Hexavalent Chromium Removal Research Project Report

To the California Department of Public Health

Research Managed By
City of Glendale, California
Department of Water & Power

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Appendix E. Phase III Bridge Study

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- California Water Service Company in partnership with the City of Glendale, California. 2011. Assessment of Single-Pass Ion Exchange Resin and Adsorptive Media for Hexavalent Chromium Removal from Drinking Water. *Submitted to the Water Research Foundation Tailored Collaboration Program,* October*.*
- Blute, N.K., Wu, Y. 2012. Phase IIIB Pilot Testing Plan. S*ubmitted to the Water Research Foundation and City of Glendale,* Updated XX.

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- Malcolm Pirnie, Inc. 2007. Experimental Design and Operations Plan for Hexavalent Chromium Removal Using Weak-Base Anion Exchange Resin: A Demonstration-Scale Study. *Submitted to the USEPA*, October (Draft).
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Environmental Engineers & Scientists

Appendix K. Phase III Demonstration Study –Quality Assurance Project Plans

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1. Executive Summary

1.1 Initiation of the Research Program

The City of Glendale has been managing a major research effort to identify technologies for removing hexavalent chromium, Cr(VI), from drinking water supplies for almost a decade. Release of the movie *Erin Brockovich* in 2000 raised public concern with any Cr(VI) in drinking water, including in the City of Glendale and neighboring utilities. At the time, little information was available on the ability of Cr(VI) treatment technologies to reach single parts-per-billion (ppb, or microgram per liter) levels when the California Maximum Contaminant Level (MCL) for total chromium was 50 ppb and the federal total chromium MCL was 100 ppb. The research program began in order to test and identify treatment technologies for achieving low ppb effluent chromium concentrations in drinking water supplies.

Before the research effort began, the California Office of Health Hazard Assessment (OEHHA) established a Public Health Goal (PHG) of 2.5 ppb for total chromium in 1999, based on a calculation of a health protective level for hexavalent chromium of 0.2 ppb (using an assumption that “total chromium would be made up of no more than 7.2% chromium VI”, which was later refuted). This original PHG was rescinded in November 2001 with the intention that a Cr(VI) specific PHG would be set. In July 2011, OEHHA set a final PHG for Cr(VI) of 0.020 ppb. The State of California is now required to set an MCL for Cr(VI), taking into consideration the PHG as well as technical feasibility of treatment levels and costs.

The primary goal of this Project Report and supporting appendices is to provide the CDPH with technical feasibility and cost data on removing Cr(VI) from drinking water. This is an integral part of setting an MCL for Cr(VI) in drinking water. Additionally, this report will meet the City’s grant reporting requirements to the U. S. Environmental Protection Agency, the U.S. Bureau of Reclamation, the California Department of Water Resources, and other contributing organizations. The USEPA recently included Cr(VI) in the Unregulated Contaminant Monitoring Rule 3 (UCMR3), which indicates that Cr(VI) will be under consideration for regulation at the federal level.

The research program is divided into several phases – Phase I Bench Testing, Phase II Pilot Testing, and the Phase III Bridge and Demonstration Studies.

1.2 Phase I Bench Testing

A bench-scale study (Phase I) led by the Los Angeles Department of Water and Power (LADWP) and co-funded by the Cities of Glendale, Burbank, and San Fernando, the American Water Works Research Foundation (now called the Water Research Foundation), and the National Water Research Institute was conducted at the University of Colorado at Boulder to screen a large array of potential treatment technologies, including ion exchange and adsorptive media, membranes, and reduction/precipitation. Phase I bench-scale testing suggested that technologies capable of removing Cr(VI) to less than 5 ppb would include the following classes of technologies: strong-base anion exchange resin in column and reactor applications, adsorptive media, membrane treatment by nanofiltration and reverse osmosis, and reduction of Cr(VI) followed by precipitation of Cr(III).

1.3 Phase II Pilot Testing

Pilot testing of seven treatment technologies (Phase II) led by the City of Glendale California followed the bench scale study to assess treatability under flow-through conditions. The research team investigated three types of anion exchange (column vs. fluidized, weak base, and strong base), zeolite media, iron-impregnated granular activated carbon (GAC), and two types of reduction/filtration (one included a coagulation step while the other did not). Three technologies emerged as leading technologies for achieving single ppb treated water concentrations: weak-base anion exchange (WBA), strong-base anion exchange (SBA), and reduction/coagulation/filtration (RCF). The advantages and disadvantages of each technology were studied in more detail in the subsequent phase.

1.4 Phase III Bridge and Demonstration Studies

A Phase III Bridge study led by the City of Glendale California was established to investigate the mechanism underlying the high capacity of the WBA resin and to evaluate necessary RCF design components. An Expert Panel consisting of the Project Advisory Committee and Academicians (described in Sections 2.3 and 2.5) was convened at the end of the Phase II to evaluate the pilot testing results, yielding a recommendation for demonstration-scale testing of WBA and RCF treatment technologies in Phase III. In spring of 2010, Glendale constructed two test facilities consisting of 425 gallons per minute (gpm) of treatment for WBA and 100 gpm for RCF. The RCF was shut down in July 2012 and the WBA continues to operate.

The RCF process is similar to conventional water treatment, with coagulation and filtration processes. Ferrous sulfate (rather than ferric iron) is used to reduce Cr(VI) to Cr(III), in the process producing iron floc onto which or with which the Cr(III) adsorbs or coprecipitates. Depending on the influent chromium concentration and iron dose, an aeration step may be used to fully oxidize all of the ferrous iron added to the process. If the pH of the water to treat is higher than approximately 7.7, pH adjustment (decrease) may also be required to achieve low chromium levels. Demonstration scale testing has shown that the RCF process with granular media filtration can reliably achieve Cr(VI) concentrations below 1 ppb and total Cr concentrations below 5 ppb. Due to the multiple treatment process steps, RCF is more labor intensive than the other leading technologies but can adjust easily to changes in influent concentration.

Phase IIIA was added to the research program to test microfiltration (MF) in place of granular media filtration in the RCF process. Establishment of the California Public Health Goal (PHG) at 0.020 ppb and the stated intention of California to set a Cr(VI)-specific MCL raised the question of whether RCF could achieve treatment targets of sub-ppb levels for total Cr. The Expert Panel recommended that Glendale test MF to achieve better particle removal, and hence chromium, removal in the RCF process. In Phase IIIA, MF was found to consistently achieve Cr(VI) and total Cr concentrations in treated water effluent below 1 ppb. In addition, Phase IIIA results showed that chlorine may be used to augment ferrous oxidation by aeration to minimize membrane fouling, without increasing Cr(VI) concentrations to greater than 1 ppb if close controls are maintained on chlorine doses. This finding has the potential to decrease the footprint and capital cost of the RCF technology as described in this study, but would need further testing to identify more optimized design criteria.

The WBA treatment technology is an anion exchange process consisting of a polymeric resin material with a strong affinity for Cr(VI). Water to be treated is adjusted to pH 6.0 for removal of Cr(VI) by the resin, then the pH-adjusted water flows through the resin beds (often in a lead/lag configuration for maximum bed life). Readjustment of pH in the effluent will be necessary for many utilities requiring corrosion control in the distribution system (i.e., those that do not have post-treatment aeration like Glendale). The WBA resin used in the research program had a very high capacity for Cr(VI), lasting more than one year before changeouts. Not a true ion exchange mechanism like SBA, the resin converts Cr(VI) to Cr(III) and retains Cr(III) on the resin. Levels below 1 ppb Cr(VI) are achievable by this technology, although breakthrough will be much shorter than the one year changeout interval using a 5 ppb limit. Total Cr effluent concentrations exceed 1 ppb within a short timeframe. Testing also revealed that the tested WBA resin can leach formaldehyde at startup, requiring pretreatment, and that the resin accumulates uranium. Both issues are discussed more extensively in this report.

SBA resin can also remove Cr(VI) from water but requires significant quantities of salt for frequent regeneration and brine disposal. SBA resin typically has a much lower capacity – approximately 2 percent of the throughput compared with WBA resin capacity for Cr(VI), as observed in pilot testing. The mechanism of SBA removal of Cr(VI) is by ion exchange, whereas WBA resin involves reduction of Cr(VI) to Cr(III). Treatment of the brine regenerant waste for SBA resin, which is likely a hazardous waste in California, may also be necessary to precipitate out Cr(VI). However, SBA can be an attractive alternative if other anion compounds such as nitrate, arsenic, and/or perchlorate require co-contaminant treatment. Treatment to 1 ppb is possible for Cr(VI) and total Cr with SBA resin.

A detailed cost evaluation of treatment options was prepared as part of the Phase III Demonstration study, including generation of cost curves for different flow rates, influent concentrations, and potential MCL treatment goals. All costs in this report assume a 100% utilization rate, which means that unit costs will be higher if processes are not used throughout the year. No blending options were included in the cost analysis but could bring down costs of treatment for systems not treating an impaired source. For example, sources not classified as “extremely impaired” could utilize side-stream treatment of partial flow. No safety factors are included in the cost estimates to ensure compliance with a potential MCL (e.g., many utilities target 80% of the MCL).

To gain a sense of the overall costs a utility may face in implementing chromium treatment, Table 1-1 summarizes the total capital and 20 year net present value (NPV) O&M costs for WBA as a function of potential MCLs.   Cost estimates for the WBA treatment systems reflect treatment to potential MCLs ranging from 1 to 25 ppb, with a lower treatment goal resulting in more frequent resin changeouts and higher cost. Figure 1-1 portrays the costs as a function of potential MCL for a 500 gpm system. Capital and O&M cost details are included in Section 5 of this report.

Table 1-1. Summary of WBA Capital and O&M Costs

System Size (gpm)	Potential Cr(VI) MCL, ppb*				
	1	2	5	10	25
10	$8,519,000	$4,019,000	$3,419,000	$3,419,000	$3,419,000
100	$36,036,000	$8,736,000	$4,836,000	$4,536,000	$4,536,000
500	$181,594,000	$33,594,000	$11,594,000	$10,594,000	$9,594,000
2,000	$605,300,000	$104,300,000	$31,300,000	$27,300,000	$24,300,000

* Resin use was assumed to be driven by total chromium treatment targets rather than Cr(VI), since Cr(VI) can reoxidize to Cr(VI) in the distribution system (Appendix B). This difference is only important at potential MCLs of 1 and 2 ppb.

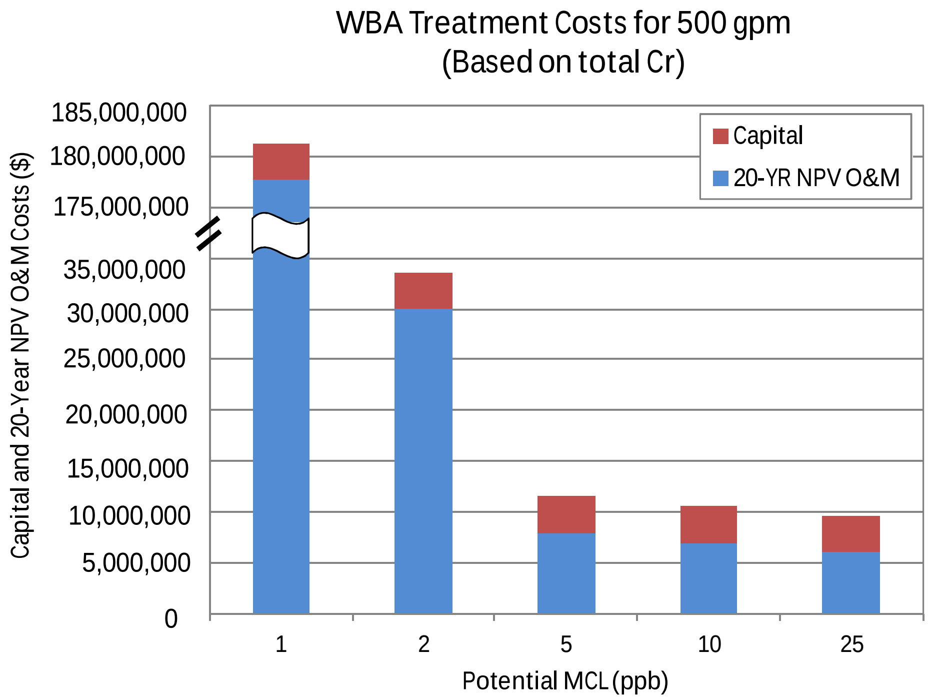


Figure 1-1. Capital and NPV Costs for Chromium Treatment for Several Potential MCLs

RCF treatment costs were developed in three ways: RCF with granular media filtration and backwash water treatment with recycling to the head of the plant to minimize water losses; RCF with granular media filtration and backwash water sent to the sewer; and RCF with microfiltration and backwash water sent to the sewer. Costs for these three RCF approaches studied in this research program are summarized in Table 1-2. The costs reflect that the granular media filtration approach can achieve less than 5 ppb, and the MF approach can reach less than 1 ppb total chromium. Capital and O&M cost details are included in Section 5 of this report.

Table 1-2. Summary of RCF Capital and O&M Costs

System Size (gpm)	RCF with MF (pressure from Pall)*	RCF with granular media filter, without recycle^	RCF with granular media filter, with recycle^
100	$6,159,000	$5,352,000	$7,388,000
500	$11,612,000	$10,639,000	$15,517,000
2,000	$25,693,000	$23,075,000	$34,903,000

* Can achieve total chromium below 1 ppb.

^ For influent Cr(VI) concentration of 50 ppb and ferrous dose of 2.5 mg/L; treatment can achieve total chromium below 5 ppb.

A summary of the costs in dollars per acre foot (including capital and O&M) is presented in Figure 1-2. This figure holds for potential MCLs of 5 ppb and higher for the WBA process. Significantly higher cost ranges would be reflected if 1 and 2 ppb endpoints are included, as shown in Table 1-1.

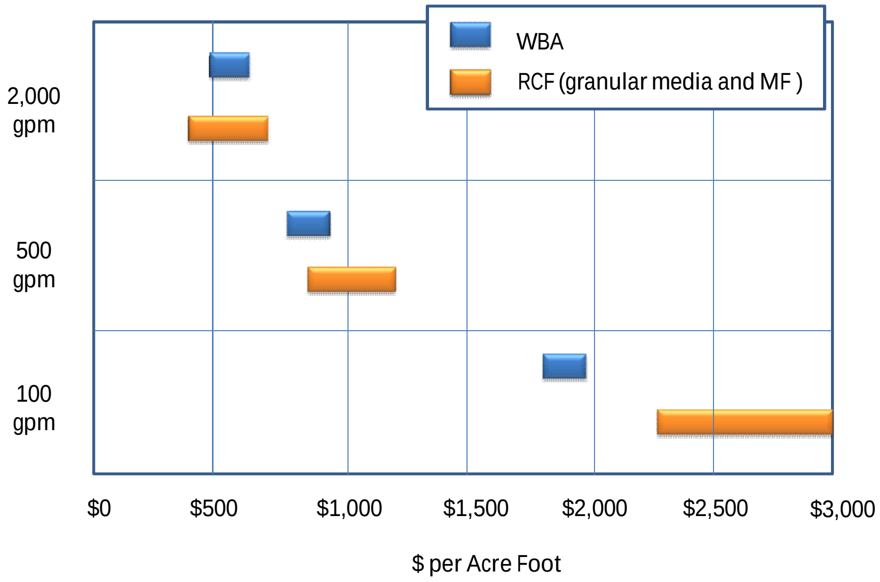


Figure 1-2. Summary of Cost Estimate Ranges for Chromium Treatment (Assuming Potential MCLs of 5 ppb or Higher)

1.5 Phase III Residuals Study

A significant consideration for the technologies due to cost and labor considerations is the generation of residuals waste, which was studied in the Phase III Association of California Water Agencies (ACWA) Residuals study. All three processes generate a waste that is classified as hazardous in the State of California by the Waste Extraction Test (WET) but is often non-hazardous according to the Federal Toxicity Characteristic Leaching Procedure (TCLP). Due to its high capacity and long life, WBA resin can also accumulate other anions, including uranium, which can trigger TENORM or LLRW disposal requirements. In the cost evaluation for this project, disposal as a TENORM was assumed, as this is a likely classification for groundwater containing any uranium due to the high affinity for the WBA resin tested at demonstration-scale.

1.6 Additional Phases - Phase IIIB Additional Resins and Adsorptive Media Pilot Testing and Phase IIIC Supplemental Demonstration Testing

Phase IIIB studies are underway to investigate additional options for Cr(VI) removal, including adsorptive media and additional ion exchange resins. Supplemental demonstration scale testing of technologies found to be successful in Phase IIIB (to be called Phase IIIC) was originally proposed but funding for this effort did not materialize so Phase IIIC was suspended.

In the Phase III Demonstration study, WBA resins were shown to offer an operationally simple means of removing Cr(VI) from drinking water. However, the one WBA resin tested at demonstration-scale (Amberlite™ PWA7) was found to leach formaldehyde during operation, specifically in start-up. Although a resin conditioning procedure was instituted to minimize formaldehyde leaching, the mechanism triggering formaldehyde release is unknown and the effectiveness of the conditioning has yielded mixed results. Without effective pre-conditioning, significant water losses (e.g., one month of operation) could be realized if a utility does not want to serve water above the Notification Level and cannot blend or dispose of the water to waste for this length of time.

Several other potential media showing promising results in industrial settings have become available and are being tested in Phase IIIB, including two non-formaldehyde-based WBA resins and two iron-based adsorptive media. Phase IIIB is being led by both the City of Glendale and the California Water Service Company. The results of Phase IIIB will be provided in a Supplemental Report expected in December 2013.

1.7 Key Considerations in Technology Selection

For utilities requiring Cr(VI) treatment, key considerations in technology selection include: co-occurring contaminants requiring removal (e.g., nitrate, perchlorate, arsenic, uranium), water quality that may impact technology effectiveness, facility sizing needs and space availability, operational requirements, residuals handling and disposal options, and cost. Water recovery rates also vary, with the RCF process having a water loss of about 3% for granular media filtration without recycle and 5% for MF, compared with less than 1% for WBA. On the other hand, the tested WBA resin leaches formaldehyde. Levels decreased to below the California Notification Level for formaldehyde using a resin conditioning procedure for one batch, but the second batch results were above the Notification Level and required almost 11 days of resin flushing before decreasing below the NL. SBA resins likely require treatment of spent brine to remove the hazardous chromium component prior to disposal. Consequently, the needs of an individual utility must be weighed to assess the right approach for a specific site and water quality.

Significant opportunity to decrease the footprint and cost for the RCF process was identified in the RCF demonstration testing studies, whereby a small chlorine dose might be used in place of aeration and less reduction time may be sufficient. Both details require additional testing at the pilot or demonstration scale, but this work indicated that both items have merit.

1.8 Financial Support for the Research Program

This research program has been financially supported by many different agencies, including: the Cities of Glendale, Los Angeles, Burbank, and San Fernando; the USEPA; the California Water Service Company; the California Department of Public Health and the California Department of Water Resources through Proposition 50; the Water Research Foundation; the Association of California Water Agencies; the National Water Research Institute; the US Bureau of Reclamation; the Metropolitan Water District of Southern California; and the San Fernando Valley Industry Group.

2. Project Background

This section describes the project background, including project origins, management approach, and budgets. Specific research objectives are detailed in subsequent sections dedicated to each phase of the research effort.

2.1 Organization and Purpose of This Report

This research work has been ongoing for many years. The work has been performed under many grants awarded to Glendale for the research work. Many of these grants require the preparation of a project report detailing the results of the research work, primarily the EPA and USBR grants and the State of California grants under Proposition 50. Because of the way the project was developed by phases that include many funding sources, it was not clearly possible to precisely identify what was performed under specific grants. For this reason, the report is prepared for the research effort as a whole with division into the various phases of work. This report is a Project Report of all work efforts through December 31, 2012. One additional component, Phase IIIB- Additional Resin and Adsorptive Media Pilot Testing, is now underway.

Development of the final Project Report was viewed as urgent, as the report contains significant information needed by CDPH and the EPA for their respective development of the maximum contaminant level (MCL) for hexavalent chromium, Cr(VI), in drinking water supplies. To set an MCL, information is needed on health effects, costs, and technical feasibility. Health effects data was used to establish the California Public Health Goal (PHG) of 0.020 ppb. This report is intended to provide information on the feasibility and costs of removing Cr(VI) from water supplies as key informational needs for setting the MCL. An Interim Report (May 1, 2012) provided information on costs and technical feasibility to develop the MCL so as not to delay that effort. This Project Report (February 28, 2013) also incorporates results from Phase IIIA MF testing and Phase III WBA demonstration testing through the rest of 2012. The remaining work in Phase IIIB will “fine tune” some of that information. Generally, all research work except for Phase IIIB is included in this Project Report. It is expected that the Phase IIIB study will be included in a supplemental project report scheduled for completion by December 2013.

The plan for this report was to prepare a summary document of approximately 100 pages on the research with the major findings discussed and the underlying detailed research reports and materials included as Appendices. These Appendices include all of the major reports created in this research program. This report was designed to be a "stand alone" document suitable for circulation to interested organizations and groups. For those interested in the entire document, the City plans to post the full report and appendices on their website. Later, the City will also prepare a public relations document for an even wider distribution of the research work.

The combination of these three report efforts should meet the diverse needs of public interests in this research and the communications requirements of the many grants.

2.2 Initiation of the Research Program

2.2.1 Drinking Water Quality Standards

Water agencies pride themselves on building customer support and trust by supplying safe, high quality drinking water. To protect the public's health, the U.S. Environmental Protection Agency (EPA) and the California Department of Public Health (CDPH) require water utilities to monitor the quality of drinking water and to meet water quality standards limiting the concentration of chemicals in drinking water supplies to protect public health.

2.2.2 Hexavalent Chromium in Water Supplies Creates Concerns

In year 2000, the movie *Erin Brockovich* brought attention to hexavalent chromium, Cr(VI), when it was discovered that a PG&E facility contaminated the drinking water supplies in Hinkley, California (near Barstow) with Cr(VI). The result was a major civil lawsuit and financial judgment against PG&E due to health problems experienced by that community. This movie and attendant publicity heightened the public perception with the presence of any Cr(VI) in water supplies.

2.2.3 The Chromium Challenge in the City of Glendale

At about this same time the movie was released, the City of Glendale was planning to take delivery of treated groundwater from a new water treatment plant that was constructed under the federal Superfund program to remove volatile organic compounds (VOCs), such as trichloroethylene (TCE) and tetrachloroethylene (PCE), from groundwater. The federal and state governments approved the distribution of this newly treated water to Glendale residents as meeting all water quality standards.

After the federal and state agencies approved the delivery of the treated water to Glendale's residents, the City Council became very concerned with the presence of any Cr(VI) in their water supplies, even though the concentration was far less than federal and state water quality standard maximum contaminant levels (MCL) for total chromium in water supplies. At that time and now, there was no specific MCL for Cr(VI) in water supplies other than Cr(VI) comprising a portion of the total Cr MCL.

2.2.4 What is Hexavalent Chromium, or Cr(VI)?

Chromium is a naturally occurring element found in rock, soil, and groundwater. It is the 11th most common element found in the Earth's crust. Chromium is commonly present in the environment in primarily two forms—Cr(III) and Cr(VI). Cr(III) is an essential human nutrient that some people even purchase as a food supplement.

Cr(VI) can be found naturally in the environment. It can also occur as an industrial by-product in manufacturing processes for stainless steel, chrome plating, dyes, pigments, leather tanning, and wood preserving. In many cases, it is suspected that these industrial by-products were discharged to the ground, in rivers, etc. and eventually reached groundwater supplies.

Toxicological studies conducted by the National Toxicology Program (NTP) concluded that Cr(VI) is carcinogenic in mice and rats by ingestion (NTP, 2008). The NTP study forms the primary basis for the development of the Cr(VI) PHG in California. Based largely on the NTP study, OEHHA established the PHG of 0.020 ppb for Cr(VI). Ongoing work led by ToxStrategies (Proctor, 2011) is investigating health impacts from lower concentrations that those tested in the NTP study (a minimum dose of 5 mg/L).

2.2.5 Glendale's Response to Water Containing Cr(VI)

Even though the Cr(VI) concentration in Glendale's treated groundwater was far below any applicable MCL by federal and state water quality standards as measured by total chromium, the Glendale City Council was reluctant to deliver the water to customers for the following reasons:

- The Cr(VI) concentration exceeded the 1999 California Public Health Goal, PHG, (a non-mandatory standard) of 2.5 ppb for total chromium (this PHG was withdrawn in 2001).

- The water delivered by the new treatment plant contained higher levels of Cr(VI) compared to water currently being delivered to Glendale water customers.
- The health effects of Cr(VI) in water supplies were not well known (and have since been investigated by the NTP study).
- The public perception to any Cr(VI) in water supplies was very strong in the community because of the movie and Erin Brockovich's continued publicity regarding the health concerns with Cr(VI).
- There was no specific water quality standard (maximum contaminant level-MCL) for Cr(VI) in drinking water supplies

Eventually the City Council accepted a target goal of 5 ppb for water delivered to its customers, with the understanding that the City would research ways to reduce the concentration of Cr(VI) in water supplies.

2.2.6 Glendale Initiates Plan and Research Efforts for Cr(VI) Removal

In 2001, the City of Glendale initiated an investigation on how to remove Cr(VI) from water supplies. The City soon realized that there was no proven feasible technology for low-level Cr(VI) removal from water.

At about this time, it became apparent that Cr(VI) was being found in water supplies in many parts of California and in other States. Because other communities in many parts of the United States had this same concern, Glendale began working with Congressman Adam Schiff to establish a $2 million three-phase effort (bench, pilot, and demonstration) to develop the technology for Cr(VI) removal from drinking water.

In 2002, with the plan developed, the Los Angeles Department of Water and Power (LADWP) and the American Water Works Association Research Foundation (now known as the Water Research Foundation) initiated the Phase I bench-scale testing with Glendale, Burbank, and San Fernando and the National Water Research Institute (NWRI) providing financial support to get the research effort underway. Senator Barbara Boxer and Congressman Adam Schiff started funding efforts for congressional grants to Glendale for Phase II and later phases with project management by the City of Glendale. More detailed information on the ten year research effort is provided in this report.

2.2.7 The Glendale Research Focus Transforms from a Local Emphasis to a Nationwide Focus

Early in the research work, the focus on all efforts was on the Cr(VI) issues facing Glendale. Because of the widespread presence of Cr(VI), the research moved away from just a Glendale matter to a nationwide issue. This also opened other funding sources for this research effort. Now, the focus is totally on the concerns of the entire water industry.

2.3 Project Management

At the start of Phase II pilot testing, Glendale developed a Project Advisory Committee (PAC) to oversee the research effort and advise Glendale on the research project. A different PAC was provided for Phase I, when managed by LADWP and AwwaRF. The agencies represented on the PAC for Phases II and III, including past and current representatives, are listed below.

- U.S. Environmental Protection Agency—Dr. Bruce Macler
- California Department of Public Health—Dr. Rick Sakaji (past member in this capacity), Ms. Heather Collins (past member), Mr. Eugene Leung
- 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

The Glendale Project Management Team is led by the following:

- Donald Froelich, Glendale Water Services Administrator (2000 to 2003) and Project Manager (part time through the research program – 2003 to current),
- Peter Kavounas, Assistant General Manager, Glendale Water and Power (2003 to 2012),
- Ramon Abueg, Chief Assistant General Manager, Glendale Water and Power (2012 to current),
- Leighton Fong, Project Engineer (2003 to present)

2.4 Research Consultants

All of the research activities for this project have been led by McGuire Environmental Consultants, which was later acquired by Malcolm Pirnie, and with Malcolm Pirnie later acquired by ARCADIS. In 2012, several key staff (Dr. Nicole Blute and Dr. Ying Wu) moved to Hazen and Sawyer and continued in their project roles at the new firm. Personnel performing and leading the research project effort have been generally unchanged over the many years.

- Phases I and II research effort was under the direction of Dr. Michael McGuire with participation by Dr. Nicole Blute
- Phases III, IIIA, and IIIB demonstration implementation and later research activities was under the direction of Dr. Nicole Blute

CDM Smith is the operator of the Glendale Water Treatment Plant (GWTP) and the Cr(VI) demonstration facilities, and key personnel are:

- Mr. Dan Hutton, GWTP Project Manager for CDM Smith
- Mr. Charles Cron, GWTP Operations Supervisor for CDM Smith

AECOM (formerly EarthTech before being acquired by AECOM) was the firm selected for the Design-Build (DB) of the Phase III Demonstration facilities. The AECOM Project Manager who led the effort was Mr. Eric Lang.

