

12-2015

METHODOLOGY FOR SELECTING THE COLUMN CONFIGURATION WITH LOWEST MEDIA REPLACEMENT COST FOR SMALL ADSORPTION SYSTEMS

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METHODOLOGY FOR SELECTING THE COLUMN CONFIGURATION WITH
LOWEST MEDIA REPLACEMENT COST FOR SMALL ADSORPTION
SYSTEMS

By

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A THESIS

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Master of Science

Major: Civil Engineering

Under the Supervision of Professor Bruce I. Dvorak

Lincoln, Nebraska

December, 2015

A METHODOLOGY FOR SELECTING THE COLUMN CONFIGURATION
WITH LOWEST MEDIA REPLACEMENT COST FOR SMALL
ADSORPTION SYSTEMS

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University of Nebraska, 2015

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GAC adsorption columns are widely used in water treatment systems. They are easy to operate and have reasonable capital and operating costs. However, the media replacement might be expensive, especially for small systems serving less than 10,000 people. Various design solutions and operating strategies may be used to reduce those expenses. For example, some column configurations (e.g., lead-lag or parallel) provide better fractional utilization rate than single configuration. In single arrangement both columns are placed in parallel and replaced simultaneously; parallel configuration is essentially the same, but with staggered replacements and effluent blending; lead-lag arrangement has two columns in-series with staggered replacements

In this research the relative adsorption costs of three configurations were simulated using the adsorption and cost models. Adsorption performance was simulated using the pore and surface diffusion model within the AdDesignS™ software and the data was modified using the spreadsheets to simulate three column configurations. Costs were modeled based on an EPA model and data from the EPA's Arsenic Treatment Technology Demonstration Program (ADP).

The breakthrough curve normalization was based on the fraction of mass transfer zone estimated from the breakthrough curve ($\%MTZ_{BT}$) and the ratio of

effluent to influent contaminant concentration ratio (C/C_0). The relative cost of operating two identical columns in different configurations was normalized using the cost of the fresh media and replacement service cost for each media replacement cycle. These two components significantly affect the configuration selection process, making systems with more frequent replacements less economical than a single arrangement with lower replacement frequency.

The lead-lag configuration was found to be more economical at C/C_0 below 0.2 and $\%MTZ_{BT}$ above 50%; parallel configuration is better at a C/C_0 above 0.4 in a wide range of $\%MTZ_{BT}$. At C/C_0 between 0.2 and 0.4, both lead-lag and parallel configurations have relative performance within $\pm 10\%$, therefore either configuration may be used, depending on other design considerations. The single configuration is not only viable, but sometimes even more economical in C/C_0 range from 0.2 to 0.4, when the simultaneous column replacement costs is significantly lower than combined cost of two one-column replacements, and when the replacement service cost is significantly higher than the cost of fresh media.

ACKNOWLEDGEMENTS

First and foremost I'd like to thank my academic advisor Dr. Bruce Dvorak for his motivation, patience, and enthusiasm over the years. I couldn't have imagined myself finishing this work and preparing for thesis defense without his continuous support by both personal meetings and countless video discussions over the Internet, regardless the time difference between our cities, various holidays and vacations.

I also want to express my sincere gratitude to my mom and dad - Larisa and Sergei, my grandpa and grandma - Ignat and Galina, and my fiancée Svetlana, who were with me all this time, at least in my heart. Those are people who always wish only good to me and push for further development no matter where I am and what I do.

No thesis defense would be possible without the two members of my defense committee - Dr. Xu Li and Dr. David Admiraal, whose help I appreciate a lot and am thankful for. They did their best in providing useful technical input and a third-party perception of my work.

All my friends Ayna, Murad, Sergei, Katia, Bhavneet, and Mohamed were not only great to spend time with here in Lincoln but also provided a good example of hard work and persistence by finishing their Bachelor's and Master's ahead of me.

Last but not least, I'm grateful to the Fulbright Scholar Program that gave me this unique opportunity to come to the US, study here, meet new people and make new friends. This program truly whips up the world and increases mutual cooperation and understanding for people all over the globe.

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LIST OF ABBREVIATIONS

AA – Activated Alumina

ADP - Arsenic Treatment Technology Demonstration Program

ARCost – Annual Replacement Cost

BT – Breakthrough Time

BV – Bed Volumes (treated)

CPHSDM – Constant Pattern Homogeneous Surface Diffusion Model

CRCost – Cycle Replacement Cost

CSD – Configuration Selection Diagram

CWS – Community Water System

EBCT – Empty Bed Contact Time

ECM – Equilibrium Column Model

FMCost – Fresh Media Cost

GAC – Granulated Activated Carbon

IAST – Ideal Adsorbed Solution Theory

MCL – Maximum Contaminant Level

MTZ – Mass Transfer Zone

NTNCWS - Non-Transient Non-Community Water Systems

O&M – Operational and Management

PDE – Partial Differential Equation

PSDM – Pore and Surface Diffusion Model

RSCost – Replacement Service Cost

RSSCT – Rapid Small Scale Column Test

SUR – Sorbent Usage Rate

US EPA – United States Environmental Protection Agency

CHAPTER 1. INTRODUCTION

1.1 Background

Although adsorption systems are based on relatively simple principles, they have been utilized for municipal water treatment applications for almost a century; and in certain cases they are considered as one of the cost-effective solutions (Crittenden et al., 2012). Various types of media can be used as an adsorbent, such as granular activated carbon (GAC), activated alumina (AA), iron oxide-based media, titanium-based media, and ion exchange resins. The operation simplicity and reliability makes adsorption systems suitable for all types of facilities from large industrial-scale treatment plants with a capacity of several hundred million gallons per day to very small, community-based systems with 10 to 20 thousand gallons a day average flow rate.

To evaluate the performance of adsorption systems at the preliminary design stage, methods like batch experiments, rapid small-scale column tests (RSSCTs), pilot tests, and computer simulations might be applied (Crittenden et al., 2005). In most cases those methods are used for adsorptive media selection and breakthrough time estimation (Crittenden et al., 1991; Thomson et al., 2005; Westerhoff et al., 2006; Scharf et al., 2010). However, there are few studies focused on the best column configuration selection, comparing the efficiency of various column arrangements and operating regimes (Narbaitz and Benedek, 1983; Dvorak et al., 2008; Denning and Dvorak, 2009; Stewart et al., 2013). In all of those studies, it is often assumed, that the media replacement cost constitutes the largest part of the total adsorption costs. Therefore, the column configurations are often compared on the basis of their sorbent

usage rate (e.g. kg/year, lb/kgal water treated, etc.) or annual media costs (\$/year for media replacement).

There are several conventional column configurations that are often applied to the adsorption systems. The simplest of them is a “single” type system, where one adsorption column or multiple columns, placed in parallel, are used to treat the contaminated influent, distributed evenly across all columns in the system. Once the media is saturated and the treated effluent reaches the target concentration level, all columns are replaced simultaneously. A more complex, “parallel” arrangement can be used to achieve better system performance in some cases. A parallel system consists of two or more adsorption columns installed in parallel. The key difference from the “single” configuration is that for “parallel” systems media changeouts are staggered and effluents from the individual columns are blended so the more concentrated effluent in one column is diluted by the effluent from the fresh column. With this approach, each column can be operated for a time above the target effluent concentration limit, improving sorbent usage rates. Another way to improve the fractional utilization rate is to use a “lead-lag” configuration, where two or more adsorption columns are installed in-series. The first, “lead” column is replaced only when the effluent from the “lag” column reaches the target concentration. Then a partially saturated “lag” column is placed as a new lead column, and a fresh column becomes a new “lag”. The lead-lag configuration provides both a better sorbent utilization rate, and redundancy, because measuring effluent concentration from the “lead” column allows a better prediction of the actual breakthrough from the “lag” column.

The column configuration evaluation framework, previously developed by Dvorak et al. (2008), Denning and Dvorak (2009), New (2009), and Stewart et al.

(2013) is based on the three key factors, describing configuration operation – effluent to influent concentration ratio (C/C_o); ratio of the mass transfer zone length to adsorption bed length (%MTZ) with the mass transfer zone being defined as a portion of the breakthrough curve from 0.1 C/C_o to 0.9 C/C_o ; and sorbent usage rate (SUR) calculated on the annual basis or per unit water treated. This framework allows selecting a configuration with the lowest SUR at a given %MTZ and C/C_o ratios. It was found that parallel and lead-lag configurations each offer benefits for certain ranges of the %MTZ and C/C_o . For instance, for a system with very low C/C_o (below 0.2) and high %MTZ, the lead-lag arrangement resulted in lower SURs, comparing to single and parallel options. In turn, at a higher C/C_o range (above 0.3) and high %MTZ, a parallel configuration has the lowest SUR value. The dividing line between lead-lag and parallel was set around 0.3 C/C_o . The single configuration never achieves a lower SUR, but almost approaches the lead-lag and parallel configuration efficiency with shorter mass transfer zones. It has also been noted, that lower SUR values are often achieved with systems that require relatively frequent replacement of media in at least one of the columns. Both lead-lag and parallel configurations require more frequent changeouts with smaller volume of media replaced at a time, whereas single configuration has lesser replacements over the same time interval, but with all columns changed simultaneously.

Whereas large municipal and industrial adsorption systems have an advantage of an economy of scale, for a relatively small water treatment system every aspect of their operating costs becomes more important. Therefore, the extra costs, associated with more frequent media replacements required for lead-lag and parallel configurations, may exceed the savings in fresh media costs, originating from the lower sorbent utilization rates. In other words, operating the adsorption system in a

single configuration with simultaneous media replacement, could, in certain conditions, be a viable and more economical option for relatively small projects.

1.2 Research objectives

The key objective of this work is to evaluate the relative performance of three adsorption column configurations based not only on their sorbent usage rates and/or annual costs of media, but also on their replacement frequencies and replacement service costs. This should allow building a simple, yet effective, configuration selection framework, which can be used by operators, design engineers, and regulators to estimate relative efficiency of three column configurations in terms of their annual replacement costs. The small adsorption systems are of a particular interest, because they often have a limited budget for the preliminary design and evaluation and can be more sensitive to variations in the replacement service cost.

The framework, based on the normalized target effluent concentration and mass transfer zone fraction, originally introduced by Dvorak et al. (2008) can be combined with the EPA adsorption cost data to analyze how extra replacement costs affect the configuration selection framework. Using the two-factor analysis for configuration selection, when one factor represents the physical performance of the adsorption system and the other one defines its relative economics, is preferable from a practical standpoint, because it allows to evaluate three configurations based on both their technical performance and adsorption economics, and select the most cost-effective column configuration.

1.3 Thesis organization

This thesis is organized into five chapters. Chapter 2 provides a brief review of relevant literature sources, focusing on the mathematical and computer modeling,

design, and evaluation of the adsorption systems. Both adsorption fundamentals and practical, cost-related approaches are discussed here. Chapter 3 describes the methodology used in this research, along with the key assumptions and limitations. Three column configurations - single, parallel, and lead-lag are defined in details in Chapter 3 with computer simulation techniques used for each of them. Chapter 4 contains key findings and results of this study with step-by-step explanations and model verification section at the end of the chapter. Chapter 4 is intended to be a portion of a manuscript that will be submitted for possible publication in a journal. Chapter 5 includes a brief summary of the primary conclusions. Finally, the Appendices include detailed numerical and cost data used for the computer simulations and graphical analysis.

CHAPTER 2: REVIEW OF MATHEMATICAL AND COMPUTER MODELS FOR ESTIMATING SORPTION SYSTEMS PERFORMANCE AND COSTS

2.1 Introduction

This chapter includes a review of commonly used practices of the fixed-bed adsorption modeling. General mathematical adsorption models are discussed first. The background and details related to the adsorption models used in this research are presented next. The application of breakthrough modeling to the estimation of the adsorption systems efficiency is provided later. The basic economics of the column adsorption in water treatment industry is described along with practical examples from the US EPA demonstration program. Finally, the potential application of combined breakthrough-cost modeling for the preliminary adsorption system design is described.

2.2 Mathematical Modeling of Fixed-Bed Adsorption

Several models can be used to simulate fixed-bed reactor adsorption. The simplest model is the Equilibrium Column Model (ECM) developed from the Ideal Adsorbed Solution Theory (IAST), which ignores the mass transfer resistances and can be used to predict the competitive adsorption effects in multi-compound mixtures (Fritz et al., 1980; Crittenden et al, 1980). The ECM is able to predict the highest sorbent usage rate (SUR) and the maximum effluent concentration for competitive adsorption.

Hand et al. (1984) developed a more complex model - a Constant Pattern Homogeneous Surface Diffusion Model (CPHSDM). The CPHSDM has several limitations and assumptions:

- mass transfer zone (MTZ) should be longer than 30 adsorbent particle diameters;
- constant hydraulic loading rate;
- the predominant mechanism of the adsorption is surface diffusion; the adsorption process doesn't depend on the adsorbate concentration;
- adsorption equilibrium is described by Freundlich isotherm;
- constant influent concentration is desired.

The authors presented a set of simple algebraic equations as a solution to this model (Hand et al, 1984) which significantly reduces the computational time and computer power required for simulation compared to solving the set of differential equation. The CPHSDM can be used for certain pairs of the adsorbent/adsorbate at the preliminary design stage to estimate system performance and sorbent usage rates. However, this model may not be suitable in cases where the pore diffusion is a predominant adsorption mechanism.

Another model, frequently used for breakthrough front simulation is the Pore and Surface Diffusion Model (PSDM) introduced by John Crittenden, Bryant Wong, William Thacker, and Vernon Snoeyink (Crittenden et al., 1980, 1986). This model utilizes a set of partial differential equations (PDE) for each compound of interest. It assumes that a local equilibrium exists at the surface of the adsorbent particle. Based on this assumption, a coupling equation can be derived to relate aqueous phase concentration of the target compound to its adsorbent phase concentration. Three key equations of the PSDM are presented here with nomenclature provided below.

The liquid phase mass balance:

$$\frac{\delta C_i(z,t)}{\delta t} + V \frac{\delta C_i(z,t)}{\delta z} + 3 \frac{k_{f,i}(1-\varepsilon)}{\varepsilon R} [C_i(z,t) - C_{p,i}(r = R, z, t)] = 0 \quad [2.1]$$

With the initial condition of

$$C_i(z, t) = 0 \text{ at } 0 \leq z \leq L, t = 0 \quad [2.2]$$

And the boundary condition:

$$C_i(z, t) = C_0 \text{ at } z = 0, t > 0 \quad [2.3]$$

The intraparticle phase mass balance is described by:

$$\frac{1}{r^2} \frac{\delta}{\delta r} \left[r^2 D_{s,i} \frac{\delta q_i(z,t)}{\delta r} + \frac{r^2 D_{p,i} \varepsilon_p}{\rho_a} \frac{\delta}{\delta r} C_{p,i}(r, z, t) \right] = \frac{\delta}{\delta t} \left[q_i(r, z, t) + \frac{\varepsilon_p}{\rho_a} C_{p,i}(r, z, t) \right] \quad [2.4]$$

With the initial condition of:

$$q_i(r, z, t) + \frac{\varepsilon_p}{\rho_a} C_{p,i}(r, z, t) = 0 \text{ at } 0 \leq r \leq R, t = 0 \quad [2.5]$$

And two boundary conditions:

$$\frac{\delta}{\delta r} \left[q_i(r, z, t) + \frac{\varepsilon_p}{\rho_a} C_{p,i}(r, z, t) \right] = 0 \text{ at } r = 0, t \geq 0 \quad [2.6]$$

$$D_{s,i} \rho_a \frac{\delta q_i(r=R,z,t)}{\delta r} + D_{p,i} \varepsilon_p \frac{\delta C_{p,i}}{\delta r} = k_{i,f} [C_i(t) - C_{p,i}(r = R, z, t)] \quad [2.7]$$

The third, coupling equation binds together the liquid mass balance and the intraparticle mass balance:

$$C_{p,i}(r, z, t) = \frac{q_i(r,z,t)}{\sum_{k=l}^m q_k(r,z,t)} \left[\frac{\sum_{k=l}^m n_k q_k(r,z,t)}{n_i K_i} \right]^{n_i} \quad [2.8]$$

Nomenclature for Equations 2.1 through 2.8 includes:

r – radial; z – axial; t – time – coordinates in axially symmetrical cylindrical system;

$C_{0,i}$ – initial concentration;

$C_i(z, t)$ – adsorbent concentration in bulk phase;

$C_{p,i}(r, z, t)$ – adsorbate concentration in the adsorbent pores;

$D_{p,i}$ – pore diffusivity;

$D_{s,i}$ – surface diffusivity;

$k_{f,i}$ – film transfer coefficient;

L – bed length;

m – number of components;

$q_i(r, z, t)$ – adsorbent phase concentration;

R – average adsorbent particle radius;

V – loading rate;

ϵ_p – particle void fraction;

ρ_a – apparent adsorbent density;

i – index of the component number.

