3-24-2008

Development of a Screening Tool to Facilitate Technology of an Innovative Technology to Treat Perchlorate-Contaminated Water

Daniel A. Craig

Follow this and additional works at: https://scholar.afit.edu/etd

Part of the Environmental Engineering Commons

DEVELOPMENT OF A SCREENING TOOL TO FACILITATE TECHNOLOGY TRANSFER OF AN INNOVATIVE TECHNOLOGY TO TREAT PERCHLORATE-CONTAMINATED WATER

THESIS

Daniel A. Craig, Captain, USAF

AFIT/GEM/ENV/08-M06

AFIT/GEM/ENV/08-M06

DEVELOPMENT OF A SCREENING TOOL TO FACILITATE TECHNOLOGY
TRANSFER OF AN INNOVATIVE TECHNOLOGY TO TREAT PERCHLORATE-
CONTAMINATED WATER

THESIS

Presented to the Faculty

Department of Systems and Engineering Management

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Engineering Management

Daniel A. Craig, BS

Captain, USAF

March 2008

DEVELOPMENT OF A SCREENING TOOL TO FACILITATE TECHNOLOGY
TRANSFER OF AN INNOVATIVE TECHNOLOGY TO TREAT PERCHLORATE-
CONTAMINATED WATER

Daniel A. Craig, BS
Captain, USAF

Approved:

//signed//   24 March 2008

————————————————————   ——————————
Mark N. Goltz (Chairman)   date

//signed//   24 March 2008

————————————————————   ——————————
Fred S. Cannon (Member)   date

//signed//   24 March 2008

————————————————————   ——————————
Alfred E. Thal, Jr. (Member)   date

Abstract

Perchlorate contamination of drinking water is a significant problem nationwide. The purpose of this study was to develop a tool to predict the cost and performance of tailored granular activated carbon (T-GAC), an innovative technology that is being evaluated as a cost-effective treatment for perchlorate-contaminated water. The ability to accurately predict performance and cost can facilitate the transfer and commercialization of innovative technologies.

In the study, a model was developed to predict T-GAC performance and life-cycle costs for removing perchlorate under varying influent water quality and technology operating conditions. The model's design parameters were obtained from laboratory rapid small-scale column tests (RSSCTs) using inverse modeling. Cost data used in the model were based on conventional GAC installations, modified to account for tailoring.

The parameterized model was used to predict the observed performance from a pilot-scale field demonstration at a water treatment plant in Southern California. The model over-predicted field performance; however, it predicted reasonably well the results of laboratory RSSCTs for two waters that were not used to calibrate the model. Using the screening model, it was found that annual operation and maintenance (O&M) costs are more significant than capital costs, and that costs associated with media regeneration or replacement dominate the O&M costs.

To my parents,
who raised me and endeavored for my future

and

To our family (C. & L.)

Acknowledgments

I would like to sincerely thank my research advisor, Dr. Mark N. Goltz, for his guidance and counsel throughout this effort. His dedication to his students and to academic excellence is remarkable.

I would also like to express my appreciation to the members of my thesis committee: Dr. Alfred E. Thal Jr. and Dr. Fred S. Cannon. In addition, I would like to thank all the members of the ESTCP project team; in particular, a grateful acknowledgement to: Chris Lutes, Trent Henderson, and Michiel Doorn of ARCADIS for their outstanding support and to William Powell who made the first pass with his research and was a valuable resource. I would like to acknowledge ESTCP for funding this project that allowed this academic pursuit to be possible.

And finally, I would like to thank my wife for her ceaseless encouragement and everlasting support as I strived to accomplish this thesis.

Daniel A. Craig

Table of Contents

List of Figures

List of Tables

DEVELOPMENT OF A SCREENING TOOL TO FACILITATE

TECHNOLOGY TRANSFER OF AN INNOVATIVE TECHNOLOGY TO

TREAT PERCHLORATE-CONTAMINATED WATER

1.0. Introduction

1.1. Motivation

Perchlorate is an oxyanion species that is frequently used as an oxidant for explosives and solid rocket fuel. Perchlorate salts readily dissociate in water forming the perchlorate anion (ClO_4^-). The resultant perchlorate anion does not readily degrade, chemically reduce or complex, or absorb onto mineral surfaces; rendering a remediation challenge for its removal in the environment. These challenges pose a significant concern as perchlorate is emerging as a significant environmental contamination problem.

Occurrence of perchlorate in the United States, from both anthropogenic and natural sources, has been wide spread. The U.S. General Accounting Office (U.S. GAO) reports that approximately 400 sites in 35 states, the District of Columbia, and two commonwealths of the United States have detected perchlorate in their soil, or drinking, surface, and groundwater (U.S. GAO, 2005). Additionally, perchlorate use and its presence in the environment have been identified at numerous Department of Defense (DoD) locations. The U.S. Environmental Protection Agency (U.S. EPA) documents that

63 DoD sites or installations have detectable perchlorate concentrations in soil, surface

water, and/or ground water (U.S. EPA, 2005).

 Figure 1-1, which shows the number of perchlorate-contaminated sites identified in each

state, as well as the maximum perchlorate concentration detected in the state, illustrates

the extent and scale of the perchlorate contamination problem in the United States (U.S.

GAO, 2005).
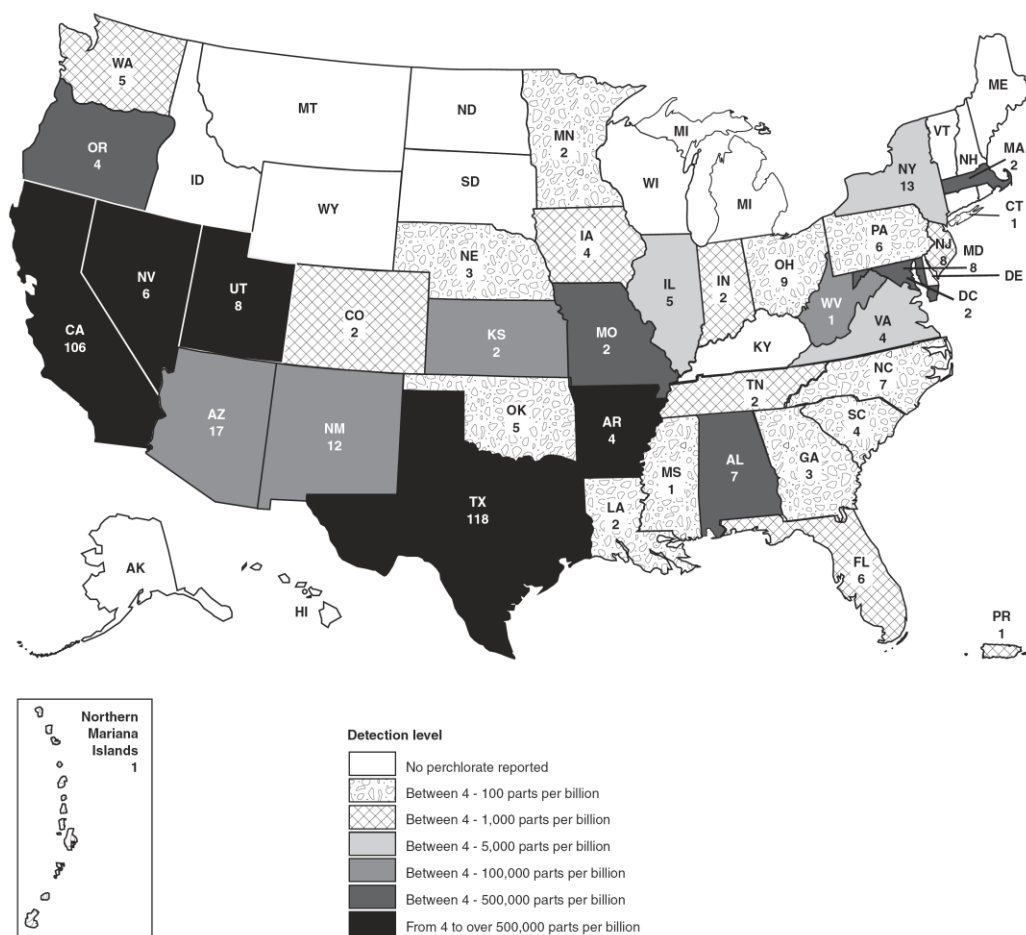
Figure 1-1 Maximum Perchlorate Concentration and Number of Perchlorate Sites Reported for Each State (U.S. GAO, 2005)

These relatively recent detections of perchlorate in the environment have spurred studies that have examined the potential human health and environmental effects of exposure to perchlorate. For example, numerous studies have been conducted examining the possible health impacts of perchlorate ingestion. The most significant health impact of perchlorate intake is that it may inhibit thyroid hormone production, as perchlorate competes with iodide for transport into the thyroid glands (National Research Council (NRC), 2005). This competition with iodide may lead to iodide deficiency if a sufficient dose of perchlorate is ingested. Significant iodide deficiency can lead to a condition of hypothyroidism which may have adverse impacts on the body's central nervous system and other key bodily functions. A particular concern is with infants, fetuses, or expectant mothers developing hypothyroidism. The NRC considers these groups to be the most sensitive and vulnerable in the population to hypothyroidism or iodide deficiency, which may lead to birth defects and developmental problems in young infants and unborn children (NRC, 2005).

To date, there is no federal mandate or promulgated regulation from the U.S. EPA specifying allowable levels of perchlorate in drinking water or clean-up standards for perchlorate-contaminated water; although, perchlorate has been listed on the U.S. EPA Contaminant Candidate List (CCL). The U.S. EPA is monitoring perchlorate under its Unregulated Contaminant Monitoring Rule (UCMR) program. The U.S. EPA places contaminants on the CCL and UCMR to establish research priorities, and monitor and collect data for regulatory consideration. Although these contaminants may be present in

drinking water, no health-based standards have been set under the Safe Drinking Water Act (SDWA); therefore, they are not regulated at the federal level.

Legislative bills in the 110th Congress are currently under review in both the U.S. House of Representatives and U.S. Senate calling for the U.S. EPA to establish drinking water and clean-up standards for perchlorate-contaminated water. Additionally, several states have established advisory action levels for perchlorate-contaminated water. More aggressively, Massachusetts and California have promulgated state drinking water regulations, setting concentration standards of 2 parts per billion (ppb) and 6 ppb, respectively.

With the evolution of states establishing perchlorate standards and the potential for federal regulation, water treatment technologies are needed that effectively and efficiently treat this emerging contaminant. A number of technologies exist for treating perchlorate. The conventional technology for treating perchlorate-contaminated water is ion exchange (IX). The basic principle of IX is to pass perchlorate-contaminated water through a polymeric matrix containing anion exchange resins. These IX resins capture perchlorate anions by an ionic displacement process where perchlorate anions "attach" to the active group of the resin in exchange for an innocuous anion previously embedded on the resin. Through this exchange process, perchlorate is captured from the treated water and a harmless anion is released into the water stream.

Several notable benefits exist with the IX approach to perchlorate remediation. Some of these advantages include: the proven ability to remove perchlorate to below 4 ppb, fast

reaction process, simple and high-flow rate operations, and regulatory acceptance (Air Force Center for Environmental Excellence, 2002)

Although IX is the principal technology currently used for treating perchlorate-contaminated water, several key limitations exist. First, the overall performance of IX is highly dependent on the water chemistry (Gu et al., 2007). Anions such as nitrate and sulfate that may be present in the water can significantly affect perchlorate removal due to competition with the perchlorate anion for IX sites. This competition degrades IX resin performance and results in the need to replace or regenerate the resin on an accelerated schedule. Another significant problem with IX is that periodic backwashing is required. Backwashing creates a perchlorate-contaminated brine stream. The brine, which consists of high concentrations of both perchlorate and other anions such as nitrate, must be further treated and disposed of, thereby increasing treatment costs (Lehman et al., 2008). An additional limitation of IX treatment is its inability to remove organic co-contaminants that may be present in perchlorate-contaminated water. This is a significant drawback in perchlorate-contaminated waters that have organic co-contaminants, as subsequent treatment processes may be required to treat the organic species.

An innovative technology to treat perchlorate-contaminated water using granular activated carbon (GAC) has been developed by researchers at Pennsylvania State University (PSU) (Parette and Cannon, 2005). What is remarkable about using GAC for perchlorate removal is that GAC is typically associated with non-ionic organic contaminant removal. However, through a process of tailoring with a cationic surfactant,

a positively charged matrix structure (micelle) is formed on the GAC that results in a significant improvement for the adsorption of perchlorate anions. The tailored form of GAC using quaternary amine tailoring groups (herein termed T-GAC) has been demonstrated in the laboratory, through the use of rapid small-scale column tests (RSSCTs), to be an effective alternative to IX resins for removing perchlorate (Parette and Cannon, 2005). Furthermore, research performed by Chen et al. (2003) has demonstrated that by thermal reactivation, a common practice with conventional GAC, spent T-GAC can be re-utilized. The ability to reactivate and re-use GAC provides a potential economic savings by reducing media costs; moreover, reduces secondary waste products that occur with IX. Moreover, on-going research at PSU hopes to demonstrate that T-GAC may be useful in simultaneously treating perchlorate and certain organic co-contaminant species.

Motivated by these potential advantages of T-GAC over IX, the Air Force Institute of Technology (AFIT) has partnered with researchers from ARCADIS, PSU, and Siemens (formerly US Filter), with funding from the DoD Environmental Security Technology Certification Program (ESTCP), to evaluate and demonstrate the cost and performance of T-GAC to remediate perchlorate-contaminated water at an active water treatment plant in Fontana, CA (ESTCP, 2005). The results of this field-demonstration are available and provide data that may be used to evaluate the technical performance and viability of this innovative approach.

1.2. Problem Statement

A barrier to innovation includes the lack of credible information needed to compare innovative technologies against conventional ones and to transfer technology used at one site to other sites without having to repeat all elements of testing (NRC, 1997). Moreover, implementing innovative environmental remediation technologies face many barriers that in-part can be overcome by disseminating credible cost and performance data (NRC, 1997). Decision makers seek technologies that are effective and efficient, rapid and simple to operate, reliable and proven (Hardisty and Ozdemiroglu, 2005). These decision makers require sufficient and credible information to take action and select a technology that will meet their needs (Alberts and Hayes, 2004). Similarly, the U.S. GAO has identified a need for the DoD to develop an accurate and consistent cost estimating methodology regarding perchlorate remediation and clean-up (U.S. GAO, 2004); as the lack of site-specific information and reliable cost estimate data has resulted in several DoD remediation projects facing dramatic cost escalations during the project's life as new information becomes available (U.S. GAO, 2003).

Therefore, to facilitate transition of the T-GAC technology to full-scale commercial application, performance and cost data obtained in laboratory- and pilot-scale studies were incorporated into a screening tool that can be applied by decision makers (project managers, consulting engineers, water purveyors, regulators, etc.) faced with managing a perchlorate contamination problem. Such a screening tool can be used to predict the performance and cost of a T-GAC system to treat perchlorate-contaminated water under given water quality and flow conditions.

1.3. Research Objectives

In a previous research study, a performance-cost model using data obtained from RSSCTs was developed (Powell, 2007). In his study, Powell (2007) showed that a model based upon techniques used to simulate and design conventional GAC systems and modified to incorporate the effects of competing ions on perchlorate adsorption, could be used to successfully predict the volume of perchlorate-contaminated water that could be treated in RSSCT columns filled with T-GAC. A limitation of Powell's model is no field data were available to help validate the model, except for a single data point obtained from a Redlands, CA study.

Now, with the availability of data from the pilot-scale field study at Fontana, CA, along with additional RSSCT results from PSU, this new information can be incorporated into performance and cost screening software to improve the accuracy and help validate the model. The improved and validated model will enable stakeholders and potential technology-users to assess the feasibility of using T-GAC to manage their particular perchlorate-contaminated water problem.

This research seeks to build on Powell's (2007) work by incorporating results from additional RSSCTs and validating the model with performance and cost data from ongoing field studies at Fontana, CA. The resulting model offers cost projections to the many stakeholders who deal with perchlorate-contaminated water. Therefore, the primary research objective for this effort was to determine if conventional GAC modeling techniques (as developed by Powell, 2007) can be used to simulate a pilot-scale T-GAC field test. Secondary objectives were to:

(1) Modify the Powell model to incorporate the results of additional laboratory RSSCTs and the Fontana pilot test.

(2) Demonstrate how technology performance and cost modeling can be applied to provide potential technology users with information in order to facilitate technology transfer and application.

1.4. Research Approach

(1) A literature review focused on four specific areas will be conducted. The first focus is to investigate the use of T-GAC to treat perchlorate-contaminated water. Second, methods for extrapolating the results of small- and pilot-scale studies to predict full-scale performance and costs are reviewed. Third, approaches to cost estimation of water treatment technologies are evaluated. Finally, an analysis of the information requirements sought by decision makers evaluating the applicability of an innovative treatment technology is appraised.

(2) RSSCT results conducted by PSU are used to quantify performance model parameters. Predictions of the parameterized model are then compared with field results for model validation.

(3) Based on performance model predictions and using cost data discovered in the literature on GAC systems (modified to account for T-GAC media costs), technology cost predictions are compared with the conventional perchlorate treatment technology to ascertain under what circumstances T-GAC may be cost-effective as an alternative treatment technology.

(4) Performance and costs results are incorporated into a performance-cost screening tool to provide stakeholders information in a useful format to facilitate technology selection, transfer and implementation.

1.5. Limitations of Research

(1) Quantification of performance model parameters is limited to and based on 12 RSSCTs conducted with water from the Fontana site that was spiked with perchlorate; these RSSCTs were conducted by PSU. Performance model validation is conducted by comparing model predictions to a single pilot-scale T-GAC technology demonstration at Fontana, CA.

(2) Fontana demonstration expenses are used to validate the cost predictions of the screening model. However, limited field data are available at this time to validate all annual operation and maintenance costs of the demonstration.

2.0. Literature Review

2.1. Introduction

The contents of this chapter provide a detailed overview of the relevant literature of this thesis. Initially discussed are the health concerns and regulatory and Department of Defense (DoD) policies related to perchlorate-contaminated water. The discussion of these topics is intended to highlight this emerging environmental issue that is faced by the DoD. Thereafter, the conventional perchlorate-contaminated water treatment technology is examined. Specifically, we seek to understand the benefits, potential limitations, and treatment costs of this technology. As perchlorate is an emerging contaminant problem, the exploration of innovative technologies that provide tangible benefits will be important to potential stakeholders who seek viable options in treating perchlorate-contaminated water. Therefore, we will review methods of extrapolating results from small-scale and pilot-scale studies to predict full-scale performance of an innovative technology, tailored granular activated carbon (T-GAC), for treating perchlorate-contaminated water. With the ability to predict cost and performance, as the final topic presented in this chapter, we will review the information required by decision makers to select among treatment technology alternatives.

2.2. Health Impacts

Perchlorate is of particular concern because of the potential health impacts that may occur when ingested. Research has shown that perchlorate may inhibit thyroid hormone production because perchlorate competes with iodide for transport into thyroid follicular cells (NRC, 2005). Significant decreases in thyroid hormone production can lead to

11

hypothyroidism, a condition of under-activity of the thyroid gland. Hypothyroidism, which results in mental and physical lethargy due to a decrease in the body's metabolic rate, is associated with a variety of symptoms. The most significant concern is the development of hypothyroidism in infants, fetuses, or expectant mothers. Severe iodide deficiency, which may result from combined maternal and fetal hypothyroidism, can lead to infant microcephaly (diminutive brain), mental retardation, deafness, mutism, paraplegia or quadriplegia, and movement disorders (NRC, 2005). For a complete discussion of health risks, the NRC report (2005) provides a thorough review of the health concerns associated with perchlorate ingestion.

2.3. Regulatory and Legislative Actions

The concern over the impact of perchlorate contamination on drinking water quality has spawned an increase in monitoring and regulatory actions. In 1998, the U.S. Environmental Protection Agency (U.S. EPA) placed perchlorate on its Contaminant Candidate List for possible regulation. Then in 1999, the U.S. EPA required drinking water monitoring for perchlorate under the Unregulated Contaminant Monitoring Rule to determine the frequency and levels at which it is present in public water supplies nationwide.

As there was a high-degree of uncertainty regarding the human health effects associated with perchlorate ingestion, and a need for improved understanding, several federal agencies requested the National Research Council (NRC) to evaluate the potential health effects related to perchlorate (NRC, 2005). In 2005, the NRC released their report which stated that a daily ingestion reference dose (RfD) of 0.0007 milligrams per kilogram of

bodyweight per day should not adversely impact the most sensitive in the population (NRC, 2005).

In 2006, the U.S. EPA officially adopted the NRC-recommended, albeit non-regulatory, RfD stating that the NRC report represented the best available scientific study regarding the toxicity of perchlorate (U.S. EPA, 2006). Assuming perchlorate ingestion is totally due to drinking water, the U.S. EPA RfD corresponds to a drinking water equivalent level (DWEL) of 24.5 ppb of perchlorate. In both 2004 and 2005, the U.S. Food and Drug Administration (U.S. FDA) conducted exploratory surveys of over 500 foods from various locations with a high-likelihood of perchlorate contamination. The surveys detected the presence of perchlorate in common foods such as fruits, vegetables, and beverages (U.S. FDA, 2004). If the U.S. EPA ultimately establishes a drinking water standard for perchlorate, the DWEL may be adjusted to account for exposure sources other than drinking water, for instance, through consumption of perchlorate-contaminated foods.

National regulation may be forthcoming. In the 110th Congress, two pending bills, one introduced in the U.S. House of Representative (H.R. 1747-Solis) and another in the U.S. Senate (S.150-Boxer), seek to amend the Safe Drinking Water Act to require that U.S. EPA establish a national primary drinking water regulation for perchlorate. Nevertheless, several states are active in establishing policy on perchlorate. For instance, in the absence of a national perchlorate standard, at least eight States have established non-regulatory action levels or advisories for perchlorate as indicated in Table 2-1. More

aggressively, Massachusetts and California have formally established maximum

contaminant level (MCL) drinking water standards of 2 ppb and 6 ppb, respectively.

Table 2-1 State Perchlorate Advisory and Regulatory Levels		
Arizona	14 ppb	Guidance Level[1]
Maryland	1 ppb	Advisory Level[1]
Nevada	18 ppb	Public Notice Standard[1]
New Mexico	1 ppb	Drinking Water Screening Level[1]
Oregon	4 ppb	Action Level[2]
New York	5 ppb	Drinking Water Planning Level[1]
	18 ppb	Public Notification Level[1]
Texas	17 ppb	Residential Protective Cleanup Level (PCL)[1]
	51 ppb	Industrial/Commercial PCL[1]
State Established Drinking Water (MCL) Standards		
Massachusetts	2 ppb	Drinking Water Standard[3]
California	6 ppb	Drinking Water Standard[4]

Sources:
(1) U.S. EPA, 2005
(2) Oregon Department of Environmental Quality, 2007
(3) California Department of Health Services, 2007
(4) Massachusetts Department of Environmental Protection, 2007

2.4. Department of Defense Policy

In response to the growing development of information related to perchlorate, the DoD has taken action. Specifically, the DoD Perchlorate Policy (signed 26 January 2006) requires active and closed installations, operational and other than operational ranges, and formerly used defense sites to comply with U.S. EPA and state standards (if/when promulgated) (Under Secretary of Defense, 2006). Additionally, the policy has established 24 ppb as the current level of concern for managing perchlorate, a threshold based on the U.S. EPA DWEL of 24.5 ppb and the NRC toxicological review of perchlorate.

Despite the absence of a national perchlorate drinking water regulation, authorities have required DoD agencies to respond to perchlorate contamination, under existing state and federal statutes and regulations. For instance, in Texas, under provisions of the Clean Water Act National Pollutant Discharge Elimination System permit program, authorities required the U.S. Navy to reduce perchlorate levels in wastewater discharges at the McGregor Naval Weapons Industrial Reserve Plant to 4 ppb (U.S. GAO, 2007).

2.5. Conventional Treatment Technology (Ion-Exchange)

With the above health and regulatory concerns in mind, treatment technologies are being sought to efficiently and effectively remove perchlorate from contaminated water. The conventional technology for the treatment of perchlorate-contaminated water is IX. In IX, perchlorate anions in the water being treated are exchanged with innocuous anions that are embedded on a polymeric resin bed. The IX resin contains permanently bound functional groups of opposite (i.e., positive) charge to the exchange ion species. These

positively charged functional groups serve as sites for the anion exchange. In the case of the perchlorate anion, positively charged amine groups are attached to the polymeric resin (Gottlieb, 2005). The number of exchange sites is limited, which requires the resin to be regenerated or replaced after exhaustion.

The two general types of IX resin for perchlorate treatment are: conventional (non-selective) and selective. The prominent issues related to the use of both selective and non-selective IX water treatment are resin regeneration, secondary waste production, perchlorate destruction, and the associated costs of these processes (Gu and Brown, 2006).

2.5.1. Non-Selective IX Resins

Two principal benefits of conventional IX technology for treating perchlorate are its effectiveness and the fact that it can be operated at high-flow rates. However, its performance is affected by (1) the presence of competitive anion species such as chloride, carbonate, nitrate, and sulfate and (2) resin selectivity (Gottlieb, 2005). The presence of competitive species increases the regeneration frequency of the resins. Resin selection is generally based on the ionic concentration (IC) of the treated water; when the IC is greater than 500 mg/L, non-selective ion exchange may become impractical or less attractive than other processes, as regeneration produces large volumes of brine that contain perchlorate and other absorbed species such as nitrates and sulfates that require pre-treatment prior to disposal (Gottlieb, 2005). Two additional limitations of conventional IX resins is that (1) treated water may require re-mineralization, and (2)

when perchlorate concentrations are relatively low, IX may be ineffective or uneconomical (Gu et al., 2003).

2.5.2. Selective IX Resins

Selective IX resins demonstrate a higher preference and greater exchange efficiency for perchlorate removal than non-selective resins. A limitation with selective resins is that the increase in ion preference also results in increased consumption of chemicals during regeneration cycles (Cheremisinoff, 2002). Thus, although perchlorate-selective IX resins improve the removal efficiency of perchlorate in the presence of competitive species, regenerating exhausted resins is cost-prohibitive. Typically, the resins are not regenerated; they are used once and disposed of (Gu and Brown, 2006). However, recent technological improvements have led to promising developments of selective IX resins that improve regeneration capabilities and perchlorate recovery while reducing secondary waste production and overall capital and O&M costs (Gu and Brown, 2006).

2.5.3. Treatment Costs

As a result of recent technological and process improvements, the general cost of IX water treatment for perchlorate has declined since its early use. Siemens (2007) estimates IX treatment costs for perchlorate removal (including cost of resin, pre-installation rinses, vessel loading and unloading, vessel sanitization, transportation, final resin disposal, and certificate of destruction) for 2007 to be in the range of $75 to $100 per acre-foot; a significant decline from cost estimates in 2000, where treatment costs ranged from $450 to $650 per acre-foot (Siemens, 2007). This treatment cost decline is attributed to

improved resin selectivity and regulatory acceptance of specific resin technology (Siemens, 2007).

2.5.4. Co-Contamination by Organic Species

Despite the effectiveness of IX in removing perchlorate and the reduction in treatment costs and improvements in IX technology, IX has a number of shortcomings. IX is unable to treat organic co-contaminants that may also be present in perchlorate-contaminated water. IX is also unable to treat waters that contain oxidants along with physical co-contaminants or oily substances that could coat the resin beads (Gottlieb, 2005). The presence of co-contaminants may result in the need for implementing multiple treatment processes, which would involve additional costs.

Nine of the twenty most common chemicals found in groundwater at Superfund sites are chlorinated solvents, with trichloroethene (TCE) being the most common contaminant detected in groundwater (NRC, 1994).   Thus, it is not surprising that when perchlorate contamination is found, it is not uncommon to also detect organic co-contaminants. To illustrate this, Table 2-2 lists current locations reported by the U.S. EPA that have perchlorate along with TCE and/or nitro-organic co-contaminants (U.S. EPA, 2007). Also noteworthy, the FY2002 DoD Defense Environmental Restoration Program Annual Report to Congress listed perchlorate, octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX), and hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX) as the three military munitions' constituents that are of greatest concern for both their widespread use and potential environmental impact (DERP, 2003).

Table 2-2 Sites with Perchlorate and Organic Co-Contaminants (U.S. EPA, 2007)		
Location	**Contaminant(s)**	**Media**
Longhorn Army Ammunition Plan Karnack, TX		
	Perchlorate	Groundwater, Soil
	TCE	Groundwater, Soil
Jet Propulsion Laboratory (NASA) Pasadena, CA		
	Perchlorate	Groundwater, Soil
	TCE	Groundwater, Soil
US Army/NASA Redstone Arsenal Huntsville, AL		
	Perchlorate	Groundwater, Soil
	TCE	Groundwater, Soil
USN Naval Surface Warfare Center White Oak, MD		
	Perchlorate	Groundwater
	HMX	Groundwater
	RDX	Groundwater, Soil
	TCE	Groundwater

2.6. Innovative Technology Review (Tailored-GAC)

In response to the growing concern with perchlorate contamination, technology

alternatives and innovations should be examined to provide potential stakeholders

feasible and cost-effective options to treat this emerging contaminant.   A promising

innovative technology for treating perchlorate-contaminated water is based on GAC.

Researchers from PSU have developed a "tailored" granular activated carbon (T-GAC)

technology that has been demonstrated to effectively remove perchlorate from water in

lab and field experiments (Chen et al., 2005a; b; Parette and Cannon, 2005; ESTCP, 2005). The technology is based on tailoring GAC using alkyl quaternary amine or other nitrogen functional groups (termed N-surfactants) which improve the carbon's anion exchange capability or affinity for perchlorate. Using laboratory-scale tests that are conventionally used to predict large-scale performance of GAC systems, the researchers at PSU have tested perchlorate adsorption using several influent concentrations of perchlorate in water (Chen et al., 2005a; b; Parette and Cannon, 2005; ESTCP, 2005).

To provide an understanding of the T-GAC technology, in this section, we will first overview general GAC process variables, review the T-GAC lab results presented in the literature, discuss the lab-scale methods and modeling techniques used for GAC (and recently, for T-GAC), to predict full-scale performance, and finally present pilot-scale results from a T-GAC treatment system.

2.6.1. Granular Activated Carbon (GAC)

GAC is conventionally used in groundwater remediation to remove organic solutes from aqueous solutions. Activated carbon is charcoal that is produced by thermally treating carbon-based solids, such as coal (bituminous, lignite, or peat), coconut shell, wood, or other natural cellulose material. The thermal treatment product is then powdered, granulated, or pelletized. The thermal treatment is based on heating coal to 800° to 1000° C in an oxygen-limited steam atmosphere that "activates" the carbon and creates macro- and micro-pore structures within the granules that increase the surface area and sites for adsorption. Additionally, the thermal treatment removes organic compounds residing on the carbon-based material to create virtually pure carbon. The resulting pure carbon

layer surfaces are un-charged and hydrophobic; therefore, they have a high affinity for organic solutes. The more hydrophobic (less soluble) an organic species is, the greater its tendency to adsorb on GAC (Faust and Aly, 1998).

