MALCOLM PIRNIE | ARCADIS

The Water Division of ARCADIS

Imagine the result

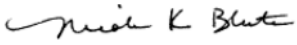
Hexavalent Chromium Treatment Residuals Management

Final Report

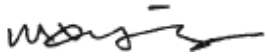
March 27, 2012

Revised January 11, 2013

ARCADIS:



Nicole K. Blute, PhD, PE
Principal Environmental Engineer

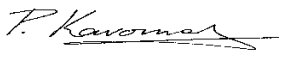


Xueying Wu, DEnv, PE
Staff Environmental Specialist

Tom Visosky, PE
Associate Vice President

James DeWolfe, PE, BCEE
Principal Environmental Specialist

APPROVAL TO DISTRIBUTE:



Peter Kavounas, PE
Assistant General Manager, City of Glendale California

Danielle Blacet
Senior Regulatory Advocate, ACWA

Hexavalent Chromium Treatment Residuals Management

Prepared for:
Association of California Water Agencies
City of Glendale, California – Department of Water and Power

Prepared by:
ARCADIS U.S., Inc.
888 West 6th Street
3rd Floor
Los Angeles
California 90017
Tel 213 614 9002
Fax 213 614 9003

Our Ref.:
05337011.0000

Date:
Finalized March 27, 2012
Revised January 11, 2013 to address comments from EPA/CH2M Hill

Tables

Figures

Appendices

1. Executive Summary

This study focused on characterizing and developing costs for Cr(VI) treatment residuals (waste) generated by two technologies, Reduction, Coagulation and Filtration (RCF) and Weak-Base Anion Exchange (WBA). Residuals have been identified as a key cost driver for both technologies in previous studies of Cr(VI) removal. The analysis performed in this project was based on the demonstration-scale study at the City of Glendale, California, which has been testing RCF and WBA for more than a year. Building upon the demonstration study results, residuals treatment and disposal options were evaluated for a broader range of water qualities to inform water utilities considering Cr(VI) treatment. Capital and operations and maintenance (O&M) costs for residuals handling/treatment and disposal were estimated for five system sizes (10 gpm, 100 gpm, 500 gpm, 2,000 gpm and 5,000 gpm) for RCF and WBA technologies. California state-wide cost implications for several potential Cr(VI) Maximum Contaminant Levels (MCLs) were also developed for systems that were included in a Cr(VI) occurrence database provided by California Department of Public Health (CDPH).

1.1 Background Information

The City of Glendale has been managing a major research effort to identify technologies for removing Cr(VI) from drinking water supplies since year 2000 in response to public concern with any Cr(VI) in drinking water supplies. As part of that effort, Cr(VI) removal cost data is being collected and is intended to inform the MCL setting process. A major part of the cost data is the identification of disposal costs for spent resin from the WBA process and sludge from the RCF process. The City of Glendale partnered with the Association of California Water Agencies (ACWA) to perform a more detailed study of these costs based to some degree on the past issues identified with the high cost of waste disposal from arsenic removal treatment systems. Glendale in turn contracted with ARCADIS to perform the technical research efforts.

1.2 WBA Residuals

WBA resin for Cr(VI) treatment is used as a single-pass, disposable media that is not regenerated. The primary WBA residuals waste products are spent resin and wastewater from resin replacement and initial backwashing. The wastewater is non-hazardous and can typically be discharged to the sewer. The spent resin generated at the City of Glendale demonstration-scale study was characterized as a non-RCRA hazardous waste for disposal in California due to chromium accumulated in the resin.

Additionally, the WBA resin tested (Amberlite PWA7) also removed uranium from the groundwater, which also classified the spent resin as a Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) waste. Although uranium levels in the groundwater were not high (i.e., 1.8 to 3.3 pCi/L), a significant amount of uranium was accumulated on the resin over the long service life. Consequently, the spent resin could be classified as a regulated radioactive waste if uranium exceeds 0.05% by weight. Regulated radioactive wastes have to be disposed in a Low Level Radioactive Waste facility with a high cost. In addition, a license issued by CDPH is required for possession and/or use of any waste containing uranium at more than 0.05% by weight. However, absorbent material added to the spent resin for the purpose of absorbing free liquid before disposal simultaneously sequestered water and reduced the uranium concentration in Glendale's spent WBA resin. If uranium concentrations are below 0.05% by weight (such as at Glendale), the aggregated resin could be disposed as a TENORM waste rather than a regulated radioactive material.

Another way to avoid spent resin becoming a regulated radioactive waste is to replace resin before uranium concentrations reach the regulatory limit. However, the resin service life might be significantly reduced, which may result in more frequent resin replacements and a higher operational cost. The costs for operation based on uranium accumulation versus Cr(VI) treatment target levels may be significantly different for different utilities. Therefore, selection of an operational approach must be evaluated on a site-specific basis, and costs may be underestimated for utilities with greater uranium concentrations.

Spent WBA resin containing no more than 0.05% source material (i.e., uranium or thorium) is not regulated radioactive waste and can be disposed of in landfills licensed to accept TENORM wastes. Due to chromium concentrations on the resin, spent WBA resin is likely to be considered a California regulated non-RCRA hazardous waste, which must be disposed in landfills also licensed to accept non-RCRA waste. This report demonstrates the variation in TENORM acceptance limits, required analyses and costs for different hazardous waste landfills. A flow chart is provided to allow utilities to navigate the way in which residuals are tested for waste disposal characterization. Landfills that can accept TENORM and non-RCRA wastes, include but not limited to Buttonwillow in California, Kettleman Hills in California, Grandview in Idaho, and Clive in Utah.

For facilities located on a Superfund site (e.g. Glendale), spent resin can only be disposed in landfills approved by USEPA for CERCLA wastes. Landfills including Buttonwillow in California, Kettleman Hills in California, Grandview in Idaho, and Clive

in Utah are approved for CERCLA and non-CERCLA wastes. Thus, spent resin generated at the WBA GS-3 well site can be disposed at one of these landfills based on waste classification (i.e., hazardous nature and radioactivity levels).

Detailed discussion of the disposal options for WBA residuals is provided in Section 3 of this report.

1.3 RCF Residuals

The primary residuals wastes for the RCF process include spent filter backwash water and solids that are thickened and dewatered for disposal. The water generated from the thickening and dewatering process can be recycled back to the RCF treatment process for water conservation, or discharged to the sewer (if allowed by the discharge permit). The dewatered solids need to be disposed in a landfill.

RCF solid residuals generated at the City of Glendale were classified a non-RCRA hazardous waste for disposal in California due to total chromium concentrations above the Total Threshold Limit Concentration (TTLC) regulatory limit, which is part of the California Waste Extraction Test. RCF residuals did not contain a significant amount of uranium. Approximately 38 pounds of dewatered solid waste was generated per day on average for a treatment flow rate of 100 gpm and influent Cr(VI) levels of 80 ppb for most of the test period. Solid waste quantities estimated by mass balance were relatively close to the actual quantities generated, supporting the use of mass balance calculations for estimating residuals quantities.

A preliminary evaluation of dewatering equipment for the RCF residuals indicated that centrifuges, plate and frame filter presses, and rotary drum vacuum presses could serve as an alternative to the passive filtration approach tested at Glendale. A discussion of the dewatering options for different system sizes is provided in Section 4.

Water samples from three other utilities representing different water qualities were evaluated using jar testing to simulate Cr(VI) removal by RCF and to evaluate residuals generation. The results showed that pH and possibly silica have significant effects on Cr(VI) removal. For water sources with pH values above approximately 8.0, pH reduction may be necessary for effective Cr(VI) removal with RCF. The effect of higher pH (i.e. 8.0) on Cr(VI) reduction might arise from ferrous consumption by oxygen, due to less ferrous available for Cr(VI) reduction. Samples spiked with higher silicate (76 mg/L as SiO_2) had less Cr(VI) reduction compared with samples containing below 30 mg/L as SiO_2. However, follow up sampling revealed that the ending pH after silica

addition may have been about 9.5, so the perceived impact of silica may have been from the formation of an iron-silica complex and/or high pH. Overall, jar testing results also showed that an Fe:Cr(VI) mass ratio of 25:1 effectively removed Cr(VI) and total Cr to below 1 ppb for influent Cr(VI) concentrations of 80 ppb or above with a pH below 7.7, silica below 30 mg/L, phosphate below 0.3 mg/L. However, a higher Fe:Cr(VI) ratio of 50:1 or 75:1 was necessary for effective Cr(VI) removal for lower influent Cr(VI) concentrations of approximately 10 ppb. For a low influent Cr(VI) concentration, the ferrous dose provided by a 25:1 ratio may not be sufficient to reduce Cr(VI) to below 1 ppb. Additionally, pH reduction was shown to improve Cr(VI) and total Cr removal, when combined with the higher Fe:Cr(VI) ratio, for lower influent Cr(VI) concentrations.

1.4 RCF Residuals Treatment Costs

Capital and O&M costs for RCF residuals treatment systems were estimated for 10-gpm, 100-gpm, 500-gpm, 2,000-gpm and 5,000-gpm RCF systems. Capital costs increase with increased system flow rate, from an estimated $0.3 million dollars for a 10-gpm RCF system to $7.4 million dollars for a 5,000-gpm RCF system.

The primary drivers for RCF O&M costs are residuals disposal and labor costs. The residuals disposal cost is relatively high resulting from non-RCRA hazardous waste classification in California. Residuals quantities will be primarily affected by ferrous dose, which depends on influent Cr(VI) concentration and the Fe:Cr(VI) ratio.

Unit treatment costs for RCF residuals are estimated for the five system sizes and four influent Cr(VI) concentrations. Unit costs decreased dramatically for larger systems, especially compared to 10 gpm, reflecting economies of scale. For all system sizes, unit costs increase with higher influent Cr(VI) concentrations.

State-wide costs for RCF residuals treatment were developed based on the capital and O&M costs estimated for the five RCF systems and Cr(VI) occurrence data provided by CDPH (Figure 1-1). Only the systems and water sources in the CDPH database as of November 2011 were considered in the cost analysis. For the five potential Cr(VI) MCL levels evaluated, the total costs for residuals treatment increase significantly with a lower MCL, as more water sources and systems would be affected (listed in Table 6-11). Net present values of O&M costs for 20 years were estimated to be at the same order of magnitude as for capital costs. Additional details are available in Section 6.

It is important to note that although Cr(VI) concentrations can be reduced to less than 1 ppb, the RCF process has not been shown to reliably achieve total Cr concentrations to

less than 5 ppb. If a utility focuses on total Cr removal (since Cr(III) can be reoxidized to Cr(VI) in the distribution system by chlorine or chloramines), then another treatment process (e.g. microfiltration to replace granular media filters) may be needed to achieve these low total Cr targets.

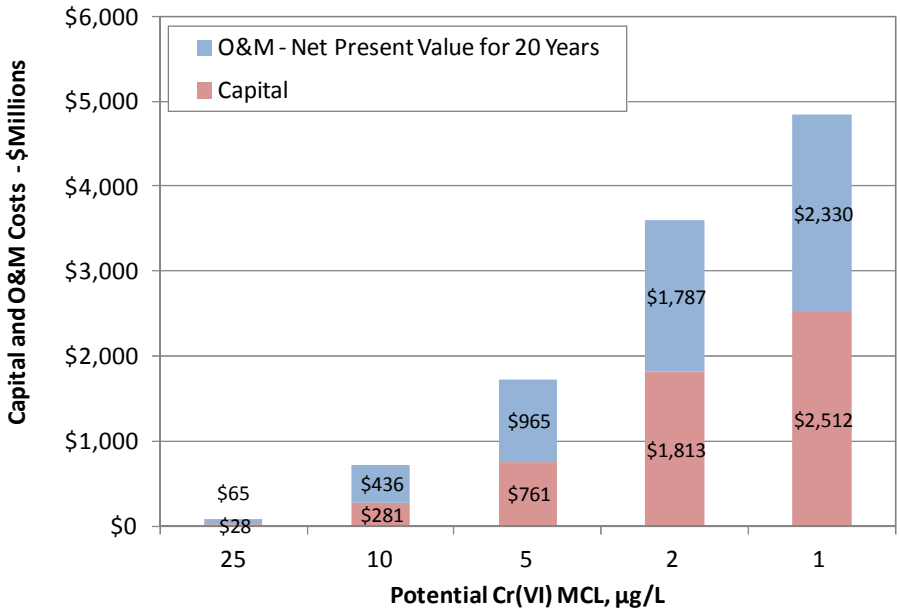


Figure 1-1. Capital and O&M Cost Estimates for RCF Residuals Treatment and Disposal for Potential Cr(VI) MCLs

For the systems and water sources in the CDPH database that would be affected by the potential Cr(VI) MCL levels.

Note: The costs are in 2011 Dollars.

1.5 WBA Residuals Treatment Costs

Capital and O&M costs for WBA residuals handling and disposal were also estimated for 10-gpm, 100-gpm, 500-gpm, 2,000-gpm and 5,000-gpm WBA systems. Capital costs for WBA residuals handling were estimated to be relatively low, as the systems consist of only a wastewater storage tank and discharge pumps. No residuals treatment is expected for WBA systems. The capital costs were estimated to increase with a greater system flow rate, from approximately $120,000 for a 10-gpm WBA system to $830,000 dollars for a 5,000-gpm WBA system.

The primary driver for WBA O&M residuals costs is spent resin disposal. The residuals disposal cost is relatively high, as spent resin is expected to be a non-RCRA

hazardous waste in California with uranium (i.e., TENORM). The residuals quantities were expected to be significantly affected by the Cr(VI) MCL to be established. As shown in Figure 7-3, a lower MCL level would result in significantly higher residuals disposal costs as more frequent resin replacement is expected. The O&M costs were based on an assumption that resin life is not significantly affected by source water Cr(VI) concentrations (i.e., that other parameters impact resin capacity more than Cr, such as we see for perchlorate-selective resins). At the time this residuals study was conducted, only Glendale water quality had been tested using the WBA resin, necessitating an assumption. Other research was initiated in the second half of 2012 to provide information on the impacts of other water quality parameters on resin life for Cr(VI) removal.

Unit treatment costs for WBA residuals decrease dramatically for larger system sizes (compared to 10 gpm), reflecting economies of scale. The potential Cr(VI) MCL also affects the unit costs significantly, with higher unit costs for a lower MCL level. Additional details are provided in Section 7.5.

State-wide costs for WBA residuals treatment suggest the total costs for residuals treatment increase dramatically with a lower MCL (Figure 1-2), as more water sources and systems would be affected and the resin usage life would be shorter to meet the lower MCL. Only the systems and water sources in the CDPH database as of November 2011 were considered in the cost analysis. Net present values of O&M costs for 20 years were estimated to be significantly higher than the capital costs, especially for the potential MCL levels less than 5 ppb. Additional details are provided in Section 7.

If a utility chooses to focus on total Cr removal rather than Cr(VI), then costs increase dramatically at the 1 and 2 ppb target treatment goals. The results shown in this summary focus on Cr(VI), but the potential impact on costs for focusing on total Cr are also contained within this report.

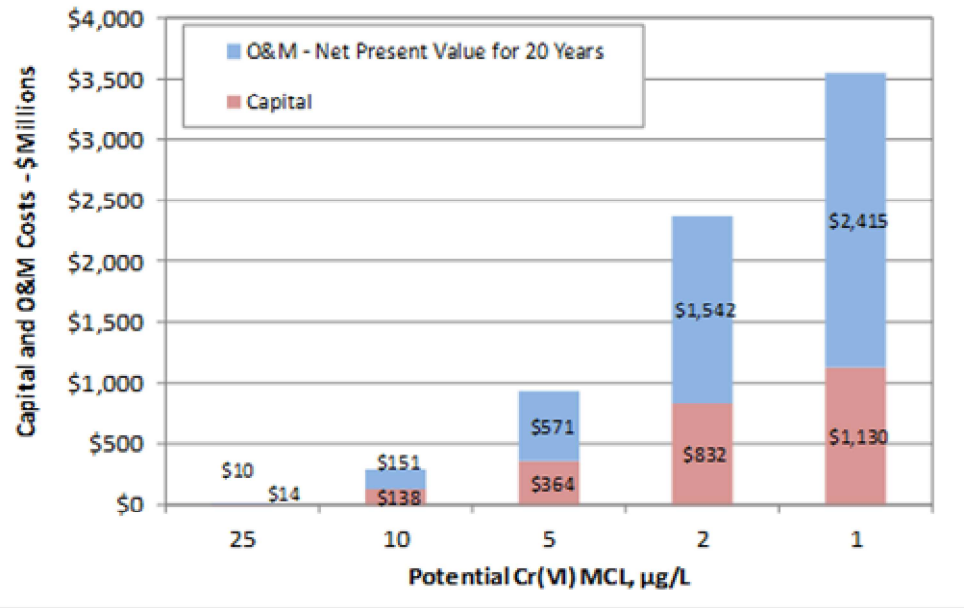


Figure 1-2. Capital and O&M Cost Estimates for WBA Residuals Handling and Disposal for Potential Cr(VI) MCLs

For the systems and water sources in the CDPH database that would be affected by the potential Cr(VI) MCL levels.

Note: The costs are in 2011 Dollars.

2. Introduction

This section describes the project background, study objectives and report organization.

2.1 Background

In 2002, the City of Glendale (California) embarked upon a four-phase research campaign to identify and install treatment technologies for removing hexavalent chromium, Cr(VI), from drinking water wells. Phase I screened a wide range of technologies for the ability to provide treated water that meets or exceeds potential regulatory requirements for Cr(VI) and total chromium in drinking water. In Phase II, a range of technologies were pilot tested. Two technologies were identified from this effort for further demonstration testing, specifically reduction/coagulation/filtration (RCF) using ferrous sulfate and weak base anion exchange (WBA). From these studies, an "Expert Panel" recommended demonstration testing of RCF and WBA technologies. Glendale operated two facilities (WBA and RCF) at the demonstration-scale as part of Phase III.

Testing in Phase II identified water treatment residuals as a key cost driver for both RCF and WBA. Hence, the Association of California Water Agencies (ACWA) requested a study of residuals disposal options and costs that built upon prior work and findings of the Phase III demonstration study. While the initial focus of this study was on the Glendale chromium removal project, the information gained is valuable to all water utilities considering the need for Cr(VI) removal facilities. This information will provided to the U.S. Environmental Protection Agency and the California Department of Public Health as they develop a specific water quality standard for Cr(VI) in water supplies.

2.2 Objectives

The objectives of this study include:

- Evaluation of uranium accumulation on resins and opportunities for disposal of spent resin as a radioactive waste or a chromium ore.
- Development of cost estimates for solids thickening and dewatering options for the RCF process, in addition to information gained in demonstration testing.

- Estimation of residuals volumes generated in the RCF process for a representative range of water qualities encompassing different utilities in California with Cr(VI) in their water supplies.
- Extrapolation of residuals cost estimates to determine the potential cost to utilities in California for compliance with several potential Cr(VI) MCLs (i.e., 0.5 ppb, 1 ppb, 2 ppb, 5 ppb, 10 ppb, 25 ppb).

2.3 Report Organization

This report consists of seven sections. Sections 1 and 2 are executive summary and introduction, respectively. Section 3 evaluates the disposal options and costs for WBA residuals for the City of Glendale. Section 4 summarizes the RCF residuals volumes, characteristics and disposal costs for the demonstration-scale testing at the City of Glendale. Section 5 presents the bench-scale jar testing of different water qualities to assess RCF residuals volumes and characteristics. Sections 6 and 7 analyze the cost implications of RCF and WBA residuals in the State of California, respectively, based on the findings from the previous sections.

2.4 Project Management

The project management for this research effort was under the direction of:

Project Advisory Committee:

- U.S. Environmental Protection Agency—Dr. Bruce Macler
- California Department of Public Health—Heather Collins (formerly with CDPH, currently with Metropolitan Water District of Southern California)
- Metropolitan Water District of Southern California—Dr. Sun Liang
- Los Angeles Department of Water and Power—Dr. Pankaj Parekh
- East Bay Municipal Utility District—Dr. Rick Sakaji

Glendale Project Management Team

- Peter Kavounas, Assistant General Manager (during the course of the study)
- Donald Froelich, Project Manager
- Leighton Fong, Project Engineer

ARCADIS:

- Dr. Nicole Blute, Project Manager (formerly with ARCADIS during this study)
- Dr. Xueying Wu, Assistant Project Manager (formerly with ARCADIS during this study)

2.5 Project Budget

The budget for the research effort was $99,000 with the costs allocated to City of Glendale for project management and CDM Constructors for operational and laboratory costs of $8,500, and ARCADIS $90,500 for completion of the bench testing, analysis of disposal options for residuals streams, and cost analysis.

An additional $7,000 was provided to Hazen and Sawyer to incorporate and respond to comments provided by EPA and CH2M Hill subsequent to the Final Report submission.

3. Disposal Options for WBA Resins

This section focuses specifically on the options for disposal of spent WBA resins. The WBA process involves the use of single-pass, non-regenerable resins for Cr(VI) removal. Residuals streams for WBA are limited to hazardous spent resin and non-hazardous backwash water. Phases II and III testing revealed that the high Cr(VI) capacity of the tested WBA resin is accompanied by efficient removal of naturally occurring uranium by the resin. Previous study results suggest approximately 100,000 bed volumes of GS-3 well water at Glendale can be treated before resin replacement to avoid the formation of regulated radioactive waste due to uranium accumulation. However, the resin[1] is expected to have a significantly longer bed life with respect to chromium, as the resin effluent chromium concentration was less than 50% of the influent concentration by the end of Phase III pilot testing (approximately 113,000 bed volumes of water treated). A longer bed life would result in less frequent resin replacement, which may translate to substantial savings since the resin and disposal are costly. However, the disposal requirements and costs associated with a mixed waste[2] required investigation to determine the feasibility of this approach. Additionally, spent resin could potentially serve as a chromium ore since it can accumulate several weight percent of chromium; this option was also evaluated.

3.1 Objectives

The purpose of this part of the study was to evaluate the following disposal options for WBA resin:

- As a mixed waste that is a California regulated, non-RCRA hazardous waste containing uranium exceeding 0.05% by weight.
- As a waste that is a California regulated, non-RCRA hazardous waste containing uranium equal or less than 0.05% by weight.
- As a chromium ore.

[1] Amberlite PWA7 resin, formerly known as Rohm & Haas Duolite A7.

[2] A mixed waste is a radioactive waste that is also a hazardous waste under Resource Conservation and Recovery Act (RCRA).

3.2 Approach

The disposal options for WBA resin were evaluated by interviewing experts, requesting information and quotations from landfills and researching radioactive waste regulations. Several experts of radioactive and hazardous wastes were consulted to discuss the disposal options for WBA resins. The experts included, but were not limited to, senior engineers with Malcolm Pirnie, specialists with landfills located in California, Idaho and Utah, a remediation expert with Siemens, and staff with California Department of Public Health Radiologic Health Branch (CDPH RHB). Landfills contacted included Energy Solutions, Waste Management, Clean Harbors, and US Ecology. Reference materials consulted included those available from the Nuclear Regulatory Commission (NRC), CDPH RHB, and US Environmental Protection Agency (USEPA).

3.3 Resin Characterization

The disposal options for WBA resin were based on spent resin analysis results from previous pilot testing and the current demonstration-scale study at Glendale. Previous pilot testing results showed the spent resin passed the federal TCLP[3] test (metal analysis), suggesting it would not be considered a federal hazardous waste (i.e. the waste would be a non-RCRA waste). However, the spent resin did not pass the California WET[4] test, specifically due to chromium concentrations exceeding the TTLC[5] component of the WET test. Thus, the resin would be classified a California regulated non-RCRA hazardous waste.

During the demonstration-scale study, resin in the lead bed was monitored for uranium at the top (25% port), middle (50% port) and bottom (75% port) resin layers on a monthly basis. The raw water contained uranium in the range of 1.8 – 3.3 pCi/L, with an average of 2.7 pCi/L, which translates to 2.7 – 5.0 ppb with an average of 4.1 ppb. Figure 3-1 shows uranium accumulation in the lead bed resin over time. At approximately 13,000 bed volumes of water treated (one month of operational time), the top resin layer (25% port) accumulated approximately 0.04% uranium. The 75% port sample resin had 0.07% uranium in approximately two months of operations. At approximately 64,000 bed volumes of water treated (4 months of operational time), uranium concentrations for the three resin layers were all beyond the regulatory limit of

[3] TCLP – Toxicity Characteristic Leaching Procedure

[4] WET – Waste Extraction Test

[5] TTLC – Total Threshold Limit Concentration

0.05% uranium by weight. By the time the first bed was replaced, uranium concentrations reached approximately 0.5% by weight, which was also likely the resin capacity for uranium because uranium leakage was observed in the vessel effluent water. The resin is considered a technically enhanced naturally occurring radioactive material (TENORM)[6]. Note that water treatment residuals are generally excluded from low level radioactive waste (LLRW) classification, which encompasses materials that are slightly above natural radiation background levels to highly radioactive materials that require extreme caution when handling. However, uranium is "source material" that is regulated by the NRC and the State of California, such that water treatment plant residuals can become classified as LLRW if uranium concentrations exceed a specified threshold (see discussion below for details).

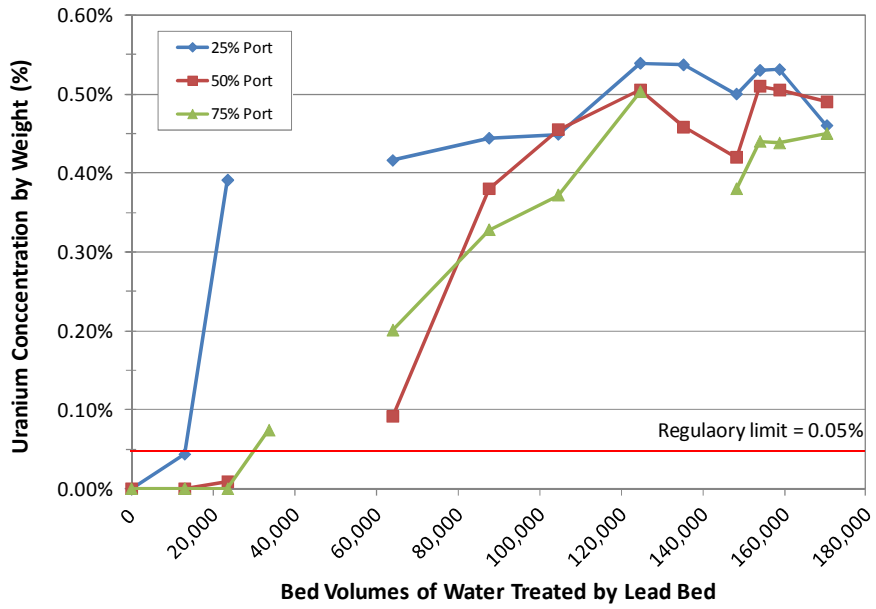


Figure 3-1. Resin Uranium Concentrations in the Lead Bed at Demonstration-Scale Study in Glendale, CA

Before disposal, the spent resin from the demonstration-scale study was comingled with absorbent material to absorb free liquid, which consequently also reduced uranium concentration to 150 mg/kg and 330 mg/kg in the two disposal bins. The

[6] TENORM is defined as naturally occurring materials, such as rocks, minerals, soils, and water whose radionuclide concentrations or potential for exposures to humans or the environment is enhanced as a result of human activities such as water treatment (USEPA, 2005).

aggregated spent resin passed the TCLP test. The spent resin was disposed at the US Ecology facility in Idaho as a TENORM waste. No additional California WET analysis was conducted because the resin was disposed out of the State of California. However, chromium accumulated on the spent resin was estimated at approximately 10,400 mg/kg (1.04%) based on mass balance calculations, which was above the TTLC limit for chromium. In addition, spent resin from the pilot-scale testing also contained chromium (5,860 mg/kg) above the TTLC limit of 2,500 mg/kg. Thus, the spent resin would be considered a non-RCRA hazardous waste if disposed in California.

During extraction of the resin, operations staff noted that the resin was difficult to remove from the vessels by the traditional "sluicing" method used for many single-pass ion exchange resins. The reason for this occurrence was unknown, and may have been related to precipitation of chromium in the beds or the long life of the resins. In any case, future resin vessels should be designed to accommodate resin removal in a different manner than the sluicing procedure.

3.4 License Requirements

Uranium and thorium are considered "source material"[7] (California Health and Safety Code, Section 114985(e)) and are subject to California state licensing and regulation. However, materials containing up to 0.05% by weight of source material are exempt from California state licensing and regulation, according to California Code of Regulation, Title 17, Division 1, Chapter 5, Section 30180(c)(2). Thus, no license is needed for possession and/or use of a resin containing source material (i.e. uranium and thorium) equal to or less than 0.05% by weight. A material containing uranium of 0.05% by weight has radioactivity of approximately 335 pCi/g for natural uranium, or 167 pCi/g for Uranium-238.

For Glendale, a resin sample collected from the top resin layer (with approximately 11,000 bed volumes of water treated) during the demonstration-scale study showed a thorium concentration below the method reporting limit of 1.1 mg/kg (i.e. < 0.0001% by

[7] "Source material means (1) uranium, thorium, or any other material which the department [CDPH RHB] declares by rule to be source material after the United States Nuclear Regulatory Commission, or any successor thereto, has determined the material to be such; or (2) ores containing one or more of the foregoing materials, in such concentration as the department declares by rule to be source material after the United States Nuclear Regulatory Commission, or any successor thereto, has determined the material in such concentration to be source material." California Codes Health and Safety Code, Section 114985 (e)

weight). Thus, thorium was not a concern for Glendale; uranium was the primary source material accumulated on the resin.

If a material contains more than 0.05% source material by weight, and a total of no more than 15 pounds of source material are in possession at any time, a general license is required (CCR Title 17, Section 30191). Under this general license, no more than 150 pounds of uranium may be possessed in any one calendar year. If more than 15 pounds of source material is possessed at any time, a specific license is required.

For the City of Glendale, approximately 13 pounds of uranium are retained in 185[8] cubic feet of the spent resin, assuming uranium in the raw water was completely removed by the lead resin bed before the first resin replacement (i.e., approximately one year of operating time). Thus, the City of Glendale would need to apply to the CDPH RHB for a general license, but no specific license is required.

3.5 Decision Tree

Figure 3-2 shows a decision tree for disposal options of solid waste generated in California. This decision tree is intended to provide a general reference for utilities removing Cr(VI) with WBA resin. For spent resin that is a California regulated non-RCRA hazardous waste and TENORM, the resin may be disposed in a hazardous waste landfill in California licensed to accept TENORM, if the uranium concentration is no more than 0.05%. Landfills licensed to accept TENORM may have differing upper limits on radioactivity.

If the uranium concentration is above 0.05% by weight, the spent resin becomes a regulated "source material" that is not exempt from the state regulation. In this case, the resin can only be disposed in a LLRW landfill. Only three commercial LLRW landfills are currently in operation: Barnwell in South Carolina, Richland in Washington, and Clive in Utah. These landfills accept LLRW from different states grouped as part of a "Compact". For example, the Barnwell facility only accepts LLRW from South Carolina, Connecticut and New Jersey. The Clive facility in Utah, which is owned and operated by Energy Solutions, is the only LLRW facility that can accept the resin as a source material generated in California. Since the resin is a non-RCRA hazardous waste and the State of Utah has no special characterization test on hazardous waste beyond the TCLP like California does, the resin could be disposed as a radioactive

[8] One WBA vessel contains a total amount of 185 ft^3 resin, although only 170 ft^3 is usable.

waste in the Clive facility in Utah, rather than a mixed waste (i.e. mixture of radioactive and hazardous waste).

The Glendale water treatment plant is located on a Superfund site. All wastes generated on a Superfund site are defined as CERCLA[9] wastes, including any hazardous substance, pollutant or contaminant. CERCLA waste transfer is regulated by the Off-Site Rule (OSR), whose purpose is to avoid environmental problems by directing these wastes to management units determined to be environmentally sound. CERCLA wastes can only be disposed at a facility approved by USEPA for CERCLA wastes, which operates in compliance with the RCRA or other applicable Federal or State requirements.

3.6 Landfill Options and Costs for Wastes from Non-Superfund Sites

For spent resin generated at non-Superfund sites, Table 3-1 lists TENORM acceptance limits, costs and contact information for four landfills that were contacted for spent resin disposal information. For Glendale, the landfill options and costs are discussed in a separate section below due to the OSR requirements. Note that the listed landfills are the ones recommended by interviewed experts, and other landfills may also be able to accept TENORM waste. Note that Waste Management requests a written document from CDPH RHB to show that the spent resin is not regulated radioactive waste in California.

As discussed earlier, if the source material concentration is above 0.05% by weight, the only facility that can accept the waste generated in California is the Clive facility in Utah. The other landfills contacted can only accept radioactive material containing source materials below 0.05%. The waste should be handled by a registered and licensed radioactive waste disposal company. Many landfills now use monitors to scan incoming trucks for radiation. If the monitors are triggered, the source must be identified and evaluated. Spent resin typically contains excess water, which needs to be removed before disposal. Free drainage of water may or may not meet criteria for solid waste disposal. Thus, additional handling and dewatering of the resin may be needed. Adding absorbent to the spent resin for the purpose of solidifying the waste could help to control the uranium concentration (as suggested by Siemens and US Ecology), although it increases the overall disposal cost due to increased volume. According to US Ecology, aggregation of radioactive material with clean material only

[9] CERCLA - Comprehensive Environmental Response, Compensation, and Liability Act

for the purpose of dilution is typically not allowed at their facility; however, adding clean absorbent material to solidify the liquids as a necessary drying procedure is acceptable. Individual utilities should contact CDPH RHB directly for any other site-specific regulations on aggregation of spent WBA resin. For Glendale, CDPH RHB indicated that aggregation of spent WBA resin with other materials that are not hazardous waste and do not contain radioactive materials may be acceptable.

All the landfills contacted require radiological analysis to verify that waste is below acceptance limits. CDPH currently does not regulate analysis methods on radionuclides. The alpha spectrometry method can be used for radioactivity of all of the uranium isotopes, and ICP-MS can be used to analyze mass concentrations of total uranium and isotopes. The California Buttonwillow landfill requires gross alpha, gross beta and gamma spectrometry analysis on a representative sample of the waste. The gamma spectrometry analysis should include measurement of all gamma emitting isotopes detected. Note that radiological analysis usually takes 30 to 45 days. Faster turnaround time is possible for additional cost. Once the resin is ready for disposal, TCLP and WET results will also be required for hazardous waste characterization for disposal in California.