More details on developing these equations and solutions to the systems of partial differential equations may be found in Friedman (1984), Sontheimer et al. (1988), and Crittenden et al. (1980, 1986).

The PSDM, along with the other models such as the ECM and CPHSDM, has been incorporated into the user interface of the AdDesignSTM software from Michigan Technological University developed by David Hokanson, David Hand, John Crittenden, Tony Rogers, and Eric Oman (Hokanson et al., 1999a, Mertz et al., 1999). This software provides a graphical interface for working with adsorption mathematical models. Models such as the PSDM have previously been used to estimate the breakthrough for a broad range of adsorbent-adsorbate combinations showing good correlation between the computer simulations and the results of bench-scale experiments (Zimmer et al., 1988; Hand et al., 1989; Hristovski et al., 2008a, 2008b, Scharf et al., 2009; Corwin and Summers, 2011).

2.3 AdDesignS™ applications to configuration selection

Although the adsorption mathematical models discussed above allow user to get only a breakthrough data, they can also be used to estimate the adsorption system efficiency. The AdDesignS™ Manual contains an example of granulated activated carbon (GAC) usage rate calculation (Mertz, 1999). It provides the user with step-by-step description of sorption usage rates (SUR) calculation. The key benefit of calculating the SUR is that various configurations can be compared based on its value at the preliminary design stage.

Denning and Dvorak (2009), New (2009), and then Stewart et al. (2013) used this technique to compare different adsorption column arrangements. The program was used to simulate the breakthrough data for certain adsorbent-adsorbate combinations and column configurations. The unit sorbent usage rates were calculated for a broad range of systems sizes, effluent concentrations, and configurations. The configuration with the lowest SUR was considered as more efficient than configurations with higher SURs for a particular size range and effluent concentration. Based on these results, zones where one particular configuration is more favorable than the others were determined on the diagram.

Considering that the fresh media cost is often the most significant part of the operational and management expenses, reaching 70 to 80% in some cases (US EPA, 2011c), the configuration with the lowest SUR should be more economical. However, including the other costs associated with media replacement (e.g., freight, labor required for media changeout, spent media analysis and disposal, etc.), into the configuration selection framework should make the configuration evaluation and selection process more accurate.

2.4 Adsorption system costs

Narbaitz and Benedek (1983) conducted one of the first attempts to consider all relevant cost factors for the design of the least expensive GAC system. They studied four general column arrangements – single, parallel, in-series, and a combination of parallel and series configurations. The costs were normalized on the annual basis resulting in a combination of annual operational and maintenance costs, and the amortized construction costs. Figure 2.1 shows the u-shaped plot for the total adsorption cost as a combination of the operational and management (O&M) cost and capital cost. From Figure 2.1, the O&M cost decreases rapidly in a certain range of empty bed contact time (EBCT), with almost no further decrease at higher EBCT values. This is mainly due to a sharp reduction in sorbent usage rate (SUR) in a particular range of EBCTs. The annualized capital cost, on the other hand, was directly proportional to the EBCT with higher system capital cost at longer EBCTs. The higher EBCTs at a constant liquid loading rate require longer adsorption columns to be used with larger vessels, amount of initial media loading, and footprint requirements, which altogether causes higher capital investment cost. Therefore, the combined annual cost consisting of the annualized capital cost and operating and management cost has an “optimal” value at a certain EBCT, where the size of the system is large enough to provide low SUR and require relatively small capital investments.

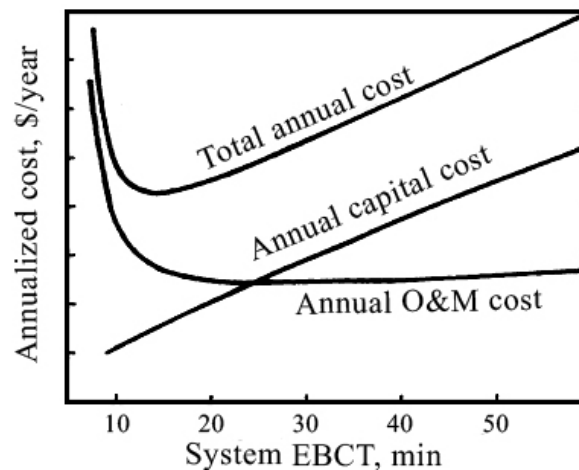


Figure 2.1 - Sample O&M, capital and total annual costs as a function of system EBCT (after Narbaitz and Benedek, 1983)

Similar trends can be observed in the US EPA evaluation report (2011) which includes the results from 28 adsorptive media systems (26 individual locations, and three separate systems at Klamath Falls, OR) participated in the US EPA Arsenic Treatment Technology Demonstration Program (ADP) conducted from July 2003 to July 2011. This program focused on evaluating various types of arsenic removal technologies available for small water treatment systems serving less than 10,000 people (including the adsorptive media, iron removal, coagulation/filtration, ion-exchange, etc.), based on their physical performance and expenses associated with system design, construction, and operation. The costs of the adsorptive media systems for community water systems (CWS; supplies water to the same population year-round) and non-transient non-community water systems (NTNCWS; serve at least 25 of the same people at least 6 month a year, such as schools, hospitals, etc.) were divided into two components - capital investment cost and operational and management cost, which allowed comparing how the system flowrate and size affected the unit cost of water treatment.

The cost data from the US EPA ADP program report (US EPA, 2011c), illustrated in Figures 2.2 and 2.3, show annualized total capital cost and unit operating and management cost as a function of the design flowrate. Following the US EPA approach total capital costs are depicted in Figure 2.2 for two system sizes (below and above 100 gallons per minute or gpm) and three types of systems (CWS series, CWS parallel, and NTNCWS).

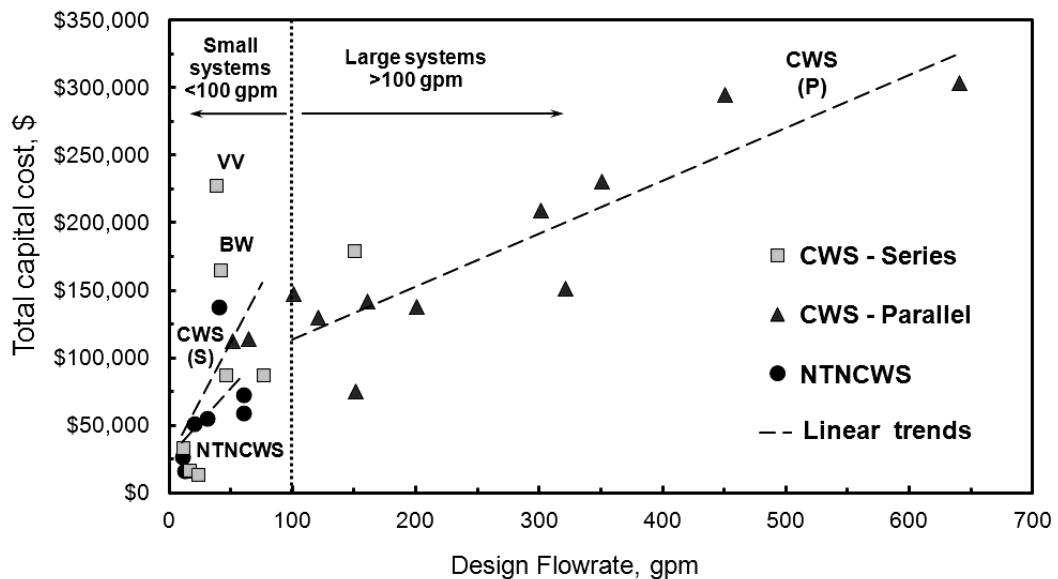


Figure 2.2 – Total capital costs for 28 AM sites participated in the US EPA ADP program (Data from US EPA, 2011c)

From Figure 2.2, the total capital cost of the smaller systems with design flowrates below 100 gpm is more vulnerable and can be significantly affected by the engineer's decisions (Valley Vista, AZ) or initial design conditions (Bow, NH). For example, in Valley Vista the facility was equipped with automatic control valves for advanced operation and backwash management. A backwash water recycling system was also installed, adding up to the capital investment cost. The Bow facility, was provided with the pre-made stainless steel vessels with the size twice as large as it was actually needed, increasing initial capital investments.

As for the operational and management costs, Figure 2.3 shows unit O&M costs for 15 adsorption sites with actual media replacement. It includes data for two NTNCWS and 17 community water systems CWS in either parallel or lead-lag arrangement. It should be noted that “parallel” system here means simply two tanks installed in parallel and replaced at the same time when reaching target effluent concentration. According to Figure 2.3, the unit replacement cost tends to decrease for systems with a higher adsorption capacity. This might be explained by the economy of scale and lower sorbent usage rates for larger systems. However, site-specific conditions, like poor performance of the adsorptive media in Reno, NV (site ID - RN), where the breakthrough for 10 $\mu\text{g/L}$ of arsenic was reached at 7,200 bed volumes (BV) instead of the proposed 38,000 BVs, can significantly affect unit operating and management cost.

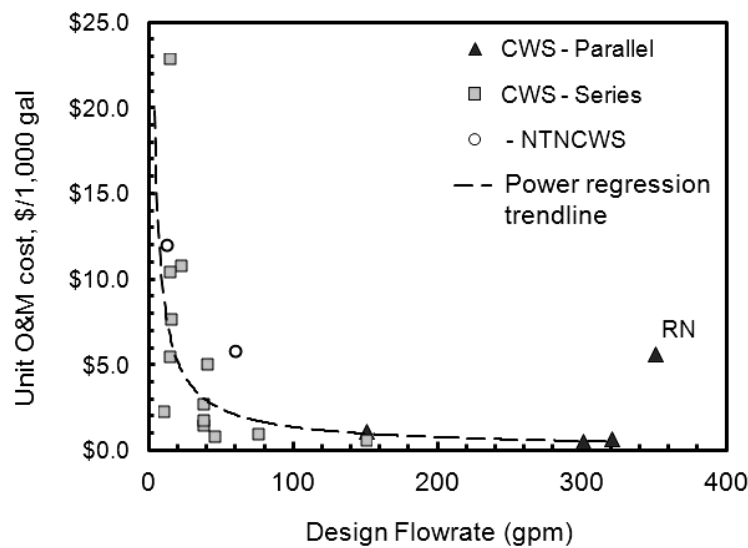


Figure 2.3 – Unit operating and management costs of adsorption media systems participated in the US EPA ADP program (Data from US EPA, 2011c)

2.5 Summary

Previous studies have revealed certain methods used in the adsorption system design. Factors like breakthrough time, sorption usage rate, utilization capacity, design flowrate, and column configuration can affect the performance of the whole system, and, which is more useful in real life – cost of the treated water. However, there is no standard guidance on how to achieve the best performance at the lowest price. Hence, there is a significant need for the regulators, designers, and operators of small systems, especially in cases where there is limited expertise related to the adsorption systems. It is possible to build up the existing work and provide more implicit instructions for the regulators, designers, and operators of small systems. For example, the breakthrough modeling software can be used to obtain estimated system operating time for various column configurations. This, in turn, can serve as initial data for cost modeling, allowing the determination of rough estimates of potential O&M cost and annualized capital investment cost, and evaluating relative costs of operating the system in single, parallel or lead-lag configuration.

CHAPTER 3: METHODS FOR IDENTIFYING THE LEAST COST COLUMN CONFIGURATION FOR SMALL ADSORPTION SYSTEMS

3.1 Introduction

Adsorptive media technology has been widely used in the water treatment industry for years. This technology combines several important qualities, including simple operation, low cost, flexibility and reliability. However, this seeming simplicity might sometimes lead to unexpected results. Past studies showed that even slight changes in the operation regime can significantly reduce or increase the adsorbent usage rate and, consequently, the cost of treated water.

This research is built upon the previous work of Dvorak et al. (2008), Denning and Dvorak (2009), New (2009), and Stewart et al. (2013). The intended audience is industry professionals – design engineers, contractors, and operators, who design, install, and run adsorption systems. It should provide a detailed example of evaluating various adsorption column configurations (i.e. single, parallel, and lead-lag) on the basis of their operational cost and the cost of the treated water, using mathematical and computer modeling.

3.2 Methods

This section describes main methods used in this research to build a configuration selection framework, starting with the AdDesignS™ software, then numerical data normalization techniques, column configuration modeling, and, finally the configuration selection diagram (CSD) used to graphically compare three configurations of interest. The last section of this chapter includes key assumptions that have been made for both physical adsorption simulations and cost estimation.

3.2.1 Chromatographic Breakthrough Front Modeling

The AdDesignSTM software from Michigan Tech (Hokanson et al., 1999a) was used to simulate various shapes of the breakthrough front, and obtain numerical and graphical data for three scenarios evaluated in this research. The pore and surface diffusion model (PSDM) within the AdDesignSTM software was selected to simulate sorption breakthrough. Other researchers have found the PSDM useful in accurately simulating various sorption systems to fit breakthrough curves (e.g., Fritz et al., 1980; Zimmer et al., 1988; Hand et al., 1989; Hristovski et al., 2008). Many of the properties for contaminants and their parameters were obtained from StEPP (Hokanson et al., 1999b), a chemical database created specifically for use with AdDesignSTM. The three scenarios modeled represent a wide range of possible treatment situations (e.g. equilibrium, mass transfer rates, adsorbent, and adsorbate). The PSDM and Freundlich isotherm parameters and data sources used for each of the scenarios are listed in Table 3.1. The first scenario was modeled based on the data from Stewart et al. (2013) and Hokanson et al. (1999a, 1999b). The second scenario was developed to reflect the real-life adsorption parameters from one of the experimental facilities in Rimrock, AZ. Data for this station were collected during the EPA Demonstration program from 2008 to 2010 (US EPA, 2008b; US EPA 2011c) and combined with previous studies on arsenic adsorption modeling from Hristovski et al. (2008).

For each individual scenario, the fixed-bed properties, contaminant properties (adsorption kinetics parameters, influent concentration, Freundlich isotherm parameters, etc) and adsorbent properties were kept constant, except those used to simulate various MTZ_{BT} ratios. To alter the MTZ_{BT} fraction of the bed, column length

was adjusted, resulting in the specific combinations of bed mass and EBCT values for each particular MTZ_{BT} ratio in the scenario.

Table 3.1 – AdDesignS™ input parameters used to simulate various adsorbent-adsorbate combinations

Parameter/Scenario	Scenario 1	Scenario 2
Adsorbent	Calgon F300 GAC	Bayoxide E33 Iron-Based Media
Surface Loading ($m^3/(m^2 \cdot h)$)	6	10.265 ^(d)
Bed Density (g/ml)	0.46 ^(c)	0.45 ^(d)
Particle Radius (cm)	0.082 ^(c)	0.02
Film Diffusion (cm/s)	$8.6 \cdot 10^{-3}$ ^(a)	$5.5 \cdot 10^{-3}$ ^(b)
Surface Diffusion (cm^2/s)	$6.2 \cdot 10^{-40}$ ^(a)	$4.0 \cdot 10^{-30}$
Pore Diffusion (cm^2/s)	$7.6 \cdot 10^{-6}$ ^(a)	$3.36 \cdot 10^{-6}$
Contaminant	Benzene	Arsenate
C_o ($\mu g/L$)	1,000	25 ^(d)
Freundlich K ($[mg/g] \cdot [L/mg]^{(1/n)}$)	16.6 ^(c)	30
Freundlich (1/n)	0.39 ^(c)	0.31

(a) Stewart et al. (2013),

(b) Hristovski et al. (2008),

(c) Hokanson et al. (1999a, 1999b)

(d) Based on Rim Rock, AZ data (US EPA, 2008b; US EPA 2011c)

3.2.2 Normalization of Concentration and Mass Transfer Zone

Previous studies used the effluent to influent concentration ratio (C/C_o) and the fraction of mass transfer zone (%MTZ) to normalize adsorption systems with different physical parameters (Denning et al., 2009; New, 2009; Stewart et al., 2013). The C/C_o is basically the ratio of system's effluent to influent concentration. For example, if the influent concentration is 60 $\mu g/L$ and the MCL is set at 30 $\mu g/L$, then the normalized C/C_o ratio is equal to 0.5. The calculation of the mass transfer zone fraction is more complex. Hand et al. (1984) described a conceptual approach on how

to calculate the length of the mass transfer zone using empirical equations and estimates of the diffusion coefficients. A graphical description of the MTZ concept is shown on Figure 3.1.