2.5 Academic Support

Academic support for the research effort was provided by many universities and research institutes for specialized research topics. The universities involved and specific involvements were:

- University of Colorado at Boulder: Professor Gary Amy - Phase I bench testing*
- University of California at Los Angeles: Professor Mel Suffet – Phase II pilot testing*
- Utah State University: Professor Laurie McNeill – Phase II pilot testing*
- Wellesley College: Professor Daniel Brabander – Phase III Bridge study
- Massachusetts Institute of Technology (facilities) – Phase III Bridge Study
- Lehigh University: Professor Arup SenGupta – Phase III Bridge Study
- Argonne National Laboratory: Mr. Steve Sutton – Phase III Bridge Study

Universities that were part of the Expert Panel selecting the demonstration testing technologies are denoted with an asterisk.

2.6 Project Budgets

The project budget for the research effort was $8.7 million. To date, the funding partners are many and include major water quality related organizations at the federal, state, regional, local, and industry levels. The interest in funding the additional research project was accelerated with the establishment of a California PHG at 0.020 ppb and the possible need of many more water agencies to add Cr(VI) removal treatment systems to their existing facilities. Some of the funding sources were outright grants and contributions, and others required matching funds. The City was able to use outright grants and contributions as part of the matching funds requirement. For other grants, the funding was complicated, but it did work to allow completion of the research project. The City of Glendale kept detailed accounting records for reporting to the many financial contributors to the research effort. Financial oversight is provided by Glendale Finance Department and its auditors, California Department of Water Resources, and the State of California Department of Finance on auditing functions.

More detailed information on the funding sources and contribution is provided in Appendix A, as well as a brief write-up on the status of the research activities.

3. Research Phases

This section describes the multiple phases of the chromium research effort, which have been called:

- Phase I – Bench scale testing (Completed)
- Phase II – Pilot scale testing (Completed)
- Phase III – Bridge and demonstration scale testing (Completed)
    - Phase IIIA – Microfiltration pilot testing in RCF (Completed)
    - Phase IIIB – Additional resin and adsorptive media pilot testing (Underway)
- Phase IV – Implementation (Future)

3.1 Summary Information on the Research Effort

The key objectives of the overall research effort by Phase and participants are shown in Table 3-1. The corresponding overall project schedule is provided in Figure 3-1.

Table 3-1. City of Glendale, California – Phases of the Overall Chromium Research Program

Implementation Phase/ Cost/ Status	Objective	Participants/ Financial Partners
Phase I Bench Study $400,000 (completed)	• Investigate chromium redox chemistry • Screen technologies at bench-scale • Evaluate national chromium occurrence	*Project Management: LADWP/WaterRF* Los Angeles Dept. of Water and Power (LADWP) Water Research Foundation (WaterRF) City of Glendale, California City of Burbank, California City of San Fernando, California National Water Research Institute
Phase II Pilot Study $750,000 (completed)	• Test mature industrial technologies and best bench study performers • Evaluate long term column performance • Estimate treatment costs	*Project Management: Glendale* City of Glendale, California U.S. Environmental Protection Agency (USEPA)
Phase III Bridge and Demonstration Study $4.45 Million (completed)	• Identify Weak Base Anion Exchange (WBA) mechanism • Construct and operate demonstration facilities • Evaluate residuals handling and disposal • Assess operational needs • Confirm and further develop treatment costs	*Project Management: Glendale* City of Glendale, California USEPA Association of California Water Agencies (ACWA) Water Research Foundation California Dept. of Public Health (CDPH)/ California Dept. of Water Resources (DWR) Proposition 50 Local Industry
Phase IIIA Operate Demonstration Facilities and Microfiltration Pilot Testing (MF) $2.5 Million (close out activities)	• Operate demonstration facilities • Operate MF pilot facilities • Evaluate Reduction-Coagulation-Filtration (RCF) treatment performance with MF • Develop design criteria for MF in the RCF process • Interim Report and cost update to CDPH • Project Report to CDPH	*Project Management: Glendale* USEPA City of Glendale, California Water Research Foundation CDPH/DWR Proposition 50 Local Industry US Bureau of Reclamation Metropolitan Water District of Southern California
Phase IIIB Resin/Media Pilot Testing $600,000 (underway)	• Test promising WBA and SBA resins & two adsorptive media • Compare technology effectiveness in two water qualities (Glendale and Livermore, California) • Project Report • Supplemental Project Report	*Project Management: Glendale & California Water Service Company* City of Glendale, California California Water Service Company Water Research Foundation DWR/CDPH Proposition 50 North American Höganäs

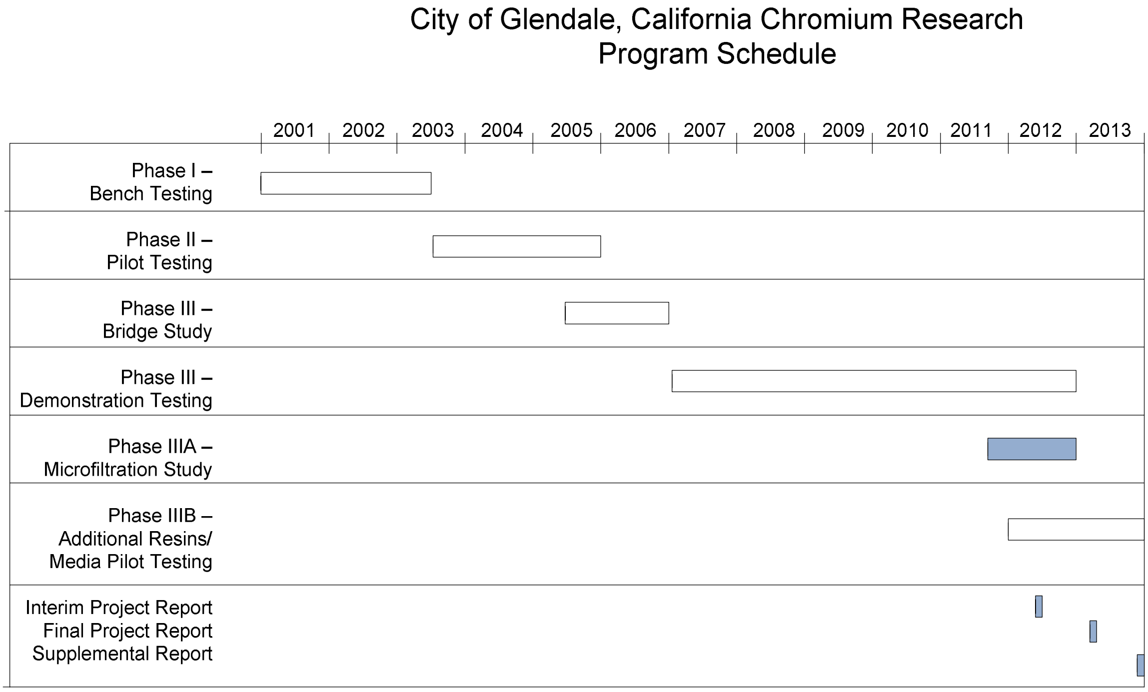


Figure 3-1. Overall Chromium Research Program Schedule

3.2 Summary of Phase I Bench Testing

Phase I bench testing is fully documented in a report submitted in 2004 (Brandhuber et al.), and attached to this report as Appendix B. An overview of the Phase I bench testing is provided in this section.

Phase I bench testing was led by the Los Angeles Department of Water and Power in partnership with the Cities of Glendale, Burbank, and San Fernando. The Phase I project included (1) an analysis of chromium occurrence and co-occurrence, (2) an evaluation of Cr(VI) removal technologies at the bench scale, and (3) an examination of chromium oxidation and reduction chemistry.

As a first step in Phase I, occurrence of Cr(VI) and total Cr were estimated using a retrospective analysis of water quality data from the National Water Information System (NWIS) database. This analysis showed that a mean Cr(VI) concentration for 1,654 groundwater sites suitable for public consumption was 4.9 ppb, and the mean total Cr was 8.2 ppb. Elevated concentrations could be found throughout the country. An analysis of co-occurrence of other water quality constituents did not reveal significant correlations between chromium and other constituents investigated. Additional information on Cr(VI) and total Cr occurrence is currently being gathered in the UCMR3 to characterize distribution in water sources in the U.S.

Phase I also investigated a range of technologies at the bench scale to screen promising approaches to Cr(VI) removal. Table 3-2 and Figure 3-2 illustrate the technologies investigated in Phase I, including various granular or resin media; anion exchange using a range of commercially available resins; membrane treatment using reverse osmosis, nanofiltration, and ultrafiltration membranes; and conventional treatment by Cr(VI) reduction and precipitation with a coagulant. The technologies were investigated using laboratory-scale testing methods at the University of Colorado (Boulder) and Utah State University (Logan). Technologies were tested with a variety of water matrices, such as distilled water with single or dual co-occurring solutes and Cr(VI) or natural water matrices (Glendale or LADWP) with Cr(VI).

Table 3-2 summarizes the key technologies tested and the effectiveness of Cr(VI) removal. Technologies identified for potential pilot testing in Phase II included:

- Anion exchange (fixed bed or dispersed contactor),
- Sulfur modified iron adsorptive media,
- Coagulation and precipitation of reduced Cr(III), and
- Membrane treatment with nanofiltration or reverse osmosis.

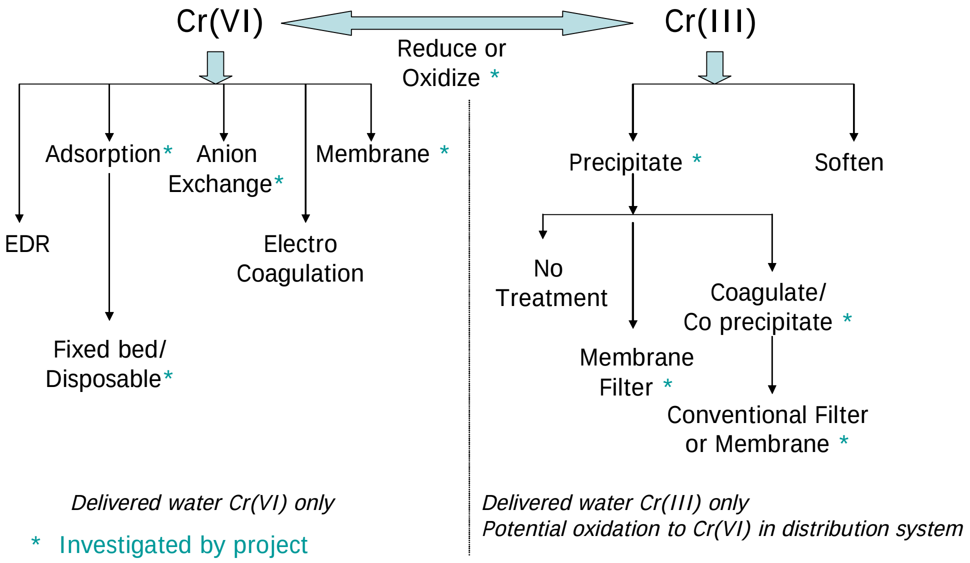


Figure 3-2. Potential Approaches for Chromium (VI) Treatment of Drinking Water

Table 3-2. Technologies Tested in Phase I and Their Relative Effectiveness

Technology Class	Bench Scale Testing	Effectiveness
Adsorption/Chelation	• Batch isotherms of 11 granular or resin-based adsorption media • Mini-column tests of three media	Excellent[1] removal for sulfur-modified iron; good[2] performance for iron-impregnated zeolite (with strong kinetics effect), and iron-coated activated alumina
Ion Exchange	• Batch isotherm of magnetized strong base anion exchange resin • Mini-column tests of four strong-base anion exchange resins	Excellent removal for strong base resins
Coagulation with Precipitation	• Jar tests of different ferrous to chromium ratios, and with and without coagulation aids • Filtration to five different size exclusion categories	Good removal for ferrous sulfate reduction; kinetics are important to the process
Membranes	• Bench top membrane tests using five different membranes (one ultrafiltration, two nanofiltration, and two reverse osmosis)	Excellent removal for one nanofiltration and one reverse osmosis membrane.

[1] Excellent removal refers to greater than 90% removal
[2] Good removal to between 50-90% removal.
Technologies with poor (<50%) removal are not discussed in the Effectiveness column of Table 3-1 but are described in Appendix B.

As shown in Table 3-2, chromium reduction with ferrous sulfate was found to be effective. Chromium is a metal that is easily reduced or oxidized, and the speciation of chromium determines the toxicity (i.e., Cr(VI) is toxic but Cr(III) is a micronutrient). A number of possible approaches using the redox activity of chromium were tested in Phase I, including reduction with three chemical reductants (stannous chloride, sulfide, and sulfite). In addition, the potential for reoxidation of Cr(III) to Cr(VI) was investigated using dissolved oxygen, free chlorine, chloramines, potassium permanganate, and hydrogen peroxide. Five different water qualities were tested in the experiments.

Dissolved oxygen was not sufficiently strong to reoxidize Cr(III) to Cr(VI), but free chlorine and chloramines at typical distribution system concentrations and for typical detention times yielded between 50% (for chloramines) and 80% (for free chlorine – shown in Figure 3-3) reoxidation of Cr(III). Given the potential for oxidation of soluble Cr(III) in the distribution system, simply reducing the Cr(VI) in water to achieve a Cr(VI) MCL, without addressing Cr(III) removal, is not optimal.

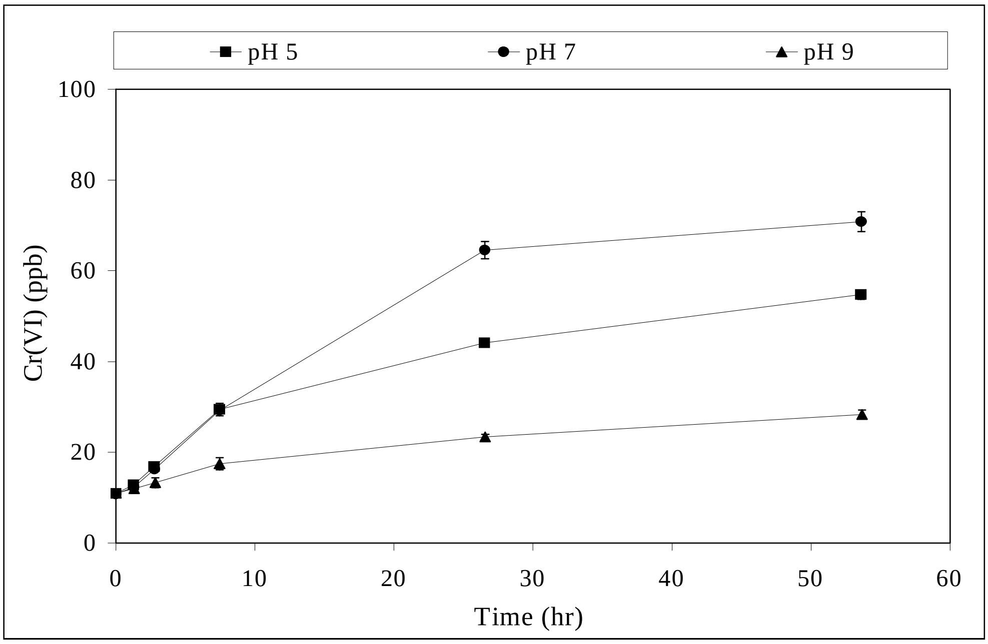


Figure 3-3. Reoxidation of Cr(III) to Cr(VI) with 1 mg/L Free Chlorine in Glendale Water

3.3 Summary of Phase II Pilot Testing

Phase II pilot testing results are fully described in a report submitted in 2005 (McGuire Environmental Consultants, 2005) and attached to this report as Appendix C. Two peer-reviewed publications were also prepared for the project (McGuire et al., 2006; Qin et al., 2005) – Appendix D. An overview of the Phase II pilot testing is provided below.

Phase II consisted of two segments: Phase II-A—vendor proof-of-technology validations, and Phase II-B—evaluation of additional technologies and effective technologies in more depth. Vendors and technologies were selected based upon pre-established criteria including maturity of technology, demonstrated performance as an industrial waste treatment or remediation process or other applications for Cr(VI) treatment, capacity and ability to scale up, technical soundness of the treatment process, and the ability to achieve NSF certification for drinking water application.

Phase I bench-scale testing suggested that technologies capable of removing Cr(VI) to less than 5 ppb would include the following classes of technologies: SBA resin in column and reactor applications, adsorptive media, membrane treatment by nanofiltration and reverse osmosis, and coagulation/precipitation of reduced Cr(III). Of these technologies, membrane treatment results in too great of water loss and was not carried forward as a viable technology for Glendale. The other three technology classes were included in pilot testing, as well as adsorptive media (zeolite and GAC) and

WBA resin. Sulfur-modified iron (SMI) adsorptive media, while promising in bench-scale work, was not technologically mature enough for pilot testing at that time. Table 3-3 lists the pilot-tested systems, type of technology, effectiveness at achieving the 5 ppb Cr(VI) goal, whether the media is regenerable (if applicable), nature of residuals streams, and other issues identified in pilot testing. Bed volumes (BV) are the number of gallons of water treated divided by the number of gallons of resin in a bed.

Table 3-3. Technologies Evaluated in Phase II Pilot Testing and Their Effectiveness

Product		Technology	Cr(VI) less than 5 ppb?	Bed Volumes to Break-through	Regen-erable?	Chromato-graphic peaking	Residuals	Other Issues
Calgon	SBA resin WT-201	Ion Exchange (Column)	Yes	1,000	Yes	Yes	Brine	
	SBA resin WT-202	Ion Exchange (Column)	Yes	1,000	Yes	Yes	Brine	
	SBA resin WT-203	Ion Exchange (Column)	Yes	350	Yes	Yes	Brine	
	SBA resin WT-204	Ion Exchange (Column)	Yes	1,400	Yes	Yes	Brine	
	Carbon F600	Adsorption	Yes	600	Yes	Not observed	-	
	Carbon F200PHA	Adsorption	Yes	600	Yes	Not observed	-	
Filtronics	Electro-media®	Reduction/ Filtration	No	N/A	N/A	Not observed	Backwash	High chemical doses tested
Orica	MIEX®	Ion Exchange (Continuous flow reactor)	Yes – Not reliably	N/A	Yes	Not observed	Brine	
US Filter/ Rohm & Haas[1]	SBA (Amberlite PWA 410Cl)	Ion Exchange (Column)	Yes	1,900	Yes	Yes	Brine	Effective regeneration
	WBA (Duolite A7)		Yes	38,000	No	Not observed	Media; backwash	Requires pH of approx. 5.5 - 6.0
WRT	Z-24™	Surface reduction/ adsorption	Yes	620	No	Not observed	Media	Requires long contact times
-	RCF	Reduction/ Coagulation/ Filtration	Yes	N/A	N/A	N/A	Backwash and dewatered solids	Most effective at ambient pH of 7-7.7

[1] The US Filter/ Rohm and Haas team is now a partnership between Siemens and Dow.

Cr(VI) and total Cr were the key parameters measured in both influent and effluent samples to determine the effectiveness of the different technologies. Although the blended Glendale source water contained an average of 10 ppb Cr(VI), Glendale elected to test a higher influent concentration of 100 ppb Cr(VI) intentionally spiked into the water. This higher influent concentration also enabled an evaluation of 95% chromium removal by the technologies, well above the method detection limits for the project (i.e., 0.2 ppb Cr(VI) and 1 ppb total Cr at the time of testing).

The impact of other water quality parameters on the technologies and the effect of the technologies on the water quality were also tested. Routine measurements for all technologies tested included pH, temperature, conductivity, alkalinity, hardness, turbidity, and iron. For anion exchange technologies, anions including sulfate, nitrate, silicate, phosphate, and arsenic were measured to determine competitive removal and any peaking from column technologies.

Pilot testing revealed that most of the technologies tested could remove Cr(VI) to levels below 5 ppb, although capacities and reliability widely varied. Table 3-3 provides a comparison of the treatment technologies in terms of the bed volumes of water treated (i.e. volume of water treated divided by the volume of media).

The SBA resin with the greatest Cr(VI) removal capacity in the pilot testing was provided by US Filter/ Rohm & Haas, compared to Calgon's four SBA resins tested. The SBA resin exhibited chromatographic peaking of nitrate and phosphate in the first quarter of bed life (i.e. before 5 ppb was achieved). Peaking resulted in a 3 to 4 times increase in the effluent concentration compared to the influent, which caused nitrate to exceed the maximum contaminant level of 10 mg/L as N. Consequently, multiple resin beds may be needed in a strong-base resin system to provide blending of nitrate.

Orica's MIEX® pilot unit was able to remove Cr(VI) to levels below 5 ppb for slightly more than half of the samples collected. Tests showed that the likely factors limiting Cr(VI) removal were resin dose and high sulfate levels of 90 mg/L. Although chromatographic peaking was not a concern in the continuously-stirred MIEX® system, reliable Cr(VI) removal to low levels (< 5 ppb) did not match the capabilities of the fixed-bed SBA resin technology.

WBA resin (from US Filter/ Rohm & Haas), which had not been used in drinking water applications at the time, showed a remarkable ability to remove and retain Cr(VI). WBA resin achieved ten to twenty times more bed volumes of treatment compared to strong-base resins (and even higher capacity in Phase III). In the process of treating Cr(VI), the WBA resin accumulated 3.2% chromium on the resin. However, successful WBA resin use for Cr(VI) removal depends on pH depression to below 6.0. Pilot findings indicated that the ideal pH range may be between 5.5 and 6.0, to maximize Cr(VI) removal and minimize Cr(III) release that may occur at pH values below 5.5. The mechanism of chromium retention by the WBA resin was not understood but was suspected to involve a speciation change of Cr(VI) to Cr(III) due to the color change of the resin to green. Additional testing of the resin mechanism of Cr(VI) removal is described in Section 3.4.1.

Adsorptive media tested in the pilot study included both WRT zeolite media and Calgon GAC. Both WRT media and Calgon GAC removed Cr(VI) to concentrations below 5 ppb, although the number of bed volumes to breakthrough was one-third of the most effective strong-base anion exchange resin. In addition, the WRT zeolite media required empty bed contact times ten to fifteen times longer than the resins and deoxygenation of the water. Pilot results confirmed literature findings that GAC is not able to treat many bed volumes before Cr(VI) breakthrough.

Two different reduction/filtration technologies were pilot-tested in Phase II. The vendor-supplied technology, provided by Filtronics, was not able to both reduce Cr(VI) and remove total Cr from the influent water. Filtronics' pilot unit included reduction of Cr(VI) to Cr(III) with sodium sulfite (or bisulfite), then oxidation of the water with sodium hypochlorite for iron precipitation on the dual-media filter. Very high concentrations of reductant and oxidant were used by Filtronics, and results showed that effective Cr(III) removal could not be achieved during the testing period.

By comparison, the reduction/coagulation/filtration (RCF) pilot unit designed and set up by the team of McGuire Environmental Consultants and CDM was highly effective in both reducing Cr(VI) and removing total Cr. This pilot unit used ferrous sulfate for reduction and precipitation of Fe-Cr particles, aeration columns to oxidize remaining ferrous iron and coagulate iron hydroxide particles, and granular media filtration (sand and anthracite) to remove the Fe-Cr particles. In pilot testing, a number of operational parameters were tested, including the iron-to-chromium dose ratio, pH of reduction and filtration, filter loading rates, and backwash needs.

Overall, Phase II pilot testing revealed that the most effective Cr(VI) removal technologies were SBA resin, WBA resin, and RCF. Of the three effective pilot-tested Cr(VI) removal technologies, regenerable SBA and RCF are more standard technologies in other drinking water and industrial wastewater treatment applications. The third successful pilot-tested technology, WBA, was distinctive in its high capacity for Cr(VI) and represented a new, innovative technology application.

For the pilot-tested technologies, residuals waste streams were tested for hazardous characteristics and investigated for possible minimization of waste stream volumes. Testing showed that SBA resin could be regenerated with a strong salt solution, which could be recycled more than once before disposal. WBA resin could be used as a disposable media due to its high capacity for Cr(VI), and residuals could be minimized by fully exhausting the resin. RCF generates backwash water and solids, which can be rapidly precipitated using a polymer. All residuals (brine or solids) associated with these three technologies were hazardous by the California Waste Extraction Test (WET). However, solids from WBA and RCF processes passed the Federal Toxicity Characteristic Leaching Procedure (TCLP) test, so they could be disposed in a non-hazardous landfill outside of California (unless specific state or federal requirements restrict the disposal, such as for a Superfund site).

3.4 Summary of Phase III Testing

Phase III testing consisted of different stages of testing, including a "Bridge Project" to obtain targeted additional pilot testing before demonstration design and construction (Section 3.4.1), demonstration-scale testing of two technologies at 425 and 100 gpm (Section 3.4.2), a residuals study funded by ACWA to investigate disposal options for waste streams and jar test the RCF process on other water qualities (Section 3.4.3), and the addition of microfiltration to the RCF process to investigate the lower limits to which the RCF can remove Cr (Phase IIIA - Section 3.5). One additional effort under the umbrella of Phase III is pilot testing of additional WBA resins and adsorptive media at Glendale and the California Water Service Company's Livermore system (Phase IIIB - Section 3.5). A final effort is in the conceptual stages to include supplemental demonstration testing of promising resins and/or adsorptive media identified in Phase IIIB pilot testing (Phase IIIC – Section 3.6) at demonstration scale, should funding become available.

3.4.1 Bridge Project Pilot Testing

The Phase III Bridge project is fully described in a report submitted in 2007 (McGuire et al.), and attached to this report as Appendix E. An overview of the Phase III Bridge project is provided in this section.

Phase II pilot testing revealed that the tested WBA resin had a high capacity for Cr(VI), which might make the resin cost effective as a disposable media. Before the WBA resin was implemented in the Phase III demonstration testing, a study designated the Phase III Bridge project was conducted to "bridge" pilot-scale and demonstration-scale testing since significant unknowns about WBA resin gave the Expert Panel pause to recommend WBA at demonstration-scale without further study. Key objectives of the Phase III Bridge Project included:

- Conducting treatment studies to confirm the efficiencies of WBA resins for Cr(VI) removal from Glendale groundwater
- Characterizing WBA resin residuals to elucidate Cr(VI) removal mechanism(s)
- Investigating residuals handling and disposal options
- Refining cost estimates of effective Cr(VI) treatment technologies (WBA, SBA, and RCF)
- Convening an expert panel to recommend treatment technologies for demonstration-scale testing

The Phase III Bridge project began with a bench-scale isotherm evaluation to screen six promising WBA resins for Cr(VI) removal from spiked Glendale groundwater at two pH values (5.9 and 6.4). Two WBA resins outperformed the other four WBA resins for Cr(VI) removal at both pH conditions and were selected for subsequent flow-through pilot testing. Of note in isotherm testing was that both resins required more than 40 days to reach equilibrium with Cr(VI) in solution. The high Cr(VI) capacities of the two resins (Duolite A7, now named PWA7, and ResinTech SIR-700) coupled with the slow kinetics to reach equilibrium indicated that a mechanism other than ion exchange might be involved in Cr(VI) removal by the WBA resins. Figure 3-4 depicts the Cr(VI) capacity of the WBA resins, whereby approximately 1.5 to 2.0% by weight was observed for Duolite A7 and up to 2.5% for ResinTech SIR-700. Duolite A7 has been NSF61 certified for drinking water applications. ResinTech SIR-700, which was not certified at the time of the Phase III Bridge study, has been recently certified for drinking water applications.

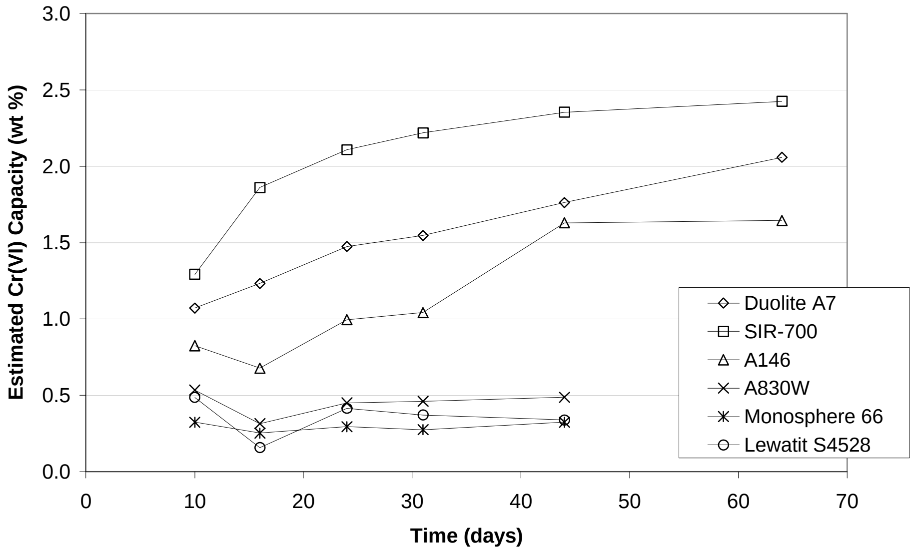


Figure 3-4. Estimated Cr(VI) capacity of the WBA resins (resin dose of 40 mg/L at pH 5.9)

Duolite A7 is now named as PWA7.