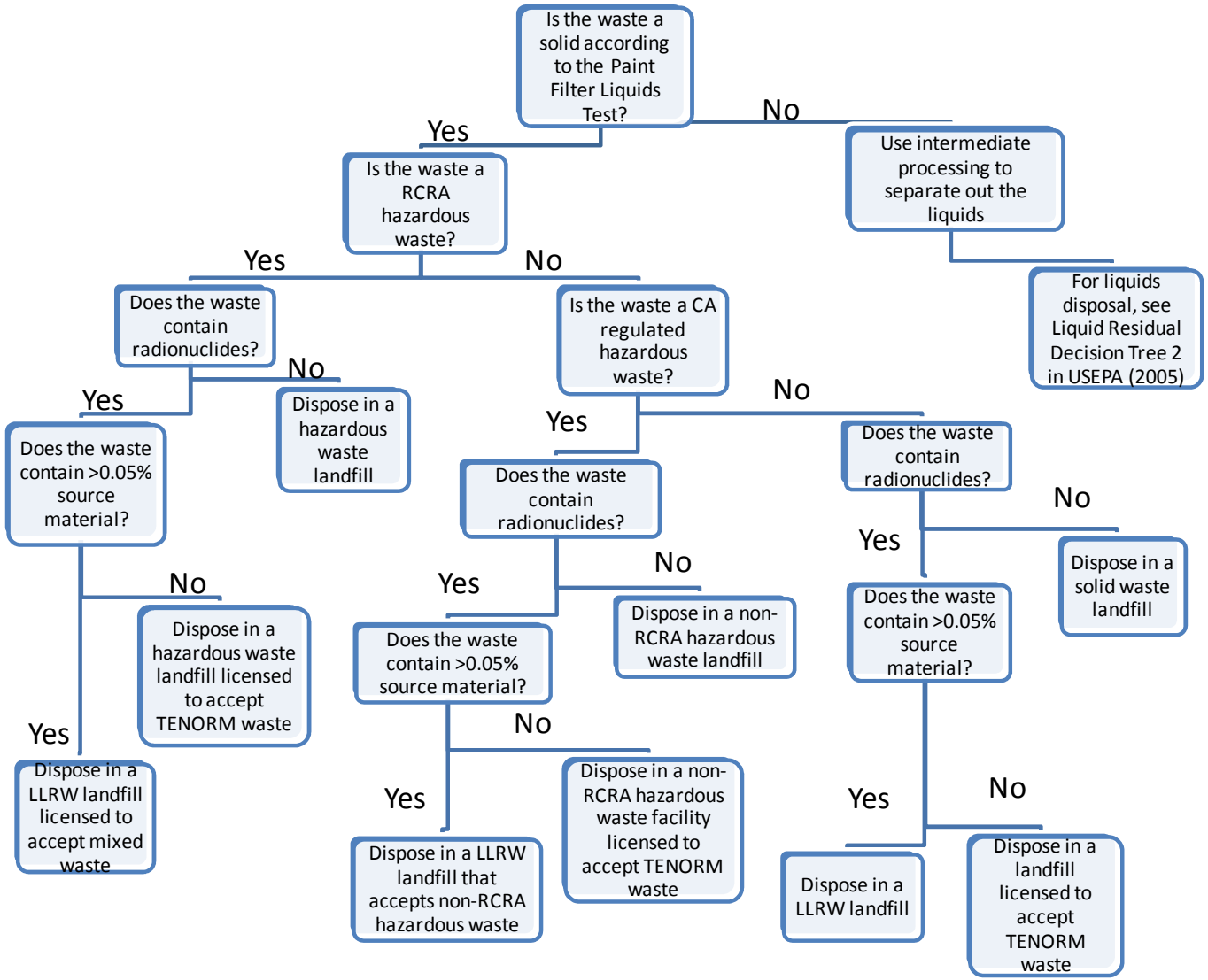


Figure 3-2. Decision Tree for Disposal of Solid Waste Generated in California

Revised based on the Decision Tree 1: Solid Residuals Disposal in USEPA (2005a).

Table 3-1. Contacted Landfill TENORM Acceptance Limits, Costs and Contacts for CA-Regulated Hazardous Waste and TENORM

Landfill	TENORM Acceptance Limits	Cost Quotes (As of August, 2010)	Notes	Total Cost for Disposal of 185 ft^3 Resin
CleanHarbors (Buttonwillow non-RCRA landfill, California)	TENORM containing radionuclides (in the decay series of U-238, U-235 and Th-232) up to 1,800 pCi/g; Cannot accept source material above 0.05% by weight.	$163 per drum for disposal, plus $21 per drum for transportation (minimum charge $210 per trip), and a demurrage charge of $103 per hour[§]	In 55-gallon drums	$4,784
		$31 per ton for disposal (minimum charge $775), plus $46 per ton for transportation (minimum 23 ton per load), and a demurrage charge of $103 per hour[§]	Bulk (23 ton minimum per load)	$1,833 (not including demurrage charge)
Waste Management (Kettleman Hills non-RCRA waste landfill, California)	TENORM containing radionuclides up to 2,000 pCi/g; Cannot accept source material above 0.05% by weight.	$30 per ton for disposal, $1,250 per trip for transportation, plus other service fees for bin mobilization ($360), bin rental ($9 per day) and bin liner ($40 each).	Bulk	$1,800 (assume only one bin needed)
US Ecology (Grandview RCRA waste landfill, Idaho)	Up to 3,000 pCi/g; Cannot accept source material above 0.05% by weight.	$265 per drum for disposal, $3,700 per truck trip. Site service for solidifying the material and verification of source material concentration below 0.05%: $900 per mobilization event, $280 per day for room and vehicle, $125 per hour for onsite personnel	In 55-gallon drums	$10,590 (not including any site service fees)
		$500 per ton, $3,700 per truck trip, $15 bin rental per day. Same site service fees as listed above.	Bulk	$5,700 (not including any site service fees)
Energy Solutions† (Clive, LLRW landfill, Utah)	No limit on NORM and TENORM waste	$150 per cubic feet for disposal (no transportation service for less than 30 drums per event) $300 per cubic feet for handling and transportation, and $100/hr for lab fee by Thomas Gray and Associates	Bulk	$84,050 (including handling and transportation, and a labor fee for 8 hours)

[§] Disposal in drums is typically more expensive than in bulk as drums are more labor intensive. For drum disposal, only a minimum of $210 for transportation will apply and no minimum of drums is required. For bulk disposal, a minimum charge of $775 for disposal and a minimum 23 ton per load for transportation (i.e. $1,058) will apply. To dispose of 185 ft^3 (i.e. 26 drums) of resin in drums, the total cost would be $4,784, including $4,238 for disposal and $546 for transportation. To dispose of the same resin amount (i.e. 4 tons) in bulk, the total cost would be $1,833, including the minimum $775 fee for disposal and $1,058 for transportation. † Interviewed experts and the Energy Solutions representative recommended disposing waste in other landfills if possible, due to high disposal costs in a LLRW landfill. Approximate conversions for PWA7 resin: 55 gallons = 7.35 cubic feet = 0.15 ton (based on resin density of 0.73 g/cm^3 or 6.08 lb/gal, assuming spent resin contains 20% excess moisture).

3.7 Landfill Options and Costs for Wastes from Superfund Sites

Wastes from a Superfund site are required to be disposed of in a landfill approved by USEPA for CERCLA wastes. According to a USEPA OSR expert interviewed, the four landfills listed in Table 3-1 are all approved by USEPA for CERCLA wastes. Thus, spent resin generated at a Superfund Site (such as the Glendale Water Treatment Plant) can be disposed in one of the four landfills or other landfills approved for CERCLA waste, based on the waste classification (for example, as a CA regulated hazardous waste and a TENORM).

3.8 Resin Operation Based on Chromium vs. Uranium

Utilities using WBA resin for Cr(VI) removal can operate the resin either based on 1) chromium removal or 2) accumulation of uranium on the resin. The first approach refers to an operation in which the resin is used until Cr(VI) saturation (or a defined water effluent concentration) is reached. For Glendale, this approach will yield a radioactive waste due to uranium buildup. The second approach is to focus on the uranium accumulation to keep uranium concentrations below the regulatory limit (i.e. 0.05% source material by weight). Resin costs and disposal costs must be weighed, along with other non-cost factors, to select the desired approach.

Demonstration-scale testing at the City of Glendale includes two vessels in lead/lag configuration. Table 3-2 compares the resin and disposal costs for the two operation approaches (i.e. Cr(VI) accumulation vs. uranium accumulation), based on data and information from the Glendale studies. Assuming for the Cr(VI) accumulation approach, the spent resin could be treated by adding absorbent materials, which also lower uranium concentrations to below the regulatory limit. Thus, the spent resin can be disposed as a TENORM waste (rather than a radioactive waste). The first approach is less expensive than the second approach (estimated $134,000 vs. $388,000 per year). Note the first approach was based on a treatment target of 5 ppb in the lag effluent. With a lower target, resin would need to be replaced more frequently than in this calculation, which would result in higher operational costs. Five potential Cr(VI) MCL levels are considered in cost estimates (Section 6), including 1, 2, 5, 10 and 25 ppb. If a MCL of 1 ppb is established, the WBA resin life would be reduced in order to meet the MCL, resulting in higher resin disposal costs. According to demonstration-scale results at Glendale, lag bed resin effluent contained approximately 1 ppb of Cr(VI) when approximately 100,000 BVs of water was treated by the lead bed. A safety factor should also be considered to ensure treated water meets the required MCL all the time. For other water utilities, resin and disposal costs could be significantly different

than Glendale, due to Cr(VI) and uranium concentrations. Issues other than costs also should be taken into consideration. A license is required for materials containing uranium concentration above 0.05% by weight. A special permit is also required for handling and transporting radioactive waste.

Table 3-2. Resin and Disposal Costs for Operations Based on Chromium vs. Uranium Accumulation

Description	Resin Operation Based on Maximum Cr(VI) Accumulation in Lead Vessel with Absorbent Material Added	Resin Operation Based on Uranium Accumulation up to 0.05% in Lead Vessel
Spent Resin Characteristics	TENORM and non-RCRA waste (Assume spent resin is blended with absorbent materials, which also reduce uranium concentrations to below regulatory limit)	TENORM and non-RCRA waste
Bed Volumes of Water Treated	180,000*	47,000**
Resin Operation Period before Replacement	1 year	3 months
Resin Replacement Frequency	1 replacement/year	4 replacement/year
Fresh Resin Cost^	$95,000/replacement	$95,000/replacement
Annual Resin Cost	$95,000/year	$380,000/year
Resin Disposal Cost	$39,000 /disposal[#]	$2,000/disposal[†]
Annual Resin Disposal Cost	$39,000/year	$8,000/year
Annual Resin and Disposal Costs	$134,000/year	$388,000/year

* Approximately 180,000 bed volumes of water were treated by the lead bed before resin replacement when Cr(VI) in the lag bed effluent reached 5 ppb.

** Approximately 47,000 bed volumes of water were treated by the lead bed before uranium in the lead resin reached approximately 0.05% by weight.

^ Based on a resin unit price of $420/cf plus $10.25/cf for deliveries less than 200 cf, and resin quantity of 193 cf per replacement (including 8 cf to account for spillage and other loss), and a resin conditioning fee of $12,000 for formaldehyde removal. In total, a resin replacement of 185 cf costs $95,038.

[#] Based on a preliminary quote from Siemens for resin exchange service and resin disposal at US Ecology's site in Idaho. The resin was meant to be disposed as a TENORM waste after dewatering treatment.

[†] Based on quotes for bulk waste from Clean Harbors and Waste Management. Other costs may also apply on a site-specific basis, such as demurrage charge and bin rental.

3.9 Disposal as a Chromium Ore

Disposal of spent WBA resin as a chromium ore was found to be problematic under most circumstances. Although many metal recycling companies would accept waste containing chromium, the presence of uranium as source material in the resin deters the recyclers due to the potential generation of regulated radioactive waste or mixed waste. For example, the International Metal Reclamation Company stated that waste containing any level of radioactive material is not acceptable. In addition to the problem of uranium, metal recycling companies usually require several percent of chromium as dry weight in the waste for chromium reclamation. The spent WBA resin from previous pilot testing (tested at pH 6.0) contained 1.46% of chromium in the top layer of the resin columns. The spent resin in the lead bed from the demonstration-scale study contained approximately 1% of chromium, based on mass balance calculation. Thus, chromium content of the spent WBA resin is below necessary levels unless run to a higher number of bed volumes. In general, disposal of WBA resin as a chromium ore does not seem to be a feasible option for Glendale but may be for other utilities without uranium accumulation or with high enough concentrations of chromium on the resin.

3.10 Summary and Conclusions

This review suggests that limited disposal options exist for solid waste containing source materials (i.e. uranium and thorium). A license issued by CDPH RHB is required for possession and/or use of any waste containing source material at more than 0.05% by weight. Additionally, material containing more than 0.05% source material has to be disposed of at a LLRW facility. All interviewed experts suggested operating the resin to less than 0.05% (considered a “bright line” in uranium-containing waste disposal options) due to licensing and regulatory requirements, potentially higher disposal costs, and difficulties in disposal. However, adding absorbent material to spent resin for the purpose of absorbing free liquid was allowed and can reduce the uranium concentration. If uranium concentrations are below 0.05% by weight, the aggregated resin could be disposed as a TENORM instead of regulated radioactive material. Utilities are urged to contact CDPH RHB before taking this approach, however, to ensure acceptability.

A preliminary cost analysis indicated that higher costs would be associated with operating resins based on uranium regulatory limits compared to maximum chromium

accumulation and use of absorbent material for the City of Glendale. Other non-cost factors must also be considered, including license requirements and special requirements for Superfund sites (if applicable). The costs for operation based on the two approaches may be significantly different for other utilities compared with Glendale, particularly due to differing Cr(VI) and uranium concentrations. Therefore, selection of an operational approach must be evaluated on a site-specific basis.

For water treatment facilities not located at a Superfund site, spent WBA resin containing no more than 0.05% source material is not regulated radioactive waste and can be disposed of in landfills licensed to accept TENORM. Due to chromium concentrations on the resin, spent WBA resin is likely to be considered a California regulated non-RCRA hazardous waste, which must be disposed in landfills also licensed to accept non-RCRA waste. Various landfills identified in Table 3-1 show different TENORM acceptance limits regardless of the source material cutoff (i.e., spent WBA resin with no more than 0.05% uranium may not meet the limits for specific landfills). Thus, it is recommended that utilities contact multiple landfills for TENORM acceptance limits, required analyses and costs at the time of treatment implementation.

For facilities located on a Superfund site (e.g. Glendale), spent resin can only be disposed in landfills approved by USEPA for CERCLA wastes. Landfills including Buttonwillow in California, Kettleman Hills in California, Grandview in Idaho, and Clive in Utah are approved for CERCLA wastes. Thus, spent resin generated at the Glendale GS-3 well site can be disposed at one of these landfills based on waste classification (i.e., hazardous nature and radioactivity levels).

Ongoing monitoring of uranium resin concentrations is a useful approach to prevent regulated radioactive waste generation if a uranium accumulation approach is selected. For example, the City of Glendale monitored uranium at 25%, 50%, and 75% of resin bed depths and vessel effluent from lead and lag vessels. Monitoring frequency should be adjusted based on the accumulation rate of uranium on the resin, especially when it approaches the regulatory limit.

Finally, due to the presence of uranium, spent WBA resin (at least the one tested) is generally not considered feasible for disposal as a chromium ore.

4. RCF Residuals at Demonstration-Scale at City of Glendale

This section focuses on the RCF residuals generated in demonstration-scale testing at City of Glendale, California. The amounts of filter backwash water and solid residuals, residuals characteristics, and disposal costs are summarized. Alternative solids thickening and dewatering options were evaluated, in addition to the Flo-trend passive filter (also called a Sludge Mate) that was used in demonstration-scale testing.

4.1 RCF Demonstration Process Overview

Figure 4-1 shows the process flow diagram for the 100-gpm demonstration-scale RCF system at the City of Glendale California. Raw water from the GN-3 well flows to the demonstration site with a flow rate of 100 gpm sent to the RCF process. Ferrous sulfate is injected into the water at a dose based on a ferrous (Fe) to chromium (Cr) mass ratio [Fe:Cr(VI)], which is typically 25:1 with variations up to 75:1 for testing purposes during the demonstration study. The influent Cr(VI) concentration is approximately 80 ppb. Thus, the ferrous dose based on the Fe:Cr(VI) ratio of 25:1 is approximately 2.0 mg/L as Fe.

After going through a static mixer, the iron-spiked influent water flows to three identical reduction tanks piped in series. Each reduction tank is equipped with a mechanical mixer and has a water volume of 1,500 gallons. The three reduction tanks in series provide a total detention time of 45 minutes for the 100 gpm water flow. The purpose of using three tanks in series is to increase mixing efficiency by minimizing short circuiting and back flow, while enabling evaluation of lower reduction times during some testing periods.

Upon exiting the reduction tanks, the water flows to an aeration tank in which air is bubbled to ensure full oxidation of ferrous iron to ferric iron and a buildup of iron particles. After aeration, water enters a 500-gallon rapid mixing tank, into which polymer (0.1 mg/L of Magnafloc Ciba E38) is injected for enhanced Fe and Cr floc formation. The mixing tank provides an additional 5 minutes for floc formation.

After rapid mix, water containing Fe and Cr floc is pumped by a progressive cavity pump to two pressurized dual media filters in down-flow mode (one duty, one standby). The dual media filters consist of approximately 24 inches of anthracite and 12 inches of sand, with a supportive underdrain. The design hydraulic loading rate for both filters is approximately 3 gallons per minute per square foot (gpm/sf). The filtered water blends with water from other Glendale wells and undergoes further treatment (for volatile

organic compounds) at the Glendale Water Treatment Plant before being served to consumers.

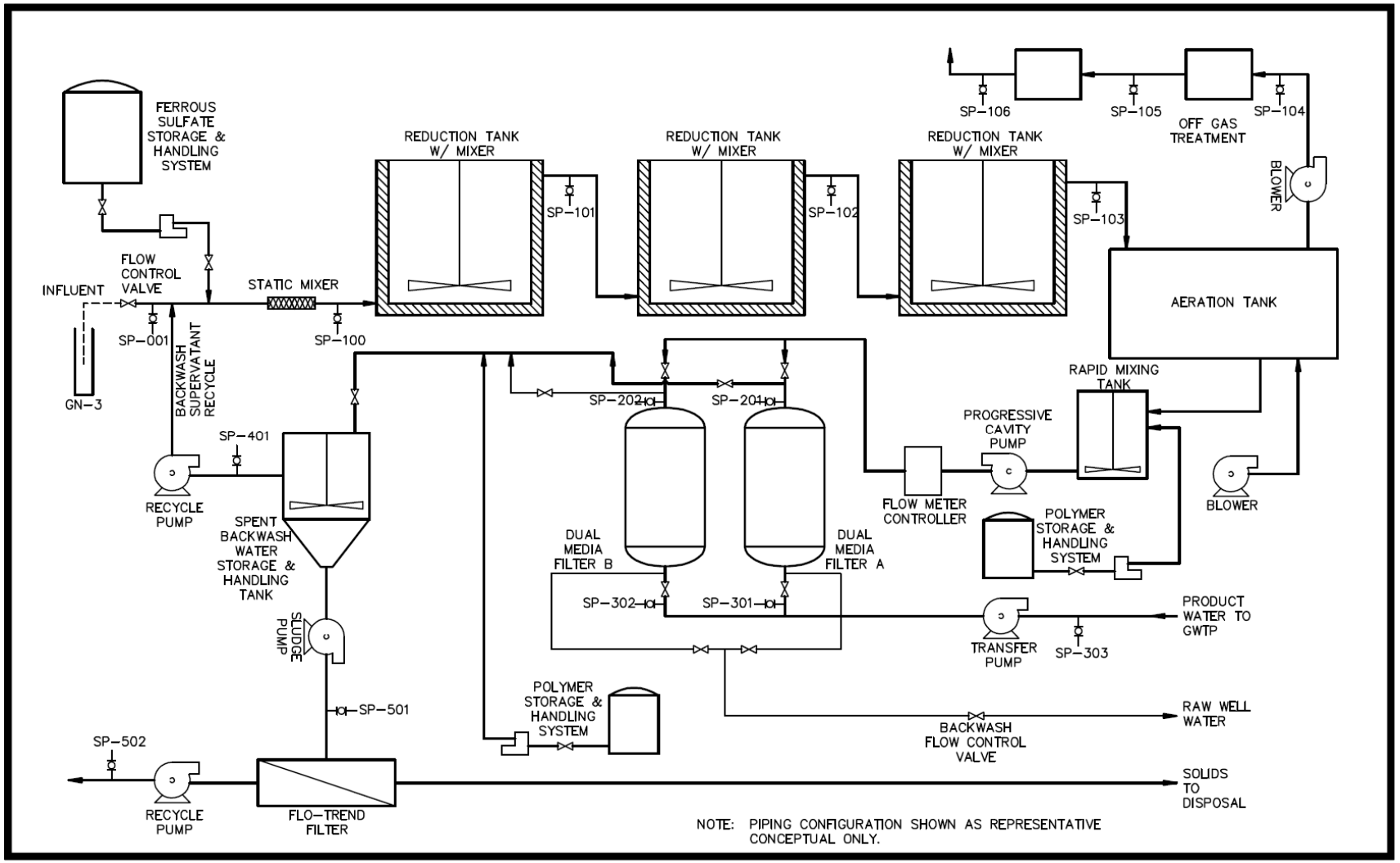


Figure 4-1. RCF Demonstration-Scale System Process Flow Diagram

4.2 Direct Filtration

Direct filtration (i.e. without a clarifier before filtration) is the approach being tested for the Cr(VI) removal RCF process, considering the relatively low solids loadings at 80 ppb Cr(VI). Based on the influent Cr(VI) concentration, ferrous dose, polymer dose, and filter operations, the estimated filter solids loading is approximately 2,100 g/m^2 for the RCF process at Glendale, as shown in Table 4-1. According to Twort et al. (2000), a range of 500 to 5,500 g/m^2 is quoted by Cleasby for solids loadings in direct filtration mode.

Considering the Glendale water contains a relatively high influent Cr(VI) concentration (i.e. 80 ppb) compared to most utilities, the RCF solids loading rate represents a conservative estimate due to the ferrous quantity added. While many groundwater sources in California contain much lower Cr(VI) concentrations, the filter solids loading rates are expected to be lower than the Glendale case (even though double the Fe:Cr(VI) ratio may be needed for lower Cr(VI) concentrations). Thus, direct filtration, compared with to sedimentation and filtration, is considered to be an appropriate approach in the cost implications analysis for RCF.

Table 4-1. Filter Solids Loading for RCF at Glendale, CA

Parameter (Unit)	Value
Flow rate, gpm	100
Influent Cr(VI), ppb	80
Fe:Cr(VI) mass ratio	25
Polymer dose, mg/L as active polymer	0.1
Dry solids concentration in filter influent, mg/L	6.1*
Filter hydraulic loading rate, gpm/sf	3
Filter run length before backwash, hours	48
Filter solids loading per run, g/m^2	2,100^

*Dry solids in filter influent = influent Cr(VI) as $Cr(OH)_3$ + 2.9 x ferrous dose as Fe + polymer dose.

^ Filter solids loading per run = filter hydraulic loading rate x dry solids concentration x filter run cycle.

4.3 Filter Backwash and Residuals Handling

The duty filter is typically operated for 48 hours before being backwashed. During backwashing, raw groundwater is pumped through the filter in an up-flow mode at a loading rate of 12 gpm/sf or higher for approximately 18 minutes. Concurrent air

scouring is also applied during backwash. Spent backwash water accounts for approximately 3% of the total flow rate in demonstration-scale testing.

Spent backwash water overflows to a separate storage/settling tank (i.e. gravity thickener), where 1.0 mg/L Magnafloc Ciba E38 active polymer (the same polymer used as flocculant) is injected and mixed so that the solids in the backwash water rapidly settle. Supernatant from the backwash storage/settling tank is recycled back to the head of the RCF system, which contains total Cr in the range of 27 – 7,400 ppb, with an average of 685 ppb and total iron in the range of 1.5 - 5.9 mg/L, with an average of 3.2 mg/L. Note that these backwash water concentrations of Cr and Fe were significantly higher than for pilot testing, indicating that sufficient settling may not have been provided in the Phase III Demonstration testing.

Settled backwash residuals are sent to a passive filtration system (called Sludge Mate, which is a felt-like material that separates solids from water). The filtrate was found to contain total Cr in the range of 1 – 2,400 ppb, with an average of 280 ppb, and total iron less than 1 mg/L. The filtrate could be recycled to the spent backwash water storage tank or sent to the sewer while dewatered solids captured on the filter were shipped to a non-RCRA hazardous waste landfill for disposal.

4.4 Solid Residuals Quantities, Characteristics and Disposal Costs

This section summarizes the solid residuals quantities, characteristics and disposal costs for the RCF demonstration process at City of Glendale.

4.4.1 Characteristics

Dewatered solid residuals samples were collected and sent to TestAmerica Laboratories, Inc. for residuals analysis, including the federal TCLP metals, California WET STLC[10] metals, TTLC metals, uranium and percent moisture. All metals were analyzed using Method SW846 6010B, except mercury by Method SW846 7470A, and uranium by Method SW846 6020. Percent moisture was analyzed using Method MCAWW 160.3 MOD. The analysis results are summarized in Tables 4-2 through 4-5, compared with the regulatory limits.

[10] STLC - Soluble Threshold Limit Concentration

TCLP metal results were all well below the regulatory limits, such that the solid residuals are not classified as a RCRA hazardous waste. TTLC metals accumulated on the solid residuals were all well below the California TTLC regulatory limits, except for chromium. Chromium concentrations in two of the three samples were 2,700 and 3,100 milligrams per kilograms (mg/kg) of wet solid, which were above the regulatory limit of 2,500 mg/kg that classifies the residuals as a California hazardous waste. In previous Phase III Bridge pilot testing, the solid RCF residuals had similar TTLC results for chromium. Thus, the solid residuals are considered a "non-RCRA hazardous waste" in California. In addition to TTLC testing, wastes in California are tested for STLC. All STLC metals results were below the regulatory limits, including total chromium. When a waste passes the TCLP test, the total chromium limit for STLC is 560 mg/L, instead of 5 mg/L if the waste does not pass the TCLP. However, exceedance of the TTLC alone is sufficient to trigger hazardous waste classification in California.

Total uranium results for the RCF residuals were below the regulatory limit of 500 mg/kg that would trigger classification as a radioactive waste. Moisture content of the dewatered solid residuals were 89%, 83% and 77% for the samples collected on 6/15/2011, 7/20/2010 and 4/21/2011, respectively. The average moisture content was approximately 83%.

Table 4-2. TCLP Metals Results for Dewatered Solid Residuals from Treating Well GN-3 in Glendale, California

Analytes	Regulatory Limit (mg/L)	Sample collected 6/15/2010 (mg/L)	Sample collected 7/20/2010 (mg/L)	Sample collected 4/21/2011 (mg/L)
Antimony	N/A	<0.25	<0.25	<0.25
Arsenic	5.0	<0.25	<0.25	<0.25
Barium	100.0	5.8	6.0	4.4
Beryllium	N/A	<0.05	<0.05	<0.05
Cadmium	1.0	<0.062	<0.062	<0.062
Chromium	5.0	<0.25	<0.25	<0.25
Cobalt	N/A	<0.050	<0.050	<0.050
Copper	N/A	<0.50	<0.50	<0.50
Lead	5.0	<0.12	<0.12	<0.12
Mercury	0.2	<0.0020	<0.0020	<0.0020
Molybdenum	N/A	<0.25	<0.25	<0.25

Analytes	Regulatory Limit (mg/L)	Sample collected 6/15/2010 (mg/L)	Sample collected 7/20/2010 (mg/L)	Sample collected 4/21/2011 (mg/L)
Nickel	N/A	<0.25	<0.25	<0.25
Selenium	1.0	<0.50	<0.50	<0.50
Silver	5.0	<0.12	<0.12	<0.12
Thallium	N/A	<0.25	<0.25	<0.25
Vanadium	N/A	<0.25	<0.25	<0.25
Zinc	N/A	<0.50	<0.50	<0.50

< MRL; N/A – not regulated

Table 4-3. TTLC Metals Results for Dewatered Solid Residuals from Treating Well GN-3 in Glendale, California

Analytes	California Regulatory Limit (mg/kg)	Sample collected 6/15/2010 (mg/kg)	Sample collected 7/20/2010 (mg/kg)	Sample collected 4/21/2011 (mg/kg)
Antimony	500	<0.48	10	30
Arsenic	500	16	18	40
Barium	10,000[#]	250	290	370
Beryllium	75	<0.095	<0.41	<0.36
Cadmium	100	0.88	<0.51	<0.45
Chromium	**2,500**	**2,000**	**2,700**	**3,100**
Cobalt	8,000	0.45	<0.82	<0.73
Copper	2,500	25	35	42
Lead	1,000	3.8	<2.0	<1.8
Mercury	20	0.042	0.042	0.085
Molybdenum	3,500*	<0.48	<2.0	<1.8
Nickel	2,000	1.5	3.8	<1.8
Selenium	100	<0.95	<4.1	<3.6
Silver	500	0.37	<2.0	<0.91
Thallium	700	1.6	<2.0	<1.8
Vanadium	2,400	200	260	300
Zinc	5,000	7.8	<6.1	7.4

All results were based on wet weight.

< Method Report Limit (MRL)

#Excluding barium sulfate;

*Excluding molybdenum disulfide.

Table 4-4. STLC Metals Results for Dewatered Solid Residuals from Treating Well GN-3 in Glendale, California

Analytes	California Regulatory Limit (mg/L)	Sample 6/15/2010 mg/L)	Sample 7/20/2010 (mg/L)	Sample 4/21/201 (mg/L)
Antimony	15	<0.50	0.70	2.2
Arsenic	5.0	<0.25	<0.25	2.8
Barium	100	14	12	13
Beryllium	0.75	<0.05	<0.05	<0.05
Cadmium	1.0	<0.05	<0.050	<0.05
Chromium	**5 or 560^**	**170**	**220**	**220**
Cobalt	80	<0.050	<0.050	0.075
Copper	25	2.1	3.2	3.2
Lead	5.0	<0.12	<0.12	<0.12
Mercury	0.2	<0.0050	0.0093	0.016
Molybdenum	350	<0.25	<0.25	<0.25
Nickel	20	<0.25	0.28	<0.25
Selenium	1.0	<0.50	<0.50	<0.50
Silver	5	<0.050	<0.12	<0.12
Thallium	7.0	<0.25	<0.25	<0.25
Vanadium	24	14	16	13
Zinc	250	0.91	1.4	1.5

^ 5 mg/L if Cr concentration in residuals is greater than the TCLP limit; 560 mg/L if Cr concentration in residuals is less than the TCLP limit

Table 4-5. Uranium and Percent Moisture Results on Dewatered Solid Residuals from Treating Well GN-3 in Glendale, California

Analytes	California Regulatory Limit	Sample collected 6/15/2010	Sample collected 7/20/2010	Sample collected 4/21/2011
Uranium	500 mg/kg	3.8 mg/kg*	10.5 mg/kg*	8.7 mg/kg*
Percent Moisture	N/A	89%	83%	77%

*Based on dry weight

N/A – not applicable

4.4.2 Quantities and Disposal Costs

Dewatered solid residuals are transferred to drums approximately once a month for temporary storage on site as part of the 100 gpm RCF system. The drums with residuals are then disposed through a contractor to Buttonwillow landfill in California, which is operated by Clean Harbors. As of September 2011, two batches of drums have been disposed of, with a total weight of 8,100 pounds (including the drum weight), which was generated during approximately seven months of operation (excluding system down times). Table 4-6 provides the quantities and actual costs for the two disposal events. The total costs include labor, equipment, waste disposal fees, transportation, etc. The average cost is $1.05/lb and $1.55/lb for the first and second batches, respectively. The higher average cost for the second batch is likely a result of relatively higher cost per drum due to a smaller quantity disposed since disposal also includes fixed costs, in addition to slightly higher prices in 2011 than 2010.

Table 4-6. Residual Disposal Costs for RCF Demonstration Process from Treating Well GN-3 in Glendale, California

Disposal Date	Number of Drums	Residual Weight in Drums (lb)	Disposal Cost* ($)	Average Unit Cost ($/Drum)	Average Unit Cost ($/lb)
8/25/2010	12	6,000	$6,295	$524.57	$1.05
5/12/2011	7	2,100	$3,254	$464.86	$1.55

*Total disposal cost includes the following fees:

- Labor, equipment and disposal service fee (15% of the total charge by Clean Harbors) by United Pumping Service, Inc.
- $235/drum disposal fee by Clean Harbors
- Freight to the disposal facility by Clean Harbors
- Recovery fee by Clean Harbors

- California hazardous waste landfill fee
- Kern County hazardous waste fee

Table 4-7 provides the residuals quantities estimated based on mass balance for the same period during which the solids disposed (listed in Table 4-6) was generated. Several assumptions were made for the mass balance calculations. 1) All ferrous iron added to water was assumed to be converted to ferric hydroxide, $Fe(OH)_3 \cdot 3H_2O$, and removed as solid residuals; 1 mg/L of ferrous iron dose as Fe generates 2.9 mg/L of solids (Baruth, 1990). 2) All hexavalent chromium in the influent water was assumed to be converted to chromium(III) hydroxide, $Cr(OH)_3$, and removed as solid residuals. 3) Solids from turbidity in groundwater are low and were ignored in the mass balance calculation. 4) All polymer added to the polymer rapid mixing tank to facilitate floc formation was removed as solid residuals. 5) The filter backwash water accounted for 3% of the influent flow rate, a value which was obtained from the demonstration-scale operational data. 6) All polymer added to the spent backwash settling tank was removed as solid residuals. 7) The residuals moisture content was 84%, which was the average content for the Sludge Mate residuals tested during June 2010 and April 2011. Based on these assumptions, the total amount of solid residuals was estimated to be 10,644 lbs with moisture during a period of 213 days of operation.

Table 4-7. Estimated Solid Residuals Quantities for the RCF Process Based on a Mass Balance Approach

Run No.	Operating Days	Fe:Cr(VI) Mass Ratio	Ferric Hydroxide Residual[1] (mg/L)	$Cr(OH)_3$[2] (mg/L)	Polymer[3] for Floc Formation (mg/L)	Polymer[4] for Solid Setting (mg/L)	Residuals with Moisture[5] (lb)
1, 2	90	25	5.80	0.16	0.1	1.0	3,872
3	6	30	6.96	0.16	0.1	1.0	307
4, 5	41	35	8.12	0.16	0.1	1.0	2,760
6 - 9	76	25	5.80	0.16	0.1	1.0	3,705
						Sum	**10,644**

1. Ferric hydroxide residuals (mg/L) = ferrous dose as Fe (mg/L) x 2.9.
2. $Cr(OH)_3$ (mg/L) = 80 µg/L x 103 / 52 / 1000. 103 and 52 are molecular weights for $Cr(OH)_3$ to Cr, respectively. 1000 is the unit conversion from µg/L to mg/L.
3. Polymer dose to the rapid mixing tank for floc formation is 0.1 mg/L.
4. Polymer dose to the spent filter backwash tank is 1.0 mg/L.
5. Residual with moisture (lb) ={ [ferric hydroxide residuals + $Cr(OH)_3$ + polymer for floc formation] x 100 gpm x operating days x 3.785 (L/gal) x 1440 (min/day) / 1000 (mg/g) / 454 (g/lb) + [polymer for solid setting x 100 gpm x 3% x operating days x 3.785 (L/gal) x 1440 (min/day) / 1000 (mg/g) / 454 (g/lb)] }/(1 – moisture content)

Table 4-8 compares the actual residuals weight to the estimated quantities based on mass balance. The total residuals weight is approximately 7,663 lb, excluding the drum weight. The estimated total residuals weight is 10,644 lb, which is 139% of the actual weight. Some factors might contribute to the difference, including solids recycled back to the treatment process, variations in operational conditions, and losses of residuals to the sewer at times. Solids weight based on mass balance is considered a conservative estimate for RCF residuals quantities. Solid residuals quantities are estimated using mass balance for RCF residuals treatment and disposal cost implications in California. Assuming residual quantities estimated using mass balance are 139% of the actual quantities, the cost estimates using mass balance approach reflect an over-estimate by 39% for residual disposal. Residuals disposal accounts for 2% to 88% of the total system O&M costs (increasing for a greater flow rate and greater influent chromium concentration). Thus, the total system O&M costs (in Appendix A) would be reduced by 1% to 25% (increasing for a greater flow rate and greater influent chromium concentration). The potential effects are smaller for a smaller flow rate and a lower influent Cr(VI) concentration. For example, for a water source with a flow rate below 500 gpm and influent Cr(VI) below 10 ppb(the case for the majority of water sources in California with detectable chromium), the total O&M cost would be reduced by a maximum of 13%.