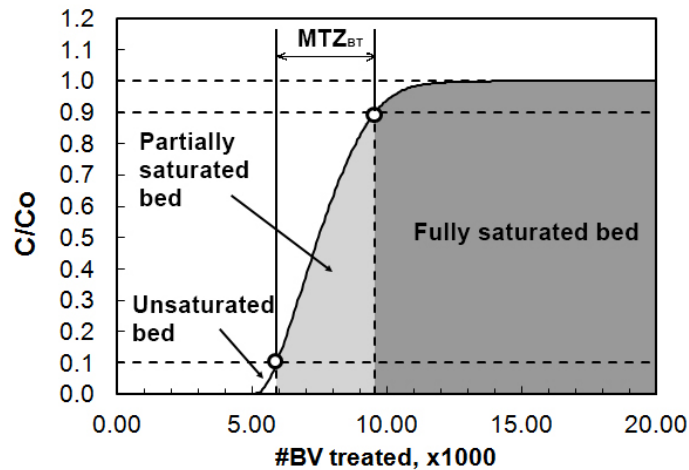


Figure 3.1 – Adsorption mass transfer zone on the breakthrough front diagram

In case of the AdDesignSTM program, the length of the MTZ is calculated automatically, providing the user with its length in centimeters. Dividing this number by the length of the adsorption bed in centimeters, the %MTZ ratio can be obtained. For instance, if the bed length is 500 cm, and AdDesignSTM estimate of the MTZ is 100 cm, then the %MTZ for this scenario is 20%.

To simplify the estimation of the mass transfer zone fraction for practitioners, a new MTZ ratio, based on the breakthrough (BT) time, was chosen. Following Worch (2012), the time-based MTZ fraction can be calculated using data from any breakthrough curve with Equation 3.1:

$$\%MTZ_{BT} = \frac{BT_{0.9} - BT_{0.1}}{BT_{0.9}} \times 100\% \quad [3.1]$$

where $BT_{0.9}$ and $BT_{0.1}$ are the times when the effluent concentration reaches 0.9 and 0.1 of the influent concentration.

Basically, the %MTZ_{BT} reflects a relative size of mass transfer zone as its fraction from the total operating time before reaching a C/C_o of 0.9. The C/C_o and %MTZ_{BT} ratios are used together to normalize the adsorption system properties, affecting the configuration selection process; each are an axis on the configuration selection diagram. The %MTZ_{BT} in this concept represents the significance of the mass transfer zone for configuration selection. The C/C_o ratio describes how much of the mass transfer zone is utilized in the selected scenario. In other words, the mass fraction zone ratio is the primary parameter to evaluate and decide whether or not more complex column configurations should be considered; if the %MTZ_{BT} value is large enough, then the C/C_o ratios should be considered to see what configuration is more suitable for the adsorption system.

3.2.3 Column Configuration Simulations

In this research, three column configurations were studied, including "single", "parallel", and "lead-lag". To simplify the analysis and make applicable to small adsorption systems, all configurations were assumed to consist of two identical columns of the same size. According to US EPA observations, single and lead-lag systems can be interchangeable with minor adjustments (US EPA, 2011).

To account for different numbers of treatment trains in the system (two trains for single and parallel, and one train for lead-lag) input parameters were adjusted to keep liquid loading rates the same across all configurations. Table 3.4 shows general system parameters used to simulate three different column arrangements. System flowrate for lead-lag configuration is equal to one half from that for single and parallel configurations. The total amount of the adsorbent in the system is the same

for three configurations. However, for lead-lag and parallel only one vessel is replaced at a time, which requires higher replacement frequency.

Table 3.2 – Key parameters used for column configuration simulations

Parameter	Single	Parallel	Lead-Lag
System flow rate (based on two columns)	Q	Q	Q/2
Column flowrate	Q/2	Q/2	Q/2
Surface loading rate	SLR	SLR	SLR
Total volume of media in the system	V	V	V
Volume of media per changeout	V	V/2	V/2
Daily operating time	T	T	2xT

The simulation techniques for each individual configuration are described below.

Single

In this study single configuration was simulated as two separate columns of the same size. Using at least two columns increases the redundancy of the systems and is generally recommended by the supervising authorities. The inflow is divided equally between two treatment trains and is blended after passing through the system. Spent media is replaced simultaneously in both vessels after effluent reaches the target breakthrough concentration. Figure 3.2 illustrates a sample breakthrough curve for single configuration with two vessels of the same size in parallel, where both tanks are replaced at the same time. During the first run Columns 1.1 and 1.2 are used to treat the influent. Upon reaching the target effluent concentration of $0.3 C/C_0$, both vessels are replaced with fresh media. Then Columns 1.2 and 2.2 are used for the second run and so on. For single column arrangement all breakthrough peaks are evenly distributed and match the breakthrough events from the individual columns.

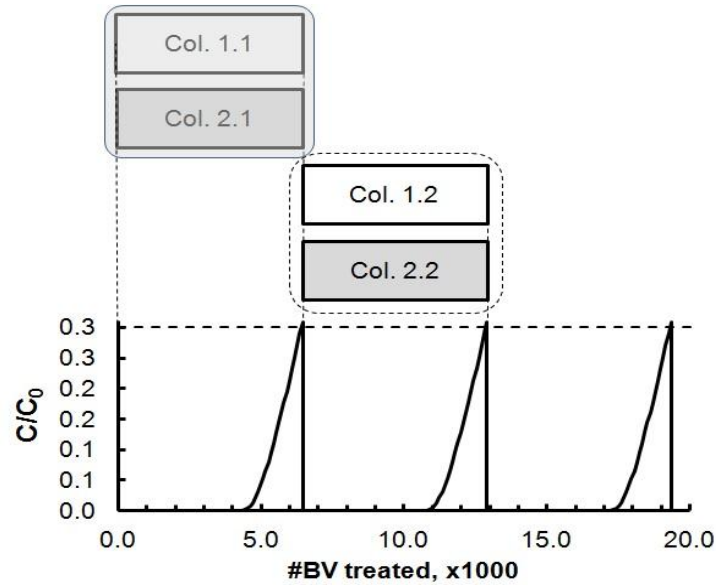


Figure 3.2 –Media replacement sequence and typical breakthrough curve profile for single configuration at 40% MTZ_{BT} and target effluent concentration ratio of 0.3.

Parallel

Two columns of the same size with staggered replacement were used to represent parallel configuration. Basically, parallel arrangement is almost identical to the single one, except for the replacement sequence. While in “Single” scheme all columns are replaced simultaneously, for parallel arrangement the replacement is staggered to allow blending of the effluent from a newly replaced column and an old column. This approach was shown to reduce the adsorbent usage rate in many cases (Hutchins, 1977; Narbaitz and Benedek; 1983, Denning, 2007; Stewart, 2010). Figure 3.4 depicts the “saw tooth” breakthrough curve for parallel configuration with staggered column replacements. During the first run, Columns 1.1 and 2.1 are used to treat contaminated water. After the blended effluent reaches target concentration, spent media in Column 1.1 is replaced with a fresh one, and the whole system continues operation with Columns 1.2 and 2.1 being used. After reaching the next

effluent concentration peak, Column 2.1 is replaced, with Columns 1.2 and 2.2 left in operation.

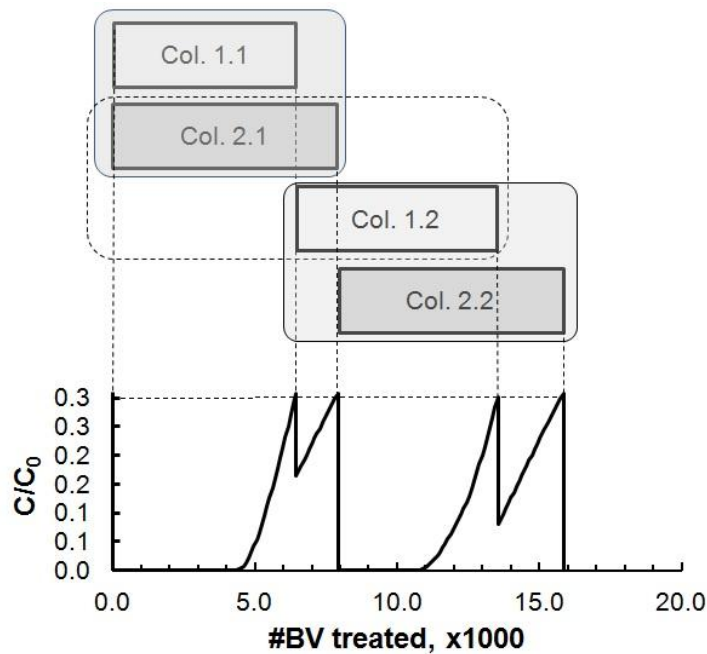


Figure 3.3 – Media replacement sequence and typical breakthrough curve profile for parallel configuration with blended effluent at 40% MTZ_{BT} and target effluent concentration ratio of 0.3.

Lead-Lag (In-series)

A distinctive point of the lead-lag arrangement is that it only treats half of the flowrate from single/parallel in order to preserve the same liquid loading rate. For lead-lag configuration two columns of the same size are also used. One column is placed in a “lead” position, the other one serves as a “lag” or “guard” column. Sample breakthrough curve for two columns placed in a lead-lag is shown in Figure 3.4. The system continues operation until the effluent from the lag column reaches the target concentration. Then, the saturated Column 1.1 is taken out of operation and Column 2.1 is connected as a new “lead”. The replaced, fresh Column 1.2 is installed in a “lag” position, providing polishing for the effluent from Column 2.1.

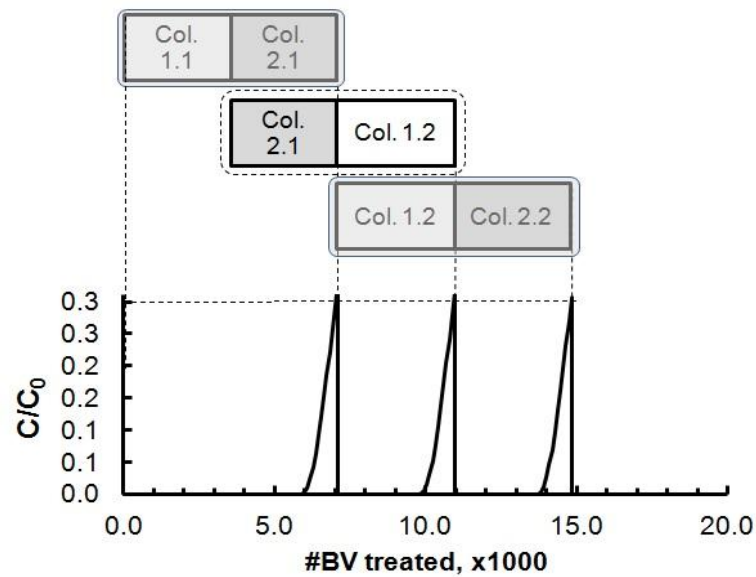


Figure 3.4 –Media replacement sequence and typical breakthrough curve profile for lead-lag configuration at 40% MTZ_{BT} and target effluent concentration ratio of 0.3.

3.2.4 Column Configuration Selection Diagram

Denning and Dvorak (2009), Dvorak and New (2010), and Dvorak and Stewart (2010) coupled the normalization approach with the breakthrough simulation results from AdDesignSTM to evaluate the performance of different adsorption system arrangements based on the sorbent usage rate (SUR). To do that, they first estimated the sorbent usage rates for a wide range of %MTZ - C/C_0 pairs in several system configurations and scenarios. Then, the diagram representing the SUR values for a particular %MTZ and C/C_0 was created for each configuration. Using these diagrams, the authors were able to determine the zones where certain configurations were most efficient, based on their SUR values. Superimposing the diagrams for three configurations (single, parallel, and lead-lag) they determined zones where one configuration was more efficient than the other two. They called this final composite diagram a configuration selection diagram (CSD). Using the CSD, an engineer should

be able to get a rough estimate of which configuration might provide a lower sorbent usage rate under the selected conditions.

3.2.5 Adsorption System Cost Analysis and Estimation

Although the costs, associated with the adsorption system design, construction, and operation depend on many variables, they can be roughly estimated based on similar example systems, cost models or using the designer's "best-guess". The total cost of the adsorption system can be divided into two main categories - capital investment costs, and operating and management costs. According to US EPA Design manual for arsenic removal systems (US EPA 2003b), capital costs mainly depend on the system flowrate, with other minor factors (pH adjustment system, backwash and regeneration system, climate and seismic zones, etc.) also affecting the cost; operating costs mainly depend on the size of the system, media replacement frequency, and media unit price, but factors like chemical demand, disposal costs, labor rates, and similar also influence the operating cost. A convenient way to account for both capital and operating costs is to use unit cost values based on 1,000 gallons of treated water. Since utilities and end customers often have the water meters installed, this way allows calculation of the primary cost of water, and prediction of public water rates.

In this study, the capital costs were assumed to be similar for all systems of the same size, disregarding the configuration used. Although parallel and lead-lag systems might require more complex piping and valve arrangement, those differences only account for a small fraction of the total capital cost and were neglected in this research. As for the operating cost, some of its components like chemical costs, maintenance costs, and utility costs were also considered to be equal for single, parallel, and lead-lag systems of the same size. Due to a higher daily operating time

for lead-lag configuration, the operating labor requirements may be slightly higher. However, since small systems often require only limited operator time, doubling the daily operating time for lead-lag configuration likely will not significantly affect its relative operating cost.

The cycle replacement cost was selected to represent relative costs of operating the adsorption system in single, parallel, and lead-lag configurations. This parameter includes both the cost of the fresh media and all other non-material costs, directly associated with media replacement (freight, unloading and loading labor, spent media analysis and disposal, etc.). The cost of fresh media is basically a function of the amount of the adsorbent (m^3 , kg, etc.) and adsorbent unit cost ($\$/m^3$, $\$/kg$, etc.). Fresh media costs are relatively low for small systems with cheap media, but are high for very large systems with expensive media. All non-material replacement costs were grouped under the term of "replacement service cost" (RSCost) to emphasize that they are independent of the type and cost of media being replaced, and are mainly a function of the amount of media and some site-specific characteristics.

The fresh media cost (FMCost) for any particular system can be directly calculated based on the volume of media being replaced and its unit cost. Although the RSCost mainly depends on the amount of media replaced, it cannot be directly calculated. One way to estimate the RSCost is to use the recommended parameters from the Cost estimating program (Battelle, 2003). This program allows estimating both capital and operational and management costs for small water systems (1 to 350 gpm) for four arsenic removal technologies, including the adsorptive media systems where spent media is disposed. There are three parameters there related to the replacement service cost – a subcontractor media replacement cost (\$5,000 fixed

number recommended), and a combination of media replacement labor time (10 to 16 hours/changeout) and operator labor time (\$30/hr fixed value recommended). Using these three parameters would result in a fixed replacement service cost of \$5,300 to \$5,480 per replacement.

Another way to estimate media replacement cost is to use cost data from multiple experimental sites. The US EPA ADP program report (US EPA, 2011c) described previously provides enough data to study the relationship between the key system variables and the media replacement cost. This report has cost data for 32 media replacement events (both actual and expected) in a range of system flowrates from 10 to 640 gpm and replaced volume of media from 2.3 to 320.0 ft³ and is summarized in Table 3.3.

Table 3.3 – Cost associated with media replacement for 32 spent media changeouts during the EPA ADP program (Data from US EPA, 2011)

Site ID	Total amount of media (ft ³)	Design flowrate (gpm)	Media unit cost (USD/ft ³)	Fresh media cost (USD)	Replacement Service Cost (USD)
PF	2.3	15	\$852	\$1,960	\$780
SU	3.0	12	\$450	\$1,350	\$960
BL	4.5	10	\$300	\$1,350	\$2,699
GF	5.0	10	\$300	\$1,500	\$2,699
WA2	6.0	14	\$499	\$2,993	\$700
WA3	6.0	14	\$293	\$1,755	\$700
DM	6.0	22	\$517	\$3,102	\$810
WS	7.5	17	\$450	\$3,375	\$2,433
KF1	10.0	30	\$595	\$5,950	\$1,750
TE	11.4	150	\$559	\$6,373	\$708
WA1	12.0	14	\$517	\$6,204	\$1,365
KF 2	20.0	60	\$385	\$7,700	\$3,500
KF3	20.0	60	\$678	\$13,560	\$3,500
VV2	22.0	37	\$99	\$2,178	\$2,188
VV3	22.0	37	\$500	\$11,000	\$2,610
RR	22.0	45	\$265	\$5,830	\$5,078
BR	22.0	40	\$300	\$6,600	\$4,590
LD	28.0	75	\$480	\$13,440	\$2,693
TN	38.0	50	\$365	\$13,870	\$4,535
VV1	44.0	37	\$99	\$4,356	\$4,375
AL	48.0	150	\$165	\$7,940	\$4,740
LI	54.0	50	\$400	\$21,600	\$16,671
RF	60.0	100	\$245	\$14,700	\$4,820
NP	71.2	145	\$274	\$19,509	\$10,007
WM	76.0	100	\$295	\$22,420	\$7,590
GE	100.0	200	\$260	\$26,000	\$5,215
AN	124.0	320	\$202	\$25,080	\$5,820
SV	160.0	300	\$156	\$24,928	\$2,800
BW	170.0	40	\$40	\$6,800	\$9,952
TA	180.0	450	\$197	\$35,539	\$6,210
RN	240.0	350	\$238	\$57,120	\$14,038
BC	320.0	640	\$150	\$48,000	\$5,600

Comparing the actual and proposed replacement service costs to the fixed value of \$5,000 shows that for both relatively small and large systems, using the fixed replacement service cost value is inaccurate, because the replacement service costs

varies greatly depending on the volume of media replaced, cost of labor, and other site-specific characteristics.