Bench-scale isotherm testing was followed by short-term mini-column testing and longer-term pilot-scale column testing. The selection of an appropriate pH for pilot-scale testing was determined using mini-columns for ten days. Mini-column testing results for pH values ranging from 5.6 to 7.2 showed different breakthrough characteristics for the two WBA resins tested. However, both resins favored low pH for Cr(VI) removal to achieve a treatment goal of less than 5 ppb. A pH of 6.0 was selected as the pH at which to test Cr(VI) removal capacities in the longer-term pilot tests.

SIR-700 and Duolite A7 WBA resins were tested in pilot-scale columns at a pH of 6.0 and ambient pH of 6.8, the latter of which was examined to evaluate the potential for reduced acid addition but more frequent resin replacement. Figure 3-5 shows the Cr(VI) breakthrough curves of both resins, highlighting the importance of a reduced pH for Cr(VI) removal. At pH 6.0, the Duolite A7 resin treated approximately 45,000 bed volumes of water before 5 ppb Cr(VI) (and total Cr) effluent concentrations were observed. The consistent removal performance over an extended period indicated that the Duolite A7 resin could be used as an effective single-pass resin for Cr(VI) removal in Glendale groundwater.

Although the SIR-700 resin treating pH 6.0 water showed an early 5 ppb breakthrough point at 2,200 BV, the Cr(VI) removal performance improved during the testing period such that effluent total Cr and Cr(VI) concentrations were less than 5 ppb at the end of the pilot-scale testing (i.e., after treating approximately 113,000 BV of water). Improved Cr(VI) removal through the testing is not typical of ion exchange breakthrough curves; additional testing was recommended but the resin was not NSF certified so it was not pursued further at that time.

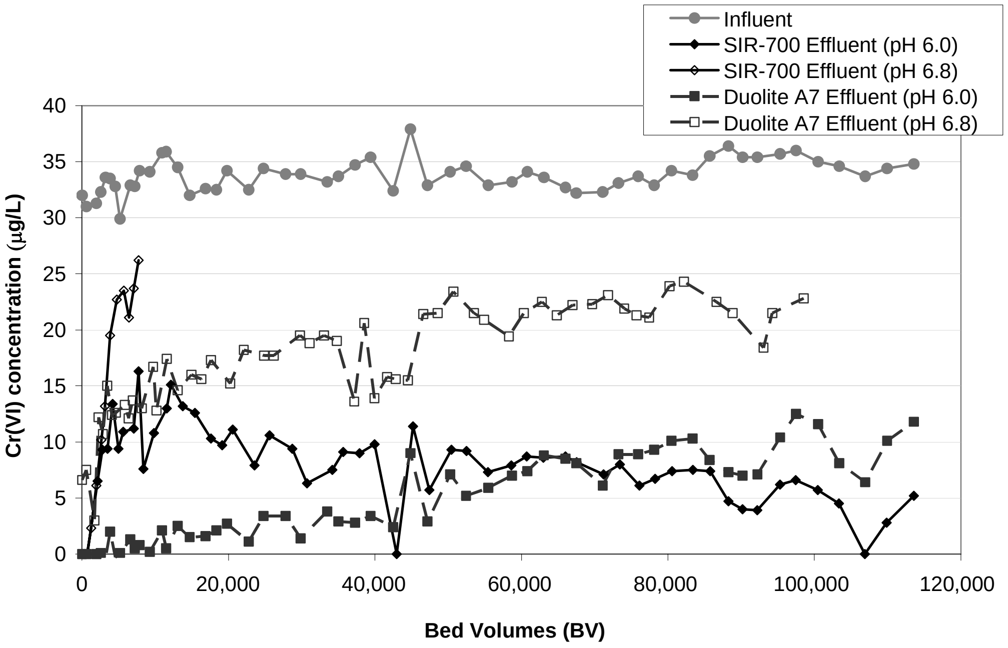


Figure 3-5. Cr(VI) Breakthrough Curves for Two WBA Resins at Two pH Values

Duolite A7 is now named as PWA7. BV = Gallons of water treated/ gallons of resin in a vessel.

Once pilot testing was complete, spent resins were removed and tested for hazardous waste characteristics. The spent SIR-700 and Duolite A7 resins operated at pH 6.0 passed the Federal TCLP but failed the California WET and thus would be characterized as non-RCRA hazardous wastes for disposal in California. The spent Duolite A7 resins also had total uranium concentrations exceeding 500 µg/g (i.e., the trigger for low-level radioactive waste designation) after treating approximately 113,000 BV of water.

Mechanisms for Cr(VI) removal with WBA resins were also investigated in the Phase III Bridge project. Chromium speciation on spent resins was assessed using x-ray absorption near-edge structure (XANES) spectroscopy. Cr(III) was the dominant species retained on both resins, comprising more than 95% of the total chromium present. The XANES analysis provided direct evidence that the reduction of Cr(VI) to Cr(III) is an important part of the Cr(VI) removal mechanism by the SIR-700 and Duolite A7 WBA resins. Additional testing of the mechanism at Wellesley College and MIT confirmed that the chromium removed is homogenously distributed on the resin beads (determined by scanning electron microscopy, SEM) and the chromium is associated with organic components of the resin rather than a specific anion like nitrate that might form a Cr(III) precipitate (as determined by x-ray diffraction, XRD, and XANES). These additional findings suggested that the WBA resin-retained chromium is unlikely to be released in a hydraulic upset event, which was one of the Expert Panel concerns.

Supplemental mechanistic studies were performed at Lehigh University to investigate remaining questions regarding use of the WBA resins for Cr(VI) removal (SenGupta et al., 2007). Testing confirmed that a low pH is necessary for optimal Cr(VI) removal, that copper preloading of the resin does not increase Cr(VI) removal (as they observed for some SBA resins), that improved performance of SIR-700 resin in the beginning of a run could be achieved if equilibrated at a slightly acidic pH of 3-4, and that the mechanism of Cr(VI) removal by WBA resins may be rate limited by intraparticle diffusion within the ion exchangers. Additional details on this study are available in Appendix E.

In addition to the technical evaluations, cost estimates of WBA resin application at the demonstration-scale were developed and compared with RCF and SBA processes. More recent cost estimates are located in Section 5.

At the conclusion of the Phase III Bridge project, the Expert Panel was convened to review technical and cost information gathered in Phases I, II, and III Bridge and provide recommendations to Glendale on Phase III Demonstration testing. Proceedings from the Expert Panel meeting are provided in Appendix E. The Expert Panel concluded that the RCF and WBA processes should be included in the Phase III Demonstration Study. The SBA process was not considered advised for testing by the Expert Panel due to brine disposal restrictions at Glendale.

3.4.2 Demonstration Testing

An overview of the Phase III Demonstration testing is provided in this section. The Phase III Demonstration testing is fully described in Section 4. A 2011 application to the U.S. Bureau of Reclamation WaterSMART grant program also provides details on the broader implications of the testing to the Southern California region (Appendix F).

The objectives for Phase III Demonstration testing included the following:

- Evaluate the performance of demonstration-scale Cr(VI) treatment technologies that were selected on the basis of Phase I bench-scale and Phase II pilot-scale testing (i.e., WBA and RCF technologies);
- Evaluate issues related to the day-to-day operations of demonstration treatment technologies and develop comprehensive operations manuals (Appendix S);
- Determine hydraulic performance and reliability of the demonstration treatment technologies;
- Evaluate the ability to scale-up bench and pilot level results to demonstration-scale with respect to Cr(VI) removal;
- Characterize treatment residuals, investigate handling and disposal requirements, and identify residuals optimization strategies;
- Verify unit cost information developed in the Phase II pilot study with actual treatment costs;
- Quantify demonstration treatment performance with respect to Cr(VI) removal over extended periods of time;
- Determine the impact of selected demonstration treatment processes on finished water quality;
- Identify other contaminants, such as arsenic, perchlorate, nitrate, uranium, and vanadium, that could be removed with the treatment systems;
- Publicly disseminate project plans and findings to a wide audience including water agencies also concerned with Cr(VI) in water supplies; and
- Assess the applicability of the technologies to small water systems.

Two facilities were constructed in the Phase III Demonstration study, including a 425 gpm WBA treatment facility at the GS-3 well and a 100 gpm RCF treatment facility receiving a side-stream of flow from the GN-3 well.

3.4.3 Residuals Study

The Phase III Residuals study is fully described in a report submitted in 2011 and finalized in 2012 (Blute et al. 2012a), and attached to this report as Appendix G. An overview of the Phase III Residuals study is provided in this section.

The Phase II Pilot testing and Phase III Bridge project revealed that the residuals generated from the leading three technologies (WBA, RCF, and SBA) are likely to be classified as California hazardous waste, leading to high costs of residuals management that comprise a significant portion of overall treatment costs. In addition, WBA resins can accumulate uranium and have the potential to be at least a technologically enhanced naturally occurring radioactive material (TENORM) or even a radioactive waste. For these reasons, ACWA sponsored a study with the City of Glendale, California to achieve the following objectives:

- Evaluation of uranium accumulation on WBA resin and opportunities for disposal of spent resin as a radioactive waste or a chromium ore;
- Estimation of residuals volumes generated in the RCF process for a representative range of water qualities encompassing different utilities around California with Cr(VI) in their water supplies;
- Development of cost estimates for solids thickening and dewatering options for the RCF process, in addition to information gained in demonstration testing; and
- 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).

A decision tree was developed in this project to elucidate WBA resin disposal options (Figure 3-6), which depend on the waste classification according to several leaching tests and solid analyses. Analysis of potential costs associated with operating the resins to avoid uranium accumulation above the radioactive waste threshold (0.05%) versus using the resins in a lead/lag vessel configuration with a target lag treatment goal (in the case of Glendale, 5 ppb Cr(VI)) revealed that the most cost effective option was the latter coupled with the use of adsorbent material to sequester water prior to disposal, which resulted in an inadvertent dilution of uranium in the spent resin and categorization of the waste as TENORM rather than radioactive waste. Disposal options for WBA resins also depend on whether the source water is part of a Superfund project (as Glendale was), which requires disposal at a USEPA-approved landfill that can accept Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) wastes. In California, the two landfills that can accept hazardous waste also can accept CERCLA waste (i.e., Clean Harbors Buttonwillow and Chemical Waste Management Kettleman Hills).

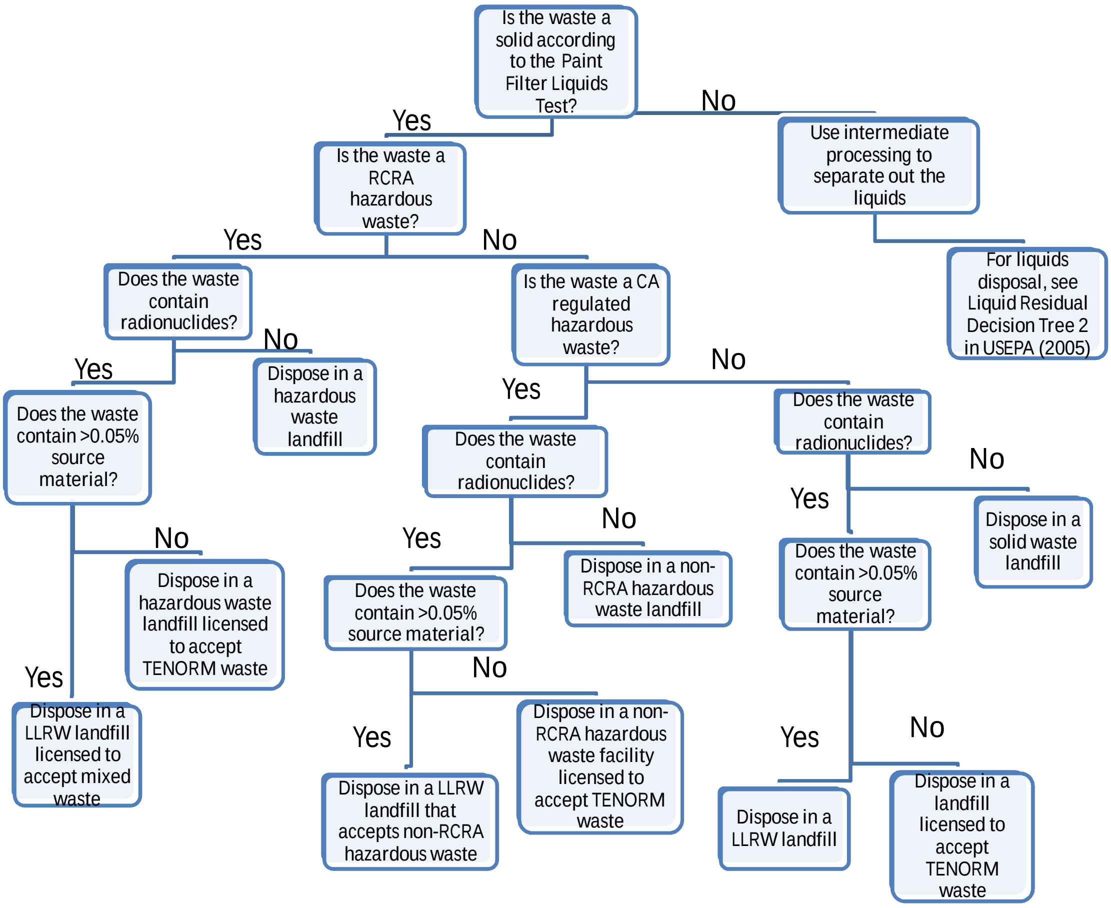


Figure 3-6. Decision Tree for Disposal of Solid Waste Generated in California

Notes:

RCRA – Resource Conservation and Recovery Act (solids classified according to toxicity leaching and characteristic procedure, TCLP)

LLRW – low level radioactive waste

TENORM – technologically enhanced naturally-occurring radioactive waste

The applicability of the RCF process to three additional utilities' water (in addition to Glendale) and the residuals volumes generated were investigated in the next phase of this Phase III Residuals study. Jar testing was performed involving 45 minutes of reduction time with ferrous sulfate, aeration, and filtration (through 0.45 and 0.1 micron pore size filters). Three Fe:Cr(VI) ratios were tested for each utility since this factor is critical in the residuals volumes generated. Glendale water was also spiked with silica and phosphate (separately), since both have been reported to impact Cr(VI) reduction/coagulation/filtration processes.

The jar testing results showed that a Fe:Cr(VI) mass ratio of 25:1 (i.e. ferrous dose of 2.75 mg/L) effectively removed Cr(VI) and total Cr to below 1 ppb for influent Cr(VI) concentrations of 80 ppb or above (Figure 3-7). However, a higher Fe:Cr(VI) mass ratio of 50:1 or 75:1 (ferrous dose of 0.65 and 0.98 mg/L, respectively) was necessary for lower influent Cr(VI) concentrations of around 10 ppb. For a low influent Cr(VI) concentration, the ferrous dose provided by a 25:1 ratio may not be sufficient to effectively 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 (Figure 3-8).

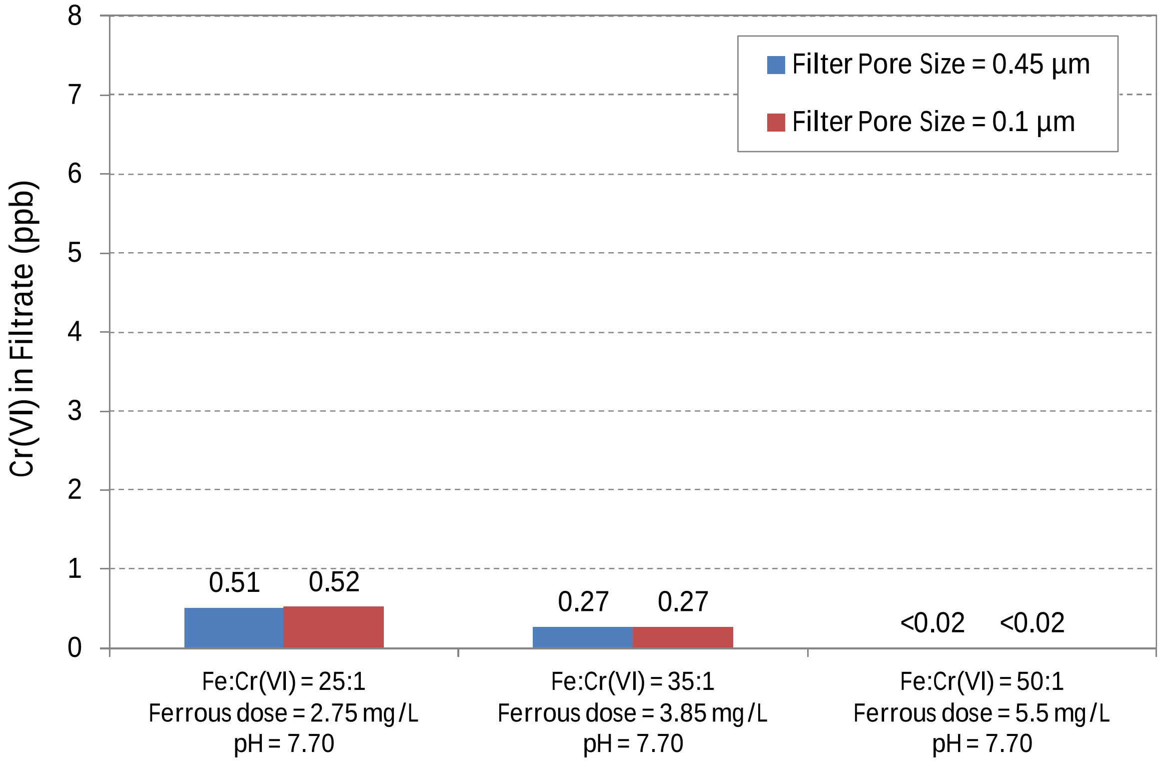


Figure 3-7. Hexavalent Chromium Removal Results for Utility II Sample (Raw Water Cr(VI) = 110 ppb)

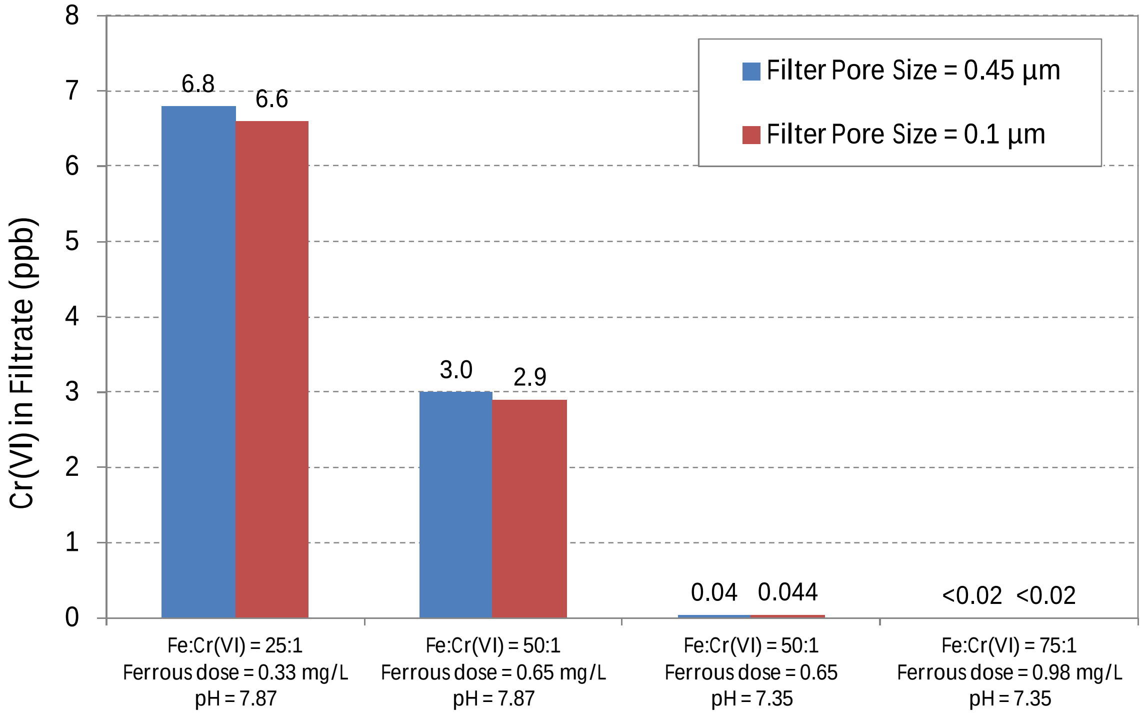


Figure 3-8. Hexavalent Chromium Removal Results for Utility I Sample (Raw Water Cr(VI) = 13 ppb)

The pH was found to have a significant impact on chromium reduction efficiency. pH levels 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 in the same water sample (Figure 3-9). The effect of pH might result from accelerated ferrous oxidation by oxygen, and therefore less ferrous for Cr(VI) reduction, which is described more thoroughly in Appendix G. Thus, for water sources with a relatively high pH level, pH reduction may be necessary for effective Cr(VI) removal to low levels using RCF (depending on necessary target Cr(VI) effluent concentrations).

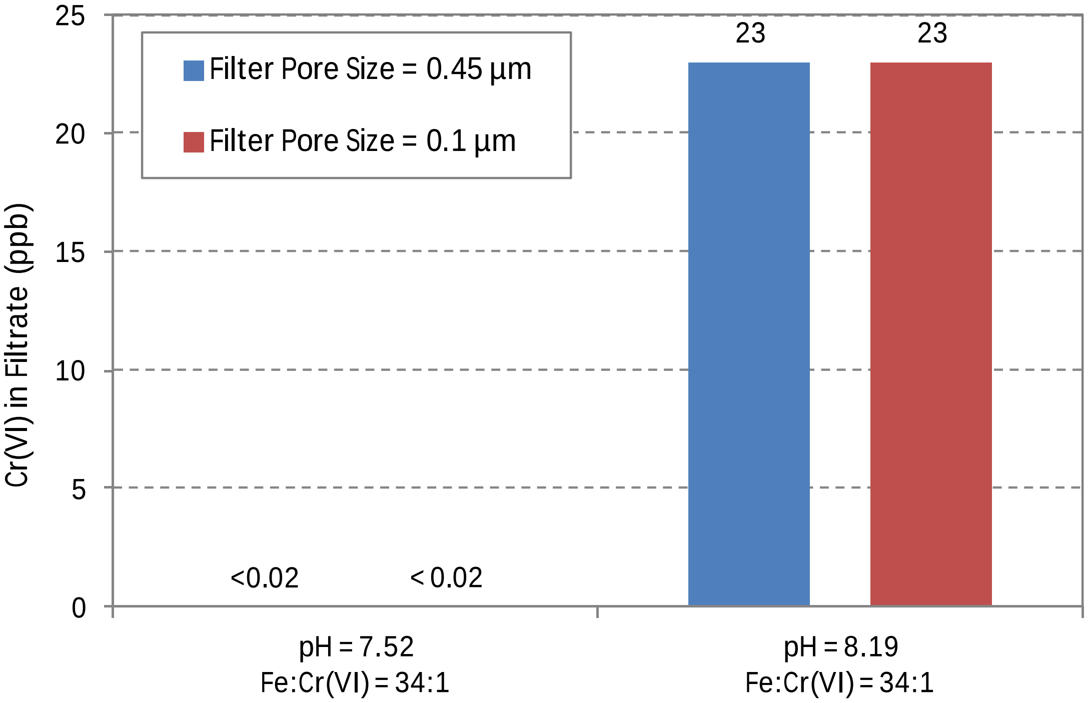


Figure 3-9. Impact of pH on Cr(VI) Removal with the RCF Process for Jar Testing of Glendale Water

Silica was also noted to inhibit Cr(VI) removal when spiked to 76 mg/L as SiO_2 from 29 mg/L SiO_2. 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. This apparent impact might be due to a higher silica concentration (e.g., formation of ferrous silica precipitate) and/or the effects of an inadvertent pH increase during silica spiking, which was later found. A slight increase in the phosphate concentration (1.3 mg/L as PO_4 compared with 0.26 mg/L as PO_4) did not show significant impacts on Cr(VI) and total Cr removal.

RCF residuals quantities were estimated based on mass balance and also with jar testing results (when enough residuals were generated to be quantifiable). Mass balance estimates were generally more conservative, but within the same order of magnitude, as the values obtained during the jar testing. As observed at Glendale, residuals for other utilities are expected to be classified as non-RCRA hazardous waste due to chromium concentrations above the Total Threshold Limit Concentration (TTLC) regulatory limit, according to mass balance calculations.

The Phase III Residuals study also included an analysis of residuals volumes generated in the Glendale Phase III Demonstration study, in addition to costs and characteristics of the residuals. For a 100 gpm system treating 80 ppb of Cr(VI) with an Fe:Cr(VI) ratio of 25:1 (ferrous dose of 2 mg/L) for a total of 30 weeks, 7,663 lbs of residuals waste was produced compared with a mass balance estimate of 10,644 lbs. Actual waste generated was characterized by 84% moisture content, which is reflected in the mass balance as well. The difference in actual versus estimated residuals was likely due to losses of residuals during recycle (or occasional discharge to the sewer during periods of investigation into bacteriological issues, which are discussed in Section 4.3.3), and conservative assumptions in the mass balance calculations that might not reflect actual operational conditions. Analysis of the RCF residuals showed that the waste was a non-RCRA hazardous waste, having passed the TCLP test and failed the California WET test for TTLC.

The options for solids thickening and dewatering were considered in the Phase III Residuals study to identify the treatment methods that are most feasible for the RCF process at different system sizes, including 10, 100, 500, 2,000, and 5,000 gpm. Spent filter backwash water typically contains a low solids concentration and requires treatment by thickening and dewatering to obtain solids disposable to landfills. 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 were reviewed and are summarized in Appendix G. 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 the waste is classified a non-RCRA hazardous waste in California). An analysis of the different components and system sizes was produced in the Phase III Residuals study to define filtration, solids thickening, and dewatering approaches used for cost estimation of RCF residuals treatment systems. Cost estimates for residuals treatment systems developed in the Phase III Residuals study were incorporated in the overall system costs that are included in Section 5.

3.4.4 Phase IIIA Microfiltration Study

The Phase IIIA Microfiltration study is described in the draft Phase IIIA report (Appendix H; Blute et al., 2012b). An overview of the Phase IIIA Microfiltration study scope is provided in this section and the results in Section 4.

Chromium removal was shown in Phases II and III to be tied to particle removal by filtration due to the association of the Cr(III) with the ferric iron particles. Granular media filtration (i.e., anthracite and sand) is currently being tested at the demonstration scale to offer a low-cost means of particle removal. However, granular media filtration has demonstrated considerable fluctuations in filter effluent turbidity and hence chromium removals, thus sub-ppb levels of total Cr have not been consistently achieved. The California PHG at a level of 0.020 ppb and the intention of California to regulate Cr(VI) has raised the question of whether more advanced filtration (i.e., MF) can achieve lower treated water concentrations. The Expert Panel recommended that Glendale test MF to achieve better particle removal, and hence chromium removal, in the RCF process. MF pilot testing was approached as an add-on to the current RCF facilities and was tested from February through July 2012.

The objectives of the Phase IIIA Microfiltration study included:

- Determining the effectiveness of MF/UF membrane technology for removing total Cr (and hence, Cr(VI) as well) to sub-ppb levels,
- Assessing whether iron fouling is problematic in direct filtration mode of operation for the RCF process, and
- Identifying design criteria for full-scale MF/UF in a RCF treatment process, which will provide the basis for cost development (which was performed as an additional effort and is included in Section 5 of this report).

Two pilot testing units, a pressure system and a submerged system, were evaluated in Phase IIIA. The pressure MF system was from Pall and the submerged UF system was from GE/Zenon. Note that the GE/Zenon submerged system is technically considered to be ultrafiltration (UF) due to the smaller pore size than typical microfiltration membranes. The membranes were run in parallel with the granular media filter that operated during the Phase III Demonstration study.