2.6.2. GAC Adsorption Process Variables

Two important variables related to GAC design are breakthrough characteristics and contact time. Additional design considerations that impact performance are column configuration and head loss. This section will discuss these process design parameters as they relate to T-GAC.

2.6.2.1. Mass Transfer Zone and Column Stages

To illustrate adsorption column performance, Figure 2-1 from Faust and Aly (1998) shows the various stages of the adsorption process. GAC adsorption systems used in drinking water applications use fixed beds with the liquid flowing downward through the adsorbent (Clark and Lykins Jr., 1989). With this configuration, absorbed solute accumulates at the top of the bed until the amount of adsorbed contaminant reaches equilibrium (T=0 in Figure 2-1). This area of dynamic liquid phase solute adsorption is the mass transfer zone. After equilibrium has been achieved, the mass transfer zone will move within the column bed (as shown when T=T/4 in Figure 2-1). When the mass transfer zone boundary has reached the column outlet or when the effluent concentration has reached a pre-determined limit, initial breakthrough is said to have been reached. As the system continues to operate past breakthrough, the column will reach full-exhaustion when the influent and effluent concentration are equal (T=T in Figure 2-1). As the column operates, the average loading concentration, defined as the ratio of the mass of

solute that is adsorbed per mass of adsorbent (x/m), increases until full-exhaustion of the

column has occurred.

ADSORBENT LOADING (x/m)
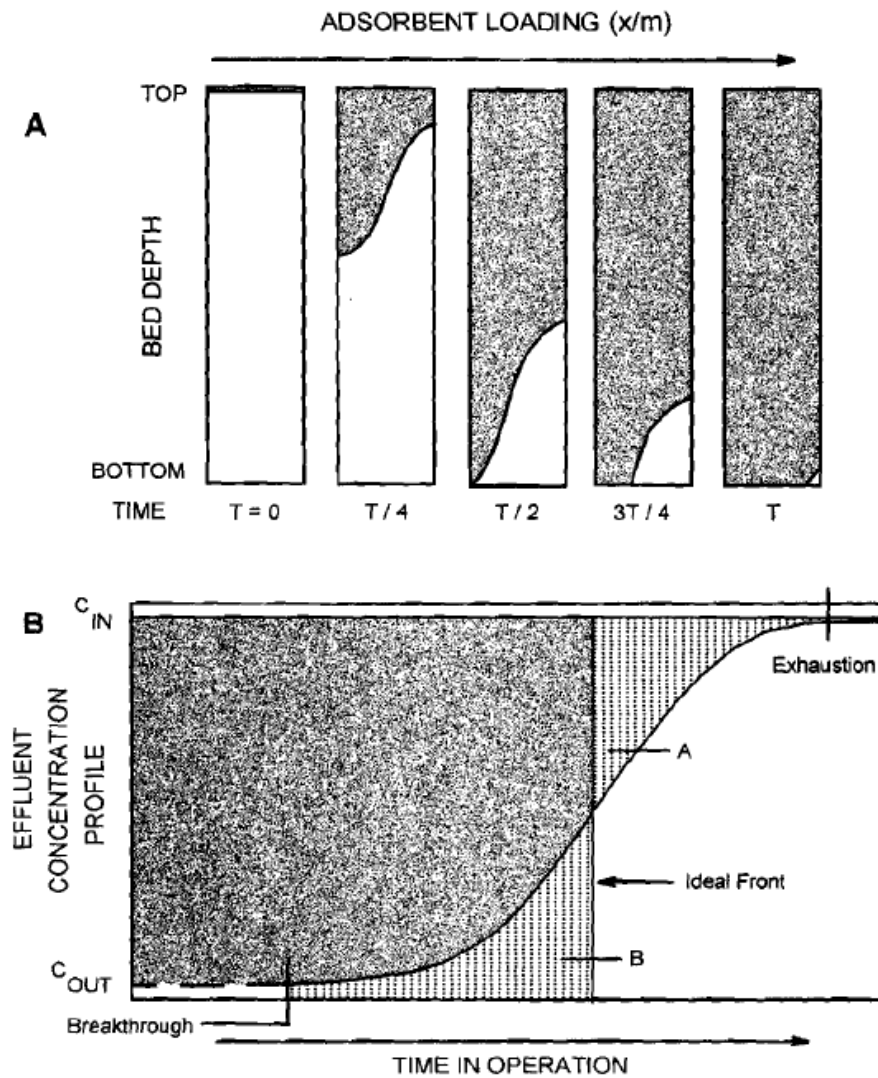
Figure 2-1 Adsorption Column Stages (Faust and Aly, 1998)

2.6.2.2. Bed Volume and Empty Bed Contact Time

The bed volume (BV) of a column is defined as the volume of media contained in the reactor (Equation 2-1).

$$BV = \frac{\text{Mass of Media in Bed (lb)}}{\text{Media Density}(\frac{lb}{ft^3})}$$

(2-1)

The empty bed contact time (EBCT) is the carbon bed volume divided by the superficial flow rate of the fluid stream through the T-GAC vessels, as shown from Equation 2-2, or simply the time required for treatment water to flow through the empty contactor.

$$EBCT = \frac{BV}{Q}$$

(2-2)

(Crittenden et al., 2005)
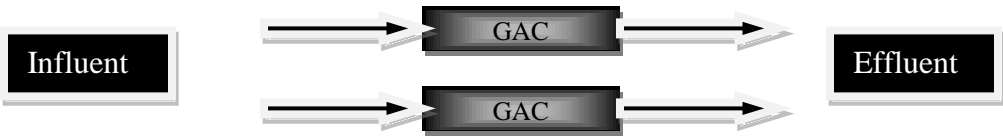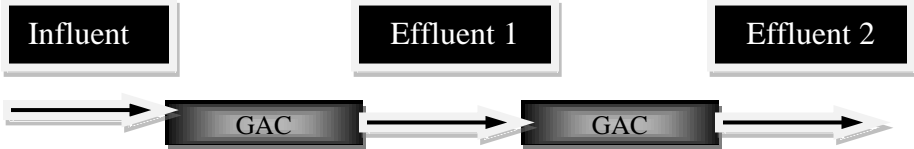
where: Q = Superficial water flow rate through the contactor [ft^3 min^{-1}]

The importance of the EBCT is that it is a measure of the time that the water to be treated and the sorbent are in contact with each other (Clark and Lykins, 1989). The longer the EBCT, the more likely that sorbed and dissolved contaminant will be in equilibrium with each other. At equilibrium, the loading concentration is maximized, which corresponds to higher capacities for carbon adsorption and improvements in the carbon utilization rate (CUR) (Faust and Aly, 1998). CUR and EBCT have the greatest effect on capital and operating costs for GAC processes (Brady, 2005). During process implementation, the EBCT can be varied by changing bed depth at constant flow or changing flow at constant bed depth.

2.6.2.3. Absorber Configuration

The two main types of GAC fixed column configurations are in-series or in-parallel.

These configurations and their principal advantages and disadvantages are summarized in

Table 2-3 (Clark and Lykins, 1989).

Table 2-3 GAC Absorber Configurations	
Parallel The most common GAC configuration for drinking water treatment is the down-flow fixed bed in parallel operation (Brady, 2005).	
Advantage:	High system pressure drops are minimized and larger total flow rates can be achieved. Most suitable in large-scale operations.
Disadvantage:	To maintain desired effluent qualities, system can't be used to full carbon saturation.
Series 	
Advantage:	Carbon utilization is maximized. After the lead bed reaches full loading capacity, the lag bed is switched to the lead position, and the former lead is replaced or regenerated. A fresh column assumes the lag position.
Disadvantage:	Head loss, and associated pumping costs, may be significant.

2.6.2.4. Reactivation of GAC

A cost advantage of GAC is that exhausted GAC can be reactivated, so that when the sorbed contaminants are removed, the adsorptive capacity is restored (Chen and Cannon, 2005b).   Resulting material losses from the reactivation process range from 10% to 20% each cycle (Marve and Ryan, 2001). The source of this attrition is caused from transport losses and carbon burn-off (Clark and Lykins, 1989).

2.6.3. Tailored GAC

Granular activated carbon in its unaltered form has a limited ability to remove perchlorate, which is a charged anion (Chen et al., 2005a).   The bed volumes of water treated before breakthrough for perchlorate is only about 10% of that for volatile hydrophobic organic species such as TCE (Na et al., 2002).   However, reasearchers at PSU have demonstrated that tailoring GAC with N-surfactants improves the carbon's ability to remove perchlorate anions from contaminated water (Chen et al., 2005a; b; Parette and Cannon, 2005). In this section, we will review T-GAC technology and several of its characteristics.

2.6.3.1. Surfactant Tailoring Agents

Chen et al. (2005a) conducted a study of the potential for T-GAC to remove perchlorate from water. By tailoring with ammonia (NH_3) gas, a high positive charge density was placed on the GAC, thereby enhancing perchlorate adsorption during rapid small-scale column tests (RSSCTs). Ammonia-tailored GAC adsorbed four times more perchlorate than virgin GAC.   The RSSCT results suggested that perchlorate adsorption was highly related to the change in the carbon surface charge; this suggested that perchlorate

adsorption is principally due to electrical attraction versus physical interaction. A

detailed discussion of RSSCTs may be found in section 2.6.4.1.

In related efforts, Parette and Cannon (2005) explored the use of quaternary ammonium

functional groups as tailoring agents. Groups that were tested are listed Table 2-4. The

quaternary amine group of the N-surfactant is an electropositively charged nitrogen atom

that acts as the attraction site for anion species such as perchlorate. The perchlorate anion

sorbs onto the N-surfactant tailored GAC (T-GAC). Parette and Cannon (2005)

demonstrated in RSSCT experiments that GAC tailored with quaternary amine

surfactants achieved a 35-fold improvement in perchlorate adsorption over virgin GAC.

Figure 2-2 compares the relative performance of the various quaternary amine tailoring

agents with virgin GAC and ammonia-tailored GAC.

Table 2-4 Quaternary Amine Functional Groups used as Tailoring Agents by Parette and Cannon (2005)	
DTAB	decyltrimethylammonium bromide
THAB	tributylheptylammonium bromide
MTAB	myristyltrimethylammonium bromide
CTAC	cetyltrimethylammonium chloride
CPC	cetylpyridinium chloride
T-50	tallowalkyltrimethylammonium chloride
2C-75	dicocoalkyldimethylammonium chloride
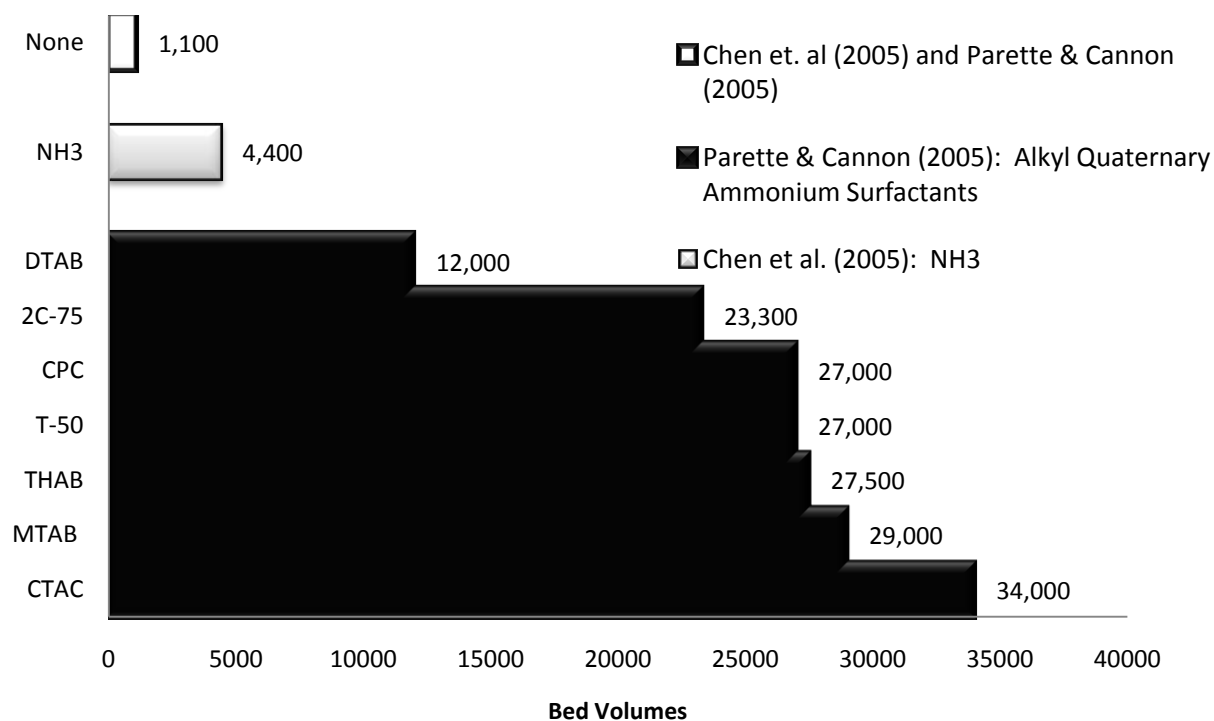
Figure 2-2. Tailored GAC RSSCT Performance.

2.6.3.2. T-GAC Structure

The tailoring compounds used on T-GAC have an interesting structure and orientation.
The alkyl chains on the N-surfactant are uncharged; as such, the hydrophobic alkyl chains
bind with the uncharged pore structures of the GAC surface. As these alkyl chains bind
to the GAC surface, the chains orient in such a manner to form micelle structures within
the pore surfaces of the GAC (as represented in Figure 2-3) where the positive charged
heads align away from the GAC surface and away from the other alkyl tails. The
resultant structure creates a matrix of positively charged adsorption sites for perchlorate.
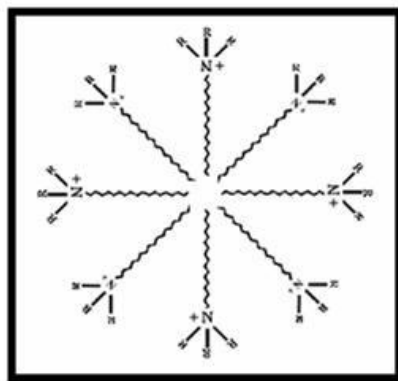
Figure 2-3 Hypothesized Micelle Alkyl Quaternary Amine Configuration Within Activated Carbon Pores (ESTCP, 2005)

2.6.3.3. N-surfactant Tailoring Process

The N-surfactants are pre-loaded onto GAC by pumping a concentrated surfactant-water solution cyclically through a GAC bed at 40-70 °C until the surfactant reaches a water-phase concentration that is approximately 10 to 20 milligrams/liter [mg/L]; then, the GAC bed is rinsed to remove residual aqueous surfactant and prepped for service (ESTCP, 2005).

2.6.3.4. Co-contaminant Adsorption by T-GAC

In addition to the principal finding that tailored GAC significantly increases the adsorption of perchlorate, ammonia-tailored GAC appears to not inhibit the adsorption of organic compounds; thus, suggesting the ability of T-GAC to remove both organic and anionic contaminant species (Chen et al., 2005a).

In another RSSCT study, groundwater that contained 1 ppb ClO_4^-, and which also contained nitro-organics HMX (0.6 ppb) and RDX (5.5–6.6 ppb), treated with CTAC-tailored GAC demonstrated a significant performance increase for perchlorate adsorption

compared to virgin GAC; however, the capacity to remove organics was notably

diminished (Parette et al., 2005). However, combining a CTAC-pre-loaded ''lead'' bed

with a virgin GAC polishing bed resulted in the concurrent removal of both perchlorate,

RDX and HMX (Parette et al., 2005).

2.6.3.5. Competition with Other Anionic Species

Based on RSSCTs using water contaminated with perchlorate (0.075 mg/L), nitrate (26

mg/L as NO_3), sulfate (30 mg/L), and other anions, Parette and Cannon (2005) reported

that between 7.3–10.1% of the quaternary ammonium sites (CTAC, T-50, 2C-75, and

CPC) were associated with adsorbed perchlorate. This result shows that T-GAC is

significantly more selective for perchlorate, even when perchlorate is in the presence of

high concentrations of other anions. Nevertheless, recent RSSCT results using CPC-

tailored GAC indicate that high concentrations of nitrate and thiosulfate may significantly

reduce T-GAC's effective adsorption capacity for perchlorate (Figure 2-4).
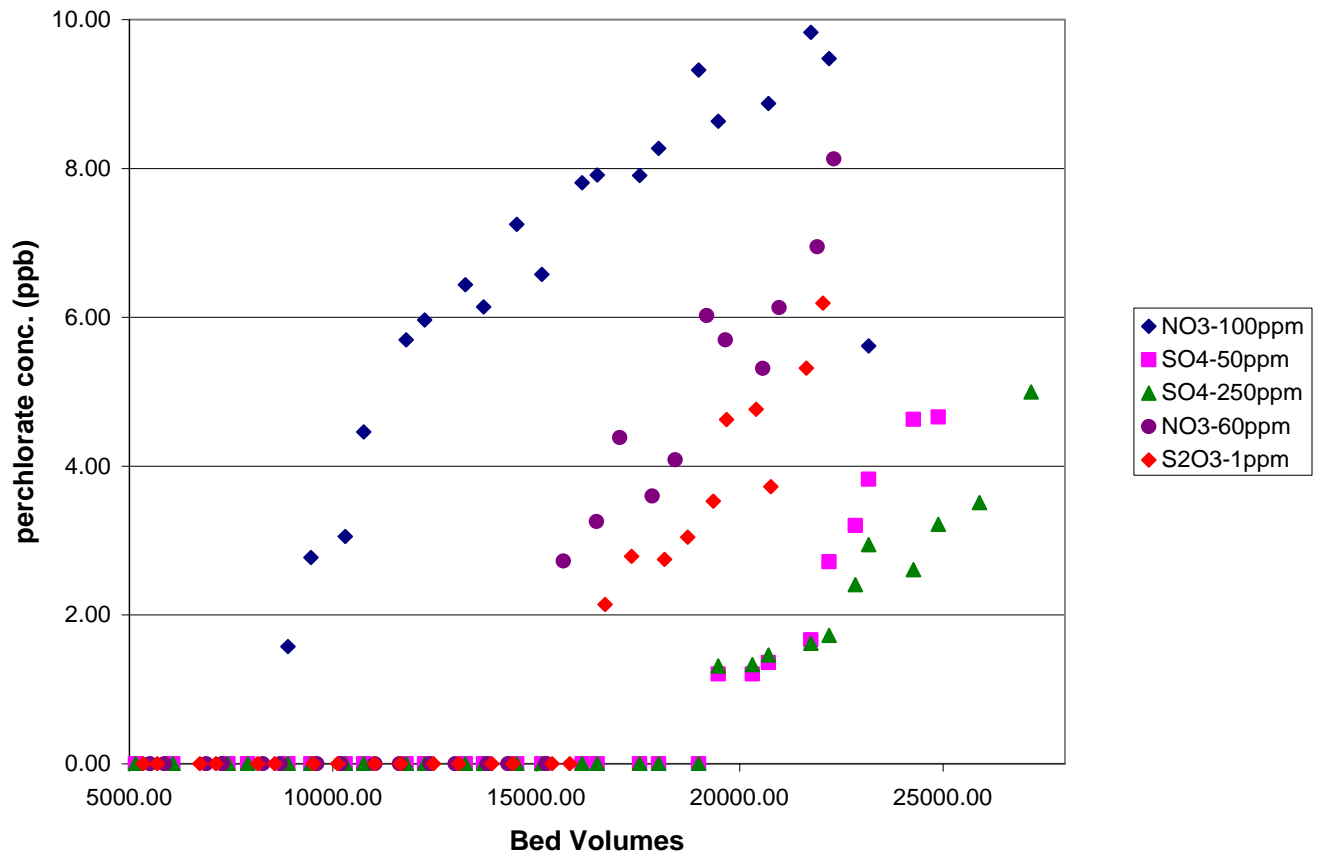
Figure 2-4.   Effects of Competitive Species on Perchlorate Breakthrough in RSSCT Tests using CPC-tailored GAC (PSU, 2007).

2.6.4. Extrapolating Results to Predict Cost and Performance

"*For innovative technologies that have undergone limited field applications,*

questions arise about predictability over a range of conditions and understanding

the scale-up can be difficult from lab-scale to pilot-scale to full-scale (NRC,

1994)."

Performance predictability is therefore vital to demonstrating technology viability. The

three primary methods for estimating full-scale GAC performance are pilot studies,

RSSCTs, and mathematical models. Pilot studies are regarded as the most reliable

method for extrapolating to full-scale performance; however, they are time and cost

intensive. As such, researchers have relied on scaled-down columns and mathematical

models to provide timely and inexpensive predictions of full-scale adsorber performance.

Therefore, in this section we will discuss the use of RSSCTs and pilot-scale studies to

predict T-GAC performance. Special attention is placed on how these controlled studies

can be used to develop and calibrate a mathematical model that can predict T-GAC

performance and costs.

2.6.4.1. Rapid Small Scale Column Tests

The lab-scale tests conducted by PSU, intended to predict full-scale performance, are

based upon conventional GAC column scaling methods that employ RSSCTs. The basis

for RSSCTs is discussed in this section.

To determine mass transfer and adsorption kinetics, pilot-scale demonstrations are

typically conducted. The primary drawbacks of large-scale trials are capital and

operational costs and time. To mitigate these challenges, full-scale GAC column

performance can be predicted using scaled-down column tests. A technique developed

and tested by Crittenden et al. (1986; 1987; 1991) has been shown to effectively predict

GAC performance using RSSCTs. The Crittenden et al. (1991) model determines the

EBCT and hydraulic loading based on a fixed-bed transfer model that relates external and

internal mass transfer.

2.6.4.1.1. Diffusivity

The diffusivity of a solute onto an adsorbent is dependent on the intra-particle mass

transfer resistance. Diffusivity can be assumed to be constant or proportional when

modeling the adsorption process. Constant diffusivity means that the intra-particle

diffusivity does not vary with adsorbent particle size. Proportional diffusivity means that

the intra-particle diffusivity is proportional to the adsorbent particle size. Based on these

two assumptions, the EBCT of a large-scale column ($EBCT_{LC}$) can be related to the

EBCT of a small scale column, such as the column used in an RSSCT ($EBCT_{SC}$) by

Equation 2-3 (Crittenden et al., 1991).

$$\frac{EBCT_{SC}}{EBCT_{LC}} = \left[\frac{d_{p,SC}}{d_{p,LC}} \right]^{2-X} = \frac{t_{SC}}{t_{LC}} \tag{2-3}$$

where: SC = Small-scale column
LC = Large-scale column
d_p = Adsorbent particle size [cm]
t = Elapsed time in the appropriate column test
[min]
X = 1 (Proportional Intra-particle Diffusivity)

Parette and Cannon (2005) and Chen et al. (2005a) conducted RSSCT experiments based

on the premise of proportional intra-particle diffusivity. However, according to Cannon

(2007), the basis of RSSCT scaling with T-GAC may vary and be dependent on the size

of the full-column that is scaled. PSU is currently examining this hypothesis. The

resulting inter-relationships, based on proportional diffusivity, between typical adsorbent

GAC particle sizes and EBCT are shown in Table 2-5.

2.6.4.1.2. Hydraulic Loading

RSSCT hydraulic loading relationships between the large and small columns are

indicated by Equations 2-4 and 2-5 (Crittenden et al.,1991).

$$\frac{v_{SC}}{v_{LC}} = \left[\frac{d_{p,LC}}{d_{p,SC}}\right] \times \left[\frac{\text{Re}_{SC\min}}{\text{Re}_{LC}}\right]$$

(2-4)

$$\text{Re} = \frac{\rho v \psi d_p}{u}$$

(2-5)

where:

ρ = Fluid density [g cm^{-3}]
v = Superficial fluid velocity [cm s^{-1}]
u = Fluid Viscosity [g cm^{-1} s^{-1}]
ψ = Sphericity of filter media [unitless]

The primary implication of the Crittenden et al. (1991) RSSCT model is that breakthrough profiles (concentration versus bed volumes treated) of the RSSCTs can be used to predict the profiles of larger scale columns. Subsequently, the knowledge of bed volumes treated (and therefore, time) to breakthrough allows designers to compute carbon utilization and specific throughput (Equation 2-6 and 2-7, respectively).

$$Specific\ Throughput = \frac{Q \times t_b}{M_{TGAC}} = \frac{BV \times t_b}{EBCT \times M_{TGAC}} = \frac{t_b}{EBCT \times \rho_{TGAC}}$$

(2-6)

Units: Liters of treated Water per gram T-GAC

(Crittenden et al., 2005)

$$CUR = (Specific\ Throughput)^{-1}$$

(2-7)

(Faust and Aly, 1998)

where:

t_b = Time to initial breakthrough [days]
M_{GAC} = Mass of T-GAC [grams]
ρ_F = Apparent density of T-GAC [grams Liter^{-1}]

2.6.4.2. Performance Modeling

Adsorption columns and operating cycles can be designed reliably on the basis of adsorption isotherm data measured during small-scale experiments to determine the mass transfer characteristics of the water to be treated (Null, 1987). Therefore, with results from the lab, a performance model to predict full-scale performance can be developed using conventional GAC modeling methods.

2.6.4.3. Freundlich Adsorption Isotherm

A number of isotherms are used to characterize adsorption; the two most commonly used are the Freundlich and Langmuir isotherms (Seader and Henley, 1998). The Langmuir isotherm is derived from simple mass-action kinetics and assumes chemisorption. Parette and Cannon (2005), based on RSSCT trials, concluded that perchlorate adsorption on quaternary ammonium T-GAC was associated with charge attraction rather than covalent bonding. Moreover, Chen et al. (2005a) effectively used the Freundich adsorption isotherm to characterize perchlorate adsorption on ammonia-tailored GAC, observing that perchlorate adsorption was highly related to change in carbon surface charge; therefore, they concluded that perchlorate adsorption is principally a function of charge rather than a physical interaction.

Assuming a non-uniform heat of adsorption distribution on the adsorbent surface, the Freundlich adsorption isotherm with T-GAC as the adsorbent and perchlorate as the solute is shown in Equation 2-8 (Faust and Aly, 1998).

$$q_e = (x/m)_{ClO4,TGAC} = K_{ClO4}C_{ClO4}^{\frac{1}{n_{ClO4}}} \qquad (2\text{-}8)$$

where: q_e = Mass of adsorbent-phase perchlorate per mass of T-GAC adsorbent at equilibrium [mg g^{-1}]
K_{ClO4} = Freundlich adsorption coefficient, (mg/g) (L/mg)$^{1/n}$
$1/n_{ClO4}$ = Freundlich adsorption exponent (unitless)
C_{ClO4} = Dissolved perchlorate equilibrium concentration (mg/L)

2.6.4.4. Multi-Component Adsorption

As discussed previously, RSSCT results indicate that there is competition between

perchlorate and other anions that reduces T-GAC's perchlorate adsorption performance

(Parette and Cannon, 2005; ESTCP, 2005). To model this competition requires

experiments on the actual waters to be treated, since multi-component isotherm behavior

cannot be predicted in general from the individual isotherms (Null, 1989).

 Powell (2007) demonstrated that the Freundlich multi-component isotherm could be

used to characterize the adsorption of a single-component (perchlorate) competing with

other anions for T-GAC adsorption sites. The Freundlich multi-component adsorption

equation is shown by Equation 2-9 (Faust and Aly, 1998).

$$q_e = (x/m)_{ClO4,TGAC} = K_{ClO4}C_{ClO4}\left(\sum_{j=1}^{k} a_{ClO4,j} C_j\right)^{\frac{1}{n_{ClO4}}-1} \qquad (2\text{-}9)$$

where: $a_{ClO4,j}$ = competition coefficient [dimensionless]
C_j = contaminant species j concentration [mg L^{-1}]

2.6.4.5. Parameter Determination

The Freundlich adsorption isotherm is derived from the assumption that there is equilibrium between chemical in the adsorbed and dissolved phase (Clark and Lykins, 1989); thus, the mass of adsorbent-phase perchlorate that is adsorbed onto T-GAC, q_e, is assumed to be in equilibrium with dissolved perchlorate, C_e. Freundlich adsorption isotherm parameters are determined by measuring q_e as a function of C_e. The best fit line of a log-log plot of q_e versus C_e may be used to determine the Freundlich adsorption coefficient and exponent.

2.6.4.6. Validity of Freundlich Equilibrium Assumption during RSSCTs

The EBCT is a measure of the hydraulic residence time of water to be treated in the adsorber bed (Clark and Lykins, 1989). At short EBCTs, it is possible that equilibrium between sorbed and dissolved chemical may not be attained. For RSSCTs of perchlorate adsorption on T-GAC, Powell (2007) suggested from empirical observations that the measured adsorbed concentration (q_e*) is some fraction of the adsorbed concentration at equilibrium (q_e), and that the ratio of q_e* and q_e (defined as %$q_e$achieved) depends on the EBCT and the adsorbent particle size. Using these definitions, Equation 2-9 can be rewritten as Equation 2-10. The relationships between %$q_e$achieved, EBCT, and GAC grain size, which are shown in Table 2-5, were empirically quantified by Powell (2007). The relationships are based on results of RSSCTs conducted at PSU using Redlands water that were run to study the effects of EBCT on performance.

$$q_e^* = \%q_e \, achieved \; x \; K_{ClO4}C_{ClO4}\left(\sum_{j=1}^{k} a_{ClO4,j}C_j\right)^{\frac{1}{n_{ClO4}}-1} \tag{2-10}$$

$$=(\text{x/m})^*_{ClO4,TGAC}$$

Table 2-5. Relationship between EBCT, GAC Particle Size, and %q$_e$achieved.

200 x 400 EBCT (minutes)	20 x 50 EBCT (minutes)	20 x 40 EBCT (minutes)	12 x 40 EBCT (minutes)	8 x 30 EBCT (minutes)	Percent Achieved Pseduo- Equilibrium
0.3	2.1	2.5	3.5	5.0	35%
0.4	2.9	3.5	5.0	7.0	66%
0.4	3.4	4.0	5.7	8.0	76%
0.5	4.2	5.0	7.1	10.0	88%
0.6	5.0	6.0	8.5	12.0	90%
0.8	6.3	7.5	10.6	15.0	92%
1.0	8.4	10.0	14.1	20.0	95%
2.0	16.8	20.0	28.3	40.0	96%

The significance of Equation 2-10 is that upon the parameterization of the Freundlich

coefficients, the adsorption performance (i.e., loading capacity) can be estimated for any

specific perchlorate or competing anion concentration. And that ultimately, the

validation of the adsorption model can occur by comparing predicted performance with

pilot-scale field results.