3.2.6 Key Assumptions and Simulation Parameters

Assumptions used for this study can be divided into two groups: technical and economical. The technical assumptions are related to the simulation software intrinsic parameters and limitations of the PSDM. Few other assumptions ensure the accurate configuration simulation and homogeneous results from spreadsheet modeling. A list of technical assumptions is provided below:

- Constant flow rate and influent concentration,
- Plug space flow conditions,
- Freundlich isotherm is used to describe adsorption mass equilibrium,
- The system operates basically with a single contaminant, with essentially no competitive adsorption,
- Chromatographic wave front moves through the column at constant rate and doesn't change its shape with time, and
- Adsorption mass transfer rates are described by the PSDM model

Since the purpose of this study was to evaluate relative performance of adsorption system configurations at the preliminary stage, few assumptions on the economics were made. First, the capital cost was assumed to be similar for all three configurations with the same size of the system and volume of media. Even though there might be some differences in piping arrangement, valve operation, etc., since piping and valves often account for less than 3% of total capital cost (US EPA, 2011c) those differences were neglected in this study. Second, differences in the cost of labor arising from the uneven operating time between the lead-lag and single/parallel

configurations are neglected due to the small fraction of labor costs compared to media replacement costs. Third, other operational and management costs, such as chemical demand, routing labor, utility cost and the like were also considered to be equal for all three configurations of two adsorption beds of the same size. With those assumptions being made, the main cost differences between three configurations will depend on the media replacement cost in terms of a combination of fresh media cost and replacement service cost.

CHAPTER 4. OPERATING COST BASED CONFIGURATION SELECTION FRAMEWORK FOR SMALL ADSORPTION SYSTEMS

4.1 Introduction

By applying fundamental principles of chromatographic breakthrough curve modeling to a selected adsorbent-adsorbate pair, a configuration selection framework can be developed. This methodology uses the relative length of the mass transfer zone (%MTZ) and the effluent to influent contaminant concentration ratio (C/C_0) to determine a column configuration with better performance. This chapter focuses on the refinement of this methodology and on incorporating aspects of media replacement economics into the framework.

4.2 Adsorption Capacity-Based Configuration Selection

The adsorption bed capacity can be thought of as the number of bed volumes of water treated by the system before reaching target effluent concentration. The actual bed capacity depends on several factors, including the influent concentration, target effluent concentration, EBCT, bed length, and the shape, length, and velocity of the MTZ. In this study, several factors such as MTZ length and column length, influent concentration and target concentration, were analyzed together, by applying the normalization methods described above.

The configuration of multiple columns operated in a single, parallel or lead-lag arrangement can also impact the overall capacity of the adsorption system (US EPA, 1999). An example comparison of the three column configurations is provided in Figure 4.1, where the total number of bed volumes (BV) treated by two identical adsorption beds are illustrated. Both parallel and lead-lag arrangements are evaluated based on the replacement cycle for a two-column system. For single configuration

two columns are replaced simultaneously. At low target effluent concentrations (target C/C_o of 0.1, illustrated in part A), single and parallel systems are similar in the number of bed volumes treated; lead-lag provides the largest amount of bed-volumes treated before reaching target concentration. The first breakthrough spike for the lead-lag system represents blended effluent from Column 1. To this point, the first column is already operated above the target maximum concentration level (lead column overshoot on part A), which improves overall fractional utilization rate for lead-lag. After that, the saturated media in the lead column is replaced, and the original lag column is placed as a new “lead”. A column with fresh media is placed to Column 2 position. After reaching the second breakthrough spike from Column 2, the initial lag column is also replaced, ending the two-column replacement cycle.

The $\%MTZ_{BT}$ is the key parameter that makes difference between single and lead-lag or parallel configurations. At low $\%MTZ_{BT}$ the zone where adsorption takes place is relatively short comparing to the overall column length, therefore better fractional utilization rates for parallel and lead-lag doesn't significantly affect relative media usage rates, compared to single. At high $\%MTZ_{BT}$, though, the mass transfer zone occupies a larger part of the column, therefore better utilization rates for parallel and lead-lag become more important. As for the C/C_o , it represents a part of the mass transfer zone that is actually utilized during the system's operation. At low target effluent concentration (e.g., target C/C_o of 0.1, illustrated in part A of Figure 4.1) most of the MTZ stays inside the column. However, for the lead-lag where the lag column is placed after the lead, the MTZ can move further, which significantly improves the media utilization rate for the lead column, At high effluent concentrations (C/C_o of 0.5, illustrated in part B of Figure 4.1) only a half of MTZ stays in the column prior to breakthrough, which makes differences between all three

configurations less important, with parallel configuration getting extra benefits due to effluent blending. Blending at high C/C_o allows operating one of the two columns in parallel configuration significantly longer, while the fresh column provides clean effluent, allowing a high concentration overshoot from the other column (parallel column overshoot).

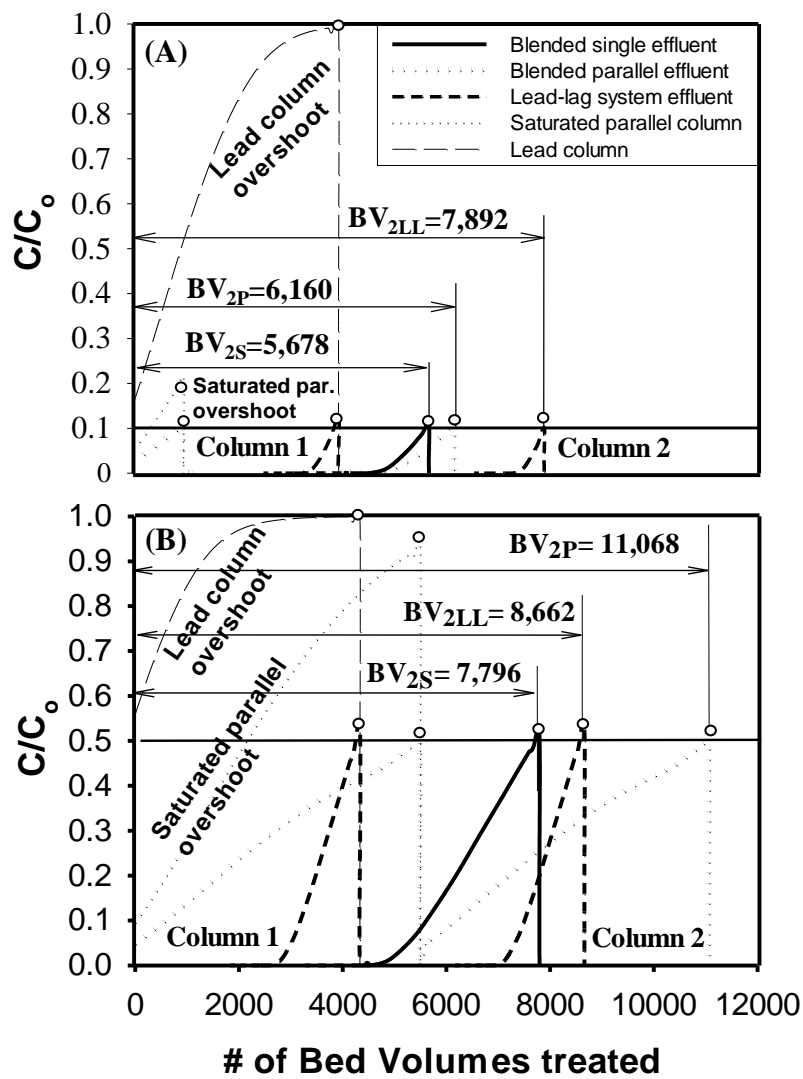


Figure 4.1 - Comparison of blended effluent profiles from a two-column system in Single, Parallel, and Lead-lag configurations for Calgon F300 treating benzene contaminated water (Run A – target $C/C_o = 0.1$, $\%MTZ_{BT} = 47\%$; run B – target $C/C_o = 0.5$, $\%MTZ_{BT} = 47\%$).

The total number of BVs treated by two columns of a certain size operated in one configuration (e.g., parallel) can be compared to the number of BVs treated by another configuration (e.g. single), consisting of the very same two columns. One way of performing the comparison would be a ratio of BVs treated by each of these configurations.

In this study, two different adsorbent-adsorbate scenarios were analyzed as noted in Section 3.2. Bed volume ratios for three configuration pairs (single/parallel, single/lead-lag, lead-lag/parallel) were determined and plotted on the C/C_o and $\%MTZ_{BT}$ axes. All of these diagrams resulted in very similar plots. Due to the differences between reviewed adsorbent-adsorbate pairs in terms of the mass transfer zone characterization, and due to a rounding error at the configuration simulation stage, the values of the bed volume ratios for a given location on the plots may vary by up to 0.03. Graphical analysis was conducted using the Sigma Plot™ software (SigmaPlot version 12.5), creating the isopleth plots based on 30 data points (six $\%MTZ_{BT}$ values and five C/C_o values) of the ratio of bed volumes treated for operating two identically sized columns for each configuration.

One comparison is for the two columns operated in a staggered parallel mode (parallel) versus two columns in parallel replaced at the same time (single configuration). Figure 4.2 illustrates isopleths for BV_{BT} ratios for single and parallel configurations as a function of C/C_o and $\%MTZ_{BT}$. For example, at C/C_o of 0.2 and $\%MTZ_{BT}$ of 40%, the BV_{BT} ratio for single to parallel is equal to 0.9. This means that a system operated in a single mode will treat about 90% as many bed volumes as the same system operated in “parallel” with staggered column replacements.

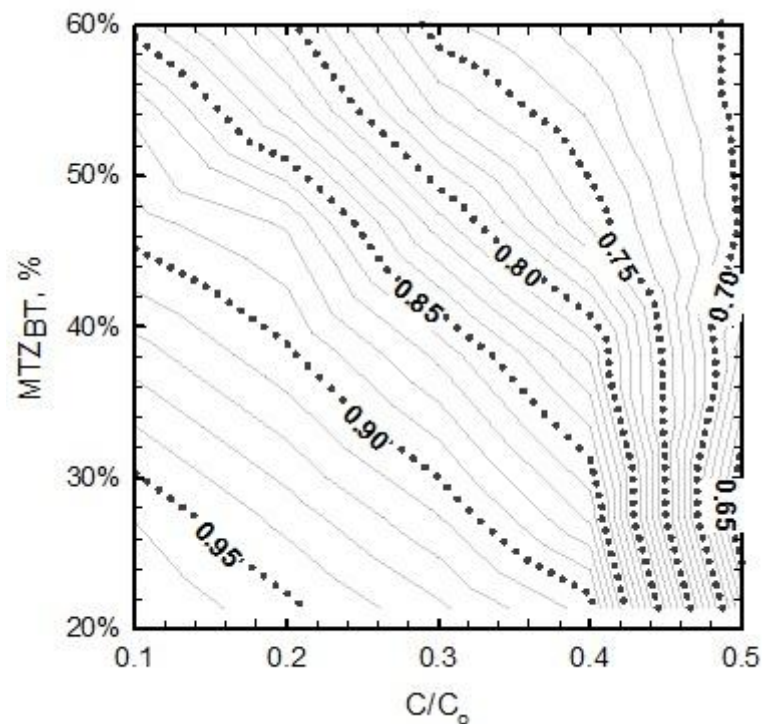


Figure 4.2 - BV_{BT} ratio isopleths for single vs parallel configurations with two column being replaced, based on the AdDesignS™ simulations for Calgon F300 treating benzene contaminated water

On Figure 4.2 at a lower C/C_o (0.1 to 0.2) and short MTZ_{BT} (30 to 40%), single to parallel BV_{BT} ratios are close to 1.0, resulting in almost the same number or bed volumes treated by two columns in single or parallel configurations. At a higher C/C_o (0.4 to 0.5), single configuration provides only 65 to 80% of bed volumes compared to parallel configuration; in this zone the BV_{BT} ratios are less sensitive to % MTZ_{BT} in a range covered in this study (20 to 60%). Therefore, operating the system in a parallel configuration can be most beneficial with long mass transfer zones and high target C/C_o ratios because effluent blending and staggered replacements at those conditions allow maximizing the fractional utilization rate and significantly prolonging system operation for parallel configuration.

Like Figure 4.2, the bed volumes treated by two columns in a single configuration and two columns in-series with staggering can be compared graphically using the isopleths for BV_{BT} ratios as a function of $\%MTZ_{BT}$ and C/C_o (Figure 4.3). On Figure 4.3 at a higher C/C_o (0.4 to 0.5) and shorter MTZ_{BT} (20 to 40%) single to lead-lag BV_{BT} ratios are around 0.90 to 0.97 with almost the same number of bed volumes treated by single and lead-lag configurations based on the two columns of media replaced. At a lower C/C_o (0.1 to 0.2) and longer MTZ_{BT} (50 to 60%) single configuration only treats 65 to 70% of bed volumes as the lead-lag configuration. As shown in Figure 4.3, operating the system in a lead-lag can be most beneficial with a higher MTZ fraction and lower C/C_o , because using two columns in-series at the specified conditions improves the fractional utilization rate and minimizes relative column replacement frequency, compared to the standard single-column arrangement.

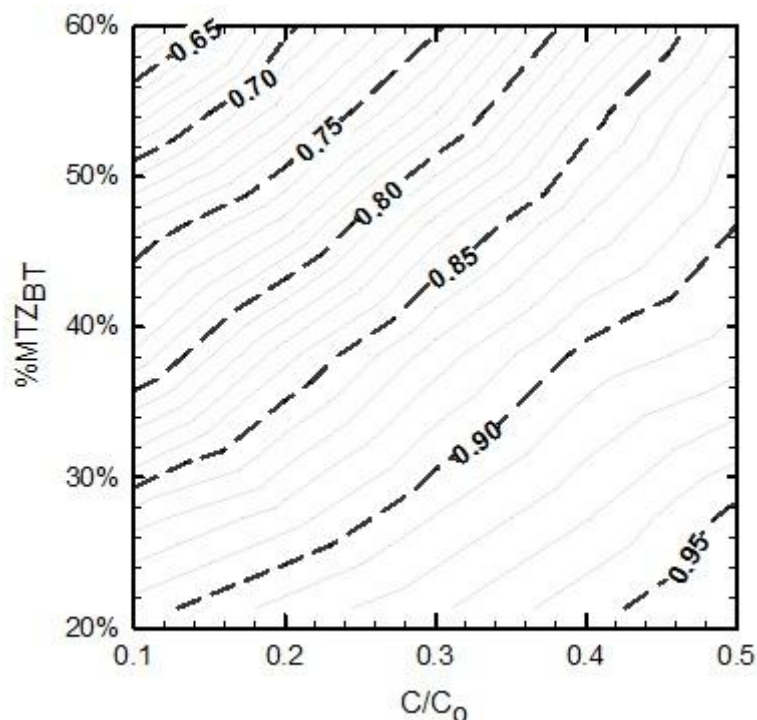


Figure 4.3 - BV_{BT} ratio isopleths for single vs lead-lag configurations with two column replaced in total, based on the AdDesignS™ simulations for Calgon F300 treating benzene contaminated water

A further comparison of two identical columns operated in lead-lag and parallel configurations is illustrated in Figure 4.4 with BV_{BT} isopleths plotted over a range of $\%MTZ_{BT}$ and C/C_o . As shown in Figure 4.4, relative performance of lead-lag and parallel configurations mainly depends on the C/C_o ratio. At C/C_o around 0.3, both lead-lag and parallel are able to treat almost the same volume of water with two columns, disregarding the $\%MTZ_{BT}$ values. At a lower C/C_o (0.10 to 0.15) and longer MTZ_{BT} (50 to 60%) lead-lag performs significantly better than parallel. At a higher C/C_o (0.45 to 0.50) parallel configurations results in a larger amount of water treated with the same number of columns used.