The MF/UF pilot testing was conducted in a series of stages as summarized in Table 3-4. Prior to the start-up of the MF/UF pilot test, two Fe:Cr(VI) ratios were identified for each of the two water sources for Stage 1a testing. Following the pilot set-up, the low Cr(VI) water was tested in Stage 1a. Jar testing was conducted after Stage 1a and before Stage 2a to evaluate chlorination of remaining ferrous to minimize membrane fouling due to ferrous iron. In Stages 3a and 3b, a low influent Cr(VI) water (approximately 15 ppb) was tested for extended periods to evaluate total Cr and Cr(VI) removal and membrane operations for development of full-scale design criteria. In Stage 4b, a high influent Cr(VI) water (approximately 80 ppb) was tested for a short period of time to evaluate total and Cr(VI) removal and membrane operations. Clean-in-place (CIP) procedures were conducted by Pall and GE/Zenon between Stages 2a, 3a, 3b and 4b.

Table 3-4. Microfiltration Pilot Testing Summary

Testing Stage	Objective
Pilot Set-up	Pilot setup, equipment testing, leak test, etc.
1a	Establish optimum Fe:Cr(VI) ratio for the low (~10-15 ppb) influent Cr(VI) concentration.
2a	Establish site-specific membrane filtration operating parameters for the low influent Cr(VI) concentration.
3a and 3b	Conduct two consecutive 30-day demonstration tests of both membrane filtration units under their respective optimum set of simulated, full-scale water treatment plant design conditions for low influent Cr(VI) concentration as established by the Stage 2a testing.
4b	After conducting a CIP, continue the pilot testing for 7 days to quantify any decline in performance and evaluate removal for a higher influent Cr(VI) concentration (~80 ppb).

3.5 Introduction to Phase IIIB Additional Resin and Adsorptive Media Pilot Testing

The Phase IIIB Additional Resin and Adsorptive Media pilot testing study is described in the proposal submitted in 2011 (California Water Service Company in partnership with the City of Glendale, California) to WaterRF and the test plan, which are attached to this report as Appendix I. An overview of the Phase IIIB study is provided in this section.

In the Phase III Demonstration study, WBA resins were shown to offer an operationally simple means of removing Cr(VI) from drinking water. The one WBA resin tested at demonstration-scale (Amberlite™ PWA7) was found to leach formaldehyde during operation, which has a Notification Level in California. A pre-treatment procedure (cross regeneration) was instituted to treat the WBA resin being tested at Glendale, which was effective with the first batch of resin but not a subsequent batch. The mechanism triggering formaldehyde release is unknown at this point. Recently, several other potential media showing promising results in industrial settings have become available and were proposed for testing in Phase IIIB to potentially alleviate formaldehyde leaching, to minimize uranium accumulation, and to offer competition in the marketplace.

The objectives of this study, which is being conducted under a cooperative agreement with the California Water Service Company (Cal Water), are to build upon existing research to identify and further test sustainable, cost-effective treatment options for removal of Cr(VI). CDPH has expressed significant interest in testing the treatment technologies in other water qualities than Glendale's to understand wider applicability. This project is:

- Determining the effectiveness of potential single-pass technologies for removal of Cr(VI) and co-occurring contaminants on different water qualities,
- Assessing the operational requirements of the treatment options, and
- Identifying costs of treatment for these new approaches.

The research plan includes pilot-scale testing of ion exchange and adsorptive media. Two promising WBA ion exchange resins and three SBA ion exchange resins are being tested in two different water qualities to determine capacity and the impact of water quality differences on their capacity. The two WBA resins (Purolite S106 and ResinTech SIR-700) lack the formaldehyde backbone structure but may have a similar capacity to the formaldehyde-based Amberlite™ PWA7 resin based on industrial trials. These two WBA resins have epoxy polyamine backbones and the vendors state that no significant leaching of other parameters has been observed. In addition to the two WBA resins, up to three SBA resins that can be operated in single-pass mode (i.e., without brine regeneration) will be tested. The SBA resins offer a lower number of bed volumes treated but also a lower material cost and no pH adjustment, which may make them attractive for small wellhead treatment systems.

Pilot testing will also include evaluation of two adsorptive media for Cr(VI) removal efficacy. One of the adsorptive media (sulfur modified iron, or SMI) showed promise in Glendale's Phase I bench-scale testing but was not ready for pilot testing in Phase II due to operational issues with the media. SMI media has reportedly evolved and is being implemented for nitrate removal elsewhere. The other media (North American Höganäs Cleanit®) is a new approach using a permeable iron composite material. Entire system needs for all of the tested media will be assessed, including any pre- and post-treatment, residuals waste disposal, labor requirements, and costs.

The Phase IIIB study is intended to provide water utilities with effective, simple treatment technologies for removal of Cr(VI), particularly for potential wellhead installations that require minimal operations. Cost curves for different influent concentrations and potential maximum contaminant levels (MCLs) will be developed for use by EPA and CDPH in setting an MCL for Cr(VI) to supplement the cost determinations in the Glendale research.

3.6 Introduction to Phase IIIC Supplemental Demonstration Testing (Future)

It was anticipated that the Phase IIIB pilot research effort would identify resins or media needing further testing at a larger scale to identify or confirm design and operational issues not encountered on a pilot scale. The proposed Phase IIIC project would conduct supplemental demonstration testing, such as using existing ion exchange vessels and pH adjustment equipment if an alternative WBA resin is successful in pilot testing. However, the decision was made to not proceed with this effort at this time due to lack of funding.

3.7 Remaining Project Schedule

The Phase III Demonstration study was officially complete as of December 31, 2011. The two demonstration-scale treatment facilities became operational in April 2010, and the demonstration testing was originally intended to be complete in one year from startup. The addition of follow-up studies, including the Phase IIIA Microfiltration study completed in 2012 and the Phase IIIB Additional Resins and Adsorptive Media Pilot study now underway have caused an extension in total project completion.

4. Phase III Demonstration Testing

This section describes the planning for and execution of the Phase III Demonstration testing, and serves as the final report for the EPA State and Tribal Grant (STAG) project conducted in Phase III.

Planning for the Phase III Demonstration study included (1) development of Experimental Plans and Quality Assurance Project Plans (QAPPs) to delineate testing goals and methods, (2) permitting to comply with State and local requirements, (3) the design-build procurement process, (4) design drawings, specifications, health and safety plans (during construction and operation), contingency plans detailing responses, and (5) operations and maintenance (O&M) manuals and startup plans. The following subsections provide a highlight of each of these components and references to the whole documents that are provided in the Appendices to this report.

4.1 Research Plan and Implementation

Planning for Phase III Demonstration testing began with the development of Experimental Plans for both the RCF and WBA processes. To fulfill USEPA requirements of the Phase III STAG grant, QAPPs were produced for each facility. An overview of the Experimental Plans and QAPPs is provided in Section 4.1.1. The City of Glendale obtained necessary permits for the new treatment facilities, including NEPA and CEQA compliance as described in Section 4.1.2.

Following planning and permitting, the City of Glendale held a competitive process to select a firm to design and build the two treatment facilities through a DB process. AECOM was selected for DB of both facilities, and they teamed with Layne Christensen to design and provide components for the RCF process. The DB process is described in Section 4.1.3. AECOM prepared design drawings and specifications (Section 4.1.4), as well as operations and maintenance plans and health and safety plans for the facilities (Section 4.1.5).

4.1.1 Experimental Plan and Quality Assurance Project Plan

The Experimental Plans for the WBA and RCF systems were prepared in 2007 and 2008, respectively. The Plans were intended to provide details necessary for the design of the demonstration-scale facilities. Components included in both Plans included:

- Identification of the facility flow rate and location for the system
- Description of the process components, including a Process Flow Diagram
- Statement of Phase III Demonstration study objectives
- Overview of data collection and monitoring procedures

- Necessary components of the O&M manual
- Initial facility operational evaluation (e.g. pump curves and corrosivity analysis for the WBA system; operational optimization strategies for the RCF system)
- Identification of information to collect for facility cost evaluations

The full Experimental Plans are included as Appendix J for the WBA system and the RCF system.

In parallel with preparation of the Experimental Plans, detailed QAPPs were written for each facility and submitted to the USEPA in 2008 (Appendix K). In accordance with guidance from the USEPA on QAPP preparation (USEPA, 2002), the QAPPs for the WBA and RCF facilities include the following elements:

- Project Management (including project organization, key points of contact, and responsibilities of project participants),
- Data Generation and Acquisition (including experimental design, sampling procedures, testing and measurement protocols, quality assurance and quality control, data management),
- Assessment and Oversight (data audit schedule, corrective action procedures, and implementation of corrective action), and
- Data Validation and Usability (data reporting, reduction, and validation).

Together, the Experimental Design and QAPP documents provided the basis of design for the demonstration facilities, as well as the O&M manual and sampling plan.

Prior to the design-build of the facilities, the Glendale Respondents Group (GRG) decided to support a switch from acid for pH reduction at the WBA facility to carbon dioxide out of concern for safety, as the treatment facility is next to residences. An analysis of carbon dioxide doses and cost compared with acid was conducted, as described in a technical memorandum attached as Appendix L (Russell et al., 2007).

4.1.2 Permitting

The Phase III Demonstration study required a number of permits, including permits prior to construction and those required to bring the constructed facilities into the existing potable water service. The list below provides a summary of the permitting actions undertaken as part of Phase III.

4.1.2.1 California Environmental Quality Act (CEQA)/National Environmental Policy Act (NEPA) Permitting

- Environmental Assessment (EA), Negative Declaration (ND), and Initial Study for the Chromium 6 Demonstration Sites, prepared August 2007.
- Notice of Intent to adopt a ND, EA, and Finding of No Significant Impact (FONSI) filed with LA County Clerk on September 7, 2007.
- Glendale City Council approved Resolution 08-143 certifying and adopting a mitigated negative declaration, mitigated monitoring program, and EA/FONSI for the two demonstration-scale Cr(VI) treatment systems, August 19, 2008.
- Notice of Determination filed with LA County Clerk on September 16, 2008.

4.1.2.2 Building and Fire Permits

Because these facilities were constructed under federal Superfund projects, they were exempt from many permit requirements. As such, both the WBA and RCF facilities did not require specific building permits. However, the City was required to comply with applicable laws as shown below.

- WBA – Los Angeles Fire Prevention Bureau, Technical Section. Hazardous Waste and Hazardous Materials Management Program, Los Angeles Certified Unified Program Agency (CUPA). Filed as potential Hazardous Waste Generator due to chromium and uranium in spent resin.
- RCF – Glendale Fire Department, Fire Protection Permit for above ground storage tank (CO_2).
- RCF – Onsite Hazardous Waste Treatment Notification, storage of ferrous sulfate and polymer, generation of hazardous waste.

4.1.2.3 CDPH Water Supply Permit Amendment

- Application submitted on May 14, 2009 to amend the City's Domestic Water Supply Permit to install a WBA chromium removal demonstration facility at the GS-3 Well before VOC treatment.
- CDPH prepared an Engineering Report dated December 17, 2009 to review and evaluate plans to install and operate the WBA facility.
- A permit amendment to operate the WBA facility was issued by CDPH on December 21, 2009 (Appendix M).

- CDPH issued a letter of authorization to operate the temporary RCF facility on December 16, 2009 (Appendix M).

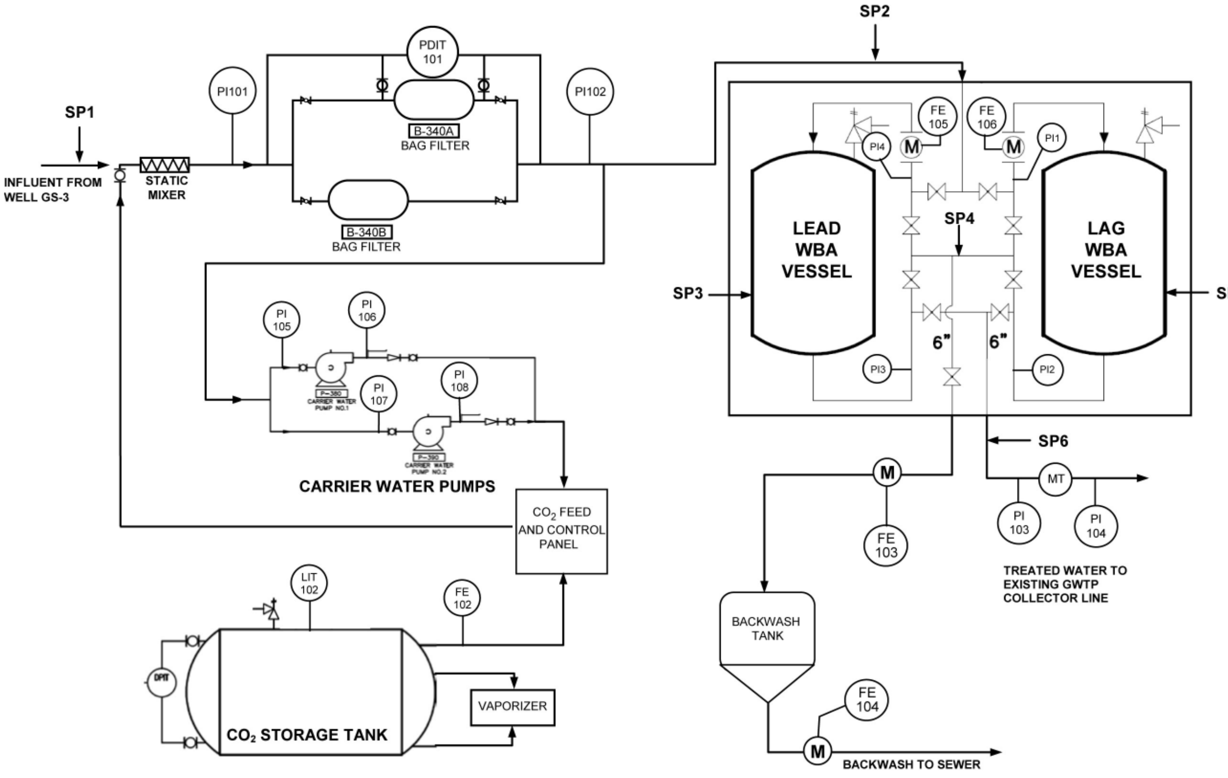
4.1.3 Design-Build Process

The City of Glendale elected to pursue a Design/Build (DB) process for designing and constructing the two Phase III Demonstration study facilities. A Request for Proposals (RFP) was issued on May 23, 2008 and proposals were due on July 3, 2008. Proposals were received from four firms, and a contract was awarded to Earth Tech by the City Council on September 9, 2008. Note that Earth Tech was subsequently acquired by AECOM, under whose name the design documents were prepared. Final design plans and specifications were submitted in May 2009, and notice of completion received from AECOM on October 27, 2010.

4.1.4 Detailed Design

Detailed design documents were prepared by AECOM for the two facilities, including general, process, civil, structural, electrical, and manufacturer drawings. In addition, process and instrumentation (P&ID) drawings and a removal plan were prepared for the WBA system. Appendix N includes the 100% design drawings for the WBA and RCF processes.

The process flow diagram and layouts for the WBA facility are shown in Figure 4-1 and Figure 4-2, including sampling points (“SP#”). The 425-gpm WBA system consists of pH adjustment using carbon dioxide and a carrier water feed system, bag filters for particle removal and to also assist in mixing CO_2 into the water, two ion exchange vessels in a lead/lag configuration, and a backwash water holding tank to allow for slow discharge of backwash water into the sewer (which is flow-constrained at the site). The system treats the entire flow from the GS-3 well. A larger well pump was required to ensure adequate flow through the vessels and delivery into the transmission main.



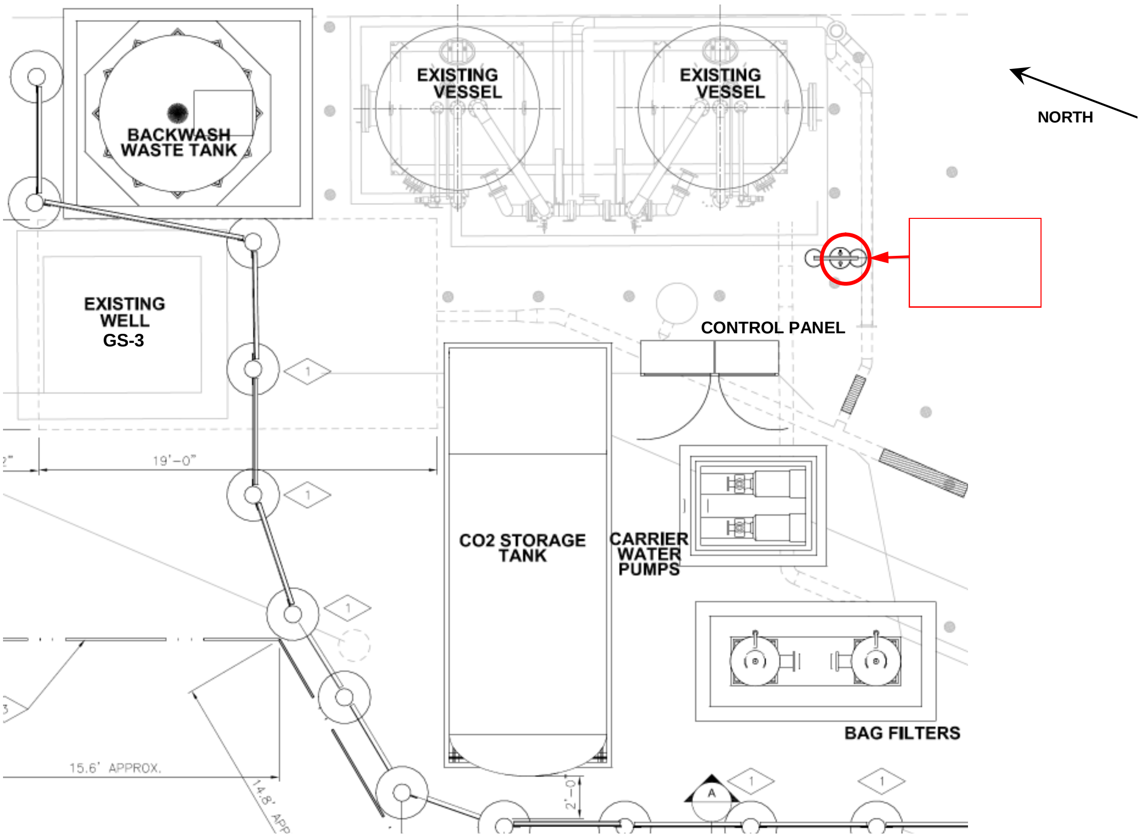
Notes:

CO_2 = carbon dioxide

GWTP = Glendale Water Treatment Plant

WBA = weak-base anion

Figure 4-1. Process Flow Diagram for the WBA Demonstration System



Note: CO_2

Figure 4-2. Site Layout for the WBA Demonstration System

The process flow diagram and layouts for the RCF facility (using granular media filtration) are shown in Figure 4-3 and Figure 4-4, including sampling point locations (“SP#”). The RCF system consists of ferrous sulfate addition with a static mixer, three reduction tanks in series (each providing 15 minutes of detention time at a system flow rate of 100 gpm), an aeration tank with a blower and PVC diffuser grid on the bottom of the tank through which air blows, granular activated carbon (GAC) off-gas treatment for the air to capture volatile organic compounds (VOCs) present in the water, a rapid mix tank into which 0.1 ppm of polymer (Magnafloc E38, a high molecular weight anionic polymer) is added, a progressive cavity pump, two 6.5 ft-diameter anthracite-sand dual media pressure filters, a settling tank for backwash solids settling (with addition of 1.0 ppm of the same polymer), and a passive dewatering phase separator. The filters were operated with 100 gpm flowing through one, while the other was offline; then the offline filter was operated while the first went into backwash. Water from the backwash water settling tank was recycled to the head of the plant during initial operations until bacterial counts (caused by other issues, as described in Section 4.3.3) led to elimination of the recycle for the demonstration tests. Water for backwashing the filters was obtained from the raw water transmission main in an effort to avoid introducing chlorine into the process, in case Cr(III) remaining on the filters would be reoxidized. Note that later Phase IIIA testing indicated that a small chlorine dose tested (i.e., a residual of less than 0.2 mg/L before filtration) was not problematic.

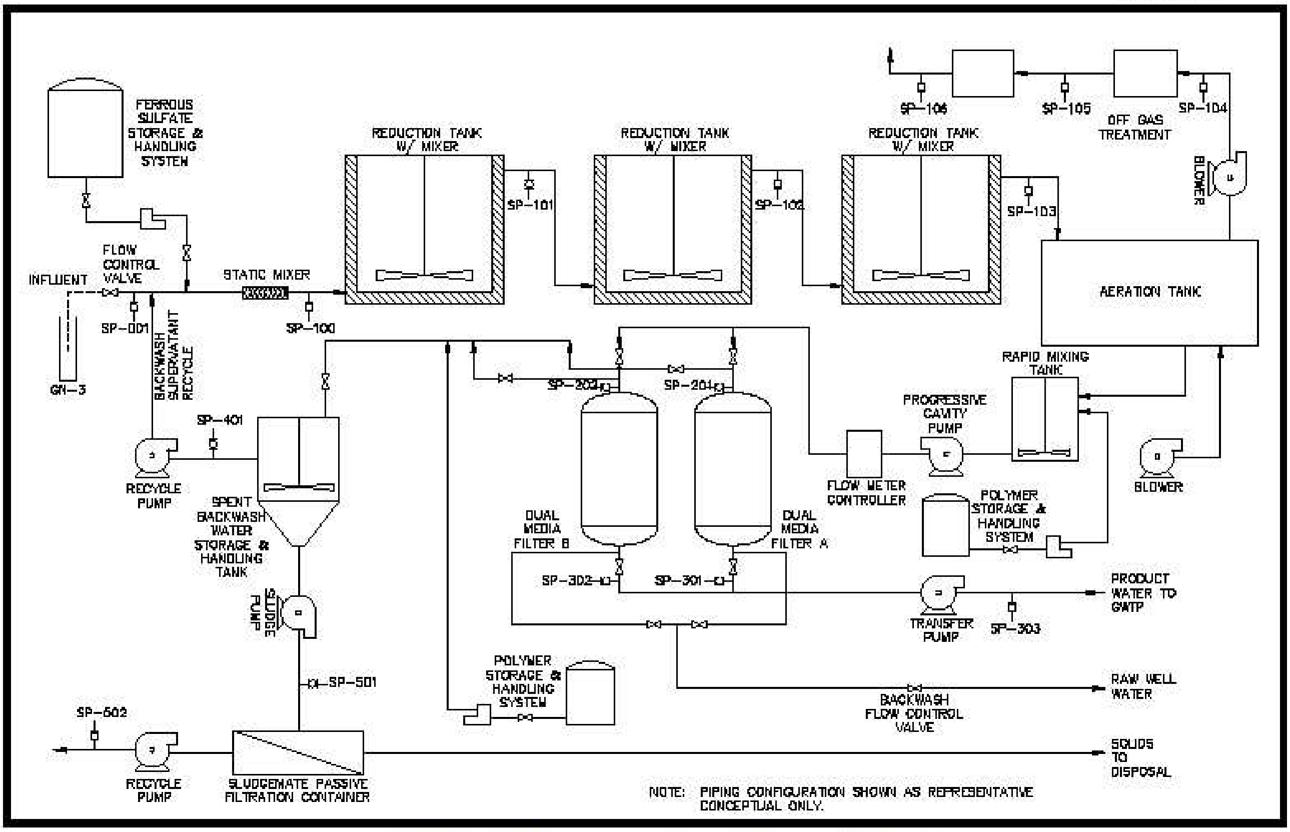


Figure 4-3. Process Flow Diagram for the RCF Demonstration System with Granular Media Filtration

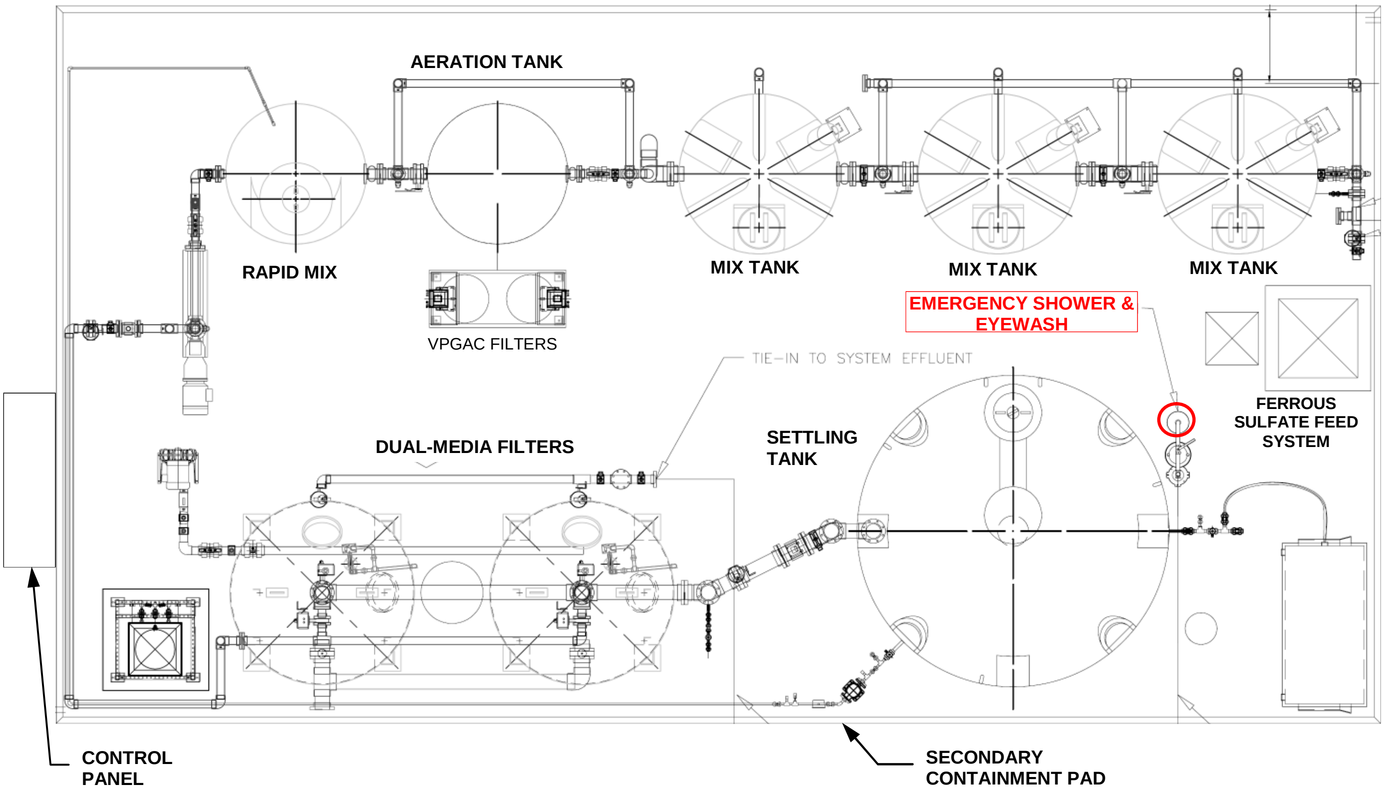


Figure 4-4. Site Layout for the RCF Demonstration System

Specifications for the construction of the two facilities were prepared by AECOM as part of the DB process. Components in the specifications included general requirements, sitework, concrete, finishes, equipment, mechanical, and electrical. The detailed construction specifications are included in Appendix O.

Task Hazard Assessments (THAs) were also developed for construction-related activities, including back filling, clearing and grubbing, confined space entry, earth moving, excavation, erosion control, geophysical survey, pre-fieldwork activities, soil sampling, and surveying. The THAs are included in Appendix P.

4.1.5 Health and Safety Plans

In addition to the detailed design drawings and specifications, ancillary plans were developed as part of the DB process. Contingency Plans were developed to provide response procedures for process failures, damage caused by external forces, chemical releases, corrective actions, preventative actions, and facility and emergency contact information (Appendix Q).

A detailed Health and Safety Plan developed for the study (Appendix R) included health and safety procedures, hazard assessments, activity specific requirements, personal protective equipment guidelines, site control measures, emergency response planning, materials safety data sheets (MSDS) for chemicals used on site, Task Hazard Assessments (providing safety information on monitoring, media replacement, confined space entry, chlorine disinfection, and radiation safety), and safety standard operating procedures (SOPs; identifying necessary safety equipment, physical hazards, operational safety procedures, and other safety considerations).

4.1.6 O&M Manuals

A key component of the DB contract was the production of O&M Manuals. The O&M Manuals were written for each of the facilities and are included in Appendix S.