2.6.5. T-GAC Studies

The performance of T-GAC has been investigated in both the lab and field. In this

section, we will present results from RSSCTs conducted by PSU as well as pilot-scale

field tests conducted at sites in Fontana and Redlands, CA. The availability of such

information is important since GAC modeling methods rely on actual performance results that are obtained from either the lab or field.

2.6.5.1. RSSCT Studies

To demonstrate the viability of N-surfactant tailored GAC on perchlorate removal, PSU has conducted several RSSCT trials with various water chemistries to determine the robustness and performance attributes of T-GAC. To simulate the adsorption capacity of pilot-scale beds being used at the trials conducted at Fontana as part of ESTCP Project ER-0546, PSU RSSCT experiments were conducted with Fontana, CA, water using CPC as the primary tailoring agent for T-GAC. Proportional diffusivity was assumed in interpreting the RSSCT results. Although it can be seen from Figure 2-2, that other N-surfactants demonstrated greater adsorption capacity for perchlorate, CPC was chosen since its use in a drinking water treatment system did not present any regulatory hurdles (it is an approved ingredient in mouthwash) (ESTCP, 2005).

Previously, PSU conducted various RSSCT trials using waters from Redlands, CA and a site in Massachusetts. These RSSCT results were the basis for the model developed by Powell (2007) and will be further analyzed as part of this thesis effort. The water quality at the various locations is shown in Appendix B. The performance results from PSU RSSCT trials used in this study are reported in Appendix A and discussed in detail in Chapter 4.

2.6.5.2. Fontana Pilot-Scale Field Study (37 gpm) ESTCP Project

The ability to predict full-scale GAC performance from pilot systems provides decision makers with a means of designing and costing the full-scale GAC system (Clark and

Lykins, 1989). Moreover, for an innovative technology, pilot-scale demonstrations offer greater insight into full-scale performance and potential economic benefits; which is a key step for evaluating technology viability.

As part of an on-going effort under ESTCP Project ER-0546, researchers seek to demonstrate the technical and economic potential for the removal of perchlorate using T-GAC. This demonstration is located at the Fontana Water Company, Fontana, California and the pilot system used water from wells 17B and 17C at the site (see Appendix B for water qualities) (ESTCP, 2005). The treatment process conceptual flow diagram and operating parameters used in the Fontana demonstration are shown in Figure 2-5 and Table 2-6, respectively.

The pilot-scale test consisted of three vessels operating in series (lead, lag, and polishing). The lead and lag vessels contain 50 cubic feet of T-GAC each and the polishing bed contains 50 cubic feet of virgin GAC. Operating flow rates averaged 37 gpm (equivalent to a 10-minute EBCT per bed or 20 minutes combined). Flow in the column was downward from top-to-bottom through each vessel. To reduce particulate accumulation that would cause significant pressure reductions, treated water is pre-filtered with a 10 micron cartridge filter prior to entering the vessel train. The polishing bed with virgin GAC serves to capture any residual or leached surfactant from exiting the system.

The lead-lag configuration of the vessels during the Fontana study is shown in Table 2-6. The first lead vessel, Bed A, was operated until it was full exhausted (effluent perchlorate concentration equaled influent concentration); this occurred approximately on June 8,

39

2007. Thereafter, the lag vessel, Bed B, was switched to the lead position and a new lag

vessel, Bed D, was installed until conclusion of the study. The performance results of the

Fontana trial are discussed in greater detail in Chapter 4.

Figure 2-5 Conceptual Process Flow Diagram (37 GPM Train)

Table 2-6 Fontana Process Characteristics Summary (37 GPM Train)		
Supply	Treatment Flow Rate = 37 gpm Fontana Water (Well 17C and 17B (See Appendix B for Water Characteristics)	
Pre-Filter	10 Micron (#2 Bag Filter) Purpose: Remove Particulate Matter	
T-GAC Vessels (Lead and Lag)	Vessel Dimensions: (48" Diameter X 72" Side), Carbon Steel Construction Carbon Grain Size: US Sieve 20 X 50 EBCT = 10 minutes per Column (20 min combined)	
	Configuration	
	At Start-Up 1/11/2007	After Re-Configuration on 6/8/2007
Bed A	Lead	Removed
Bed B	Lag	Lead
Bed D	--	Lag
GAC Vessel (Bed C)	Acts as polishing bed to remove leached N-surfactant	
Outflow	Treated water flows to holding pond	

2.6.5.3. Redlands Field Study

A previous field demonstration of the T-GAC technology was conducted at a water

treatment plant at Redlands, CA. The pilot-scale T-GAC system was demonstrated by

Siemens (formerly USFilter). The system and influent characteristics of water for this

pilot-scale system are detailed in Table 2-7. Treatment results from the field trial and the

corresponding PSU RSSCT results are shown in Figure 2-6.

Table 2-7. Redlands Field Demonstration Plant Design and Influent Water Characteristics Summary [Powell (2007)]
Plant Design: Two T-GAC CPC-tailored GAC beds configured in series at an EBCT of 7.76 minutes each (for a total of 15.52 minutes).

Perchlorate	75 ppb
Nitrate	16 ppm
Sulfate	30 ppm
Chloride	7.2 ppm
Bi-Carbonate	145 ppm
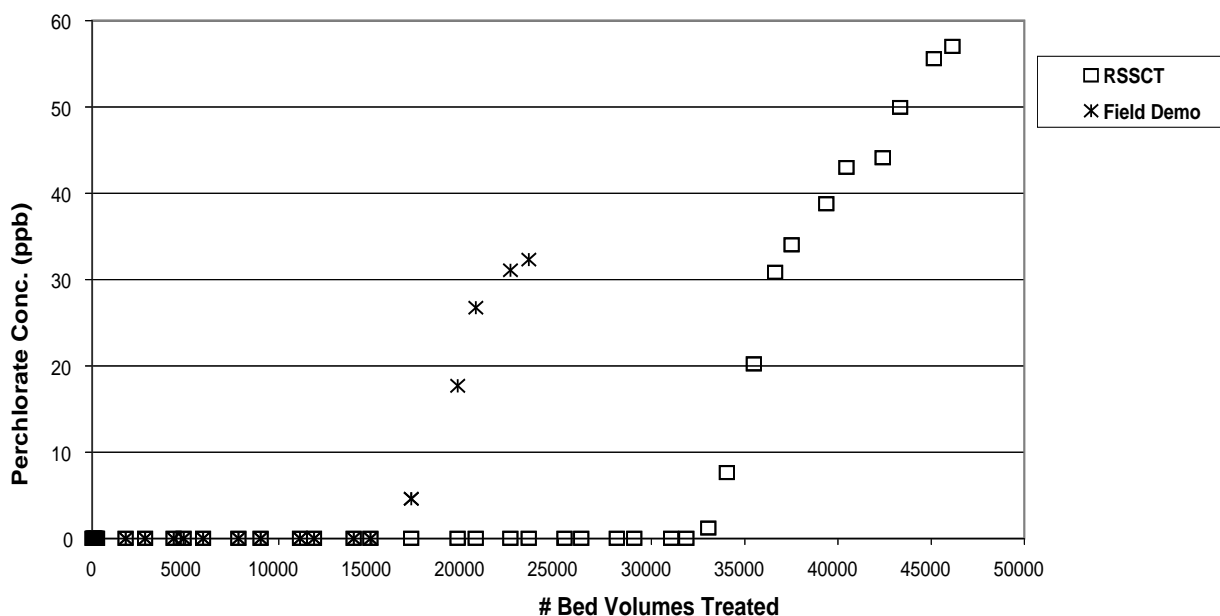
**Figure 2-6. Redlands Pilot-Scale and RSSCT Treatment Performance
[after Powell (2007)]**

2.7. Information Required by Decision Makers for Technology Selection

The availability of performance and cost information is important for potential users to

decide on the appropriate technology suitable for their treatment objectives. Relevant

performance, cost, and time information needs to be made available to decision makers to

help them decide how to make the "best" allocation of limited resources (Cooper et al.,

2001).   When considering water treatment technologies, stakeholders need to have a

clear understanding of the capital and operating costs of implementing the technology;

moreover, this information should be consistent, reliable, and readily available to

decision makers (NRC, 1997). Beyond cost, other factors are important to potential users

of innovative remediation technologies.   With this in mind, this section examines the

important considerations and information requirements of decision makers when selecting remediation technologies.

2.7.1. Reporting Innovative Technology Cost and Performance Data

Provided that the technology meets the remediation objectives, project cost is the most significant factor in technology selection. Understandably, when offered several alternatives, stakeholders select the technology that will meet remediation objectives and regulatory standards as cost effectively as possible (NRC, 1994). This cost factor becomes especially important in terms of technology transfer of innovative technologies; stakeholders must be convinced that the technology in question can accomplish remediation more economically, effectively, and efficiently than competing conventional technologies (Goltz et al., 1998).

If cost is the only consideration, discounted cash analysis provides the decision maker a valid way of deciding among different alternatives; however, establishing cost data for innovative remediation technologies in order to compare costs is difficult. The implications of misleading cost data are significant; thus, it is important that data be presented clearly, so that decision makers can easily compare alternatives (NRC, 1997). Therefore, the NRC (1997) suggests that to overcome potential bias or error in selection, uniform cost reporting among technologies be used to facilitate the comparison of technologies and speed their acceptance; the primary challenge is developing the ability to compare technology alternatives at different sites (NRC, 1997). The most common cash flow analysis method for evaluating capital budgeting alternatives is through the use of discounted methods such as net present value (Grinyer et al., 1999). For *ex situ*

environmental remediation, cost per unit volume treated (e.g. $/acre-foot) is the most common (NRC, 1997).

Providing cost and performance information on innovative remediation technologies in a useful format that satisfies the needs of decision makers is important to facilitate technology transfer.   Recommendations offered by the National Research Council (NRC, 1997) are listed in Table 2-9. Addressing the NRC recommendations as well as providing users a site-specific technology screening instrument, Mandalas et al. (1998) demonstrated that technology transfer can be facilitated by making available user-friendly technology screening software that provides stakeholders the information sought for technology selection.

Table 2-8 Recommendations for Innovative Remediation Technology Cost and Performance Reporting (NRC, 1997)	
Performance	Report technology's ability to reduce contaminant mass, concentration, mobility, and toxicity.
	Report data at specified point of maximum effect.
	Include field evidence that demonstrates how the technology reduces risk.
Cost	Report cost per unit volume of contaminated matrix and cost per weight of contaminant treated.
	Report both capital and operating costs.
	Specify discount rate and tax benefit assumptions.
	Use standardized template sites to compare the costs of difference technologies.

2.7.2. Technology Utility

While cost is crucial, other factors also play important roles in technology selection.

Ease of implementation, robustness over a range of site conditions, ability to handle

variable waste streams, and maintenance requirements are among many of the important

technology selection criteria for decision makers (NRC, 1994). These and other

qualitative benefits like technology simplicity, dependability, and acceptance are also

important factors that cannot necessarily be described in monetary terms. Hardisty and

Ozdemiroglu (2005) summarize technology characteristics that users identified as

desirable in Table 2-8.

Table 2-9 Technology Advantages Frequently Described as Benefits in Literature (Hardisty and Ozdemiroglu, 2005)	
Fast	Achieves desired remediation quickly compared to alternatives
Effective/Efficient	Removes large mass or higher percentage of contaminant and works better than alternatives.
Cost Effective	Removes more contaminant per unit of expense.
Simple	Installation and operation does not involve significant effort.
Dependable	System has less maintenance and lower downtime than alternatives.
Accepted	Method has been widely used and demonstrated.

3.0. Methodology

3.1. Introduction

This chapter details the methodology used to develop models that predict performance and cost of the T-GAC technology to treat perchlorate-contaminated water. A general outline of the methodology is shown in Figure 3-1.

Powell (2007) Performance Model Validation
- Run Powell's (2007) model to simulate the Fontana 37 GPM field-study to validate the model and determine the forecasting error for prediction.

Performance and Cost Model Development &Validation
- Reparameterize the Powell (2007) model to incorporate the results of additional RSSCTs and the Fontana 37 GPM field-study.
- Develop cost model and validate by comparing to Fontana 37 GPM field-study actual costs.

Screening Model Development
- Develop a user-friendly Excel based screening model that couples the performance and cost sub-models.
- Apply screening model to analyze cost and performance under various conditions.

Figure 3-1. Methodology Flow Diagram

3.2. Resources for Model Development

Performance results from small-scale and pilot-scale field demonstrations are the basis for the development of the model. Model parameter quantification used numerical tools to obtain best fits of model simulations to experimental data; a process discussed in greater detail in section 3.4. Specific details of these resources are discussed in the following sub-sections.

3.2.1. Laboratory/Small-Scale Trials

RSSCTs were conducted by PSU with Fontana, Redlands, de-ionized, and Massachusetts water. A comprehensive list of the PSU trials evaluated in this research is contained in Appendix A. Water chemistries of the sites are located in Appendix B.

3.2.2. Pilot-Scale Field Demonstration Results

Demonstration project results from Fontana under ESTCP project ER-0546 are located in Appendix C.

3.2.3. Numerical Tools

Error analysis and spreadsheet optimization used to generate this model was performed using Microsoft Excel 2007.

3.3. Powell (2007) Performance Model Validation

Prior to the development of the model, the Powell (2007) model was used to predict T-GAC performance for the field conditions of the Fontana 37 GPM study. The parameters used in the Powell (2007) model are shown in Table 3-1.

Table 3-1. Powell (2007) Optimized Parameters for Freundlich Multi-Component Isotherm Model

Ion Concentration (mg/L)	Competition Coefficient, a_j
Nitrate (NO_3^-)	0.0169
Thiosulfate	0.332
Sulfate (SO_4^{2-})	0 (No-Competition)
Chloride	0 (No-Competition)
Bicarbonate	0.000226
$K = 30.3$ (mg/g)(L/mg)$^{1/n}$	$1/n = 0.153$
Total Error	43.8%
Mean Error	3.99%
Sample Size: 11	

Over the 11 RSSCTs, Powell (2007) reports that the mean simulation error (best-fit) was less than 4%; therefore, suggesting his model accurately simulates the performance of the results used to construct his model.

3.4. Performance Model Development

After conducting the baseline evaluation of the Powell (2007) performance model, the performance model was modified in this study to incorporate the results of additional laboratory RSSCTs from PSU as well as the 37 gpm Fontana pilot test. The approach for determining the performance model parameters is discussed in this section.

3.4.1. Determining T-GAC Adsorptive Capacity

Consistent with previous work by Powell (2007), as discussed in Chapter 2, this study models perchlorate adsorption on T-GAC using the multi-component Freundlich adsorption isotherm (Equation 2-9). This equation was modified, as discussed in Powell

(2007), based on the assumption that equilibrium adsorption may not be achieved at relatively low EBCTs and relatively large adsorbent particle sizes. Equation 2-10 accounts for the assumption that q_e^*, the sorbed perchlorate concentration at a given EBCT and adsorbent particle size, is less than q_e, the sorbed perchlorate concentration at equilibrium, by the factor "*%q_e achieved.*"

$$q_e = (x/m)_{ClO4,TGAC} = K_{ClO4}C_{ClO4}\left(\sum_{j=1}^{k} a_{ClO4,j} C_j\right)^{\frac{1}{n_{ClO4}}-1} \tag{2-9}$$

$$q_e^* = \%q_e\, achieved\ x\ K_{ClO4}C_{ClO4}\left(\sum_{j=1}^{k} a_{ClO4,j} C_j\right)^{\frac{1}{n_{ClO4}}-1} \tag{2-10}$$

$$= (x/m)^*_{ClO4,TGAC}$$

3.4.1.1. Determining %q_e achieved

The %q_e achieved, which is the ratio of the adsorbed perchlorate concentration at a given EBCT and adsorbent particle size to the equilibrium concentration of adsorbed perchlorate, is a key parameter required for estimating the adsorption performance of T-GAC. Powell (2007) empirically derived the relationship between the %q_e achieved parameter and the EBCT and adsorbent size values. Table 2-5 shows the %q_e achieved for particular EBCTs and adsorbent sizes.

3.4.1.2. Determining the Mass of Adsorbent-Phase Perchlorate

The mass of adsorbent-phase perchlorate adsorbed onto T-GAC can be calculated from a

mass balance across the column (Figure 3-2).
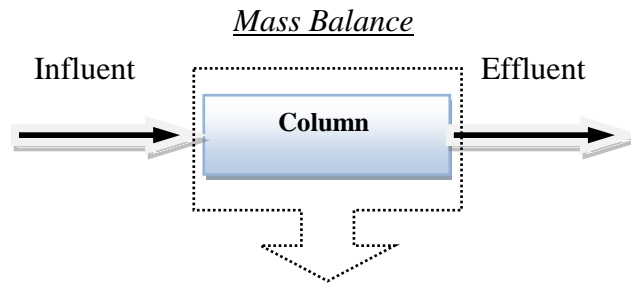
Mass Balance

Plant Flow (Q) x Time to Initial Breakthrough (t_b) x [Influent Concentration (C_o) – Effluent
Concentration (C_1)]

$\xrightarrow{yields}$ Mass Solute Adsorbed

Figure 3-2. Column Mass Balance.

Assuming the effluent perchlorate concentration is negligible, the sorbed concentration of

adsorbent-phase perchlorate on T-GAC (x/m), where m is the mass of adsorbent, may be

obtained by dividing the mass of contaminant adsorbed, x. by m, as shown in Equation 3-

1.

$$(x/m)_{ClO4} = \frac{Q \times t_b \times C_{0,ClO4}}{\rho_{TGAC} \times BV} = \frac{\#BVs \times C_{0,ClO4}}{\rho_{TGAC}} \qquad (3\text{-}1)$$

Where: $C_{O,ClO4}$ = Influent perchlorate concentration[mg L^{-1}]
     BV = Bed volume of column (L)
     #BVs = Number of bed volumes to initial breakthrough
     ρ_{TGAC} = Density of T-GAC (g L^{-1})

Adsorbed concentration calculations for RSSCTs with Fontana water were performed by PSU and are listed in Appendix A.

Equation 3-1 if re-arranged to determine #BVs is expressed in Equation 3-2.

$$\#BVs = \frac{(x/m)_{ClO4} \times \rho_{TGAC}}{C_{O,ClO4}} \tag{3-2}$$

3.4.1.3. Determining Freundlich Parameters K and 1/n

The determination of the Freundlich adsorption parameters is typically based on correlating the equilibrium liquid phase perchlorate concentration (C_0) with the adsorbed concentration (x/m). Freundlich parameter values are then found from a logarithmic plot of sorbed concentration as a function of dissolved perchlorate concentrations; yielding parameters K and 1/n from the y-intercept (log K) and slope (1/n) of the best-fit linear equation from Equation 3-3.

$$\mathrm{Log}\left(\frac{x}{m}\right)_{ClO4,TGAC} = \mathrm{Log}\ (K) + \frac{1}{n}\ \mathrm{Log}\ (C_0) \tag{3-3}$$

Equilibrium sorbed concentration values are not currently available; however, PSU has conducted RSSCT experiments with perchlorate-spiked Fontana water; influent perchlorate concentrations ranged from 13 ppb to 500 ppb. Therefore, Freundlich K and 1/n values are determined from values that, in-concert with the competition coefficients discussed in the next section, minimized the error between experimental and modeled results. This is accomplished by using spreadsheet optimization to select model parameters (K, 1/n, and $a_{ClO4,j}$) that results in the loading capacity values (calculated by

51

Equation 2-11) which minimizes the error between the model predicted values (calculated by Equation 3-2) and the RSSCT measured bed volumes to initial breakthrough (#BVs).

3.4.1.4. Determining Competition Coefficients ($a_{ClO4,j}$)

To account for competition between perchlorate and other anions that may be present in the water to be treated, several RSSCTs were conducted by PSU using various waters that were spiked with varying influent concentrations of nitrate, thiosulfate, chloride, sulfate, and bi-carbonate.   The influent concentrations and breakthrough volumes for these RSSCT experiments are shown in Appendix A. To estimate the competition coefficient, $a_{ClO4,j}$, which accounts for competition between perchlorate and anion j, the performance model (Equation 2-10) was used to simulate the results of the RSSCTs that were conducted with perchlorate and anion j. The value of $a_{ClO4,j}$ that minimized the error between experimental and modeled results was determined.

3.4.2. Performance Model Calibration

To calibrate the model parameters, we compared 12 actual RSSCT perchlorate-breakthrough results for Fontana water with model-simulated values. The comparison was done using the mean absolute percentage error (MAPE) calculated by Equation 3-4 (McClave et al., 2005).

$$MAPE = \frac{\sum_{t=1}^{m} \left| \frac{A_t - S_t}{A_t} \right|}{m} \times 100 \qquad \text{(3-4)}$$

where: A_t = Actual parameter value
S_t = Model simulated value
m = Number of series comparison

To determine model parameters K, 1/n, and $a_{ClO4,j}$, the respective parameter value that results in the lowest MAPE was the objective function and basis for minimizing simulation error.

3.4.3. Performance Model Predictions

The purpose of identifying the model parameters is to calculate the sorbed concentration at initial breakthrough based on the given competitive species concentrations, perchlorate concentrations, and the EBCT.   The predicted perchlorate-loading is then the source for predicting the number of BVs to breakthrough for columns operated in either single bed, in series, or in parallel configurations. Moreover, by analyzing the Fontana pilot-scale study, which used a column configuration that is conventionally used in large-scale systems, full-scale performance can be simulated. In this section, the methodology for estimating the bed volume treated to reach initial breakthrough, bed volume treated to reach column saturation, in-series performance benefits, and the effects of column re-configuration on performance are discussed.

3.4.3.1. Bed Volume Treated to Initial Breakthrough

The predicted perchlorate-loading is used to predict the number of bed volumes of perchlorate-contaminated water that can be treated before perchlorate initially

breakthrough. Bed volumes to initial breakthrough (#BVs) are determined from Equation 3-2.

3.4.3.2. Estimated Performance Benefits of Series Configuration

Equation 3-2 can be directly applied to predict the number of BVs of water that can be treated to initial breakthrough by a single column or parallel rows of single columns. However, as discussed in Chapter 2, a typical full-scale adsorption plant is commonly operated with columns in series to offer additional cost and performance benefits by allowing the process columns to operate beyond initial breakthrough, until they are fully saturated by the target contaminant.   Analysis of the Fontana 37 GPM study offers important information regarding series performance as Beds A, B, and D were operated in series until fully saturated.

Series operations consist of two stages. First, the lead bed is operated to full saturation. Second, the lag bed is re-configured as the lead bed and operated to full saturation. At Fontana, Bed B (the initial lag bed) was moved to the lead position after Bed A reached adsorbent exhaustion. After Bed B reached saturation, Bed D became the defacto lead bed (though water still flowed through the exhausted Bed B); therefore, Bed D can be evaluated in the same manner as Bed B. Comparison of the bed volumes treated to full saturation versus the bed volumes treated to initial breakthrough gives an estimate of the benefits of series configuration. These benefits can be quantified, using Equation 3-5, as the ratio of additional bed volumes treated in a series configuration to the bed volumes treated by a single column or a parallel series of single columns.

$$\text{Benefits of Series Configuration} \quad = \frac{BV(Final) - BV(Initial)}{BV(Initial)} \qquad \text{(3-5)}$$

where:
BV (Final) = #BVs treated to reach full saturation
BV (Initial) = #BVs treated to reach initial breakthrough

3.4.3.3. Performance of Lag-Bed Re-configured To Lead

When a bed that was initially in the lag position is moved to the lead position (for example, Beds B and D at Fontana), it will breakthrough faster than a bed which started in the lead position (e.g., Bed A). Presumably, this is because when the bed is in a lag position, some fraction of its adsorptive capacity is used up by compounds that are transported through the lead bed. To account for this, we will use Equation 3-6, with values obtained at Fontana, to quantify the reduction in bed volumes treated due to a bed initially being in the lag position.

$$\gamma = 1 - \frac{BV(Lag - to - Lead)}{BV(Lead\ Only)} \qquad \text{(3-6)}$$

where:
γ = Reduction in performance due to a bed initially being in the lag position

BV (Lag-to-Lead) = #BVs treated to reach initial breakthrough for a lead bed that was initially in the lag position (e.g. beds B and D at Fontana)

BV (Lead Only) = #BVs treated to reach initial breakthrough for a bed that is initially in the lead position (e.g. bed A at Fontana)

3.4.3.4. Column Bed-Life

The column bed-life is dependent on the mode of operation of the process and the flow rate of water through the system. The two design modes considered are single column and series operation. If operated as a single column, the column bed life can be calculated from Equation 3-7. When operating in single column mode, BV(capacity) is defined as the bed volumes that may be treated up to initial breakthrough. At breakthrough, the column is removed for media regeneration or replacement and the process repeats.

$$Bed\ Life = \frac{BV(Capacity)}{BV(Treatment\ Rate)} \qquad (3\text{-}7)$$

where: BV (Capacity) = #BVs treated to reach initial breakthrough as calculated from Equation 3-2 (single column mode) [#BVs]

BV (Treatment Rate) = Water flow through the column [#BVs/day]

If series operation is used, the three-stage process shown in Figure 3-3 is followed. At the completion of the three-stages, all T-GAC beds (A, B, and D) are removed for media regeneration or replacement and the three-stage process repeats. Series bed life is calculated for each bed using Equation 3-7 with the value of BV(capacity) defined in Table 3-2.

Stage I

```
→ [ Bed I ] → [ Bed II ] → [ Polishing Bed ] →
```

Bed A　　　　　T-GAC lead bed (operated to full saturation)

Bed B　　　　　T-GAC lag bed

Polishing Bed　Virgin GAC (captures leached tailoring surfactant)

Stage II

```
→ [ Bed II ] → [ Bed III ] → [ Polishing Bed ] →
```

Bed A　　　　　Removed

Bed B　　　　　Former lag bed, re-configured to lead (operated to full saturation)

Bed D　　　　　New T-GAC lag bed

Polishing Bed　Remains

Stage III

```
→ [ Bed II ] → [ Bed III ] → [ Polishing Bed ] →
```

Bed B　　　　　After saturation remains in-place

Bed D　　　　　Remains in lag bed configuration, but acts as defacto lead bed (operated to initial breakthrough)

Polishing Bed　Remains

Figure 3-3. Series Process Operation

**Table 3-2. BV(capacity) Value to Use In Equation 3-7
to Calculate Bed Life of a Column in a Series Configuration**

	BV(capacity) =
Bed A:	#Bed volumes treated to reach <u>full</u> saturation breakthrough as calculated from Equations 3-2 and 3-5 [#BVs]
Bed B:	#Bed volumes treated to reach <u>full</u> saturation breakthrough (after re-configured to lead) as calculated from Equations 3-2, 3-5, and 3-6 [#BVs]
Bed D:	#Bed volumes treated to reach <u>initial</u> breakthrough as calculated from Equations 3-2 and 3-6 [#BVs]

3.4.3.5. Carbon Utilization Rate

The T-GAC utilization rate is determined from plant flow rate, predicted column breakthrough, and media density and is calculated using Equation 2-7.   It is assumed that the virgin GAC polishing bed that follows the T-GAC beds is replaced annually. The actual replacement or regeneration schedule may be different, based on conditions.

3.4.4. Performance Model Assumptions

The important underlying assumptions for the development of the performance model are the following:

 (1) *%qe achieved* can be approximated as derived by Powell (2007): Powell (2007) empirically determined the value of *%qe achieved* as a function of EBCT and adsorbent particle size based on the results of the PSU RSSCT using Redlands water. This study assumes the relationship is valid.

(2) Temperature variations do not need to be accounted for: For groundwater remediation in the aqueous phase, data on adsorption obtained in the range of 50° to 70° F is generally appropriate and performance variations caused by temperature variation is assumed insignificant (Marve and Ryan, 2001)

3.5. Cost Determination

Cost is a key factor needed by stakeholders who want to decide whether the T-GAC technology is appropriate for treating perchlorate-contaminated water at a particular site. Cost, along with performance predictions, may also be used as a metric to compare the T-GAC technology to alternatives. Costs can be broken down as capital and operating costs, which may be converted to an estimate of overall project life-cycle cost for ease of comparison with the costs of alternative technologies.

3.5.1. Cost Reporting

The National Research Council (NRC, 1997) recommended that costs be reported as unit treatment costs to facilitate technology comparisons, as well as to assist technology transfer and commercialization. In this study, unit costs will be provided in the form of dollars per acre foot ($/acre-foot); the common reporting format for IX, the conventional perchlorate-treatment technology. This cost estimate will be calculated based on discounted cash analysis (discount rates considered are discussed in section 3.5.6) of annualized capital and annual operation and maintenance costs except where stated otherwise.

3.5.2. Background on Cost Information

In 1979, the U.S. Environmental Protection Agency (U.S. EPA) published a comprehensive study of water treatment technology costs, to include GAC columns, that separated capital costs into categories for site work, housing, manufactured equipment, labor, plumbing, valves, electrical and instrumentation, housing, and miscellaneous start-up and contingency costs (U.S. EPA, 1979). In addition, annual operating costs were considered and reported for labor, maintenance, and electrical. Reported GAC system costs were based on the plant flow (gpm) of single columns and included in the report in the form of tables and graphs. The primary advantage to using the U.S. EPA report to estimate costs is that the tables and graphs enable interpolation, so that process costs could be calculated for any plant flow rates. However, the associated disadvantage was that the cost estimator must manually identify the costs in the tables and graphs. To improve usability, the Bureau of Reclamation, in partnership with researchers at the National Institute of Standards and Technology, developed the Water Treatment Estimation Routine (WaTER) which was based on the 1979 U.S. EPA treatment cost figures (Wilbert et al., 1991). An Excel worksheet-based program, WaTER simplified cost estimation for each of the treatment technologies and updated costs with the latest industry cost indexes. Notably, cost outputs from WaTER were based on empirical equations derived from the U.S. EPA data. Despite its simplicity, a limitation of the WaTER program is that it generalizes costs into broad categories of capital and O&M; however, this reduces the ability to tailor and incorporate costs specific to unique processes such as those related to T-GAC. Therefore, the WaTER program was not used; rather, the U.S. EPA tabulated data was best-fitted into linear or exponential function

60

equations. Further discussion of the resultant cost functions is presented in the following section. Nevertheless, the WaTER program highlights the usefulness of an automated approach to estimating costs and efficacy of the U.S. EPA's 1979 cost figures. In the current study, all T-GAC costs, except for the cost of buying, transporting, and disposing of the T-GAC media itself, were calculated using the U.S. EPA data that were best-fit to empirical equations.