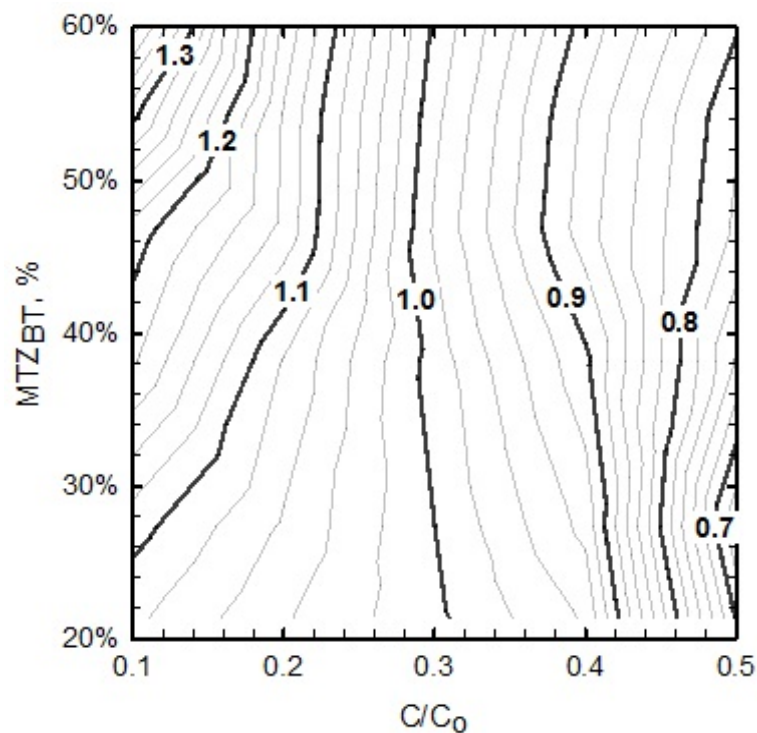


Figure 4.4 - BV_{BT} ratio isopleths for lead-lag vs parallel configurations with two column replaced in total, based on the AdDesignS™ simulations for Calgon F300 treating benzene contaminated water

Due to the case-specific operational or risk-related factors, in some situations a designer may recommend to use configuration that is not the most efficient according

to Figure 4.4. For instance, when there is a great uncertainty about the speed of the breakthrough front a lead-lag system could allow for easier monitoring of the effluent concentration without risking violating the contaminant concentration requirements.

The results of the graphical analysis illustrated in Figures 4.2 to 4.4 correspond well to the findings of previous studies. Crittenden et al. (1987) recommended utilizing the simplest column arrangement (e.g., single) in cases with a short mass transfer zone, where the column is three to five times longer than the MTZ (%MTZ around 20 to 30%). Both Hutchins (1977) and Crittenden et al. (1987) found that the lead-lag arrangement can be most beneficial with a gradual, long MTZ and stringent effluent concentration requirements. For cases with long MTZ, which cannot be contained in one bed, and when the target effluent concentrations are relatively high (C/C_0 above 0.3) parallel configuration should be considered, because it provides better fractional utilization rate and benefits most from the staggered operation and effluent blending (Crittenden et al., 1987; Hutchins, 1977; Narbaitz and Benedek, 1983).

4.3 Sorbent Usage Rate-Based Configuration Selection

The BV_{BT} ratio gives a good estimation of relative media replacement intervals for selected column configurations. Assuming the same column size across all configurations, the BV_{BT} ratio can be easily converted into the sorbent usage rate ratio (SUR):

$$SUR = \frac{\text{Amount of the replaced media}}{\text{Volume of water treated}} = \frac{V_{REP}}{BV_{BT} \times V} \quad [4.1]$$

where V_{REP} is the volume of fresh media required to replace two adsorption beds; V is the total volume of media in two columns, and BV_{BT} is a number of bed volumes treated to the target maximum effluent concentration.

Individual SURs can be calculated for all modeled configurations from the following equations, with subscripts S - for single, P - for parallel, and LL - for lead-lag:

$$SUR_S = \frac{V_{REP}}{BV_{2S} \times V}; \quad SUR_P = \frac{V_{REP}}{BV_{2P} \times V}; \quad SUR_{2LL} = \frac{V_{REP}}{BV_{2LL} \times V} \quad [4.2]$$

where BV_{2S} , BV_{2P} , BV_{2LL} are the number of bed volumes treated with two columns of media by single, parallel, and lead-lag configurations respectively.

To compare any two selected configurations to each other, the SUR ratios can be used:

$$\frac{SUR_P}{SUR_S} = \frac{\frac{V_{REP}}{BV_{2P} \times V}}{\frac{V_{REP}}{BV_{2S} \times V}} = \frac{BV_{2S}}{BV_{2P}} \quad [4.3]$$

$$\frac{SUR_{LL}}{SUR_S} = \frac{\frac{V_{REP}}{BV_{2LL} \times V}}{\frac{V_{REP}}{BV_{2S} \times V}} = \frac{BV_{2S}}{BV_{2LL}} \quad [4.4]$$

$$\frac{SUR_{LL}}{SUR_P} = \frac{\frac{V_{REP}}{BV_{2LL} \times V}}{\frac{V_{REP}}{BV_{2P} \times V}} = \frac{BV_{2P}}{BV_{2LL}} \quad [4.5]$$

From the Equations 4.3, 4.4, and 4.5 the SUR ratios for all configuration pairs depend solely on the BV_{BT} ratios obtained previously in Section 4.4 of this chapter. Combining three individual Figures 4.2, 4.3, and 4.4, following the approach used by Denning and Dvorak (2009), New et al. (2009), and Stewart et al. (2013), a configuration selection diagram (CSD) can be built to simplify the selection process

for design engineers. Figure 4.5 represents both - the adsorption bed capacity and sorbent usage rate based configuration selection.

On Figure 4.5 the shaded region shows the uncertainty zone around C/C_0 of 0.3 where the amount of treated water obtained from the lead-lag and parallel systems is within $\pm 10\%$. For target C/C_0 ratio from 0.1 to 0.3, the configuration selection based on the relative amount of water treated per unit media is mainly between a single and lead-lag ($BV_{BT(2S)}/BV_{BT(2LL)}$). At a low C/C_0 (0.1 to 0.2) and high %MTZ_{BT} (55 to 60%), single configuration provides only 65 to 70% of bed volumes treated using the same amount of media as lead-lag. For target C/C_0 ratios from 0.3 to 0.5, either single or parallel system provides larger amount of water treated per unit media ($BV_{BT(2S)}/BV_{BT(2P)}$), with single configuration reaching only 70 to 75% of parallel configuration capacity at higher C/C_0 (0.45 to 0.50) disregarding the fraction of the mass transfer zone.

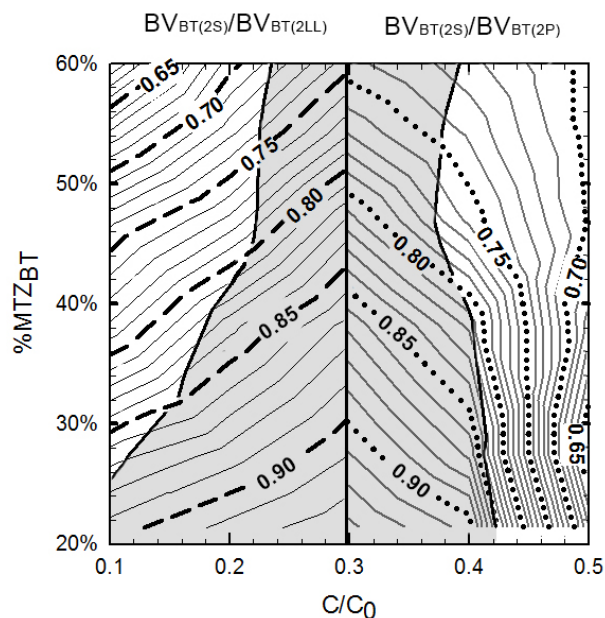


Figure 4.5 – SUR (BV_{BT}) ratio based configuration selection diagram for Calgon F300 and E33 media treating benzene and arsenate contaminated water respectively.

Fractions on figure are the ratios of bed volumes treated. The grey zone marks a region where number of BVs treated by lead-lag and parallel is within $\pm 10\%$ range.

Even though the bed volume ratios provide a good estimation of relative configuration efficiency, for small adsorption systems extra operational costs associated with frequent media replacements (freight, labor time, etc.) can become of concern and their effects should be evaluated. The fractions of fresh media cost and replacement service cost in overall cycle replacement cost (e.g., \$/kgal) for 15 sites, participated in the EPA demonstration program (US EPA, 2011c) with actual media replacement, are illustrated in Figure 4.6.

The systems illustrated in Figure 4.6 varied in the unit cost (\$/ft³) of fresh media by over an order of magnitude. Although for many small systems the cost of fresh media is the major expense during the replacement, for some systems the replacement cost might highly depend on the replacement service costs (e.g., freight, labor, analysis and disposal, etc.), which can account for as much as 50 to 60% of the total replacement expenses. Therefore, to improve the system configuration selection, the method, based solely on the amount of water treated per unit media, should be modified to include the replacement service cost components.

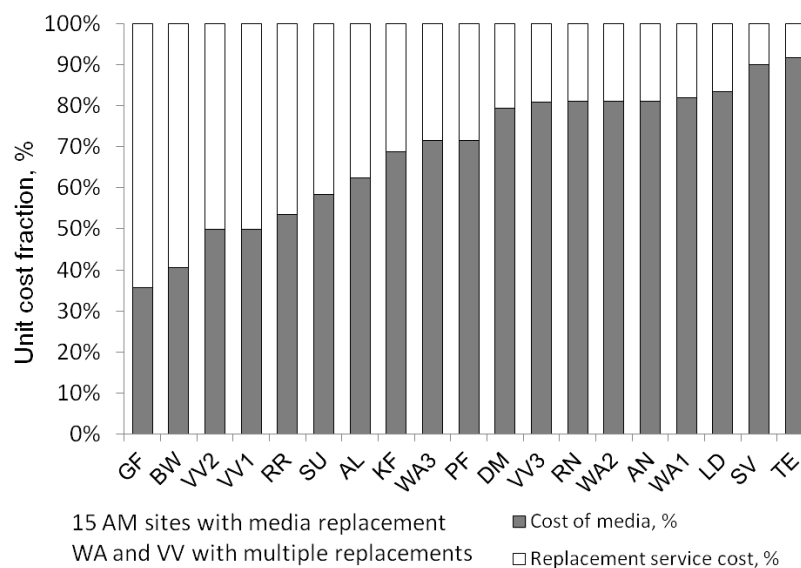


Figure 4.6 - Fraction of media cost component in total replacement costs. Abbreviations on the abscissa are for each US EPA ADP project site (US EPA, 2011c)

4.4 Annual Replacement Cost Based Configuration Selection

Cost ratios are an important step towards the comprehensive modeling of relative configuration efficiency. While the BV_{BT} and SUR parameters only represent the physical side of the adsorption system performance, the cost ratios provide extra information about relative economics. In this study, variations of capital costs of three configurations (single, parallel, and lead-lag) of the same size were neglected, assuming only minor changes are needed, such as additional valves and piping, to switch from one configuration to another. According to the US EPA ADP program report (EPA, 2011c) for small adsorption systems piping costs account for a minor part of total capital cost on average, making the differences between three configurations very small.

All operational costs associated with media replacement were combined into the Cycle Replacement Cost (CRCost), which is the total amount of money needed to replace the spent media in two columns with the fresh media. Cycle replacement cost consists of the Replacement Service Cost (RSCost) and Fresh Media Cost (FMCost). The former parameter (RSCost) includes all non-material costs needed for spent media replacement: media analysis and disposal fee (if any), cost of labor for media replacement, and freight costs for both spent media and fresh media to transport it to and from the site. This parameter works as a limiting factor for systems with more frequent replacements, making them economically ineffective, compared to configurations with less frequent replacements. The latter parameter (FMCost) is simply a function of media unit cost ($\$/m^3$, $\$/kg$, etc) and amount of replaced media (m^3 , kgs, etc), and favors configurations with smaller media volume needed for each replacement (like parallel and lead-lag).

To combine all of the above parameters and use them for configuration comparison, the Annual Replacement Cost (ARCost) was calculated (Eq. 4.6), based on the total cost of the replacement and volume of water treated to breakthrough:

$$ARCost = \frac{\text{Cycle Replacement Cost}}{\text{Vol. of water treated}} = \left(\frac{CRCost, \$}{BV_{BT} \times V, 1000 \text{ gallons}} \right) \quad [4.6]$$

To compare any two configurations based on their annualized replacement costs, the ARCost ratios can be calculated for single and parallel, single and lead-lag, and lead-lag and parallel configurations:

$$\frac{ARCost_P}{ARCost_S} = \frac{\frac{CRCost_P}{BV_{BT(2P)} \times V}}{\frac{CRCost_S}{BV_{BT(2S)} \times V}} = \frac{BV_{BT(2S)}}{BV_{BT(2P)}} \times \frac{1}{\left(\frac{CRCost_{2S}}{CRCost_{2P}} \right)} \quad [4.7]$$

$$\frac{ARCost_{LL}}{ARCost_S} = \frac{\frac{CRCost_{2LL}}{BV_{BT(2LL)} \times V}}{\frac{CRCost_{2S}}{BV_{BT(2S)} \times V}} = \frac{BV_{BT(2S)}}{BV_{BT(2LL)}} \times \frac{1}{\left(\frac{CRCost_{2S}}{CRCost_{2LL}} \right)} \quad [4.8]$$

$$\frac{ARCost_{LL}}{ARCost_P} = \frac{\frac{CRCost_{2LL}}{BV_{BT(2LL)} \times V}}{\frac{CRCost_{2P}}{BV_{BT(2P)} \times V}} = \frac{BV_{BT(2P)}}{BV_{BT(2LL)}} \times \frac{1}{\left(\frac{CRCost_{2LL}}{CRCost_{2P}} \right)} \quad [4.9]$$

where $CRCost_{(2S)}$, $CRCost_{(2P)}$, and $CRCost_{(2LL)}$ are the cycle replacement costs for single, parallel, and lead-lag arrangements respectively.

Lead-lag and parallel configurations have similar replaced media volumes; therefore, for one adsorption site their fresh media costs and replacement service cost are assumed to also be the same. Since cycle replacement costs for lead-lag and parallel are equal (same amount of media is replaced at once), Equation 4.9 can be simplified:

$$\frac{CRCost_{2LL}}{CRCost_{2P}} = 1.0. \quad \text{Thus: } \frac{ARCost_{2LL}}{ARCost_{2P}} = \frac{BV_{BT(2P)}}{BV_{BT(2LL)}} \quad [4.10]$$

According to the Equations 4.7 and 4.8, annual replacement cost ratios for single and parallel, and single and lead-lag depend on two main factors – BV_{BT} ratio and CRCost ratio. From the Equation 4.10, annual replacement cost ratios for lead-lag and parallel can be estimated from the BV_{BT} ratios only. The BV_{BT} ratios have already been discussed in Section 4.4 of this chapter. The CRCost ratios for single and parallel or single and lead-lag can be calculated from Equation 4.11, with cycle replacement cost shown as a sum of fresh media cost and replacement service cost for each configuration:

$$\frac{CRCost_{2S}}{CRCost_{2P/2LL}} = \frac{RSCost_{2S} + FMCost}{RSCost_{2P/2LL} + FMCost} \quad [4.11]$$

where $RSCost_{(2S)}$ and $RSCost_{(2P/2LL)}$ are the replacement service costs for single and parallel/lead-lag configuration; $FMCost$ is the total cost of media in the system (cost of media in two columns).

The cycle replacement cost ratios for single and parallel/lead-lag configuration obtained from the Equation 4.11 are plotted in Figure 4.7 for a range of cost ratios. In Figure 4.7 the x-axis is the ratio of the replacement service cost (RSCost) to the fresh media cost (FMCost), which will be called “Service-to-Fresh Media Cost Ratio” subsequently. A low value represents cases where the cost of transportation and replacement services is much smaller than the cost of the fresh media. The y-axis is the ratio of the replacement service cost for two columns replaced simultaneously ($RSCost_{(2xV)}$) to the service cost of two separate one-column replacement ($2xRSCost_{(V)}$), which will be called the “Service Cost Ratio” subsequently. A low value on the vertical axis represents a case where the cost for media transportation and

replacement services is not very dependent on the amount of media being replaced, such as a small system where the same delivery truck could be used to replace either one or two columns.