Key components of the O&M Manuals include:

- Facility operating parameters – design flow rates, chemical doses, filter headloss maxima
- Sewer discharge limits
- Personnel and staffing requirements
- Facility description
- Process monitoring and control, including instrumentation equipment and control setpoints and actions triggered by reaching the setpoints
- Facility start-up and shutdown procedures, including short and long-term shutdowns
- Valving configurations
- Emergency shutdown procedures
- Monitoring and sampling plan based on the Experimental Design and QAPP documents
- System maintenance, including preventive maintenance, routine duties, spare parts
- Recordkeeping and reporting frequency and components
- Troubleshooting guide to operations
- Waste management

Brief Startup Plans were also developed as an appendix of the O&M Manuals to delineate roles and responsibilities, pre-operation checks, procedures to start the facilities, and initial sampling and monitoring protocols.

4.2 Data Analysis – WBA Process

Treatment effectiveness of the demonstration-scale facilities was evaluated by monitoring key chemical and process parameters at different locations in the treatment train, as described in Section 4.1.4.

4.2.1 Water Quality

To assess the performance of the PWA7 resin in chromium removal, both Cr(VI) and total Cr analyses were measured weekly in raw water, pH-adjusted water, lead bed effluent, and lag bed effluent. The target of Phase III Demonstration testing was 5 ppb Cr(VI) on the lag bed effluent, which triggered replacement of the lead bed and switching of the lag bed into the lead position. In the breakthrough curves that follow, “bed volumes” are used to reflect a normalized quantity of water treated. One bed volume corresponds to the volume of the resin bed, such that the number of bed volumes of water treated is the ratio of water throughput to the volume of resin (i.e., bed volumes treated = water flow rate x time / resin bed volume). For the Phase III Demonstration testing, one bed volume is 170 cubic feet of usable resin (a total of 185 cf was installed but a portion is not considered usable because it is below the nozzle height).

Figure 4-5 shows the influent Cr(VI) concentration and the breakthrough curves for the two vessels. Bed volumes of water treated for lead bed effluent were based on a resin bed volume of 170 cf. Bed volumes of water treated for the lag bed were based on a resin bed volume of 340 cf (lead + lag beds). Effluent exceeding 5 ppb Cr(VI) was reached after approximately 172,000 bed volumes of water treated by the initial lead vessel, corresponding to approximately 360 total days of operation (Figure 4-6). At that point, the lead bed effluent was between 15 and 20 ppb Cr(VI). After the resin in the lead vessel was changed out, the lag vessel was placed into the lead position. The total number of bed volumes of water treated by that initial lag bed was 364,000 bed volumes, or approximately 940 days of operation (including the service days before the resin changeout), when the effluent of that bed reached 14 ppb Cr(VI).

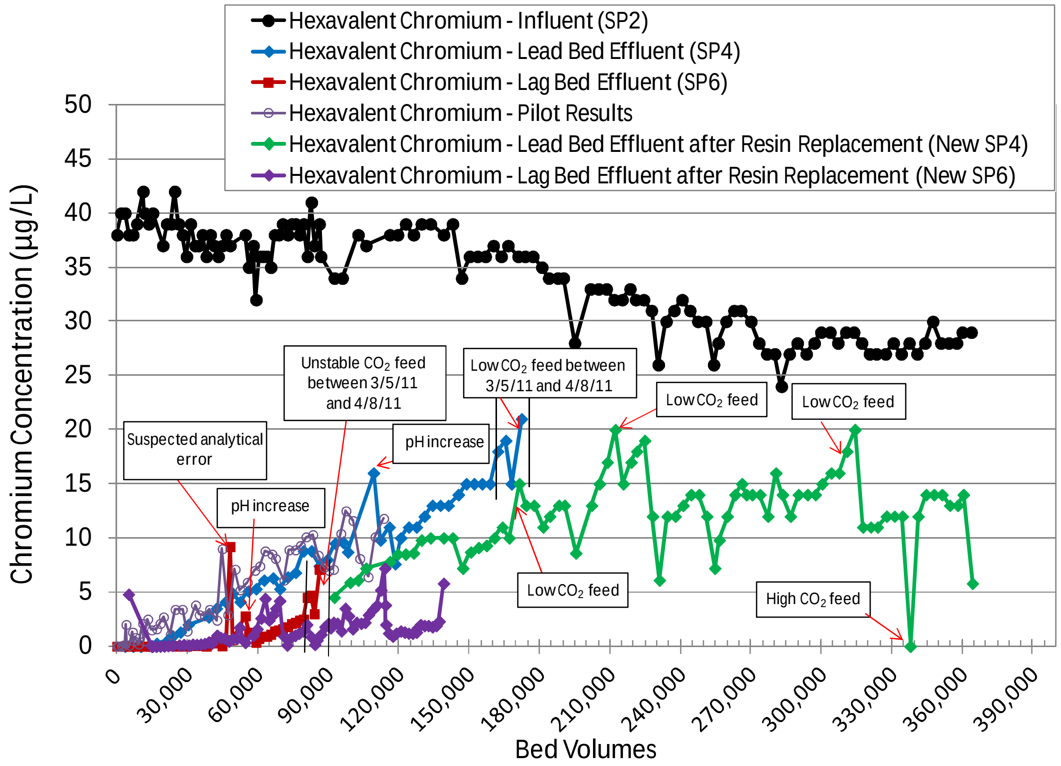


Figure 4-5.WBA Breakthrough Curves for Cr(VI) by Number of Bed Volumes

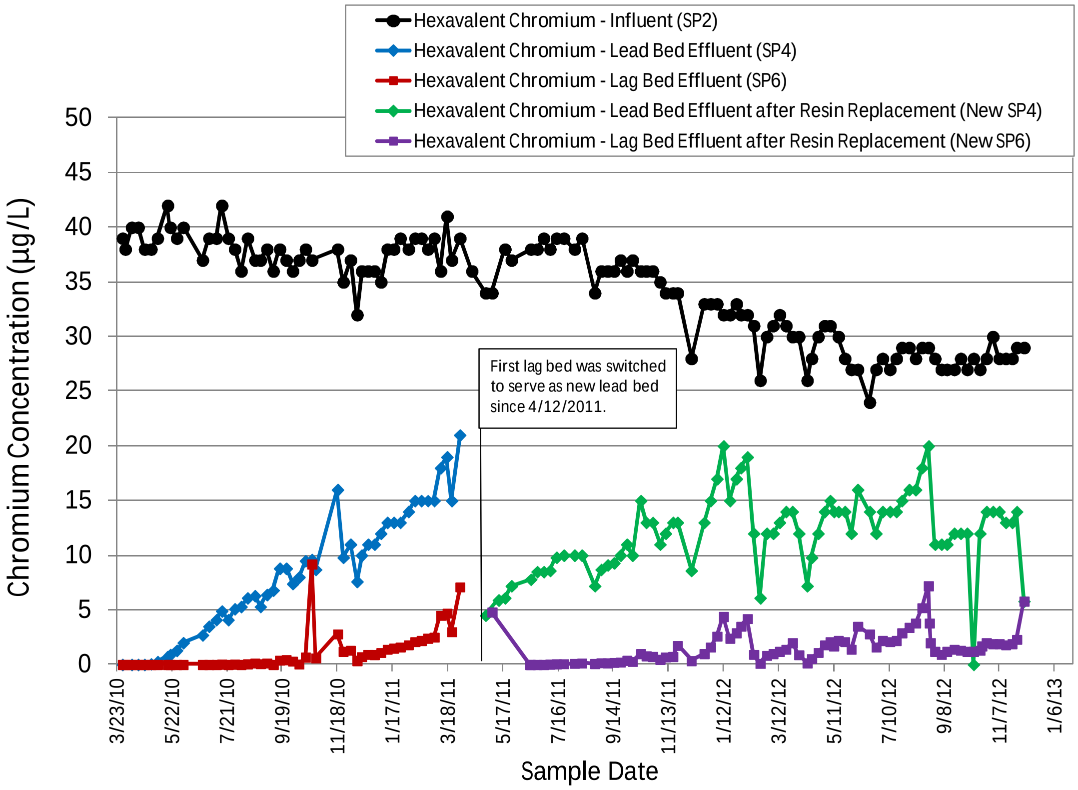


Figure 4-6. WBA Breakthrough Curves for Cr(VI) by Date

Total Cr was also closely monitored for several reasons, including (1) conversion of Cr(VI) to Cr(III) by the WBA resins, as shown in the Phase III Bridge project, (2) lack of a direct test for Cr(III), and (3) known conversion of Cr(III) to Cr(VI) by free chlorine or chloramines under distribution system conditions. Figure 4-7 provides the breakthrough curves for total Cr showing that approximately 172,000 bed volumes were treated before the effluent reached 5 ppb total Cr, which was the same as the value observed for Cr(VI). The number of bed volumes treated to reach this value corresponded to approximately 360 days of operation (Figure 4-8).

The total chromium concentration accumulated on the resin as calculated by mass balance using the breakthrough curve for the lead vessel was estimated to be 10,300 mg/kg, or 1.03% by weight. Chromium accumulation represents operation to approximately 20 ppb (i.e., 50% of the influent concentration). These results are consistent with the Phase III Bridge study isotherm testing showing approximately 1.5 to 2.0% capacity on the PWA7 (a.k.a. Duolite A7) resin, as shown in Figure 3-4.

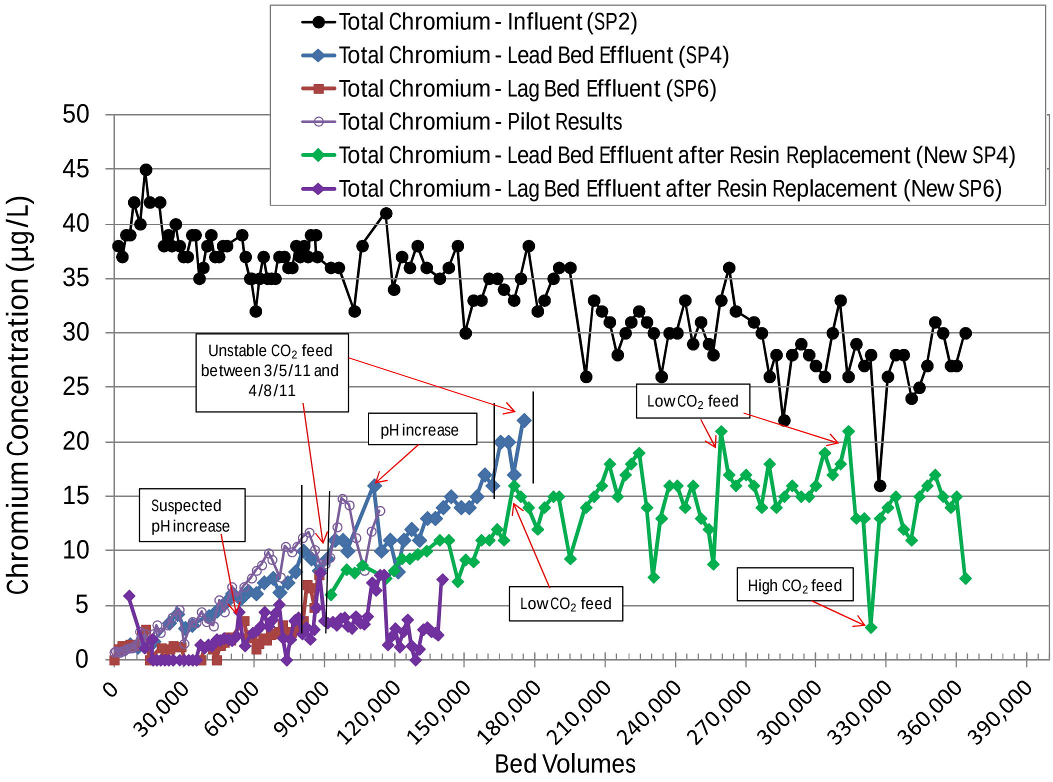


Figure 4-7. WBA Breakthrough Curves for Total Cr by Number of Bed Volumes

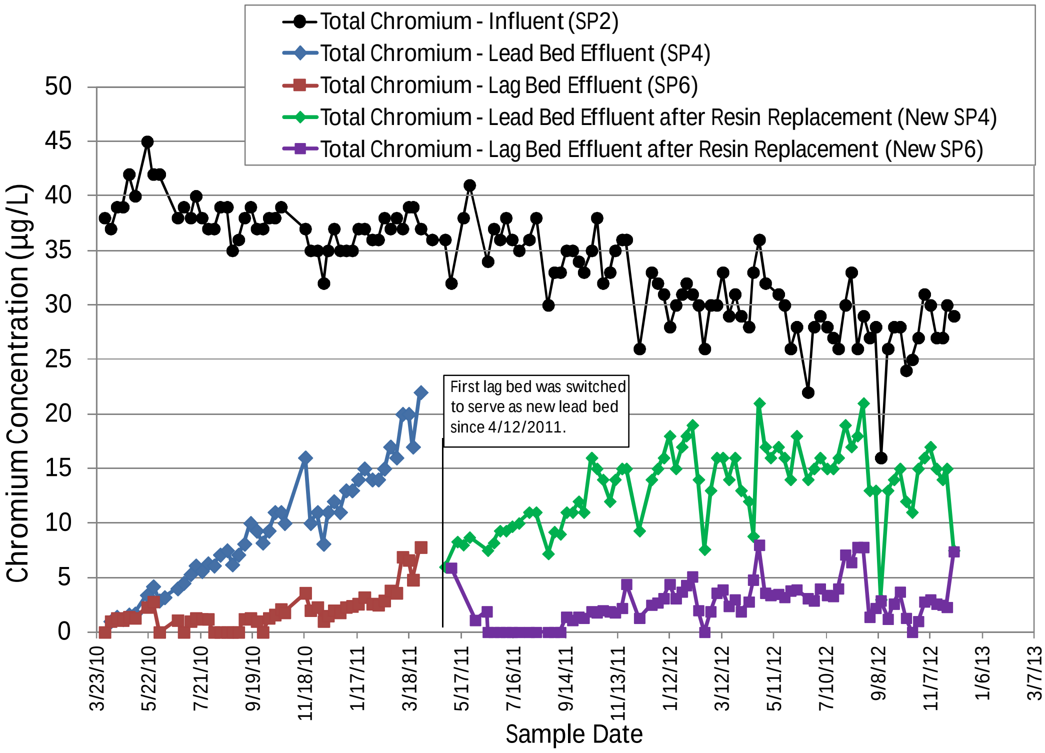


Figure 4-8. WBA Breakthrough Curves for Total Cr by Date

More variability was observed in total Cr concentrations before 5 ppb was reached when compared with Cr(VI). Table 4-1 shows the approximate number of bed volumes of water treated for the listed lag bed effluent concentrations. The observed variability may arise from more uncertainty in the total Cr method detection limits and potential method interferences for total Cr compared with Cr(VI), as well as the potential for Cr(III) leakage from the resin. Although the table provides the point at which the effluent exceeds the identified threshold, total Cr values occasionally dipped back below that threshold, indicating variability. Phase IIIA testing (Appendix H) discusses the positive bias in total Cr data that was identified as an issue for low and sub-ppb concentrations.

Table 4-1. Number of Bed Volumes of Water Treated by the Lead Vessel for Different Lag Bed Effluent Concentrations

	Approximate Number of Bed Volumes	
Effluent Concentration	**Cr(VI)**	**Total Cr**
0.02 ppb	50,000 BV	<3,300 BV
1 ppb	131,000 BV	3,300 BV
2 ppb	149,000 BV	23,000 BV
5 ppb	172,000 BV	172,000 BV

* Reporting limits used were 0.02 ppb for Cr(VI) and 1 ppb for total Cr

Other water quality parameters were also measured to determine if any impacts of WBA treatment were observed in the effluent. pH of the raw water from the GS-3 well averaged 6.8 when analyzed immediately after collection to minimize carbon dioxide offgassing. Table 4-2 provides a summary of the range and averages of other water quality values observed during Phase III Demonstration testing. Little difference was observed between influent and effluent sample averages or ranges for sulfate, nitrate, phosphate, silica, and alkalinity. Most field samples of iron were lower than 0.1 mg/L except for one influent sample (0.11 mg/L) and two effluent samples (0.14 and 0.24 mg/L). All were below the secondary MCL for iron of 0.3 mg/L, but consideration should be given to performing more iron analyses in future studies (particularly using laboratory methods rather than field screening methods) to more closely investigate any potential removal or release of iron from the resins.

Table 4-2. Summary of Additional Routine Water Quality Analyses through the WBA Process

	Influent (SP2)		Lag Bed Effluent (SP6)	
Water Quality Parameter	**Average**	**Range**	**Average**	**Range**
Temperature (°C)	20.5 (n=2)	20.3-20.7	20.3 (n=72)	17.3-23.9
Sulfate (mg/L)	93 (n=13)	91-95	93 (n=14)	91-95
Nitrate (mg/L as N)	8.7 (n=15)	8.4-9.1	8.7 (n=15)	8.5-9.1
Phosphate (mg/L as PO_4)	0.29 (n=13)	0.08-0.62	0.32 (n=15)	0.15-0.69
Silica (mg/L as SiO_2)	34 (n=14)	32-35	32 (n=15)	14-37
Iron (mg/L)	0.04 (n=13)	0.01-0.11	0.07 (n=14)	0-0.24
Alkalinity (mg/L as $CaCO_3$)	215 (n=2)	210- 220	213 (n=3)	210-220
Conductivity (µS/cm)	948 (n=18)	880-989	949 (n=14)	919-995
Turbidity (NTU)	0.29 (n=14)	0.05–0.94	0.38 (n=15)	0.06-1.2

In addition to routine water quality sampling during the Phase III Demonstration study, samples were collected to evaluate any potential contaminants that might be released from the resin at startup. Details about these analyses are provided in Section 4.2.3, including issues of simultaneous compliance.

4.2.2 Key Operational Data and Observations

The critical component for WBA operation was pH adjustment to 6.0, which was maintained using an online pH probe with alarms if values deviated beyond pH values of 5.7 on the low end or 6.3 on the upper end. The carbon dioxide dose required to achieve a pH of 6.0 was approximately 50 lbs per hour, or 233 mg/L based on a flow rate of 425 gpm. This actual rate is lower than the estimated dose of 64 lbs/day (290 mg/L) calculated using the Tetra Tech Rothburg, Tamburini, and Winsor (RTW) model. Carbon dioxide feed rate was controlled by online pH reading. Figure 4-9 displays online pH readings and carbon dioxide does (calculated based on actual carbon dioxide feed rate and water flow rate) during the demonstration-scale testing. pH was maintained in the target range of 5.7 and 6.3, except for several occasions. However, carbon dioxide dose more widely fluctuated. The median carbon dioxide dose (50th percentile) was 179 mg/L. WBA effluent Cr(VI) concentrations trended with carbon dioxide doses (Figure 4-10). When the carbon dioxide dose was relatively low, Cr(VI) concentrations tend to spike or increase. When the carbon dioxide dose was relatively high, Cr(VI) levels decreased. The results indicated that the WBA resin could accommodate some fluctuations in carbon dioxide dose, but that enhanced capacity could be achieved with a higher carbon dioxide dose (i.e., a slightly lower pH).

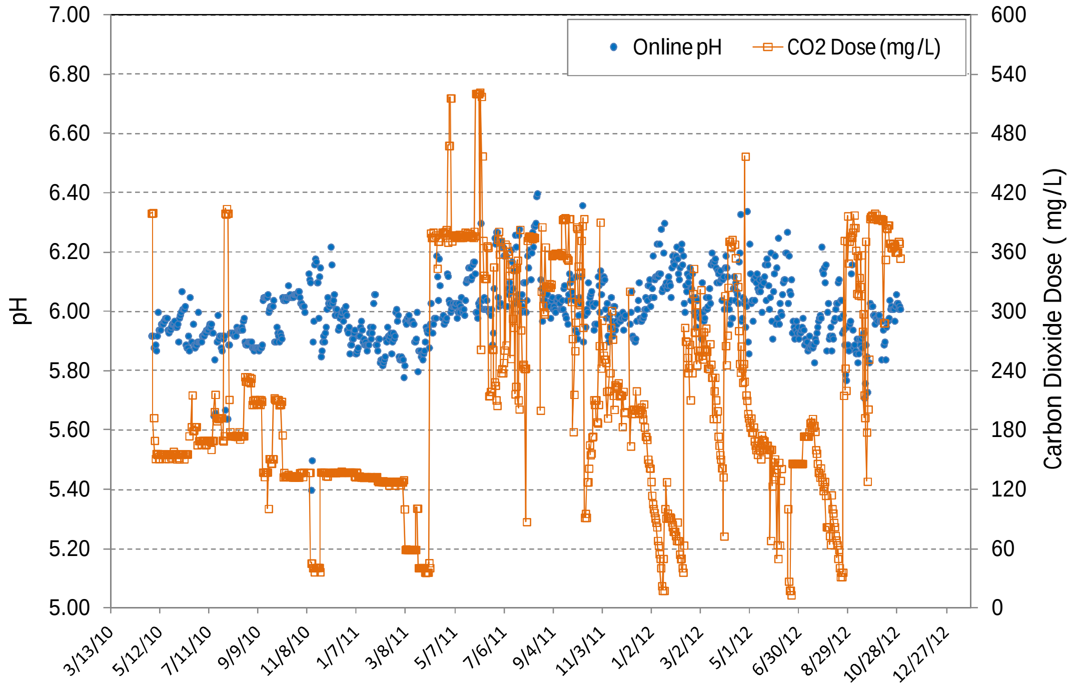


Figure 4-9. Caron Dioxide Dose and pH Online Readings during WBA Demonstration Testing

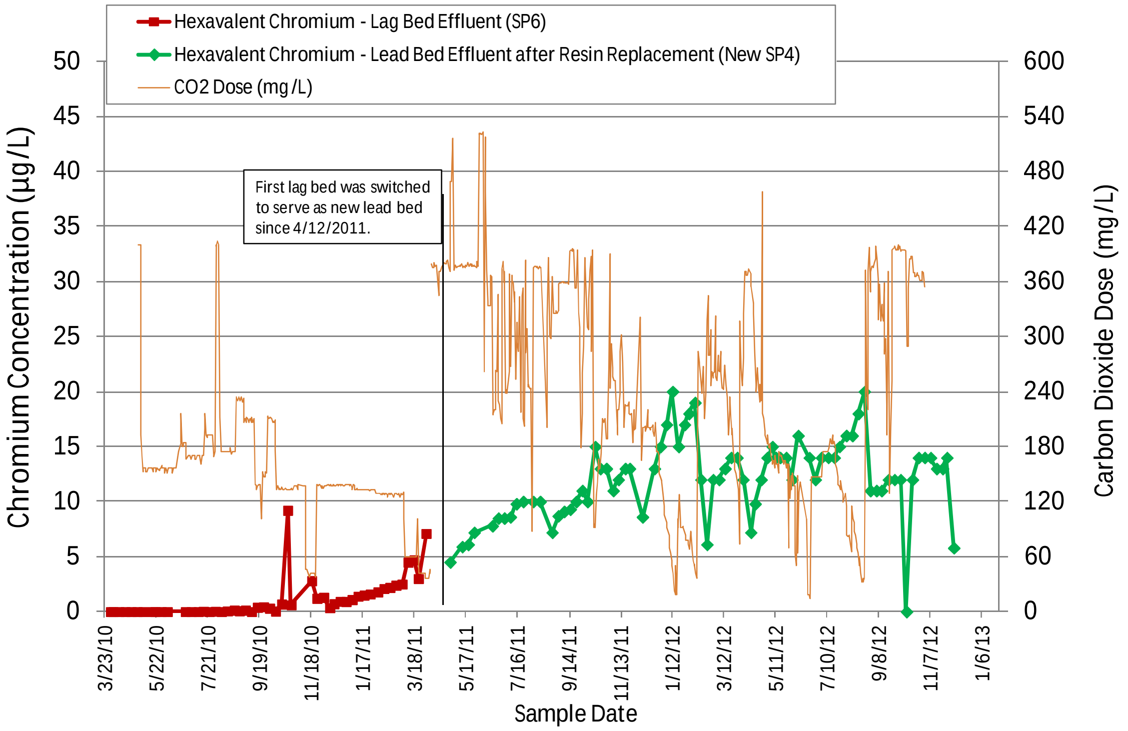


Figure 4-10. Carbon Dioxide Dose and WBA Breakthrough Curve for Cr(VI) by Date

Ten micron bag filters were used to capture solids to prevent buildup on the resin beds, and have not required replacement during the year and a half of operations to date (noting that the wells are not "sanders" with a lot of sand and silt pulled up from the aquifer). As a result of good pre-filtration and the nature of the resin, no backwashing besides the initial bed stratification backwashing step was required during a year of operation.

Operational observations about the WBA process include sound issues and ease of operations. The WBA facility is located adjacent to a neighborhood, separated from houses by a chain link fence and a two-lane street. Refilling of the carbon dioxide storage tank, which occurred approximately every 3 weeks, and the carrier water pumps to introduce the CO_2 into the water flow created significant noise that elicited complaints. Sound issues were ameliorated by enclosing the carrier water pumps and wrapping the enclosure in a sound blanket.

The WBA system in general was considered to be a much simpler operation than the RCF process, requiring approximately 1 to 2 operator hours per day for operation and checks. There were, however, major labor demands in the study due to preconditioning, start-up, and water disposal in dealing with the formaldehyde leaching. This would vary with the local wastewater discharge requirements and effectiveness of the preconditioning procedure.

4.2.3 Simultaneous Compliance Issues

Precedent for contaminant release from new resins exists for strong-base anion exchange resins in the form of nitrosamines, even though the resins may have National Sanitation Foundation (NSF) 61 certification. As a part of the Phase III Demonstration study, potential contaminants that may be released from WBA resins during startup were closely examined since the water was intended for potable use. CDPH specified the monitoring constituents in the facility's operating permit, including aldehydes, ketones, semi-volatile organic chemicals including tentatively identified compounds (TICs), and nitrosamines. These parameters were measured at the start of the testing and monthly thereafter, with all non-detects except formaldehyde and acetaldehyde (up to 240 ppb). Formaldehyde was of concern because levels exceeded the California Notification Level of 100 ppb.

In addition to formaldehyde and acetaldehyde, glyoxal and methyl glyoxal were detected in resin effluent or resin flush water. Both glyoxal and methyl glyoxal were non-detect (<10 ppb) in source water. Glyoxal was detected in lag vessel effluent in 2 out of 35 samples, and concentrations were non-detect at all other sampling locations, including resin flush water. Methyl glyoxal was only detected in lag resin effluent in one out of 35 samples at 21 ppb. No regulatory limits currently exist for glyoxal or methyl glyoxal.

During the initial startup, PWA7 WBA resin was loaded into the previously chlorinated and rinsed vessels using non-chlorinated water on November 30, 2009. The following day, resin was backwashed with three bed volumes using pH-adjusted groundwater then forward flushed for 82 minutes at 425 gpm. Vessels were then held stagnant for analyses of samples collected during the forward flush at multiple time points. Formaldehyde concentrations of 620 ppb and 900 ppb were detected in the two lag bed effluent (SP6) samples collected at 0 and 57 minutes, respectively.