Table 4-8. Actual Residuals Weight Generated at GN-3 in Glendale vs. Estimates Calculated By Mass Balance

Item	Weight
Actual residuals disposed including drums	8,100 lb
Empty drum weight	437 lb (i.e.23 lb per drum x 19 drums)
Actual residuals excluding drums	7,663 lb
Estimated residuals based on mass balance	10,644 lb

4.5 Solids Thickening and Dewatering Options

This section reviews residuals treatment methods typically used to process spent filter backwash water, and identifies the treatment methods feasible for RCF residuals that are used for cost estimates in Section 6. Spent filter backwash water typically contains a low solids concentration and is treated by thickening and dewatering to obtain solids disposable to landfills (as shown in Figure 4-2). Filter backwash water is produced over a relatively short time period but at a high instantaneous flow rate. Equalization is often used to capture and store the backwash water, and release it over a longer period of time at a lower flow rate. Reduction of the flow rate through equalization helps

to reduce downstream treatment device sizing and the impacts to the main treatment plant if recycle is used. Thickening is often achieved by gravity thickeners. Dewatering can be performed using various technologies, which are reviewed and summarized in the following subsections. Supernatant from thickening and filtrate from dewatering process can be recycled back to the equalization tank or for water conservation. However, potential bacterial growth and/or carryover from the recycled water needs to be monitored and evaluated. Dewatered solids are usually disposed in landfills; while land application may be an alternative for non-hazardous wastes, it is not an option for RCF solids residuals (since it is classified a non-RCRA hazardous waste in California).

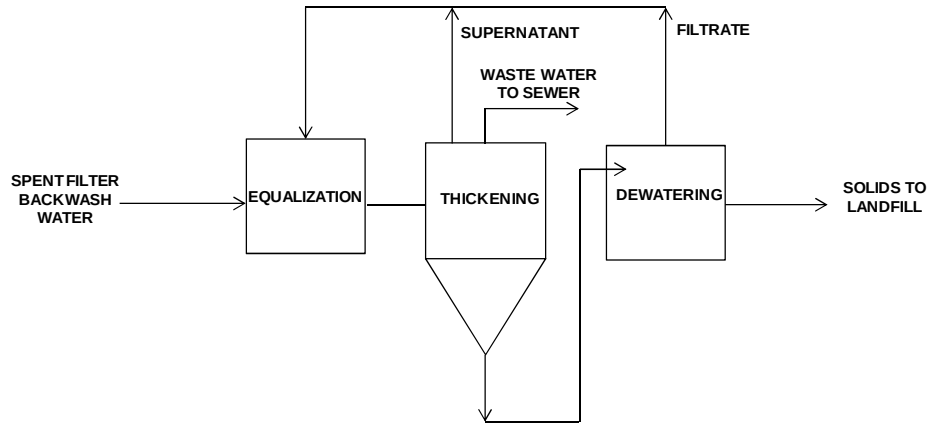


Figure 4-2. Spent Filter Backwash Water Treatment Process

4.5.1 Gravity Thickening

Gravity thickening (such as was applied in the Glendale system) is typically accomplished in a circular tank with a cone bottom designed and operated similarly to a solids-contact clarifier or sedimentation tank. Residuals are introduced to the tank and allowed to settle and compact in the cone bottom. The settled residuals are discharged from the tank to further treatment; the supernatant is often recycled or discharged to sewer. Gravity thickening tanks are feasible for small systems, as the tank sizes are relatively small. For medium and large systems, the sizes of gravity tanks usually require a significant footprint and are impractical.

Plate settlers are an alternative configuration to thicken residuals using gravity settling with a smaller footprint. Figure 4-3shows an example plate settler. Plate settlers provide a faster and more efficient way to remove solids from water by increasing the settling surface area while decreasing vertical settling distance. Spent filter backwash water is introduced to the settling basin though inlet ports. As the liquid flows upward, the solids settle on the inclined, parallel plates and slide into the sludge hopper at the bottom.

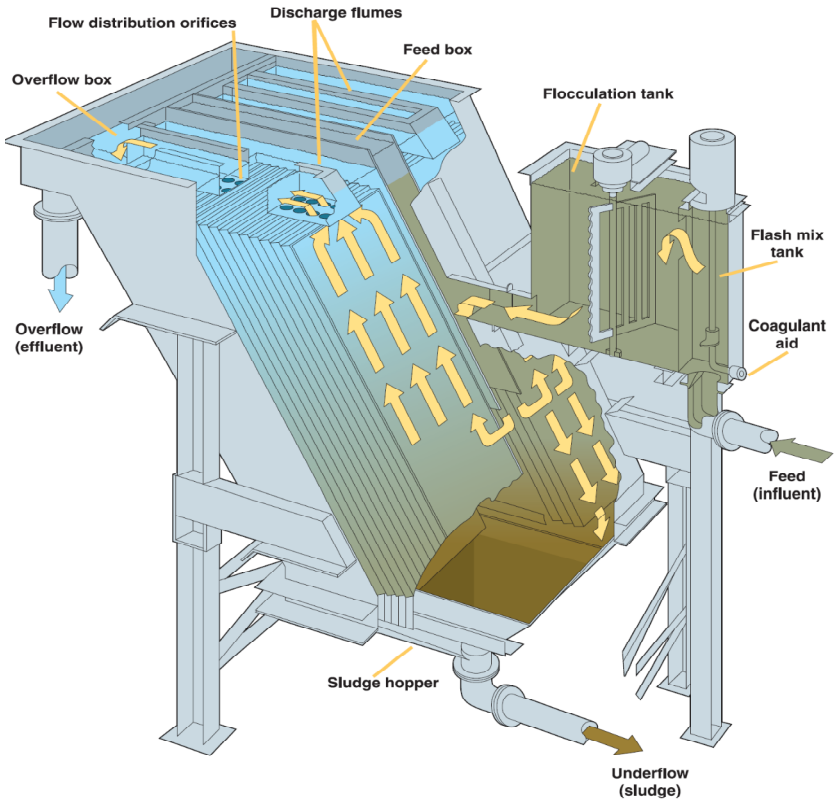


Figure 4-3. Schematic of a Plate Settler

Ref: http://www.parkson.com/sites/default/files/documents/document-lamella-ecoflow-brochure-482.pdf

4.5.2 Dewatering

Dewatering can be categorized into non-mechanical and mechanical dewatering processes. Table 4-9 summarizes the non-mechanical as well as mechanical dewatering processes.

4.5.2.1 Non-Mechanical

Non-mechanical processes often refer to evaporation ponds, drying beds, and storage lagoons, which all require a large surface area and favorable climate conditions. Considering the land requirement and potential exposure to hazardous waste as a result of residuals open to the atmosphere, these non-mechanical dewatering processes were considered suboptimal for RCF residuals.

4.5.2.1.1 Containerized Passive Filtration

Another type of non-mechanical dewatering process that holds more promise for the RCF process is passive filtration, which uses a special filter installed in a container to separate solids from water by gravity. The Sludge Mate system used in the Glendale RCF process is one of the passive filtration dewatering units available in the market. The Sludge Mate container receives settled residuals from the gravity thickener tank, and the felt-like material installed on the sides of the container allow water to pass through while retaining the solids in the material. Dewatering using a Sludge Mate can take a relatively long time, usually several hours to days, depending on the solids and hydraulic loading rates. No power is required for passive filtration, so the O&M cost is relatively low. The dewatered residuals at Glendale typically contain between approximately 11% and 23% solids.

4.5.2.2 Mechanical

The principal types of mechanical dewatering devices include centrifuges, plate and frame filter presses, belt filter presses and vacuum filtration (summarized in Table 4-9). Mechanical dewatering processes have relatively high capital and O&M costs compared to non-mechanical processes for the same flow. Mechanical dewatering is generally not applicable to very small water plants due to the high capital costs associated with these technologies and limited equipment sizes available.

4.5.2.2.1 Centrifuges

A centrifuge is a sedimentation device in which the solids/liquid separation is improved by rotating the residuals at high speeds to enhance the settling process. Feed

residuals are typically conditioned with polymer. The two basic types of centrifuges include solid-bowl (scroll) and basket centrifuges. The scroll centrifuge, which is a continuous feed unit, is more widely used for dewatering water treatment residuals (Crittenden et al., 2005). The basket centrifuge is a batch process with larger units that require greater operator and monitoring time (Crittenden et al., 2005). Dewatered residuals solids concentrations can vary in the range of 15 to 70 percent, depending on the type of residuals and feed solids concentration (Crittenden et al., 2005). Centrifuges generally require less land but have higher capital and O&M costs than non-mechanical alternatives; thus, centrifuges are more applicable to larger water systems (USEPA, 1993). Centrifuges were considered a feasible option for chromium treatment residuals dewatering.

4.5.2.2.2 Plate and Frame Filter Presses

Plate and frame filter presses, also called filter presses, dewater residuals by forcing the water from the residuals under high pressure. Pressure filter presses operate as batch processes. A filter press consists of a number of plates or trays supported in a common frame. A filter cloth is mounted on the face of each plate. Residuals filled into the plates or trays are pressed against a fixed and moving end to force the liquid through the filter cloth and plate outlet. The plates are then separated and the dewatered residuals are removed. The filter cloth needs to be washed frequently to remove solids. In general, the dewatered residuals (also called filter cake) can contain 30 to 40 percent solids concentrations, with proper residuals conditioning (e.g., polymer and lime addition to increase solids concentration) (Crittenden et al., 2005). Filter presses generally require little space but high capital and O&M costs (USEPA, 1993). Filter presses were considered a feasible option for chromium treatment residuals dewatering.

4.5.2.2.3 Gravity and Pressure Belt Filters

Residuals can also be dewatered using belt filters. If only gravity is applied, the approach is called gravity belt filters. If gravity and pressure are combined, the approach is called gravity and pressure belt filters, or belt filter presses. The feed residuals are typically conditioned using coagulant and polymer. Residuals applied onto the belt are dewatered by gravity, and free water is released from the residuals and drained through the belt. Dewatered residuals may contain solids up to 20 percent with proper conditioning (Crittenden et al., 2005). For belt filter presses, the residuals from the gravity dewatering process are further processed in a compression zone, where it is squeezed between two moving belts. Additional dewatering occurs by shearing as the residuals move to the outlet. Dewatered residuals may contain solids in the range of 15 – 60 percent (Crittenden et al., 2005). Belt filter presses generally

require less capital and less space than plate and frame filter presses (Crittenden et al., 2005). However, belt filters are not optimal for chromium treatment residuals dewatering, considering the potential exposure to hazardous residuals and liquid.

4.5.2.2.4 Rotary Drum Vacuum Filters

Rotary drum vacuum filters dewater residuals by applying a vacuum to the other side of filter cloth on the rotary drum surface. These filters typically operate in continuous mode. Filter cloth is attached onto the drum. Liquids from the residuals are drawn by the vacuum to the center of the rotary drum and directed to discharge piping. Solids remain on the filter and are discharged to a conveyor. Filter cloth washing is required as part of maintenance. Feed residuals typically require lime or polymer conditioning. Dewatered residuals may contain solids in the range of 15 – 40 percent (Crittenden et al, 2005). Rotary drum vacuum filters are mostly exposed to the atmosphere (i.e. without containment). However, they can also be provided in an enclosed container/hood for vapor and hazardous containment. Rotary drum vacuum filters can be feasible for chromium treatment residuals dewatering, when provided in enclosed containment to avoid exposure to hazardous residuals.

Table 4-9. Summary of Dewatering Processes for Chromium RCF Residuals

Process	Applicable Conditions	Advantages	Disadvantages	Feasibility for Cr RCF Residuals
Non-Mechanical				
Evaporation Ponds and Drying Beds	Favorable climatic conditions. Typically used for residuals containing high TDS, such as RO and IX waste.	Low O&M cost	Require large surface area	Not feasible due to hazardous waste exposure
Storage Lagoons	Favorable climatic conditions, best suited for dewatering lime softening process residuals.	Low O&M cost	Require large surface area	Not feasible due to hazardous waste exposure
Containerized Passive Filtration (e.g. Sludge Mate)	Small and medium-sized systems	Low O&M cost, easy operation	Require relatively large space. Lower solids concentrations than mechanical processes.	Feasible
Direct Discharge	Applicable to different types of residuals and system sizes.	Low capital cost, easy operation	Subject to NPDES or sewer permit	Site specific, may or may not be feasible, depending upon permit limit
Mechanical				
Centrifuges	Large systems	Require little land. Likely higher solids concentrations in dewatered residuals than non-mechanical.	Loud operation. High capital cost, less labor intensive than filter presses, but more intensive than non-mechanical alternatives	Feasible
Plate and Frame Filter Presses	Large systems	Require little land. High solids concentrations in dewatered residuals.	High capital cost, labor intensive	Feasible
Gravity and Pressure Belt Filters	Large systems	Require little land. Lower capital than plate and frame filter presses.	Exposure of liquid and solids during the gravity draining process	Infeasible due to potential exposure to hazardous.

Process	Applicable Conditions	Advantages	Disadvantages	Feasibility for Cr RCF Residuals
Rotary Drum Vacuum Press	Medium to large systems	Quiet operation. Require little land. Decent solids concentrations in dewatered residuals.	Mostly operated in open atmosphere. Higher O&M cost than non-mechanical.	Feasible, but only if with enclosed containment to minimize exposure.

Revised based on USEPA, 2000. *Technologies and Costs for Removal of Arsenic from Drinking Water*, page 4-3.

4.6 Summary and Conclusions

The RCF demonstration-scale study results at the City of Glendale showed that the RCF residuals were a non-RCRA hazardous waste due to the total chromium concentration above the California WET TTLC regulatory limit. Thus, the solid wastes require disposal in a non-RCRA hazardous waste landfill (if in California). Approximately 38 pounds of dewatered solid waste was generated per day on average for a 100 gpm system, with influent Cr(VI) levels of 80 ppb for most of the test period. Solid waste quantities estimated using mass balance were in the same order of magnitude as the actual quantities generated. A general evaluation of dewatering equipment indicated that centrifuges, plate and frame filter presses, and rotary drum vacuum presses could serve as alternatives to the passive filtration approach tested at Glendale, particularly at larger flow rates.

5. Assessment of RCF Residuals Volumes and Dewatering Options for Different Water Qualities

Different water qualities might affect the quantity of residuals generated in the RCF process and hence treatment and disposal costs. One objective of this study was to estimate the residuals volumes generated in the RCF process for a representative range of water qualities in California for utilities with Cr(VI) in their water supplies. This section summarizes the bench-scale test results of three different water qualities, compared to results for the baseline Glendale water quality.

5.1 Objectives

The objectives of this bench-scale test included the following:

- Investigate the impacts of ferrous doses for different water qualities on chromium removal in groundwater,
- Estimate quantities of residuals waste generated through treatment, and
- Characterize residuals generated for proper disposal.

5.2 Materials and Methods

This section describes the materials and methods used in the bench-scale jar tests.

5.2.1 Water Samples

Based on a literature review, water quality parameters identified that could affect the ferrous dose for Cr(VI) reduction include silica, phosphate, arsenate, and possibly sulfate and chloride. Silica at concentrations as low as 0.1 mg/L have been found to significantly inhibit Cr(VI) reduction at pH 7.5 with a Fe:Cr(VI) mass ratio of 10:1 (Brandhuber et al., 2004). Phosphate, sulfate, and chloride could all interfere with the oxidation of ferrous to ferric iron or the adsorption to or precipitation of ferric hydroxide, and could thus potentially affect the removal of Cr(VI) (Aoki and Munemori, 1982; Ryden and Syers, 1987; S.K. De, 2003; Tamura et al., 1976).

Water sources at three utilities were identified to represent a range of water qualities in Northern and Southern California, including Cr(VI) concentrations and the potential parameters identified in the literature that could impact treatment. Table 5-1 lists the raw water quality for the selected water sources.

A 5-gallon water sample was collected from the identified raw water source at each utility. The samples were collected from the wells and kept cool until the jar tests were conducted. Water samples were analyzed the same day using field instruments for pH, turbidity, conductivity, ferrous iron, and total iron, with the exception of Utility III. pH was monitored the day of sampling for Utility III, and the remaining parameters were measured after receiving the sample from Northern California for jar testing. In addition to these field parameters, Cr(VI), total Cr, phosphate, arsenic, silica, sulfate, and chloride were measured by MWH laboratories. Cr(VI) levels reported by MWH were used to determine the appropriate ferrous sulfate dose during jar testing.

Table 5-1. Raw Water Quality for Samples from Glendale and Three Other Utilities Tested

Parameter (unit)	Glendale	Utility I	Utility II	Utility III
Sampling Date	6/1/11	6/16/11	6/30/11	7/25/11
pH	7.52	7.87	7.70	7.97
Turbidity (NTU)	0.19	0.18	0.22	0.19
Conductivity (µS/cm)	1,042	566	916	1,006
Alkalinity as $CaCO_3$ (mg/L)	260	100	240	300
Ferrous Iron (mg/L)	0.02	0.00	0.02	0.01
Total Iron (mg/L)	0.05	0.17	0.01	0.04
Cr(VI), lab (µg/L, or ppb)	78	13	110	9.6
Total Cr, lab (µg/L, or ppb)	80	13	110	9.5
Phosphate as PO_4 (mg/L)	0.26	0.01	0.17	0.25
Arsenic (µg/L)	0.88	5.6	0.44	1.2
Silica as SiO_2 (mg/L)	29	20	25	34
Sulfate (mg/L)	96	69	98	52
Chloride (mg/L)	58	19	33	91

5.2.2 Analytical Methods

Table 5-2 presents the analytical methods for the water quality parameters tested.

Table 5-2. Field and Laboratory Analytical Methods

Parameter	Field or Lab Analysis	Method	Method Detection Limit
Alkalinity	Lab	SM 2320B	0.8 mg/L as $CaCO_3$
Arsenic	Lab	EPA 200.8	0.06 µg/L
Chloride	Lab	EPA 300.0	0.02 mg/L
Conductivity	Field	SensION5	0.1 µS/cm
Cr(VI)	Field	Hach Method 8023	10 µg/L
Cr(VI)	Lab	EPA 218.6	0.009 µg/L
Total Cr	Lab	EPA 218.6	0.09 µg/L
Ferrous Iron	Field	Hach Method 8146	0.02 mg/L
Total Iron	Field	Hach Method 8008	0.02 mg/L
pH	Field	pH meter	--
Phosphate as PO_4	Lab	4300P-E/365.1	0.007 mg/L
Silica	Lab	EPA 200.7	0.5 mg/L
Sulfate	Lab	EPA 300.0	0.06 mg/L
Turbidity	Field	Turbidity Meter 2100P	0.02 NTU

5.2.3 Test I – City of Glendale Sample

The purpose of this testing was to compare the quantity of solid residuals generated by jar testing with solids generated in the demonstration-scale study.

The detailed jar testing procedures are provided as follows:

1. A raw water sample was collected from the well feeding the RCF process on June 1, 2011. The water was analyzed in the field for Cr(VI) to confirm the concentration was in the expected range; a split sample was sent to MWH laboratories for additional Cr(VI) analysis with a lower detection limit.

2. Two cylindrical beakers were each filled with one liter of the water sample. The samples were analyzed in parallel in order to maintain enough water for all of the analyses.
3. The water was dosed with ferrous sulfate based on a Fe:Cr(VI) mass ratio of 25:1 and the Cr(VI) concentration in the raw water.
4. The water was mixed at 300 rpm for 1 minute to simulate rapid mixing by the static mixer and then at 100 rpm for 45 minutes to simulate mixing in the reduction tanks.
5. The jars were aerated for 5 minutes using a portable air tank and flexible, inert tubing. The end of the flexible tubing was perforated to simulate aeration in the RCF processes at Glendale (a diffuser stone was not used as ferric and chromium precipitates were expected to block the openings). The air to water ratio was approximately 4:1 by volume, which was calculated to be 1.7 standard cubic feet per hour (SCFM). Air flow rate was measured using a flow meter. A particulate filter was installed between the air source and diffuser to prevent introduction of particulates by the air flow into the sample. After the aeration step was complete, Cr(VI) and ferrous were tested to confirm that all ferrous was converted to ferric and all Cr(VI) was reduced to Cr(III).
6. A Ciba MagnaFloc E38 polymer dose of 0.1 mg/L as active polymer was added to the water.
7. The water was mixed at 250 rpm for 5 minutes to simulate the rapid mixing tank, and then at 50 rpm for 5 minutes to simulate the mixing in the filter vessel's head space.
8. 10 minutes were provided to allow floc to settle after the mixing.
9. Characteristics of the settled floc were recorded based on visual observation, including size, shape and color etc.
10. Approximately 600 mL of settled water sample from one jar was filtered using 0.45 micron filters. Cr(VI) and total iron in the filtrate were measured on site, and samples for lab analysis were collected for Cr(VI) and total Cr.
11. The remaining settled water (slightly more than 400 mL) was filtered using 0.1 micron filters. Cr(VI) and total iron in the filtrate were measured on site, and lab samples were collected for Cr(VI) and total Cr.
12. The jar not used for filtering was then dosed with Ciba MagnaFloc E38 polymer of 1.0 mg/L as active polymer while mixing at 280 rpm.

13. One liter of water (from the jar dosed with the higher concentration of polymer) was then transferred into an Imhoff cone, and allowed at least 45 minutes for the floc to settle. The volume of the settled solids was recorded.
14. A Flo-Trend filter was cut to fit in the vacuum filtration unit and weighed to determine its dry weight.
15. The filter was placed in the filtration unit, and the sample from the Imhoff cone was filtered through.
16. The filter was then dried for at least 48 hours in an oven and weighed.
17. The mass of solids was calculated by subtracting the filter mass from the mass of the filter with solids.

5.2.3.1 Effect of pH, Phosphate and Silica

The effects of pH, phosphate and silica concentrations were tested separately using the same raw water from Glendale. Raw water pH was adjusted from 7.52 to 8.19 using a sodium hydroxide solution. Phosphate concentration was increased from 0.26 mg/L to 1.3 mg/L by adding a stock phosphate solution to another sample. Silica concentration was increased from 29 to 74 mg/L as SiO_2 in a third sample by adding a stock silica solution. The adjusted water samples were tested following the same procedures (Steps 1 to 11 described above) for Cr(VI) and total Cr removal.

5.2.4 Test II – Three Other Utilities Samples

The jar testing for the three additional utility samples followed the same procedures as discussed in Section 5.2.3, except for the first step. Each utility sample was first tested at three Fe:Cr(VI) ratios to identify the optimum ferrous dose. The solids quantities and characteristics were investigated.

5.2.4.1 Identify Optimum Ferrous Dose

Three Fe:Cr(VI) ratios were tested to identify the optimum ferrous dose for each of the three waters. Fe:Cr(VI) ratios of 25:1 and 50:1 were tested first. The third Fe:Cr(VI) ratio was based on the results from the first two ratios. If the 50:1 ratio was effective for Cr(VI) and total Cr removal, then a 35:1 ratio was chosen. Otherwise, 75:1 was tested as the third ratio. Table 5-3 provides the Fe:Cr(VI) ratios tested for the utility samples.

Based on the chromium removal from the first two Fe:Cr(VI) doses tested, raw water pH was also reduced to enhance chromium removal for Utility I and III samples (as listed in Table 5-3).

Table 5-3. Fe:Cr(VI) Mass Ratios and pH Tested for the Other Three Utility Samples

Utility I	Fe:Cr(VI) Ratio	25:1	50:1	75:1
	pH	7.87	7.87 and 7.35	7.35
Utility II	Fe:Cr(VI) Ratio	25:1	35:1	50:1
	pH	7.70	7.70	7.70
Utility III	Fe:Cr(VI) Ratio	25:1	50:1	75:1
	pH	7.97	7.97 and 7.50	7.97

5.2.4.2 Solid Residuals Quantities

Solid residuals were quantified using the Imhoff cone (Step 15) and dry weight of solids captured on the Flo-Trend filter material (Steps 16 and 17). The solids weight was intended to be determined by subtracting the filter mass from the mass of the filter with solids. The filter material was noted to retain moisture at a significant amount before and after use for solids filtration as the filter material can only tolerate up to 82 ºC, and therefore was not completely dried. The solids generated in the jar testing were in such small quantities (mostly less than 0.005 gram per liter of sample) that their weight was significantly affected by the moisture content. Thus, solids weight could not be accurately determined by weighing the filter, although efforts were made to dry the filters with solids, scrub and rinse solids off the filter and re-dry the filter to quantify the startup weight. Instead, mass balance (as described in Section 4.4.2) was used to calculate the theoretical solids weight to provide a conservative approach for cost estimation.

5.2.4.3 Solid Residuals Characteristics

The jar testing would need to be repeated many times to generate a sufficient volume for solid characterization analysis. A 0.5 gram minimum solid sample is needed for total chromium analysis; however, the result cannot be corrected by moisture content and no matrix spike and matrix spike duplicate can be conducted for this volume (i.e., 5 grams is required for complete analysis). Ten grams of solids are needed for moisture content analysis. For TCLP metals and CA WET metals analysis, 25 grams of solids are needed. Thus, mass balance was used (instead of lab analysis) to estimate total

chromium concentrations in the solid residuals generated. Meanwhile, each utility sample that was treated and filtered through a 0.45 micron filter was also sent to MWH Laboratories for analysis of TCLP metals. By comparing metal concentrations in the raw and treated water (i.e. filtered), the potential metals in the solid residuals that could trigger hazardous characteristics were identified.

5.3 Results

5.3.1 Glendale Sample

The raw water treated by the demonstration-scale RCF process at the City of Glendale was jar tested to evaluate the reliability of jar testing on simulating RCF removal of chromium and estimating residuals quantities. Additionally, the effects of pH, phosphate and silica on chromium removal were also evaluated using Glendale water as the background water quality matrix.

5.3.1.1 Chromium Removal

Figure 5-1 shows Cr(VI) removal for the Glendale water sample using the jar testing. The ferrous dose of 2.6 mg/L was based on the field Cr(VI) result of 105 ppb, which corresponds to a Fe:Cr(VI) mass ratio of 34:1 based on the lab Cr(VI) result of 78 ppb. Cr(VI) concentrations in the 0.45 and 0.1 micron filtrate were below method reporting limit (0.02 ppb) and 0.13 ppb, respectively, which are in good agreement with the demonstration-scale test results. The Cr(VI) results prove that Cr(VI) was effectively reduced to Cr(III) in the jar testing.

Figure 5-2 shows the total chromium removal using the jar testing. Total chromium in the 0.45 and 0.1 micron filtrate were below the method reporting limit (1 ppb), which are similar to the results for an Fe:Cr(VI) ratio of 35:1 observed in the demonstration testing. Total chromium removal using the two pore sizes (0.45 and 0.1 micron) are similar, which suggests the size of most ferric and chromium particles formed was above 0.45 micron, while a small portion of total chromium might be present in dissolved or colloidal form. In general, the jar testing results regarding chromium removal are in good agreement with the demonstration-scale results, suggesting the jar testing procedures provided a good simulation of the demonstration-scale testing process.

5.3.1.2 Effect of pH

The effect of raw water pH on chromium removal by the RCF process was also evaluated using jar testing and another aliquot of the same Glendale water containing 78 ppb of Cr(VI). The raw water pH was adjusted from 7.52 to 8.19 to investigate the effect of a higher pH level, while the other testing conditions were the same. Figure 5-3 compares the Cr(VI) concentrations in the 0.45 and 0.1 micron filter effluent for the two pH levels. The higher pH sample had much more Cr(VI) remaining in the filtered water compared with the lower pH sample, showing that reduction was not complete at the higher pH.

Figure 5-4 shows the total Cr removal results for the two pH levels (7.52 and 8.19). Similar to the Cr(VI) results, a higher total Cr concentration was observed in the treated high pH sample compared with the low pH sample. Total chromium analysis measures both Cr(VI) and Cr(III). Therefore, Cr(VI) that was not reduced to Cr(III) was also detected in the total chromium analysis, which explains the same total Cr and Cr(VI) levels in the high pH sample. Cr(VI) that was reduced to Cr(III) was removed by the filtration. Overall, the results indicate that a raw water pH level significantly above 7.5 could have a negative effect on Cr(VI) removal by the RCF process.

Incomplete Cr(VI) reduction at the higher pH may indicate insufficient ferrous available for reaction with Cr(VI), which might be caused by competing oxidation of ferrous by oxygen. The oxidation rate of ferrous by oxygen increases at a higher pH level (Fendorf and Li, 1996). Based on this hypothesis, increasing the ferrous dose might help with Cr(VI) reduction to a certain level at a higher pH. Findings reported in Section 5.3.2 indicate that a higher ferrous dose at high pH can yield more Cr(VI) reduction, indicating that ferrous dose may lessen the impact of the higher pH. More testing is needed to further evaluate the effects of different pH levels (i.e. above 7.5 but below 8.2) and various raw water qualities, as only the Glendale water was tested at one higher pH level in this study.

The potential for Fe(II) side reactions besides oxidation from oxygen was also considered. For example, siderite ($FeCO_3$) is oversaturated at pH 8.0, although it is also oversaturated at pH 7.5 based on the measured alkalinity and ferrous dose (assuming none of the ferrous is oxidized by oxygen before it could precipitate). However, testing of a higher ferrous dose with a high pH yielded more chromium reduction (Section 5.3.2), whereas a larger ferrous dose would result in a greater degree of oversaturation for siderite (i.e., the opposite effect than was observed).

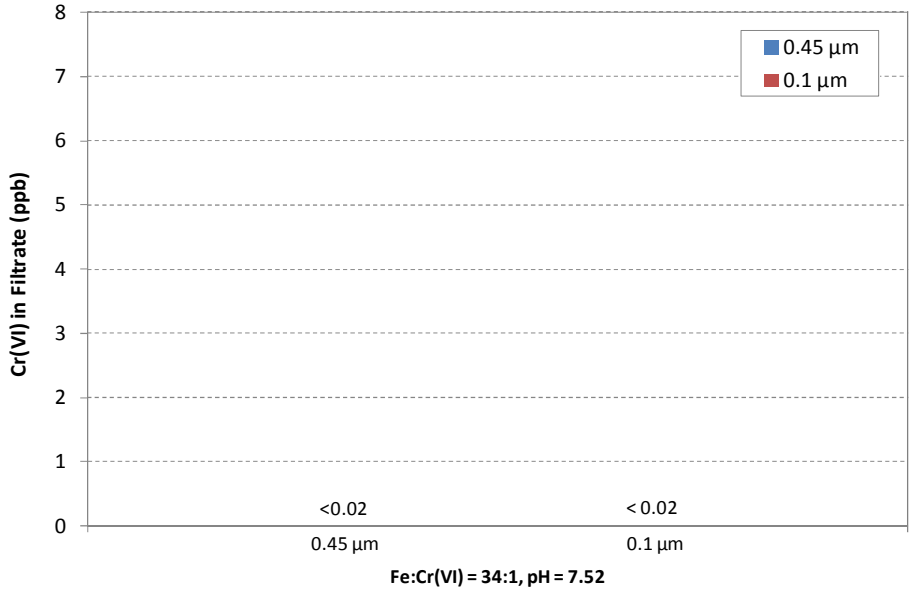


Figure 5-1. Jar Testing Results of Hexavalent Chromium Removal for Glendale Water Sample (Raw water pH = 7.52, Cr(VI) = 78 ppb)

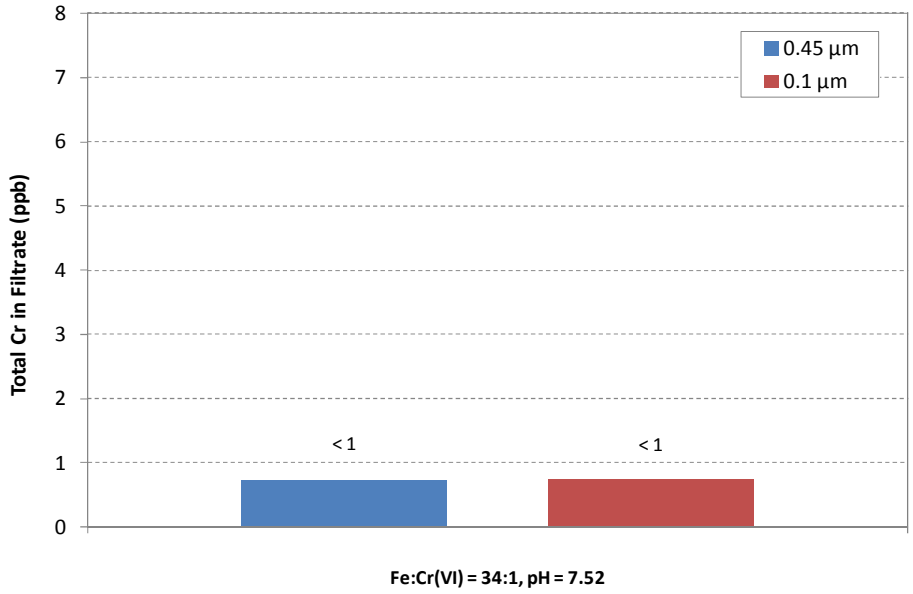


Figure 5-2. Jar Testing Results of Total Chromium Removal for Glendale Water Sample (Raw water pH = 7.52, Cr(VI) = 78 ppb)

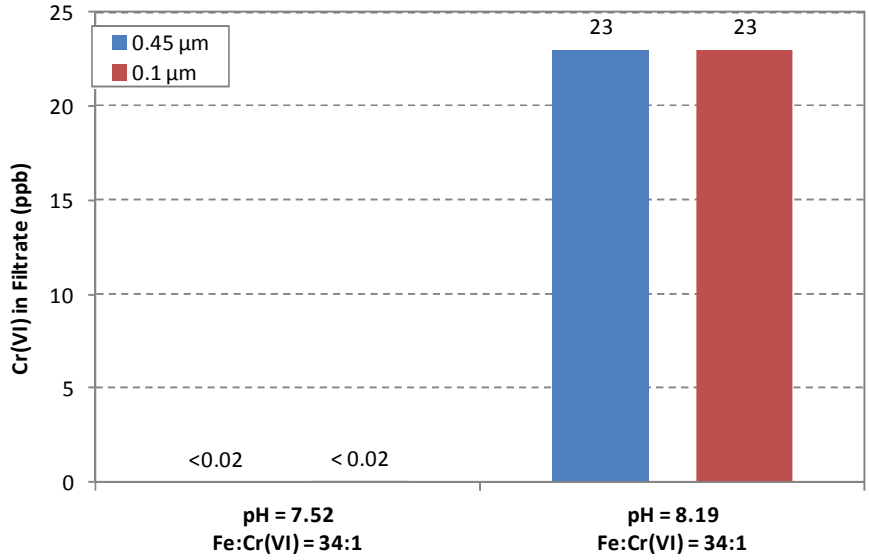


Figure 5-3. Effect of Raw Water pH on Hexavalent Chromium Removal

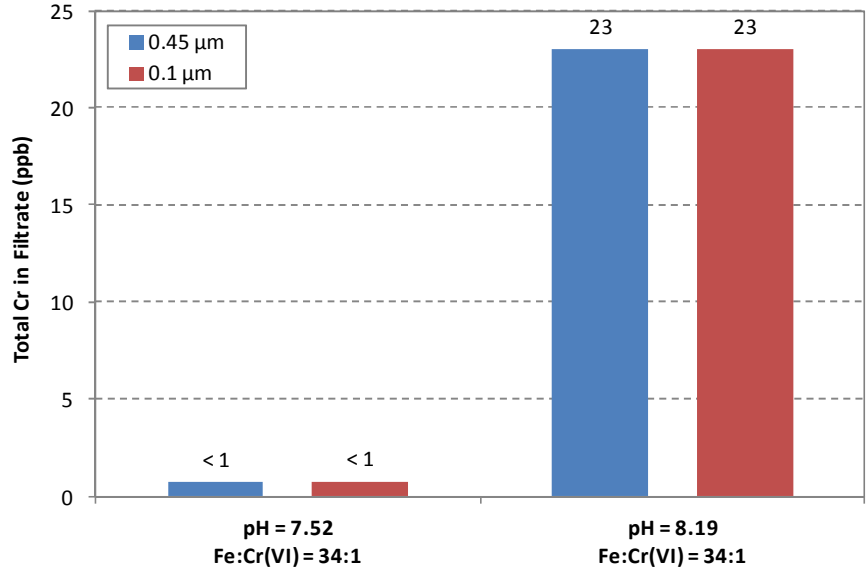


Figure 5-4. Effect of Raw Water pH on Total Chromium Removal

5.3.1.3 Effect of Phosphate

The effect of phosphate in raw water on chromium removal was also evaluated using the jar testing and an aliquot of the same Glendale water containing 78 ppb of Cr(VI). The Glendale water sample contained orthophosphate at a level of 0.26 mg/L as PO_4. Phosphate in the same sample was spiked to 1.3 mg/L as PO_4, which represents a typical phosphate level applied in drinking water treatment for corrosion control. Figure 5-5 compares Cr(VI) concentrations in the filtered water for the two phosphate levels. The sample with the higher phosphate concentration had a slightly higher Cr(VI) concentration in the filtered water. Total chromium concentrations in the filtered water were at the same levels for the two phosphate concentrations (Figure 5-6). Overall, the results suggest the effects of a higher phosphate concentration (i.e. 1.3 mg/L as PO_4) on Cr(VI) and total chromium removal by the RCF process are minimal.