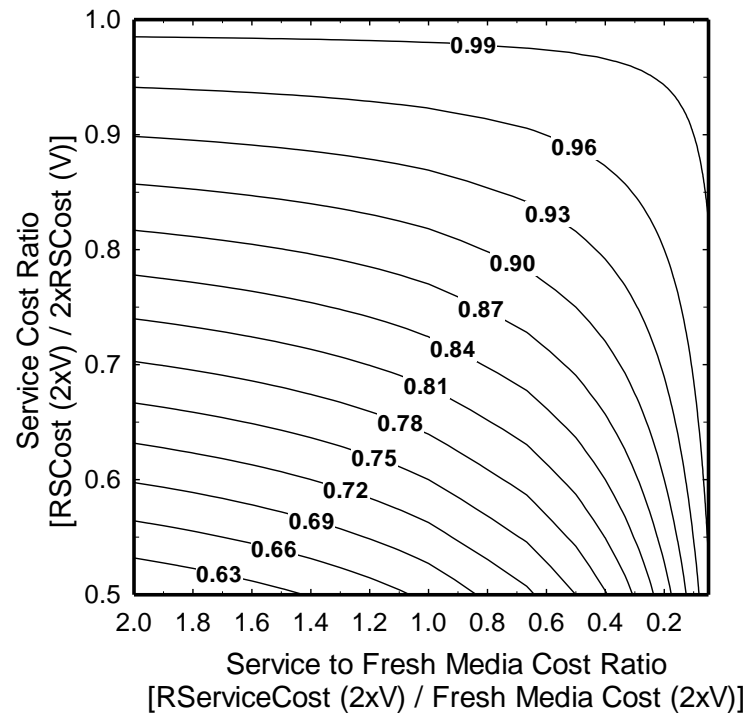


Figure 4.7 – Cycle replacement cost ratio isopleths for single/parallel or single/lead-lag configurations with two-column media changeout

From Figure 4.7, at a low service cost ratio (e.g. at 0.5) and a high service to fresh media cost ratio (e.g. at 2.0, when the service cost is twice as large as the fresh media cost), the resulting CRCost ratio for single vs parallel or single vs lead-lag is between 0.63 to 0.67. This basically means that changing two columns at the same time would be only 63 to 67% of the cost required for the two separate changeouts. In turn, at a high service cost ratio (up to 1.0) and a low service to fresh media cost ratio (0.5 and lower) the cycle replacement cost ratio might reach a very high value of 0.90 to 0.99. For such a high CRCost ratio, making two separate replacements would cost nearly the same as changing columns simultaneously with almost no penalty for having more frequent replacements for parallel and lead-lag configurations.

Using the bed volume ratios and the cycle replacement cost ratios obtained from Figures 4.5 and 4.7, a relative configuration performance of two configurations can be estimated based on their relative annual replacement cost. For example, if the BV_{BT} ratio from Figure 4.5 for comparing single to lead-lag configurations ($BV_{BT(2S)}/BV_{BT(2LL)}$) is equal to 0.7, and the CRCost ratio ($CRCost_{(S)}/CRCost_{(LL)}$) from Figure 4.7 is equal to 0.9 then:

$$\frac{ARCost_{LL}}{ARCost_S} = \frac{BV_{BT(S)}}{BV_{BT(LL)}} \times \left(\frac{1}{\frac{CRCost_S}{CRCost_{LL}}} \right) = 0.7 \times \frac{1}{0.9} = 0.78 \quad [4.12]$$

The ARCost ratio of 0.78 from Equation 4.12 for lead-lag to single comparison means that the annual replacement cost for lead-lag configuration is expected to be only about 78% of that of a single configuration due to significantly lower amount of bed volumes treated by single configuration with the same amount of media, and relatively low cost penalty for doing frequent replacements for lead-lag configuration.

4.5 Cost-based Configuration Selection Verification

To show the potential application of the cost-based configuration selection model described previously, three adsorption systems from the US EPA ADP program (US EPA, 2011c) were chosen – Dummerston, VT, Klamath Falls, OR, and Lead, SD. Those sites cover a range of target effluent concentration ratios from 0.24 to 0.45 C/C_o and %MTZ_{BT} from 45 to 60%.

The C/C_o values were determined as a ratio of arsenic maximum contaminant level (MCL) to the average concentration in raw water. The %MTZ_{BT} was estimated from the breakthrough curves, obtained from the individual site reports (US EPA, 2011a; US EPA, 2008d; US EPA, 2011d). Figure 4.8 shows sample breakthrough

curve from the Klamath Falls, Oregon project site. The system was operated in-series allowing for a very high effluent concentration from the lead column.

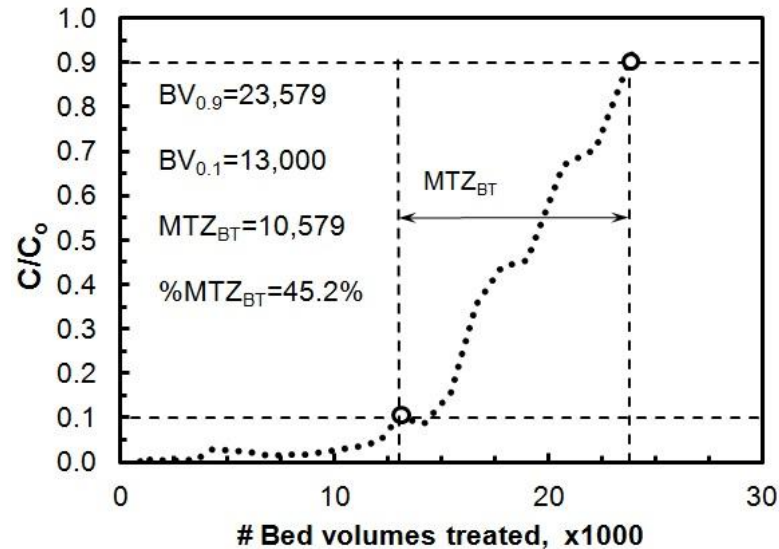


Figure 4.8 – Example of $\%MTZ_{BT}$ calculation from an actual breakthrough curve at Klamath Falls, Oregon (US EPA, 2011a)

For ArsenXP media system in Klamath Falls, OR, the effluent hasn't completely reached the target concentration, therefore the 0.9 C/C_0 breakthrough point was estimated using extrapolation and set at around 22,500. Using Equation 4.1, the $\%MTZ_{BT}$ was calculated for target effluent concentration ratios of 0.1 and 0.9. Using the site's $\%MTZ_{BT}$ and C/C_0 values, the BV_{BT} ratios can be estimated from Figure 4.5.

As for the cost component, the FMCost and RSCost ratios were also calculated based on the US EPA reports using the amount of media and media unit price for FMCost parameter, and a sum of all other replacement costs (freight, analysis, disposal, unloading and loading labor, etc.) for RSCost parameter. The service-to-fresh media cost ratios ($RSCost_{(2xV)}$ to $FMCost_{(2xV)}$) for three selected locations ranged from 0.20 to 0.29 representing the cases where the replacement service cost is less than 30% of the fresh media cost.

The last component to evaluate is the service cost ratio ($RSCost_{(2xV)}$ to $RSCost_{(V)}$). This component was hard to estimate from the US EPA reports, because, for most of the systems with actual media replacement, the volume being replaced was constant for all changeouts. Due to a lack of reliable data, the statistical analysis was used to estimate the relationship between the replaced volume of media and the replacement service cost. Figure 4.9 shows replacement service cost for the adsorption media systems from the US EPA ADP program plotted against the volume of media being replaced. A trend line was built using power regression for 25 out of 32 media replacement events, resulting in a $R^2=0.80$. Seven sites had an unusually high replacement service cost and were not included in the analysis (e.g. related to radioactive content in the source water).

Replacement service cost for one-column and two-column RSCosts can be calculated using following equations:

$$2RSCost(V) = 2 \times 396.65 \times V^{0.67}; \quad [4.13]$$

$$RSCost(2 \times V) = 396.65 \times (2 \times V)^{0.67} \quad [4.14]$$

Resulting in a service cost ratio of:

$$\frac{RSCost(2 \times V)}{2 \times RSCost(V)} = \frac{396.65 \times (2 \times V)^{0.67}}{2 \times 396.65 \times V^{0.67}} = 2^{-0.33} = 0.795 \quad [4.15]$$

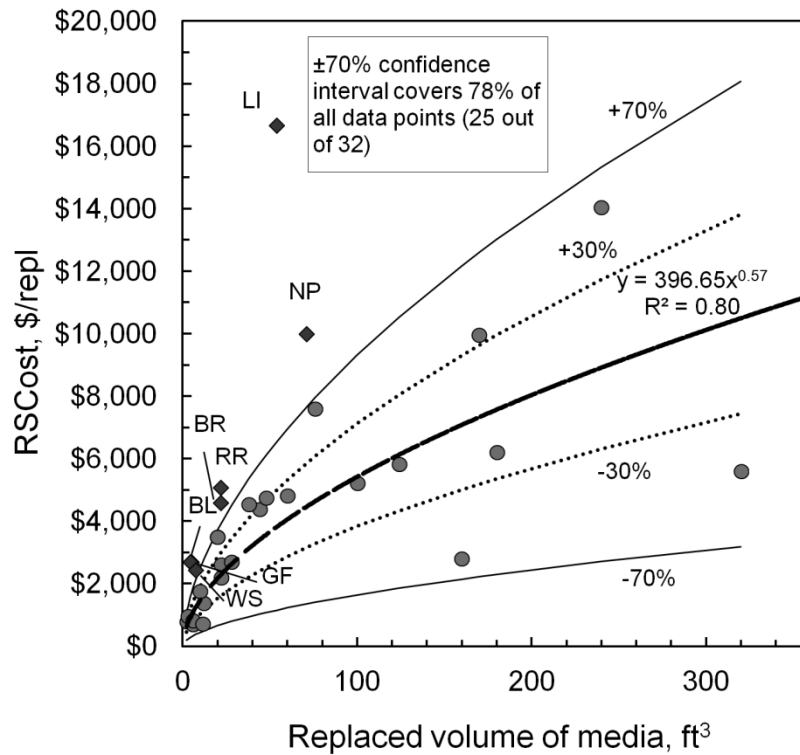


Figure 4.9 – Replacement service costs from the adsorption systems participated in the EPA demo program (not included: LI – Lake Isabella, CA; NP – Nambe Pueblo, NM; BR – Bruni, TX; RR – Rim Rock, AZ; BL - Buckeye Lake, OH; GF - Goffstown, NH; Woodstock, CT).

The service cost ratio of 0.795 means that replacing two columns together for single mode operation would cost around 0.8 times less than that for two separate one-column replacements with parallel/lead-lag operation. All previously described values for DM, KF, and LD sites are combined in Table 4.1

Table 4.1 – Estimated parameters for configuration selection from the EPA Arsenic Treatment Technology Demonstration Program

#	Site name	Dummerstone, VT	Klamath Falls, OR	Lead, SD
1	Media used	A/I Complex 2000	ArsenXP™	LayneRT™
2	Target C/C_o (MCL/average C_o)	0.24	0.3	0.45
3	%MTZ _{BT} (estimated from the BT curve)	60%	45%	51%
4	BV _{BT} ratios (from Figure 4.5)	0.72	0.83	0.72
5	FMCost, USD (reported)	\$3,100.0	\$11,900.0	\$13,440.0
6	RSCost, USD (reported)	\$810.0	\$3,500.0	\$2,693.0
7	RSCost/FMCost	0.26	0.29	0.20
8	$RSCost_{2xV}/2xRSCost_V$ (estimated from the statistics)		0.795	
9	CRCost ratios (from Figure 4.7)	0.95	0.94	0.96
10	ARCost ratios (BV _{BT} ratio/CRCost ratio)	0.76	0.88	0.75
11	Configuration used	Lead-lag	Lead-lag	Parallel

The CRCost ratios from Row #9 of Table 4.1 were estimated from Figure 4.7 using the service to media cost ratio for horizontal axis and service cost ratio for vertical axis. In this example a standard service cost ratio of 0.795 was used calculated from Equation 4.15. At given conditions, the CRCost ratio ranged from 0.94 to 0.96 meaning that one simultaneous two-column media changeout for single arrangement would be 94 to 96% of the cost of two separate one-column replacements with parallel/lead-lag operation. However, if for a certain adsorption system the service cost ratio is much smaller than 0.795 (e.g., 0.5 to 0.6), then the resulting CRCost ratio will be significantly lower, reaching the values of 0.65 to 0.70,

and making frequent media changeouts for parallel and lead-lag relatively more expensive, compared to a less often replacements with single configuration.

Finally, the annualized replacement cost ratios can be calculated from the BV_{BT} and $CRCost$ ratios provided in Rows #4 and #9 of Table 4.2 using Equations 4.7 and 4.8. At a target C/C_o below 0.3 the $ARCost$ ratio calculated from Equation 4.8 represents the relative performance of lead-lag and single configurations in terms of their replacement costs over the volume of water treated (\$/kgal treated). The $ARCost$ value of 0.76 for Dummerstone, VT system (site ID - DM) means that the annual replacement cost for lead-lag configuration is expected to be about 24% lower, than that of a single configuration. At C/C_o values above 0.3, the $ARCost$ ratio calculated from Equation 4.7 shows the relative performance of parallel and single configurations in terms of their annual replacement costs (\$/kgal treated). The $ARCost$ value of 0.75 for Lead, SD adsorption site (site ID - LD) means that annual replacement cost for parallel configuration is expected to be at least 25% lower than that of a single configuration.

It should also be noted, that in Table 4.2 at a higher $\%MTZ_{BT}$, more complex configurations provide a higher gain in the efficiency, as compared to a single-column arrangement. This can be a result of two key factors – relatively low total replacement cost ratios, allowing to benefit from more frequent replacements of smaller columns; and long, gradually character of the mass transfer zone, at which both parallel and lead-lag configurations provide better fractional utilization, comparing to a single configuration.

Single configuration, however, may be economical when one or both of the conditions listed below are true. First, when the BV_{BT} ratio (for parallel and single or lead-lag and single) is relatively low, which usually occurs when the mass transfer

zone is short (e.g. MTZ_{BT} below 35%). For short MTZ_{BT} the fractional utilization for the single configuration is not much lower than that of parallel or lead-lag, thus there is relatively little difference in sorbent usage rates between the configurations. A second situation is when the total replacement cost ratio is relatively low, which occurs with a relatively cheap fresh media comparing to the service cost, and especially when the service cost ratio for two versus one column replacement is low. For these conditions, the sorbent usage rate is less important and single configuration allows reducing the replacement service cost by having less frequent media changeouts.

4.6 Replacement Cost-Based Configuration Selection Framework

Previous sections described the individual steps that may be used when making a decision on the most suitable column configuration. Figure 4.5, developed in Section 4.3, allows estimating the BV_{BT} ratios for two selected configurations using the $\%MTZ_{BT}$ and target C/C_o of a system. Figure 4.7, from Section 4.4 represents the CRCost ratio isopleths for single to parallel or single to lead-lag in a certain range of service cost ratios and service-to-fresh media cost ratios. Section 4.5, then, provides an example of the application of those two concepts to a real-life situation, where any of the three column configurations is possible. Based on the estimated BV_{BT} ratios and the corresponding CRCost ratios, the annual replacement cost ratio (ARCost) was calculated, showing the relative performance of either lead-lag to single or parallel to single configurations.

Since the key parameter – the ARCost ratio depends on the BV_{BT} ratio, and the CRCost from Figure 4.7 is a function of the service cost ratio and the service-to-

fresh media cost ratio, it is possible to develop a series of diagrams similar to Figure 4.5, but with the isopleth values adjusted for the specific CRCost ratios.

The impact of adsorption replacement service cost and fresh media cost on the relative cost of three column configurations is demonstrated in Figure 4.10. All 15 parts of the figure have the same axes as Figure 4.5, but the corresponding cost ratios vary. In Figure 4.10, the horizontal set of figures covers a certain range of the service to fresh media cost ratios ($RSCost_{(2V)}$ to $FMCost_{(2V)}$). The value of 2.0 represents an extreme case when the replacement service cost is twice as large as the fresh media cost. The 0.5 value refers to the opposite situation when the service cost is only a half of the fresh media cost. The intermittent case when those two costs are equal is possible at a service to fresh media cost ratio of 1.0.

The vertical set of figures refers to the service cost ratio ($RSCost_{(2V)}$ to $2xRSCost_{(V)}$) variations and also has two extremes. A 1.0 value applies to systems where the service cost for one simultaneous two-column replacement (not including the cost of fresh media) is the same as for the two separate one-column replacement events. A 0.5 value on the vertical axis represents another extreme, where the service cost to replace two columns simultaneously is half of the combined cost of two separate one-column replacements. That might be a case, when for a small system a large truck is used, which can contain either one or two columns during the trip. The 0.625, 0.750 and 0.875 numbers on the vertical axis are the intermediate values.