Model cost estimation will be based on the capital and annual operation and maintenance costs listed on Table 3-3. The methodology for determining these respective costs is discussed in the following sections.

Table 3-3. Capital and Annual Operation and Maintenance Cost Factors

Capital Cost	Annual Operation and Maintenance Costs
Excavation, Site, and Concrete Work[1]	Energy[1]
Manufactured Equipment[1]	Maintenance Material Costs[1]
Labor[1]	Labor[1]
Pumps, Piping, and Valves[1]	Media Replacement and Regeneration
Electrical and Instrumentation[1]	Disposal
Housing[1]	Transport
Miscellaneous and Contingency[1]	

1- Based on U.S. EPA (1979)

3.5.3. Capital Cost Function Development

Empirical formulation of capital cost functions was determined by best-fitting tabulated data reported by the U.S. EPA (1979) into linear or exponential function equations; the selection of which equation type to use was based entirely on which of these equations yielded a better-fit. The graphs of U.S. EPA (1979) cost data published in 1979 dollar costs are located in Appendix D.

61

Although, the U.S. EPA costs provided a foundation for developing the cost functions, directly applying these functions in the screening software requires modification to account for series or parallel operation, as the U.S. EPA costs are based on a single column process. The resultant equations and considered assumptions are discussed herein.

3.5.3.1. Excavation, Site, and Concrete (ESC) Work

The ESC costs (in 1979 dollars) for a single-column are estimated by Equation 3-8. To account for series and parallel train operation, Equation 3-9 is applied.

$$ESC = 127.4 \times gpm^{0.315} \tag{3-8}$$

$$ESC = T \times C \times (127.4 \times gpm^{0.315}) \tag{3-9}$$

where: gpm = plant flow rate (gallons per minute)

C = # columns per train; screening model default is set as three (two T-GAC beds and one virgin GAC polishing bed)

T = # Process Trains

Equation 3-8 treats ESC costs as a unit cost function. In other words, the ESC cost calculated in Equation 3-9 is assumed to be the cost per column. Additional capital cost factors that are based on this unit cost approach are: manufactured equipment, construction labor, and housing.

3.5.3.2. Manufactured Equipment (ME)

ME costs are based on the use of cylindrical, pressurized, down-flow steel columns with associated supports and an initial charge of carbon. The ME costs (in 1979 dollars) for a

single-column are estimated by Equation 3-10. To account for series and parallel train operation, Equation 3-11 is used.

$$ME = 74.13 \times gpm + 1382 \tag{3-10}$$

$$ME = T \times C \times (74.13 \times gpm + 1382) \tag{3-11}$$

3.5.3.3. Construction Labor (L)

L costs (in 1979 dollars) for a single-column are estimated by Equation 3-12. To account for series and parallel train operation, Equation 3-13 is applied.

$$L = 928.8 \times gpm^{0.454} \tag{3-12}$$

$$L = T \times C \times (928.8 \times gpm^{0.454}) \tag{3-13}$$

3.5.3.4. Pumps, Piping, and Valves (PPV)

PPV costs (in 1979 dollars) for a single-column are estimated by Equation 3-14. To account for series and parallel train operation, Equation 3-15 is applied.

$$PPV = 329.1 \times gpm^{0.565} \tag{3-14}$$

$$PPV = T \times \left[329.1 \times (gpm \times C)^{0.565} \right] \tag{3-15}$$

Equation 3-14 relates the cost of the pumps, piping, and valves to the flow rate. To consider multiple columns, Equation 3-15 is derived assuming the majority of PPV costs are attributed to the pump requirements (i.e., size); therefore, PPV costs are related to the quantity of pumps and the appropriate size of the pumps required for each train. As an assumption to predict PPV costs, for a series configuration, the cost of the pump per train

63

is based on the combined additive flow rate of each column. For instance, if 35 gpm of treated water is processed in the plant for a three-column-in-series train, the combined additive flow rate would be 105 gpm (i.e., 3 x 35 gpm). Based on the individual pump cost for each train, the overall PPV cost for the process is then multiplied by the number of trains (i.e., each train contains one pump).

3.5.3.5. Electrical and Instrumentation (EI)

EI costs (in 1979 dollars) for a single-column are estimated by Equation 3-16. To account for series and parallel train operation, Equation 3-17 is used.

$$EI = 2.072 \times gpm + 635.5 \tag{3-16}$$

$$EI = T \times [2.072 \times (gpm \times C) + 635.5] \tag{3-17}$$

Because a significant proportion of the electrical and instrumentation costs are to support the pumping requirements of the process, EI costs for series or parallel operations are up-scaled in the same manner PPV costs were.

3.5.3.6. Housing (H)

Housing, to protect the T-GAC system from the elements, is a user-selected option in the cost model. If selected, H costs (in 1979 dollars) for a single-column are estimated by Equation 3-18. To account for series and parallel train operation, Equation 3-19 is used.

$$H = 4637 \times gpm^{0.154} \tag{3-18}$$

$$H = T \times C \times [4637 \times gpm^{0.154}] \tag{3-19}$$

3.5.3.7. Miscellaneous and Contingency (MC)

MC costs (in 1979 dollars) for a single-column are estimated by Equation 3-20. To account for series and parallel train operation, Equation 3-21 is applied.

$$MC = 918.2 \times gpm^{0.377} \tag{3-20}$$

$$MC = 918.2 \times (gpm \times T \times C)^{0.377} \tag{3-21}$$

The basis for estimating MC costs for multiple column processes is based on combining the costs of every column in operation; this is an approach similar to that used in estimating PPV and EI costs. The main difference is that we assume MC costs relate to the total flow through all the columns, so the flow rate in gpm is multiplied by the number of trains (T) and the number of columns in each train (C).

3.5.4. Annual Operation and Maintenance Cost Function Development

In the same way capital cost functions were empirically formulated, operation and maintenance cost functions were determined by best-fitting tabulated data reported by the U.S. EPA (1979) into linear or power function equations. The empirical functions and the assumptions used to derive estimates for multi-column configurations are discussed in the following sub-sections.

3.5.4.1. Energy

Energy costs are based on building and process energy requirements (kw-hr/year). Building energy requirements are calculated in the screening model using Equation 3-22, if housing is selected as a requirement in the user-options; otherwise, building energy costs are omitted. U.S. EPA building energy loads are based on heating, lighting, and

ventilation of the structure; process energy requirements include both supply and backwashing pumping (U.S. EPA, 1979). To account for multi-column and train operations, the screening model calculates process energy load requirements (kw-hr/year) from Equation 3-23.

$$\text{Building Energy Load} = T \times 5170 \times (\text{gpm})^{0.388} \qquad (3\text{-}22)$$

$$\text{Process Energy Load} = T \times C \times 66.50 \times \text{gpm} \qquad (3\text{-}23)$$

The cumulative energy loads calculated from Equations 3-22 and 3-23 are used to calculate the expected annual energy costs. Although, actual energy costs are site-specific, the most recent average industrial retail price of electricity reported from the U.S. Energy Information Administration (U.S. EIA) is $0.0616 per kW-hour (U.S. EIA, 2006)

3.5.4.2. Maintenance Material (MM)

Maintenance material costs are based on replacement parts and supplies used for the routine maintenance and operation of the columns. The reported U.S. EPA materials costs also accounted for the replacement of virgin GAC media once per year in the polishing bed. As the media costs will be separately calculated (shown in section 3.5.4.4), to discount this factor it is assumed that 1/3 of the costs per column are applied to replacement parts and supplies only. To account for a multiple train operation, Equation 3-24 relates the number of columns to the 1979 U.S. EPA based MM costs (in 1979 dollars).

$$\mathrm{MM} = \mathrm{T} \times \frac{C}{3} \times 14.19 \times \mathrm{gpm} \qquad\qquad (3\text{-}24)$$

3.5.4.3. Maintenance Labor Hours

The U.S. EPA (1979) projected maintenance labor hours include: routine maintenance tasks and monitoring the performance of the columns for quality assurance. Based on the U.S. EPA (1979) labor projections, Equation 3-25 is premised for multi-train operation.

$$\text{Maintenance Labor Hours} = \mathrm{T} \times (0.469 \times \mathrm{gpm} \times C + 108.4) \qquad (3\text{-}25)$$

Labor wage rates are assigned at \$29.44 per hour which are based on *"Installation, Maintenance, and Repair Occupations"* for the top 10% percentile of this group as reported by Bureau of Labor Statistics (BLS, 2006).

3.5.4.4. Media Costs

GAC, and in-turn T-GAC, media costs are variable and priced as a commodity (Peschman, 2007). The costs of replacement carbon will be based on the specific type used (e.g., coal based, coconut, etc.). Moreover, as stated in Chapter 2, a common approach for replenishing GAC media is through regeneration of the media. To account for the savings that might be realized by media regeneration, Cannon (2007) suggests using the costs in Table 3-4 as the basis for economic analyses.

Table 3-4. Market Potential Media Costs

	Virgin GAC	T-GAC
Replaced (new)	\$1.00/lb	\$2.50/lb
Regenerated	\$0.50/lb	\$2.00/lb

3.5.4.5. Disposal and Transport

If regeneration is presumed, then media disposal costs are not applicable. Conversely, if media is replaced, then exhausted media must be disposed of. Cost estimates for disposal are based on disposal fees reported by ECHOS Assembly Cost Data (2002) (reported by R.S. Means) for "*landfill hazardous solid bulk waste*" as $170 per ton (Richard, 2003). To transport bulk media for either disposal or off-site regeneration, transportation costs are calculated at $2 per mile plus a minimum trailer transportation charge of $760, based on ECHOS Assembly Cost Data (2002) reported by R.S. Means for "*bulk solid hazardous waste transport*" (Richard, 2003). Transport distances are specified as 250 miles, which is the approximate mileage from the California Inland Empire Area (locality of the Fontana and Redlands sites), to Parker, AZ (location of a Siemens GAC regeneration facility).

3.5.5. Cost Adjustment to 2007 Dollars

Capital and annual operation and maintenance cost factors generated from Equations 3-8 to 3-25 are reported in 1979 U.S. dollars. Table 3-5 lists the latest Chemical Engineering cost indexes and the ratio of these indexes for 2007 to 1979, which are required to adjust calculated costs to 2007.

Table 3-5. Economic Indicators (Chemical Engineering Journal, 1980; 2007)

Cost Indices	1979	2007	Ratio Indexes 2007/1979
Chemical Engineer Plant Index (CECPI)	236.6	531.5	2.2
Equipment	262.2	632.9	2.4
Construction Labor	193.2	317.4	1.6
Buildings	228.8	478.6	2.1
Pipe, valves, and fittings	300.2	747.4	2.5
Process Instruments	228.7	428.6	1.9

3.5.6. Discount Cash Flow Analysis and Total Annualized Costs

Based on the capital costs calculated, to account for prevailing interest and bond rates for amortization and project funding, Equation 3-26 is used to determine equivalent annualized capital costs (EACC) for any bond period life.

$$\text{EACC} = \text{Total Capital Cost} \times \frac{i\,(1+i)^N}{(1+i)^N - 1} \qquad (3\text{-}26)$$

where: i = bond rate

N = # compounding periods

Discount interest rates used for cost effectiveness, lease/purchase, and cost analysis for government procurements and cost comparisons as reported by the U.S. Office of Management and Budget (U.S. OMB) are shown in Table 3-6. The U.S. OMB specifies the use of nominal discount rates for discounting nominal flows, such as occurs in lease-purchase analysis. U.S. OMB reported real interest rates discount inflation premiums and

are specified for constant-flow analysis, as encountered in cost-effectiveness analysis.

Cost analysis in this effort is based on cost-effectiveness; therefore, the real interest rate

at a 20-year period (2.8%) is used.

Table 3-6. U.S. OMB Discount Rates Reported in Percent (U.S. OMB, 2008)

	3-Year	5-Year	7-Year	10-Year	20-Year	30-Year
Nominal Interest Rates	4.1	4.3	4.4	4.6	4.9	4.9
Real Interest Rates	2.1	2.3	2.4	2.6	**2.8**	2.8

3.5.7. Unit Treatment Costs

Unit treatment costs are reported in units of dollars per acre-foot. These costs are

calculated from the total annual costs divided by the annual treatment volume in acre-

feet. Total annual costs are equal to the sum of annualized capital costs (EACC) and

annual operation and maintenance costs.

3.5.8. Cost Model Assumptions

The important underlying assumption for the development of cost model is the following:

(1) The GAC capital and annual costs reported in the U.S. EPA (1979) cost data (shown

in Appendix D) range from 1.7 to 350 gpm. Cost analysis for plant flow rates greater

than 350 gpm are extrapolated with the assumption that the respective best-fit empirical

equation (Equations 3-8 to 3-25) will continue with its empirically described trend.

4.0. Results and Discussion

4.1. Introduction

In this chapter, parameters for use in the performance model are obtained. The parameterized model is then used to predict performance of the T-GAC technology in the field, as well as to construct a technology cost model. The cost model is ultimately applied to compare T-GAC costs with the costs of conventional IX treatment of perchlorate-contaminated water.

4.2. Determination of Performance Model Parameters

The performance results discussed in this section are presented in the following order. First, the Powell (2007) model is used to simulate T-GAC performance of RSSCTs using Redlands, Fontana, and Massachusetts water, and predict the results of pilot-scale trials at Redlands and Fontana. Then, 12 RSSCT results with Fontana water are used to determine new model parameters. Six of the available Fontana RSSCTs were not available during Powell's (2007) study. The Fontana water chemistry applied in the model was based on the average influent chemistry entering the 37 GPM system reported in Appendix B. Model parameters are obtained by minimizing the MAPE between model simulations and RSSCT results from Fontana water. Predictions of the parameterized model are then compared with field results, to help validate the model and its underlying assumptions.

4.2.1. Powell (2007) Model Comparision

Parameters in the Powell (2007) model were obtained by minimizing the difference between RSSCT bed volumes treated to initial breakthrough and model-simulated bed

71

volumes treated; model parameters are reported in Table 4-1. As reported by Powell

(2007), the best-fit parameterized model simulations were within 4% of the 11 RSSCT

experimental results. At the time of Powell's study, Fontana field results were not

available to validate the model-simulated results. As they are available now, and based

on the original model derived by Powell, Figure 4-1 depicts the difference between model

predictions and performance results from RSSCTs with Redlands, Fontana, and

Massachusetts water and pilot-scale trials at Redlands and Fontana.

Table 4-1. Powell (2007) Model Parameters

Freundlich Adsorption Coefficients					
K			30.3		
1/N			0.153		
Multi-Component Coefficients (Inhibition Effects)					
Perchlorate	Thiosulfate	Nitrate	Bi-carbonate	Sulfate	Chloride
1.00	0.332	0.0169	0.000226	0.00	0.00
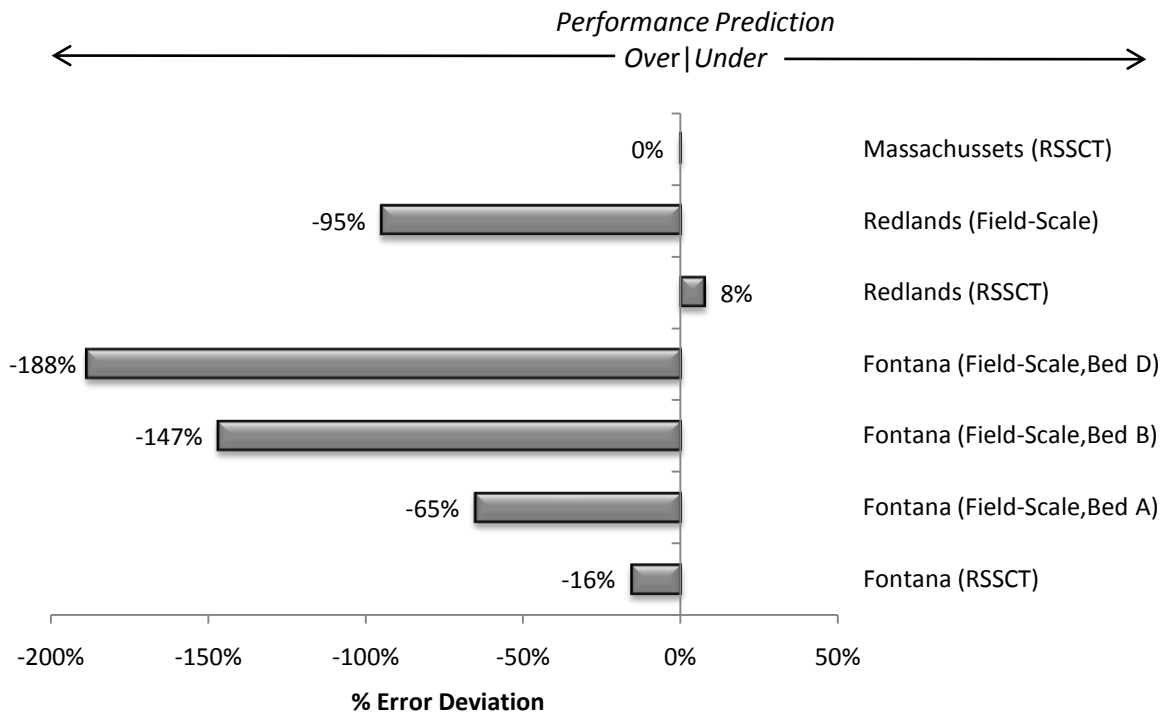
Figure 4-1. Powell (2007) Model Prediction Error

Note in Figure 4-1, and subsequent comparison figures, that a negative percent error deviation indicates an over-prediction of performance by the model while a positive percent error deviation corresponds to an under-prediction by the model. That is, a positive percent error deviation corresponds to a conservative model prediction.

Looking at Figure 4-1, it is apparent that Powell's (2007) model does a good job in accurately simulating the RSSCT trials for three different waters (though note that the model parameters were obtained using the RSSCT data). However, the model significantly over-predicts the pilot-scale results at Fontana and Redlands.

4.2.2. Best-Fit Model Parameters

The model parameters that best fit the 12 RSSCT perchlorate-breakthrough results for Fontana water are shown in Table 4-2. Two interesting observations are noted from comparing the values reported by Powell (2007) in Table 4-1 and the best-fit parameters shown in Table 4-2. First, the model parameters are similar despite the different RSSCT results used to quantify the respective models. This suggests that model parameters for Freundlich K, 1/n, and a_{ij} (for nitrate, sulfate, bi-carbonate, and chloride) are perhaps, however, not conclusively, independent of water chemistry. Second, the exception to this similarity is the competition coefficient for thiosulfate is one order of magnitude higher with Powell's (2007) model parameters. A possible explanation for this variance may be traced to the difference in chemistry between RSSCTs used to parameterize thiosulfate competition. To determine thiosulfate competition, Powell (2007) used RSSCT results with de-ionized and distilled water that contained perchlorate (1000 ppb) and thiosulfate (ranging from 10 ppb to 1000 ppb). Conversely, thiosulfate competition in this study was based on thiosulfate spiking (ranging between 1 to 10 ppm) of Fontana water that contained perchlorate (13 ppb) and additional anion species (e.g., nitrate, sulfate, etc.). Therefore, thiosulfate competition may be attenuated when in the presence of other anion species.

Parameter values from Table 4-2 were then used to predict technology performance at the Redlands and Fontana field sites, as well as to predict RSSCT results when Redlands and Massachusetts water was tested. Results are shown in Figure 4-2.

74

Table 4-2. Best-Fit Model Parameters

Freundlich Adsorption Coefficients	
K	30.07
1/N	0.148

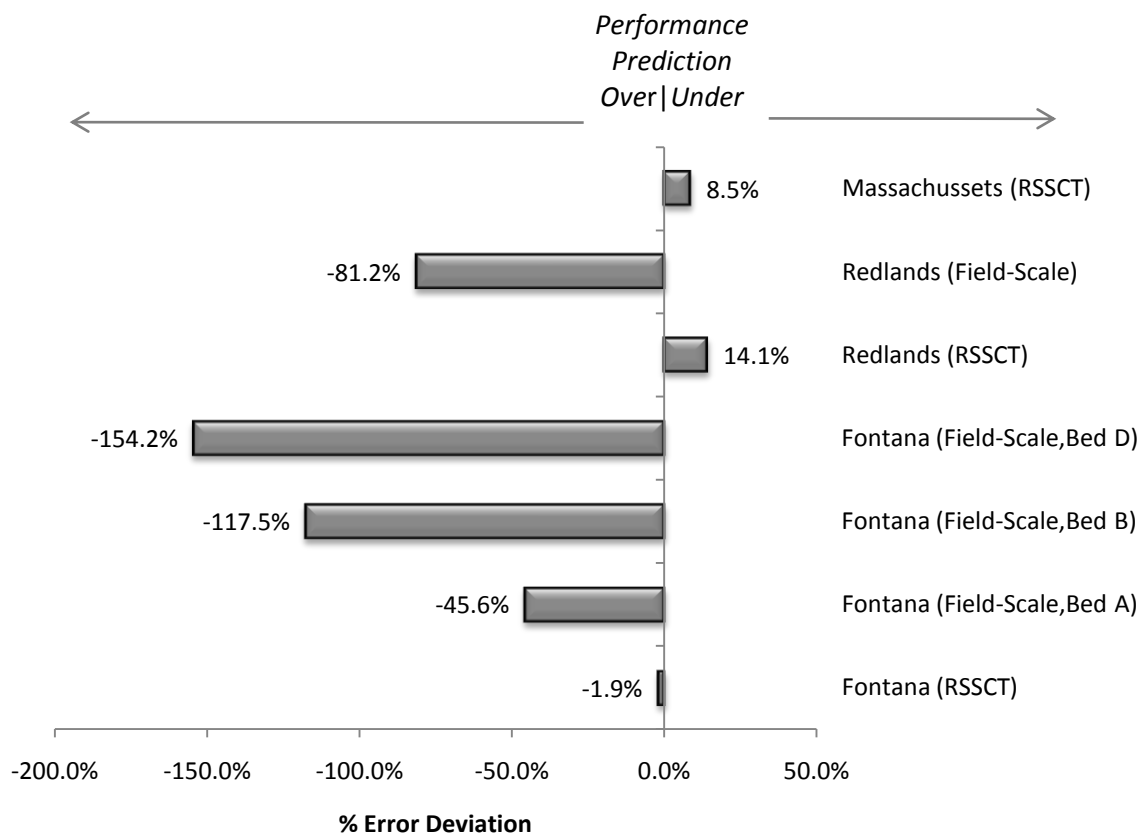| **Multi-Component Coefficients (Inhibition Effects)**					
Perchlorate	Thiosulfate	Nitrate	Bi-carbonate	Sulfate	Chloride
1.00	0.028	0.021	0.00	0.00	0.00

Figure 4-2. Difference between Model Predictions (Using Table 4-2 Parameters) and RSSCT and Pilot-Scale Results.

We see from Figure 4-2 that the model, using parameters obtained from RSSCTs with Fontana water, predicts RSSCT performance at Massachusetts and Redlands reasonably well, with errors of 8.5% and 14.1%, respectively. This is somewhat significant, as it shows that model simulations using the parameters obtained from RSSCTs with one water (from Fontana) can relatively accurately predict results of RSSCT studies for other waters (from Massachusetts and Redlands). Additionally, we see from Figure 4-2 that the model moderately improves the predictions of pilot-scale results for Fontana Bed A and Redlands shown in Figure 4-1 by 19.5% and 13.6%, respectively. Nevertheless, the current model still significantly over-predicts the pilot-scale trials at both Fontana and Redlands, with errors of -45.6% and -81.2%, respectively.

Moreover, the model predictions for Fontana Beds B and D are significantly over-predicted by the model as well. Subsequently, in section 4.3, we will delve into greater detail about how series operation impacted the performance of Fontana Beds B and D, and how the model might be revised to account for the impact of series operation on performance.

As was the case with Powell's (2007) model, it appears that the current performance model adequately simulates RSSCT performance; however, the model consistently over-estimates pilot-scale performance. As a reference mark, Crittenden et al. (2005) state that model errors for GAC systems typically range from 20 to 50%. Therefore, it is seen from the 46% discrepancy between the RSSCT breakthrough results and the Fontana 37 GPM system that there may be a problem with up-scaling RSSCT results. Several factors have been addressed by the ESTCP project team, such as: temperature difference between lab

and field, competition with reduced sulfur species, surfactant biodegradation and desorption, channeling at the relatively slow superficial velocities used in the field, and inapplicability of the proportional diffusivity assumption to scale up RSSCTs for T-GAC (ESTCP, 2007). Later on in this chapter we will develop and apply model correction factors to compensate for the discrepancies between model predictions and pilot-scale results.

4.2.2.1. Competition Coefficients

In this section, we discuss the significance of the competition coefficients' values, which are shown in Table 4-2.

4.2.2.1.1. Nitrate

The best-fit model calibration, using the 12 RSSCT perchlorate-loading results for Fontana water, where nitrate concentrations varied from 34 ppm to 100 ppm, yielded a competition coefficient of 0.021. Relative to the normalized perchlorate coefficient (a_{ClO4}) value of 1, this indicates that T-GAC is 47.6 times more selective for perchlorate than nitrate. Despite the high-selectivity of T-GAC for perchlorate, it is also necessary to consider the relative concentrations of perchlorate and the competing ion in order to evaluate whether competition has an impact on perchlorate adsorption. In the case of nitrate-rich Fontana water, competition between nitrate and perchlorate for adsorption sites may be significant, as indicated in Figure 4-3.

	Nitrate Concentration of 34 ppm	Nitrate Concentration of 60 ppm	Nitrate Concentration of 100 ppm
■ ClO4-	1.8%	1.0%	0.6%
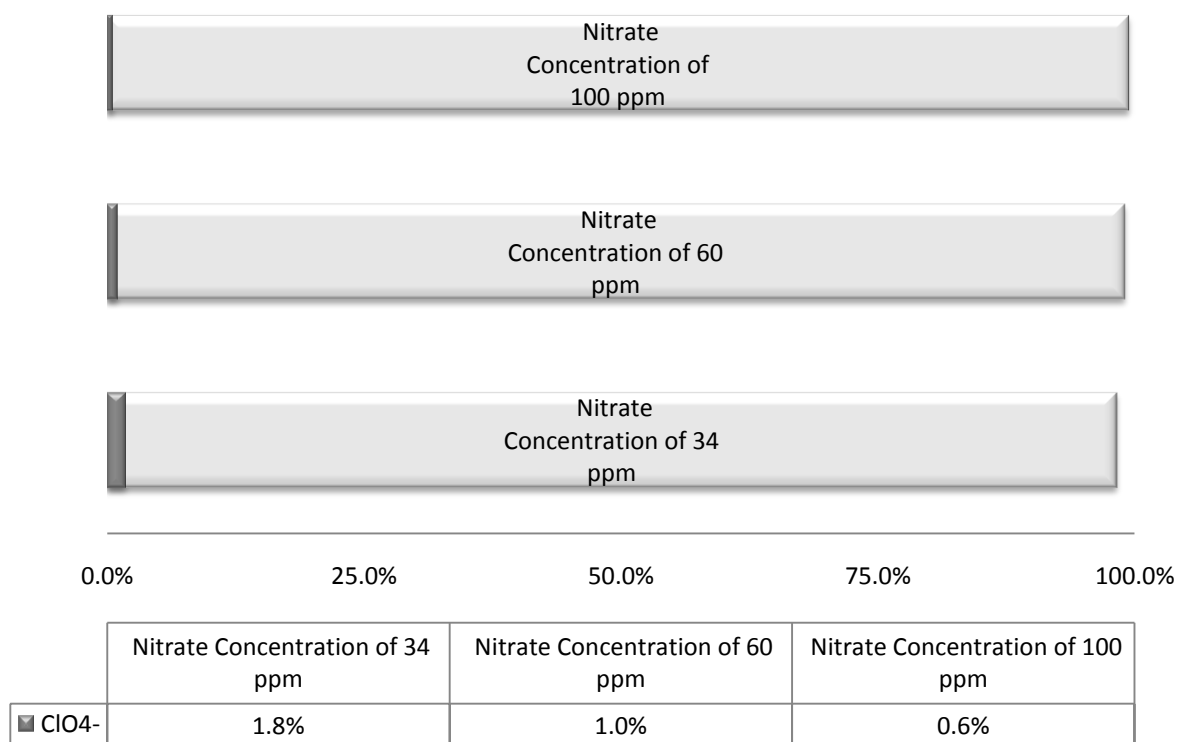
Figure 4-3. Relative perchlorate and nitrate adsorption on T-GAC for various nitrate concentrations. In Fontana water nitrate concentration = 34 ppm, perchlorate concentration = 13 ppb

4.2.2.1.2. Thiosulfate

Model calibration for thiosulfate competition using the 12 RSSCT perchlorate-loading results for Fontana water, which included two thiosulfate-spike trials with 1 ppm and 10 ppm, yielded a competition coefficient of 0.028. Thus, selectivity of T-GAC for perchlorate over thiosulfate is similar to the selectivity of T-GAC for perchlorate over nitrate. However, since typical thiosulfate concentrations will be considerably less than nitrate concentrations in natural waters, the impact of thiosulfate on T-GAC performance is expected to be considerably less than the impact of nitrate.