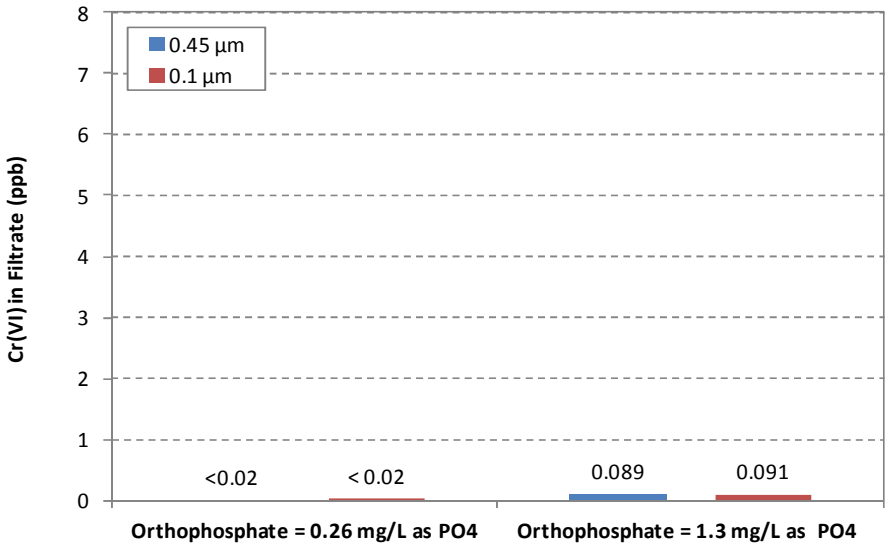


Figure 5-5. Effect of Raw Water Phosphate on Hexavalent Chromium Removal

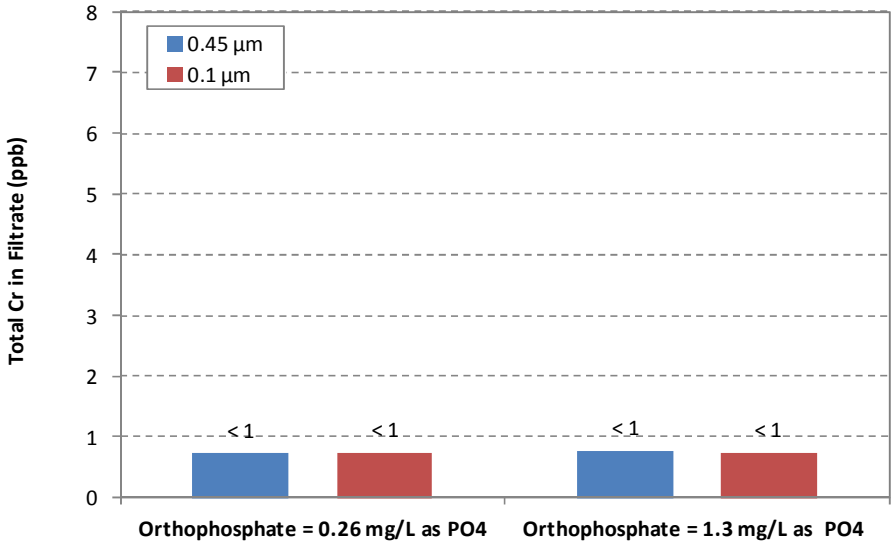


Figure 5-6. Effect of Raw Water Phosphate on Total Chromium Removal

5.3.1.4 Effect of Silica

The effect of silica in raw water on chromium removal was evaluated using the jar testing and an aliquot of the same Glendale water containing 78 ppb of Cr(VI). The Glendale water sample contained silica of 29 mg/L as SiO_2. The silica level in the water was spiked to 74 mg/L as SiO_2 to represent a high silica level that is sometimes found in groundwater sources.

Figure 5-7 compares the Cr(VI) concentrations in the filtered water with the two silica levels. The higher silica sample had a much higher Cr(VI) concentration in the filtered water, compared to the sample that was not spiked. Similar total chromium levels as Cr(VI) were detected in the filtered samples (Figure 5-8). Additionally, the particles formed in the spiked sample during the coagulation step were visibly different (light brown and yellow) compared with the unspiked sample (dark brown).

The results suggest silica at a high concentration (i.e. 74 mg/L as SiO_2) may have a negative impact on chromium removal by the RCF process. These results are consistent with previous findings by Brandhuber et al. (2004), proposing a mechanism by which silica could interfere with Cr(VI) reduction and precipitation by forming an

Fe(II) silica precipitate, greenalite [$Fe_2Si_2O_5(OH)_4$], that reduces ferrous available for Cr(VI) reduction. Greenalite forms predominantly between pH 7.5 and 9.5, so the impact may be less at pH values below 7.5 (Brandhuber et al., 2004).

Another factor that may have impacted the jar testing was that spiking of silica inadvertently increased the pH, which may have contributed to incomplete Cr(VI) reduction. Follow up testing showed on another aliquot of Glendale water using the silica stock solution increased the raw water pH to 9.5 as a result of silica spiking as the silica standard solution used contained sodium hydroxide. As discussed above, Cr(VI) reduction by ferrous can be impacted by higher pH. Thus, the impact of silica on Cr(VI) reduction could be due to pH increase and/or the formation of greenalite. Additional study is needed to identify the primary factors.

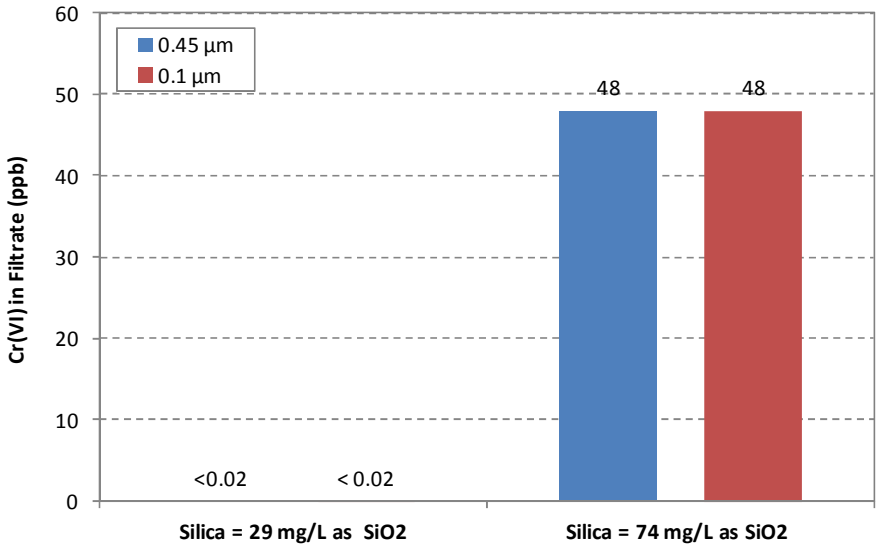


Figure 5-7. Effect of Raw Water Silica on Hexavalent Chromium Removal

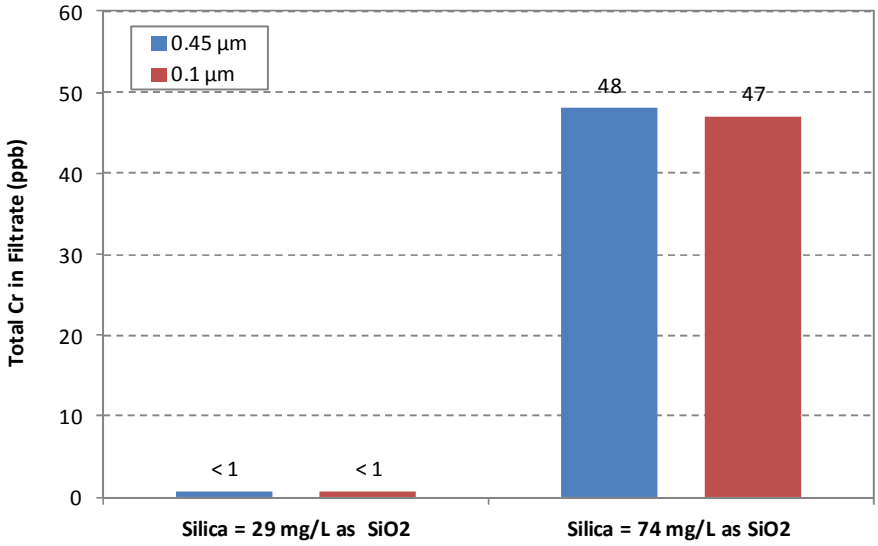


Figure 5-8. Effect of Raw Water Silica on Total Chromium Removal

5.3.1.5 Solid Residuals Quantity

Settled solids in the Imhoff cone were approximately 1 mL/L (Figure 5-9). Dry solids weight determined via mass balance is approximately 8.9 mg/L, which is a conservative estimate assuming all ferrous, chromium and polymer were converted to solids waste. Dry solids weight obtained from the jar testing was 5.5 mg/L, which was the same order of magnitude as the mass balance determined weight.

Figure 5-9. Settled Solids in Imhoff Cone for Glendale Water Sample with Fe:Cr(VI) of 34:1

5.3.1.6 Solid Residuals Hazardous Characteristics

Solid residuals for the Glendale sample were not characterized during the jar testing, since the Glendale demonstration-scale study has shown the RCF solid residuals is a non-RCRA hazardous waste due to a total chromium level above the TTLC regulatory limit for chromium.

5.3.2 Utility I Sample

The water from Utility I contained Cr(VI) at a lower level of 13 ppb, compared to 78 ppb in the Glendale sample. pH in the Utility I sample was 7.87, which was significantly higher than the Glendale sample pH level of 7.52. Additionally, the Utility I sample contained lower conductivity, alkalinity and chloride, and higher arsenic concentrations (as listed in Table 5-1).

5.3.2.1 Ferrous Dose

The Utility I sample was tested using three Fe:Cr(VI) ratios, 25:1, 50:1 and 75:1, which correspond to ferrous doses of 0.33, 0.65 and 0.98 mg/L, respectively. In addition, a lower pH level of 7.35 was tested for the Fe:Cr(VI) ratios of 50:1 and 75:1 to investigate the effect of a lower pH on chromium removal.

Figure 5-10 shows Cr(VI) concentrations in filtered water using 0.45 and 0.1 micron pore size filters for the Utility I sample. The results for 0.45 and 0.1 micron filters are similar. With Fe:Cr(VI) ratios of 25:1 and 50:1 (at pH 7.87), Cr(VI) concentrations in treated water were above 1 ppb, indicating insufficient Cr(VI) reduction. With an Fe:Cr(VI) ratio of 50:1 and pH 7.35, Cr(VI) was effectively removed to 0.04 ppb, indicating that a lower pH level facilitated chromium removal (reduction) in the RCF process. A higher Fe:Cr(VI) ratio of 75:1 with pH 7.35 resulted in better Cr(VI) removal to non-detect (<0.02 ppb).

Figure 5-11 shows total Cr concentrations in the filtered water for the Utility I sample. Similar to the Cr(VI) results, Fe:Cr(VI) ratios of 25:1 and 50:1 at pH of 7.87 resulted in total Cr concentrations above 2 ppb. However, Fe:Cr(VI) ratios of 50:1 and 75:1 at pH of 7.35 effectively removed total chromium to below 1 ppb. These results suggest the Utility I water quality needs a pH reduction and a higher Fe:Cr(VI) ratio than 25:1 for effective Cr(VI) and total chromium removal. The necessary Fe:Cr(VI) ratio and pH reduction level are dependent on the targets of Cr(VI) and total chromium removal.

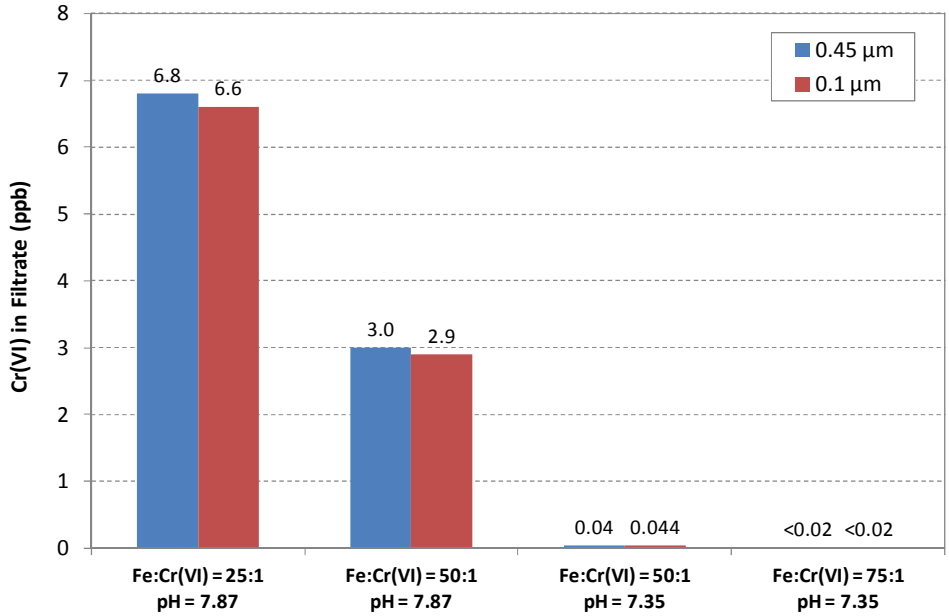


Figure 5-10. Hexavalent Chromium Removal Results for Utility I Sample (Raw Water Cr(VI) = 13 ppb)

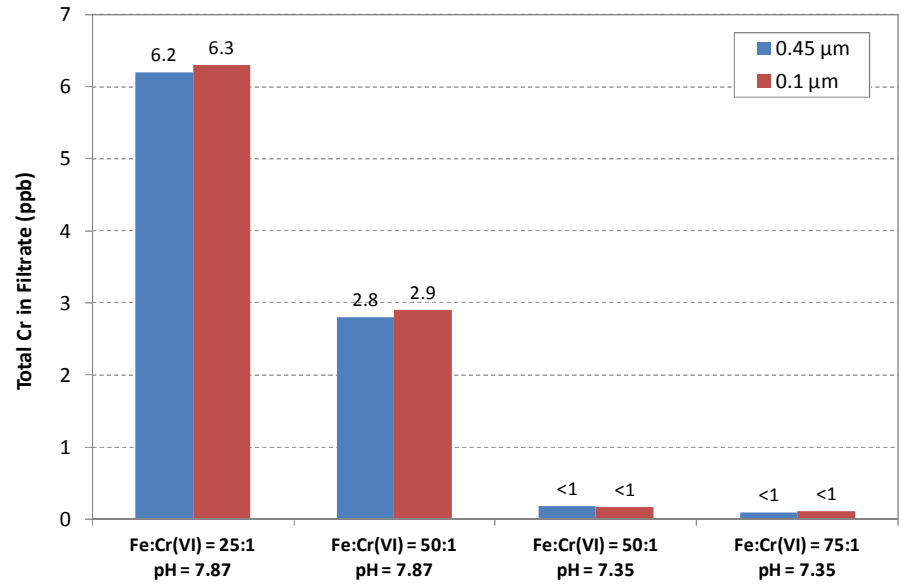


Figure 5-11. Total Chromium Removal Results for Utility I Sample (Raw Water Cr(VI) = 13 ppb)

5.3.2.2 Solid Residuals Quantity

No visible settled solids were observed in the Imhoff cone for all Fe:Cr(VI) ratios tested at the two pH levels for Utility I water. Dry solids weights determined via mass balance were approximately 2, 3 and 4 mg/L for the Fe:Cr(VI) ratios of 25:1, 50:1 and 75:1, respectively. The mass balance did not account for the weight of arsenic particles, considering arsenic concentrations were in the low µg/L range, two orders of magnitude less than the ferrous and polymer doses. The dry solid weights obtained in the jar testing were below 1 mg/L for all Fe:Cr(VI) ratios tested. Thus, the solids weight determined via mass balance is considered to be a more conservative estimate than results from jar testing.

5.3.2.3 Solid Residuals Hazardous Characteristics

Solid residuals hazardous characteristics were projected based on metal concentrations in the raw and treated water. The difference between raw and treated water was used to estimate the metal concentrations accumulated in the solid residuals. Dry weight estimated via mass balance was used as the solid weight. Metals concentrations in dry solids above the TTLC regulatory limits for hazardous waste were anticipated.

Concentrations of the metals regulated by California WET in the raw and jar tested water are summarized in Table 5-4, compared to the regulatory limits of TTLC. Among the regulated metals, arsenic and total chromium concentrations in the solid residuals were estimated to be above the TTLC regulatory limits, indicating the residuals could be a hazardous waste regulated in California. When a solid waste contains metal(s) above the TTLC limit(s), the waste is regulated as a hazardous waste in California no matter if it passes the TCLP and the STLC tests or not.

TCLP (as well as STLC) limits represent the metal concentrations in leachate under simulated landfill conditions, rather than the metal concentrations in the solid residuals as for the TTLC. Metal concentrations in the solid residuals are not directly comparable to TCLP (as well as STLC) regulatory limits. Thus, it could not be determined if the residuals for the Utility I sample would be a RCRA hazardous waste or not.

Table 5-4. Metal Concentrations in Raw and Treated Utility I Sample for Hazardous Characterization

Metals	MDL (µg/L, or ppb)	Raw Conc. (µg/L, or ppb)	Treated (pH = 7.35, Fe:Cr(VI) = 75:1 0.45 µm) (µg/L, or ppb)	Calculated Accumulation in dry solid residuals (mg/kg)	TTLC Regulatory Limit (mg/kg)
Antimony	0.2	<0.2	<0.2	N/A	500
Arsenic	0.06	5.8	0.43	**1,343**	500
Barium	0.001	58	58	N/A	10,000[#]
Beryllium	0.05	<0.05	<0.05	N/A	75
Cadmium	0.01	<0.01	<0.01	N/A	100
Chromium	0.09	13	0.18	**3,205**	2,500
Cobalt	0.05	0.095	0.22	N/A	8,000
Copper	0.2	0.58	0.28	75	2,500
Lead	0.04	0.15	<0.04	N/A	1,000
Mercury	0.04	<0.04	<0.04	N/A	20
Molybdenum	0.06	1	1.3	N/A	3,500*
Nickel	0.3	0.59	1.1	N/A	2,000

N/A – not applicable (when the metal concentration was non-detect in the raw water, or the treated concentration was higher than the raw water).

[#]Excluding barium sulfate.

*Excluding molybdenum disulfide.

5.3.3 Utility II Sample

The Utility II sample contained 110 ppb of Cr(VI), higher than 78 ppb in the Glendale sample. pH in the Utility II sample was slightly higher (7.70) than the Glendale sample (7.52). Phosphate, arsenic and chloride concentrations were lower than in the Glendale sample. Water quality parameters for the Utility II sample are listed in Table 5-1.

5.3.3.1 Ferrous Dose

The Utility II sample was tested using three Fe:Cr(VI) ratios of 25:1, 35:1 and 50:1 with the original raw water pH of 7.70, corresponding to ferrous iron doses of 2.75, 3.85 and 5.50 mg/L, respectively. Figure 5-12 shows Cr(VI) concentrations in water filtered through 0.45 and 0.1 micron filter pore sizes. An Fe:Cr(VI) ratio of 25:1 resulted in a Cr(VI) concentration of 0.51 ppb in treated water. Higher Fe:Cr(VI) ratios improved Cr(VI) removal to 0.27 ppb and non-detect (<0.02 ppb). Total chromium concentrations are slightly higher than the corresponding Cr(VI) concentrations but all are below the MRL, although they exhibit a similar trend, as shown in Figure 5-13. No pH reduction was necessary to achieve total chromium concentrations below 1 ppb. The results suggest an Fe:Cr(VI) ratio of 25:1 may be sufficient for the Utility II water quality to achieve chromium removal to below 1 ppb, and a higher ratio may further improve chromium removal efficiency.

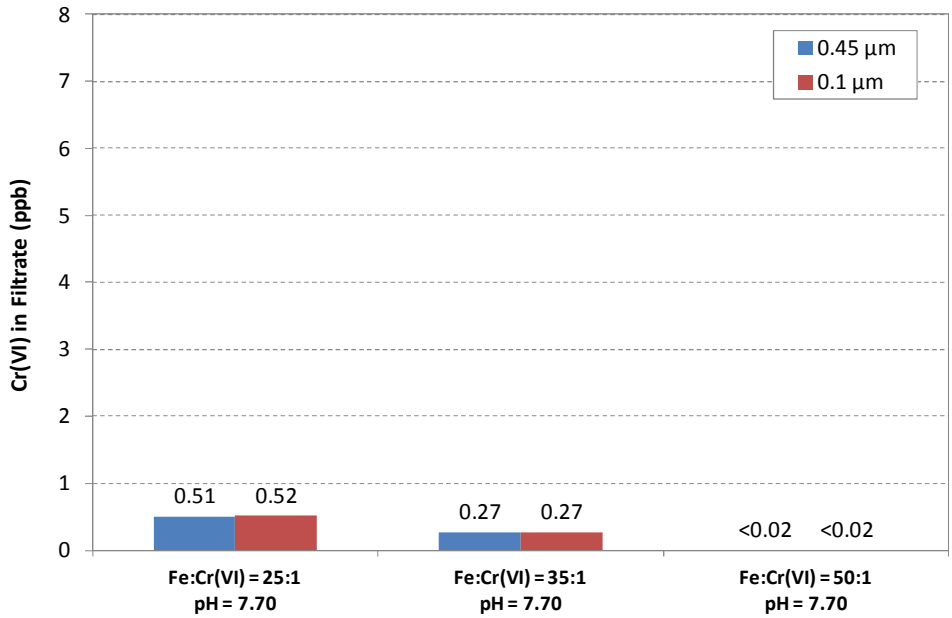


Figure 5-12. Hexavalent Chromium Removal Results for Utility II Sample (Raw water Cr(VI) = 110 ppb)

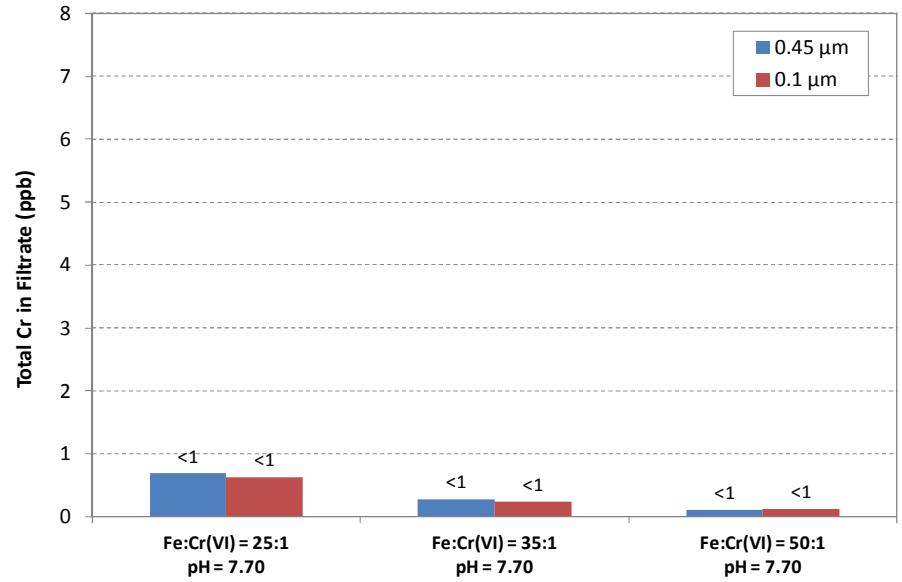


Figure 5-13. Total Chromium Removal Results for Utility II Sample (Raw water Cr(VI) = 110 ppb)

5.3.3.2 Solid Residuals Quantity

Settled solids in the Imhoff cone were approximately 1.2, 1.4 and 1.6 mL/L for the Fe:Cr(VI) ratios of 25:1, 35:1 and 50:1, respectively. Dry solid residuals based on mass balance were approximately 9, 13 and 17 mg/L, respectively. The dry solids obtained during the jar testing were 6.5, 7.7 and 10 mg/L, respectively, which were lower than the mass balance values but within the same order of magnitude.

5.3.3.3 Solid Residuals Hazardous Characteristics

Table 5-5 presents the results of metals regulated under California WET and TCLP. The chromium concentration in the solid residuals was estimated to be 6,465 mg/g, which was above the TTLC limit of 2,500 mg/kg. Thus, the solid residuals for the Utility II sample would likely be characterized as a hazardous waste in California. For the same reasons discussed in Section 5.3.2.3, it could not be determined if the solid residuals are a RCRA hazardous waste or not, without TCLP analysis.

Table 5-5. Metal Concentrations in Raw and Treated Utility II Sample for Hazardous Characterization

Metals	MDL (µg/L, or ppb)	Raw (µg/L, or ppb)	Treated (pH = 7.70 Fe:Cr(VI) =50:1; 0.45 µm) (µg/L, or ppb)	Calculated Accumulation in dry solid residuals (mg/kg)	TTLC Regulatory Limit (mg/kg)
Antimony	0.2	<0.2	<0.2	N/A	500
Arsenic	0.06	0.54	0.29	15	500
Barium	0.001	140	120	1,176	10,000[#]
Beryllium	0.05	<0.05	<0.05	N/A	75
Cadmium	0.01	<0.01	<0.01	N/A	100
Chromium	0.09	110	<0.09	**6,465**	2,500
Cobalt	0.05	0.2	0.61	N/A	8,000
Copper	0.2	9.7	0.49	542	2,500
Lead	0.04	0.30	<0.04	N/A	1,000
Mercury	0.04	<0.04	0.04	N/A	20
Molybdenum	0.06	4.4	4.6	N/A	3,500*
Nickel	0.3	1.4	2.6	N/A	2,000

N/A – not applicable (when the metal concentration was non-detect in the raw water, or the treated concentration was higher than the raw water).

[#]Excluding barium sulfate.

*Excluding molybdenum disulfide.

5.3.4 Utility III Sample

The Utility III sample contained Cr(VI) at a concentration of 9.6 ppb, which was lower than the Cr(VI) level of 78 ppb in the Glendale sample. The pH in the Utility III sample was 7.97. The Utility III sample contained similar phosphate, arsenic and silica concentrations, and lower sulfate and higher chloride levels than in the Glendale sample.

5.3.4.1 Ferrous Dose

The Utility III sample was tested using three Fe:Cr(VI) ratios of 25:1, 50:1 and 75:1, which correspond to ferrous doses of 0.24, 0.48 and 0.72 mg/L, respectively. The Fe:Cr(VI) ratio of 50:1 was tested at two pH levels, i.e. 7.97 and 7.50. Figure 5-14 shows Cr(VI) results in the filtered water using 0.45 and 0.1 micron pore sizes. Since the results of the two pore sizes are very close, only the results for 0.45 micron are discussed here for simplicity (after results are shown in the figures). Treated Cr(VI) concentrations with the Fe:Cr(VI) ratios of 25:1 and 50:1 at pH level of 7.97 were 4.5 and 1.6 ppb, respectively. With the lower pH of 7.50, Cr(VI) removal was improved from 1.6 to 0.086 ppb remaining in the sample, with the same Fe:Cr(VI) ratio of 50:1. A higher Fe:Cr(VI) ratio of 75:1 without pH reduction also resulted in better Cr(VI) removal than the Fe:Cr(VI) ratio of 50:1; however, the treated Cr(VI) concentration (0.62 ppb) was slightly higher than the one with pH reduction (0.086 ppb). The Cr(VI) results again indicate that pH has a significant impact on Cr(VI) reduction.

Total chromium results are shown in Figure 5-15. Fe:Cr(VI) ratios of 25:1 and 50:1 at pH 7.97 generated total Cr concentrations slightly higher than the Cr(VI) levels in treated water. The effect of pH reduction compared with a higher Fe:Cr(VI) ratio was less dramatic for total Cr than for Cr(VI) removal. Compared to the results of the Utility I sample, the total Cr results also suggest a pH reduction combined with a higher Fe:Cr(VI) ratio of 75:1 may be necessary to achieve effective total chromium removal to significantly below 1 ppb in waters with low Cr(VI) concentrations.

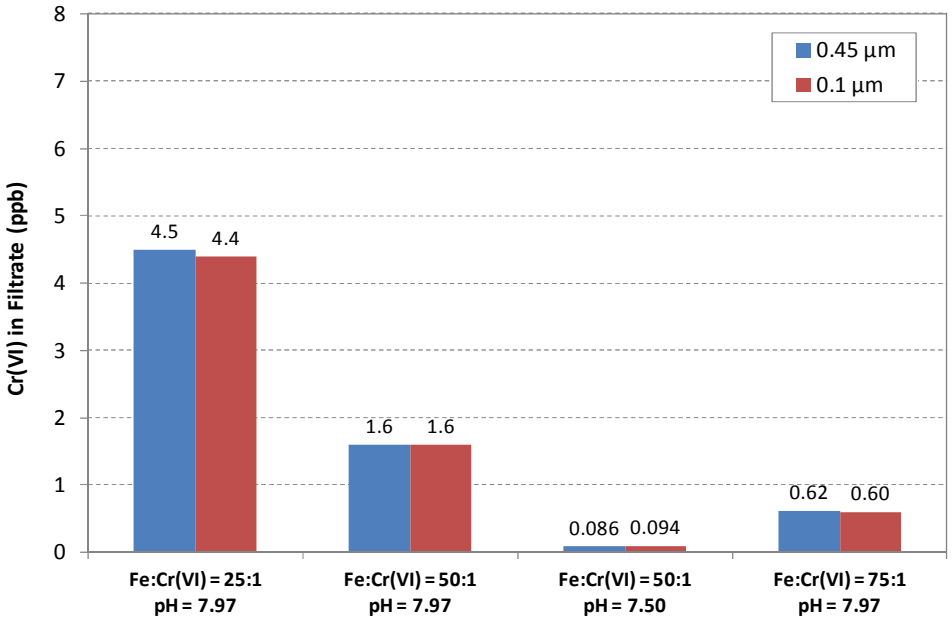


Figure 5-14. Hexavalent Chromium Removal Results for Utility III Sample (Raw water Cr(VI) = 9.6 ppb)

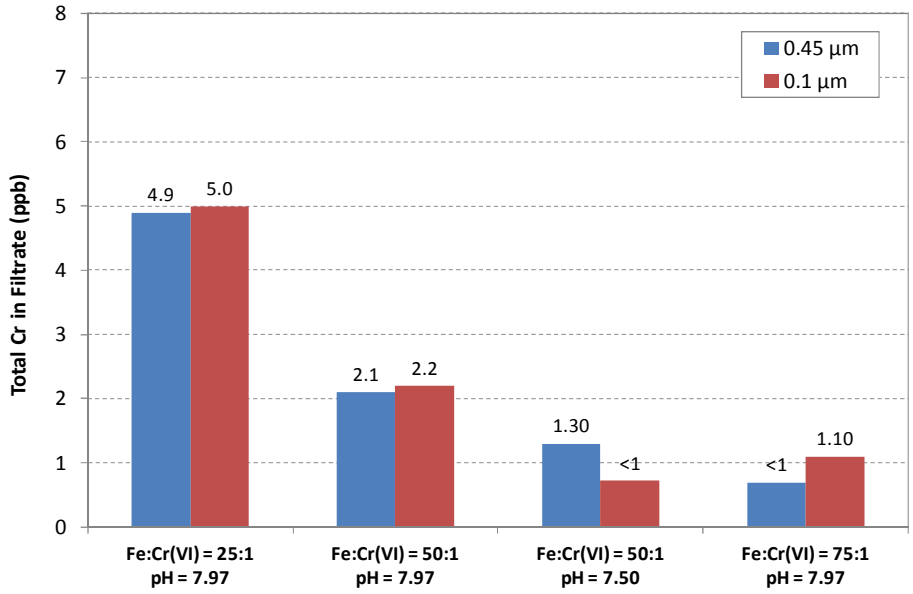


Figure 5-15. Total Chromium Removal Results for Utility III Sample (Raw water Cr(VI) = 9.6 ppb)

5.3.4.2 Solid Residuals Quantity

Similar to the Utility I sample, settled solids in the Imhoff cone were not visible for all the Fe:Cr(VI) ratios tested for Utility III. Dry solid weight based on mass balance was 1.8, 2.5 and 3.2 mg/L for Fe:Cr(VI) ratios of 25:1, 50:1 and 75:1, respectively. The mass balance calculation assumed all chromium was removed as solid residuals. The solids obtained during the jar testing were less than 1 mg/L for each Fe:Cr(VI) ratio tested.