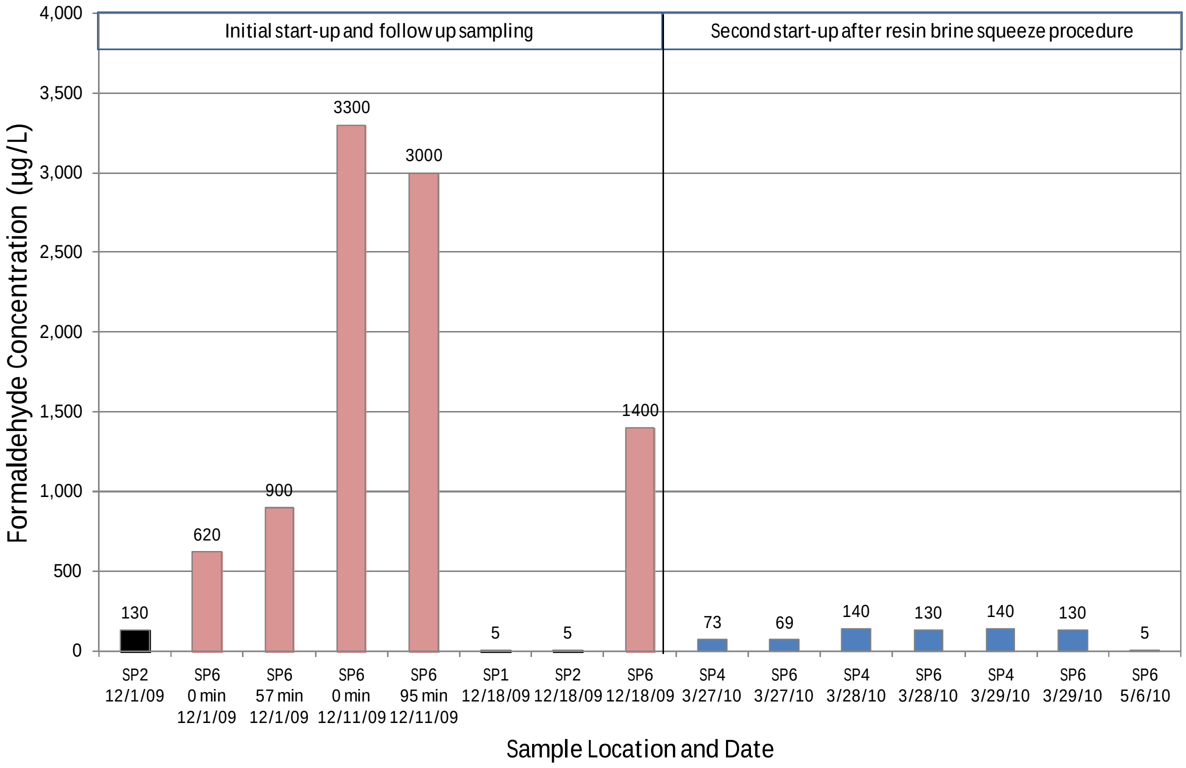


Figure 4-11.Formaldehyde Release from WBA Resin as a Function of Time and Sampling Location

Once the high formaldehyde levels were discovered (Figure 4-11), the vessels were forward flushed, and two more samples were collected at 0 and 95 minutes on December 11th to verify the formaldehyde concentrations. Even higher formaldehyde concentrations of 3,300 ppb and 3,000 ppb were detected in the two SP6 samples collected on December 11th after the resin was stagnant in the vessels for 10 days. To check the formaldehyde concentration in groundwater, a raw water sample was collected from the GS-3 well on December 16th, which contained 5 ppb of formaldehyde. To identify the formaldehyde source, another round of samples was collected from SP1 (raw water), SP2 (pH adjusted water) and SP6 (lag vessel effluent) while the vessels were forward flushed on December 18th. The results showed low levels of formaldehyde (i.e. 5 ppb) in the SP1 and SP2 samples, and a high level of formaldehyde (i.e. 1,400 ppb) in the SP6 sample.

A number of factors point to the resin as the source of formaldehyde in the treated water. First, very low formaldehyde concentrations were detected in the pH adjusted water entering the lead vessel (SP2), which showed that raw water was not the source. Second, formaldehyde levels in the lag vessel effluent initially increased and then decreased with more flushing, which could be explained by a release of formaldehyde in the resin accumulated during stagnation. Third, the resin had a phenol-formaldehyde backbone structure.

The resin was removed from the vessels and transferred to the Siemens Washington Avenue Facilities in Los Angeles for removal of formaldehyde and disinfection, since HPC increased in the water during vessel stagnation. Corrective procedures for disinfection and removal of excess formaldehyde were developed for the resin, consisting of water flushes, 4% caustic wash followed by 5% hydrochloric acid wash, repeated caustic and acid washes once (cross regeneration procedure). The procedure required more than one day of processing. The objectives were to achieve a formaldehyde concentration below 100 ppb, negative total coliform and E. Coli, and HPC below 500 CFU/mL before Glendale would accept the resin at the site.

Each vessel of resin was treated separately during the period of March 23 through 25, 2010. Resin effluent was sampled and analyzed for formaldehyde, total coliform, E. coli and HPC during the treatment process. While awaiting lab results, the resin was flushed with water at a minimum flow rate of 30 gpm to prevent bacterial contamination that could arise from storing the resin. After treatment, formaldehyde concentrations in the resin effluent were reduced to 78 ppb and 28 ppb for the two beds.

Following treatment, the resin was transported back to the study site and reloaded into the disinfected vessels on March 27, 2010. During the second start-up, the resin in both vessels was backwashed then forward flushed. Formaldehyde was monitored during the restart. Raw well water was continuously run through the vessels after the second start-up began. Formaldehyde samples were collected from SP4 and SP6 daily from March 27th to March 29th, 2010. The results were in the range of 69 ppb to 140 ppb, which were much lower than the first start-up. Subsequently, formaldehyde was monitored at SP6 on a monthly basis, and all samples (May through August 2010) contained 5 ppb of formaldehyde or less.

After approximately one year of operation (April 2010 to April 2011), the lead bed resin was disposed and replaced with new resin in April 2011. The new resin was preconditioned at the Siemens Washington Avenue Facility using “hot water wash” of approximately 20 bed volumes at 130 °F followed by water wash of approximately 20 bed volumes at ambient temperature, without caustic and acid rinses. Formaldehyde in preconditioned resin effluent was 89 ppb using Hach method 8110. The preconditioned new resin was then loaded to the vessel at GS-3 on April 28, 2011. Higher formaldehyde levels (335 ppb and 651 ppb using Hach method 8110 on April 28 and 1,500 ppb by lab analysis on April 29) were detected in the new resin effluent at the plant. On May 2, 2011, formaldehyde concentrations in new resin effluent were 870 ppb and 917 ppb using the Hach method, while the raw water and the previous lag bed effluent (switched to serve as lead at the time) contained no formaldehyde. The new resin bed was flushed with water for approximately one month until June 2011. Formaldehyde levels decreased to 106 ppb on June 9, 2011. This resin replacement experience suggests the “hot water wash” preconditioning procedure was not effective for permanent formaldehyde removal. Subsequent bench testing by Dow on PWA7 resin confirmed that the cross regeneration procedure is currently the best option for reducing formaldehyde concentrations.

No increase in formaldehyde concentration was observed in cross regenerated resin effluent during a temporary plant shutdown in December 2011, indicating that the formaldehyde leaching did not continue once it was flushed from the resin.

In December 2012, the lead bed resin (previously served as lag bed) was disposed and replaced with fresh resin. The fresh resin was pre-conditioned at the Siemens Washington Avenue Facility using 0.4% caustic soda and 5% hydrochloric acid washes only once and with caustic soda first rather than second, compared with two cycles of caustic and acid washes in 2009. Formaldehyde was 169 ppb in the sample collected at the Siemens Facility before the pre-conditioned resin was loaded into the vessels at Glendale on December 5, 2012. After the resin was backwashed and forward flushed, formaldehyde in resin effluent was 540 ppb on the same day. Formaldehyde levels gradually decreased to below 100 ppb (i.e. 99 ppb) after 11 days of operations (with water diverted to the Los Angeles River).

The recent resin replacement experience suggests the pre-conditioning procedure without a true cross regeneration procedure was not as effective. Dow is currently conducting lab testing to optimize the resin conditioning procedures. However, a utility considering using the PWA7 resin should consider the potential need for disposal of significant quantities of water or exceedance of the formaldehyde Notification Level if the cross regeneration procedure is not fully effective.

4.2.4 Residuals Volumes and Characterization

Phase III Demonstration testing revealed that the spent WBA resin was classified as a non-RCRA hazardous and TENORM waste for disposal in California as anticipated based on Phase III Bridge project findings (Section 3.4.1) . A thorough analysis of the resin classification and disposal options is provided in Appendix G as part of the Phase III Residuals study.

The volumes of WBA residuals generated included 185 cubic feet of resin after approximately 360 days of operation for the lead vessel. The 3.3 tons of resin was comingled with 12 tons of bentonite clay (i.e., absorbent material) to sequester free liquid. Siemens in partnership with US Ecology provided turn-key service to remove the resin from the vessel, comingle the residuals with absorbent material, and transport the material to the Grandview RCRA waste landfill in Idaho. Uranium concentrations in the aggregated resin were 150 mg/kg (0.015%) and 330 mg/kg (0.033%) in two disposal bins, which is below the regulatory limit of 0.05% to trigger radioactive waste categorization.

4.2.5 WBA Resin Availability

The WBA resin (Amberlite™ PWA7) tested in the Glendale Phase III Demonstration study was found to leach formaldehyde during operation as described above. The manufacturer once indicated that resin production would be discontinued due to the formaldehyde issue. However, the manufacturer conducted further research afterwards and reported that resin preconditioning procedures consisting of acid and caustic rinses (cross regeneration) can effectively remove excess formaldehyde. Thus, the resin will continue to be manufactured and is available on the market. However, the mechanism triggering formaldehyde release remains unknown. Recently, several other potential WBA resins showing promising results in industrial settings have become available and are being tested in Phase IIIB (discussed in Section 3.5).

4.3 Data Analysis – RCF Process

Treatment effectiveness of the RCF demonstration-scale facilities was evaluated by monitoring key chemical and process parameters at different locations in the treatment train, as described in Section 4.1.4.

A number of variables were tested with the RCF system (Table 4-3), including the amount of reduction time (15, 30, or 45 minutes), the presence of aeration after reduction, filter run times (24, 48, or 72 hours), Fe:Cr(VI) mass ratio (25:1, 50:1, 75:1), and influent Cr(VI) concentration (approximately 75-80 ppb and 11 ppb). The higher concentration of 75-80 ppb was achieved by taking a 100 gpm side stream of the GN-3 water before mixing into the Glendale North (GN) transmission main water (with 5-15 ppb Cr(VI) levels) . During weeks 35 to 41, influent water piped from the GN transmission main was used to represent a lower Cr(VI) concentration, although concentrations fluctuated between approximately 4 and 82 ppb and effluent results varied. Consequently, this lower influent concentration test condition was performed again during weeks 54-55 at a higher sampling frequency and with tighter controls on influent concentrations.

During the first several months of testing, total Cr effluent concentrations were not as good as observed in Phase III Bridge pilot testing (i.e., less than 1 ppb). The team performed troubleshooting of the system and found that the PVC grid through which air bubbles in the aeration tank flowed had partially clogged holes due to iron precipitation. Consequently, weeks 4 through 17 are conservatively categorized as “no aeration” since the point at which the grid clogged is not known. A significant lesson learned in the testing is the importance of visually inspecting the aeration tank bubble production, since the operation of the blower into a closed tank did not indicate a problem with clogging yet the grid holes were occluded when the tank cover was removed. Subsequently, larger holes were drilled in the PVC on two occasions, settling on a size of approximately 0.5 inches in diameter to avoid clogging.

Table 4-3. Matrix of Experimental Conditions for Runs during RCF Operations

1 - 3	4/13/10 – 5/3/10	1	65 – 70 ppb	45 min.	No	25:1	24 hrs	
14	7/13/10 – 7/19/10	3	75-80 ppb	45 min.	Maybe	30:1	48 hours starting 7/14	
18-20	8/10/10 – 8/30/10	5	75-80 ppb	45 min.	Yes	35:1	48 hours	Discovered no bubbles on 8/9; redrilled holes
26	10/1/10 – 10/6/10	7	75-80 ppb	45 min.	No	25:1	48 hours	

Weeks	Dates	Run Number	Optimization Variables					
			Approx. Raw Cr(VI) Conc.	Reduction Time	Aeration Step?	Fe:Cr(VI) Mass Ratio*	Filter Run Length	Other
30-32	3/9/11- 3/27/11	9	75-80 ppb	30 min.	Yes	25:1	48 hours	
33-34	5/19/11-5/31/11	10	75-80 ppb	45 min.	Yes	25:1	48 hours	
35-39	6/1/11-7/6/11	11	Fluctuating (4 – 80 ppb)	45 min.	Yes	25:1	48 hours	
40-41	7/7/11-7/17/11	12	Fluctuating (79 – 82 ppb)	45 min.	Yes	75:1	48 hours	
42 - 44	7/19/11- 8/10/11	13	75-80 ppb	15 min.	Yes	25:1	48 hours	Collected 3 sample sets per week
45 - 46	8/11/11- 8/23/11	14	75-80 ppb	45 min.	Yes	50:1	48 hours	Collected 3 sample sets per week
47 - 48	8/24/11- 9/3/11	15	75-80 ppb	30 min.	Yes	50:1	48 hours	Collected 3 sample sets per week
48 -49 (cont'd)	9/12/11 - 9/19/11	15	75-80 ppb	30 min	Yes	50:1	48 hours	Collected 3 sample sets per week

Weeks	Dates	Run Number	Optimization Variables					
			Approx. Raw Cr(VI) Conc.	Reduction Time	Aeration Step?	Fe:Cr(VI) Mass Ratio*	Filter Run Length	Other
50 -51	9/20/11 – 10/3/11	16	75-80 ppb	45 min.	Yes	50:1	48 hours	Collected 3 sample sets per week
52 – 53	10/4/11 – 10/17/11	17	75-80 ppb	45 min.	Yes	25:1	Run one filter for a longer period (72 hrs)	Collected 3 sample sets per week
54-55	10/18/11 – 10/31/11	18	10 – 15 ppb	45 min	Yes	50:1	48 hours	Collected 3 sample sets per week

*Ferrous dose can be calculated by multiplying raw Cr(VI) concentration with Fe: Cr(VI) mass ratio.

4.3.1 Water Quality

Influent raw water quality to the RCF system is characterized in Table 4-4. As demonstrated in the Phase III Residuals study (Section 3.4.3 and Appendix G), key parameters shown to impact the RCF process include pH and silica. The water was also characterized for other parameters in case other constituents are found to impact performance in subsequent studies.

Table 4-4. Summary of Influent Water Quality Data for the RCF Demonstration Process

Water Quality Parameter	Influent Concentration or Level	
	Average	Range
Alkalinity as $CaCO_3$ (mg/L)	260 (n = 19)	240 - 270
Arsenic (ppb)	1.1 (n = 19)	1.0 – 1.8
Conductivity (µMho/cm)	976 (n = 2)	910 – 1,042
Chloride (mg/L)	57.5 (n = 2)	57 - 58
pH	7.7 (n = 73)	6.9 – 8.1
Phosphate as PO_4 (mg/L)	0.26 (n=1)	Not applicable
Silica as SiO_2 (mg/L)	30 (n = 3)	29 - 31
Sulfate (mg/L)	95 (n=2)	94 - 96
Temperature (°C)	20.9 (n = 119)	18.1 – 25.5
Total Iron (mg/L)	0.03 (n = 22)	<0.01 – 0.08
Turbidity (NTU)	0.26 (n = 15)	0.06 – 0.78

To assess the performance of the RCF system in chromium removal, both Cr(VI) and total Cr analyses were measured at least once per week at multiple locations in the treatment process, including influent, post-ferrous addition, reduction tank effluents, aeration tank effluent, and filter effluent.

The overall effectiveness of the RCF process is depicted in Figure 4-10 and 4-11 for Cr(VI) and for total Cr. Cr(VI) effluent concentrations ranged from below the MRL (<0.02 ppb) to 0.19 ppb throughout testing of 45 minutes of reduction time[1], with the

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[1] Data from weeks 35 to 41 when influent concentrations fluctuated and Fe:Cr(VI) dosing was not properly controlled are excluded.

exception of two outliers of 2.2 ppb and 1.9 ppb. Paired samples collected to measure total Cr concentrations ranged from below the MRL (< 1 ppb) to 5.1 ppb[2], with the exception of three outliers of 7.1 ppb, 7.1 ppb and 29.5 ppb. The data indicate that the RCF process is effective at reducing Cr(VI) to less than 1 ppb with 45 minutes of reduction time even without aeration, but that total Cr removal to levels consistently below 4 ppb required oxidation (such as by aeration). Iron to Cr(VI) ratios of 25:1 to 35:1 were sufficient for good total Cr removals for the limited number of sampling points obtained.

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[2] Ibid.

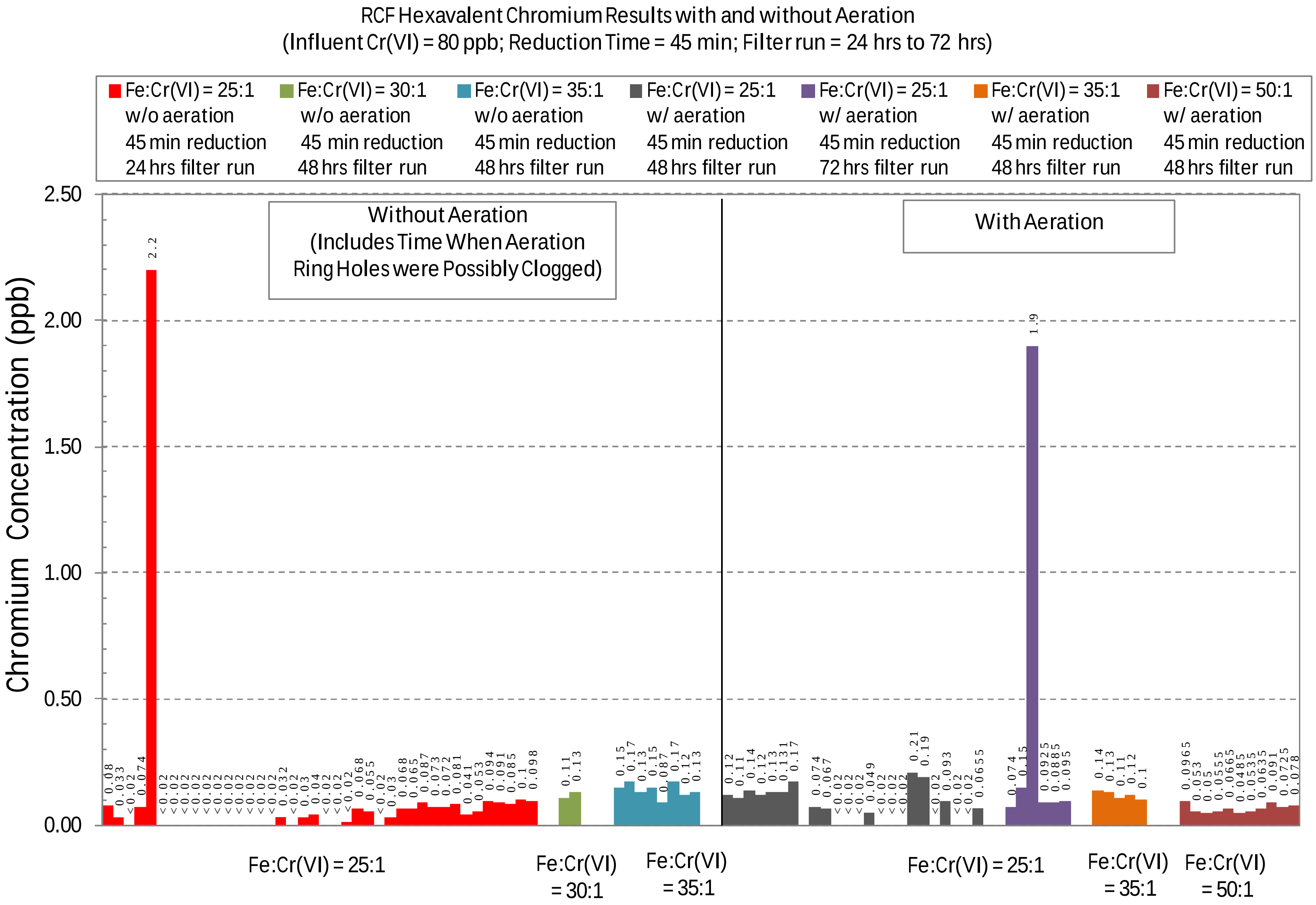

Figure 4-12. Cr(VI) Concentrations in RCF Process Filter Effluent – 45 minute Reduction Time

Note: Two samples collected on 5/17/2010 were not included, which were suspected to be impacted by filter backwash and contained Cr(VI) of 1.5 ppb and 2.1 ppb.

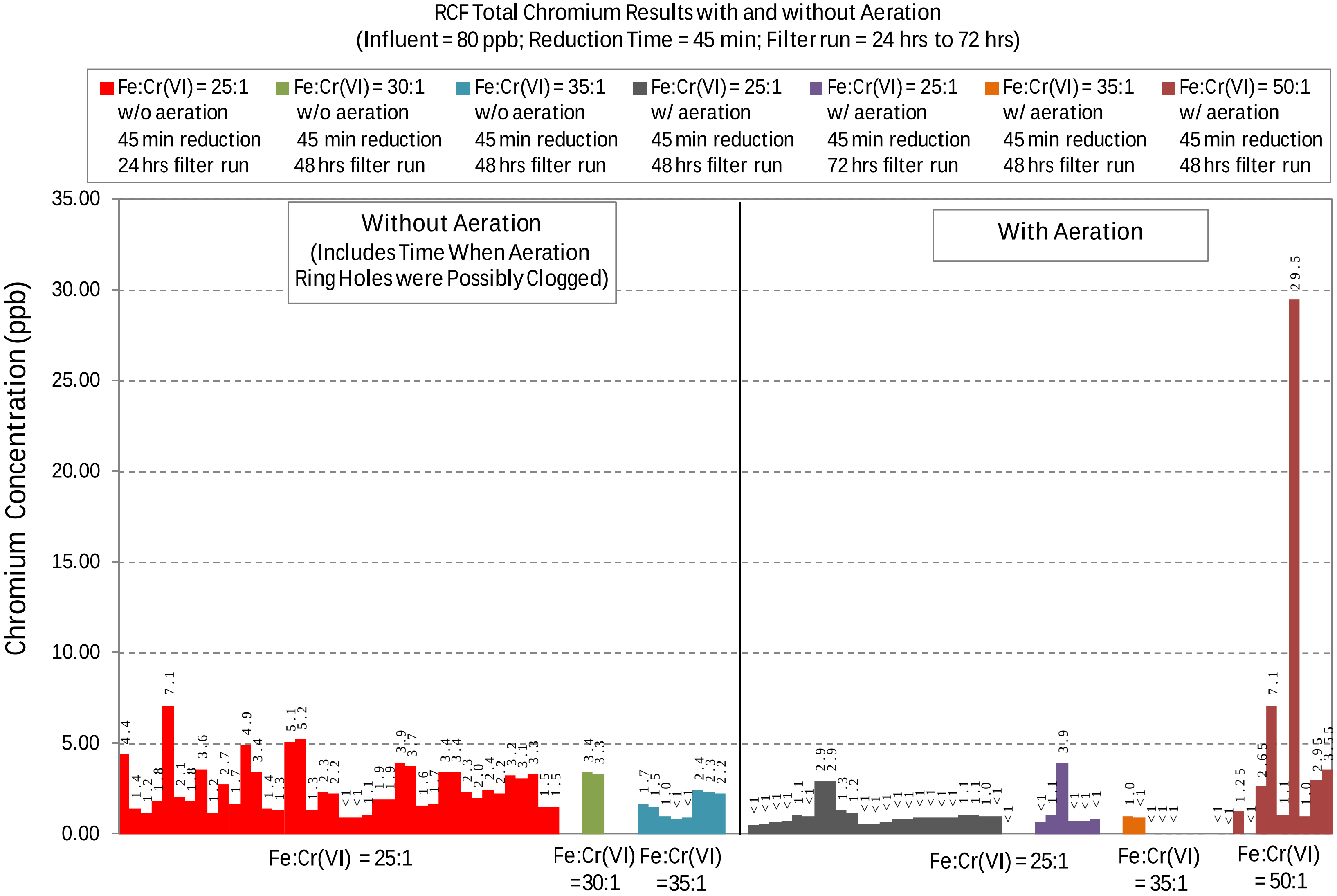

Figure 4-13. Total Cr Concentrations in RCF Process Filter Effluent - 45 minute Reduction Time

Notes: Two samples collected on 5/17/2010 were not included, which were suspected to be interfered by filter backwash and contained total Cr of 6.2 ppb and 5.2 ppb.

The impact of reduction time on the RCF process was tested in Phase III, holding the Fe:Cr(VI) ratio variable constant. Figure 4-14 shows Cr(VI) filter effluent concentrations for 45 minutes, 30 minutes, and 15 minutes of reduction time (i.e., three, two, or one tank in series) with influent Cr(VI) concentrations of 75 – 80 ppb and filter run times of 48 hours with aeration. Results show better performance for 30 and 45 minutes compared with 15 minutes for this Fe:Cr(VI) ratio (ferrous dose of 2.0 mg/L). A similar pattern was observed for total Cr (Figure 4-15), although the magnitude of the difference was greater for total Cr.

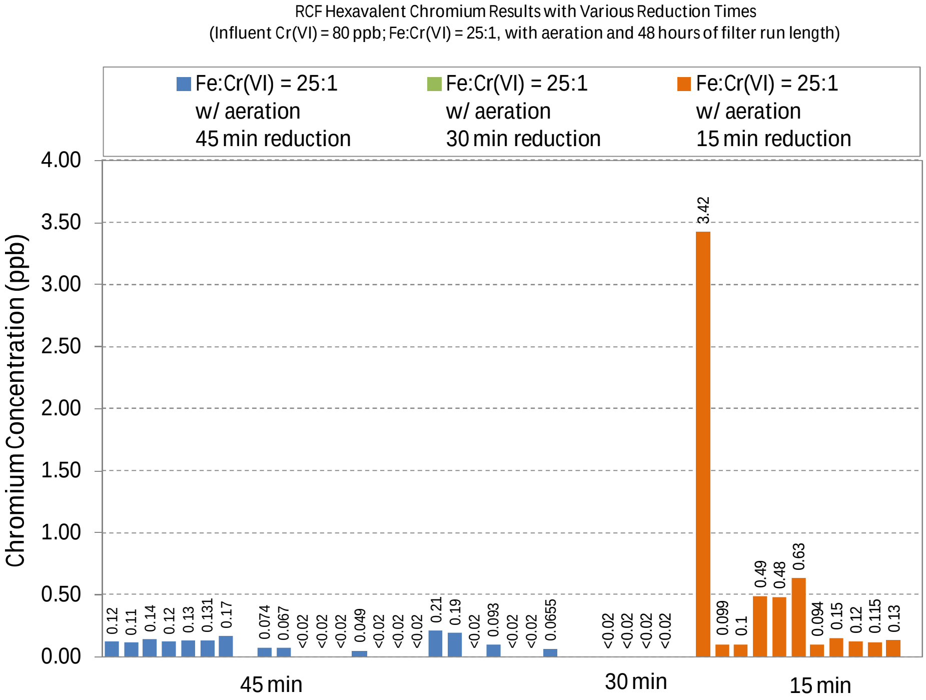

Figure 4-14. Cr(VI) Concentrations in RCF Process Filter Effluent as a Function of Reduction Time

Note: Ferrous target dose was 2.0 mg/L.

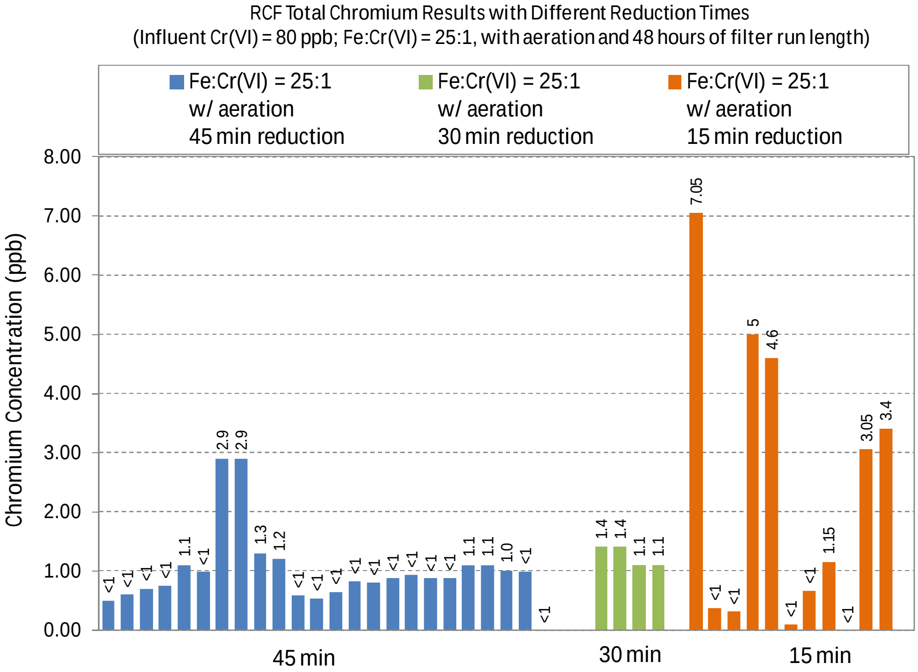

Figure 4-15. Total Cr Concentrations in RCF Process Filter Effluent as a Function of Reduction Time

Note: Ferrous target dose was 2.0 mg/L.

During weeks 45 to 51, a higher Fe:Cr(VI) ratio of 50:1 was applied to evaluate whether better removals could be achieved at double the ferrous dose for the 75-80 ppb influent (ferrous dose approximately 4 mg/L). Figure 4-16 shows the Cr(VI) results from this period, and Figure 4-17 presents the corresponding total Cr data. Improved removals were not observed for 50:1 compared with 25:1 at an influent concentration of 75-80 ppb, and appeared to be worse compared with Figure 4-13.