4.2.2.1.3. Sulfate, Chloride, and Bi-carbonate

Model calibration of RSSCT trials with 14, 50, and 250 ppm sulfate spikes in Fontana water yielded a competition coefficient of zero, thus indicating no observable inhibition of perchlorate adsorption on T-GAC due to the presence of sulfate. Similarly, RSSCTs with chloride spikes to 250 ppm showed no inhibition of perchlorate adsorption on T-GAC due to the presence of chloride. These model outcomes support PSU RSSCT breakthrough results as shown in Figure 4-4. Figure 4-4 shows that there is no inhibition due to the presence of sulfate, chloride, and bi-carbonate, and in fact, it appears that the performance is enhanced in the presence of bi-carbonate and chloride. Researchers at PSU attribute the increase in performance when bi-carbonate levels are elevated to a shift in chemical equilibrium, thereby, improving T-GAC's adsorptive capacity (ESTCP, 2007).
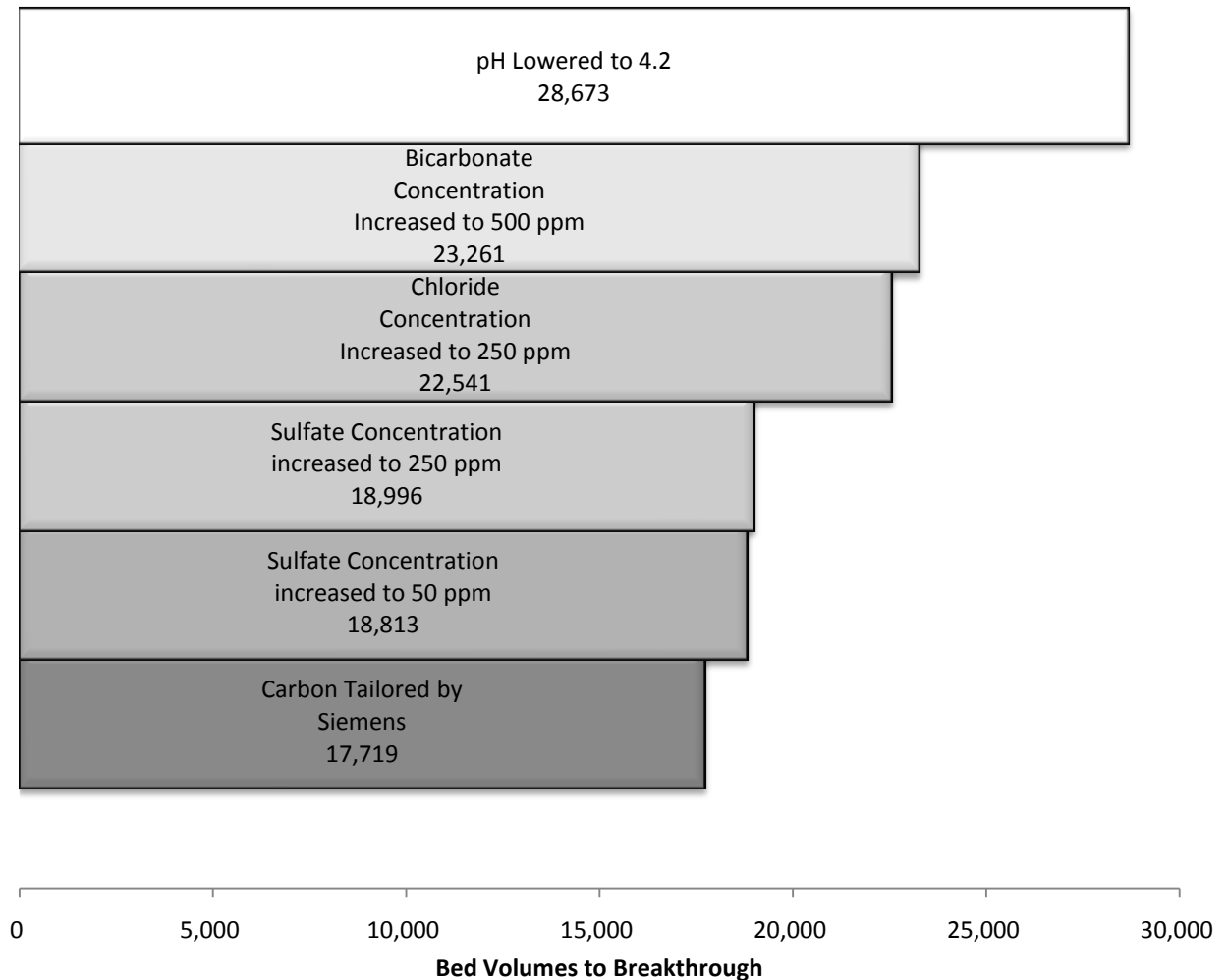
Figure 4-4. PSU RSSCT Bed Volumes to Breakthrough for Fontana Water with Various Levels of Sulfate, Chloride, and Bicarbonate Added (and pH lowered)

4.3. Estimated Performance Benefits of Series Configuration

As discussed in Chapter 2, a performance benefit of operating adsorption columns in series is that series operation allows the columns to be fully utilized; instead of removing the column at initial breakthrough, the column can be used until it is totally saturated. The Fontana 37 GPM system was operated to full saturation for Bed A (the initial lead

bed), Bed B (the initial lag bed which was re-configured to lead after Bed A reached full saturation), and Bed D (the lag bed following Bed B after re-configuration). The breakthrough performance for these columns is shown in Figure 4-5. The bed volumes reported in Figure 4-5 for Bed A and Bed B are based on the bed's performance in the lead position. Bed D remained in the lag position though it acted as the defacto lead bed after Bed B reached full saturation; the reported BVs for Bed D are based on the BVs after Bed B reached full-saturation, or as the mass transfer zone transferred to Bed D.

	Bed D	Bed B	Bed A
☐ Initial Breakthrough	7,100	8,300	12,400
■ Full Saturation	19,500	16,000	17,300
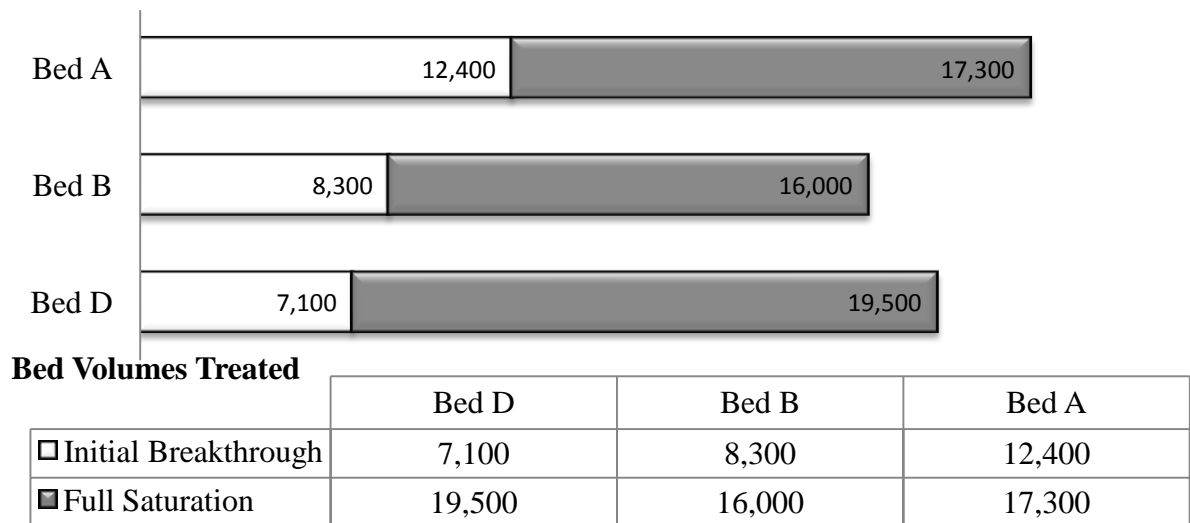
Source: Data obtained from ESTCP Project ER-0546 (2007)

Figure 4-5. Fontana Pilot-Scale Column Performance (37 GPM)

Based on the column performances at Fontana, Equation 3-7 is used to quantify the performance benefits of series operation, the results of this calculation are shown in Figure 4-6.

Figure 4-6. Increased Performance of Lead Bed Due to Series Operation (Based on Data from Fontana 37 GPM System)

From Figures 4-5 and 4-6, we can make some observations. First, allowing the initial

lead bed (Bed A) to operate to full-saturation rather than to initial breakthrough results in

a 40% increase in the volume of water that can be treated (17,300 BVs vs 12,400 BVs).

Second, the BVs that can be treated before initial breakthrough in Beds B and D have

been reduced by an average of 38% relative to Bed A. This reduction in performance due

to operation in the lag position is illustrated in Figure 4-7. We attribute this reduction to

Bed B and D's exposure to compounds that pass through the lead bed when B and D are

in the lag position, thereby reducing their capacity. Note, however, that Beds B and D

exhibit an overall increase in performance as they are operated to full-saturation in series

82

mode, which results in an average 134% increase over the bed volumes they can treat before initial breakthrough. Breakthrough profiles for Beds A, B, and D are located in Appendix C.
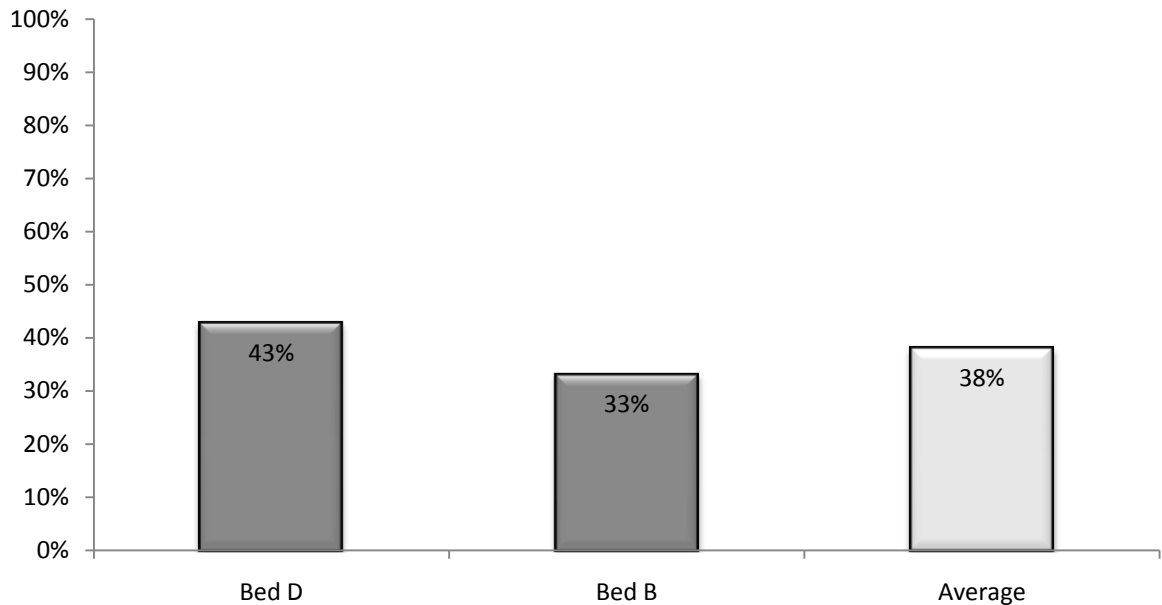
Figure 4-7. Lag Bed Performance Reduction (Relative to Lead Bed) After Column Re-Configuration As Lead. Fontana Pilot-Scale (37 GPM)

We may adjust for the reduction in performance for columns initially in the lag position by reducing predicted bed volumes to initial breakthrough by 38% (per Figure 4-7). This adjustment is reflected in Table 4-3. After the adjustment, we note that the difference in model-predicted bed volumes of water treated to initial breakthrough and the pilot-scale results for Fontana Beds B and D has improved to -58% and -35%, respectively.

Table 4-3. Model Predictions Adjusted to Account for Series Column Performnace

| | Predicted | | Predicted *(Adjusted)* | Observed | |
	BVs to Initial Breakthrough	Lag Bed Performance Reduction	BVs to Initial Breakthrough	Bed Volumes to Initial Breakthrough	Model Error Deviation
Fontana Bed D	18,051	38%	**11,209**	8,300	**-35%**
Fontana Bed B	18,051	38%	**11,209**	7,100	**-58%**

Average Deviation = - 46%

4.4. Model Correction Factors and Final Model Comparison

As previously discussed, when used to predict technology performance at the Fontana field site, the best-fit parameter values shown in Table 4-2 over-predict the observed performance of Bed A by 46% (per Figure 4-2). We will assume that perhaps due to an up-scaling effect or some other undetermined phenomenon it is necessary to correct RSSCT results by this 46% to predict pilot-scale performance. Applying this correction factor, as expressed from Equation 4-1, to Figure 4-2, while also accounting for the reduction in performance for columns initially in the lag position, results in the adjusted comparison of modeled and field results for initial breakthrough depicted in Figure 4-8.

$$\text{Corrected Model} = \quad = \frac{\text{Model Prediction}}{\text{Correction Factor}} \text{x} \ (1 - \text{Lag Bed Performance Reduction}) \qquad (4\text{-}1)$$

where: Model Prediction = Using best-fit parameter values shown in Table 4-2
Correction Factor = (1− %error) and % error = − 46%
Average Lag Bed Performance Reduction = 38% (For Fontana Bed B
and D as shown in Table 4-2); 0% for Fontana Bed A and Redlands
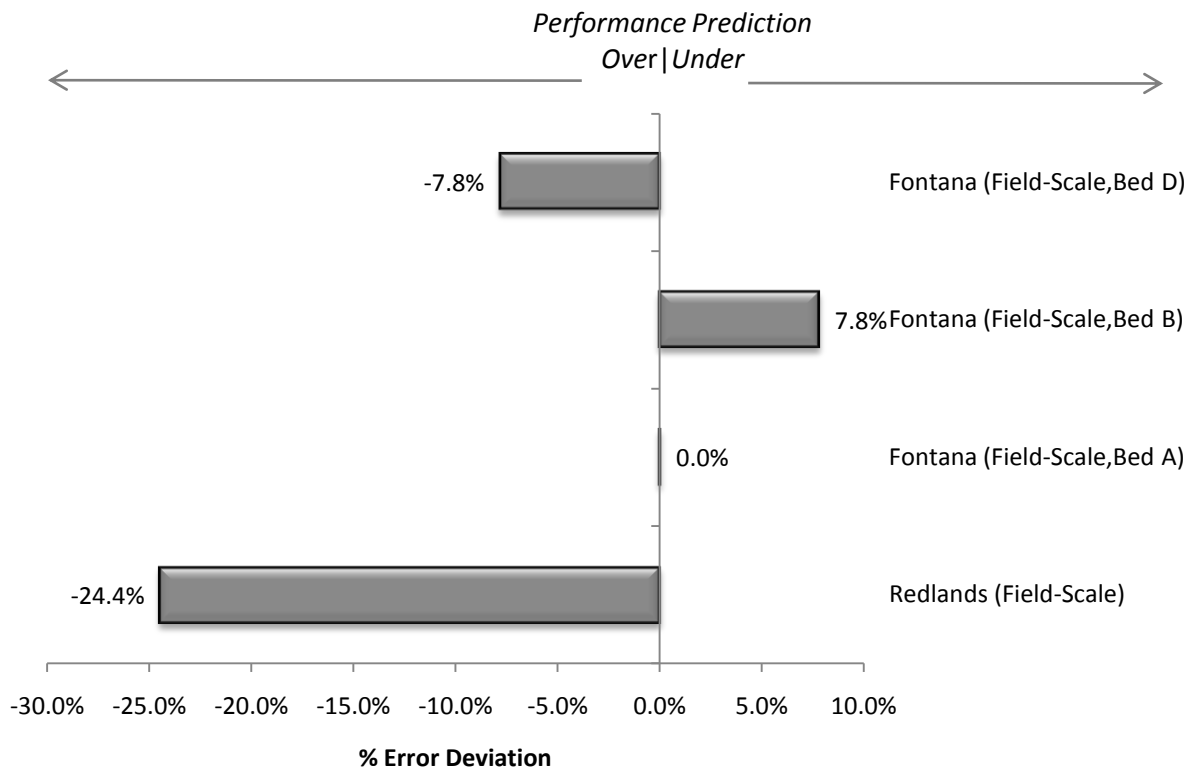Field-Scale Bed

Figure 4-8. Difference between Corrected Model Predictions (Using Best-Fit Parameters Obtained from RSSCTs with Fontana Water) and Pilot-Scale Results.

4.5. Cost Model Predictions

In this section, the cost model is validated by comparing model cost estimates with actual expenses at the 37 GPM Fontana pilot-scale demonstration. Cost model simulations are then used to estimate the costs to build and operate a full-scale T-GAC system based on various engineering design decisions and parameter values (e.g., flow rate and chemistry of water to be treated, media size, whether media will be regenerated or replaced). Based upon cost model simulations, we will examine how competitive the technology is when compared to the conventional IX treatment technology. Lastly, using the cost model, we will determine the variables that have the most influence on overall cost and examine cost reduction strategies.

4.5.1. Cost Model Validation

To validate cost predictions, the cost model, as described in Chapter 3, was applied to the 37 GPM Fontana pilot-scale field demonstration to compare cost model estimates with actual pilot-scale field expenses. In Table 4-4, model-estimated and actual capital expenses are compared. As can be seen, the cost model seems to accurately predict pilot-scale capital costs within 1% (though the remarkable accuracy of the prediction is apparently fortuitous). Since the cost model estimate is only being compared to actual capital costs for a single, non-commercial, system, model validation is inconclusive. Nonetheless, for this comparison, results are encouraging, suggesting that the approach proposed to estimate capital costs is reasonable.

Table 4-4. Comparison of Cost Model Estimates to Fontana 37 GPM Field Demonstration Capital Costs

Capital Cost Factors	Model Predicted	Fontana Expenses	Explanation of Field-Expenses
Site Preparation	$2,500.	$5,530.	Based on 50-50 split of 37 GPM and 6-Condition Column costs[1]
Manufactured Equipment	$30,140.	$76,840	Includes all expenses needed to produce, transport, install, and start-up the system on-site.[2]
Tailoring GAC Media Cost (CPC)	$15,600[4].		
Pumps, Piping, and Valves	$11,810.		
Miscellaneous and Contingency	$12,240.	$12,240	Engineering and design drawings
Electrical and Instrumentation	$1,630.	$3,630.	Based on 50-50 split of 37 GPM and 6-Condition Column costs[3]
Labor	$23,730.	————	Labor costs were included in expenses and not broken out separately
Total Capital Costs	$97,650.	$98,240.	Deviation of 0.6%

Note 1: Total site preparation expense is $11,050 for the entire Fontana demonstration. Site preparation cost for the 37GPM plant is considered to be half.

Note 2: Complete cost to furnish the T-GAC system is $86,200. This cost includes media change-out and installation of Bed D. To discount this media-change-out, $9,356 was subtracted; bed volume: 375 gallons (approximately 1,562 pounds of T-GAC media in vessel); $5.99/lb CPC tailored T-GAC media (Peschman, 2007); 1,565 lb x $5.99/lb = $9,356).

Note 3: Total electrical and instrumentation expense is $7,250 for the entire Fontana demonstration. Electrical and instrumentation cost for 37GPM plant is considered to be half.

Note 4: Tailoring media cost is based on demonstration media expenses ($5.99/lb) minus estimated virgin GAC cost ($1.00/lb) (Cannon, 2007); 1,565 lb/bed x $4.99/lb x 2 beds = $15,619.

Actual operation and maintenance costs for a year are unavailable at Fontana. Model estimates of annual operation and maintenance costs are shown in Table 4-5. These costs assume energy costs are $0.0616 per kW-hr (EIA, 2006), T-GAC media costs are $5.99

per lb of CPC tailored T-GAC (Peschman, 2007), virgin GAC is $1.00 per lb (Cannon, 2007), labor hourly wage rates are $53.00 (senior technician grade-level), and media is not regenerated. T-GAC media costs used in this comparison are based on the costs for the demonstration project, which are not believed to represent the media costs on the open market which may be obtained because of economies of scale (Cannon, 2007).   As media costs projections are not presently reported for full-scale use by Siemens (Peschman, 2007), it is important to note that in subsequent sections, the cost analysis is based on the costs projected for full-scale application by Cannon (2007) as reported in Table 3-4.

Table 4-5. Cost Model Estimates of Fontana 37 GPM Field Demonstration Annual Operation and Maintenance Costs

Operation and Maintenance	Annual Costs
Energy Costs[1]	$500.
Maintenance Material Costs	$1,200.
Labor Costs[2]	$8,500.
Total Media Costs[3]	$35,000.
Disposal	$600.
Transport	$4,600.
Total =	**$50,400.**

Note 1: Process energy requirements are predicted as 7,481 kw-hr/year.

Note 2: Labor costs are based on predicted labor hours of 161 per year.

Note 3: Total media costs are based on projected annual virgin GAC and T-GAC CURs. Virgin GAC CUR for the polishing bed is based on a one-time annual bed replacement rate (i.e.1,502 lb/year) and T-GAC CUR is based on a projected rate of 5,593 lb/year.

Unfortunately, only data on actual labor hours for the Fontana field-demonstration were readily available. During the Fontana 37 GPM demonstration, over a 34-week period, on average 3 hours per week was spent on operation and maintenance by a senior technician. Based on this average, it is projected that annually 156 labor hours will be spent operating and maintaining the 37 GPM system. The cost model predicts 161 labor hours are required annually to operate and maintain the 37GPM system. Thus, at least in predicting labor hours, the cost model estimate is accurate within 5% for the 37 GPM Fontana system.

To further validate the model, additional data on other operation and maintenance costs (e.g. energy, disposal, maintenance material, media) should be collected, over the course of a year, at the 37 GPM Fontana demonstration.

4.5.2. Cost Projections for Commercial Full-Scale Systems

As overall costs are impacted by engineering design decisions and parameter values, this section will consider how the following variables impact cost:

1. Flow rate

2. Influent water quality

3. Parallel vs Series Operation

4. Media Regeneration vs Replacement

5. Housing

6. Media Size

7. EBCT

The cost analysis presented in this section is based on estimates from the cost model. Cost factors and calculations that are used in the model are described in detail in Chapter 3; however, a summary of the values used in this analysis are listed in Table 4-6 for reference.

Unless otherwise stated, influent water quality is based on Fontana water, the T-GAC media size is U.S. Sieve # 20 X 50, single-bed EBCT is 10 minutes (for the 3-bed treatment train: 20 minutes total EBCT through T-GAC beds and 10 minutes through the polishing bed). When columns are operated in series, the benefits of series operation are incorporated into the calculation. The series operation train follows the 37 GPM Fontana demonstration configuration and consists of two T-GAC beds followed by a virgin GAC polishing bed. Beds are equivalent in volume, with each bed having a 10-minute EBCT. For parallel operation, two trains are operated simultaneously. Each train consists of one T-GAC bed followed by a virgin GAC polishing bed. For parallel and series comparisons, total plant flow rates and single bed EBCTs are equivalent (each parallel train will have a 20 minute total EBCT in contrast to the series trains having a 30 minute EBCT). Finally, media price for change-out is based on the assumed conditions of regeneration.

Table 4-6. Cost Analysis Factors		
Energy Costs	$0.06	per kw-hr
Technician Labor Wage	$29.40	per hour
Media Size	U.S. Sieve 20 x 50 @ 10 min EBCT	
GAC Media Costs (Virgin)	$1.00	per lb of GAC
GAC Media Cost (When regenerated)	$0.50	per lb of GAC
T-GAC Tailoring Costs	$1.50	per lb of GAC
Transport Costs	$540.	From Inland Empire Area, CA to treatment facility (Parker, AZ)
+ Minimum Charge	$760.	Trailer Fee (per column)
Disposal Costs	$170.	per ton
Annual Days of Operation	360	days
Hours of Operation Per Day	24	hours
Amortization Period	20	years
Discount Rate	2.8 %	

4.5.2.1. Flow Rate

Figure 4-9 plots model cost predictions to treat Fontana water as a function of plant flow rate.
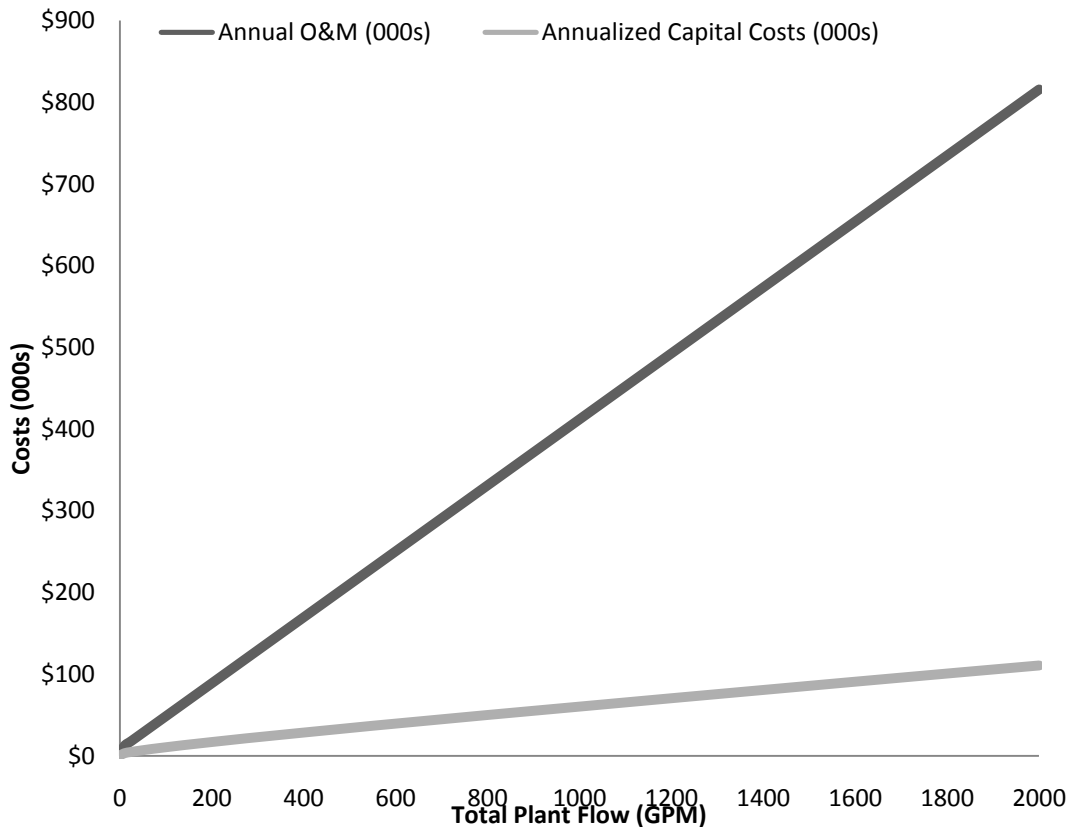
Figure 4-9. Annualized Capital and Operation and Maintenance Costs for Series Operation

Figure 4-9 illustrates that annualized capital and operation and maintenance costs increase significantly as plant flow increases. However, when considered in terms of unit costs (treatment costs per acre-foot), Figure 4-10 illustrates that as the plant flow increases, unit costs decrease.   However, the economy of scale associated with increasing the plant flow rates is best observed from 10 gpm to 400 gpm. Unit treatment costs marginaly decrease above 400 gpm.
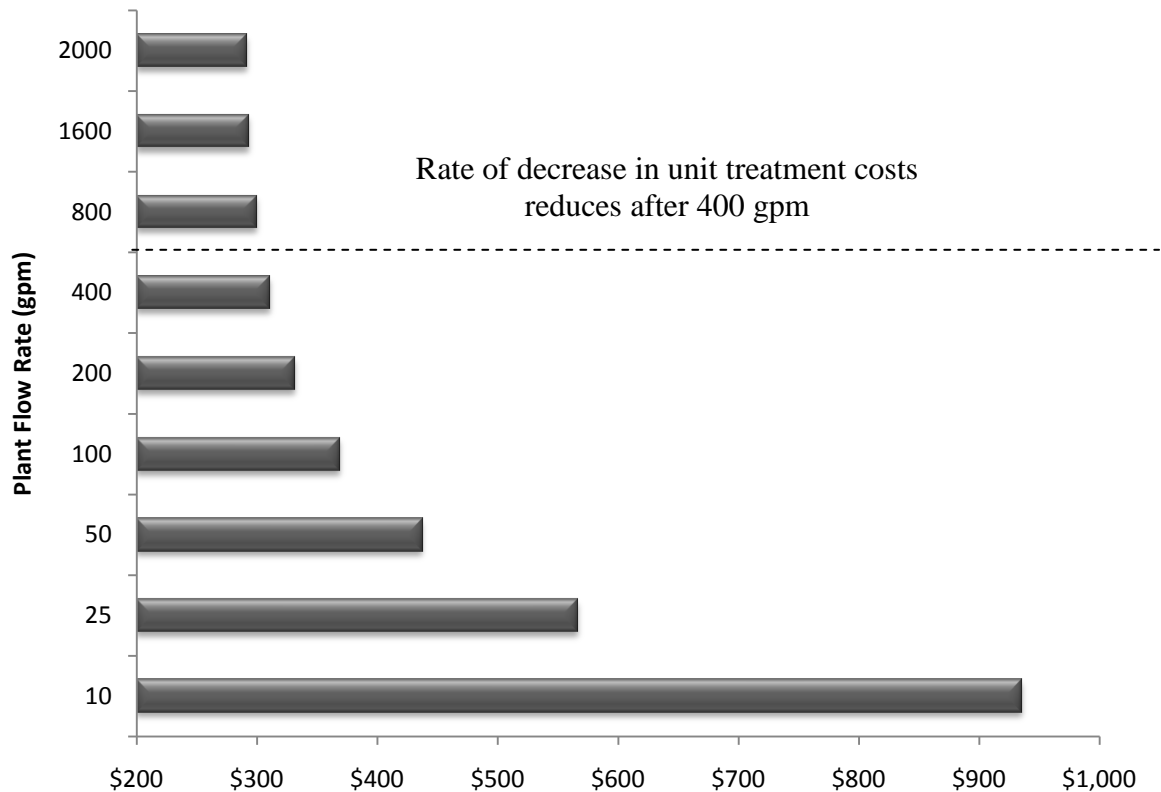
Figure 4-10. Unit Treatment Costs for Fontana Water

4.5.2.2. Influent Water Quality

Unit treatment costs depicted in Figure 4-11 show the influence of influent water quality on overall treatment costs; perchlorate and nitrate concentrations for the three waters in Figure 4-11 are listed in Table 4-7 (complete water chemistry for the three water sources is located in Appendix B). Of the three waters, Fontana water has the highest concentration of any known competing compound (specifically, nitrate), and the treatment costs for Fontana water are consistently the highest at all flow rates of the three waters. Unit treatment costs for Redlands water (with a nitrate concentration of 16 ppm and the highest perchlorate concentration) are second highest while unit costs to treat Massachusetts water, which has the lowest levels of perchlorate and nitrate, are lowest.