5.3.4.3 Solid Residuals Hazardous Characteristics

Table 5-6 presents concentrations of metals regulated by the California WET TTLC. Chromium concentrations in the solid residuals were estimated to be 3,040 mg/kg, which was above the TTLC regulatory limit of 2,500 mg/kg. Thus, the solid residuals generated for the Utility III sample would likely be classified as a hazardous waste in California. For the same reasons discussed in Section 5.3.2.3, it cannot be determined whether the solids are a non-RCRA or RCRA waste without conducting the TCLP test.

Table 5-6. Metal Concentrations in Raw and Treated Utility III Sample for Hazardous Characterization

Metals	MDL (µg/L, or ppb)	Raw (µg/L, or ppb)	Treated (pH = 7.70 Fe:Cr(V) =50:1; 0.45 µm) (µg/L, or ppb)	Calculated Accumulation in dry solid residual (mg/kg)	TTLC Regulatory Limit (mg/kg)
Antimony	0.2	<0.2	<0.2	N/A	500
Arsenic	0.06	1.4	1.1	120	500
Barium	0.001	290	270	8,000	10,000[#]
Beryllium	0.05	<0.05	<0.05	N/A	75
Cadmium	0.01	<0.01	<0.01	N/A	100
Chromium	0.09	8.4	0.8	**3,040**	2,500
Cobalt	0.05	0.16	0.2	N/A	8,000
Copper	0.2	1.7	0.85	340	2,500
Lead	0.04	0.23	<0.04	N/A	1,000
Mercury	0.04	<0.04	<0.04	N/A	20

Metals	MDL (µg/L, or ppb)	Raw (µg/L, or ppb)	Treated (pH = 7.70 Fe:Cr(V) =50:1; 0.45 µm) (µg/L, or ppb)	Calculated Accumulation in dry solid residual (mg/kg)	TTLC Regulatory Limit (mg/kg)
Molybdenum	0.06	1.7	1.0	280	3,500*
Nickel	0.3	1.7	2.1	N/A	2,000

N/A – not applicable (when the metal concentration was non-detect in the raw water, or the treated concentration was higher than the raw water).

#Excluding barium sulfate; *Excluding molybdenum disulfide.

5.4 Summary and Conclusions

The jar testing results suggest both 0.45 and 0.1 micron pore sized filters effectively removed chromium particles formed during the reduction and coagulation steps of the RCF process. This finding suggests that microfiltration may be effective for enhanced removal of Cr-associated particles.

pH was found to have a significant impact on chromium reduction efficiency. The effect of pH might be caused by expedited ferrous oxidation by oxygen at a higher pH. Increased pH levels, especially above 8, resulted in treated Cr(VI) concentrations that were two orders of magnitude higher compared with the treated Cr(VI) concentrations for a pH of 7.5. Thus, for water sources with a relatively high pH level, pH reduction may be necessary for effective Cr(VI) removal using RCF.

Silica was also noted to inhibit Cr(VI) removal when spiked to 76 mg/L as SiO_2. The impact of silica might be contributed by pH increase resulting from silica spiking or formation of ferrous silica precipitate. However, silica at levels close to or below 30 mg/L as SiO_2 did not result in a noticeable impact on Cr(VI) and total Cr removal. A slight increase in the phosphate concentration (1.3 mg/L as PO_4) did not show significant impacts on Cr(VI) and total Cr removal.

The jar testing results showed that a Fe:Cr(VI) ratio of 25:1 effectively removed Cr(VI) and total Cr to below 1 ppb for influent Cr(VI) concentrations of 80 ppb or above. However, a higher Fe:Cr(VI) ratio of 50:1 or 75:1 was necessary for effective Cr(VI) reduction for lower influent Cr(VI) concentrations of approximately 10 ppb. For a low influent Cr(VI) concentration, the ferrous dose provided by a 25:1 ratio may not be sufficient to completely reduce Cr(VI). Additionally, pH reduction was shown to improve Cr(VI) and total Cr removal, when combined with the higher Fe:Cr(VI) ratio.

RCF residuals quantities estimated based on mass balance were more conservative, but within the same order of magnitude, as the values obtained during the jar testing due to the low residuals quantities generated and experimental limitations. The residuals were estimated to be classified as non-RCRA hazardous waste due to chromium concentrations above the TTLC regulatory limit and demonstration-scale experience at Glendale.

Jar testing provides valuable information on residuals in different water qualities. Pilot-scale testing can further help to evaluate residuals quantities and characteristics for a specific water quality (in addition to operational assessments).

6. RCF Residuals Treatment Cost Implications in the State of California

This section describes the RCF residuals treatment and disposal costs for a range of system sizes (10, 100, 500, 2,000 and 5,000 gpm) with various influent Cr(VI) concentrations (5, 10, 25 and 50 ppb). The system sizes were selected to represent different system size categories as specified by EPA (listed in Table 6-1). The influent Cr(VI) concentrations were selected to represent different levels of Cr(VI) contamination in water sources, which have an impact on O&M costs. Capital and O&M costs were estimated for the five system sizes with different influent Cr(VI) concentrations. State-wide costs were then developed based on the system costs and Cr(VI) occurrence data for California.

Table 6-1. Flow Rates for Cost Estimating

USEPA System Size Category Based on Population	Population	Assumed Flow Rate	Selected RCF Flow Rate for Cost Estimate (gpm)
"Very Small"	25 – 500	1 - 100 gpm	10
"Small"	501 – 3,300	1 - 100 gpm	100
"Medium"	3,301 – 10,000	100 gpm – 1 MGD	500
"Large"	10,001 – 100,000	1 MGD – 5 MGD	2,000
"Very Large"	>100,000	> 5 MGD	5,000

6.1 Cost Estimating Basis

The expected level of accuracy for the cost estimates presented in this section is classified by the Association for the Advancement of Cost Engineering International (AACE) as International Class 5 estimates. Typical uses for Class 5 estimates include assessment of initial viability, evaluation of treatment trains, and long range capital planning. Typical accuracy ranges for Class 5 estimates are -20% to -50% on the low side and +30% to +100% on the high side. The basis of the estimates performed for this study includes manufacturer's quotes for equipment and percentages for common construction items.

6.2 Design Criteria

Table 6-2 presents the design criteria used for costing RCF residuals treatment systems for the five system sizes. As filter backwash water is the primary residual for the RCF process, the design and operation of filters provides the basis for the residuals treatment systems. Thus, filter design and operations are also described. The demonstration-scale study at the City of Glendale is based on granular media filtration. Therefore, the residuals treatment systems presented are also designed based on granular media filtration. Microfiltration (MF) was being tested at Glendale to run in parallel with granular media filtration and at the time of this report was prepared, the testing was completed at the time of this report was revised. The difference between residuals treatment systems for MF and granular media filtration are discussed in Section 6.5.

Pressurized filters were selected as the filter vessel type in this analysis; however, gravity filters may also be feasible, especially for large systems. Horizontal pressurized filters were selected for 2,000 and 5,000 gpm systems due to limitations on large-sized vertical vessels. For thickening processes, gravity thickeners in parallel were selected for 10 gpm and 100 gpm systems; one equalization tank followed by one plate settler thickener was selected for the larger systems since plate settlers have a smaller footprint than gravity thickeners. Thickened residuals were assumed to have a solids concentration of 1.5%. For the dewatering process, passive filtration containers (e.g., Sludge Mate) were applied for systems up to 2,000 gpm. However, mechanical dewatering might also be selected. Mechanical dewatering was selected for the 5,000 gpm system. However, a Sludge Mate type of approach could also be applied, depending on land availability and operational preference. Centrifuges were used as the mechanical dewatering equipment for cost estimate development; however, other type of dewatering devices may also be applied. Utilities may choose their preferred mechanical dewatering equipment identified as feasible for RCF residuals in Table 4-9, as no one type is absolutely better than the other.

Table 6-2. RCF Filtration and Residual Treatment Systems Design Criteria

Process	RCF System Size (gpm)				
	10	**100**	**500**	**2,000**	**5,000**
Granular Media Filtration (pressurized or gravity)	Pressurized				
Granular Media Filtration (vertical or horizontal)	Vertical filters			Horizontal filters	
Solids thickening	Two gravity thickeners in parallel		Equalization tank + Plate settler thickener		
Solids concentration in gravity and plate settler residuals effluents	1.5%				
Dewatering	Passive Filtration (Sludge Mate)				Centrifuge

Table 6-3 lists RCF operations and filter backwash parameter assumptions that affect residuals quantities and operations of the residuals treatment systems. Based on the jar testing results (Section 5), an Fe:Cr(VI) ratio of 75:1 was used to represent a conservative ferrous dose for estimating residuals quantities for influent Cr(VI) concentrations of 5 and 10 ppb. An Fe:Cr(VI) of 50:1 was used for influent Cr(VI) concentrations of 25 and 50 ppb. Based on operations of the demonstration-scale system at City of Glendale and observed solids loading rates, filter run cycles were assumed to be 72 hours for influent Cr(VI) concentrations of 5 and 10 ppb, and 48 hours for influent concentrations of 25 and 50 ppb. Considering the relatively low solids loading rates at Glendale, the assumed filter run cycles are conservative and might be extended significantly if shown no negative impact on chromium removal. The polymer doses and filter hydraulic loading rate (HLR) were based on the demonstration-scale testing at City of Glendale. A filter backwash HLR of18 gpm/sf is a conservative estimate, as the value is higher than the current HLR of 12 gpm/sf at Glendale.

Table 6-3. RCF Operations and Granular Media Filter Backwash

Item	Assumption
Influent Cr(VI) concentrations	5, 10, 25 and 50 ppb
Fe:Cr(VI) mass ratio	75:1 for influent Cr(VI) concentrations of 5 and 10 ppb; 50:1 for influent Cr(VI) concentrations of 25 and 50 ppb
Polymer dose added to filter influent	0.1 mg/L as active polymer
Polymer dose added to spent filter backwash water	1 mg/L as active polymer
Filter hydraulic loading rate	3 gpm/sf
Filter run cycle	72 hours for influent Cr(VI) concentrations of 5 and 10 ppb; 48 hours for influent Cr(VI) concentrations of 25 and 50 ppb
Filter backwash hydraulic loading rate	18 gpm/sf
Filter backwash duration	21 minutes

6.3 Capital Costs for Five System Sizes

This section presents capital costs developed for the RCF residuals treatment systems for the five system sizes.

6.3.1 Assumptions

Capital cost development relied on the following assumptions:

- Processes were sized based on residuals flow rates and solids concentrations, which depend on system flow rate and influent Cr(VI) concentration. An influent Cr(VI) concentration of 50 ppb was used for process sizing to represent a conservative estimate.
- Process sizing is not affected by potential Cr(VI) MCLs or treatment target levels. The RCF process is not amenable to selection of a target effluent concentration. Demonstration testing suggests that total Cr concentrations between 1 ppb and 5 ppb can be achieved with granular media filtration.
- Solids quantities were estimated using mass balance, which was shown to be a conservative and reasonable approach for representing the residuals

quantities generated during the demonstration-scale RCF study at City of Glendale.

- All solids captured on the filter media are effectively removed by each filter backwash.
- Filters are not included in the capital costs for residuals treatment systems.
- Filter backwash water is available at a sufficient pressure and flow rate. Costs of supplying the backwash water are not included in the capital costs for residuals treatment systems.
- No pH adjustment is included in the residuals treatment process.
- Supernatant from thickeners, filtrate from Sludge Mate containers, and centrate from centrifuges are recycled back to the RCF process. Alternatively, the supernatant might be discharged to the sewer, which would result in sewer discharge fees, or stored onsite and hauled away, which would require a storage tank and disposal costs. Costs were developed for recycling to the head of the plant.
- An equipment installation cost of 30% was included on top of the equipment quotes to account for tax, freight, installation and vendor services. A number of other common factors (listed in Table 6-4) were based on the installed equipment costs to provide the total direct costs.
- General factors (listed in Table 6-5) were based on the total direct costs, including contractor's overhead and profit, project level allowance (contingency) and engineering, legal and administrative.

Table 6-4. Capital Cost Factors Assumptions

Item	Percentage	Description
General Requirements	7.5%	"Division 1" requirements including labor supervision, field offices, temporary utilities, health and safety, office supplies, clean up, photographs, survey, erosion control, coordination, testing services, and record documents
Earthwork	5%	Excavation, backfill, and fill required to construct the project
Site Work	5%	Roadways, curb and gutter, sidewalk, and landscaping
Valves, piping, and appurtenances	15%	Major system piping and valves
Electrical, Instrumentation and Control	15%	Motor control center (MCC), conduit and wire, programmable logic controller (PLC) and supervisory control and data acquisition (SCADA) equipment

Table 6-5. Engineering Factors Assumptions

Item	Percentage	Description
Contractor's Overhead and Profit	20%	Includes bonds, mobilization and demobilization, insurance, overhead and profit, and management reserves
Project Level Allowance	20%	Budget item to cover change orders due to unforeseen conditions
Engineering, Legal and Administrative	20%	Includes permits, legal fees, and engineering fees for design and construction.

6.3.2 Residual Treatment Systems

This section provides a high level preliminary design of the RCF residuals treatment systems for purposes of developing Class 5 costs.

6.3.2.1 For 10-gpm RCF System

Figure 6-1 shows a process flow diagram of the residuals treatment system for a 10-gpm RCF system. The residuals treatment system was designed to handle filter backwash water from a 3.5-ft diameter pressurized filter. A 3.5-ft filter was used, considering this is the smallest standard filter size on the market. However, a smaller

filter can be obtained with special design and manufacture. The system consists of the following major equipment:

- Two 4,600-gal gravity thickeners, one duty and one standby. Each gravity thickener is designed to hold spent filter backwash water from one backwash of 3.5-ft diameter filter. If a smaller sized filter is used, the size of the gravity thickeners could be reduced.
- A polymer storage and feed system,
- Two 2-CY Flo-Trend passive filtration containers. Each container is designed to hold thickened residuals for approximately four months.
- Recycle pumps and residuals pumps, one duty and one standby.

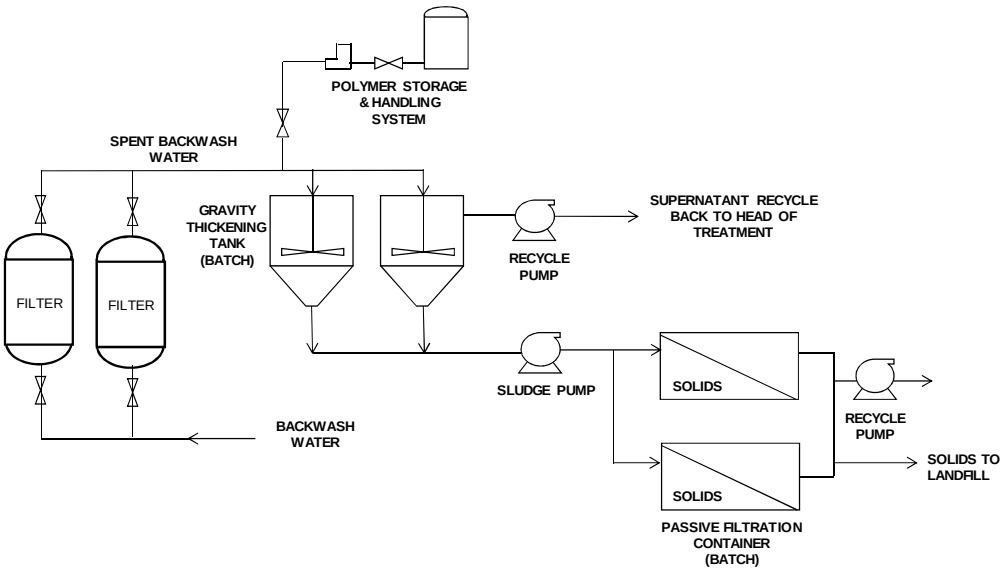


Figure 6-1. Process Flow Diagram of the Residuals Treatment System for a 10-gpm RCF System

6.3.2.2 For 100-gpm RCF System

Figure 6-2 shows a process flow diagram of the residuals treatment system for a 100-gpm RCF system. The residuals treatment system was designed to handle filter

backwash water from a 6.5-ft pressurized filter. The system consists of the following major equipment:

- Two 13,000-gal gravity thickeners, one duty and one standby. Each gravity thickener is designed to hold spent filter backwash water from one backwash.
- A polymer storage and feed system.
- Two 6-CY Flo-Trend passive filtration containers. Each container is designed to hold thickened residuals for approximately one month.
- Recycle pumps and residuals pumps, one duty and one standby.

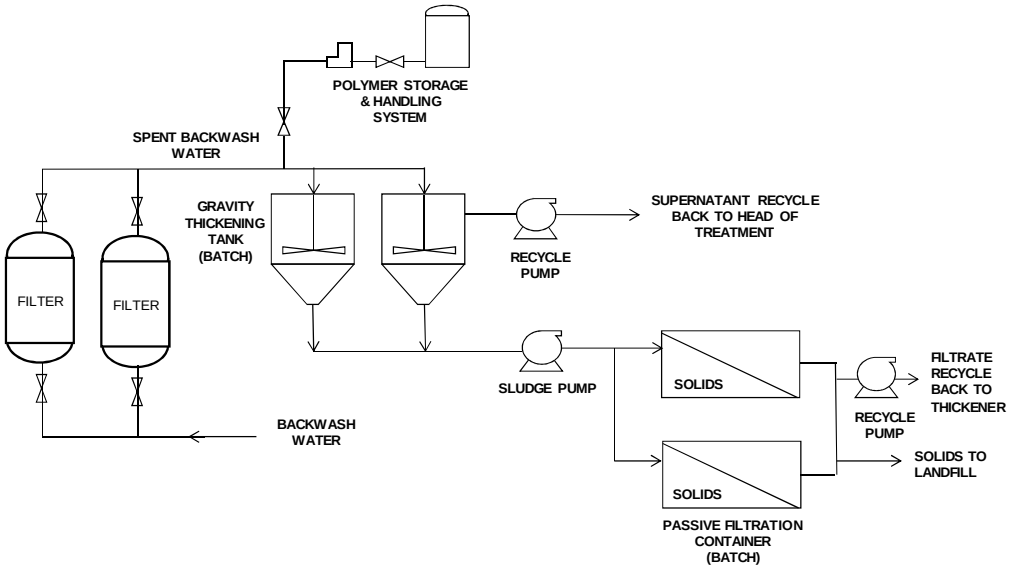


Figure 6-2. Process Flow Diagram of the Residuals Treatment System for a 100-gpm RCF System

6.3.2.3 For 500-gpm RCF System

Figure 6-3 shows a process flow diagram of the residuals treatment system for a 500-gpm RCF system. The residuals treatment system is designed to handle filter backwash water from four 8-ft pressurized filters. The system consists of the following major equipment:

- One 90,000-gal equalization tank with mixer, which is designed to hold filter backwash water from the four filters.

- One plate settler thickener, which receives a continuous flow from the equalization tank.
- A polymer storage and feed system.
- Three 15-CY Flo-Trend passive filtration containers. Each container is designed to hold thickened residuals for approximately nineteen days.
- Recycle pumps and residuals pumps, one duty and one standby.

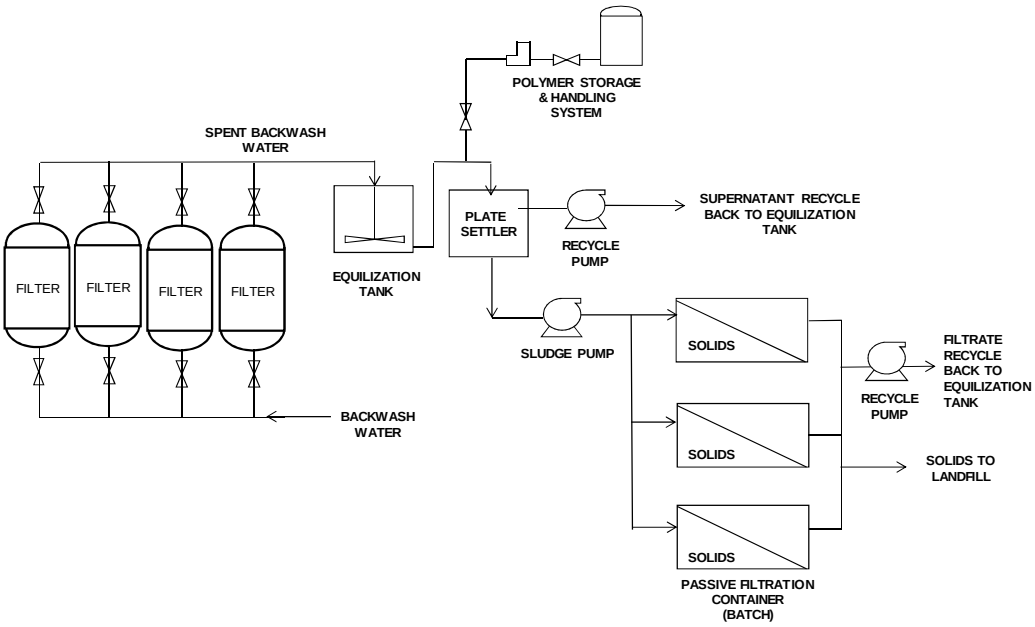


Figure 6-3. Process Flow Diagram of the Residuals Treatment System for a 500-gpm RCF System

6.3.2.4 For 2,000-gpm RCF System

Figure 6-4 shows a process flow diagram of the residuals treatment system for a 2,000-gpm RCF system. The residuals treatment system is designed to handle filter backwash water from two 10-ft horizontal pressurized filters with four cells per filter. The system consists of the following major equipment:

- One 280,000-gal equalization tank with mixer, which is designed to hold filter backwash water from all filters.

- One plate settler thickener, which receives a continuous flow from the equalization tank.
- A polymer storage and feed system.
- Three 40-CY Flo-Trend passive filtration containers. Each container is designed to hold thickened residuals for approximately seven days.
- Recycle pumps and residuals pumps, one duty and one standby.

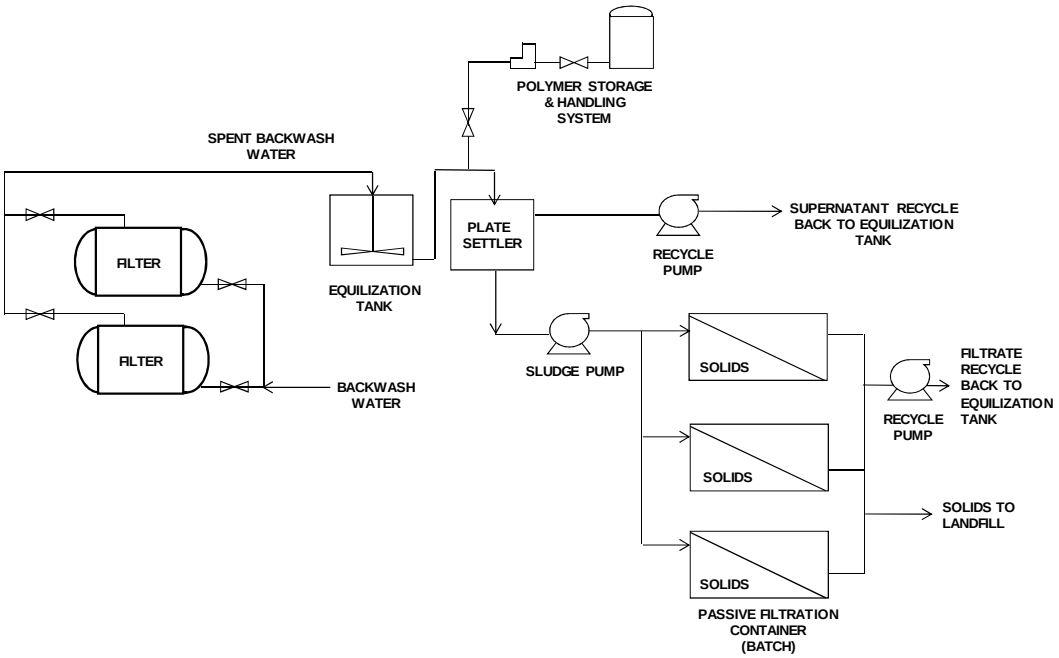


Figure 6-4. Process Flow Diagram of the Residuals Treatment System for a 2,000-gpm RCF System

6.3.2.5 For 5,000-gpm RCF System

Figure 6-5 shows a process flow diagram of the residuals treatment system for a 5,000-gpm RCF system. The residuals treatment system was designed to handle filter backwash water from four 10-ft pressurized filters with four cells per filter. The system consists of the following major equipment:

- One 670,000-gal equalization tank with mixer, which is designed to hold filter backwash water from all filters.
- One plate settler thickener, which receives a continuous flow from the equalization tank.
- A polymer storage and feed system.
- Three centrifuges, including two duty units and one standby.
- Centrifuge ancillary systems, including polymer blending unit, residuals feed pump, conveyors, liquid collection containers, dewatered solids containers etc.
- Recycle pumps and residuals pumps for equalization tank and plate settler thickener, one duty and one standby.

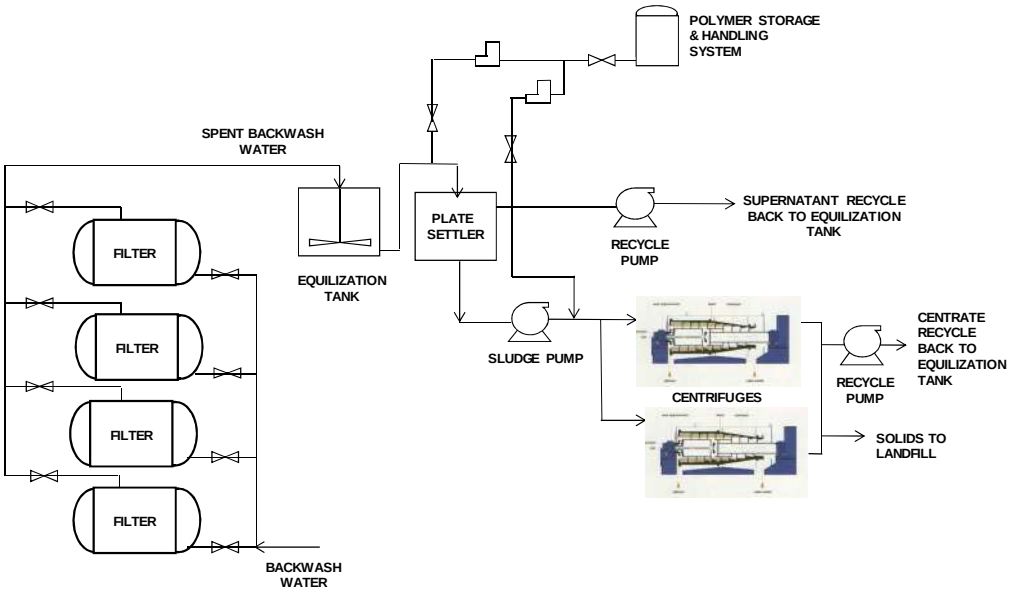


Figure 6-5. Process Flow Diagram of the Residuals Treatment System for a 5,000-gpm RCF System

6.3.3 Capital Costs

Table 6-6 and Figure 6-6 present the capital costs developed for the residuals treatment systems for the five system sizes. Details are attached in Appendix A. The capital cost of a 10-gpm system is relatively high for the flow rate, as it was designed to

treat filter backwash water from a 3.5-ft diameter filter vessel, which is the smallest modular filter available. A smaller filter could be used with special design and manufacture, which would result in a lower capital cost. On the high end, the capital cost of a 5,000-gpm residuals treatment system was estimated to be approximately $7.4 million, which is due to the high costs for centrifuges and ancillary equipment.

Cost curves were prepared to enable interpolation of costs between the discrete levels for which costs were directly determined (i.e., 10, 100, 500, 2,000, 5,000 gpm). Different regression types were attempted to fit the capital costs for the five system sizes, including linear, polynomial, exponential and power. The linear and polynomial regressions provided R^2 values of 0.96 and 0.99, respectively. However, the linear regression best reflects the costs for systems with flow rates of below 1,000 gpm. Since the majority of water sources had design flow rates below 1,000 gpm but above 100 gpm (details in Section 6.6), the linear regression approach was selected for the cost equation. The linear regression curve is less reliable at flow rates of 100 gpm or below (underestimating costs). However, on aggregate, the linear cost curve better reflects the total costs for all systems.

Table 6-6. Capital Costs for RCF Residuals Treatment Systems

RCF System Flow Rate (gpm)	Capital Costs for Residuals Treatment System (in 2011 dollar)
10	$ 290,000
100	$ 560,000
500	$ 1,290,000
2,000	$ 1,920,000
5,000	$ 7,440,000

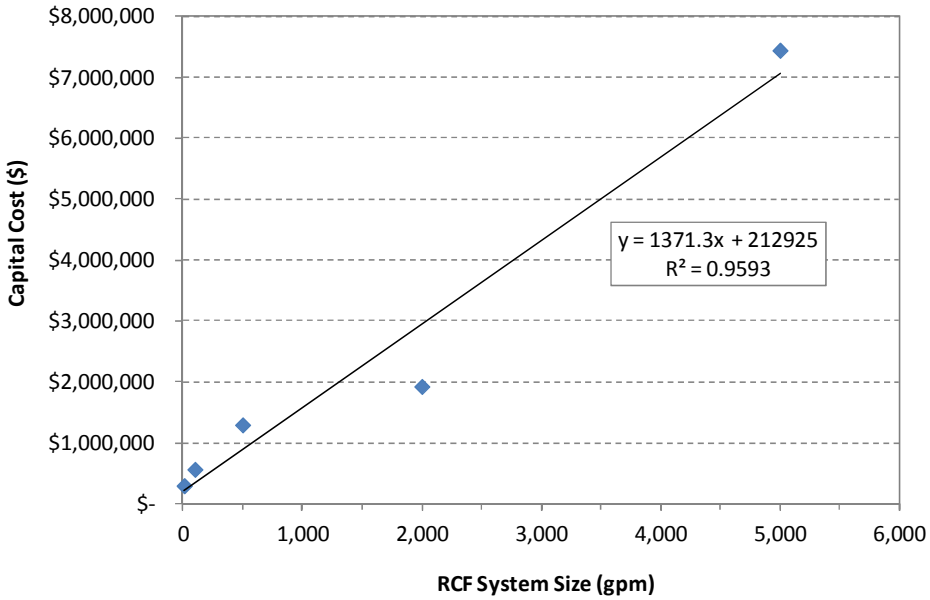


Figure 6-6. Capital Costs for RCF Residuals Treatment

6.4 Annual O&M Costs for Five System Sizes

This section presents annual O&M costs developed for the RCF residuals treatment systems for the five RCF system sizes.

6.4.1 Assumptions

Annual O&M costs were based on the following assumptions:

- A utilization rate of 100% of the design flow was assumed for simplicity.
- Solid residuals quantities depend on influent Cr(VI) concentration and Fe:Cr(VI) ratio. An Fe:Cr(VI) ratio of 75:1 was assumed for influent Cr(VI) concentrations of 5 ppb and 10 ppb. A Fe:Cr(VI) ratio of 50:1 was assumed for influent Cr(VI) concentrations of 25 ppb and 50 ppb. The jar test results suggest pH and silica could significantly affect ferrous dose required for efficient Cr(VI) removal. For this cost estimate, it is assumed that the raw water has a pH less than 7.7 and contains silica at low or moderate levels (i.e. < 34 mg/L.

- Dewatered solid residuals have a moisture content of 85%, which was observed for the dewatered solids during the Glendale demonstration testing of RCF. Mechanical dewatering is expected to generate solids with lower moisture content and higher solids concentrations. Thus, 85% moisture (i.e. 15% solids) is a conservative estimate for solid waste quantities.
- Dewatered solid residuals are non-RCRA hazardous wastes (in California).
- The landfill disposal cost for dewatered solid residuals is $1.55 per pound, based on the Glendale study. Utilities that generate residuals in large quantities might have significant cost savings, considering the relatively small quantities generated at the demonstration-scale at Glendale.
- All liquid waste is recycled back to the RCF process, thus no liquid waste discharge costs are included in the O&M costs.
- A polymer dose of 10 pounds per ton of solids was used to estimate polymer usage for effective solids dewatering by centrifuges.
- The polymer cost is $23.21 per gallon, which is the cost for the demonstration study at Glendale.
- The electricity cost is $0.10/kWh.
- Labor costs are estimate based on $100,000 per full time employee per year (loaded).
- Maintenance costs are estimated as 3% of installed equipment costs, with a minimum of $5,000 per year.
- No field and laboratory analysis costs are included in the O&M costs.

6.4.2 Annual O&M Costs

Figure 6-7 presents the estimated annual O&M costs for RCF residuals treatment and disposal. The annual O&M costs were based on a utilization rate of 100% of the design flow rate for simplicity. In reality, a lower utilization rate would be expected. The O&M costs for a lower utilization rate can be estimated by multiplying the costs in the figure by the actual utilization rate. The O&M costs are significantly affected by source water Cr(VI) concentrations, as a higher Cr(VI) level requires more ferrous addition and generates more solid residuals. Solid residuals disposal cost is the primary driver of the O&M costs. For a residuals treatment system handling residuals from a 5,000-gpm RCF system, the annual O&M cost is estimated approximately $0.54 million to $2.0 million for influent Cr(VI) concentrations of 5 ppb to 50 ppb. This

analysis assumes that the effluent treatment concentration that can be achieved is less than 5 ppb for all influent concentrations.

Different regression types were attempted to fit the O&M costs for the five system sizes, including linear, polynomial, exponential and power. The linear regression provided the highest R^2 values for all influent Cr(VI) concentrations. Thus, the linear regression was used to develop state cost implications in Section 6.6.