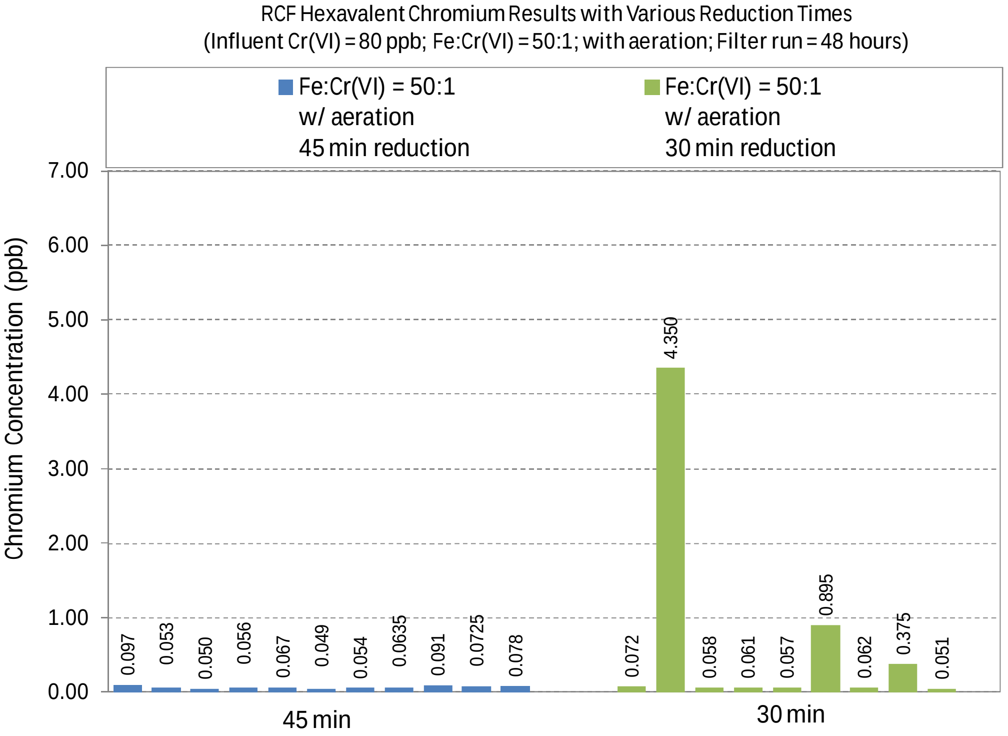

Figure 4-16. Cr(VI) Concentrations in RCF Process Filter Effluent at a Higher Fe:Cr(VI) Ratio

Note: Ferrous target dose was approximately 4.0 mg/L.

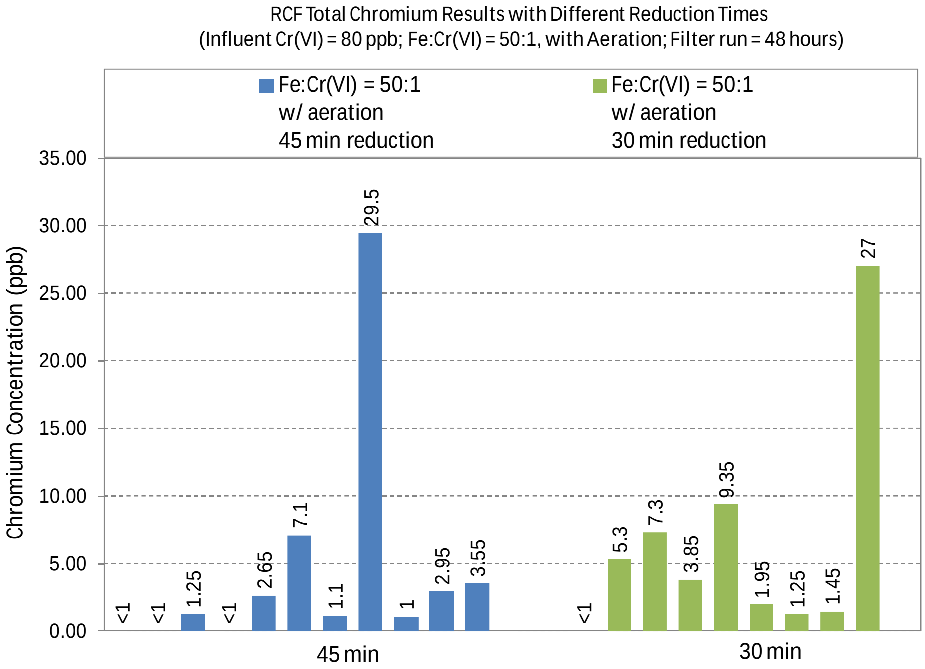

Figure 4-17. Total Cr Concentrations in RCF Process Filter Effluent at a Higher Fe:Cr(VI) Ratio

Note: Ferrous target dose was approximately 4.0 mg/L.

A lower influent concentration of 12-14 ppb was also tested with an Fe:Cr(VI) ratio of 50:1 (ferrous dose of 0.6 to 0.7 mg/L) for two weeks (weeks 54 to 55). Cr(VI) concentrations in filter effluent were between 0.05 ppb and 0.13 ppb (Figure 4-18), suggesting the ferrous dose was sufficient for Cr(VI) reduction. Corresponding total Cr levels were in the range of 1.5 ppb to 2.95 ppb. The Phase III Residuals study jar testing (Appendix G) found that lower Cr(VI) concentrations of about 10 ppb achieved better chromium removals at a higher Fe:Cr(VI) ratio of 50:1, compared with a ratio of 25:1.

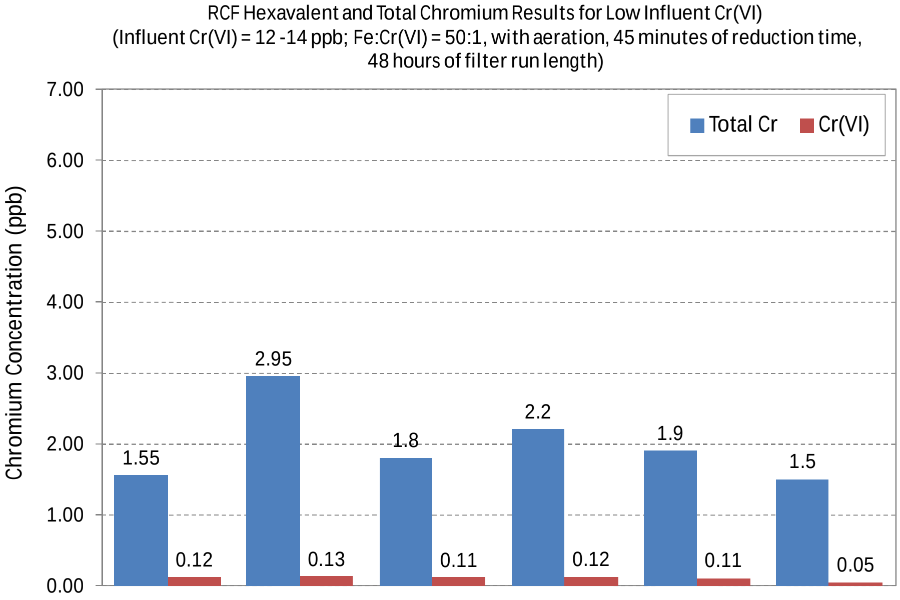

Figure 4-18. Cr(VI) and Total Cr Concentrations in RCF Process Filter Effluent for Low Influent Cr(VI) at a Higher Fe:Cr(VI) Ratio

Note: Ferrous target dose was 0.6 to 0.7 mg/L, depending on the influent Cr(VI) concentration.

Phase II Pilot testing and Phase III Bridge testing showed that total Cr removal is tied to the effectiveness of filtration in removing ferric iron particles. Peaks in effluent total Cr concentrations in the filter effluent corresponded to spikes in iron and turbidity. Figure 4-19 provides a plot of total Cr concentrations versus total iron concentrations and turbidity in the filter effluent for paired samples. Regressions were not strong, but in general, the trend observed was that high total Cr values corresponded to higher iron and turbidity values.

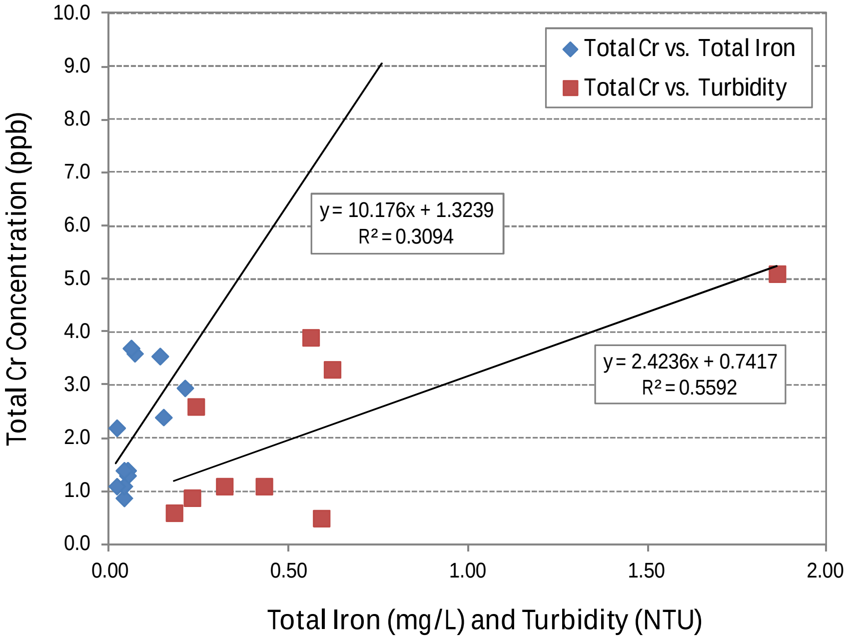

Figure 4-19. Total Chromium Concentrations versus Total Iron Concentrations and Turbidity in RCF Filter Effluent

Filter run time was investigated during Phase III Demonstration testing to evaluate whether filters could be run longer, thereby reducing the quantity of backwash water and the amount of downtime on filters. Filter run times of 24, 48, and 72 hours were tested. Figure 4-20 provides total Cr data for the three run times when the influent Cr(VI) concentration was 75-80 ppb, the Fe:Cr(VI) ratio was 25:1, and 45 minutes of reduction time was used. The results show that a longer filter run time did not negatively impact Cr(VI) removal. The converse (i.e., whether improved performance was observed with longer run times) cannot be proven with the data available, since (1) the 24 hour filter run times reflect a time period when aeration may not have been effective due to a potentially clogged diffuser grid, and (2) chromium profiles through a run were not collected. However, turbidity was measured online during filter runs and generally indicated improved performance during a run, which would arise from improved particle removal resulting from buildup of solids on the filter media that assists with removal of additional particles.

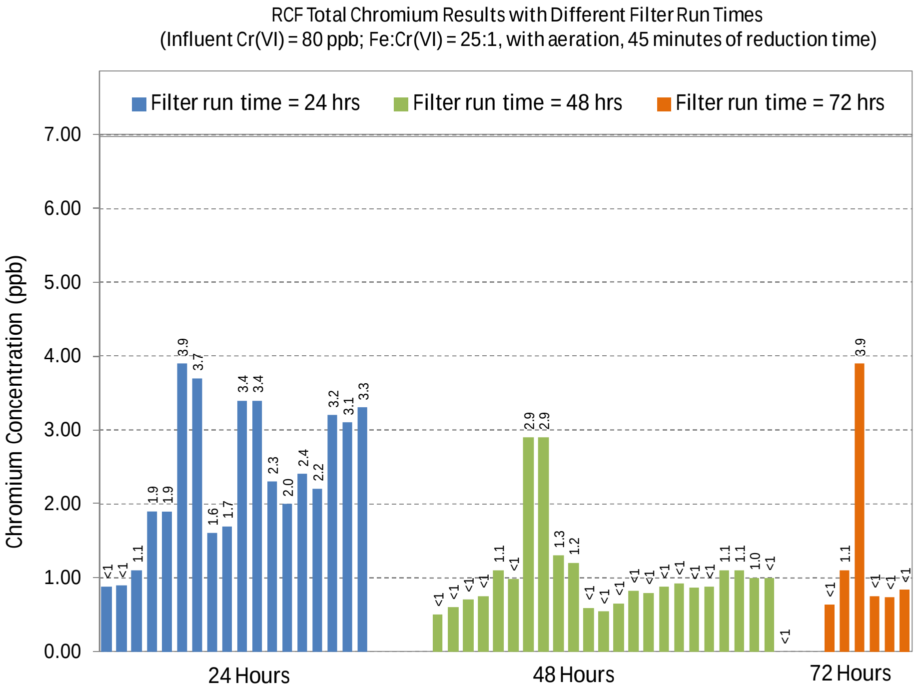

Figure 4-20. Total Cr in Filter Effluent vs. Filter Run Time

Note: Ferrous target dose was 2.0 mg/L.

Prior testing in the Phase III Residuals study indicated that pH had a significant impact on chromium reduction efficiency. Increased pH levels for reduction, 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. The raw water influent pH of the GN-3 water at Glendale was sufficient at an average of 7.7 to allow for efficient Cr(VI) reduction. A natural pH change can be observed through the process due to off-gassing of carbon dioxide and stripping of carbon dioxide during the aeration process (Figure 4-21).

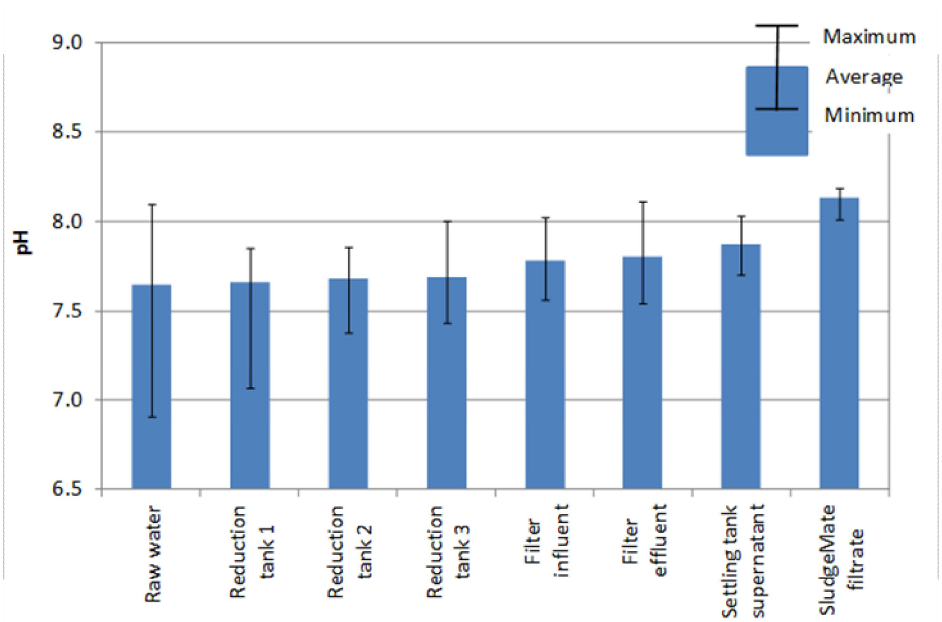

Figure 4-21. pH Values Through the RCF Demonstration Process

Oxidation-reduction potential (ORP) throughout the RCF process was also monitored. The general trends through the process, as shown in Figure 4-22, support the expected reduction in ORP after ferrous sulfate is added, and increase in ORP after aeration and filtration. Variability of the ORP readings was high, as evidenced by the error bars reflecting maximum and minimum data values. For example, a comparison of specific data points with and without aeration on (not shown) did not show a discernible difference in the ORP values entering the filters.

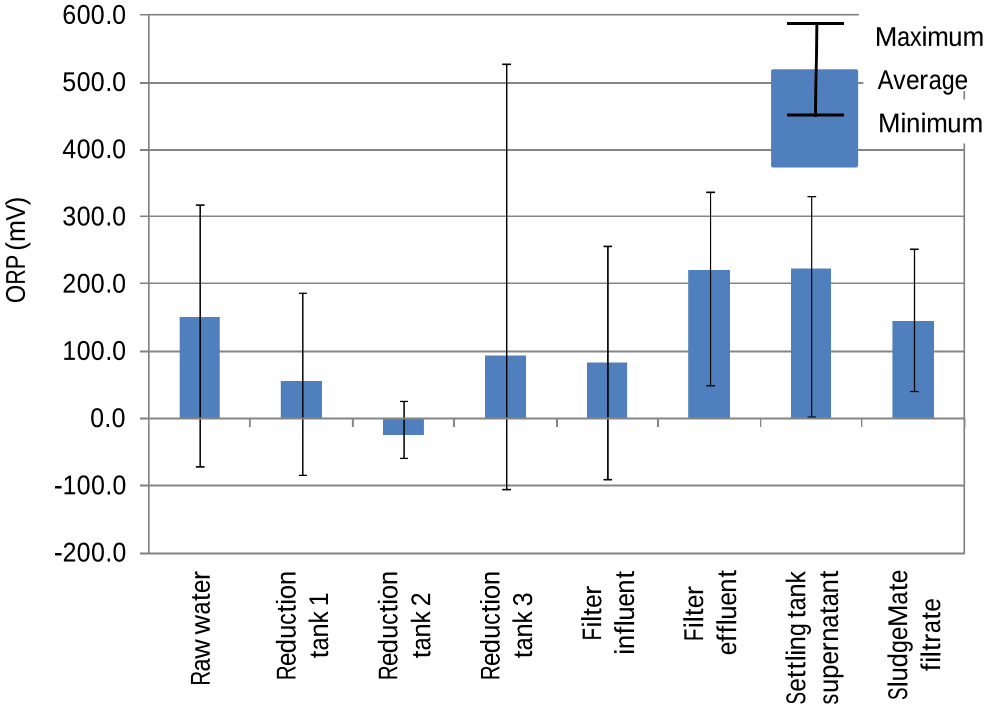

Figure 4-22. Oxidation Reduction Potential through the RCF Demonstration Process

4.3.2 Key Operational Data and Observations

Key operational data for the RCF process include chemical consumption of ferrous sulfate and polymer, and modifications to the backwashing procedure for improved filter media cleaning.

Ferrous sulfate solution of 5% as ferrous was used during the demonstration study. Approximately 2,100 gallons (38 drums, 55 gal per drum) of ferrous sulfate solution were consumed during an operational period of 55 weeks. Mass balance calculations using the quantity of water treated in the RCF system (59.3 million gallons) and the estimated iron doses for different influent concentrations as shown in the matrix provides an estimate of 2,300 gallons of ferrous sulfate used. The estimates and actual use quantities are within 10%.

Polymer (Ciba Magnafloc E38) with 28% active polymer was used during the demonstration study. Approximately 15 gallons of neat polymer was consumed during an operational period of 14 months.

The backwashing protocol was amended through operational troubleshooting due to limited settling tank volume and in an effort to improve cleaning of the filter media. The amended procedure is described as follows:

1. Filter draw down pumping at about 34 gpm for 1,300 gallons (about 38 min)
2. High air scour at 50 cfm for 2.5 min, followed by low air scour at 25 – 30 cfm for 4 minutes
3. Filter slow fill at 150 gpm for 2.5 minutes (with air)
4. Filter fast fill at 275 gpm for 2.3 minutes (with air)
5. Backwash at a high flow of 400 gpm for 18 minutes

The primary observation noted by operations staff regarding the RCF process is the significantly greater operational attention required compared with the WBA system. The 100 gpm RCF system is estimated to have required approximately 5-6 hours per day for routine operation and monitoring, plus the additional time needed to troubleshoot, replace malfunctioning equipment parts and track down simultaneous compliance issues like bacterial contamination in the process.

4.3.3 Simultaneous Compliance Issues

Two simultaneous compliance issues were investigated as part of the Phase III Demonstration testing of the RCF process: bacterial contamination in the system and removal of VOCs with the aeration step.

A significant amount of troubleshooting occurred during Phase III Demonstration testing of the RCF process arising from high bacteria counts. Since Glendale was serving the treated RCF effluent, CDPH mandated frequent monitoring of HPC and total coliforms with triggers to divert the water if the values exceeded set thresholds.

When the high bacteria counts were first observed in Phase III Demonstration testing, it was difficult to pinpoint the source of the bacteria from the data. Operations staff conducted a methodical campaign to eliminate potential variables and hone in on the source of the contamination. The system was disinfected several times but the bacteria growth recurred. High bacterial concentrations in the settled backwash water tank and SludgeMate effluent were identified, so recycle of settled backwash water to the head of the plant was stopped and the water sent to the sewer. When bacterial contamination continued, a closer look at the polymer system revealed that the polymer day tank was the primary source of bacteria to the RCF system.

The Magnafloc E38 polymer (28% active polymer) was purchased as a neat solution, then “activated” (by diluting and stirring the solution) and further diluted before being added to the RCF process. Diluted polymer was stored in a polymer day tank outside, and the day tank was refilled daily with fresh solution.

Figure 4-23 shows HPC results for raw, activated and diluted polymer in the day tank. The results show that bacterial concentrations were higher in the activated polymer than the raw polymer, and highest in the diluted polymer in the day tank. The team hypothesized that bacteria were introduced from the activated polymer (including from the polymer dilution water used – which was potable water but had high HPC values at times), then the bacterial populations increased as the organic-rich water sat outside in warm temperatures. The small quantity of polymer remaining in the bottom of the day tank when new diluted polymer was added each day could have contributed to the overall bacterial levels. One solution that was considered near the end of testing was periodic cleaning of the day tank; this approach should be considered when designing a full-scale facility.

Time did not allow verification that day tank cleaning would resolve the bacteria issue. If this was the case, then recycling of the backwash water may not have been prohibitive and water loss could have been reduced.

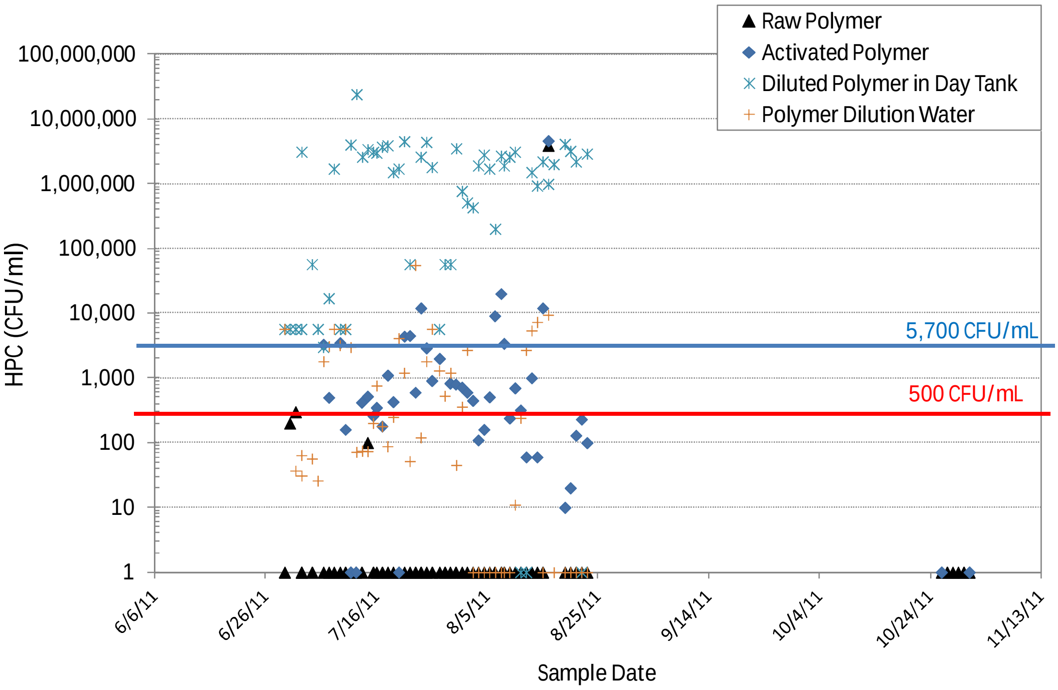

Figure 4-23. HPC Results for Raw, Activated Polymer and Diluted Polymer in Day Tank

The RCF process includes an aeration step intended to ensure that all of the ferrous iron added is oxidized to ferric hydroxide particles, which are then removed by filtration. For some utilities, like Glendale, raw water can also contain VOCs that may be partially removed by an aeration step. For large-scale facilities, local air quality management districts like the South Coast Air Quality Management District (AQMD) impose restrictions on the quantity of VOCs that can be emitted to the air. As a result, the Phase III RCF Demonstration facility at Glendale included off-gas treatment (vapor-phase GAC) to capture any emitted VOCs. In addition, the stripping observed in the process was quantified to assess how much removal of different VOCs was experienced.

Table 4-5 presents the VOCs detected in the aeration influent during the Phase III Demonstration testing. Trichloroethylene (TCE), tetrachloroethylene (PCE) and 1,1-dichloroethylene (1,1-DCE) were the VOCs with the highest concentrations detected in the aeration influent, among the 17 VOCs detected. VOC removal by aeration varied significantly for different compounds (from 8% to 100%). On average, 39% to 47%

removal was achieved for TCE, PCE and 1,1-DCE. Vapor phase GAC was used to treat aeration off gas, which consisted of two canisters in lead/lag configuration. The lead canister was replaced after approximately 10 months of operation, in advance of breakthrough.

Table 4-5. VOCs Removal by Aeration Process

VOCs Detected in Aeration Influent	Aeration Influent (SP 103)		Aeration Effluent (SP 201)		Percent Removal for Paired Samples*	
	Average (ppb)	Range (ppb)	Average (ppb)	Range (ppb)	Average	Range
1,1,2-Trichloroethane	0.38	0.28 - 0.44	0.35	0.26 - 0.41	8%	0% - 39%
1,1-Dichloroethane	2.03	0.15 - 3.20	1.38	0 - 3.00	34%	0% - 100%
1,1-Dichloroethylene (1,1-DCE)	33.0	ND - 77.0	17.9	ND - 72.0	47%	0% - 100%
cis-1,2-Dichlorethylene	3.44	ND - 4.70	2.42	ND - 4.30	31%	0% - 100%
trans-1,2-Dichloroethylene	0.19	ND - 0.27	0.10	ND - 0.27	58%	0% - 100%
1,2-Dichloroethane	1.20	ND -1.70	0.94	ND -1.70	22%	0% - 100%
Bromodichloromethane	0.14	0.11 - 0.16	0.10	ND - 0.14	29%	7% - 100%
Carbon tetrachloride	7.19	ND - 11.00	3.84	ND - 10.00	46%	0% - 100%
Carbon disulfide	0.33	0.10 - 0.78	0.29	ND - 0.92	41%	0% - 100%
Chloroethane	0.13	0.11 - 0.15	ND	ND	40%	0% - 100%
Chloroform	4.27	ND - 5.90	2.97	ND - 5.80	30%	0% - 100%
Chlorodibromomethane	0.12	0.07 - 0.19	ND	ND	100%	0% - 100%
Chloromethane	0.14	ND - 0.26	0.20	ND - 0.61	19%	0% - 100%
Methyl tertiary-butyl ether	0.08	ND - 0.14	0.07	ND - 0.14	40%	0% - 100%
Tetrachloroethylene (PCE)	24.5	ND - 170.0	15.7	ND - 97.0	43%	0% - 100%
Trichloroethylene (TCE)	421.8	ND - 560.0	265.3	ND - 510.0	39%	0% - 100%
Total Trihalomethanes (TTHM)	4.28	0.88 - 5.90	2.94	ND - 5.80	33%	0% - 100%

*For non-detects, zero was used for calculations of percent removals.

4.3.4 Residuals Volumes and Characterization

Phase III Demonstration testing revealed that the spent RCF residuals were classified as a non-RCRA hazardous waste for disposal in California as anticipated based on Phase II Pilot testing (Appendix C).

Actual volumes of RCF residuals generated in the Phase III Demonstration study were compared with projected volumes in the Phase III Residuals study using a mass balance approach (Appendix G). During a period of 213 days of operation, approximately 7,663 lbs of residuals (8,100 lbs including empty drum weight) were produced for a flow rate of 100 gpm and between 25:1 to 35:1 Fe:Cr(VI) mass ratios for an influent Cr(VI) concentration of 75-80 ppb. The average moisture content of the dewatered residuals that were passively dewatered in the SludgeMate container was 84%. Mass balance calculations of the residuals quantity is slightly greater at 10,644 lbs but includes a number of conservative assumptions. Residuals waste in the Phase III Demonstration study was disposed in drums to the Buttonwillow landfill.

