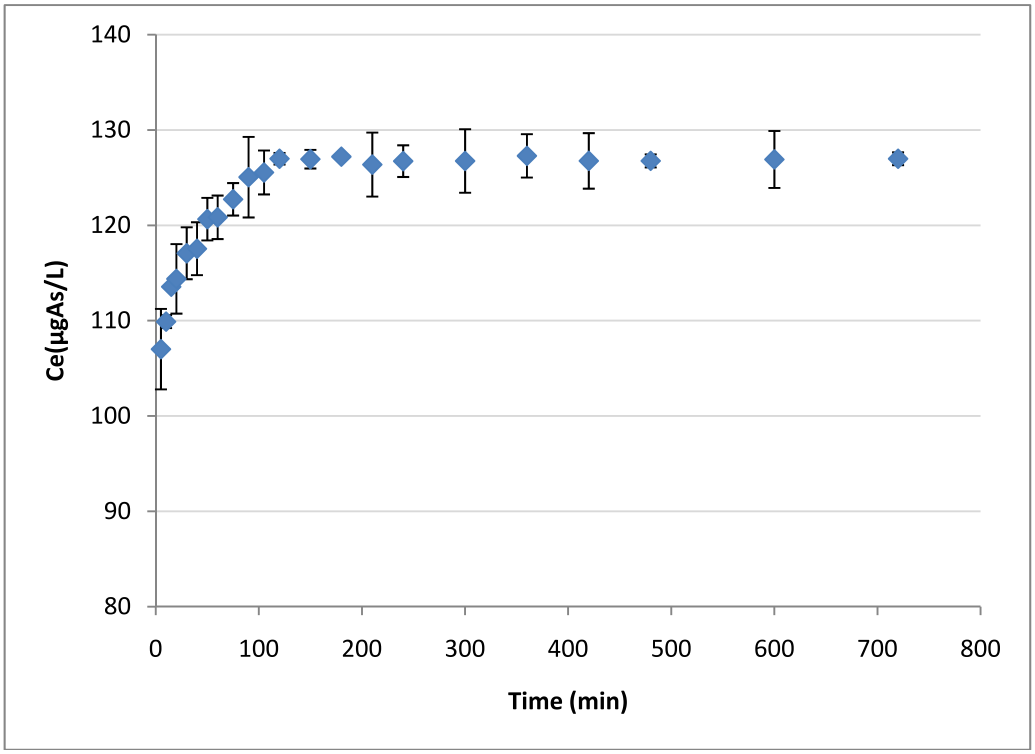

Figure F 4. Breakthrough curve for 2M-24hr Fe-GAC. Error bars represent upper and lower 95% confidence intervals.

Table F 5. Data on breakthrough curves of 2 M-72hr Fe-GAC

Empty bed contact time	time	Bed Volumes	Ce	C/Co	Δ BV	Δ C adsorbed	ΔM	L passed
0.0937	5	53.36	99.99	0.86	53.36	16.65	3.38	0.20
0.0937	10	106.72	105.41	0.90	53.36	11.22	2.27	0.20
0.0937	15	160.09	108.41	0.93	53.36	8.22	1.67	0.20
0.0937	20	213.45	110.98	0.95	53.36	5.66	1.15	0.20
0.0937	30	320.17	110.99	0.95	106.72	5.64	2.29	0.41
0.0937	40	426.89	110.29	0.95	106.72	6.34	2.57	0.41
0.0937	50	533.62	111.19	0.95	106.72	5.44	2.21	0.41
0.0937	60	640.34	112.26	0.96	106.72	4.37	1.77	0.41
0.0937	75	800.43	111.93	0.96	160.09	4.70	2.86	0.61
0.0937	90	960.51	112.18	0.96	160.09	4.45	2.71	0.61
0.0937	105	1120.60	112.92	0.97	160.09	3.71	2.26	0.61
0.0937	120	1280.68	113.97	0.98	160.09	2.66	1.62	0.61
0.0937	150	1600.85	114.68	0.98	320.17	1.95	2.37	1.22
0.0937	180	1921.02	116.02	0.99	1921.02	0.61	4.46	7.30
0.0937	210	2241.20	116.53	1.00	320.17	0.10	0.12	1.22
0.0937	240	2561.37	115.79	0.99	320.17	0.85	1.03	1.22
0.0937	360	3842.05	115.91	0.99	640.34	0.72	1.76	2.43
0.0937	420	4482.39	116.05	1.00	640.34	0.58	1.42	2.43
0.0937	480	5122.73	113.61	0.97	640.34	3.03	7.36	2.43
0.0937	600	6403.42	116.56	1.00	1280.68	0.07	0.34	4.87
0.0937	720	7684.10	115.89	0.99	1280.68	0.75	3.63	4.87

Conditions: Challenge groundwater; Co = 116.63µAs/L

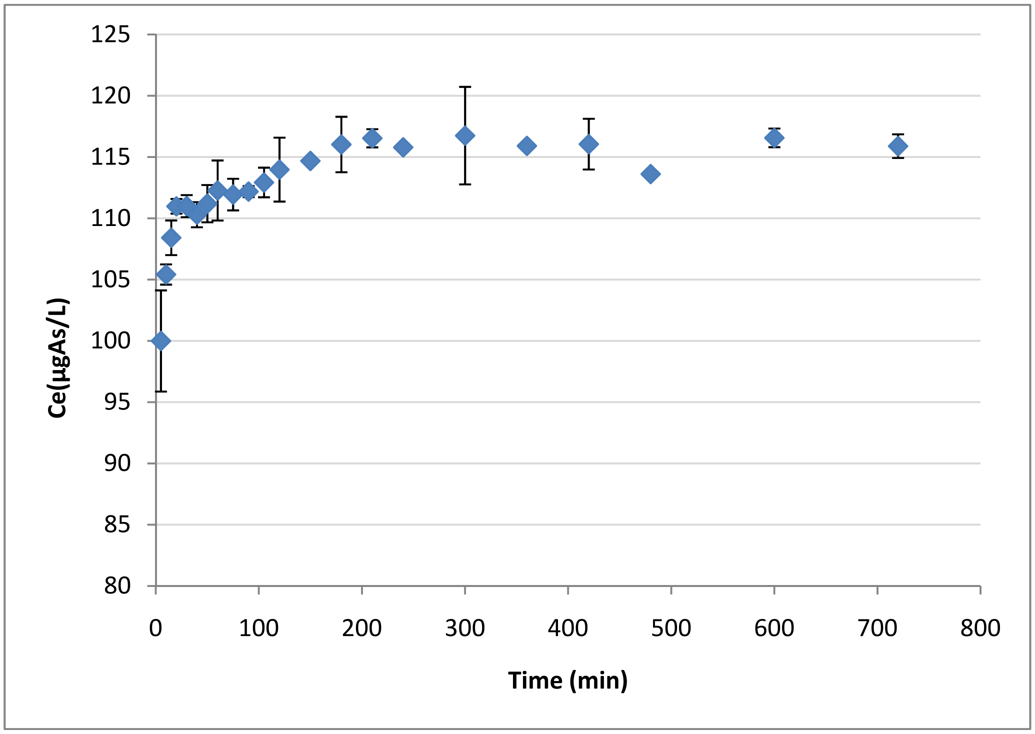

Figure F 5. Breakthrough curve for 2M-72hr Fe-GAC. Error bars represent upper and lower 95% confidence intervals