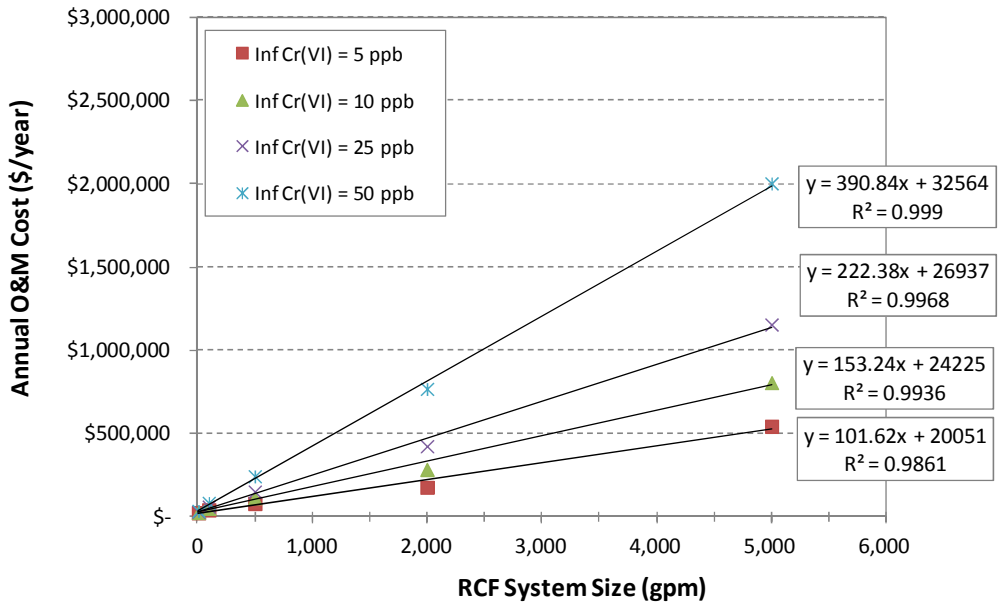


Figure 6-7. RCF Residual Treatment and Disposal O&M Costs Based on A 100% Utilization Rate

6.5 Unit Treatment Costs ($/AF)

Unit costs of RCF residuals treatment and disposal were developed based on annualized capital costs and annual O&M costs. Annualized capital costs were estimated using a 4.5% discount rate and a life cycle of 20 years. Figure 6-8 shows RCF residuals treatment and disposal unit costs for the five system sizes with four different influent Cr(VI) concentrations. For a 10-gpm system, the unit cost estimate ranges from $2,971 per acre-foot (AF) to $3,647/AF. The unit cost decreases significantly for larger system sizes, reflecting significant economies of scale to install a 100-gpm versus a 10-gpm system and even a 500-gpm system versus a 100-gpm

system. Very small systems would be particularly impacted by the residuals treatment and disposal costs. The effect of influent Cr(VI) concentration is significant for all system sizes. A higher influent Cr(VI) concentration would generate more residuals for treatment and disposal.

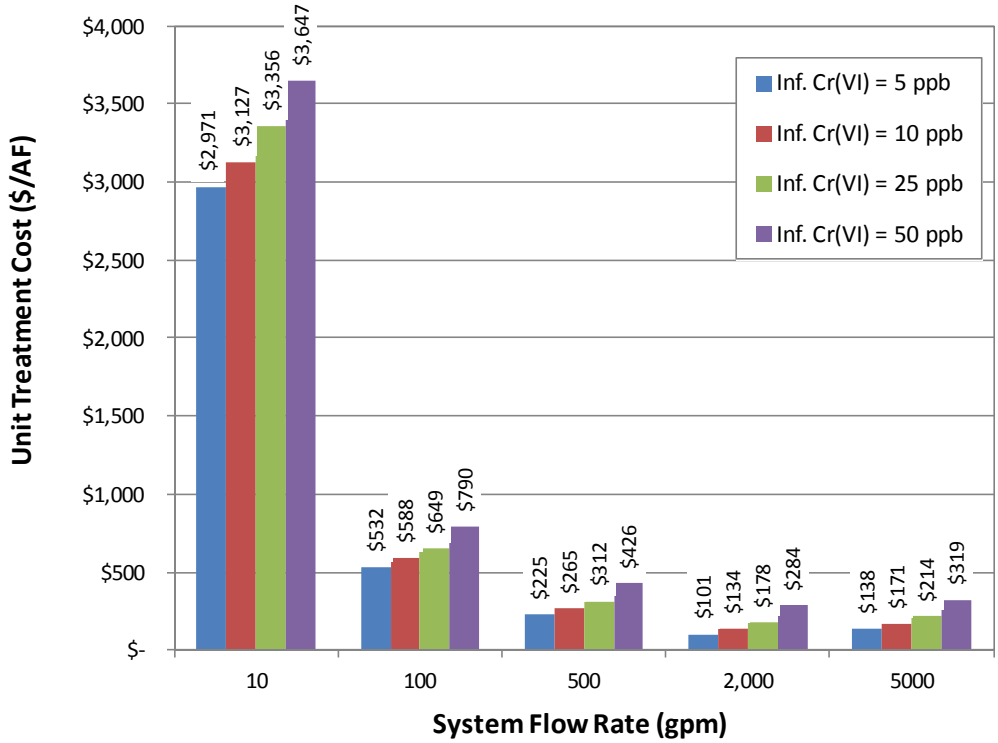


Figure 6-8. RCF Residuals Treatment and Disposal Unit Costs ($/AF)

6.6 Comparison to Arsenic Residuals Disposal Costs

A previous study was conducted to evaluate residuals disposal costs for arsenic treatment (Frey et al., 2003), including coagulation, regenerable ion exchange, nanofiltration, activated alumina and granular ferric hydroxide. The arsenic study only estimated residuals disposal costs for these technologies, without cost estimates for treatment facilities and O&M costs. Among the technologies evaluated for arsenic residuals, coagulation is similar to RCF for Cr(VI) treatment. Therefore, Cr(VI) residuals disposal costs only (without capital and other O&M costs) are compared to the arsenic residuals from coagulation.

Figure 6-9 compares annual costs for Cr(VI) RCF residual disposal with arsenic coagulation residual disposal for the five system sizes. The arsenic residuals costs are estimated by dividing the state-wide costs for the system size category (Table B.2 in the arsenic study) by the number of systems (listed in Table 6.1 in the arsenic study). The arsenic residuals costs are for an arsenic MCL of 2 ppb, which was estimated using a treatment target of 1 ppb in the arsenic study. The black line represents the arsenic residuals disposal costs presented in the arsenic study, adjusted to 2011 dollars using Engineering News Record (ENR) indices. The arsenic solid residuals from coagulation were assumed to be non-RCRA California hazardous waste, and the residuals disposal costs were based on $163.30 per 55-gallon drum ($0.36/lb) for 10 gpm and $116.51 per ton ($0.06/lb) for greater than 10 gpm, which were much lower than the actual $1.55/lb cost for RCF residuals disposal in 55-gal drums during the Glendale study. Drum disposal is expected to be representative considering Cr(VI) concentrations in most water sources in California are relatively low (i.e. <10 ppb), thus, small quantities of residuals would be generated. However, for utilities with high flow rate and/or high Cr(VI) concentrations, RCF residuals disposed in bulk (i.e. tons) are expected to result in significant cost savings.

On Figure 6-9, the orange line represents arsenic residual costs adjusted by using $1.55/lb as the unit disposal cost. The adjusted arsenic residual costs are comparable to the Cr(VI) residual costs with the four influent concentrations and close to the Cr(VI) residuals with an influent concentration of 10 ppb. Note that the comparison between arsenic and Cr(VI) residual costs are rough due to different approaches of cost estimate and different technologies (although RCF are similar to coagulation) but provide a useful comparison.

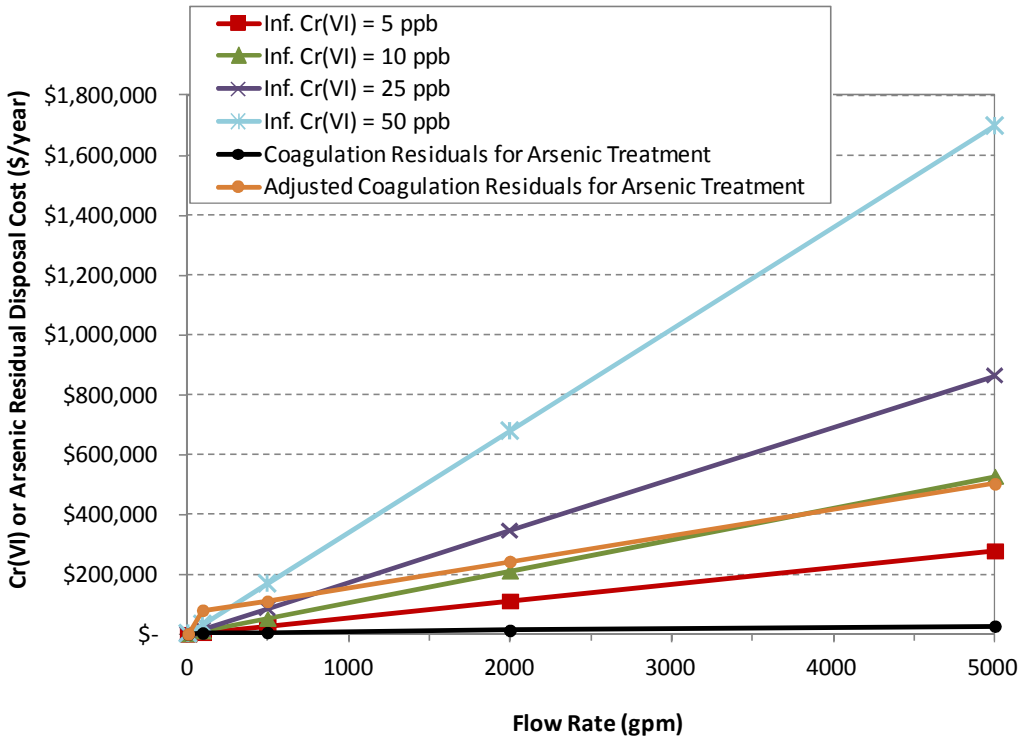


Figure 6-9. Cr(VI) RCF Residual Costs versus Arsenic Coagulation Residual Costs

Note: Arsenic costs are for an arsenic MCL of 2 ppb and a treatment target of 1 ppb. The black line represents average costs per system, which was adjusted from 2003 dollars to 2011 dollars, as determined by Frey et al. (2003). The orange line represents costs adjusted by a unit disposal cost of $1.55/lb.

6.7 Microfiltration vs. Granular Media Filtration

The capital and O&M costs for RCF residuals treatment are based on granular media filtration. Granular media filtration is shown to effectively remove Cr(VI) and total Cr to below 5 ppb (typically total Cr values fall between 1 and 3 ppb). Sub-ppb levels have been observed for Cr(VI) but not consistently for total Cr. MF achieved better total Cr removal compared to granular media filtration due to much smaller pore sizes, as observed in MF pilot testing at Glendale. The pilot results showed total Cr removal consistently to below 1 ppb. For Cr(VI) treatment targets below 2 ppb, MF would replace granular media filters in the RCF process. The differences for MF and granular media residuals treatment systems are discussed as below.

The primary wastewater from MF system is membrane backwash wastewater, which can account for a few percent of the total flow. The backwash wastewater can be

discharged to a surface water under the National Pollutant Discharge Elimination System (NPDES), to a sanitary sewer, or via other approaches (e.g. evaporation ponds, underground injection). Recycling is desired for water conservation; however, may pose significant challenges to membranes due to solids accumulated and carried back to the process via the recycle water.

Assuming membrane backwash waste water is to be treated, sizing of the thickening equipment (gravity thickeners, equalization tanks and plate settlers) could be reduced for MF systems. The thickening process is designed to handle spent filter backwash water from media filters in a batch mode. MF is expected to have more frequent backwashes with a smaller quantity in each backwash compared with granular media filters, although the overall water recovery rate for MF is expected to be lower than granular media filtration. Thus, a smaller sized thickening system may be sufficient to handle MF backwash water without the need to handle a large quantity of media filter backwash water at one time. Consequently, the capital cost for MF residuals treatment systems are expected to be lower than those presented for granular media filtration. MF membranes generally are not tolerant of polymer (with the exception of submerged membranes), so polymer addition to spent backwash water might need to be reduced or completely eliminated to avoid polymer carry over to the RCF water treatment process if backwash water recycling is desired. However, solids settling in gravity thickeners or plate settlers may not be as effective without polymer. Pilot testing is recommended to evaluate the potential impacts of polymer addition to thickening and dewatering processes on MF membrane performance, and the effectiveness of solids thickening and dewatering without polymer.

Without polymer addition to MF systems, the quantities of solid waste generated would be slightly lower than for granular media. However, the reduction in waste quantities is expected to be small, as the polymer doses to the granular media filter systems are approximately one order of magnitude lower than the ferrous iron dose. Thus, polymer only accounts for a small portion of the solid residuals quantities. In addition to the effect on residuals quantities, polymer reduction or elimination would also result in savings in polymer chemical costs.

Additional residuals from MF systems include spent chemical cleaning water for membrane maintenance cleans and clean-in-place (CIP) procedures. This wastewater typically contains relatively high concentrations of chlorine and acids and may need to be handled separately than regular membrane backwash wastewater. The chemical cleaning water is typically discharged to the sewer due to high concentrations of chemicals and low pH levels. Alternatively, the chemical cleaning waste could also be

hauled away and disposed. Nonetheless, the additional costs for handling/disposing the chemical cleaning wastewater need to be added to the capital and O&M costs if MF is considered.

6.8 State-Wide Cost Implications

State-wide cost implications were developed for Cr(VI) residuals treatment and disposal based on the Cr(VI) occurrence database provided by CDPH in November 2011, and the capital and O&M costs estimated for five RCF residuals systems. Only the systems and water sources reported in the CDPH database were considered. Five potential Cr(VI) MCLs were evaluated: 1, 2, 5, 10 and 25 ppb. The Cr(VI) results reported to the Cr(VI) database had a Cr(VI) reporting limit of 1 ppb, so water sources with Cr(VI) concentrations below 1 ppb could not be quantified.

6.8.1 Data Sources

The Cr(VI) occurrence data included primarily Unregulated Contaminant Monitoring Rule (UCMR) results completed during 2001- 2002 and continued monitoring volunteered by some systems until October 2011. In addition, Cr(VI) data collected between 1994 – 2000 were also included, which account for a small portion of the occurrence data (i.e. approximately 2.1% of the total results). Overall, a total of 1,689 community systems and non-transient non-community systems were monitored at 6,793 sample stations (raw and treated water) with a total of 25,013 water samples included in the database. The systems in the CDPH database account for roughly 37% of all community and non-transient non-community systems in California.

The database includes Cr(VI) results for both raw and treated water for various sources, including active, standby, abandoned, and destroyed sources, etc. Only active and standby raw water sources were considered in the cost analysis. Inactive, abandoned or destroyed, purchased sources, agricultural wells, and monitoring wells were excluded from residuals cost analysis. Additionally, a total of 1,735 water sources with only one sample analyzed were excluded from the database for the cost analysis, as CDPH indicated only water sources with two or more samples are typically considered for MCL cost analysis.

Table 6-7 lists the numbers of water systems, water sources and Cr(VI) samples in the screened database. Very small systems accounted for 37.0% of all the systems in the database, followed by large systems (23.3%), small systems (18.1%), medium systems (11.7%) and very large systems (6.9%). System size and population were assigned to individual systems by retrieving information from the Safe Drinking Water Information System (SDWIS) Federal Database of October 2010. A total of 30 systems (3.1% of the total systems) were not found in the SDWIS Federal Database, so their system sizes and populations served could not be identified.

The numbers of raw water sources for the systems in each size category are also listed in Table 6-7. For very small systems, on average 1.6 sources were monitored per system. The number of water sources increased from 2.4 for small systems to 21.9 for very large systems. A total of 18,944 samples were analyzed for the water sources identified in the screened database for further Cr(VI) residuals cost analysis.

Table 6-7. Active and Standby Raw Water Sources with Two or More Cr(VI) Samples in the CDPH Database for Cr(VI) Residuals Cost Analysis

EPA System Size Category (Population Served)	**Number of Systems**	**Percentage by System**	**Number of Raw Water Sources** (Active + Standby)	**Average Number of Raw Water Sources Monitored per System**	**Number of Cr(VI) Samples**
Very small (<500)	360	37.0%	566	1.6	1,993
Small (501 – 3,300)	176	18.1%	427	2.4	1,243
Medium (3,301 – 10,000)	114	11.7%	418	3.7	1,543
Large (10,001 – 100,000)	227	23.3%	1,483	6.5	5,187
Very Large (>100,000)	67	6.9%	1,466	21.9	8,637
Uncategorized* (unknown)	30	3.1%	75	2.5	341
Sum	974	100.0%	4,435	Not Applicable	18,944

*Systems not listed in the Public Water System Inventory from Safe Drinking Water Information System Federal Database (October 2010).

Table 6-8 summarizes the water sources based on water source type, i.e. groundwater or surface water. Of the raw water sources, 94.3% (4,184 out of 4,435) were groundwater and 5.7% (251 out of 4,435) were surface water. This may reflect the fact that groundwater sources are typically greater in numbers but smaller in flow rate compared with surface water sources.

Table 6-8. Groundwater vs. Surface Water Sources in the CDPH Database for Cr(VI) Residuals Cost Analysis

Water Type	Number of Water Sources	Percentage by Water Sources	Number of Cr(VI) Samples
Groundwater	4,184	94.3%	17,421
Surface Water	251	5.7%	1,523
Sum	4,435	100.0%	18,944

The Cr(VI) results in the database had a reporting limit of 1 ppb. Thus, Cr(VI) results below 1 ppb were considered non-detect for the Cr(VI) residuals cost analysis. However, the current method detection limit for Cr(VI) is significantly lower (approximately 0.02 – 0.06 ppb). Water sources with Cr(VI) levels below 1 ppb but above the current method detection limit were not included in this costs analysis.

6.8.2 General Approach Used to Develop State-Wide Cost Estimates for RCF Residuals Treatment

Based on the screened database described in Section 6.8.1, the approach below (illustrated in Figure 6-10) was followed to estimate the state-wide costs associated with handling residuals from treating source waters containing Cr(VI) at concentrations exceeding potential MCLs using the RCF process. This approach was based on similar costs development efforts described in AwwaRF (1995) and Russell et al. (2009), including the following steps:

1. Calculate the average Cr(VI) concentration for each water source, assuming non-detects (i.e. below 1 ppb) were equal to zero.
2. Identify water sources with an average Cr(VI) concentration ≥ 1 ppb.
3. Estimate design and average flow rates for each system with Cr(VI) by plugging the population data into the following regression equations developed by the USEPA (2005b).

   Groundwater Systems:
   - Design flow (mgd) = 0.39639 x population $^{0.97708}$ /1,000
   - Average daily flow (mgd) = 0.06428 x population $^{1.07652}$ / 1,000

   Surface Water Systems:
   - Design flow (mgd) = 0.36971 x population $^{0.97757}$ /1,000
   - Average daily flow (mgd) = 0.10540 x population $^{1.02058}$ / 1,000

4. For groundwater sources, estimate the design and average flow rates for each source by dividing the system flow rates by the total number of wells for groundwater systems listed in Table 6-9. As illustrated in Figure 6-10, flow rates for each groundwater source in surface water systems were estimated using the system flow rate divided by the number of wells. For surface water sources, estimate the design and average flow rates for each source by dividing the system flow rates by the total number of entry points for surface water systems listed in Table 6-9.
5. Assign capital costs for treating each contaminated source, using design flow rate of each source and the capital cost equation shown in Figure 6-6.
6. Assign O&M costs for treating each contaminated source, using average flow rate of each source and the O&M cost equations shown in Figure 6-7.
7. Tally capital and O&M costs to treat each contaminated source with a Cr(VI) concentration exceeding a given value (1, 2, 5, 10 and 25 ppb).

Table 6-9. Numbers of Water Sources for Groundwater and Entry Points for Surface Water Systems

Population Served	Number of Wells^	Median Number of Entry Points*
<100	1.5	1
101 – 500	2.0	1
501 – 1,000	2.3	1
1,001 – 3,300	3.1	1
3,301 – 10,000	4.6	1.8
10,001 – 25,000	9.8	3
25,001 – 50,000	9.8	4
50,001 – 75,000	16.1	5
75,001 – 100,000	16.1	5.5
100,001 – 500,000	49.9	6
500,001 – 1 million	49.9	21

^Source: USEPA, 1999. *Regulatory Impact Analysis and Revised Health Risk Reduction and Cost Analysis for Radon in Drinking Water*. EPA 815-D-99-002.

*Source: AwwaRF, 1995. *Estimating the Cost of Compliance with Drinking Water Standards: A User's Guide*.

Only one system serving a population of >1 million had water sources with average Cr(VI) levels ≥ 1 ppb. Flow rates for these water sources were obtained from a previous project.

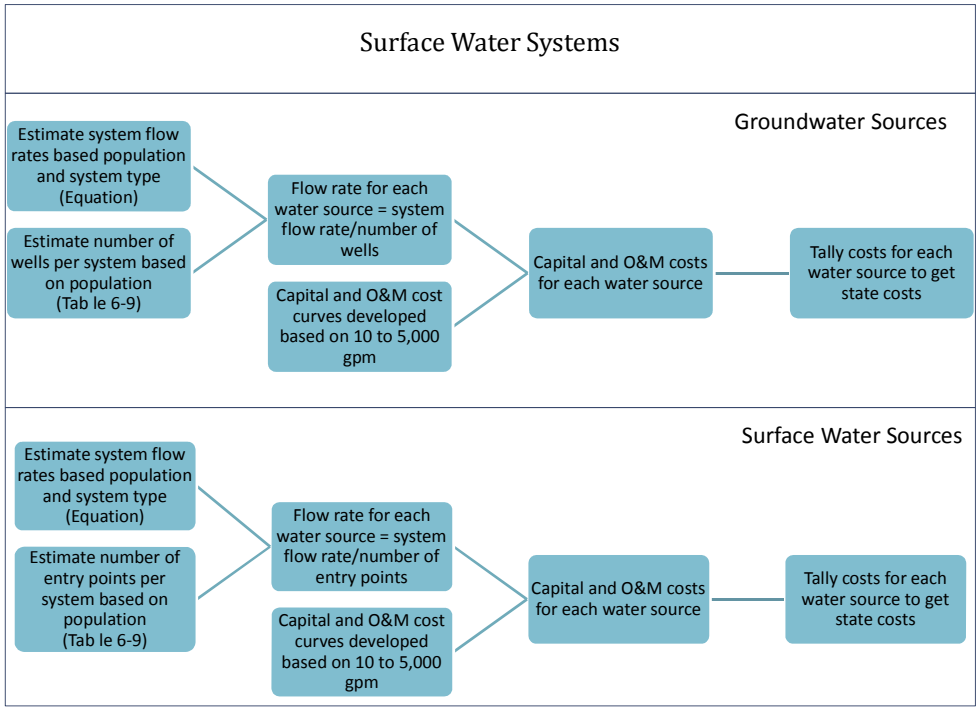


Figure 6-10. Approach Used to Develop State-Wide Cost Estimates

6.8.3 Water Sources for Cr(VI) Residuals Cost Analysis

Table 6-10 lists the number of water sources and systems that had average Cr(VI) concentrations equal to or above 1 ppb. A total of 2,252 water sources had average Cr(VI) concentrations above 1 ppb, including 41.1% in the range of >2.0 – 5.0 ppb, 25.5% in the range of 1.0 – 2.0 ppb, 21.0% in the range of >5.0 – 10.0 ppb, 11.02% in the range of >10.0 – 25.0 ppb. Only 22 water sources had average Cr(VI) concentrations of >25.0 – 50.0 ppb, and 4 water sources had average Cr(VI) concentrations greater than >50.0 ppb. The numbers of water systems showed a similar distribution in the various Cr(VI) concentrations ranges. Some systems had water sources that fell into different ranges. A total of 524 water systems were identified with water sources containing Cr(VI) at levels of ≥ 1 ppb.

Among the 2,252 water sources and 524 systems, 39 water sources (all groundwater) and 14 systems could not be found in the EPA SDWIS Federal database, so their flow

rates could not be estimated due to the lack of population information. These water sources were not included in this Cr(VI) residuals cost analysis.

Table 6-10. Water Sources and Systems with Average Cr(VI) Concentrations ≥ 1 ppb

Average Cr(VI) Concentration (ppb)	Number of Systems	Percentage by Systems*	Number of Water Sources	Percentage by Water Sources
1.0 – 2.0	245	46.8%	575	25.5%
>2.0 – 5.0	288	55.0%	926	41.1%
>5.0 – 10.0	178	34.0%	472	21.0%
>10.0 – 25.0	91	17.4%	253	11.2%
>25.0 – 50.0	11	2.1%	22	1.0%
>50.0	4	0.8%	4	0.2%
Sum	524*	-	2,252	100.0%

* A total of 524 systems had water sources with average Cr(VI) concentrations ≥ 1 ppb. Some systems were counted more than once, as they had water sources that fell into different average Cr(VI) concentration categories.

The numbers of water sources and systems in the CDPH database that would be affected by potential Cr(VI) MCLs are summarized in Table 6-11. For an MCL of 25 ppb, 26 sources from 13 systems would be affected. For an MCL of 10 ppb, the number of sources affected would increase to 279. An estimated 751 sources would be affected if an MCL is established at 5 ppb.

Table 6-11. Estimated Numbers of Water Sources and Systems in the CDPH database that Would be Affected by Potential Cr(VI) MCLs, Based on CDPH Occurrence Data

Potential Cr(VI) MCL (ppb)	Number of Systems	Number of Water Sources
25	13	26
10	94	279
5	221	751
2	411	1,677
1	524	2,252

6.8.4 Blending and Side Stream Treatment

Estimated costs described in Section 6.8 are based on treatment capacities of a whole flow without alternatives to treatment such as blending with another water source, in order to provide easy to use cost building blocks to CDPH for further cost analysis for the State of California. In reality, a utility might be able to blend sources or treat a partial flow, depending on the influent water concentration and the regulatory limit, to reduce the treatment needs.

Blending is an acceptable form of treatment in California, except for extremely impaired sources or sources with high iron and manganese concentrations. Blending to meet the MCL may be possible if a water utility has a low Cr(VI) supply that can be used to blend down the high Cr(VI) water to meet the MCL.

Partial stream treatment may be another option, whereby only a portion of a high Cr(VI) water might need treatment to achieve a Cr(VI) MCL. The possibility for blending and side-stream treatment is site specific, which is why it was not included in this costing effort.

6.8.5 Capital Costs

The following assumptions were used to develop capital costs for Cr(VI) residuals handling:

- All contaminated water sources with average Cr(VI) concentrations above a potential MCL level would need Cr(VI) treatment. Blending and source abandonment were not considered in this analysis.
- One treatment system would be installed for each contaminated water source (i.e., centralized treatment for well fields was not considered).
- Capital costs were based on the design flows of individual water sources.
- Costs for land acquisition and site preparation were not included in the capital costs.
- The MCL is based on Cr(VI) rather than total Cr (see Section 6.8.8 for additional discussion).

Table 6-12 lists the capital costs for RCF residuals treatment for the five potential Cr(VI) MCLs. For a potential MCL of 25 ppb, the total capital costs for residuals treatment at the 26 water sources that would be affected was estimated to be approximately $28 million dollars. A lower MCL level would result in a higher capital cost. For a potential MCL of 1 ppb, the capital cost was estimated to be approximately $2.5 billion dollars because many more systems would be affected.

Table 6-12. State-Wide Capital Costs for RCF Residuals Handling

Potential Cr(VI) MCL (ppb)	Number of Systems Affected	Number of Water Sources Affected	Capital Costs ($Millions) (in 2011 Dollars)
25	13	26	$ 28
10	94	279	$ 281
5	221	751	$ 761
2	411	1,677	$ 1,813
1	524	2,252	$ 2,512

6.8.6 O&M Costs

The following assumptions are used for O&M cost development:

- O&M costs are based on the average flow rates and average Cr(VI) concentrations for individual water sources.
- Net present value for 20 years was estimated based on an inflation rate of 2.5% and a discount rate of 4.5%.
- The MCL is based on Cr(VI) rather than total Cr (see Section 6.8.8 for additional discussion).

Table 6-13 lists the estimated annual and net present values for 20 years of O&M costs for RCF residuals handling. For a potential MCL of 25 ppb, the annual O&M cost was estimated to be $4 million dollars, and the net present value for 20 years would be approximately $65 million dollars. With a potential MCL of 1 ppb, the annual O&M cost was estimated to be $139 million dollars, with a net present value for 20 years of $2.3 billion dollars. Note the O&M costs reflect the assumption that water sources requiring Cr(VI) treatment contain low or moderate silica concentrations (i.e. < 34 mg/L).

Table 6-13. O&M Cost Estimates for RCF Residuals Treatment and Disposal for Systems and Water Sources in the CDPH Database that Would be Affected by Potential Cr(VI) MCL Levels

Potential Cr(VI) MCL (ppb)	Number of Systems	Number of Water Sources	Annual O&M Cost ($Millions) (in 2011 Dollars)	Net Present Value for 20 years of O&M Costs ($Millions) (in 2011 Dollars)
25	13	26	$ 4	$ 65
10	94	279	$ 26	$ 436
5	221	751	$ 58	$ 965
2	411	1,677	$ 107	$ 1,787
1	524	2,252	$ 139	$ 2,330

6.8.7 Total Costs

The estimated capital and O&M costs for RCF residuals treatment and disposal for the different potential Cr(V) MCL levels are shown in Figure 6-11. A total cost of $93 million dollars was estimated for a Cr(VI) MCL of 25 ppb. With a lower MCL level, the costs increase significantly as more water sources and systems would be affected. A total of $4.8 billion dollars was estimated for a MCL of 1 ppb. The estimated costs are relatively high due to the widespread occurrence of Cr(VI) in California at low levels and the relatively high disposal costs for Cr(VI) residuals in California as a non-RCRA hazardous waste.

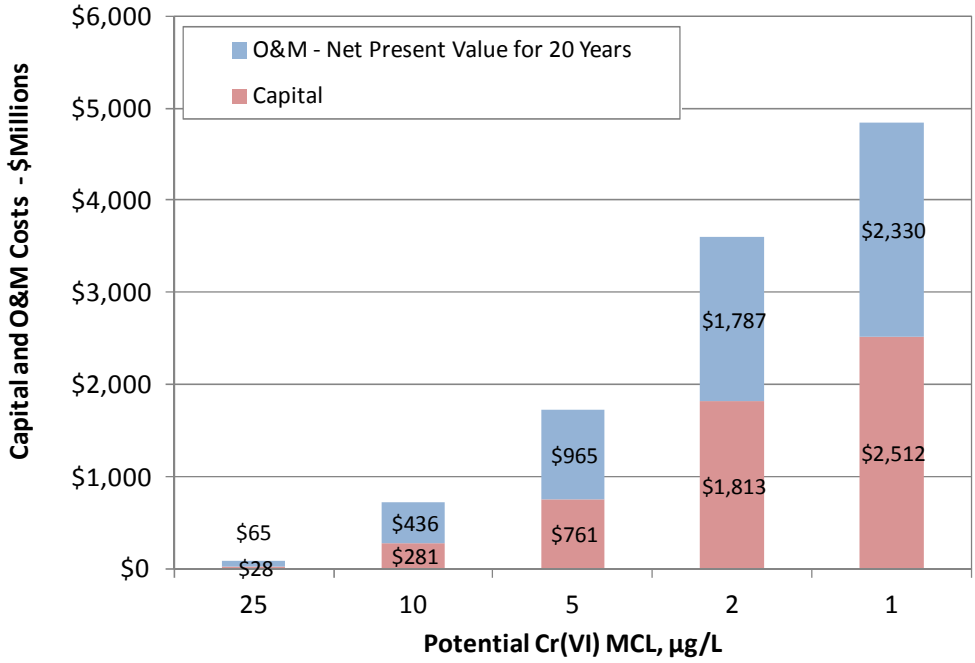


Figure 6-11. Capital and O&M Cost Estimates for RCF Residuals Treatment and Disposal for Potential Cr(VI) MCLs

Note: The costs are in 2011 Dollars.
For the systems and water sources in the CDPH database that would be affected by the potential Cr(VI) MCL levels.

6.8.8 Impact of a Focus on Total Cr Removal at Low Treatment Targets on Technology Selection and Cost

The RCF residuals costs described above are based on a Cr(VI) treatment target. Previous Phase I testing showed that Cr(III) can be converted to Cr(VI) by disinfectant residual in the distribution system. A focus on total Cr removal is therefore needed to avoid reconversion by the time the water reaches the consumer's tap. Should regulation of total Cr be based on total Cr or if a utility chooses to focus on total Cr removal, then the RCF process may not reliability treat the water to achieve 1 and 2 ppb total Cr water quality targets using granular media filtration. MF testing was being conducted when this report was prepared and was completed when this report was revised. The MF testing suggests total Cr could be removed to below 1 ppb. If total Cr is the goal, then total costs for RCF residuals treatment statewide would be lower than

estimated in this report because the technology would not be applicable to utilities seeking lower treatment targets. Alternative approaches would be required (e.g., refer to Section 7.6 for discussion about WBA).

6.9 Summary and Conclusions

Figure 6-6 summarizes the capital costs for RCF residuals treatment for 10-gpm, 100-gpm, 500-gpm, 2,000-gpm and 5,000-gpm RCF systems. The capital costs increase with increased system flow rate, from $0.3 million dollars for a 10-gpm RCF system to $7.4 million dollars for a 5,000-gpm RCF system.

Figure 6-7 summarizes the O&M cost estimates for residuals treatment on the same RCF systems. The primary drivers for O&M costs are residuals disposal and labor costs. The residuals disposal cost is relatively high resulting from non-RCRA hazardous waste classification in California. Residuals quantities will be primarily affected by ferrous dose, which depends on the influent Cr(VI) concentration and the Fe:Cr(VI) ratio. A higher influent Cr(VI) concentration would result in a greater residuals quantity, and therefore a higher disposal cost. For a water source with a relatively high silica concentration (i.e., > 34 mg/L), a higher ferrous dose might be required, which would result in greater residuals quantity and a higher disposal cost.

Unit treatment costs for RCF residual treatment are summarized in Figure 7-4. The unit cost decreases significantly for larger system sizes, especially from 10 gpm to 100 gpm, reflecting economies of scale. The influent Cr(VI) concentration also affects the unit cost significantly, with a higher unit cost for a higher influent Cr(VI) concentration.

State-wide costs for RCF residuals treatment were summarized in Figure 6-11, which were developed based on the capital and O&M costs estimated for the five RCF systems and Cr(VI) occurrence data provided by CDPH. Only the systems and water sources in the CDPH database were considered for the state-wide costs. For the five potential Cr(VI) MCL levels evaluated, the total costs for residuals treatment increase significantly with a lower MCL, as more water sources and systems would be affected (listed in Table 6-11). Net present values of O&M costs for 20 years were estimated to be at the same order of magnitude as for capital costs.

7. WBA Residual Cost Implications in the State of California

This section describes the WBA residuals treatment and disposal costs for a range of system sizes (10, 100, 500, 2,000 and 5,000 gpm). Capital and O&M costs were estimated for the five system sizes. State-wide costs were then developed based on the system costs and Cr(VI) occurrence data in California for the systems and water sources included in the CDPH database.