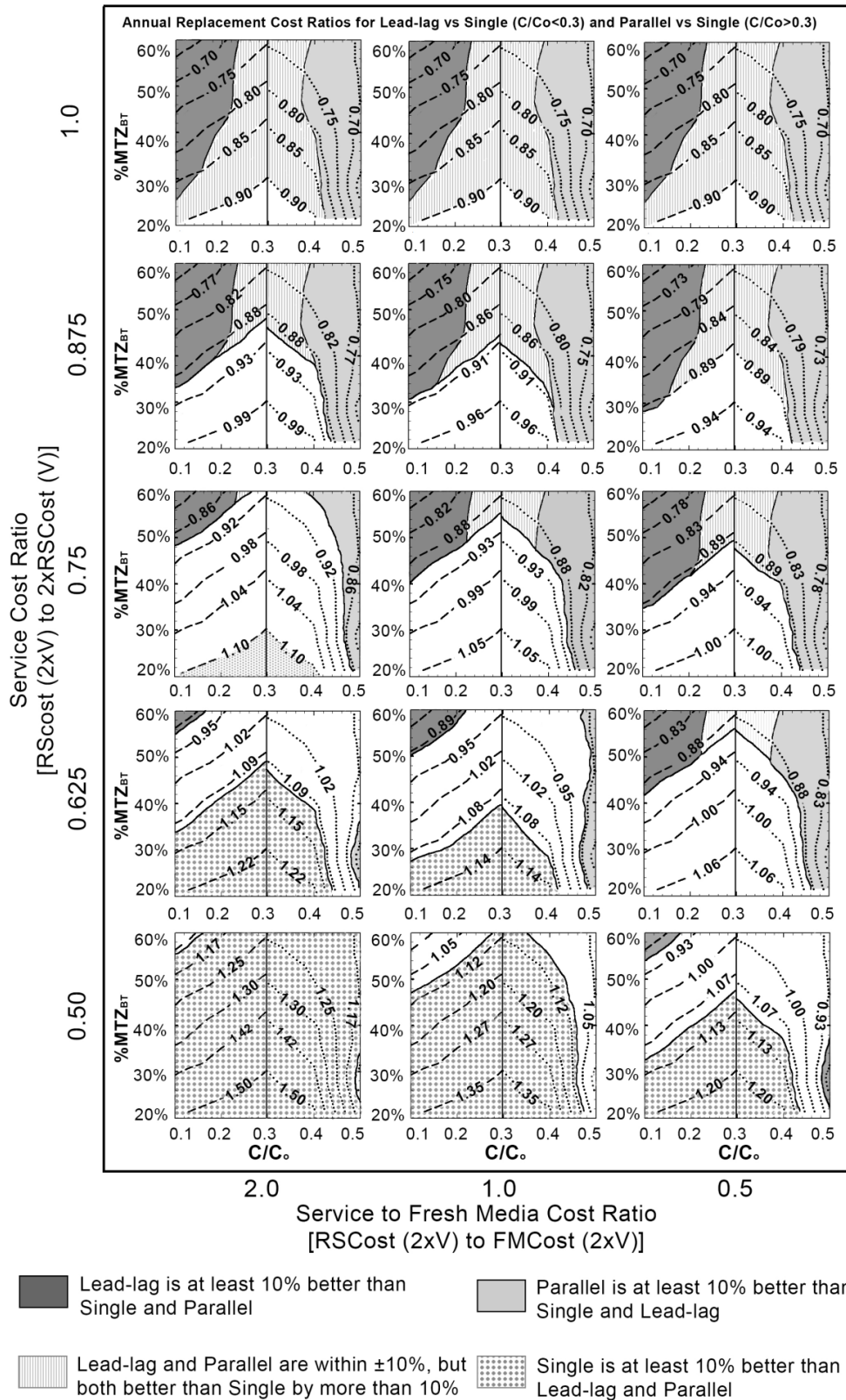


Figure 4.10 – Impact of the replacement service cost and fresh media cost on the relative annual replacement costs of three column configurations

The zones in Figure 4.10 with different shading can provide a sense of the cost trade-offs between the operating configurations. The darker shading represents cases where lead-lag provides at least 10% savings in media replacement cost compared to single and parallel. The lighter shade means that parallel results in at least 10% lower annual replacement cost than the other two configurations. The zone with a vertical hatch means that both lead-lag and parallel are at least 10% better than single, but their relative annual replacement cost is within $\pm 10\%$. The zone with a dotted hatch is where single configuration is better than lead-lag and parallel by at least 10%. It should be noted that in some cases specific column configurations, such as lead-lag arrangement, might be used regardless the operating cost to comply with regulatory requirements and reduce the risk of unexpected breakthrough and consequently the maximum contaminant level (MCL) violation.

As shown in Figure 4.10, when the service cost ratio is quite large (e.g. 1.0), the small configuration selection diagrams are essentially the same, regardless of the service to fresh media cost ratio. As the service cost ratio becomes smaller, the fresh media cost starts to play a bigger role in configuration selection, with single configuration being most cost competitive at larger service to fresh media cost ratios. At very low service cost ratios (e.g. close to 0.5), single configuration is expected to be more economical than lead-lag or parallel, especially with relatively short %MTZs.

A set of five key steps can be followed in order to use Figure 4.10 to estimate the replacement cost relationships for different configurations for a specific situation.

1. Confirm that the key assumptions used to develop this framework apply to the system under consideration. These assumptions include:

- Flow rate and concentration variations are adequately reflected in the breakthrough profile used to estimate the %MTZ,
 - Competitive adsorption does not result in a significant contaminant concentration overshoot on the breakthrough curve (as discussed in Denning and Dvorak, 2009), and
 - No time dependent changes occur in adsorption parameters.
2. Estimate the %MTZ_{BT} from a breakthrough profile and estimate the target C/C_0 value.
 3. Estimate two ratios –service cost ratio and service to fresh media cost ratio, based on the available cost information.
 4. Based on the service cost ratio and service to fresh media cost ratio, in Figure 4.10 identify which diagram(s) best represents the situation.
 5. From the small diagram(s) identify which configuration(s) may provide the lowest annualized replacement cost at a given %MTZ_{BT} and target C/C_0 .

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

A systematic approach for preliminary selection of the column configuration for adsorptive treatment systems was further developed and includes media replacement costs and sorbent usage. This framework can be used by the designers of small adsorption systems, operators, and regulators.

Several assumptions were made in order to keep the final column evaluation framework simple and applicable at the early design stages, when both technical and cost-related data might be limited. It was assumed that all configurations consist of two identical adsorption columns with the same liquid loading rate. It was assumed that these systems may not be constantly operated during the day, often for less than 12 hours a day, and that the lead-lag configuration would be operated at half the flow rate, but twice the length of time. Differences in the capital and operational labor costs between the configurations were assumed to be negligible.

Although parallel and lead-lag configurations might have a slightly higher capital cost due to a larger number of valves and more complex piping system, those expenses typically contribute to a minor part of total capital cost. In cases when those assumptions are not held true, individual site-specific analysis should be conducted to account for all major factors, affecting the configuration selection process. The following generalizations were made from this study:

- The fraction of the mass transfer zone ($\%MTZ_{BT}$), estimated from the breakthrough curve, and effluent to influent concentration (C/C_o) ratios, can be effective for data normalization for configuration selection purposes.

- Cost associated with media replacement can be normalized using the service to fresh media cost ratio and the service cost ratio. The former ratio describes the importance of the replacement service cost component in total cycle replacement cost. The latter ratio represents a certain "cost-penalty" for doing more frequent one-column replacements, instead of replacing both columns at the same time.
- The parallel configuration was found to treat more bed volumes of water per the same amount of media at higher C/C_o ratios (above 0.4 C/C_o) comparing to single (20 to 25% more) or lead-lag (15 to 20% more). Considering the same media replacement costs for parallel and lead-lag, using parallel arrangement should be more beneficial in this region, than the lead-lag arrangement.
- The lead-lag configuration can be most beneficial at lower C/C_o ratios, with stringent target effluent concentration requirements (below 0.2 C/C_o), especially for relatively gradual mass transfer zones (MTZ_{BT} greater than 40%).
- At a C/C_o around 0.3 both parallel and lead-lag systems perform within 10%, based on their annual replacement costs, so the choice between them depends on other factors, such as operating simplicity, system reliability, preferences for a shorter or longer daily operating time, etc.
- When the cost component is applied, single configuration becomes more economical, when either sharp mass transfer zone ($\%MTZ_{BT}$ below 20%) or the cycle replacement cost ratio is low (CRCost ratio below 0.8). In those cases single configuration has the fractional utilization rate similar to parallel

and lead-lag, and has lower replacement costs due to a less frequent media changeouts.

5.2 Recommendations for future research on configuration selection

This research attempted to utilize both physical adsorption modeling and adsorption system costs modeling for column configuration selection in small adsorption systems. This attempt can be further developed by reviewing the following topics in greater details:

- For the simplicity, all configurations of the same size were assumed to have similar capital cost in this study. More detailed cost estimation based on the cost modeling or case-studies can be used to predict the capital cost of single, parallel, and lead-lag configurations, and evaluate its effects on the unit cost of treated water.
- The proposed approach for estimating relative configuration performance based on the savings in total replacement cost might be tested on the real-world adsorption system to identify the decision framework precision and potential improvements.
- A potential application of the presented methodology using ratios can be considered not only for configuration selection, but for the adsorption system design in general. Although this might require more complex mathematical modeling, it should allow to develop reliable "rule-of-thumb" principles for system sizing, adsorptive media selection, and configuration selection.

REFERENCES

- Ali, I., & Gupta, V. K. (2007). Advances in water treatment by adsorption technology. *Nature Protocols*, 1(6), 2661-2667.
- Battelle (2003). Arsenic removal cost estimating program, US EPA National Risk Management Research Laboratory (EPA/600/C-03/079), provided by Thomas J. Sorg, EPA NRMRL, Cincinnati, OH.
- Chaudhary, D., Vigneswaran, S., Jegatheesan, V., Ngo, H., Moon, H., Shim, W., & Kim, S. (2003). Granular activated carbon (GAC) adsorption in tertiary wastewater treatment: experiments and models. *Water Science & Technology*, 47(1), 113-120.
- Corwin, C. J., and Summers, R. S. (2011). Adsorption and desorption of trace organic contaminants from granular activated carbon adsorbers after intermittent loading and throughout backwash cycles. *Water Research*, 45(2), 417-426.
- Creek and Davidson (1999). Treatment Technologies for the Removal of Methyl Tertiary Butyl Ether (MTBE) from Drinking Water: Air Stripping, Advanced Oxidation Processes, Granular Activated Carbon, Synthetic Resin Sorbents, Second Edition
- Crittenden, J.C., Wong, B.W.C., Thacker, W.E., Snoeyink, V.L., Hinrichs, R.L. (1980) Mathematical Model of Sequential Loading in Fixed-Bed Adsorbers. *Journal of the Water Pollution Control Federation*, 52(11), 2780-2794.

Crittenden, J.C., Hutzler, N.J., Geyer, D.G., Oravitz, J.L., Friedman, G. (1986).

Transport of Organic Compounds with Saturated Groundwater Flow: Model Development and Parameter Sensitivity. *Water Resources Research*, 22(3), 271-284.

Crittenden, J.C., Hand, D.W., Arora, H., Lykins Jr., B.W. (1987) Design

Considerations for GAC Treatment of Organic Chemicals. *J. – Am. Water Works Assoc.*, 79(1), 74-82.

Crittenden, J.C., Trussel, R.R., Hand, D.W., Howe, K.J., Tchobanoglous, G. (2012)

Water Treatment: Principles and Design, Third Edition, Wiley and Sons Inc., Hoboken, N.J.

Cumming L.J., Wang L., Chen R.S.C. 2007. *Arsenic and antimony removal from*

drinking water by adsorptive media. National risk management research laboratory of research and development. U.S. Environmental Protection Agency, Cincinnati, Ohio 45268, 63.

Denning, P.C, and Dvorak, B.I. (2009) “Maximizing Sorbent Life: Comparison of

Columns in Parallel, Lead-Lag Series, and with Bypass Blending,” *Water Environment Research*, 81(2) 206-216.

Dvorak, B.; Lawler, D.; Speitel, G. Jr.; Jones, D.; and Boadway, D. (1993) “Selection

Among Treatment Technologies for Waters Contaminated with Synthetic Organic Chemicals,” *Water Environment Research*, 65(7), 827-838.

Dvorak, B.I., Maher, M.K. (1999) GAC Contactor Design for NOM Removal:

Implications of EBCT and Blending. *J. Environ. Eng.*, 125(2), 161-165.

Dvorak, B.I., Morley, M.C., Denning, P.C. (2008) Relative Impact on GAC Usage Rates of Operating Strategies for Treatment of a Contaminated Groundwater,” *Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management*, ASCE, 12(2), 60-69.

Faust, S. D., and Aly, O. M. (1998). *Chemistry of water treatment* (Second edition). Chelsea, MI: Ann Arbor Press.

Fritz, W., Merk, W., Schlunder, E.U. (1980). “Competitive Adsorption of Two Dissolved Organics onto Activated Carbon.” *Chemical Engineering Science*, 36(4), 743-757.

Hand, D.W., Crittenden, J.C., Thacker, W.E. (1984) Simplified Models for Design of Fixed-Bed Adsorption Systems. *J. Environ. Eng.*, 110(2), 440-456.

Hand, D.W., Crittenden, J.C., Arora, H., Miller, J.M., Lykins Jr., B.W. (1989) Designing Fixed-Bed Adsorbers to Remove Mixtures of Organics. *J. – Am. Water Works Assoc.*, 81(1), 67-77.

Hokanson, D.R., Hand, D.W., Crittenden, J.C., Rogers, T.N., Oman, E.J. (1999a) *AdDesignS™ Adsorption Design Software*, Version 1.0. Michigan Technological University, Houghton, MI.

Hokanson, D.R., Rogers, T.N., Hand, D.W., Crittenden, J.C., Oman, E.J. (1999b) *StEPP™ Software to Estimate Physical Properties*, Version 1.0. Michigan Technological University, Houghton, MI.

- Hristovski, K. D., Westerhoff, P. K., Crittenden, J. C., Olson, L. W. (2008). "Arsenate Removal by Iron (Hydr)Oxide Modified Granulated Activated Carbon: Modeling Arsenate Breakthrough with the Pore Surface Diffusion Model." *Separation Science and Technology*, 43 (11/12), 3154-3167.
- Hutchins, R.A. (1977) Designing Granular Activated Carbon Systems for Maximum Performance. *Proceedings of the Annual WWEMA Industrial Pollution Conference*, WWEMA, Atlanta, GA, 491-512.
- Hyun, Y. (2004) Optimization Study of an Existing GAC Treatment System Former Nebraska Ordinance Plant, Mead, NE. *Thesis presented to the University of Nebraska-Lincoln in partial fulfillment of the requirements for the degree of M.S. in Environmental Engineering*.
- Mertz, K.A., Gobin, F., Hand, D.W., Hokanson, D.R., Crittenden, J.C. (1999) *User's Manual – Adsorption Design Software for Windows (AdDesignSTM)*, Center for Clean Industrial Treatment Technologies, Michigan Technological University, Houghton, MI.
- Narbaitz, R.M., Benedek, A. (1983) Least Cost Process Design for Granular Activated Carbon Adsorbers. *Journal of the Water Pollution Control Federation*, 55(10), 1244-1251.
- New, C.W. (2009) Maximizing Sorbent Life with Bypass Blending, M.S. Thesis, University of Nebraska – Lincoln.