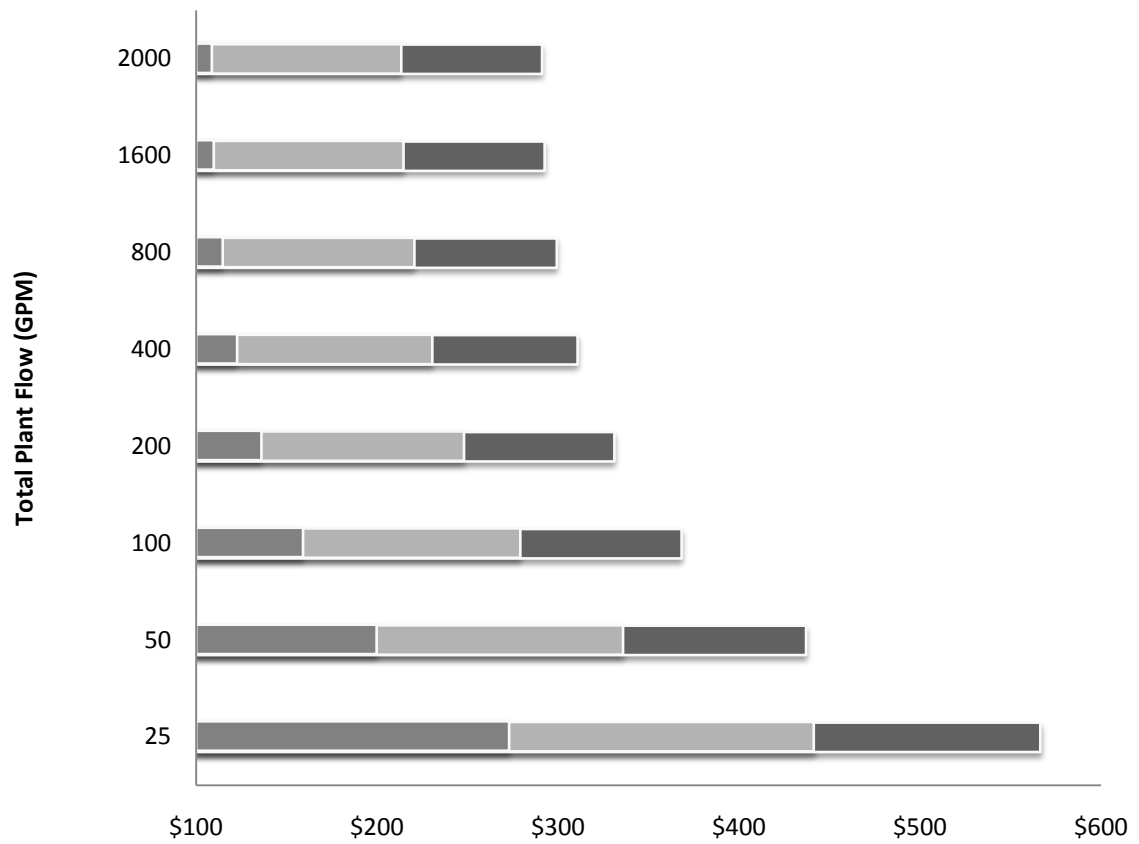|	25	50	100	200	400	800	1600	2000
■ Mass.	$273	$200	$159	$136	$123	$115	$110	$109
■ Redlands	$441	$336	$279	$248	$231	$221	$215	$213
■ Fontana	$567	$437	$368	$331	$311	$299	$293	$291

Cost per Acre-Foot

Figure 4-11. Unit Treatment Costs for Different Water Sources

**Table 4-7. Perchlorate and Nitrate Concentrations
at Fontana, Redlands, and Massachusetts**

Water Source	Perchlorate Concentration	Nitrate Concentration
Fontana	13 ppb	34 ppm
Redlands	75 ppb	16 ppm
Massachusetts	5.6 ppb	0.4 ppm

4.5.2.3. Parallel vs Series Operation

Figure 4-12 depicts cost versus flow for Fontana water treatment using parallel trains.

As with series operation, annualized capital and operating costs increase with increases in

flow. Figure 4-13a shows that unit costs for parallel operation decline as total plant flows

increase, and that compared with series operation, at low flows unit treatment costs are

relatively high; although cost differences between the two modes of operation are

negligible as total plant flows go above 800 gpm for Fontana Water.   Figure 4-13b

compares the cost difference of parallel relative to series operation. It can be seen that

annual capitalized costs for series operation are higher than parallel. The main cause of

this increase is due to manufactured equipment (bed columns).   The model predicts that

four relatively smaller columns require less overall capital expenditure than three

significantly larger columns. However, the annual operation and maintenance costs are

higher for parallel operation; this is attributed to media costs expenses that result from

operating columns to initial breakthrough.
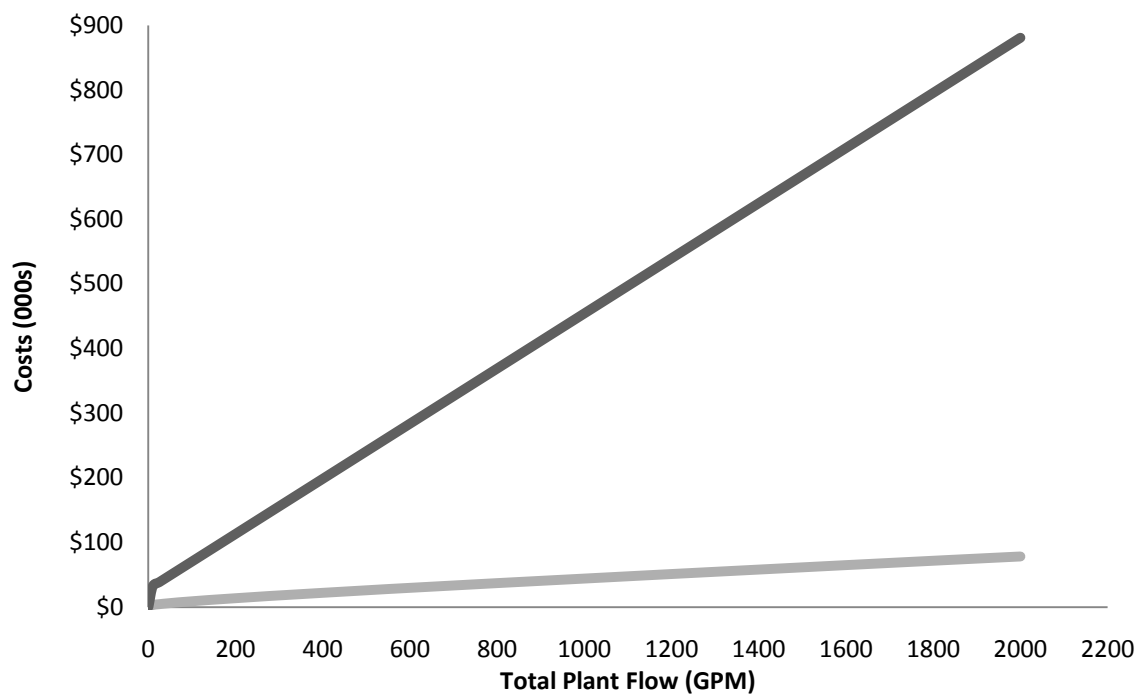
Figure 4-12. Annualized Capital and Operation and Maintenance Costs for Parallel Operation

	10	25	50	100	200	400	800	1600	2000
■ In-Series	$935	$567	$437	$368	$331	$311	$299	$293	$291
■ Parallel (2 Trains)	$2,213	$1,080	$695	$499	$399	$347	$319	$305	$302

Total Plant Flow (GPM)
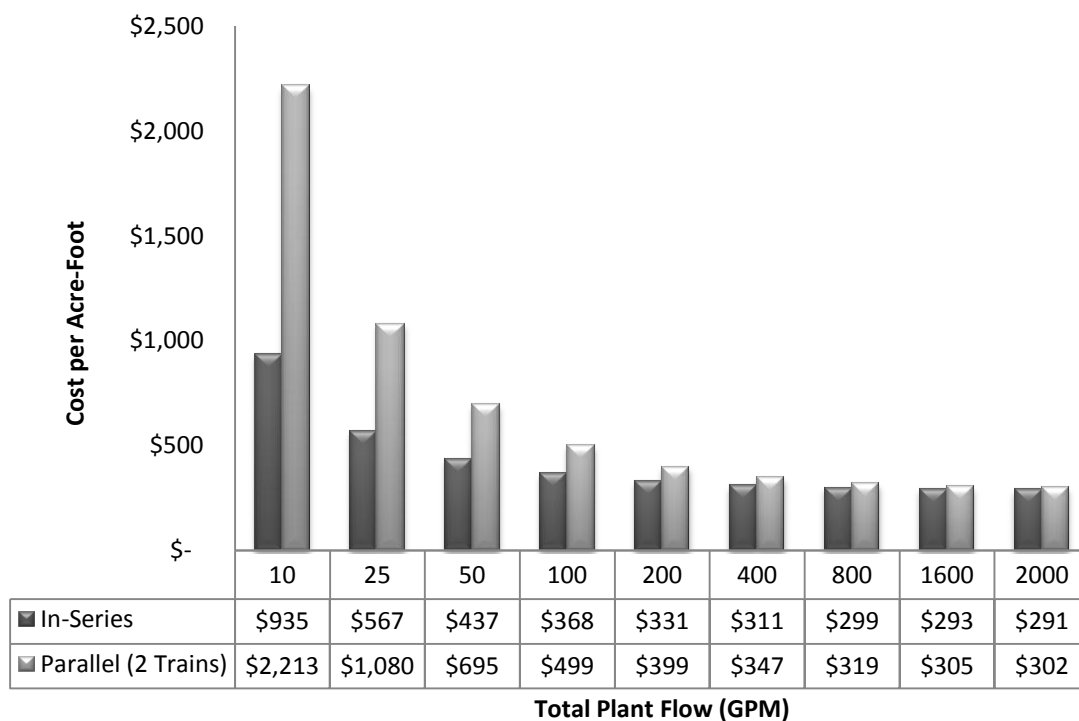
Figure 4-13a. Comparison of Parallel vs Series Operation to Treat Fontana Water
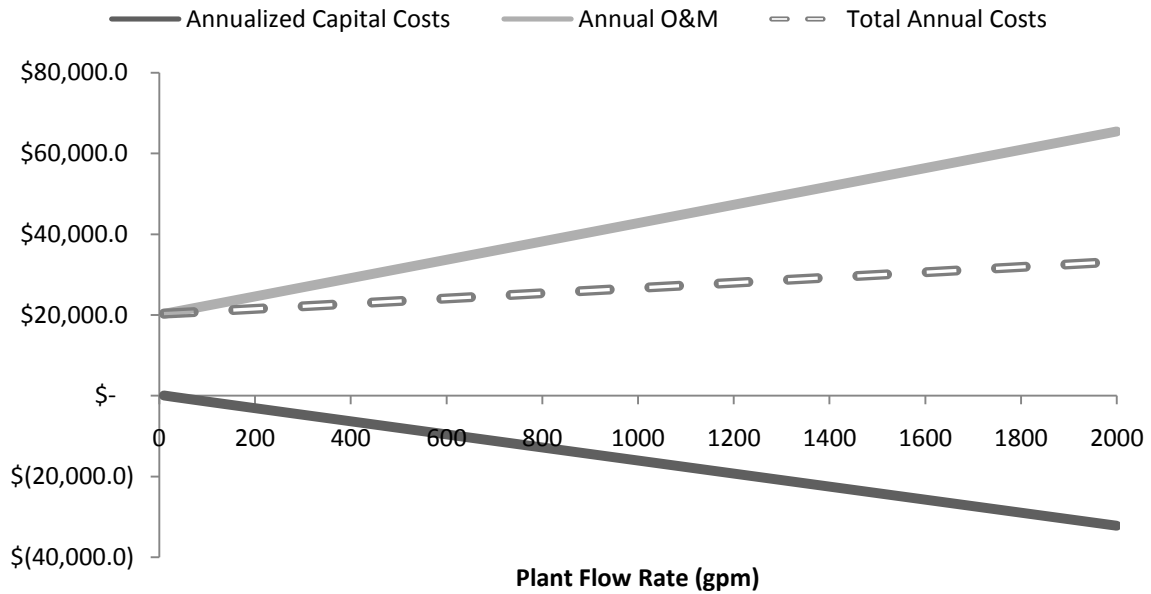
**Figure 4-14b. Cost Difference of Parallel Relative to Series Operation
to Treat Fontana Water**
Cost figures are shown as parallel minus series costs

4.5.2.4. Cost Savings of Regeneration versus Replacement

Figure 4-14 depicts, for both series and parallel operation, the potential cost savings per

acre foot of water treated that may be achieved by regenerating, rather than replacing,

spent media. Figure 4-14 shows that regeneration consistently results in cost savings,

with the greatest savings achieved (up to 21%) at higher flow rates.
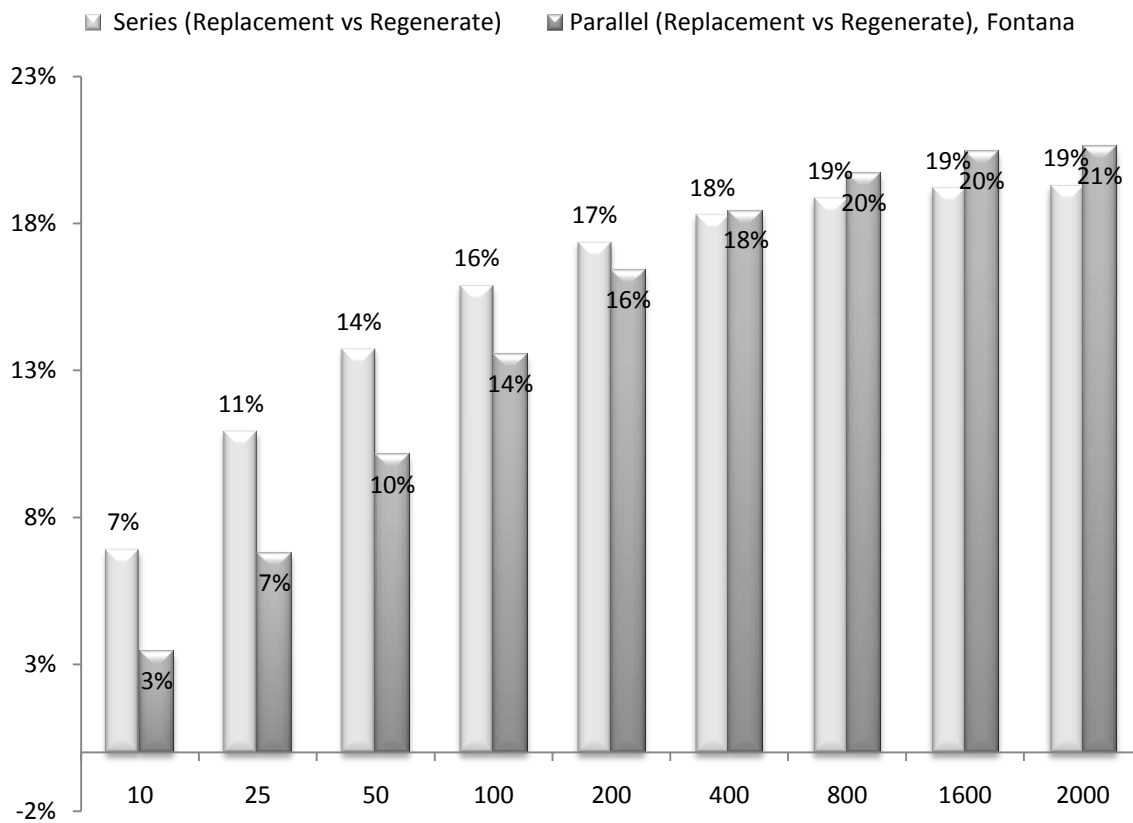
Figure 4-15. Cost Savings from Media Regeneration

4.5.2.5. Cost Increase with Housing

Figure 4-15 shows the cost impact of enclosing the plant, in order to protect it from the elements, as a function of plant size and column configuration. This figure illustrates that housing cost increases most significantly with operating flow rates less than 400 gpm. Table 4-8 shows the unit treatment cost estimates for Fontana water based on flow rate and mode of operation (parallel vs series).
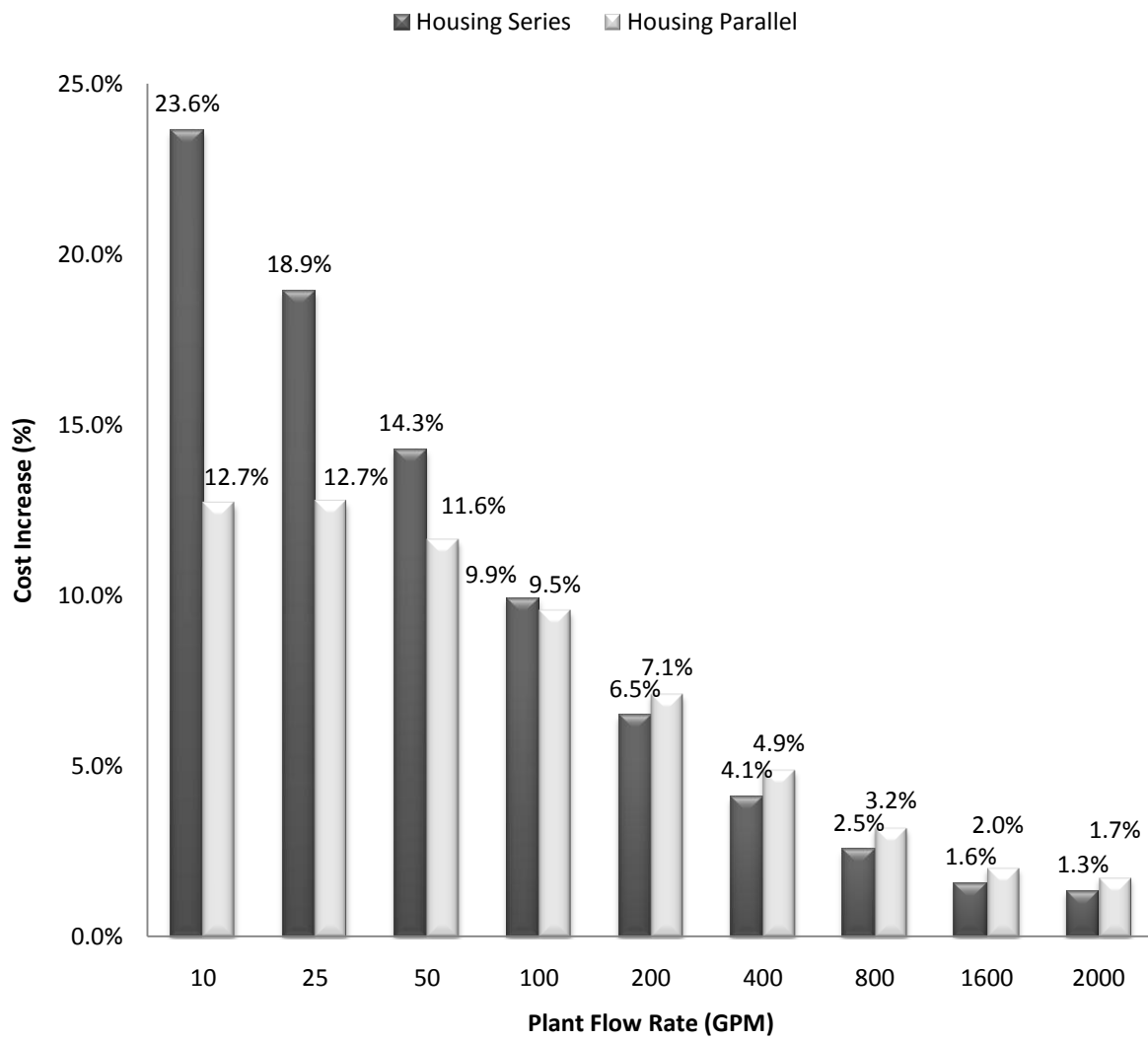
Figure 4-16. Cost Increase of Housing Plant

Table 4-8. Model Cost Estimates (per Acre-Foot) Comparing Series and Parallel Operation and Whether or Not the Plant is Housed for Fontana Water

Total Plant (GPM)	Series		Parallel	
	No Housing	With Housing	No Housing	With Housing
10	$935	$1,156	$2,213	$2,494
25	$567	$674	$1,080	$1,217
50	$437	$499	$695	$776
100	$368	$405	$499	$547
200	$331	$353	$399	$427
400	$311	$323	$347	$363
800	$299	$307	$319	$329
1600	$293	$297	$305	$311
2000	$291	$295	$302	$307

4.5.2.6. Media Size

A comparison of Figure 4-16 and 4-17 illustrates the inter-relationship of EBCT and media-size. Based on a 5-minute EBCT with Fontana Water, Figure 4-16 shows that media size has a significant impact on overall cost; media sizes of 20 X 40 and 20 X 50 are most economical in this case. Conversely, when the EBCT is 10 minutes, Figure 4-17 shows that media size is less significant in determining unit treatment costs. This

outcome can be related to the assumption that equilibrium adsorption may not be achieved at relatively low EBCTs and relatively large adsorbent particle sizes as stated in section 3.4.1. Based on this assumption, media size should be considered in conjunction with EBCT to minimize treatment costs. It is important to note that the cost model does not consider the increased power cost of having to pump water through fine media (with the associated increase in headloss). This increased cost may be significant depending on the specific design parameters.
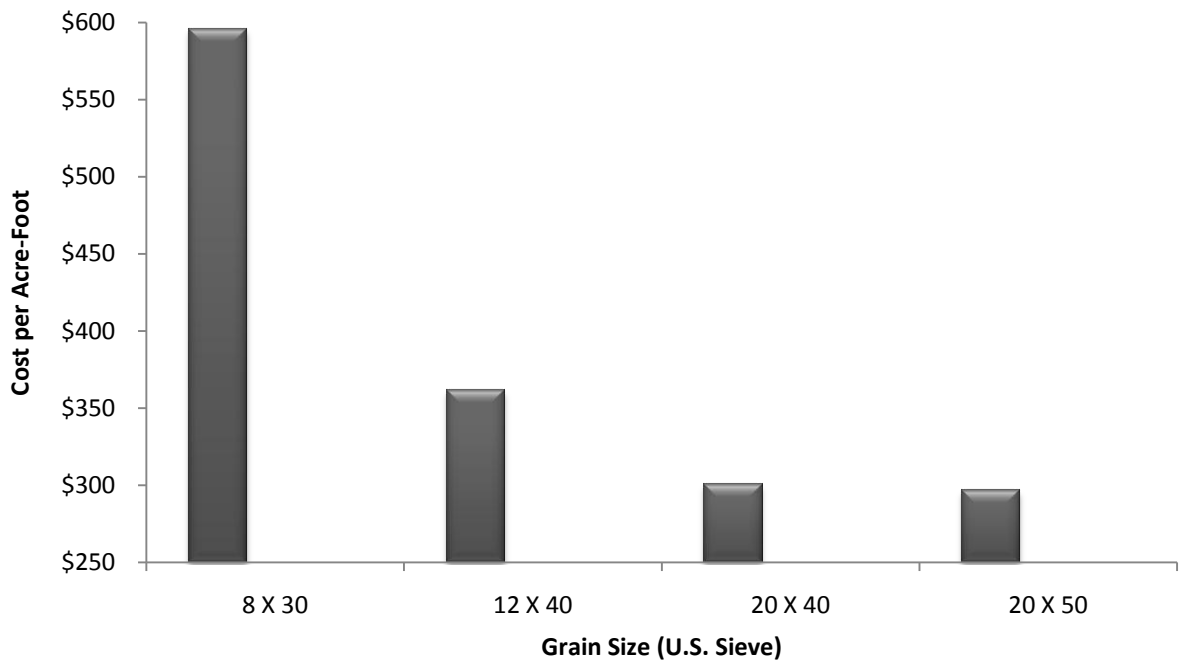
Figure 4-17. Unit Treatment Costs as a Function of Media Size (per Acre-Foot) for Fontana Water (5 minute EBCT)
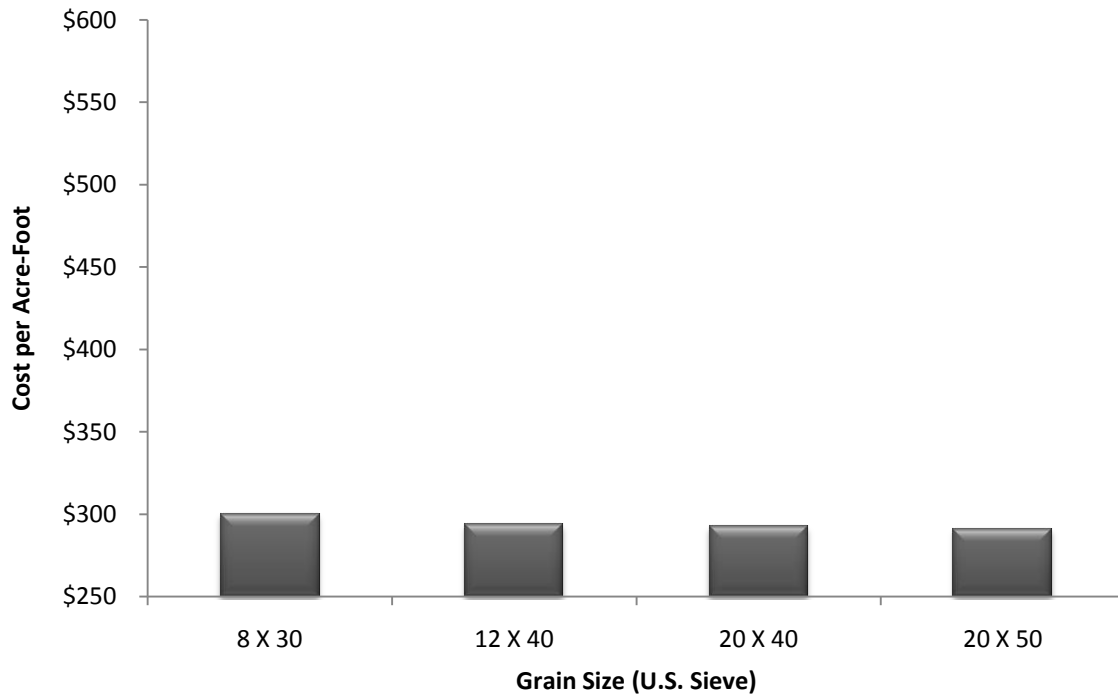
Figure 4-18. Unit Costs as a Function of Media Size (per Acre-Foot) for Fontana Water (10 minute EBCT)

4.5.2.7. EBCT

Column EBCT directly impacts performance and cost. As discussed in Chapter 2, the parameter *"%qachieved"* is dependent on EBCT. Therefore, as the EBCT increases, solute adsorption (and bed capacity) is expected to increase, thus, reducing treatment costs. Figure 4-18 depicts this effect and shows that costs are minimized when the EBCT is greater than 4.5 minutes.
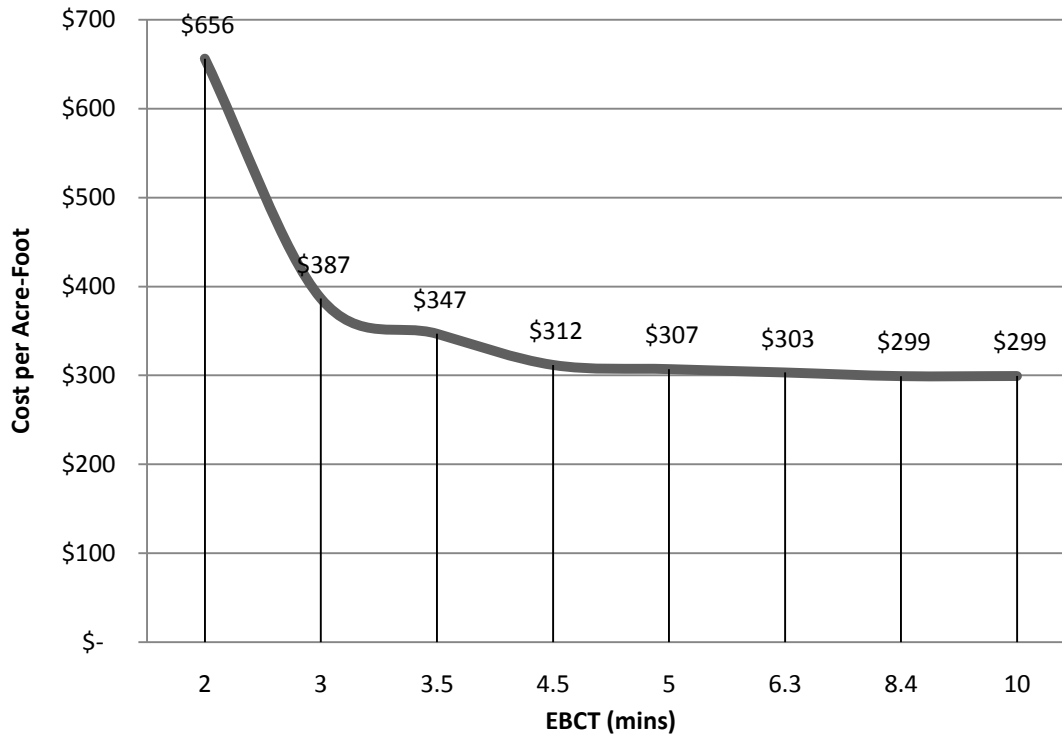
Figure 4-19. Unit Costs as a Function of EBCT for Fontana Water
Values based on series operation of two T-GAC beds plus one polishing bed. Plant flow rate is 800 gpm. Media grain size: 20 X50. Fontana Water. Media is regenerated. No Housing

4.5.2.8. Design Option Costs

Based on the results in the preceding sections, here we will demonstrate the application

of using the model to consider model design options and the resultant impact on unit

treatment cost. In Table 4-9 we examine five scenarios, Cases I through V. Case I

represents a system operating in series, with a single-bed EBCT of 4.5 minutes, T-GAC

media size of 8 X 30, and media replaced after utilization; the resulting unit treatment

cost is $782 per acre-foot. In Case II, we consider the impact of using the media grain

size that results in the lowest unit cost (20 X 50 media, as shown in Figure 4-16);

treatment costs are reduced significantly to $388 per acre-foot. Case III considers the

effect of operating at a single-bed EBCT of 8.4 minutes. Overall costs decrease slightly, as the increased capital costs associated with installing larger columns to accommodate the larger EBCT are more than offset by the reduction in operating cost that results from the increased bed capacity at the larger EBCT. Case IV increases the plant flow rate to 2,000 gpm. Finally, in Case V, the cost reduction achieved through regeneration is shown; yielding a treatment cost of $291 per acre-foot. If we further examine the cost factors that drive unit treatment costs for Fontana, we can see from Figure 4-21 that the cost drivers are: media (69%), annualized capital (12%), labor costs (9%), and maintenance material (7%).