7.1 Cost Estimating Basis

The expected level of accuracy for the cost estimates presented in this section is classified by AACE as International Class 5 estimates, which are described in Section 6.1.

7.2 Design Criteria

The primary residuals generated in the WBA process are spent resin and resin flush water after resin replacement. Table 7-1 presents the WBA design criteria, which provides the basis for residuals quantities and the residuals handling system capacities.

Both spent resin and wastewater generation depends on resin operational life, which is determined by the Cr(VI) treatment target level or the MCL. As the Cr(VI) MCL has not been established, six potential MCL levels were considered in this cost evaluation (Table 7-2). Based on the Cr(VI) breakthrough curves obtained from the demonstration-scale testing at Glendale, treated water bed volumes (BVs) for each Cr(VI) target level was identified. The resin life was assumed to be not significantly affected by source water Cr(VI) concentrations (i.e., that other parameters impact resin capacity more than Cr, such as is observed perchlorate-selective resins). Note that this assumption requires testing using other utilities' water qualities.

The values in Table 7-2 reflect the bed volumes of water treated by the lead vessel before a resin replacement. No significant diminished capacity in the lag vessel was observed after the first resin replacement when the lag vessel was switched as lead vessel. Additional testing should be considered to verify the replacement frequency for other utilities, since resin replacement cost accounts for the major part of the WBA O&M cost.

The quantity of resin flush water is estimated to be approximately 43 bed volumes of water, which is based on the WBA operating experience at Glendale. Thus, the flush water quantity during each replacement depends on the resin bed volume. For the purpose of this evaluation, it was assumed that the WBA systems with a flow rate of 10, 100 or 500 gpm have two vessels in lead-lag configuration, while the 2,000 and 5,000-gpm systems consist of multiple lead-lag trains of 12-ft vessels.

In Section 7, spent resin disposal cost is based on the actual cost for spent resin disposed as a non-RCRA, TENORM waste in the Grandview RCRA waste landfill in Idaho. The disposal cost was largely affected by uranium accumulated on the resin. Uranium concentrations in Glendale's groundwater are between 1.8 and 3.3 pCi/L, with an average of 2.7 pCi/L (i.e., 2.7 – 5.0 ppb with an average of 4.1 ppb). For utilities with higher uranium levels, uranium may accumulate on the resin at a faster rate. For utilities with lower uranium levels, uranium could accumulate on the resin with a slower rate, which might result in a lower uranium concentration at the time of resin disposal depending on the length of service life. For utilities with lower uranium concentrations in their water sources, spent resin might be disposed as a non-RCRA hazardous waste (i.e. not a TENORM waste) with a lower cost associated with that disposal. For more accurate cost estimates for state-wide implications, data analysis of uranium concentrations for sources that might need Cr(VI) treatment is recommended.

This evaluation also assumes that resin pretreatment to remove formaldehyde (i.e., a "brine squeeze" procedure) will be conducted before installation of the resin, as required at Glendale for PWA7 resin. It is suggested that utilities verify formaldehyde concentrations in resin flush water right before installation of the resin to avoid extra costs resulting from dealing with formaldehyde leaching once installed. In case high formaldehyde concentrations are detected after the resin is installed, resin flushing could be used to reduce formaldehyde levels and the flush wastewater needs to be properly disposed (e.g. sewer discharge, depending on local restrictions). The associated costs for flushing and wastewater disposal are dependent of formaldehyde levels and a utility's discharge options. In general, these costs are expected to be a relatively small portion of the overall residual disposal costs, considering the high disposal costs for non-RCRA and TENORM waste disposal.

Table 7-1. Weak Basin Anion Exchange Design Criteria

Item	Assumption
Resin	Dow Amberlite™ PWA7
Empty bed contact time	3 min
Resin operational life	Listed in Table 7-2
Flush water during resin replacement	43 bed volumes

Table 7-2. WBA Resin Replacement Thresholds

Potential Cr(VI) MCL (ppb)	Bed Volumes Treated
0.5*	120,000
1*	132,000
2*	150,000
5	172,000
10	260,000
25	480,000

* Note that total Cr was not removed to less than 2 ppb without significantly diminished bed life – refer to Section 7.6 for discussion.

7.3 Capital Costs for Five System Sizes

The WBA resin is used in single-pass and non-regenerable mode, with resin expected to be disposed to a landfill. Thus, the WBA residuals system only handles the wastewater from resin replacement.

7.3.1 Assumptions

Capital costs were based on the following assumptions:

- The wastewater is discharged to the sewer without treatment.
- An equipment installation cost of 30% on top of the equipment quotes to account for tax, freight, installation and vendor services.
- A number of other common factors (listed in Table 6-4) based on the installed equipment costs to provide the total direct costs;

- General factors (listed in Table 6-5) based on the total direct costs, including contractor's overhead and profit, project level allowance (contingency) and engineering, legal and administrative.
- The MCL is based on Cr(VI) rather than total Cr (see Section 6.8.8 for additional discussion).

7.3.2 Capital Costs

The WBA residuals handling system is straightforward and consists of a wastewater storage tank and discharge pumps (one duty and one standby), as shown in Figure 7-1. The storage tank is designed to hold wastewater from one resin replacement. The discharge pumps are estimated to have relatively small capacities, as a discharge flow rate limit is often imposed on sewer connections.

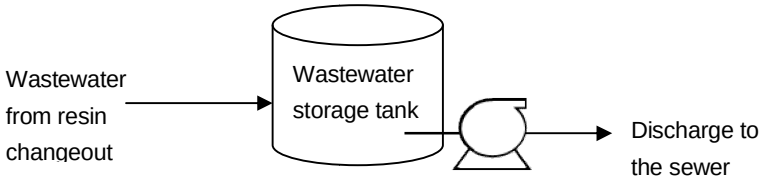


Figure 7-1. WBA Residual Handling System Schematic

Table 7-3 and Figure 7-2 show the estimated capital costs for the five WBA systems. Details are attached as Appendix B. The capital costs increase from $120,000 for 10-gpm system to $0.8 million for 2,000-gpm system. The capital cost for systems with a flow rate of greater than 2,000 gpm is expected to be similar to the cost for 2,000 gpm system, assuming only one vessel is replaced with new resin per replacement, thus, the amount of wastewater per replacement does not increase much for a larger system.

Different regression types were attempted to fit the capital costs for the system sizes of 10 to 2,000 gpm, including linear, polynomial, exponential and power. The cost for 5,000 gpm was not included in the regression analysis, considering systems with design flow rates greater than 2,000 gpm are estimated to have similar costs for 2,000 gpm. The power regression provided the highest R^2 value and reflection of costs when interpolated, so this approach was used for state cost implications in Section 6.8. For systems with design flow rates greater than 2,000 gpm, the capital costs for 2,000 gpm were used in the state cost analysis.

Table 7-3. WBA Residuals Handling System Capital Cost Estimates

WBA System Flow Rate (gpm)	Capital Cost for Residuals Handling System (in 2011 Dollars)
10	$ 120,000
100	$ 270,000
500	$ 510,000
2,000	$ 830,000
5,000	$ 830,000

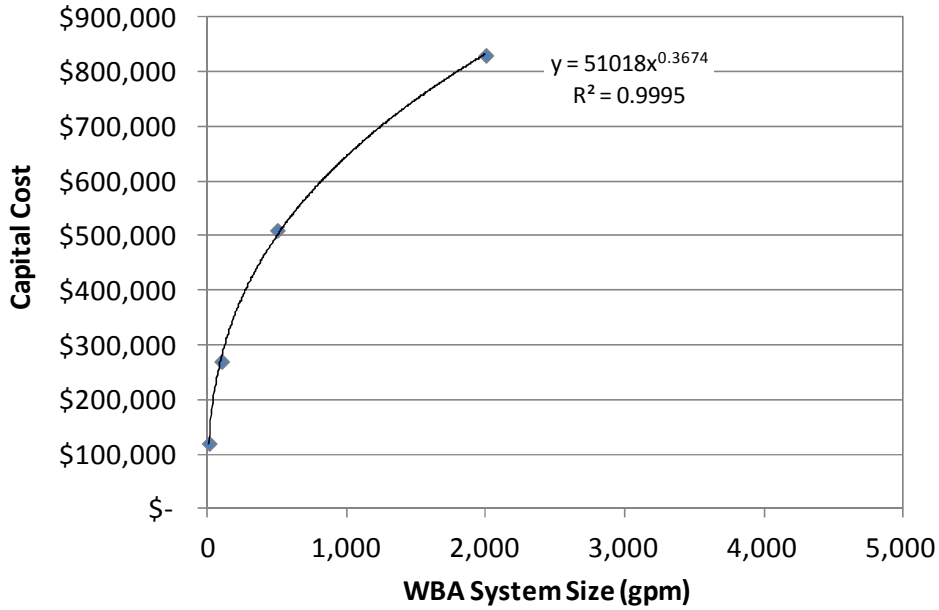


Figure 7-2. Capital Costs for WBA Residuals Handling

7.4 Annual O&M Costs for Five System Sizes

This section presents annual O&M costs developed for the WBA residuals handling and disposal for the five WBA system sizes.

7.4.1 Assumptions

The annual O&M costs for WBA residuals handling and disposal were estimated based on the assumptions in Table 7-4. The resin life was assumed to be not significantly affected by source water Cr(VI) concentrations (i.e., that other parameters impact resin capacity more than Cr, such as observed for perchlorate-selective resins). In addition, The MCL is based on Cr(VI) rather than total Cr (see Section 6.8.8 for additional discussion).

The solid waste (i.e. spent resin) is assumed to be a non-RCRA hazardous and TENORM waste, which is expected to be true for most groundwater sources. However, for water sources containing no uranium, the spent resin would not be a TENORM waste. In this case, the resin disposal cost is expected to be lower than $326/cf.

Table 7-4 Weak Basin Anion Exchange Residuals Assumptions

Item	Assumption
Resin operational life	Listed in Table 7-2
Solid waste characteristics	Non-RCRA hazardous and TENORM waste, which requires handling using absorbent material for dewatering before disposal
Solid waste disposal	$326/cf *, including waste handling and disposal fees
Wastewater characteristics	Non-hazardous waste, which is discharged to the sewer
Wastewater disposal	$3/hcf, plus a quarterly discharge fee of $900
Electricity	$0.10/kWh
Labor	$100,000 per full time employee per year
Maintenance	3% of installed equipment costs
Chemicals	No chemicals needed for residuals handling/treatment
Field and lab analysis	Not included

hcf- hundred cubic feet

*based on a recent quote from Dow and Siemens

7.4.2 Annual O&M Costs

Figure 7-3 presents the annual O&M costs for WBA residuals, specifically residuals handling and disposal. Detailed costs are included in Appendix B. WBA residuals

O&M costs are significantly affected by Cr(VI) treatment target levels, due to the relatively high costs for resin disposal. The O&M costs were based on 100% utilization rate for simplicity. The O&M costs for a lower utilization rate can be estimated by multiplying the costs in the figure by the actual utilization rate.

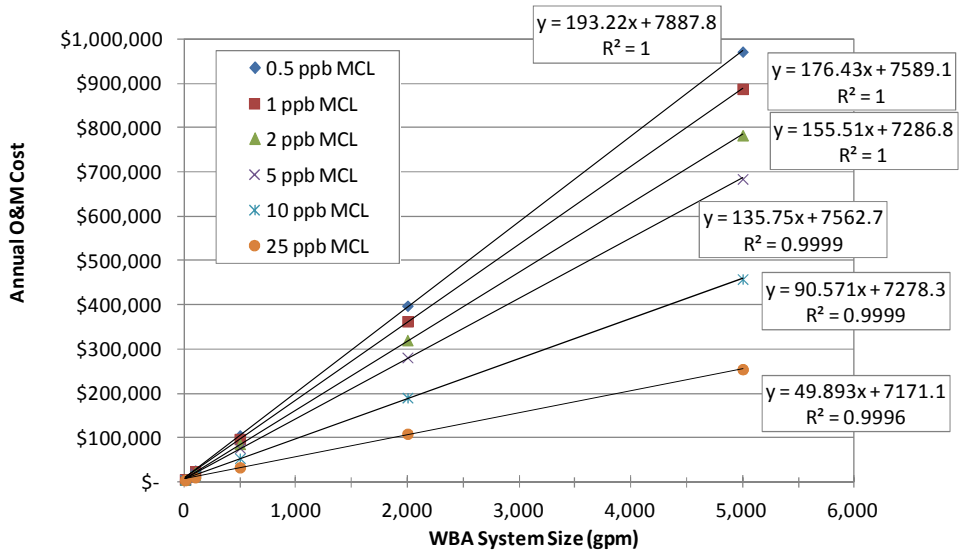


Figure 7-3. WBA Annual Residuals Handling and Disposal Costs Based on a 100% Utilization Rate

7.5 Unit Treatment Costs ($/AF)

Figure 7-4 presents the estimated unit residuals treatment/disposal costs in dollars per acre-foot ($/AF) for the five WBA systems with different target effluent Cr(VI) concentrations (i.e., potential Cr(VI) MCLs). Annualized capital costs were estimated based on a 4.5% discount rate and a 20-year life cycle. For a 10-gpm system, the unit cost estimate ranges from $888 to $1,006 per AF. The unit cost decreases significantly for larger system sizes, reflecting economies of scale to install a 100 gpm versus a 10 gpm system and even a 500 gpm versus a 100 gpm system. Very small systems would be particularly impacted by the residuals treatment and disposal costs.

The effect of the potential Cr(VI) MCL is significant for all system sizes, especially larger systems. For a 10-gpm system, the unit cost based on a 25 ppb MCL is

approximately 90% of the cost based on 1 ppb MCL highlighting the larger fraction capital cost plays at the lower flow rate. For a 5,000-gpm system, the unit treatment cost based on a 25 ppb MCL is approximately one third of the unit cost based on a 1 ppb MCL.

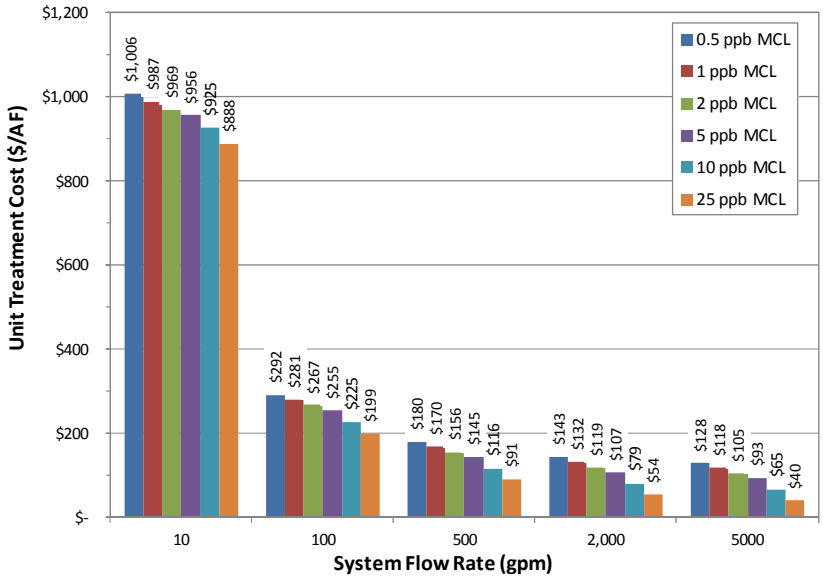


Figure 7-4. WBA Residuals Treatment and Disposal Unit Costs ($/AF)

7.6 Annual O&M Costs Based on Total Chromium Removal

The WBA costs described above are based on a Cr(VI) treatment target. As discussed in Section 6.8.8 for the RCF process, utilities may elect to focus on total Cr removal since Cr(III) can be reoxidized to Cr(VI) in the distribution system. For WBA, the total Cr concentrations in WBA lag bed effluent samples were higher than Cr(VI) during the initial breakthrough of chromium. For example, total Cr in treated water reached 1 ppb at approximately 3,300 BVs and 2 ppb at approximately 23,000 BVs. However, Cr(VI) in the treated water reached 1 ppb at approximately 132,000 BVs and 3 ppb at approximately 150,000 BVs. Total Cr and Cr(VI) concentrations in treated water converged when Cr(VI) exceeded 3 ppb. Therefore, we performed an additional analysis of potential treatment costs for the low 1 and 2 ppb endpoints, relying on the total Cr breakthrough curves.

WBA O&M costs for residuals would be higher for chromium removal based on total Cr, especially for the potential MCLs equal to and below 2 ppb. Figure 7-5 shows the WBA O&M costs for residuals based on total Cr removal to 1 ppb and 2 ppb, compared to Cr(VI) removal to the same levels. For a potential MCL of 1 ppb, annual O&M costs for residuals based on total Cr removal are estimated to be approximately 40 times of the costs based on Cr(VI) removal. For a potential MCL of 2 ppb, annual O&M costs based on total Cr are approximately 6.5 times of the costs based on Cr(VI) removal.

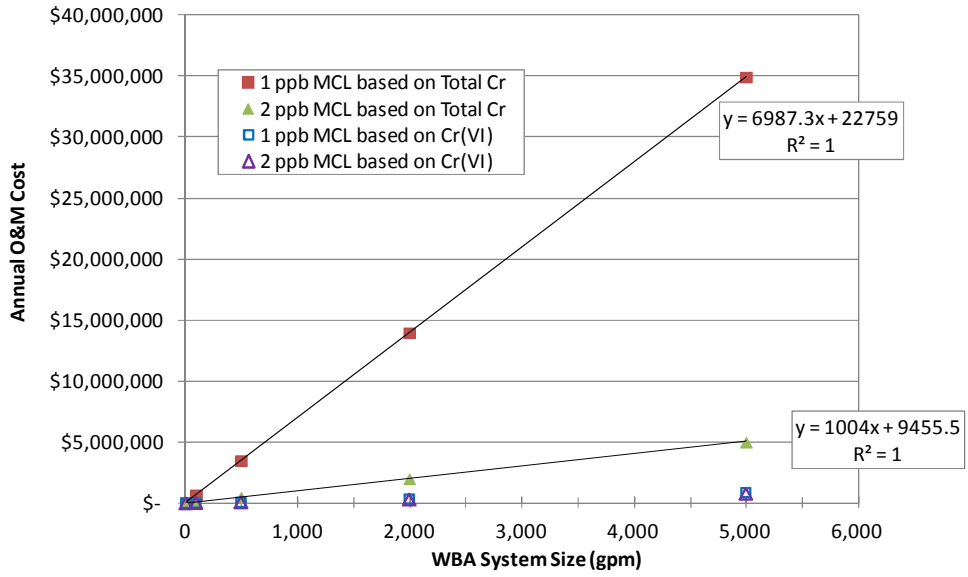


Figure 7-5. WBA Annual Residuals Handling and Disposal Costs Based on Total Cr Removal to 1 ppb and 2 ppb with a 100% Utilization Rate

7.7 Comparison to Arsenic Residual Disposal Costs

Similar to Section 6.6, Cr(VI) WBA residual disposal costs were compared to arsenic treatment costs reported by Frey et al. (2003), only this time for regenerable IX. WBA residuals consist primarily of spent resin (non-RCRA hazardous and TENORM) with limited resin flush water (non-hazardous). However, regenerable IX residuals consist of resin rinse water (non-hazardous liquid), untreated brine (hazardous liquid) and solids from post-brine treatment (non-RCRA hazardous). Thus, the Cr(VI) WBA residuals costs and arsenic regenerable IX residuals costs are not directly comparable.

Nevertheless, Figure 7-6 shows Cr(VI) WBA residuals annual costs and arsenic regenerable IX residuals annual costs. The arsenic residual costs are estimated by dividing the state-wide costs for the system size category (Table B.2 in the arsenic study) by the number of systems (listed in Table 6.1 in the arsenic study). The arsenic residuals costs are for an arsenic MCL of 2 ppb, which was estimated using a treatment target of 1 ppb in the arsenic study. The arsenic residual disposal costs were adjusted to 2011 dollars using ENR indices. In general, Cr(VI) WBA residuals cost estimates are lower than the arsenic residuals costs since brine disposal is not required for WBA.

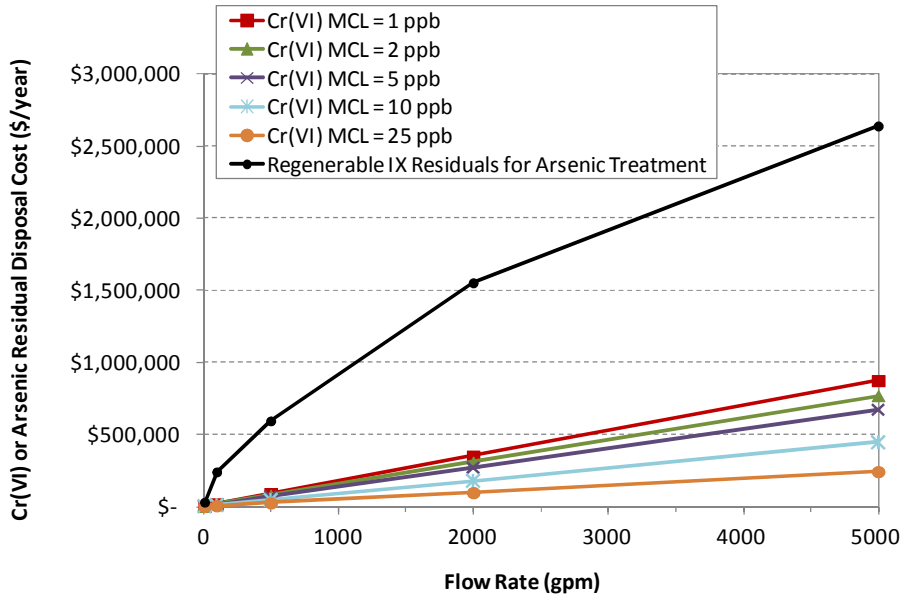


Figure 7-6. Cr(VI) WBA Residuals Costs versus Arsenic Regenerable IX Residual Costs

Note: Arsenic costs are for arsenic MCL of 2 ppb and a treatment target of 1 ppb. The black line represents average costs per system, which was adjusted from 2003 dollars to 2011 dollars.

7.8 State-Wide Costs Implications

The same Cr(VI) occurrence database and approach for RCF residuals costs development in Sections 6.8.1 to 6.8.3 were used for WBA residuals costs. The costs for a potential MCL of 0.5 ppb could not be determined due to the reporting limit of 1 ppb for results reported to the database. Only the systems and water sources in the CDPH database were considered in the state-wide cost analysis.

7.8.1 Capital Costs

The following assumptions are used for capital costs development:

- All water sources with average Cr(VI) concentrations above a potential MCL level would need Cr(VI) treatment. Blending and source abandonment were not considered as potential options in this analysis.
- One treatment system would be installed to each contaminated water source (i.e., centralized treatment for well fields was not considered).
- Capital costs were based on the design flows of individual water sources.
- Costs for land acquisition and site preparation were not included in the capital costs.

Table 7-5 lists the capital costs for WBA residuals handling for the potential Cr(VI) MCLs evaluated. The capital costs for WBA residuals handling were estimated to be an order of magnitude lower than the capital costs for RCF residuals. For a potential MCL of 25 ppb, the total capital costs for WBA residuals handling would be approximately $14 million dollars. With a lower MCL level of 1 ppb, the capital costs would increase to approximately $1.1 billion dollars.

Table 7-5. Estimated Capital Costs for WBA Residuals Handling and Disposal for Systems and Water Sources in the CDPH Database that Would Be Affected by Potential Cr(VI) MCL Levels

Potential Cr(VI) MCL (ppb)	Number of Systems Affected	Number of Water Sources Affected	Capital Costs ($ Millions – 2011 Dollars)
25	13	26	$ 14
10	94	279	$ 138
5	221	751	$ 364
2	411	1,677	$ 832
1	524	2,252	$ 1,130

7.8.2 O&M Costs

The O&M costs for WBA residuals handling and disposal were estimated based on the cost curves in Figure 7-3 for the potential Cr(VI) MCL levels evaluated. Table 7-6 lists the estimated annual O&M costs and net present value for 20 years. The O&M costs

for WBA residuals were estimated to be significantly higher than those for RCF residuals, primarily due to the high cost for spent resin disposal as a non-RCRA hazardous and TENORM waste. The cost estimates here are based on an assumption that all water sources contain uranium at levels similar to the concentration observed in the Glendale's water. However, some water sources may contain no uranium; thus, the spent resin would not be a TENORM waste. Alternately, some residuals in high uranium waters could be a mixed low level radioactive waste. The estimated annual O&M costs for WBA residuals in this cost estimate range between $0.6 million and $144 million dollars for the potential MCL levels from 25 ppb to 1 ppb. The net present values for 20 years were estimated to increase from approximately $10 million dollars for 25 ppb to roughly $2.4 billion dollars for 1 ppb.

Table 7-6. Estimated O&M Costs for WBA Residuals Handling and Disposal for Systems and Water Sources in the CDPH Database that Would Be Affected by Potential Cr(VI) MCL Levels

Potential Cr(VI) MCL (ppb)	Number of Systems	Number of Water Sources	Annual O&M Cost (in Millions - 2011 Dollars)	Net Present Value for 20 years of O&M Costs ($ Millions - 2011 Dollars)
25	13	26	$ 0.6	$ 10
10	94	279	$ 9	$ 151
5	221	751	$ 34	$ 571
2	411	1,677	$ 92	$ 1,542
1	524	2,252	$ 144	$ 2,415

7.8.3 Total Costs

The estimated capital and O&M costs for WBA residuals handling and disposal for the different potential Cr(V) MCL levels are shown in Figure 7-7. In general, the costs are relatively high due to the waste characteristics of non-RCRA hazardous and TENORM waste. A total cost of $24 million dollars was estimated for WBA residuals handling and disposal, if a Cr(VI) MCL is 25 ppb. With a lower MCL level, the costs were expected to increase significantly as more water sources and systems would be affected and the resin usage life would be significantly shorter. A total of $3.5 billion dollars was estimated for a MCL of 1 ppb if focusing on Cr(VI); costs would be even higher if focused on total Cr. The estimated total costs for WBA residuals are generally in the same order of magnitude as RCF residuals.

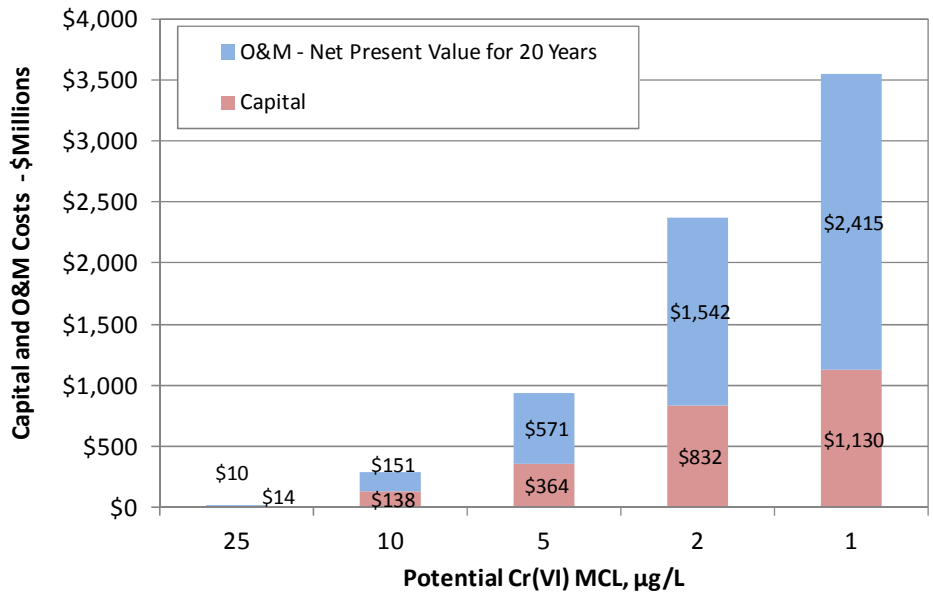


Figure 7-7. Capital and O&M Cost Estimates for WBA Residuals Handling and Disposal for Potential Cr(VI) MCLs

Note: The costs are in 2011 Dollars.

7.9 Summary and Conclusions

Figure 7-2 summarizes the capital costs for WBA residuals handling for 10-gpm, 100-gpm, 500-gpm, 2,000-gpm and 5,000-gpm WBA systems. The capital costs for WBA residuals handling systems were estimated to be relatively low, as the systems consist of only a wastewater storage tank and discharge pumps. No residuals treatment is expected for WBA systems. The capital costs were estimated to increase with a greater system flow rate, from $120,000 for a 10-gpm WBA system to $830,000 dollars for a 5,000-gpm WBA system.

Figure 7-3 summarizes the annual O&M costs for residuals treatment for the same WBA systems. The primary driver for O&M costs is residuals disposal. The residuals disposal cost is relatively high, as spent resin is expected to be a non-RCRA hazardous waste classified as TENORM, which likely requires handling before disposal. The residuals quantities were expected to be significantly affected by the

Cr(VI) MCL to be established. A lower MCL level would result in significantly higher residuals disposal costs as more frequent resin replacement is expected. The O&M costs were based on an assumption that resin life is not significantly affected by source water Cr(VI) concentrations (i.e., that other parameters impact resin capacity more than Cr, such as we see for perchlorate-selective resins; this assumption needs to be verified).

Unit treatment costs for WBA residual treatment are summarized in Figure 7-4. The unit costs decrease dramatically for larger system sizes, especially for 10 gpm versus 100 gpm, reflecting significant economies of scale. The effect of lower potential Cr(VI) MCLs is significant for all system sizes.

State-wide costs for WBA residuals treatment were summarized in Figure 7-7, which were developed based on the capital and O&M costs estimated for the five WBA systems and Cr(VI) occurrence data provided by CDPH. Only the systems and water sources in the CDPH database were considered. For the five potential Cr(VI) MCL levels evaluated, the total costs for residuals treatment increase dramatically with a lower MCL, as more water sources and systems would be affected (listed in Table 6-11) and the resin usage life would be shorter to meet the lower MCL. Net present values of O&M costs for 20 years were estimated to be significantly higher than the capital costs, especially for the potential MCL levels less than or equal to 5 ppb.

WBA O&M costs for residuals would be higher if based on total Cr removal than based on Cr(VI) removal for potential MCLs at or below 2 ppb, as shown in Figure 7-5. The higher costs are due to more frequent resin replacements based on total Cr removal compared with a Cr(VI) endpoint.

8. References

AwwaRF, 1995. *Estimating the Cost of Compliance with Drinking Water Standards: A User's Guide*.

Aoki and Munemori, 1982. Recovery of Chromium(VI) from Wastewaters with Iron(III) Hydroxide I. Adsorption Mechanism of Chromium(VI) on Iron(III) Hydroxide. *Water Res*, 18:793-796.

Baruth, EE (ed.), 1990. *Water Treatment Plant Design*. 4th Edition. Page 17.6.

Brandhuber, P., Frey, M., McGuire, M.J., Chao, P., Seidel, C., Amy, G., Yoon, J., McNeill, L. and Banerjee, K., 2004. *Treatment Options for Low-Level Hexavalent Chromium Removal Tested at Bench Scale*. Published by AwwaRF.

California Code of Regulation Title 17, Division 1, Chapter 5, Subchapters 4.0, 4.5 and 4.6.

Crittenden, J.C., Trussell, R.R., Hand, D.W., Howe, K.J. and Tchobanoglous, G., 2005. *Water Treatment: Principles and Design*. Second Edition.

Fendorf, S.E. and Li, G., 1996. Kinetics of Chromate Reduction by Ferrous Iron. *Environ. Sci. Technol*., 30:1614-1617.

Frey, M., MacPhee, M.J. and Bernosky, J., 2003. Arsenic Residuals Research Report: Implications for Alternative Arsenic MCLs for California Water Systems. Prepared for Association of California Water Agencies.

Russell, C.G., Roberson, J.A., Chowdhury, Z. and McGuire, M.J., 2009. National cost implications of a perchlorate regulation. *J.AWWA*, 101:3:54.

Ryden and Syers, 1987. Inorganic Sorption and Interactions with Phosphate Sorption by Hydrous Ferric Oxide Gel. *European Journal of Soil Science*, 38:2:211-217.

S.K. De, 2003. Adsorption of Phosphate Ion by Hydrous Ferric, Chromic and Aluminum Oxides, Part I. Without Organic Materials Added. *Colloid & Polymer Science*, 179:2:134.

Tamura, Goto and Nagayama, 1976. Effect of Anions on the Oxygenation of Ferrous Ion in Neutral Solutions*. J. Inorg. Nucl. Chem,* 38:113-117.

Twort, A.C., Ratnayaka, D.D. and Brandt, M.J., 2010. *Water Supply*, 5th Edition.

USEPA, 1999. *Regulatory Impact Analysis and Revised Health Risk Reduction and Cost Analysis for Radon in Drinking Water*. EPA 815-D-99-002.

USEPA, 1993. *Large Water System Byproducts Treatment and Disposal Cost Document. Office of Water*. EPA 811-D-93-002.

USEPA, 2005a. *A Regulator's Guide to the Management of Radioactive Residuals from Drinking Water Treatment Technologies*. Office of Water, EPA 816-R-05-004.

USEPA, 2005b. Economic Analysis for the Final Stage 2 Disinfectants and Disinfection By-products Rule. EPA 815-R-05-010, Office of Water, Washington.

Appendix **A**

Capital and O&M Costs for RCF Residuals Treatment Systems

OPINION OF PROBABLE PROJECT COST

Client	Association of California Water Agencies City of Glendale, Water and Power
Project	Hexavalent Chromium Treatment Residuals Management
Item	Residuals Treatment System for 10-gpm RCF System

Project No. 05337011.0000	
By: Y.W.	Ckd: T.V. & Y.W.
Date: 11/30/2011	Date: 1/18/2012

DESCRIPTION	QTY	UNIT MEAS.	UNIT COST	TOTAL COST	COMMENTS
Equipment					
Gravity Thickener	2	EA	$ 9,000	$ 18,000	Quote from Plastic-Mart for 4,600-gallon cone bottom tank with stand.
Flo-Trend SludgeMate Container	2	EA	$ 6,530	$ 13,060	Quote from Flo-Trend for 2-CY SludgeMate container.
Polymer Feed System	1	LS	$ 11,400	$ 11,400	Quotes from Siemens & C.P. Crowley
Pumps	1	LS	$ 8,000	$ 8,000	Includes all sludge pumps and recycle pumps, one duty and one standby.
Subtotal				$ 50,000	Rounded up to $1000
Equipment Installation Cost	30%			$ 15,000	Including tax, freight, installation and manufacturer services.
Chemical Storage Containment	8	CY	$ 1,250	$ 10,000	
Equipment Concrete Pads	32	CY	$ 1,250	$ 40,000	
Subtotal (Installed Equipment Costs)				$ 115,000	Rounded up to $1000
General Requirements	7.5%			$ 8,625	Division 1 requirements, including labor supervision, field offices, temporary utilities, health and safety, office supplies, clean up, photographs, survey, erosion control, coordination, testing services, and
Earthwork	5%			$ 5,750	Excavation, backfill, and fill required to construct project
Site Improvements	5%			$ 5,750	Roadways, curb and gutter, sidewalk and landscaping
Valves, Piping, and Appurtenances	15%			$ 17,250	Major system piping and valves
Electrical, Instrumentation and Controls	15%			$ 17,250	PLC and SCADA equipment to control
Total Direct Costs				$ 170,000	Rounded up to $1000
Contractor's Overhead and Profit	20%			$ 34,000	Includes bonds, mobilization and demobilization, insurance, overhead and profit, and management reserves
Construction Total				$ 204,000	Rounded up to $1000
Project Level Allowance (contingency)	20%			$ 40,800	Budget item to cover change orders due to unforeseen conditions
Engineering, Legal and Administrative	20%			$ 40,800	Includes permits, legal fees and engineering fees for design and
Project Total				$ 290,000	Rounded up to $10,000
Low Estimate				$ 203,000	-30%
High Estimate				$ 435,000	+50%

Notes:

1. This opinion of probable cost is based on AACE Class 5 estimate guidelines. The high and low estimates fall into the acceptable range. These estimates are generally used to compare alternatives.
2. Opinion of Probable Cost in 2011 dollars.
3. Costs for land or easements are not included.