- Scharf, R. G., Johnston, R. W., Semmens, M. J., & Hozalski, R. M. (2010). Comparison of batch sorption tests, pilot studies, and modeling for estimating GAC bed life. *Water Research*, 44(3), 769-780.
- Snoeyink, V.L., Summers, R.S. (1999) Chapter 13, Adsorption of Organic Compounds, Letterman, R.D. (Ed.), *Water Quality and Treatment*, Fifth Edition, McGraw-Hill, NY.
- Summers, R. S., Kim, S. M., Shimabuku, K., Chae, S., & Corwin, C. J. (2013). Granular activated carbon adsorption of MIB in the presence of dissolved organic matter. *Water Research*, 47(10), 3507-3513.
- Stewart, B. A; New, C. W; Hosni, A, and Dvorak, B. I (2013) A Framework for Evaluating Sorbent Usage Rate of Various Sorption Column Configurations with and without Bypass Blending, *Journal of Environmental Engineering (ASCE)*, 139(4) 554-563.
- United States Environmental Protection Agency (EPA/456/F-99-004, May 1999). *Choosing an adsorption system for VOC: carbon, zeolite, or polymers?* Retrieved July 6th, 2015 from <http://www.epa.gov/ttnchie1/mkb/documents/fadsorb.pdf>
- United States Environmental Protection Agency (EPA/815-R-00-028, December 2000). *Technologies and Costs for Removal of Arsenic from Drinking Water*. Retrieved July 6th, 2015 from http://water.epa.gov/drink/info/arsenic/upload/2005_11_10_arsenic_treatments_and_costs.pdf

- United States Environmental Protection Agency (US EPA) (2003a) *Arsenic Treatment Technology Evaluation Handbook for Small Systems*. July 2003, EPA 816-R-03-014.
- United States Environmental Protection Agency (US EPA) (2003b) *Design Manual: Removal of Arsenic from Drinking Water by Adsorptive Media*. March 2003, EPA/600/R-03/019.
- United States Environmental Protection Agency. (EPA/600/R-08/141, December 2008a). *Arsenic Removal from Drinking Water by Adsorptive Media. U.S. EPA Demonstration Project at Queen Anne's County, Maryland. Final Performance Evaluation Report*. Retrieved from July 6th, 2015 from <http://nepis.epa.gov/Exe/ZyPDF.cgi/P1002V56.PDF?Dockey=P1002V56.PDF>
- United States Environmental Protection Agency. (EPA/600/R-08/008, March 2008b). *Arsenic Removal from Drinking Water by Adsorptive Media. U.S. EPA Demonstration Project at Rimrock, AZ. Final Performance Evaluation Report*. Retrieved July 6th, 2015 from <http://nepis.epa.gov/Adobe/PDF/P1009CYA.pdf>
- United States Environmental Protection Agency. (EPA/600/R-08/051, April 2008c). *Assessing Arsenic Removal by Metal (Hydr)Oxide Adsorptive Media Using Rapid Small Scale Column Tests*. Retrieved July 27th, 2015 from <http://nepis.epa.gov/Exe/ZyPDF.cgi/P10012K8.PDF?Dockey=P10012K8.PDF>

United States Environmental Protection Agency. (EPA/600/R-08/081, July 2008d).

Arsenic Removal from Drinking Water by Adsorptive Media. U.S. EPA

Demonstration Project at Dummerston, VT. Final Performance Evaluation Report.

Retrieved July 6th, 2015 from

<http://nepis.epa.gov/Exe/ZyPDF.cgi/P10012TI.PDF?Dockey=P10012TI.PDF>

United States Environmental Protection Agency. (EPA/600/R-10/165, December

2010). *Arsenic Removal from Drinking Water by Adsorptive Media. U.S. EPA*

Demonstration Project at Upper Bodfish in Lake Isabella, CA. Final Performance

Evaluation Report. Retrieved July 6th, 2015 from

<http://nepis.epa.gov/Exe/ZyPDF.cgi/P100AF2A.PDF?Dockey=P100AF2A.PDF>

United States Environmental Protection Agency. (EPA/600/R-11/035, April 2011a).

Arsenic Removal from Drinking Water by Adsorptive Media. U.S. EPA

Demonstration Project at Oregon Institute of Technology at Klamath Falls, OR.

Final Performance Evaluation Report. Retrieved July 6th, 2015 from

<http://nepis.epa.gov/Exe/ZyPDF.cgi/P100BHL5.PDF?Dockey=P100BHL5.PDF>

United States Environmental Protection Agency. (EPA/600/R-11/074, July 2011b).

Arsenic Removal from Drinking Water by Adsorptive Media. U.S. EPA

Demonstration Project at Geneseo Hills Subdivision in Geneseo, IL. Final

Performance Evaluation Report. Retrieved July 6th, 2015 from

<http://nepis.epa.gov/Exe/ZyPDF.cgi/P100BL2J.PDF?Dockey=P100BL2J.PDF>

United States Environmental Protection Agency. (EPA/600/R11/090, September 2011c). *Costs of Arsenic Removal Technologies for Small Water Systems. US EPA Arsenic Removal Demonstration Program*. Retrieved June 18th 2015 from <http://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100CAXP.PDF>

United States Environmental Protection Agency. (EPA/600/R-11/035, April 2011d). *Arsenic Removal from Drinking Water by Adsorptive Media. U.S. EPA Demonstration Project at Lead, South Dakota. Final Performance Evaluation Report*. Retrieved July 6th, 2015 from <http://nepis.epa.gov/Exe/ZyPDF.cgi/P1009J41.PDF?Dockey=P1009J41.PDF>

Water Environment Federation (WEF), *Design of Municipal Wastewater Treatment Plants, MOP № 8*, 1998.

Westerhoff, P., De Haan, M., Martindale, A., & Badruzzaman, M. (2006). Arsenic adsorptive media technology selection strategies. *Water quality research journal of Canada*, 41(2), 171-184.

Worch, E. (2012). *Adsorption technology in water treatment: Fundamentals, processes, and modeling*. Berlin: De Gruyter.

Zimmer, G., Crittenden, J.C., Sontheimer, H., Hand, D.W. (1988) *Design Considerations for Fixed-Bed Adsorbers that Remove Synthetic Organic Chemicals in the Presence of Natural Organic Matter*. 1988 AWWA Conference Proceedings, Orlando, FL, 211-220.

**APPENDIX A. COST COMPONENTS DISTRIBUTION FOR SYSTEMS
FROM THE US EPA ARSENIC DEMONSTRATION PROGRAM**

This Appendix includes a set of diagrams showing visual representation of several cost components analyzed in this study.

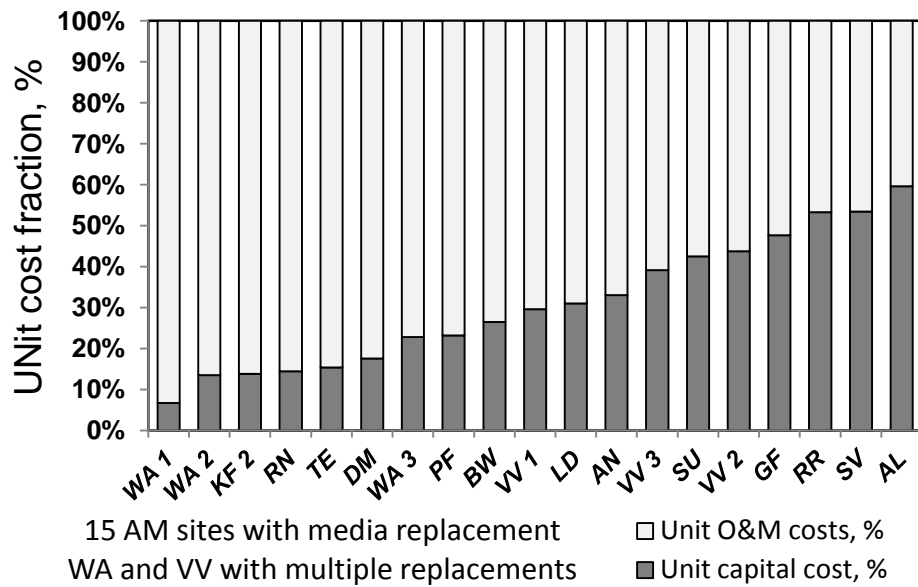


Figure A.1 – Relationship between capital and operating cost for systems with actual media replacement based on the unit cost of treated water (Data from US EPA, 2011)

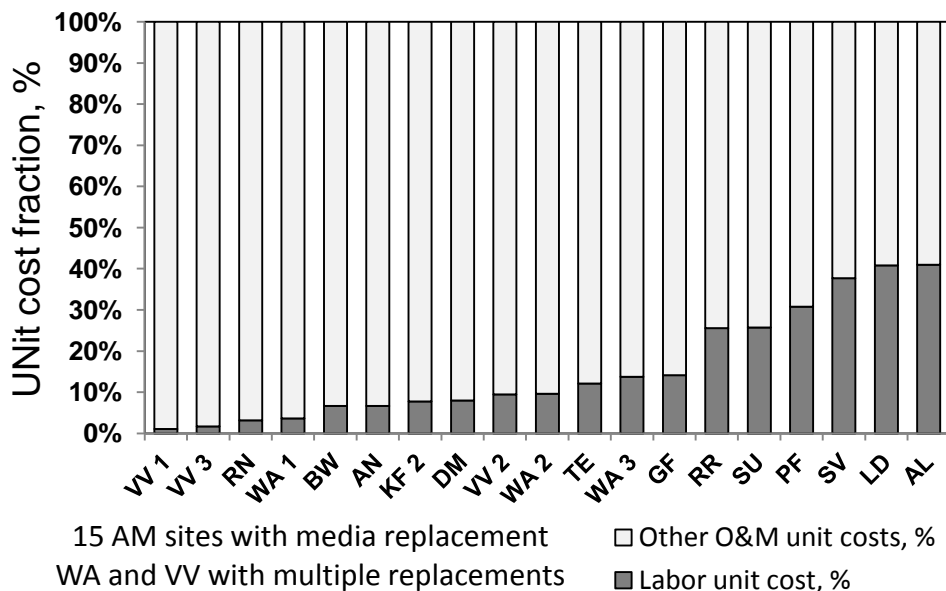


Figure A.2 – Fraction of labor cost component in the total operational and management unit cost based on the unit cost of treated water (Data from US EPA, 2011)

APPENDIX B. CYCLE REPLACEMENT COST RATIO CALCULATION

SPREADSHEET

Service to Fresh Media Cost ratio	Service Cost ratio	Cycle Replacement Cost (CRCost) for Single with simultaneous	Cycle Replacement Cost for Lead-lag (Parallel) with two individual column replacements	Cycle Replacement Cost ratio Single vs Lead-lag (Parallel)
RSCost (2xV) to FMCost (2xV)	RSCost (2xV) to RSCost (V)	CRCost (2xV) (Single)	2xCRCost (V) (Par. or Lead-lag)	CRCost(2xV)/ 2xCRCost(V)
2.00	1.15	\$ 30,000.0	\$ 44,782.6	0.670
1.90	1.15	\$ 29,000.0	\$ 43,043.5	0.674
1.80	1.15	\$ 28,000.0	\$ 41,304.3	0.678
1.70	1.15	\$ 27,000.0	\$ 39,565.2	0.682
1.60	1.15	\$ 26,000.0	\$ 37,826.1	0.687
1.50	1.15	\$ 25,000.0	\$ 36,087.0	0.693
1.40	1.15	\$ 24,000.0	\$ 34,347.8	0.699
1.30	1.15	\$ 23,000.0	\$ 32,608.7	0.705
1.20	1.15	\$ 22,000.0	\$ 30,869.6	0.713
1.10	1.15	\$ 21,000.0	\$ 29,130.4	0.721
1.00	1.15	\$ 20,000.0	\$ 27,391.3	0.730
0.67	1.15	\$ 25,000.0	\$ 32,391.3	0.772
0.50	1.15	\$ 30,000.0	\$ 37,391.3	0.802

Figure B.1 – Sample Cycle Replacement Cost ratio calculation spreadsheet

APPENDIX C. LIST OF ADSORPTION SYSTEMS PARTICIPATED IN THE US EPA ARSENIC REMOVAL DEMONSTRATION PROGRAM

Table C.1 –Technical and cost parameters for adsorptive media systems from the US EPA arsenic removal demonstration program
(Data from US EPA, 2011)

Site ID	Design flowrate (gpm)	Design configuration	Arsenic concentration in the raw water (µg/L)	C/C ₀ ratio	Media type	Replaced volume of media (ft ³)	Media unit cost (\$/ft ³)	Fresh media cost (\$)	Replacement service cost (\$)	Cycle replacement cost (\$)
GF	10	Lead-lag	29.7	0.34	AD-33™ - G	5.00	\$300.0	\$1,500.0	\$2,699.0	\$4,199.0
BL	10	Lead-lag	15.4	0.65	ARM 200	4.50	\$300.0	\$1,350.0	\$2,699.0	\$4,049.0
SU	12	Lead-lag	31.7	0.32	A/I Complex 2001	3.00	\$450.0	\$1,350.0	\$960.0	\$2,310.0
WA2	14	Lead-lag	39.1	0.26	A/I Complex 2000	6.00	\$498.8	\$2,993.0	\$700.0	\$3,693.0
WA3	14	Lead-lag	39.1	0.26	GFH®	6.00	\$292.5	\$1,755.0	\$700.0	\$2,455.0
WA1	14	Lead-lag	39.1	0.26	A/I Complex 2000	12.00	\$517.0	\$6,204.0	\$1,365.0	\$7,569.0
PF	15	Lead-lag	25	0.40	ArsenX ^{np}	2.30	\$852.0	\$1,960.0	\$779.6	\$2,739.6
WS	17	Lead-lag	24.7	0.40	Adsorbia™	7.50	\$450.0	\$3,375.0	\$2,433.0	\$5,808.0
DM	22	Lead-lag	42.2	0.24	A/I Complex 2000	6.00	\$517.0	\$3,102.0	\$810.0	\$3,910.0
KF1	30	Lead-lag	29.8	0.34	ArsenX ^{np}	10.00	\$595.0	\$5,950.0	\$1,750.0	\$7,700.0
VV2	37	Lead-lag	39.4	0.25	AAFS50	22.00	\$99.0	\$2,178.0	\$2,188.0	\$4,366.0
VV3	37	Lead-lag	39.4	0.25	AAFS50	22.00	\$500.0	\$11,000.0	\$2,610.0	\$13,610.0
VV1	37	Lead-lag	39.4	0.25	AAFS50	44.00	\$99.0	\$4,356.0	\$4,375.0	\$8,731.0
BW	40	Lead-lag	46.4	0.22	G2®	170.00	\$40.0	\$6,800.0	\$9,952.0	\$16,752.0

Table C.1 –Technical and cost parameters for adsorptive media systems from the US EPA arsenic removal demonstration program (Continued)

Site ID	Design flowrate (gpm)	Design configuration	Arsenic concentration in the raw water ($\mu\text{g/L}$)	C/C ₀ ratio	Media type	Replaced volume of media (ft ³)	Media unit cost (\$/ft ³)	Fresh media cost (\$)	Replacement service cost (\$)	Cycle replacement cost (\$)
BR	40	Lead-lag	57.6	0.17	AD-33™ - P	22.00	\$300.0	\$6,600.0	\$4,590.0	\$11,190.0
RR	45	Lead-lag	59.7	0.17	AD-33™ - G	22.00	\$265.0	\$5,830.0	\$5,078.0	\$10,908.0
TN	50	Single	34.9	0.29	Bayoxide® E33	38.00	\$365.0	\$13,870.0	\$4,535.0	\$18,405.0
LI	50	Single	41.7	0.24	ArsenX ^{np}	54.00	\$400.0	\$21,600.0	\$16,671.0	\$38,271.0
KF 2	60	Lead-lag	29.8	0.34	ARM200	20.00	\$385.0	\$7,700.0	\$3,500.0	\$11,200.0
KF3	60	Lead-lag	29.8	0.34	Adsorbia™	20.00	\$678.0	\$13,560.0	\$3,500.0	\$17,060.0
LD	75	Lead-lag	22.2	0.45	ArsenX ^{np}	28.00	\$480.0	\$13,440.0	\$2,693.0	\$16,133.0
RF	100	Single	36	0.28	AD-33™ - G	60.00	\$245.0	\$14,700.0	\$4,820.0	\$19,520.0
WM	100	Single	45	0.22	AD-33™ - P	76.00	\$295.0	\$22,420.0	\$7,590.0	\$30,010.0
NP	145	Single	32.2	0.31	AD-33™ - G	71.20	\$274.0	\$19,508.8	\$10,007.0	\$29,515.8
TE	150	Single	12.7	0.79	Isolux™ - 302M	11.40	\$559.0	\$6,372.6	\$707.8	\$7,080.4
AL	150	Lead-lag	40.2	0.25	SORB 33-P	48.00	\$165.0	\$7,940.0	\$4,740.0	\$12,680.0
GE	200	Single	19.6	0.51	AD-33™ - G	100.00	\$260.0	\$26,000.0	\$5,215.0	\$31,215.0
SV	300	Single	20.1	0.50	SORB 33-G	160.00	\$155.8	\$24,928.0	\$2,800.0	\$27,728.0
AN	320	Single	23.5	0.43	SORB 33-P	124.00	\$202.0	\$25,080.0	\$5,820.0	\$30,900.0
RN	350	Single	67.2	0.15	GFH®	240.00	\$238.0	\$57,120.0	\$14,038.0	\$71,158.0
TA	450	Single	14	0.71	SORB 33-P	180.00	\$197.4	\$35,539.0	\$6,210.0	\$41,749.0
BC	640	Single	14	0.71	SORB 33-G	320.00	\$150.0	\$48,000.0	\$5,600.0	\$53,600.0