Table 4-9. Cost (per acre-foot) for Five Designs for Treating Fontana Water

Case: Unit Treatment Costs ($/per acre-foot)	I Series, 4.5 min EBCT, 500 gpm, Media: 8 X 30 (Replaced)	II Series, 4.5 min EBCT, 500 gpm, Media: 20 X 50 (Replaced)	III Series, 8.4 min EBCT, 500 gpm, Media: 20 X 50 (Replaced)	IV Series, 8.4 min EBCT, 2000 gpm, Media: 20 X 50 (Replaced)	V Series, 8.4 min EBCT, 2000 gpm, Media: 20 X 50 (Regeneration)
Energy	$8	$8	$8	$8	$8
Maintenance Material	$20	$20	$20	$20	$20
Labor	$30	$30	$30	$27	$27
Media	$631	$267	$258	$258	$200
Disposal	$22	$10	$10	$10	$-
Transport	$32	$14	$7	$2	$2
Annualized Capital	$40	$40	$42	$34	$34
Total	$782	$388	$374	$358	**$291**
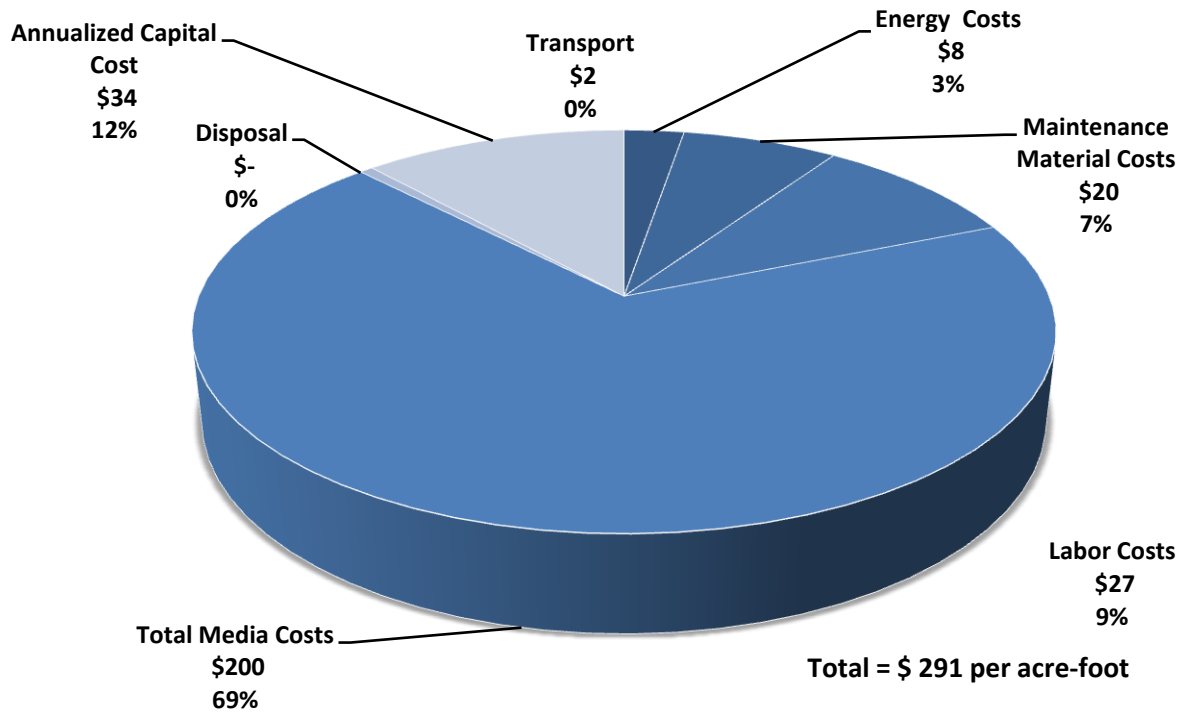
Figure 4-20. Modeled Cost Breakout for Treating Fontana Water (Case V)

4.5.3. Cost Comparison with Conventional IX Technology

Unit treatment costs using IX are estimated to range between $75 to $100 per acre foot which includes cost of resin, pre-installation rinses, vessel loading and unloading, vessel sanitization, transportation, final resin disposal, and certificate of destruction (Siemens, 2007). In this section we compare T-GAC costs with this benchmark, and consider what column performance breakthroughs and media unit costs values are needed so that the T-GAC technology can be cost-competitive. To appropriately compare T-GAC model predicted costs to Siemens (2007) IX estimated cost figures, unit treatment costs in this section are based solely on media replacement, transportation, and disposal. Annual cost factors not included in this analysis are: annualized capital, process energy, maintenance

material, and labor.   Additionally, costs associated with obtaining certificates of

destruction for T-GAC were not included in the model.

4.5.3.1. Initial Breakthrough Volume

Model performance predictions, in terms of bed volumes to initial breakthrough, are

based on media size, EBCT, and influent chemistry. Figure 4-20 relates cost to bed

volumes to initial breakthrough. We observe that as bed volumes to initial breakthrough

increase (due to changes in influent water chemistry or system design) unit treatment

costs decrease significantly. In addition, Figure 4-20 illustrates that although improved

T-GAC performance will have significant cost reduction benefits, it will be difficult to

match unit treatment costs for IX without substantial improvements in T-GAC adsorption

capacity.
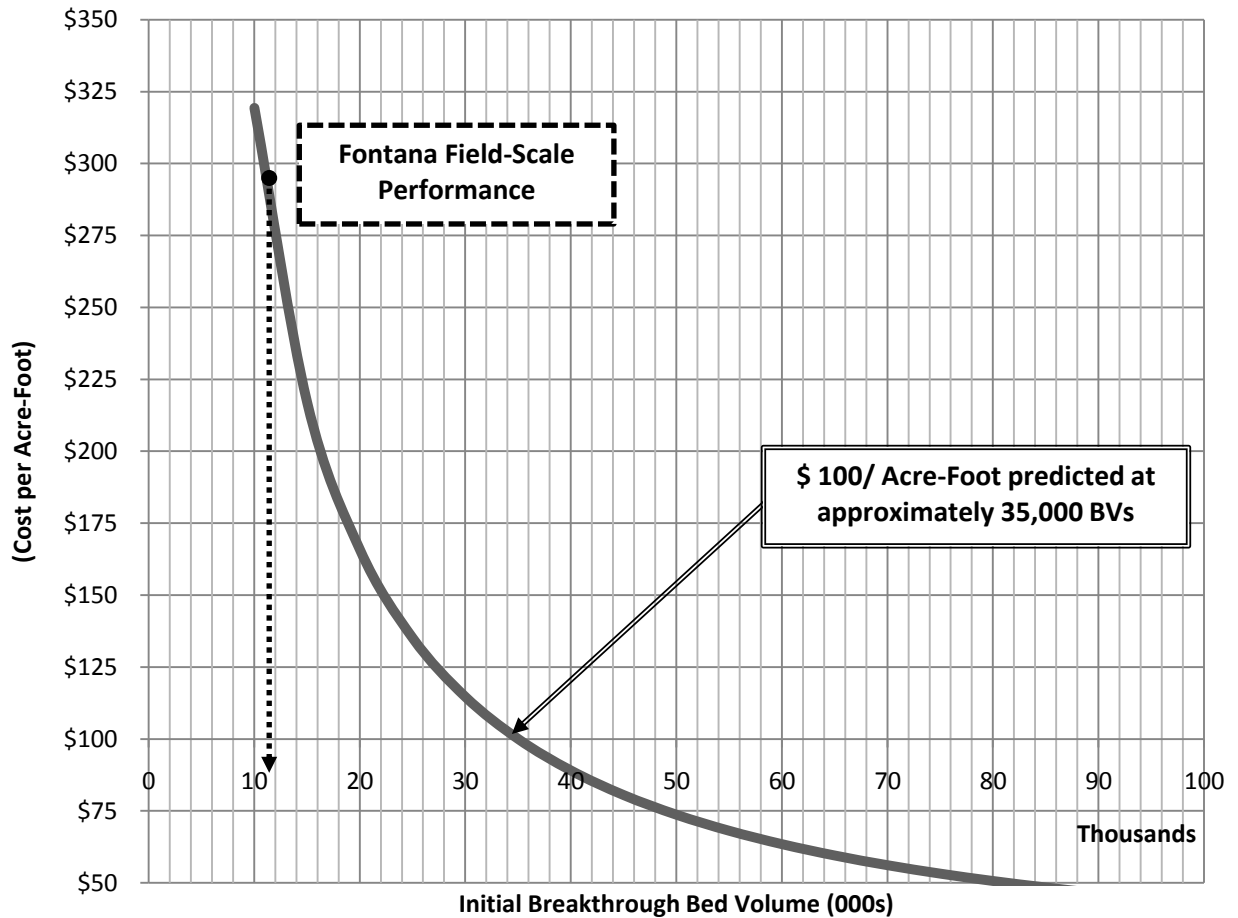
**Figure 4-21. Cost per Acre-Foot vs Bed Volumes Treated Before
Initial Breakthrough of Lead Bed**
*Values based on series operation of two T-GAC beds plus one polishing bed. Columns
operate at an EBCT of 4.5 minutes per column. Grain Size: U.S. Sieve 20 X 50. Column
Bed Volume: 9,000 Gallons. Design Flow Rate: 2,000 GPM. No Housing.
Media Replacement Costs: $2.50/lb for T-GAC and $1.00/lb for GAC.*

4.5.3.2. Media Cost

According to the cost sensitivity analysis performed by Powell (2007), media cost has the

largest impact of any factor on determining overall treatment costs. Using model

predictions with Fontana water, Figure 4-21 depicts how overall treatment cost varies

with media costs.
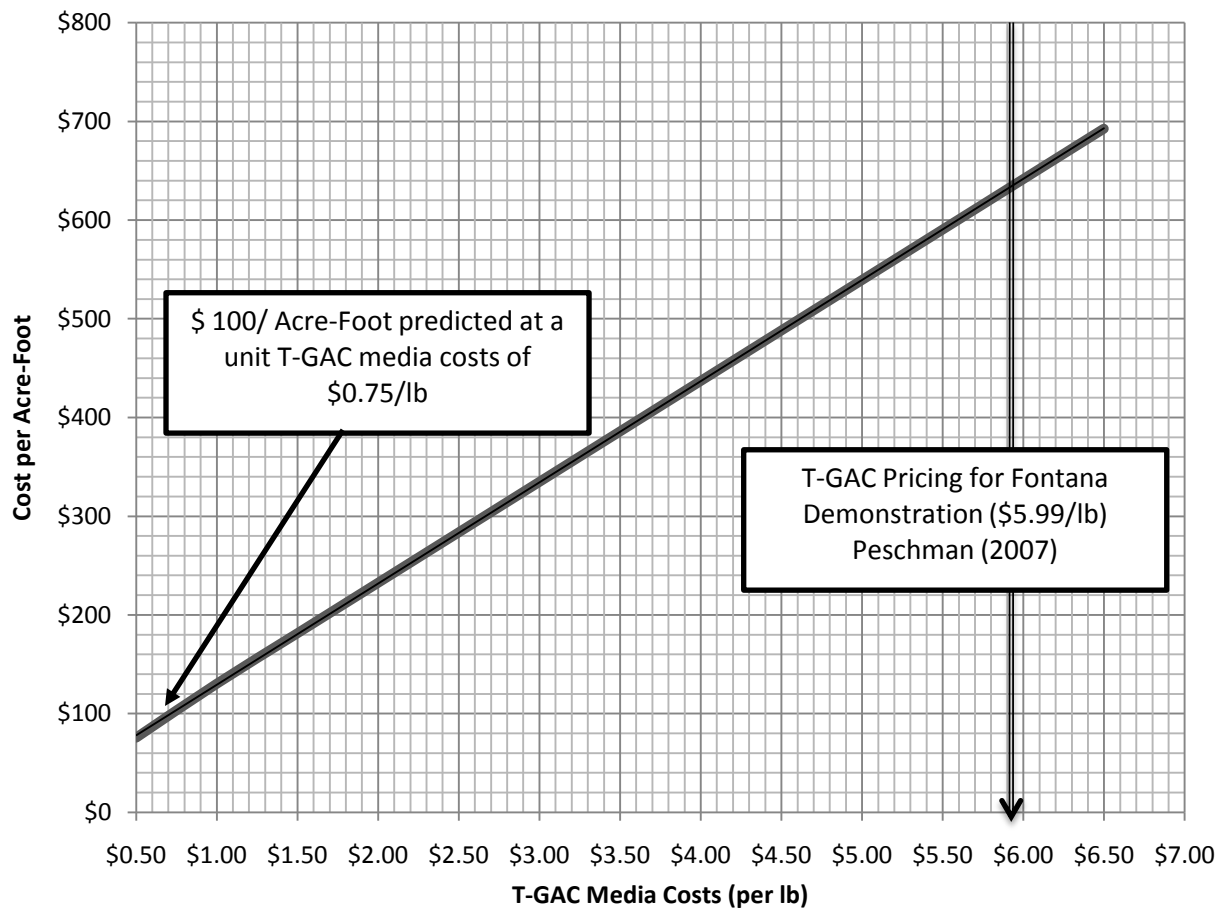
Figure 4-22. Overall Unit Treatment Cost as a Function of Media Cost.
Values based on series operation of two T-GAC beds plus one polishing bed. Columns operate at an EBCT of 4.5 minutes per column. Grain Size: U.S. Sieve 20 X 50. Column Bed Volume: 4,500 Gallons. Design Flow Rate: 1,000 GPM. Media is regenerated.

Figure 4-21 is based on current model performance predictions with Fontana water and shows that treatment cost is linearly related to the price of T-GAC. Specifically, this figure shows for every dollar increase in media cost, unit treatment costs increase approximately $102 per acre-foot of treated water. Furthermore, $100 per acre-foot treatment costs can be achieved with unit T-GAC media costs of $0.75 per pound.

5.0. Conclusions and Recommendations

5.1. Summary

Results obtained from RSSCTs (lab-scale tests designed to predict large-scale performance) have been used to parameterize a model developed by Powell (2007) to predict performance of an innovative technology that uses Tailored-GAC (T-GAC) to treat perchlorate-contaminated water. The model considers adsorption of perchlorate onto the T-GAC and inhibition of perchlorate adsorption due to the presence of competing anionic species. The parameterized model was used to predict the observed performance from a pilot-scale demonstration at Fontana, CA; however, model predictions were not accurate. Therefore, the model was adjusted to reflect the performance observed at Fontana to develop a technology cost model which was then partially validated based on the Fontana demonstration costs. Notably, the model reasonably predicted RSSCT performance for two distinct water chemistries not used to generate the model parameters.

The cost model developed in this study provides potential technology users with a convenient tool that can be used to compare costs of alternative T-GAC designs. It is hoped that this user-friendly tool will be useful in facilitating transfer and commercialization of the T-GAC technology for treating perchlorate-contaminated water.

5.2. Conclusions

This study had three research objectives, which were presented in the first chapter. In this section, we review how well the study met these objectives, and we also present final

conclusions and discuss the potential for technology transfer and commercialization, based on performance and cost-competiveness.

5.2.1. Objective # 1

The primary research objective for this study is to determine if conventional GAC modeling techniques (as developed by Powell, 2007) can be used to simulate a pilot-scale T-GAC field test.

Model predictions of the Powell (2007) model were compared with pilot-scale results from water treatment plants at Fontana and Redlands, CA. Model predictions of bed volumes of water treated to initial breakthrough significantly over-estimated observed performance (by 65% for Fontana and 95% for Redlands). Despite this outcome, Powell's model accurately simulated the results of RSSCTs over three distinct water sources (with absolute discrepancies of: 0% for Massachusetts, 8% for Redlands, and 16% for Fontana waters).

5.2.2. Objective # 2

Following the base-line evaluation of the Powell model, a secondary objective of the research was to modify the model to incorporate additional (and corrected) results of laboratory RSSCTs, as well as the results of the Fontana pilot test.

The Powell (2007) model was re-parameterized based on the results of 12 RSSCTs that were conducted using perchlorate-spiked Fontana water. The re-parameterized model was used to predict bed volumes of water treated to initial breakthrough for RSSCTs that were conducted using water from the Massachusetts and Redlands sites. Predictions for

the two waters were in reasonable agreement with observed initial breakthrough values, with errors of 8% and 14% for Massachusetts and Redlands waters, respectively.

The re-parameterized model was also used to predict pilot-scale results at Fontana and Redlands. It was found that the model over-predicted the field results for Fontana Bed A and Redlands by 46% and 81%, respectively, a small improvement over the original model. Based on these results, it is not evident that conventional GAC modeling techniques can effectively predict performance of a T-GAC system treating perchlorate-contaminated water.   However, the causes for the discrepancy between the observed pilot-scale and RSSCT performance differences are unknown.   Fontana demonstration project members are currently investigating a range of possible explanations. For instance, competition with reduced sulfur species, surfactant biodegradation and desorption, channeling at the relatively slow superficial velocities used in the field, and inapplicability of the proportional diffusivity assumption to scale up RSSCTs for T-GAC are considered factors to explain the deviation (ESTCP, 2007).   Moreover, the underlying assumptions used to genearate this model are perhaps incorrect. Temperarture differences between the lab and field which are assumed neglible may in fact appreciably impact performance. Additionally, the empirically quanitifed non-equilibrium assumption as derived by Powell (2007) may be inaccurate. Nevertheless, as a result of the model deviation, a final model developed to help meet the third objective, included adjustments to account for the over-predictions that were revealed when the model that was re-parameterized based on RSSCT results was used to predict field performance.

111

5.2.3. Objective # 3

The final objective of this research was to demonstrate how technology performance and cost modeling can be applied to provide potential technology users with information in order to facilitate technology transfer and commercialization. This objective has been met with the development of a screening model.

The screening model is based on two sub-models, one that predicts performance (and is based upon the adjusted model referred to in Objective #2) and one which estimates capital, operation, and maintenance costs from the predicted performance.

The cost component of the model is principally derived from conventional GAC cost data found in the literature that has been modified to account for the tailoring of GAC. T-GAC media cost is based on actual field costs. The screening model was used to estimate capital costs at the Fontana 37 GPM field study; model predictions were nearly identical to actual capital cost expenses.

To provide potential users with information on the performance and expected costs of full-scale implementation, design considerations such as water flow rate, whether or not the media is regenerated or replaced, media size, EBCT, plant housing, plant configuration (series versus parallel operation), and influent water quality were evaluated. The model allows potential technology users to specify the above design values to predict capital, annual, and overall unit treatment costs.

Using the screening model, it was found that annual operation and maintenance (O&M) costs are more significant than capital costs, and that costs associated with media

regeneration or replacement dominate the O&M costs. Decreases in media costs, labor expenses, and maintenance material would significantly reduce overall treatment costs. However, unless cost reductions are significant or there is substantial improvement in the capacity of the T-GAC media to adsorb perchlorate, T-GAC technology may not be cost competitive with conventional IX technology.

5.3. Recommendations

5.3.1. Performance Modeling

- **Future research should compare model predictions to full-scale operation and incorporate the results of additional pilot-scale data.** Additional pilot-scale field data will aid in validating the model. Moreover, future research should examine larger scales of operation and parallel plant configurations to compare model predictions applicable to commercial applications and designs.

- **Model parameter quantification and validation over more diverse water chemistries.** In this study, competition between perchlorate and thiosulfate, nitrate, sulfate, chloride, and bi-carbonate was considered. With additional data, competition coefficients can be quantified for other anions which may be present in waters to be treated.

- **Effect of Non-Competitive Species on Overall Inhibition.** PSU RSSCT results with Fontana water suggest that the presence of chloride and sulfate (species that don't appear to compete with perchlorate for T-GAC adsorption sites), moderately improves breakthrough performance. These species may reduce the

effect of anions such as nitrate that do compete with perchlorate for sites. Future research should examine this phenomenon and if observed, incorporate the effect of non-competing species into the screening model.

- **T-GAC adsorption capacity for organic co-contaminants.** The literature review indicated that organics such as TCE are frequently found as co-contaminants at perchlorate contamination sites. There may be benefits obtained by using T-GAC to simultaneously treat perchlorate and organic contaminants. Current IX technology is ineffective in treating organics. Therefore, future research should examine the effectiveness and costs of applying T-GAC technology to treat water that contains perchlorate and organic co-contaminants.

- **RSSCT Scaling.** Based on the discrepancy of model results, their potentially may be a problem with up-scaling RSSCT results. This may be the result of a number of factors. Conceivable factors that have been discussed by members of the Fontana demonstration project team are: temperature difference between lab and field, competition with reduced sulfur species, surfactant biodegradation and desorption, channeling at the relatively slow superficial velocities used in the field, and inapplicability of the proportional diffusivity assumption to scale up RSSCTs for T-GAC (ESTCP, 2007).

- **Column design factors that impact performance.** The current model includes design considerations such as water flow rate, influent perchlorate concentration, column configuration, media size, and EBCT. Additional plant design considerations should be examined to help optimize performance and cost. For

instance, as particle size increases the length of the mass transfer zone decreases; however, as the particle size increases head loss across the column increases. Similarly, optimum hydraulic surface loading rates (rate of volume of water passing through a unit area of bed) should be established in the model. Proper hydraulic loading will ensure that treatment trains are not overloaded with excessive throughput.

5.3.2. Cost Modeling

- **Validation of annual operation and maintenance costs.** The cost model has not been validated with regard to annual operation and maintenance costs. Media change-out, maintenance, material, labor, and energy requirements are significant cost drivers. Model validity is dependent on the accuracy of these O&M cost predictions.

- **Compare actual capital costs with model predictions.** Cost analyses conducted using the model indicates that there are economies of scale. The current model accurately predicted the 37 GPM Fontana field demonstration capital cost; however, the technology would typically be applied commercially at a much larger scale. Thus, model predictions should be validated at these larger scales.

Appendix A

Penn State University (PSU) Rapid Small Scale Column Tests (RSSCT) Breakthrough Results

Table A-1. Observed Bed Volumes and Adsorption Loading Rates at Breakthrough for RSSCT Runs Conducted by PSU

Trial	Description	Simulated EBCT @ Media Size (*note 1*)	Reported Bed Volumes to Breakthrough	Tailoring Agent	Reported Loading Rate [mg CLO4- per g T-GAC]	Evaluated in Powell (2007)	Note
De-Ionized/Distilled							
1	1000 ppb ClO4-	20 min./ 8 x 30	14,250	CPC	29.688	Yes	2
2	+ Thiosulfate Concentration 10 ppb	20 min./ 8 x 30	13,750	CPC	28.646	Yes	2
3	+ Thiosulfate Concentration 100 ppb	20 min./ 8 x 30	12,250	CPC	25.521	Yes	2
4	+ Thiosulfate Concentration 1 ppm	20 min./ 8 x 30	11,000	CPC	22.917	Yes	2
5	+ Thiosulfate Concentration 10 ppm	20 min./ 8 x 30	4,000	CPC	8.333	Yes	2
Fontana Water							
6	Virgin GAC	10 min./ 20 x 50	643	None	0.0204	No	3
7	Carbon Tailored by PSU	10 min./ 20 x 50	16,495	CPC	0.330	Yes	3 & 4
8	Carbon Tailored by Siemens	10 min./ 20 x 50	17,719	CPC	0.318	No	3 & 4
9	Carbon tailored with Arquad 2C-75	10 min./ 20 x 50	18,990	Arquad 2C-75	0.338	No	3 & 4
10	Perchlorate Concentration Increased to 50 ppb	10 min./ 20 x 50	15,182	CPC	2.080	Yes	3 & 4
11	Perchlorate Concentration Increased to 500 ppb	10 min./ 20 x 50	9,212	CPC	11.400	Yes	3 & 4
12	Nitrate Concentration Increased to 60 ppm	10 min./ 20 x 50	15,243	CPC	0.198	No	3 & 4
13	Nitrate Concentration Increased to 100 ppm	10 min./ 20 x 50	7,880	CPC	0.160	Yes	3 & 4
14	Water Spiked with 1 ppm Thiosulfate	10 min./ 20 x 50	15,826	CPC	0.283	No	3 & 4
15	Water spiked with 10 ppm Thiosulfate	10 min./ 20 x 50	13,707	CPC	0.298	No	3 & 4
16	Sulfate Concentration increased to 50 ppm	10 min./ 20 x 50	18,813	CPC	0.340	Yes	3 & 4
17	Sulfate Concentration increased to 250 ppm	10 min./ 20 x 50	18,996	CPC	0.358	Yes	3 & 4
18	Chloride Concentration Increased to 250 ppm	10 min./ 20 x 50	22,541	CPC	0.372	No	3 & 4
19	Bicarbonate Concentration Increased to 500 ppm	10 min./ 20 x 50	23,261	CPC	0.445	No	3
20	pH Lowered to 4.2	10 min./ 20 x 50	28,673	CPC	0.502	No	3
Redlands Water							
21	Virgin GAC	20 min./ 8 x 30	1,000	None	0.156	No	2
22	Tailored Agent: CTAC	22 min./ 8 x 30	34,000	CTAC	5.313	Yes	2
23	Tailored Agent: CPC @ 15.52 min EBCT	15.52 min./ 8 x 30	33,000	CPC	5.090	Yes	2
24	Tailored Agent: CPC @ 8 min EBCT	8 min./ 8 x 30	27,000	CPC	4.219	Yes	2
25	Tailored Agent: Arquad T-50	8 min./ 8 x 30	27,000	Arquad T-50	4.219	Yes	2
26	Tailored Agent: Arquad 2C-75	7 min./ 8 x 30	23,000	Arquad 2C-75	3.594	Yes	2
Tap Water							
27	Unknown Composition	20 min./ 8 x 30	9,000	Ultracarb	15.000	No	2
28	Unknown Composition	20 min./ 8 x 30	10,000	Aquacarb	16.667	No	2
Massachusetts Water							
29	Tailored Agent: CTAC @ 5 min EBCT	5 min./ 8 x 30	210,000	CTAC	2.450	Yes	2

Note 1: PSU RSSCTs Conducted with 200 X 400 GAC Mesh Media Size to Simulate the Reported EBCT and Indicated Grain Size
Note 2: Source: Powell (2007)
Note 3: Source: ESTCP (2007)
Note 4: Used for Determination of Model Parameters
Note 5: Unknown Water Chemistry

Appendix B

Water Characteristics

B.1. Fontana Water Quality

Production wells FWC #17B and FWC #17C pump water through the Fontana 37 GPM pilot-scale field treatment system. Groundwater chemistry for both production wells is summarized in Table B-1 (ESTCP, 2005). Model quantifcation was based on the average chemistry reported in Table B-1.

Table B-1. Fontana Water Chemistry

Well	#17B	#17C	Average
Perchlorate (µg/L)	18	8.6	13
Nitrate (mg/l)	36	33	34
Chloride (mg/l)	11	11	11
Sulfate (mg/l)	14	14	14
Carbonate/Bi-Carbonate (mg/l)	Non-detect/192	Non-detect/186	Non-detect/189
pH	7.5	7.5	7.5
Total Dissolved Solids (mg/l)	250	238	244
Specific Conductance (µmho/cm)	415	388	401
Volatile Organic Compounds (µg/L)	Non-detect	Non-detect	Non-detect

B.1. Redlands, Massachusetts, and Distilled/Deionized Water Quality

Table B-1. Water Chemistry for Redlands, Massachusetts, and Distilled/Deionized

Well	Redlands[1]	Massachusetts[1]	Distilled/Deionized[2]
Perchlorate (µg/L)	75	5.6	1000
Nitrate (mg/l)	16	0.4	
Chloride (mg/l)	7.2	7.6	
Sulfate (mg/l)	30	6.9	
Bi-Carbonate (mg/l)	145		

Sources: (1) ESTCP (2005), *(2)* After Powell (2007)

Appendix C

Fontana 37 GPM Demonstration Project Results (ESTCP, 2007)

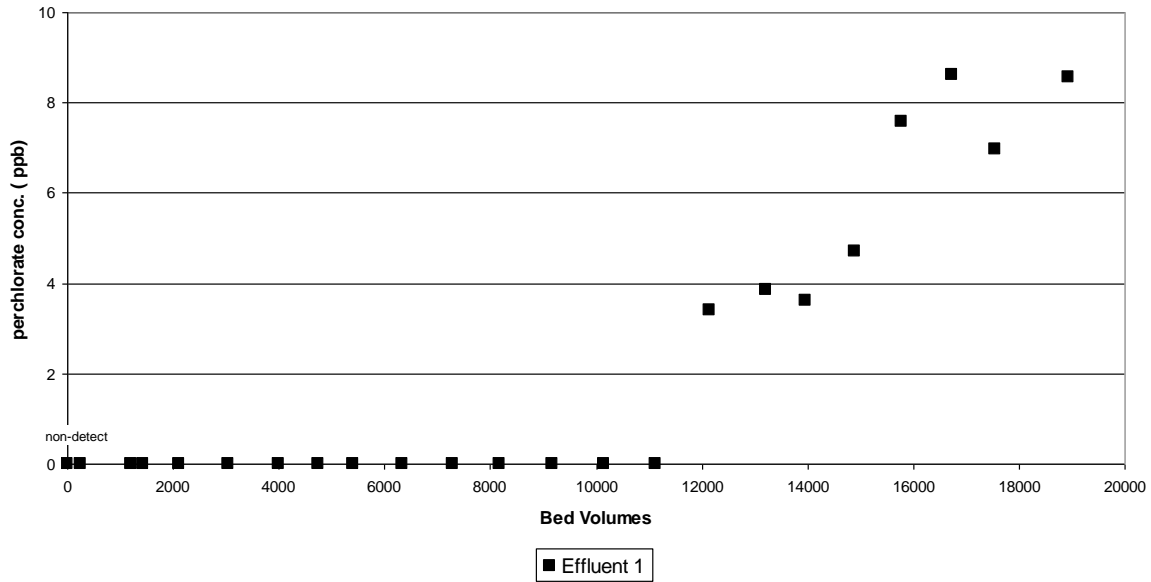**Figure C-1. Bed A Breakthrough Curve (Perchlorate Effluent Concentrations)**