MALCOLM PIRNIE | ARCADIS
The Water Division of ARCADIS

OPINION OF PROBABLE PROJECT COST

Client	Association of California Water Agencies City of Glendale, Water and Power
Project	Hexavalent Chromium Treatment Residuals Management
Item	Residuals Treatment System for 100-gpm RCF System

Project No. 05337011.0000	
By: Y.W.	Ckd: T.V. & Y.W.
Date: 11/30/2011	Date: 1/18/2012

DESCRIPTION	QTY	UNIT MEAS.	UNIT COST	TOTAL COST	COMMENTS
Equipment					
Gravity thickener	2	EA	$ 32,085	$ 64,170	Quote from Plastic-Mart for 13,000-gallon cone bottom tank with stand.
Flo-Trend SludgeMate Container	2	EA	$ 14,200	$ 28,400	Quote from Flo-Trend for 6-CY SludgeMate container.
Polymer Feed System	1	EA	$ 11,400	$ 11,400	Quotes from Siemens & C.P. Crowley
Pumps	1	LS	$ 10,000	$ 10,000	Includes all sludge pumps and recycle pumps, one duty and one standby.
Subtotal				$ 114,000	Rounded up to $1000
Equipment Installation Cost	30%			$ 34,200	Including tax, freight, installation and manufacturer services.
Chemical Storage Containment	8	CY	$ 1,250	$ 10,000	
Equipment Concrete Pads	54	CY	$ 1,250	$ 67,500	
Subtotal (Installed Equipment Costs)				$ 226,000	Rounded up to $1000
General Requirements	7.5%			$ 16,950	Division 1 requirements, including labor supervision, field offices, temporary utilities, health and safety, office supplies, clean up, photographs, survey, erosion control, coordination, testing services, and record documents
Earthwork	5%			$ 11,300	Excavation, backfill, and fill required to construct project
Site Improvements	5%			$ 11,300	Roadways, curb and gutter, sidewalk and landscaping
Valves, Piping, and Appurtenances	15%			$ 33,900	Major system piping and valves
Electrical, Instrumentation and Controls	15%			$ 33,900	PLC and SCADA equipment to control
Total Direct Costs				$ 333,000	Rounded up to $1000
Contractor's Overhead and Profit	20%			$ 66,600	Includes bonds, mobilization and demobilization, insurance, overhead and profit, and management reserves
Construction Total				$ 400,000	Rounded up to $1000
Project Level Allowance (contingency)	20%			$ 80,000	Budget item to cover change orders due to unforeseen conditions
Engineering, Legal and Administrative	20%			$ 80,000	Includes permits, legal fees and engineering fees for design and construction
Project Total				$ 560,000	Rounded up to $10,000
Low Estimate				$ 392,000	-30%
High Estimate				$ 840,000	+50%

Notes:

1. This opinion of probable cost is based on AACE Class 5 estimate guidelines. The high and low estimates fall into the acceptable range. These estimates are generally used to compare alternatives.
2. Opinion of Probable Cost in 2011 dollars.
3. Costs for land or easements are not included.

MALCOLM PIRNIE | ARCADIS
The Water Division of ARCADIS

OPINION OF PROBABLE PROJECT COST

Client	Association of California Water Agencies City of Glendale, Water and Power
Project	Hexavalent Chromium Treatment Residuals Management
Item	Residuals Treatment System for 500-gpm RCF System

Project No. 05337011.0000	
By: Y.W.	Ckd: T.V. & Y.W.
Date: 11/30/2011	Date: 1/18/2012

DESCRIPTION	QTY	UNIT MEAS.	UNIT COST	TOTAL COST	COMMENTS
Equipment					
Equalization tank	1	EA	$ 121,154	$ 121,154	Adjusted installed costs from RS Means for 90,000-gal tank, which was divided by 1.3 to exclude installation cost (assuming a installation cost of 30%).
Plate Settler	1	EA	$ 59,000	$ 59,000	Quote from Meurer Research, Inc. and Parkson for a system handles a 26-gpm sludge flow.
Flo-Trend SludgeMate Container	3	EA	$ 25,685	$ 77,055	Quote from Flo-Trend for 15-CY SludgeMate container.
Polymer Feed System	1	EA	$ 11,400	$ 11,400	Quotes from Siemens & C.P. Crowley
Pumps	1	LS	$ 15,000	$ 15,000	Includes all sludge pumps and recycle pumps, one duty and one standby.
Subtotal				$ 284,000	Rounded up to $1000
Equipment Installation Cost	30%			$ 85,200	Including tax, freight, installation and manufacturer services.
Chemical Storage Containment	8	CY	$ 1,250	$ 10,000	
Equipment Concrete Pads	110	CY	$ 1,250	$ 137,500	
Subtotal (Installed Equipment Costs)				$ 517,000	Rounded up to $1000
General Requirements	7.5%			$ 38,775	Division 1 requirements, including labor supervision, field offices, temporary utilities, health and safety, office supplies, clean up, photographs, survey, erosion control, coordination, testing services, and record documents
Earthwork	5%			$ 25,850	Excavation, backfill, and fill required to construct project
Site Improvements	5%			$ 25,850	Roadways, curb and gutter, sidewalk and landscaping
Valves, Piping, and Appurtenances	15%			$ 77,550	Major system piping and valves
Electrical, Instrumentation and Controls	15%			$ 77,550	PLC and SCADA equipment to control
Total Direct Costs				$ 763,000	Rounded up to $1000
Contractor's Overhead and Profit	20%			$ 152,600	Includes bonds, mobilization and demobilization, insurance, overhead and profit, and management reserves
Construction Total				$ 916,000	Rounded up to $1000
Project Level Allowance (contingency)	20%			$ 183,200	Budget item to cover change orders due to unforeseen conditions
Engineering, Legal and Administrative	20%			$ 183,200	Includes permits, legal fees and engineering fees for design and construction
Project Total				$ 1,290,000	Rounded up to $10,000
Low Estimate				$ 903,000	-30%
High Estimate				$ 1,935,000	+50%

Notes:

1. This opinion of probable cost is based on AACE Class 5 estimate guidelines. The high and low estimates fall into the acceptable range. These estimates are generally used to compare alternatives.
2. Opinion of Probable Cost in 2011 dollars.
3. Costs for land or easements are not included.

OPINION OF PROBABLE PROJECT COST

Client	Association of California Water Agencies City of Glendale, Water and Power
Project	Hexavalent Chromium Treatment Residuals Management
Item	Residuals Treatment System for 2,000-gpm RCF System

Project No. 05337011.0000	
By: Y.W.	Ckd: T.V. & Y.W.
Date: 11/30/2011	Date: 1/18/2012

DESCRIPTION	QTY	UNIT MEAS.	UNIT COST	TOTAL COST	COMMENTS
Equipment					
Equalization tank	1	EA	$ 137,385	$ 137,385	Adjusted installed costs from RS Means for 280,000-gal tank, which was divided by 1.3 to exclude installation cost (assuming a installation cost of 30%).
Plate Settler	1	EA	$ 78,000	$ 78,000	Quote from Meurer Research, Inc. and Parkson for a system handles a 88-gpm sludge flow.
Flo-Trend SludgeMate Container	3	EA	$ 38,430	$ 115,290	Quote from Flo-Trend for 40-CY SludgeMate container.
Polymer Feed System	1	EA	$ 11,400	$ 11,400	Quotes from Siemens & C.P. Crowley
Pumps	1	LS	$ 22,000	$ 22,000	Includes sludge pumps and recycle pumps for equalization tank and plate settlers, one duty and one standby.
Subtotal				$ 365,000	Rounded up to $1000
Equipment Installation Cost	30%			$ 109,500	Including tax, freight, installation and manufacturer services.
Chemical Storage Containment	8	CY	$ 1,250	$ 10,000	
Equipment Concrete Pads	230	CY	$ 1,250	$ 287,500	
Subtotal (Installed Equipment Costs)				$ 772,000	Rounded up to $1000
General Requirements	7.5%			$ 57,900	Division 1 requirements, including labor supervision, field offices, temporary utilities, health and safety, office supplies, clean up, photographs, survey, erosion control, coordination, testing services, and record documents
Earthwork	5%			$ 38,600	Excavation, backfill, and fill required to construct project
Site Improvements	5%			$ 38,600	Roadways, curb and gutter, sidewalk and landscaping
Valves, Piping, and Appurtenances	15%			$ 115,800	Major system piping and valves
Electrical, Instrumentation and Controls	15%			$ 115,800	PLC and SCADA equipment to control
Total Direct Costs				$ 1,139,000	Rounded up to $1000
Contractor's Overhead and Profit	20%			$ 227,800	Includes bonds, mobilization and demobilization, insurance, overhead and profit, and management reserves
Construction Total				$ 1,367,000	Rounded up to $1000
Project Level Allowance (contingency)	20%			$ 273,400	Budget item to cover change orders due to unforeseen conditions
Engineering, Legal and Administrative	20%			$ 273,400	Includes permits, legal fees and engineering fees for design and constructior
Project Total				$ 1,920,000	Rounded up to $10,000
Low Estimate				$ 1,344,000	-30%
High Estimate				$ 2,880,000	+50%

Notes:

1. This opinion of probable cost is based on AACE Class 5 estimate guidelines. The high and low estimates fall into the acceptable range. These estimates are generally used to compare alternatives.
2. Opinion of Probable Cost in 2011 dollars.
3. Costs for land or easements are not included.

MALCOLM PIRNIE | ARCADIS
The Water Division of ARCADIS

OPINION OF PROBABLE PROJECT COST

Client	Association of California Water Agencies City of Glendale, Water and Power
Project	Hexavalent Chromium Treatment Residuals Management
Item	Residuals Treatment System for 5,000-gpm RCF System

Project No. 05337011.0000	
By: Y.W.	Ckd: T.V. & Y.W.
Date: 11/30/2011	Date: 1/18/2012

DESCRIPTION	QTY	UNIT MEAS.	UNIT COST	TOTAL COST	COMMENTS
Equipment					
Equalization tank	1	EA	$ 222,769	$ 222,769	Adjusted installed costs from RS Means for 670,000-gal tank, which was divided by 1.3 to exclude installation cost (assuming a installation cost of 30%).
Plate Settler	1	EA	$ 157,000	$ 157,000	Quote from Meurer Research, Inc. and Parkson for a system handles a 220-gpm sludge flow.
Centrifuges	3	EA	$ 300,000	$ 900,000	Quote from Andritz for D5L Centrifuge.
Centrifuges Ancillary System	1	LS	$ 250,000	$ 250,000	Includes polymer blending, pumps, centrate container, conveyor, and dewatered solids containers etc.
Polymer Feed System	1	EA	$ 31,000	$ 31,000	Based on previous experience with similar chemical feed systems.
Pumps	1	LS	$ 32,000	$ 32,000	Includes all sludge pumps and recycle pumps, one duty and one standby.
Subtotal				$ 1,593,000	Rounded up to $1000
Equipment Installation Cost	30%			$ 477,900	Including tax, freight, installation and manufacturer services.
Chemical Storage Containment	352	CY	$ 1,250	$ 440,000	
Equipment Concrete Pads	230	CY	$ 1,250	$ 287,500	
Centrifuge Building	1	LS	$ 200,000	$ 200,000	
Subtotal (Installed Equipment Costs)				$ 2,999,000	Rounded up to $1000
General Requirements	7.5%			$ 224,925	Division 1 requirements, including labor supervision, field offices, temporary utilities, health and safety, office supplies, clean up, photographs, survey, erosion control, coordination, testing services, and
Earthwork	5%			$ 149,950	Excavation, backfill, and fill required to construct project
Site Improvements	5%			$ 149,950	Roadways, curb and gutter, sidewalk and landscaping
Valves, Piping, and Appurtenances	15%			$ 449,850	Major system piping and valves
Electrical, Instrumentation and Controls	15%			$ 449,850	PLC and SCADA equipment to control
Total Direct Costs				$ 4,424,000	Rounded up to $1000
Contractor's Overhead and Profit	20%			$ 884,800	Includes bonds, mobilization and demobilization, insurance, overhead and profit, and management reserves
Construction Total				$ 5,309,000	Rounded up to $1000
Project Level Allowance (contingency)	20%			$ 1,061,800	Budget item to cover change orders due to unforeseen conditions
Engineering, Legal and Administrative	20%			$ 1,061,800	Includes permits, legal fees and engineering fees for design and constructi
Project Total				$ 7,440,000	Rounded up to $10,000
Low Estimate				$ 5,208,000	-30%
High Estimate				$ 11,160,000	+50%

Notes:

1. This opinion of probable cost is based on AACE Class 5 estimate guidelines. The high and low estimates fall into the acceptable range. These estimates are generally used to compare alternatives.
2. Opinion of Probable Cost in 2011 dollars.
3. Costs for land or easements are not included.

O&M Costs for RCF Residuals Handling and Disposal

RCF System Size = 10 gpm

Influent Cr(VI) Concentration (µg/L)	Residuals Disposal	Chemicals	Labor	Parts Replacement	Electricity	Annual O&M
5	$ 557	$ 13	$ 20,000	$ 5,000	$ 50	$ 25,620
10	$ 1,056	$ 13	$ 22,000	$ 5,000	$ 75	$ 28,144
25	$ 1,727	$ 13	$ 25,000	$ 5,000	$ 100	$ 31,840
50	$ 3,396	$ 13	$ 28,000	$ 5,000	$ 130	$ 36,539

RCF System Size = 100 gpm

Influent Cr(VI) Concentration (µg/L)	Residuals Disposal	Chemicals	Labor	Parts Replacement	Electricity	Annual O&M
5	$ 5,573	$ 131	$ 30,000	$ 7,000	$ 100	$ 42,804
10	$ 10,556	$ 131	$ 33,000	$ 8,000	$ 150	$ 51,836
25	$ 17,274	$ 131	$ 35,000	$ 9,000	$ 200	$ 61,605
50	$ 33,958	$ 131	$ 40,000	$ 10,000	$ 250	$ 84,339

RCF System Size = 500 gpm

Influent Cr(VI) Concentration (µg/L)	Residuals Disposal	Chemicals	Labor	Parts Replacement	Electricity	Annual O&M
5	$ 27,865	$ 654	$ 38,000	$ 15,000	$ 400	$ 81,919
10	$ 52,778	$ 654	$ 45,000	$ 16,000	$ 500	$ 114,932
25	$ 86,370	$ 654	$ 48,000	$ 17,000	$ 600	$ 152,624
50	$ 169,789	$ 654	$ 55,000	$ 18,000	$ 700	$ 244,143

RCF System Size = 2,000 gpm

Influent Cr(VI) Concentration (µg/L)	Residuals Disposal	Chemicals	Labor	Parts Replacement	Electricity	Annual O&M
5	$ 111,458	$ 2,616	$ 40,000	$ 23,000	$ 1,500	$ 178,574
10	$ 211,111	$ 2,616	$ 45,000	$ 25,000	$ 1,800	$ 285,527
25	$ 345,481	$ 2,616	$ 48,000	$ 27,000	$ 2,100	$ 425,197
50	$ 679,156	$ 2,616	$ 55,000	$ 30,000	$ 2,400	$ 769,173

RCF System Size = 5,000 gpm

Influent Cr(VI) Concentration (µg/L)	Residuals Disposal	Chemicals	Labor	Parts Replacement	Electricity	Annual O&M
5	$ 278,645	$ 61,044	$ 100,000	$ 90,000	$ 15,000	$ 544,689
10	$ 527,778	$ 61,044	$ 100,000	$ 100,000	$ 18,000	$ 806,822
25	$ 863,702	$ 61,044	$ 100,000	$ 110,000	$ 21,000	$ 1,155,746
50	$ 1,697,891	$ 61,044	$ 100,000	$ 120,000	$ 24,000	$ 2,002,935

Net Present Value for 20 Years

RCF System Sizes (gpm)	Influent Cr(VI) Concentration, µg/L			
	5	10	25	50
10	$ 429,121	$ 471,384	$ 533,304	$ 611,998
100	$ 716,929	$ 868,219	$ 1,031,834	$ 1,412,607
500	$ 1,372,073	$ 1,925,020	$ 2,556,339	$ 4,089,210
2,000	$ 2,990,983	$ 4,782,364	$ 7,121,722	$ 12,883,050
5,000	$ 9,123,119	$ 13,513,638	$ 19,357,846	$ 33,547,612

Appendix **B**

Capital and O&M Costs for WBA Residuals Treatment Systems

MALCOLM PIRNIE | ARCADIS
The Water Division of ARCADIS

OPINION OF PROBABLE PROJECT COST

Client	Association of California Water Agencies City of Glendale, Water and Power
Project	Hexavalent Chromium Treatment Residuals Management
Item	Residuals Treatment System for 10-gpm WBA System

Project No. 05337011.0000	
By: Y.W.	Ckd: T.V. & Y.W.
Date: 11/30/2011	Date: 1/18/2012

DESCRIPTION	QTY	UNIT MEAS.	UNIT COST	TOTAL COST	COMMENTS
Equipment					
Wastewater Storage Tank	1	EA	$ 7,700	$ 7,700	Quotes from Core-Rosion; 2,000 gal
Pumps	2	EA	$ 4,832	$ 9,664	Quotes from ITT & Cortech, 100 gpm @15 ft; 1 duty/ 1 stdy
Subtotal				$ 17,000	Rounded up to $1000
Equipment Installation Cost	30%			$ 5,100	Including tax, freight, installation and manufacturer services.
Equipment Concrete Pads	6	CY	$ 1,250	$ 7,500	
Subtotal (Installed Equipment Costs)				$ 30,000	Rounded up to $1000
General Requirements	7.5%			$ 2,250	Division 1 requirements, including labor supervision, field offices, temporary utilities, health and safety, office supplies, clean up, photographs, survey, erosion control, coordination, testing services, and
Earthwork	5%			$ 1,500	Excavation, backfill, and fill required to construct project
Site Improvements	5%			$ 1,500	Roadways, curb and gutter, sidewalk and landscaping
Valves, Piping, and Appurtenances	15%			$ 4,500	Major system piping and valves
Electrical, Instrumentation and Controls	1	LS		$ 30,000	Tank level sensors and local pumps control, which are connected to PLC and SCADA.
Total Direct Costs				$ 70,000	Rounded up to $1000
Contractor's Overhead and Profit	20%			$ 14,000	Includes bonds, mobilization and demobilization, insurance, overhead and profit, and management reserves
Construction Total				$ 84,000	Rounded up to $1000
Project Level Allowance (contingency)	20%			$ 16,800	Budget item to cover change orders due to unforeseen conditions
Engineering, Legal and Administrative	20%			$ 16,800	Includes permits, legal fees and engineering fees for design and
Project Total				$ 120,000	Rounded up to $10,000
Low Estimate				$ 84,000	-30%
High Estimate				$ 180,000	+50%

Notes:

1. This opinion of probable cost is based on AACE Class 5 estimate guidelines. The high and low estimates fall into the acceptable range. These estimates are generally used to compare alternatives.
2. Opinion of Probable Cost in 2011 dollars.
3. Costs for land or easements are not included.

OPINION OF PROBABLE PROJECT COST

Client	Association of California Water Agencies City of Glendale, Water and Power
Project	Hexavalent Chromium Treatment Residuals Management
Item	Residuals Treatment System for 100-gpm WBA System

Project No. 05337011.0000	
By: Y.W.	Ckd: T.V. & Y.W.
Date: 11/30/2011	Date: 1/18/2012

DESCRIPTION	QTY	UNIT MEAS.	UNIT COST	TOTAL COST	COMMENTS
Equipment					
Wastewater Storage Tank	1	EA	$ 52,000	$ 52,000	Quotes from Superior & BH; 19,000 gal
Pumps	2	EA	$ 4,832	$ 9,664	Quotes from ITT & Cortech, 100 gpm @15 ft; 1 duty/ 1 stdy
Subtotal				$ 62,000	Rounded up to $1000
Equipment Installation Cost	30%			$ 18,600	Including tax, freight, installation and manufacturer services.
Equipment Concrete Pads	13	CY	$ 1,250	$ 16,250	
Subtotal (Installed Equipment Costs)				$ 97,000	Rounded up to $1000
General Requirements	7.5%			$ 7,275	Division 1 requirements, including labor supervision, field offices, temporary utilities, health and safety, office supplies, clean up, photographs, survey, erosion control, coordination, testing services, and
Earthwork	5%			$ 4,850	Excavation, backfill, and fill required to construct project
Site Improvements	5%			$ 4,850	Roadways, curb and gutter, sidewalk and landscaping
Valves, Piping, and Appurtenances	15%			$ 14,550	Major system piping and valves
Electrical, Instrumentation and Controls	1	LS		$ 30,000	Tank level sensors and local pumps control, which are connected to PLC and SCADA.
Total Direct Costs				$ 159,000	Rounded up to $1000
Contractor's Overhead and Profit	20%			$ 31,800	Includes bonds, mobilization and demobilization, insurance, overhead and profit, and management reserves
Construction Total				$ 191,000	Rounded up to $1000
Project Level Allowance (contingency)	20%			$ 38,200	Budget item to cover change orders due to unforeseen conditions
Engineering, Legal and Administrative	20%			$ 38,200	Includes permits, legal fees and engineering fees for design and
Project Total				$ 270,000	Rounded up to $10,000
Low Estimate				$ 189,000	-30%
High Estimate				$ 405,000	+50%

Notes:

1. This opinion of probable cost is based on AACE Class 5 estimate guidelines. The high and low estimates fall into the acceptable range. These estimates are generally used to compare alternatives.
2. Opinion of Probable Cost in 2011 dollars.
3. Costs for land or easements are not included.

OPINION OF PROBABLE PROJECT COST

Client	Association of California Water Agencies City of Glendale, Water and Power
Project	Hexavalent Chromium Treatment Residuals Management
Item	Residuals Treatment System for 500-gpm WBA System

Project No. 05337011.0000	
By: Y.W.	Ckd: T.V. & Y.W.
Date: 11/30/2011	Date: 1/18/2012

DESCRIPTION	QTY	UNIT MEAS.	UNIT COST	TOTAL COST	COMMENTS
Equipment					
Wastewater Storage Tank	1	EA	$ 100,000	$ 100,000	Quotes from Superior & BH; 95,000 gal
Pumps	2	EA	$ 4,832	$ 9,664	Quotes from ITT & Cortech, 100 gpm @15 ft; 1 duty/ 1 stdy
Subtotal				$ 110,000	Rounded up to $1000
Equipment Installation Cost	30%			$ 33,000	Including tax, freight, installation and manufacturer services.
Equipment Concrete Pads	50	CY	$ 1,250	$ 62,500	
Subtotal (Installed Equipment Costs)				$ 206,000	Rounded up to $1000
General Requirements	7.5%			$ 15,450	Division 1 requirements, including labor supervision, field offices, temporary utilities, health and safety, office supplies, clean up, photographs, survey, erosion control, coordination, testing services, and record documents
Earthwork	5%			$ 10,300	Excavation, backfill, and fill required to construct project
Site Improvements	5%			$ 10,300	Roadways, curb and gutter, sidewalk and landscaping
Valves, Piping, and Appurtenances	15%			$ 30,900	Major system piping and valves
Electrical, Instrumentation and Controls	1	LS		$ 30,000	Tank level sensors and local pumps control, which are connected to PLC and SCADA.
Total Direct Costs				$ 303,000	Rounded up to $1000
Contractor's Overhead and Profit	20%			$ 60,600	Includes bonds, mobilization and demobilization, insurance, overhead and profit, and management reserves
Construction Total				$ 364,000	Rounded up to $1000
Project Level Allowance (contingency)	20%			$ 72,800	Budget item to cover change orders due to unforeseen conditions
Engineering, Legal and Administrative	20%			$ 72,800	Includes permits, legal fees and engineering fees for design and construction
Project Total				$ 510,000	Rounded up to $10,000
Low Estimate				$ 357,000	-30%
High Estimate				$ 765,000	+50%

Notes:

1. This opinion of probable cost is based on AACE Class 5 estimate guidelines. The high and low estimates fall into the acceptable range. These estimates are generally used to compare alternatives.
2. Opinion of Probable Cost in 2011 dollars.
3. Costs for land or easements are not included.

MALCOLM PIRNIE | ARCADIS
The Water Division of ARCADIS

OPINION OF PROBABLE PROJECT COST

Client	Association of California Water Agencies City of Glendale, Water and Power
Project	Hexavalent Chromium Treatment Residuals Management
Item	Residuals Treatment System for 2,000-gpm WBA System

Project No. 05337011.0000	
By: Y.W.	Ckd: T.V. & Y.W.
Date: 11/30/2011	Date: 1/18/2012

DESCRIPTION	QTY	UNIT MEAS.	UNIT COST	TOTAL COST	COMMENTS
Equipment					
Wastewater Storage Tank	1	EA	$ 150,000	$ 150,000	Quotes from Superior & BH; 189,000 gal
Pumps	2	EA	$ 4,832	$ 9,664	Quotes from ITT & Cortech, 100 gpm @15 ft; 1 duty/ 1 stdy
Subtotal				$ 160,000	Rounded up to $1000
Equipment Installation Cost	30%			$ 48,000	Including tax, freight, installation and manufacturer services.
Equipment Concrete Pads	110	CY	$ 1,250	$ 137,500	
Subtotal (Installed Equipment Costs)				$ 346,000	Rounded up to $1000
General Requirements	7.5%			$ 25,950	Division 1 requirements, including labor supervision, field offices, temporary utilities, health and safety, office supplies, clean up, photographs, survey, erosion control, coordination, testing services, and record documents
Earthwork	5%			$ 17,300	Excavation, backfill, and fill required to construct project
Site Improvements	5%			$ 17,300	Roadways, curb and gutter, sidewalk and landscaping
Valves, Piping, and Appurtenances	15%			$ 51,900	Major system piping and valves
Electrical, Instrumentation and Controls	1	LS		$ 30,000	Tank level sensors and local pumps control, which are connected to PLC and SCADA.
Total Direct Costs				$ 488,000	Rounded up to $1000
Contractor's Overhead and Profit	20%			$ 97,600	Includes bonds, mobilization and demobilization, insurance, overhead and profit, and management reserves
Construction Total				$ 586,000	Rounded up to $1000
Project Level Allowance (contingency)	20%			$ 117,200	Budget item to cover change orders due to unforeseen conditions
Engineering, Legal and Administrative	20%			$ 117,200	Includes permits, legal fees and engineering fees for design and construction
Project Total				$ 830,000	Rounded up to $10,000
Low Estimate				$ 581,000	-30%
High Estimate				$ 1,245,000	+50%

Notes:

1. This opinion of probable cost is based on AACE Class 5 estimate guidelines. The high and low estimates fall into the acceptable range. These estimates are generally used to compare alternatives.
2. Opinion of Probable Cost in 2011 dollars.
3. Costs for land or easements are not included.

OPINION OF PROBABLE PROJECT COST

Client	Association of California Water Agencies City of Glendale, Water and Power
Project	Hexavalent Chromium Treatment Residuals Management
Item	Residuals Treatment System for 5,000-gpm WBA System

Project No. 05337011.0000	
By: Y.W.	Ckd: T.V. & Y.W.
Date: 11/30/2011	Date: 1/18/2012

DESCRIPTION	QTY	UNIT MEAS.	UNIT COST	TOTAL COST	COMMENTS
Equipment					
Wastewater Storage Tank	1	EA	$ 150,000	$ 150,000	Quotes from Superior & BH; 189,000 gal
Pumps	2	EA	$ 4,832	$ 9,664	Quotes from ITT & Cortech, 100 gpm @15 ft; 1 duty/ 1 stdy
Subtotal				$ 160,000	Rounded up to $1000
Equipment Installation Cost	30%			$ 48,000	Including tax, freight, installation and manufacturer services.
Equipment Concrete Pads	110	CY	$ 1,250	$ 137,500	
Subtotal (Installed Equipment Costs)				$ 346,000	Rounded up to $1000
General Requirements	7.5%			$ 25,950	Division 1 requirements, including labor supervision, field offices, temporary utilities, health and safety, office supplies, clean up, photographs, survey, erosion control, coordination, testing services, and
Earthwork	5%			$ 17,300	Excavation, backfill, and fill required to construct project
Site Improvements	5%			$ 17,300	Roadways, curb and gutter, sidewalk and landscaping
Valves, Piping, and Appurtenances	15%			$ 51,900	Major system piping and valves
Electrical, Instrumentation and Controls	1	LS		$ 30,000	Tank level sensors and local pumps control, which are connected to PLC and SCADA.
Total Direct Costs				$ 488,000	Rounded up to $1000
Contractor's Overhead and Profit	20%			$ 97,600	Includes bonds, mobilization and demobilization, insurance, overhead and profit, and management reserves
Construction Total				$ 586,000	Rounded up to $1000
Project Level Allowance (contingency)	20%			$ 117,200	Budget item to cover change orders due to unforeseen conditions
Engineering, Legal and Administrative	20%			$ 117,200	Includes permits, legal fees and engineering fees for design and
Project Total				$ 830,000	Rounded up to $10,000
Low Estimate				$ 581,000	-30%
High Estimate				$ 1,245,000	+50%

Notes:

1. This opinion of probable cost is based on AACE Class 5 estimate guidelines. The high and low estimates fall into the acceptable range. These estimates are generally used to compare alternatives.
2. Opinion of Probable Cost in 2011 dollars.
3. Costs for land or easements are not included.

O&M Costs for WBA Residuals Handling and Disposal

WBA System Size = 10 gpm

Treated Cr(VI) Target (µg/L)	Resin Disposal	Wastewater Discharge	Labor	Parts Replacement	Electricity	Annual O&M
0.5	$ 1,900	$ 3,600	$ 600	$ 900	$ 500	$ 7,000
1	$ 1,700	$ 3,600	$ 500	$ 900	$ 500	$ 6,700
2	$ 1,500	$ 3,600	$ 400	$ 900	$ 500	$ 6,400
5	$ 1,300	$ 3,600	$ 400	$ 900	$ 500	$ 6,200
10	$ 900	$ 3,600	$ 300	$ 900	$ 500	$ 5,700
25	$ 500	$ 3,600	$ 100	$ 900	$ 500	$ 5,100

WBA System Size = 100 gpm

Treated Cr(VI) Target (µg/L)	Resin Disposal	Wastewater Discharge	Labor	Parts Replacement	Electricity	Annual O&M
0.5	$ 19,100	$ 3,700	$ 600	$ 2,900	$ 500	$ 26,300
1	$ 17,400	$ 3,700	$ 500	$ 2,900	$ 500	$ 24,500
2	$ 15,300	$ 3,700	$ 400	$ 2,900	$ 500	$ 22,300
5	$ 13,300	$ 3,700	$ 400	$ 2,900	$ 500	$ 20,300
10	$ 8,800	$ 3,600	$ 300	$ 2,900	$ 500	$ 15,600
25	$ 4,800	$ 3,600	$ 100	$ 2,900	$ 500	$ 11,400

WBA System Size = 500 gpm

Treated Cr(VI) Target (µg/L)	Resin Disposal	Wastewater Discharge	Labor	Parts Replacement	Electricity	Annual O&M
0.5	$ 95,000	$ 4,000	$ 600	$ 6,180	$ 500	$ 105,780
1	$ 87,000	$ 3,900	$ 500	$ 6,180	$ 500	$ 97,580
2	$ 76,000	$ 3,900	$ 400	$ 6,180	$ 500	$ 86,480
5	$ 67,000	$ 3,900	$ 400	$ 6,180	$ 500	$ 77,480
10	$ 44,000	$ 3,800	$ 300	$ 6,180	$ 500	$ 54,280
25	$ 24,000	$ 3,700	$ 100	$ 6,180	$ 500	$ 33,980

WBA System Size = 2,000 gpm

Treated Cr(VI) Target (µg/L)	Resin Disposal	Wastewater Discharge	Labor	Parts Replacement	Electricity	Annual O&M
0.5	$ 382,000	$ 5,100	$ 1,100	$ 10,380	$ 500	$ 398,580
1	$ 347,000	$ 5,000	$ 1,000	$ 10,380	$ 500	$ 363,380
2	$ 305,000	$ 4,800	$ 900	$ 10,380	$ 500	$ 321,080
5	$ 266,000	$ 4,700	$ 800	$ 10,380	$ 500	$ 281,880
10	$ 176,000	$ 4,300	$ 500	$ 10,380	$ 500	$ 191,180
25	$ 95,000	$ 4,000	$ 300	$ 10,380	$ 500	$ 109,680

WBA System Size = 5,000 gpm

Treated Cr(VI) Target (µg/L)	Resin Disposal	Wastewater Discharge	Labor	Parts Replacement	Electricity	Annual O&M
0.5	$ 954,000	$ 5,000	$ 2,800	$ 10,380	$ 500	$ 972,180
1	$ 868,000	$ 7,400	$ 2,600	$ 10,380	$ 500	$ 888,380
2	$ 764,000	$ 7,000	$ 2,200	$ 10,380	$ 500	$ 783,580
5	$ 666,000	$ 6,600	$ 2,000	$ 10,380	$ 500	$ 684,980
10	$ 441,000	$ 6,200	$ 1,300	$ 10,380	$ 500	$ 458,880
25	$ 239,000	$ 5,300	$ 700	$ 10,380	$ 500	$ 255,380

Net Present Value for 20 Years

WBA System Size (gpm)	Potential Cr(VI) MCL, µg/L					
	0.5	1	2	5	10	25
10	$ 117,245	$ 112,220	$ 107,195	$ 103,845	$ 95,471	$ 85,421
100	$ 440,505	$ 410,356	$ 373,508	$ 340,009	$ 261,288	$ 190,941
500	$ 1,771,733	$ 1,634,390	$ 1,448,473	$ 1,297,730	$ 909,148	$ 569,139
2,000	$ 6,675,907	$ 6,086,335	$ 5,377,842	$ 4,721,272	$ 3,202,117	$ 1,837,055
5,000	$ 16,283,265	$ 14,879,679	$ 13,124,360	$ 11,472,886	$ 7,685,886	$ 4,277,418