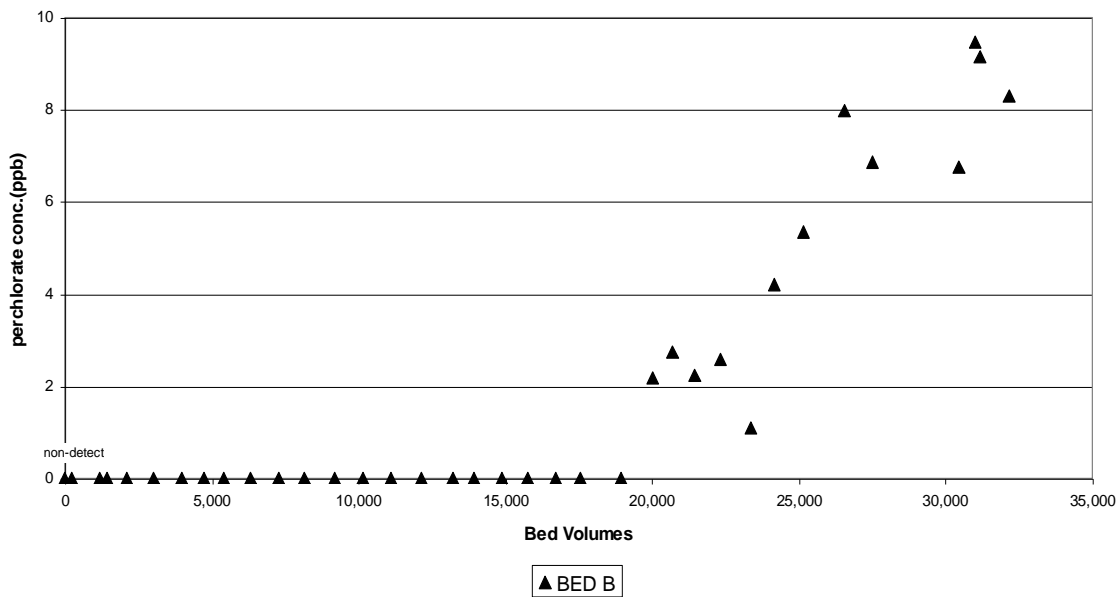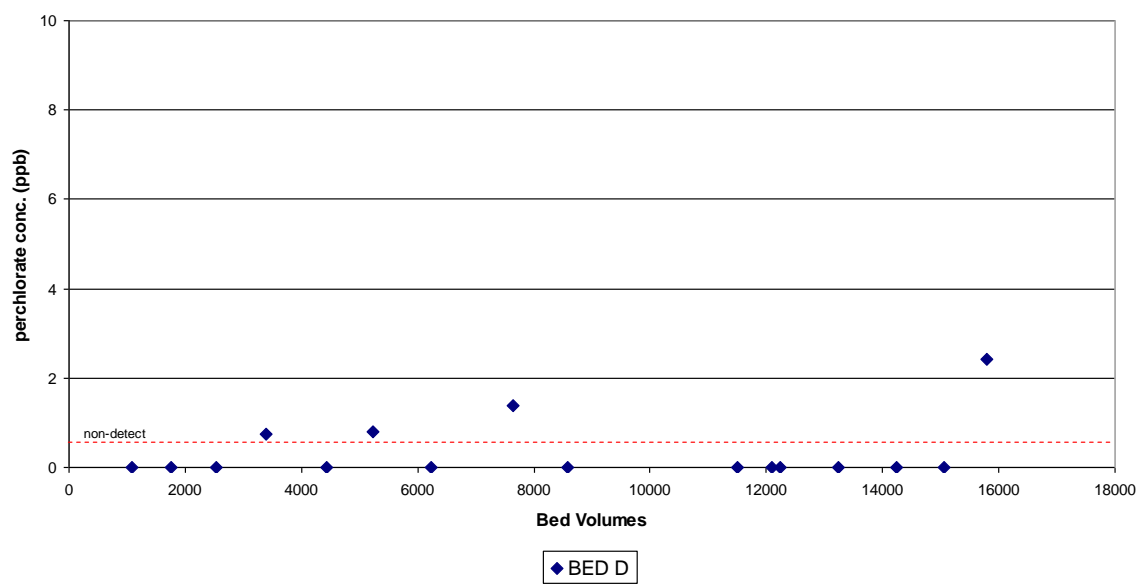**Figure C-2. Bed B Breakthrough Curve (Perchlorate Effluent Concentrations)**
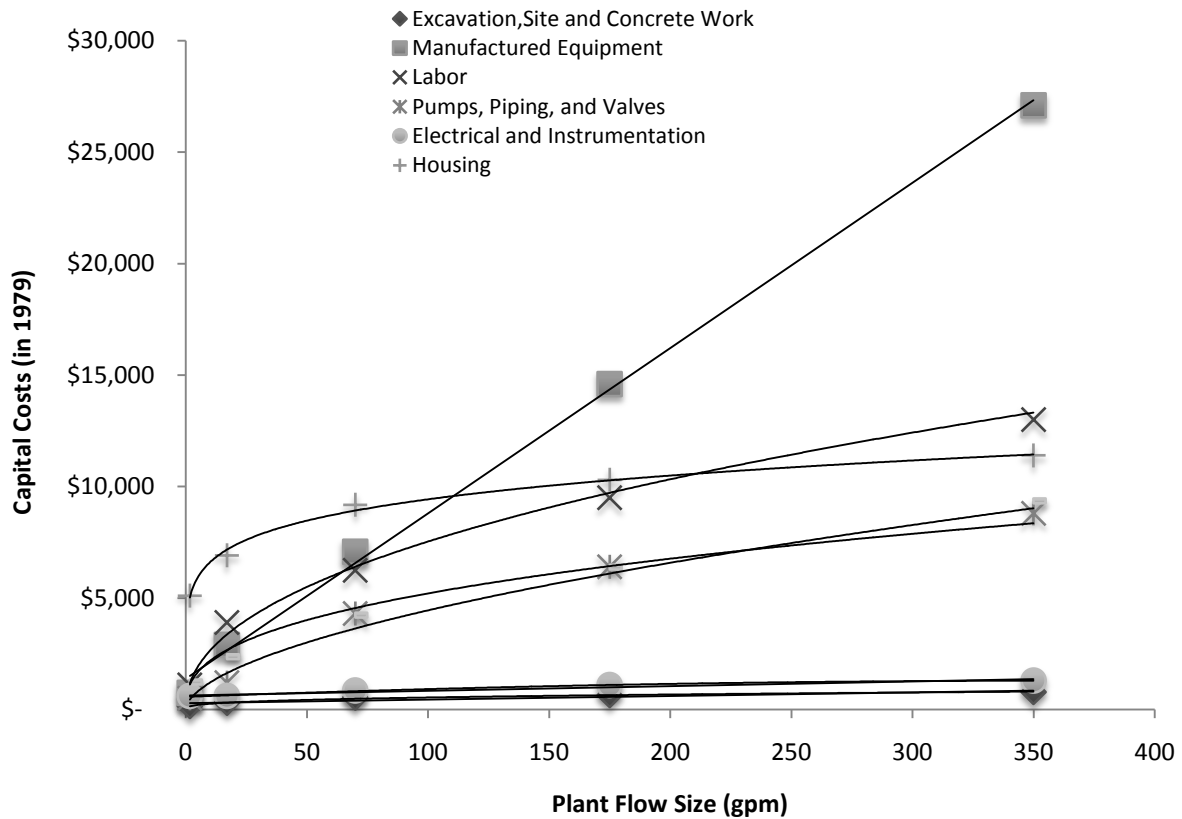
Figure C-3. Bed D Breakthrough Curve (Perchlorate Effluent Concentrations)

U.S. Environmental Protection Agency Granular Activated Carbon (GAC) Construction and Annual Operation and Maintenance Costs (U.S. EPA, 1979)

Figure D-1. Construction Costs for Package GAC Columns

Best-Fit Trendline Equation

Manufactured Equipment Cost = 74.13x + 1382.
R² = 0.997

Electrical and Instrument Costs = 2.072x + 635.5
R² = 0.933

Housing Costs = $4637.x^{0.154}$
R² = 0.994

Misc. and Contingency = $918.2x^{0.377}$
R² = 0.984

Excavation, Concrete, and Site Work = $127.4x^{0.315}$
R² = 0.994

Labor Costs = $928.8x^{0.454}$
R² = 0.992

Pumps, Piping, and Valves = $329.1x^{0.565}$
R² = 0.976

Figure D-2. Building and Process Energy Requirements per Year (kw-hr/year)

Best-Fit Trendline Equation

Building Energy Load = $5170.x^{0.388}$
$R^2 = 0.990$
Process Energy Load = $66.50x$
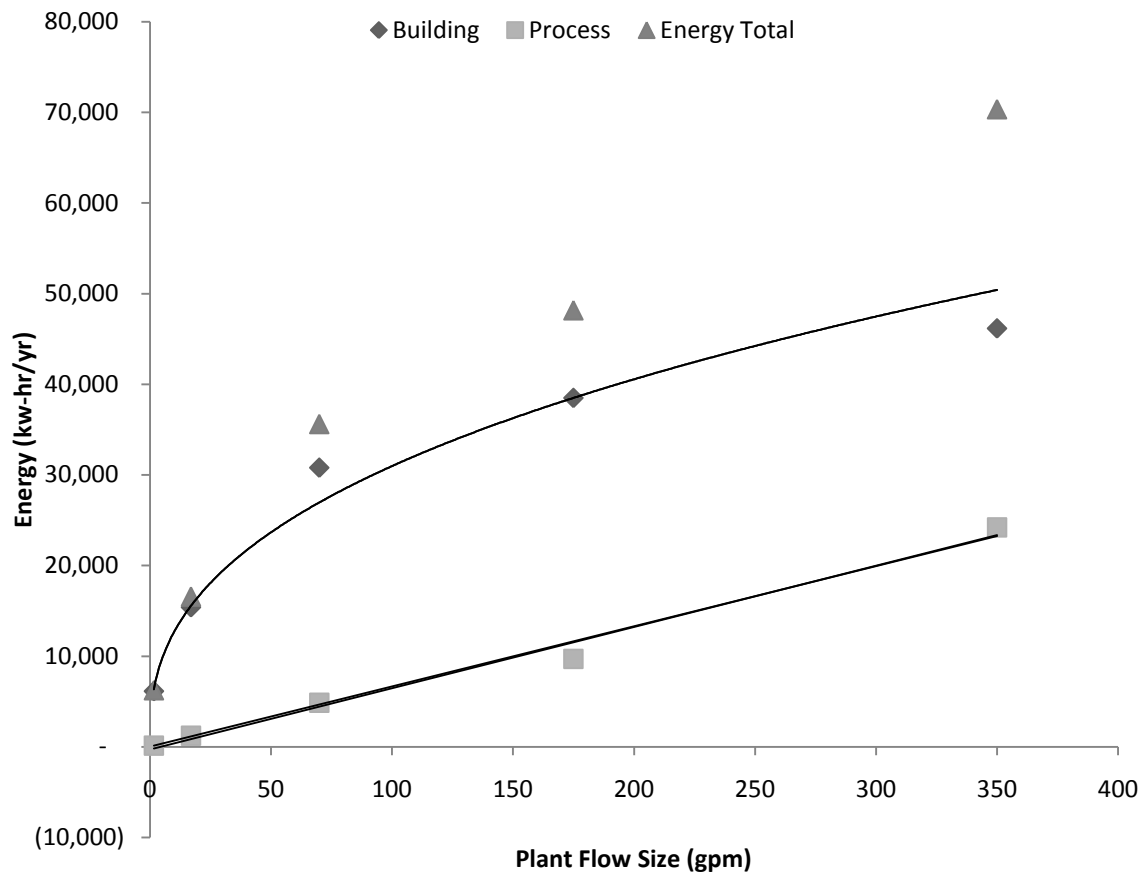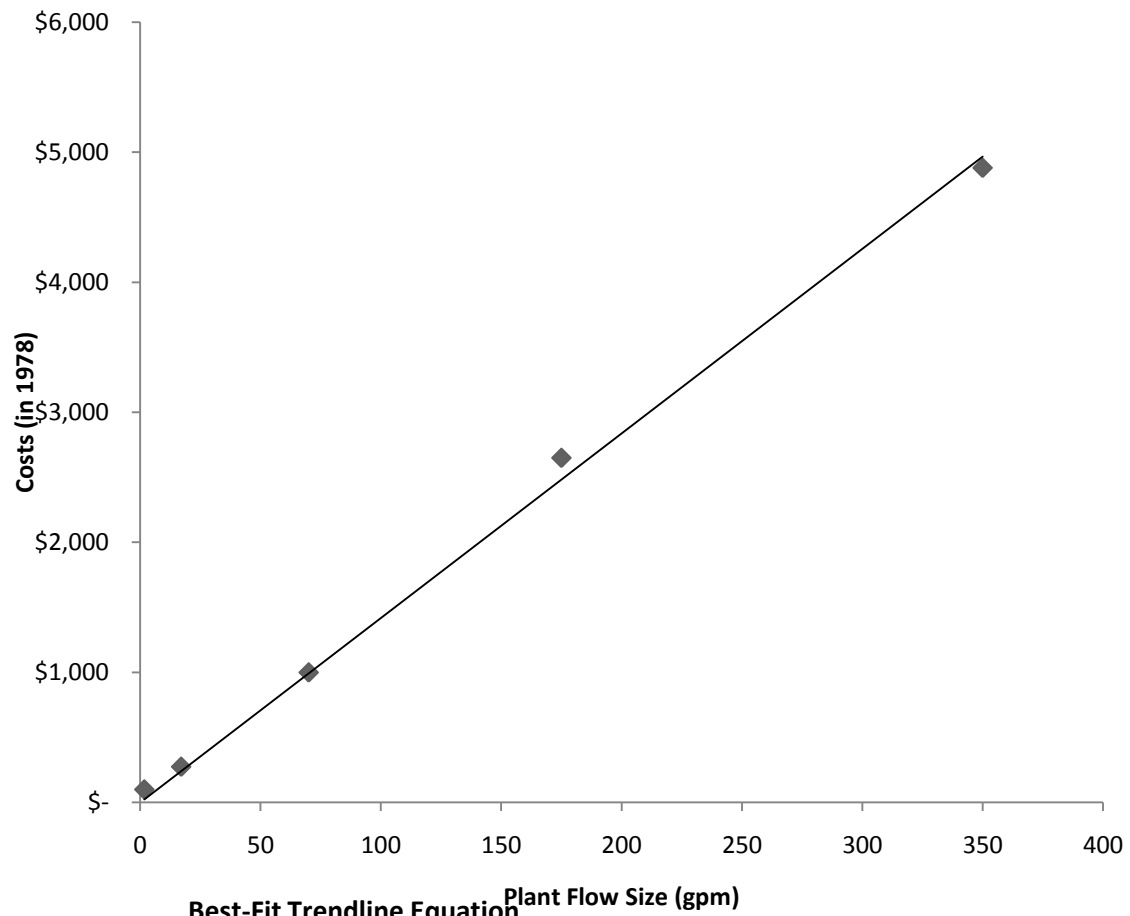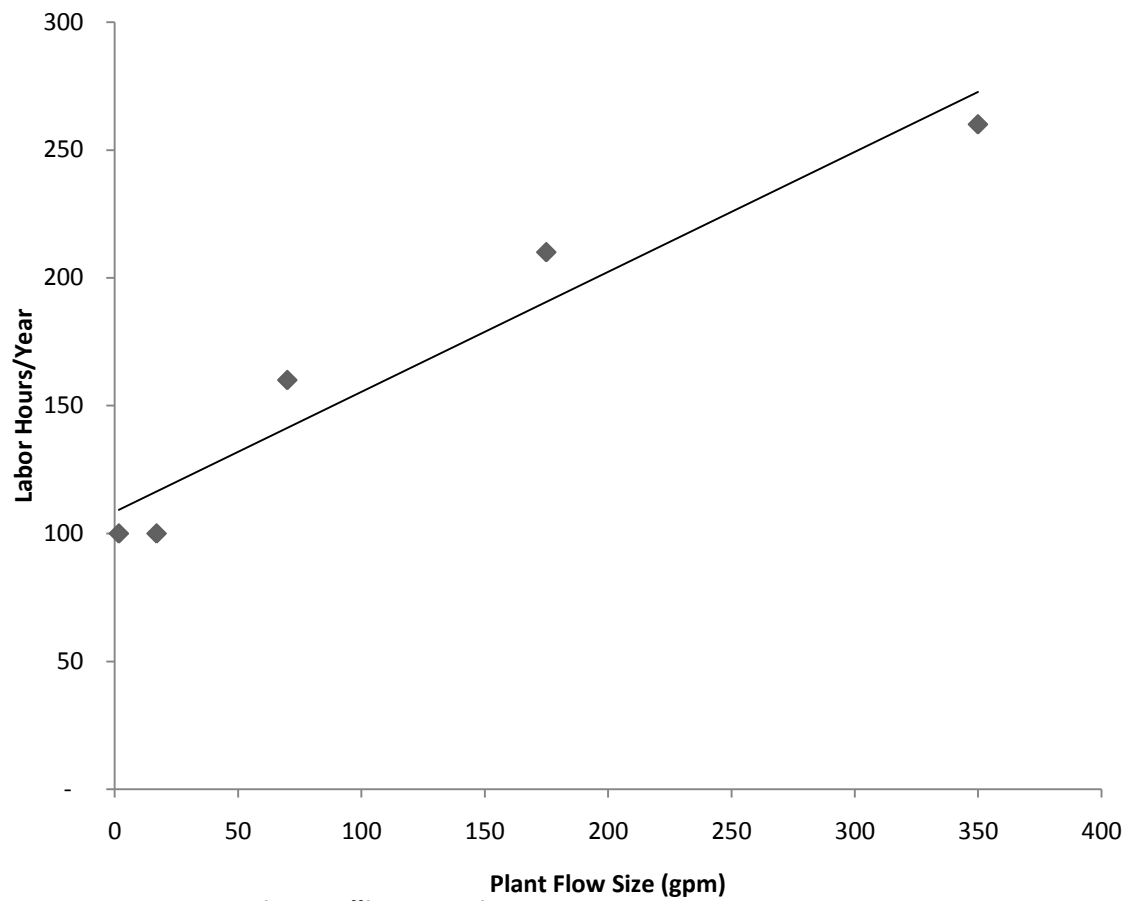$R^2 = 0.987$

Figure D-3. Annual Maintenance Material Costs

Best-Fit Trendline Equation

Maintenance Material Costs = 14.19x

$R^2 = 0.997$

Figure D-4. Annual Operation and Maintenance Labor Hours

Best-Fit Trendline Equation

Annual Labor Hours = 0.469x + 108.4

$R^2 = 0.936$

Bibliography

Air Force Center for Environmental Excellence. (2002, August). *Perchlorate Treatment Technology Fact Sheet*. Retrieved January 8, 2008, from: http://www.afcee.brooks.af.mil/products/techtrans/perchloratetreatment/ionexchange.pdf

Alberts, D. S., and Hayes, R. E. (2004). "Power to the Edge: Information Age Transformation." CCRP Publication Series.

Bureau of Labor Statistics (BLS): Department of Labor. (2006, May). "Occupational Employment and Wages (Installation, Maintenance, and Repair Occupations)." Retrieved February 21, 2008, from: www.bls.gov

Brady, R. D. (2005). Activated Carbon Processes. *Water Treatment Plant Design, Fourth Edition* (American Water Works Association, American Society of Civil Engineers). McGraw-Hill.

Cannon, F.S. Professor of Civil and Environmental Engineering, Pennsylvania State University, University Park PA. Personal interview. December 5, 2007.

Chemical Engineering Journal. (1980). Economic Indicators. *Chemical Engineering,* May, 7.

Chemical Engineering Journal. (2007). Economic Indicators. *Chemical Engineering*, December, 76.

Chen, W., Cannon, F. S., and Rangel-Mendez, J. R. (2005). Ammonia-Tailoring of GAC to Enhance Perchlorate Removal. II: Perchlorate Adsorption. *Carbon*, 43(3), 581-590.

Chen, W., Cannon, F. S., (2005). Thermal Regeneration of Ammonia-Tailored Granular Activated Carbon Exhausted with Perchlorate. *Carbon*, 43(13), 2742-2749.

Cheremisinoff, N. P. (2002). *Handbook of Water and Wastewater Treatment Technologies.* Woburn, MA: Butterworth-Heinemann.

Clark, R. M., and Lykins Jr., B. W. (1989). *Granular Activated Carbon: Design, Operation Cost.* Chelsea, MI: Lewis Publishers.

Cooper, M., Redman, A., and Smith, M. (2001). Capital Budgeting Models: Theory vs. Practice. *Business Forum*, 26 ½, 15-19.

Crittenden, J.C., Berrigan, J.K., Hand, D.W. (1986). Design of Rapid Small-Scale Adsorption Tests for a Constant Diffusivity. *Journal Water Pollution Control Federation*. 58(4), 312-319.

Crittenden, J.C., Berrigan, J.K., Hand, D.W., Lykins, B. (1987). Design of Rapid Fixed-Bed Adsorption Tests for Non-Constant Diffusivities. *Journal 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 American Water Works Association*, 83(1), 77-87.

Crittenden, J. C., Trussell, R. R., Hand, D. W., Howe, K. J., and Tchobanoglous, G. (2005). *Water Treatment: Principles and Design, Second Edition*. Hoboken, NJ: John Wiley and Sons.

Defense Environmental Restoration Program (DERP). (2003*). Fiscal Year 2002 DERP Annual Report to Congress.* From Defense Environmental Network and Information Exchange (DENIX): https://www.denix.osd.mil/denix/denix.html

Environmental Security Technology Certification Program (ESTCP). (2005, August). *Reducing Ion Exchange Treatment Costs by up to 40 Percent Using Tailored Activated Carbon.* ESTCP Technology Demonstration Plan Project ER-0546 Final. United States Department of Defense.

Environmental Security Technology Certification Program (ESTCP). (2007). Project ER-0546. Fontana 37 GPM Pilot-Scale Field Demonstration Project Data.

Faust, S. D., and Aly, O. M. (1998). *Chemistry of Water Treatment, 2nd Edition*. Boca Raton, Florida: Lewis Publishers.

Goltz, M. N., Mandalas, G. C., Hopkins, G. D., and McCarty, P. L. (1998). Technology Transfer of an Innovative Remediation Technology from the Laboratory to the Field: A Case Study of In Situ Aerobic Cometabolic Bioremediation. *Environmental Engineering and Policy*, 1(2), 117-124.

Gottlieb, M. C. (2005). Ion Exchange Application in Water Treatment. In E. E. Baruth, *Water Treatment Plant Design, Fourth Edition* (American Water Works Association, American Society of Civil Engineers). McGraw-Hill.

Grinyer, J. R., Sinclair, D., and Ibrahim, D. N. (1999). Management Objectives in Capital Budgeting. *Financial Practice and Education*, 9(2), 12-22.

Gu, B., and Brown, G. M. (2006). Recent Advances in Ion Exchange for Perchlorate Treatment, Recovery, and Destruction. In B. Gu, and J. D. Coates, *Perchlorate: Environmental Occurrence, Interactions and Treatment*. New York: Springer Science + Business Media.

Gu, B., Brown, G. M., and Chiang, C.-C. (2007). Treatment of Perchlorate-Contaminated Groundwater Using Highly Selective Regenerable Ion-Exchange Technologies. *Environmental Science Technology*, 41, 6277-6282.

Gu, B., Brown, G. M., and Ku, Y. –K. (2003). *Treatment of Perchlorate-Contaminated Groundwater Using Highly-Selective Regenerable Anion-Exchange Resins at Edwards Air Force Base*. ORNL/TM-2002/53.

Hardisty, P. E., and Ozdemiroglu, E. (2005). *The Economics of Groundwater Remediation and Protection*. Boca Raton FL: CRC Press.

Lehman, S. G., Badruzzaman, M., Adham, S., Roberts, D. J., and Clifford, D. A. (2008). Perchlorate and Nitrate Treatment by Ion Exchange Integrated with Biological Brine Treatment. *Water Research*, 42(4-5), 969-976.

Letterman, R. D. (1999). *Water Quality and Treatment: A Handbook of Community Water Supplies (American Water Works Association) Fifth Edition*. McGraw-Hill.

Mandalas, G., Christ, J., and Goltz, M. (1998). Software to Aid Transfer of an Innovative In Situ Bioremediation Technology. *Bioremediation Journal*. 2(1), 7-15.

Marve, H., and Ryan, D. R. (2001). *Groundwater and Soil Remediation: Process Design and Cost Estimating of Proven Technologies*. Reston, VA: ASCE Press.

McClave, J. T., Benson, G. P., and Sincich, T. (2005). *Statistics: For Business and Economics, Ninth Edition*. Upper Saddle River, NJ: Pearson Prentice Hall.

Na, C., Cannon, F. S., and Hagerup, B. (2002). Perchlorate Removal via Iron-Preloaded GAC Borohydride Regeneration. *Journal of the American Water Works Association*, 94(11), 90-102.

National Research Council (NRC). (1994). *Alternatives for Ground Water Cleanup*. Washington, DC: National Academy Press.

National Research Council (NRC). (1997). *Innovations in Ground Water and Soil Cleanup: From Concept to Commercialization*. Washington, DC: National Academy Press.

National Research Council (NRC). (2005). *National Research Council Health Implications of Perchlorate Ingestion*. Washington, DC: National Academy of Sciences.

Null, H. R. (1987). *Selection of a Separation Process and Economics*. In R. W. Rousseau, *Handbook of Separation Process*. John Wiley and Sons.

Nyer, E. K. (1992). *Groundwater Treatment Technology, 2nd Edition*. New York: Von Nostrand Reinhold.

Parette, R., and Cannon, F. S. (2005). The Removal of Perchlorate from Groundwater by Activated Granular Carbon Tailored with Cationic Surfactants. *Water Research*, 39, 4020–4028.

Parette, R., Weeks, K., and Cannon, F. (2005). Removing Low ppb Level Perchlorate, RDX, and HMX from Groundwater with Cetyltrimethylammonium Chloride (CTAC) Pre-Loaded Activated Carbon. *Water Research*, 39, 4683–4692.

Peschman, T. Manager, Remediation Services. Siemens Water Technologies Corporation, Roseville MN. Personal correspondence. December 12, 2007.

Powell, W. (2007). *Development of a Screening Model for Design and Costing of an Innovative Tailored Granular Activated Carbon Technology to Treat Perchlorate-Contaminated Water*. MS thesis, AFIT/GEM/ENV/07-M12. School of Engineering and Management, Air Force Institute of Technology (AU), Wright-Patterson AFB, OH. (ADA465968).

Richard, R. R. (2003). *Environmental Remediation Estimating Methods, Second Edition*. Kingston, MA: Reed Construction Data.

Seader, J. D., and Henley, E. J. (1998). *Separation Process Principles*. New York: John Wiley and Sons, Inc.

Siemens Water Technologies (Siemens). (2007, December 5). "Inland Empire Area Sidebar Presentation [Presented by Henderson, T., ARCADIS, ER-0546]." Environmental Security Technology Certification Program 2007 Annual Conference. Washington, DC.

Under Secretary of Defense (USD). (2006, January 26). *Official Memorandum: Policy on Department of Defense Required Actions Related to Perchlorate*. Department of Defense.

United States Energy Information Agency (U.S. EIA), (2006). *Average Retail Price of Electricity to Ultimate Customers by End-Use Sector, 1995 through 2006.* Retrieved January 22, 2008, from Electrical Power Annual: http://www.eia.doe.gov/

United States Environmental Protection Agency (U.S. EPA). (1979). *Estimating Water Treatment Costs.* Cincinnati, OH: EPA, Municipal Environmental Research Laboratory. (EPA-600/2-79-162c).

United States Environmental Protection Agency (U.S. EPA). (1989). *Report and Recommendations of the Technology Innovation and Economics Committee: Recommendations for Action on Technology Innovation*. Washington, DC: EPA, Office of Cooperative Environmental Management.

United States Environmental Protection Agency (U.S. EPA). (2002). Retrieved November 27, 2007, from *Handbook on the Management of Ordnance and Explosives at Closed, Transferring, and Other Sites*: http://www.epa.gov/fedfac/pdf/IFUXOCTTHandbook.pdf

United States Environmental Protection Agency (U.S. EPA), (2005, March 25). *Known Perchlorate Releases in the United States*. Retrieved November 27, 2007, from: www.epa.gov/fedfac/documents/perchlorate_links.htm#nas

United States Environmental Protection Agency (U.S. EPA). (2006). *Assessment Guidance for Perchlorate*. Signed: January 26, 2006.

United States Environmental Protection Agency (U.S. EPA). (2007). *Superfund Information System*. Retrieved December 20, 2007, from U.S.EPA: http://cfpub.epa.gov/supercpad/cursites/srchsites.cfm

United States Food and Drug Administration (U.S. FDA). (2004, November). *2004-2005 Exploratory Survey Data on Perchlorate in Food*. Retrieved November 25, 2007, from: http://www.cfsan.fda.gov/~dms/clo4data.html

United States General Accounting Office (U.S. GAO). (2003, December). *Munitions: DOD Needs to Develop a Comprehensive Approach for Cleaning Up Contaminated Sites*.

United States General Accounting Office (U.S. GAO). (2004, May). *Department of Defense Operational Ranges: More Reliable Cleanup Cost Estimates and a Proactive Approach to Identifying Contamination Are Needed*.

United States General Accounting Office (U.S. GAO). (2005, May). *Perchlorate: A System to Track Sampling and Cleanup Results Is Needed*.

United States General Accounting Office (U.S. GAO). (2007, July). *Environmental Contamination: Department of Defense Activities Related to Trichloroethylene, Perchlorate, and Other Emerging Contaminants*.

United States Office of Management and Budget (U.S. OMB). (2008). *Circular No. A-94, Appendix C: Discount Rates for Cost-Effectiveness, Lease Purchase, and Related Analysis* (Revised January 2008).

Wilbert, M. C., Pellegrino, J., Scott, J., and Zhang, Q. (1991). *Water Treatment Estimation Routine (WaTER)*, Water Desalination Research and Development Program Report No. 43 (R-99-04). Bureau of Reclamation: United States Department of the Interior.

			Form Approved
REPORT DOCUMENTATION PAGE			*Form Approved* OMB No. 074-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of the collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to an penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)* 27-03-2008	**2. REPORT TYPE** **Master's Thesis**	**3. DATES COVERED** *(From – To)* Sept 2006 – Mar 2008
4. TITLE AND SUBTITLE Development of a Screening Tool to Facilitate Technology Transfer of an Innovative Technology to Treat Perchlorate-Contaminated Water.		**5a. CONTRACT NUMBER**
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Craig, Daniel A., Captain, USAF		**5d. PROJECT NUMBER**
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S) Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/EN) 2950 Hobson Way WPAFB OH 45433-7765		**8. PERFORMING ORGANIZATION REPORT NUMBER** AFIT/GEM/ENV/08-M06
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Andrea Leeson, Environmental Security Technology Certification Program 901 N. Stuart St., Ste 303, Arlington, VA 22203		**10. SPONSOR/MONITOR'S ACRONYM(S)** **ESTCP**
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Perchlorate contamination of drinking water is a significant problem nationwide. The purpose of this study was to develop a tool to predict the cost and performance of tailored granular activated carbon (T-GAC), an innovative technology that is being evaluated as a cost-effective treatment for perchlorate-contaminated water. The ability to accurately predict performance and cost can facilitate the transfer and commercialization of innovative technologies. In the study, a model was developed to predict T-GAC performance and life-cycle costs for removing perchlorate under varying influent water quality and technology operating conditions. The model's design parameters were obtained from laboratory rapid small-scale column tests (RSSCTs) using inverse modeling. Cost data used in the model were based on conventional GAC installations, modified to account for tailoring. The parameterized model was used to predict the observed performance from a pilot-scale field demonstration at a water treatment plant in Southern California. The model over-predicted field performance; however, it predicted reasonably well the results of laboratory RSSCTs for two waters that were not used to calibrate the model. Using the screening model, it was found that annual operation and maintenance (O&M) costs are more significant than capital costs, and that costs associated with media regeneration or replacement dominate the O&M costs.

15. SUBJECT TERMS
Perchlorate, contaminated groundwater, granular activated carbon, cost estimation, technology transfer, water treatment, modeling.

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Mark N. Goltz, AD-24, DAF (ENV)
REPORT U	**ABSTRACT** U	**c. THIS PAGE** U	UU	145	**19b. TELEPHONE NUMBER** *(Include area code)* (937) 255-3636 x4638; e-mail: mark.goltz@afit.edu

Standard Form 298 (Rev: 8-98)
Prescribed by ANSI Std. Z39-18