The quantity of backwash water consumed in the RCF process was approximately 3% of the system flow (100 gpm), although the backwash handling tank was thought by operations staff to be undersized based on high turbidities observed when a filter was successively backwashed. No measurable impact on system performance was observed with recycle.

4.3.5 MF Testing Results

Phase IIIA MF pilot testing was conducted in four phases, consisting of ferrous dose optimization (Stage 1a), membrane flux optimization (Stage 2a), two extended runs each at low influent Cr(VI) concentration followed by clean-in-place (CIP) procedures (Stages 3a and 3b), and a final shorter run at a higher influent Cr(VI) concentration (Stage 4b). Multiple runs were employed to evaluate the effectiveness of cleaning and the potential for irreversible fouling of the membranes. Jar testing was also conducted before Stage 1a to assess ferrous iron doses and removals with filter sizes representative of MF, and between Stages 1a and 2a to evaluate the impact of a small chlorine dose on ferrous iron oxidation and potential Cr(III) oxidation.

Initial jar testing results confirmed previous observations that a higher ferrous iron ratio is better for a low Cr(VI) water (i.e., approximately 15 ppb). Based on this jar testing, ferrous iron to hexavalent chromium, Fe: Cr(VI), mass ratios of 50:1 and 75:1 yielded lower total Cr results, whereas a Fe: Cr(VI) ratio of 25:1 was sufficient for the higher Cr(VI) water (i.e., approximately 80 ppb). Testing of potential reoxidation when a small chlorine dose was added to reduction tank effluent water showed no discernible impact on Cr(VI) concentrations when the chlorine dose was optimized to ferrous iron concentrations and yielded less than 0.2 mg/L free chlorine residual. Slight oxidation was observed in later pilot testing (described below).

Stage 1a (ferrous dose optimization) confirmed jar testing results demonstrating the importance of the ferrous dosing to Cr(VI) reduction and total Cr removal. Stage 2a (flux optimization) confirmed that total Cr and Cr(VI) removal were independent of the flux. An analytical issue arose in Stage 2a, resulting in false high total Cr values due to use of a less sensitive laboratory instrument. Before the analytical problem was identified, the ferrous iron dose was increased from 0.65 mg/L (based on Fe: Cr(VI) ratio of 50:1) to a constant dose of 2 mg/L. The idea behind this ferrous iron dose increase was to provide sufficiently large floc for Cr(III) association with iron and removal by the membranes, with 2 mg/L selected because it was the maximum iron dose recommended by Pall for their system. The GE/Zenon, being a submerged rather than pressure configuration, could have accepted higher iron concentrations had that been necessary, considering the unit has lower membrane packing density and lower fluxes compared with pressurized systems. After the analytical problem was identified, all MF effluent samples, which were still available, were re-analyzed for total Cr.

Results obtained in Stage 3a with the higher ferrous iron concentration showed improved removal of total Cr, with all results less than or equal to 1 ppb, and six out of nine samples less than the total Cr MRL of 0.2 ppb. Cr(VI) concentrations in MF effluent samples ranged from below the MRL (0.020 ppb) to 0.037 ppb, indicating nearly complete reduction. The second extended run in Stage 3b showed total Cr concentrations for the Pall system equal to or below the MRL of 0.2 ppb for all but one data point, and less than or equal to 0.3 ppb for the GE/Zenon system (Figure 4-21). Cr(VI) concentrations in Pall and GE/Zenon effluents ranged from 0.03 to 0.26 ppb, and indicated that a small chlorine dose in the break tank may have oxidized a small fraction of Cr(III) to Cr(VI) in the treatment process. Overall, the results show both MF systems consistently removed total Cr and Cr(VI) to less than 1 ppb.

In Stage 4b with Cr(VI) influent concentrations of 80 to 89 ppb, MF treated water total Cr concentrations ranged from below the MRL of 0.2 ppb to 0.6 ppb for both Pall and GE/Zenon systems, demonstrating effective total Cr removal under these conditions of a 2 mg/L iron dose and higher influent chromium concentration. Cr(VI) was effectively reduced by the MF pretreatment process. MF effluents contained Cr(VI) concentrations below 0.6 ppb, with minor reoxidation from the small chlorine dose before the membranes compared with initial chromium concentrations. The results showed that both membrane systems removed Cr to below 1 ppb for high Cr(VI) water. Results of this testing also revealed improved performance of the RCF system using MF compared with granular media filtration (ranging from 1 to 5 ppb through Stages 3b and 4b), as hypothesized when the project began.

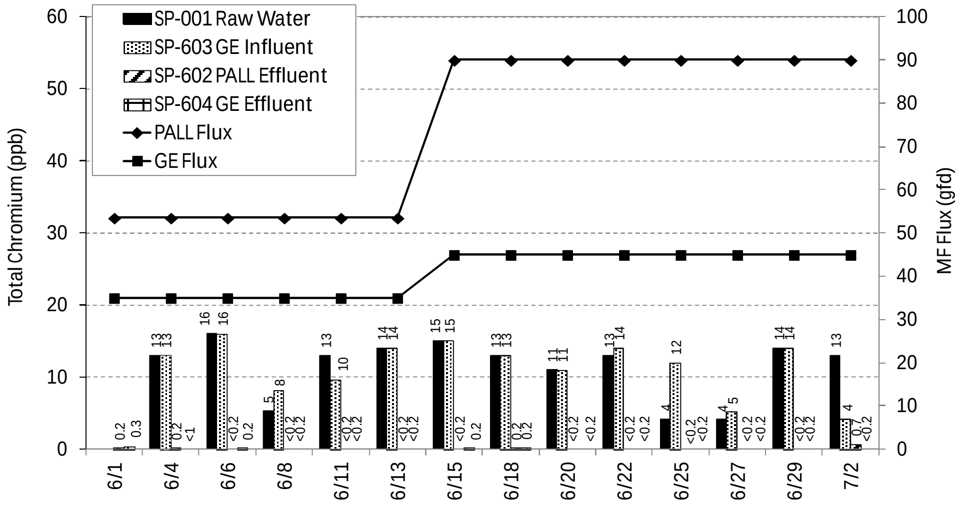

Figure 4-24. Total Cr Removal Using RCF with MF/UF in Stage 3b of Testing

Pilot testing showed that membrane fouling was reversible with CIP procedures. Two initial fouling episodes occurred that were unexplained by the system operations and water quality characteristics, but the membrane permeability was effectively recovered by CIPs (including one special CIP event) and did not suffer in the subsequent extended runs. Although conducted during pilot testing, Pall concluded that maintenance cleans during full-scale runs would likely not be needed during a 30-day run at a flux of 90 gfd, based on the low membrane fouling rates observed in the pilot testing. A flux of 90 gfd is considered high compared to typical fluxes used for pressurized MF systems. A more conservative flux is typical for full-scale design and was used in this analysis.

One unexpected finding during this study was the necessity of acid digestion to eliminate a positive interference caused by carbon-argon complex formation during measurement by inductively-coupled plasma mass spectrometry (ICP-MS). The use of the carbon-correction feature in analytical runs can eliminate some of this interference, but this work (and other concurrent research efforts) showed that acid digestion may be necessary to quantify total Cr at sub-ppb levels. With acid digestion, an MRL of 0.2 ppb is possible, compared with an MRL of 1 ppb without digestion. Eurofins Eaton Analytical laboratory indicated a special calibration procedure was needed to achieve the MRL of 0.2 ppb.

Overall, the findings from this Phase IIIA MF study provide evidence that the RCF treatment process with microfiltration can yield treated water with chromium concentrations below 1 ppb. Use of upstream ferrous iron, coupled with a small dose of chlorine to protect the membranes from ferrous iron fouling, was compatible and offers utilities a treatment option for removing Cr(VI) to low levels. This work, including operational conditions tested, forms the basis for cost development of treatment in Section 5.

5. Cost Estimates of Treatment

This section presents layouts and cost estimates for the two Cr(VI) treatment technologies, WBA and RCF (with granular media filtration or MF), that were evaluated in the Phase III Demonstration testing. The purpose of the estimates is to develop cost information to support the CDPH cost-benefit analysis of a range of Cr(VI) maximum contaminant levels (MCLs) under regulatory consideration, using information gathered from real-world experience in the Phase III Demonstration testing.

Estimated costs described in this section are based on treatment capacities of a whole flow without including 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. Blending is an acceptable form of treatment in California, except for extremely impaired sources or sources with high iron and manganese concentrations. Glendale continues to raise a thought of only treating a side stream of high Cr(VI) water to potentially meet the MCL with a margin of safety. Other utilities that have water sources with low Cr(VI) levels may also consider blending as an alternative to treating the whole flow. Blending would result in reduced capital and O&M costs compared to those shown in this analysis.

Table 5-1 lists the design flows and potential Cr(VI) MCLs that were considered in the cost estimates for WBA and RCF (with granular media filtration or MF) treatment. Capital and O&M costs for WBA treatment were developed for four different design flows, ranging from 10 to 2,000 gpm. O&M costs for the WBA systems were based on compliance with five potential MCLs identified in conjunction with CDPH and USEPA, including 1, 2, 5, 10, and 25 ppb. RCF capital and O&M costs were developed for 100, 500, or 2,000 gpm systems, excluding the 10 gpm size due to the complexity of the system. O&M costs were based on compliance with a 5, 10, or 25 ppb Cr(VI) MCLs, excluding 1 and 2 ppb since RCF is not proven to consistently achieve those levels for total Cr. For RCF with MF, capital costs were developed for two types of MF membranes (submerged and pressure) for 100, 500 and 2,000 gpm systems. O&M costs were based on compliance with 1, 2, 5, 10 and 25 ppb, considering MF was shown to remove Cr(VI) and total Cr to below 1 ppb. No safety factors for compliance were considered for the O&M costs for WBA, RCF with granular media filtration or MF (e.g., use of a 50% or 80% factor to ensure consistent operational achievement of an MCL).

The design flows were selected to capture the range of treatment plant capacities required to serve very small to large public water systems (PWSs), as defined by the

USEPA and listed in Table 5-2. Based on the California Cr(VI) occurrence data analyzed in the ACWA residual study (Appendix G), this flow range captured a majority of systems (i.e., very large systems accounted for only 6.9% of PWSs with Cr(VI) detected in their water sources, and may require larger treatment systems than developed in this analysis).

Table 5-1: Design Flows and Potential Cr(VI) MCLs Evaluated for WBA and RCF Treatment

Treatment System	Design Flows Evaluated	Potential Cr(VI) MCLs Evaluated
WBA	10, 100, 500, and 2,000 gpm	1, 2, 5, 10, and 25 ppb
RCF with granular media filtration	100, 500, and 2,000 gpm	5, 10, and 25 ppb
RCF with MF	100, 500, and 2,000 gpm	1, 2, 5, 10, and 25 ppb

Table 5-2. Flow Rates for Cost Estimating

USEPA System Size Category Based on Population	Population	Assumed Flow Rate	Selected 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

MGD – million gallons per day.

5.1 Approach for Developing WBA and RCF (with Granular Media Filtration or MF) Cost Estimates

Figure 5-1 illustrates the approach used to develop WBA and RCF (with granular media filtration or MF) capital costs, which is a Work Breakdown Structure (WBS) method generally accepted in engineering practice. The basis of the cost estimates developed in this study includes the following:

- Design criteria based on pilot (Phase II) and demonstration (Phase III) scale results for WBA and RCF(with granular media filtration or MF) treatment;

- Manufacturer quotations for equipment (i.e., two vendor quotes were obtained for each equipment line item in most cases, unless otherwise specified in Appendix T);
- 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 5-3) based on the installed equipment costs to provide the total direct costs;

Contractor’s overhead and profit of 20% (listed in

- Table 5-4) on top of the total direct costs to provide the total construction costs;

Other general factors (listed in

- Table 5-4) based on the total construction costs, including project level allowance (contingency), engineering, legal and administrative.

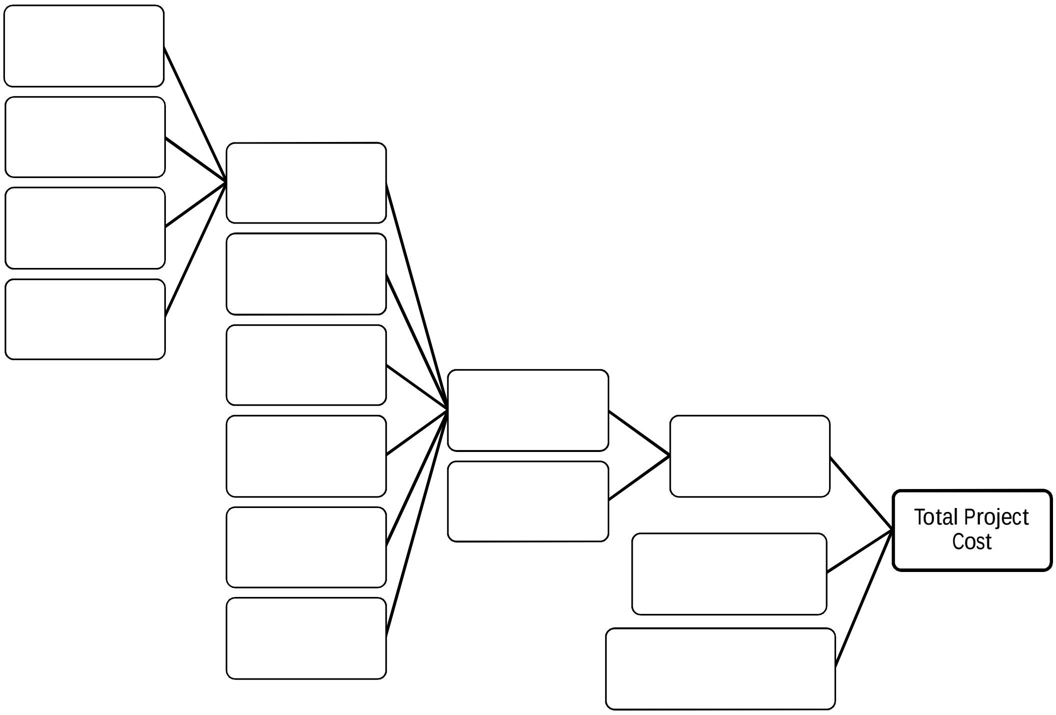

Figure 5-1. Approach for Developing WBA and RCF Estimates

Table 5-3. 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 5-4. 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.

An alternative approach for costs estimating was considered and compared to the WBS approach described above. Generalized cost factors were developed in a workshop held by USEPA (listed in Table 5-5), and were used to develop arsenic treatment costs (USEPA, 2000). The total capital costs are broken into three major categories: process/equipment costs, construction and engineering. The percentages in Table 5-5 were for small systems, which were agreed upon by most workshop participants. However, no general agreement was reached for large systems. Some participants suggested greater percentages for construction (25 to 50%) and engineering (25%), while others suggested similar percentages as for smaller systems.

Table 5-5. Cost Factors Developed by USEPA (1997) and Used in Arsenic Costs Estimates for Small Systems

Item	Percentage of Total Capital Cost	Description (1)
Process	40%	Equipment
Construction	40%	Site work, electrical work, instrumentation and controls, mechanical,
Engineering	20%	Engineering design , construction and project management

(1) Based on USEPA, 1997. Discussion Summary: EPA Technology Design Workshop.

To compare the two approaches, capital costs for a 100-gpm RCF system were developed using the WBS approach and the generalized cost factors in Table 5-5. It is unclear whether the process cost in the USEPA cost factors approach refers to installed equipment (i.e. with installation costs, chemical storage containment and equipment pads) or uninstalled equipment. Assuming the reference is to installed equipment costs, the total capital costs for a 100-gpm RCF system are estimated to be $2,400,000 and $2,200,000 using the WBS and USPEA cost factors approaches, respectively. In general, the two approaches generated comparable capital costs for this example. Assuming the USEPA process refers to uninstalled equipment costs, the total capital costs would be $1,700,000 using the USEPA cost factors.

If higher construction and engineering percentages are used for large systems (i.e. process 30%, construction 40%, engineering 30% of the total capital cost), the total capital costs for a 2,000-gpm RCF system are estimated to be $8,500,000 and $11,000,000 using the WBS and USPEA cost factors approaches, respectively, assuming the process in the USEPA cost factors approach refers to installed equipment costs. Assuming the USPEA process refers to uninstalled equipment costs, the total capital costs would be $6,600,000 using the USPEA cost factors.

The WBS approach provides more detailed break downs in the cost items and clearer assumptions, which should be more useful for CDPH. In addition, the WBS costs fall into the potential range of costs that would be calculated using USEPA cost factors depending on the assumptions. Therefore, the WBS approach was used to develop WBA and RCF (with granular media filtration or MF) capital costs.

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. Accuracy ranges for Class 5 estimates are -20% to -50% on the low side, and +30% to +100% on the high side. A typical rate of -30% to +50% was applied to the cost estimates in this report to demonstrate the accuracy range of estimates.

5.2 Design Water Quality

Table 5-6 presents the design raw water quality for WBA and RCF(with granular media filtration or MF) treatment for Cr(VI) removal. The listed design concentrations were selected based on Glendale water quality and groundwater quality for several nearby Southern California cities.

The pH, alkalinity, calcium, TDS, chloride and sulfate concentrations affect the sizing and costs for pre- and post-pH adjustment systems. The average concentrations were input into the Tetra Tech RTW model to estimate the quantity of acid or CO_2 required to adjust the pH to 6.0 prior to WBA. Note that the sizing and costs of pH adjustment systems would vary for water systems with different pH, alkalinity, and calcium concentrations.

Table 5-6. Design Raw Water Quality for WBA and RCF

Parameter (unit)	Design Value
Cr(VI) (ppb)	50(1)
pH (pH units)	7.3
Alkalinity (mg/L as $CaCO_3$)	191
Calcium (mg/L as Ca)	79
Total dissolved solids (mg/L)	412
Chloride (mg/L)	75
Sulfate (mg/L)	65
Uranium (pCi/L)	2.7(2)
Volatile organic compounds (ppb)	500(3)

(1) Design concentration for RCF with granular media filtration capital costs. It was assumed the ferrous dose for RCF with MF did not change with the influent Cr(VI) concentration, such that the influent Cr(VI) did not affect its capital or O&M costs. The influent Cr(VI) concentration was not assumed to impact resin usage and was thus not included as a design parameter for the WBA systems.

(2) Uranium concentrations observed at well GS-3 in Glendale.

(3) VOC concentrations observed at well GN-3 in Glendale.

For RCF with granular media filtration systems, an influent Cr(VI) concentration of 50 ppb was used for process sizing; influent Cr(VI) concentrations of 5, 10, 25 and 50 ppb were used for estimating O&M costs. For RCF with MF, it was assumed a constant ferrous dose of 2.0 mg/L applied to all influent Cr(VI) concentrations, so the influent Cr(VI) concentration would not affect capital and O&M costs. For WBA systems, the resin life was assumed to be insignificantly affected by source water Cr(VI) concentrations (i.e., other parameters impact resin capacity more than Cr(VI), such as nitrate and sulfate observed for perchlorate-selective resins). Thus, the raw water Cr(VI) concentration was not a variable design parameter for WBA. Note that this assumption requires testing for validation. On-going research is expected to provide more information.

Uranium concentrations observed in Glendale's groundwater were assumed for all system sizes. A VOC concentration of 500 ppb was also assumed based on observed VOC concentrations in Glendale's GN-3 well. The presence of regulated VOCs may necessitate inclusion of off-gas treatment for an aeration processes incorporated in the WBA or RCF treatment systems.

5.3 Weak Base Anion Exchange Cost Estimates

Figure 5-2 shows a process flow diagram for WBA used in this cost evaluation. Carbon dioxide gas (CO_2) is added to the raw water to reduce the pH to 6.0. The water then passes through a bag filter for particle removal, followed by pressure vessels containing the WBA resin. The vessels are arranged in a lead/lag configuration. When Cr(VI) concentrations in the lag vessel effluent reach a target level (e.g., 1, 2, 5, 10, or 25 ppb), the resin in the lead vessel is assumed to be removed for offsite disposal and replaced with fresh resin. The lead and lag vessels are switched after each resin replacement to maximize resin usage. Following WBA treatment, the pH in the finished water is adjusted by aeration (coupled with off-gas treatment) to prevent corrosive conditions arising from low pH water entering a distribution system.

As illustrated in Figure 5-2, capital and O&M costs for WBA presented in this section were based on the use of CO_2 for pH adjustment prior to ion exchange treatment and aeration for post pH adjustment. Costs were also developed for the use of hydrochloric acid and caustic as alternative strategies for pH adjustment. However, CO_2 addition and aeration were determined to be more cost effective for the assumed raw water quality. Details of the costs for the different pH adjustment strategies are provided in Appendix U.

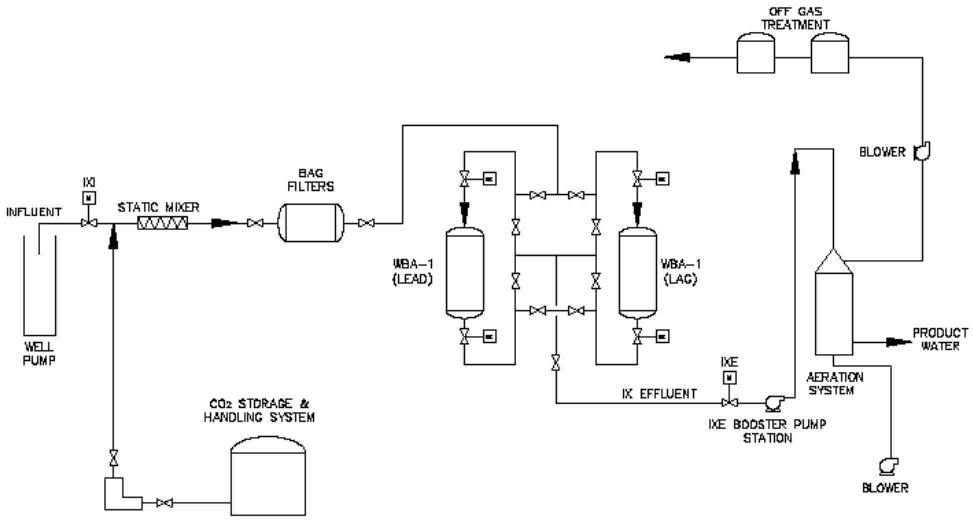

Figure 5-2: Weak Base Anion Exchange Process Flow Diagram

5.3.1 Design Criteria

Table 5-7 provides the preliminary design criteria used to size the WBA process and to estimate costs for each design flow. The ion exchange systems were designed to achieve the following two conditions:

1. Meet the resin manufacturer-recommended ranges for hydraulic and surface loading rates and empty bed contact time (listed in Table 5-7); and,
2. Accommodate resin volumes resulting in changeout frequencies ranging from every year (for a 1 ppb target effluent concentration) to every three years (for a 25 ppb effluent Cr(VI) concentration).

Table 5-7: Weak Base Anion Exchange Design Criteria

Item	**Assumption**
Surface Loading Rate	4 gpm/sf minimum (8.5 gpm/sf used in Phase III study; another utility's recent system quotes based on 8.8 gpm/sf)
Hydraulic Loading Rate	2.5 gpm/cf
EBCT per Vessel	3 minutes
Resin	Dow Amberlite^{TM} PWA7
Bag Filter Mesh Size	10 µm
Operating pH	6.0

5.3.2 Capital Costs

Capital costs were developed for 10, 100, 500, and 2,000 gpm WBA systems.

5.3.2.1 Assumptions

Capital cost development included the following assumptions:

- Excess capacity for redundancy was not included unless otherwise noted.
- Process sizing was assumed to be unaffected by the potential Cr(VI) MCLs (i.e. resin would be exchanged more frequently to achieve a lower MCL but facilities would be the same size).
- A raw water pump was assumed to already exist with adequate pump pressure to convey the water flow through the WBA process. Booster pumps were assumed to be required to lift the water through an aeration tower for post-pH adjustment.
- Product water pumping and storage were not included.
- Land cost was not included.
- Equipment/operator building was not included.
- Pumps (i.e., chemical feed, waste discharge) included one standby unit to ensure undisrupted service in the case of equipment breakdown.
- Carbon dioxide feed systems were sized based on the design water quality (Table 5-6) and RTW modeling of CO_2 dose needed to achieve pH 6.0.

- First fill resin costs were based on installation of Dow Amberlite^{TM} PWA7 at a cost of $408 per cubic foot (cf) of resin and a $73.95/cf resin preparation fee.[3] The resin preparation fee includes the cost to conduct a cross regeneration procedure to remove formaldehyde, and resin delivery. Resin preparation procedures are still evaluated by Dow for formaldehyde removal effectiveness. Thus, the resin preparation fee might change significantly if different procedure is determined more effective.
- Booster pumping to transfer the ion exchange effluent for post-pH adjustment was assumed to provide 15-ft of additional pressure at each design flow rate.
- Aeration was designed for CO_2 stripping to achieve a positive Langelier Saturation Index (LSI) and Calcium Carbonate Precipitation Potential (CCPP). The aluminum forced draft aerators include a blower and air distribution tray.
- Aeration off-gas is assumed to need treatment by vapor phase GAC (VPGAC), which is included in the capital costs. However, aeration off-gas treatment might not be needed for water sources with low VOCs levels.
- WBA backwash waste tanks were sized to accommodate storage of 43 bed volumes to flush resin during the initial fill and for periodic backwashing, as needed. This storage accommodates a maximum discharge rate of 20 gpm over an assumed eight (8) hours based on discharge restrictions to the sewer at Glendale, California. The waste discharge pumps are sized to provide up to 100 gpm flow, but with dial-down capabilities to 20 gpm.
- Concrete equipment pads for the CO_2 feed system, ion exchange system, and aeration tower were assumed to cost $1,250 per cubic yard.

5.3.2.2 10 gpm, 100 gpm, 500 gpm, and 2,000 gpm WBA systems

Table 5-8 lists the major equipment/construction items for each WBA system.

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[3] Siemens quote provided on November 29, 2011. Resin and resin preparation costs verified with Siemens on December 14, 2011. The costs were adjusted to 2012 dollars.

Table 5-8: Major Equipment Components for 10, 100, 500, and 2,000 gpm WBA Systems

Major Equipment	10 gpm	100 gpm	500 gpm	2,000 gpm
CO_2 Storage and Handling System(1)	1.5 lb/hr; (2) 380 lb cylinders	15 lb/hr; 6 ton storage	75 lb/hr; 14 ton storage	300 lb/hr; 50 ton storage
Bag Filters (1 duty/1 standby)	10 µm	10 µm	10 µm	10 µm
WBA System:	See Table 5-7 for specifications			
Backwash System(2)	2,000-gal tank	19,000-gal	95,000-gal	189,000-gal
Booster pump (1 duty/1 standby)	15-ft	15-ft	15-ft	15-ft
Aeration System (w/ off-gas treatment)(3)	10-ft height, 300 cfm blower (4)	10-ft height, 300 cfm blower	10-ft height, 1,519 blower	10-ft height, 6,075 cfm blower

(1) Feed system to provide 300 mg/L CO_2 based on design water quality and 14 days of storage.

(2) Each backwash system includes 1 duty and 1 standby discharge pump.

(3) Each forced draft aeration system includes vapor-phase GAC for off-gas treatment comprised of two (2) adsorbers in series with a heater. Aeration towers are designed to provide a 3:1 air-to-water ratio in cfm/gpm.

(4) This is the smallest aerator provided by Siemens.

Table 5-9 lists the design specifications for the WBA systems. Each system is based on a lead/lag configuration for the ion exchange vessels. The 10 gpm and 2,000 gpm systems incorporate two lead/lag trains operated in parallel. Note, that other vessel sizes are feasible and site-specific vessel selection would be based on vendor quotes and bid selection.

Table 5-9: Design Specifications for the WBA Vessels

WBA System Specifications	10 gpm	100 gpm	500 gpm	2,000 gpm
IX vessel configuration	2 lead/lag trains	1 lead/lag train	1 lead/lag train	2 lead/lag trains
Total number of vessels	4	2	2	4
Vessel diameter, ft	1	4	8	12
Volume of resin per vessel, cf	3	50	250	500
Total resin volume for first fill, cf	12	100	500	2,000
Surface loading rate, gpm/sf	6.4	8.0	9.9	8.8
HLR, gpm/cf	1.7	2.0	2.0	2.0
EBCT per vessel, min	4.5	3.7	3.7	3.7

Table 5-10 lists the capital costs for each WBA system size rounded to two significant figures. Details of the capital cost estimate are included in Appendix T.

Table 5-10. Capital Cost Estimates for WBA Systems

WBA System Flow Rate	Capital Cost Estimate (In 2012 Dollars)	Level 5 AACE Accuracy Range (-30% to +50%)
10 gpm	$920,000	$640,000 - $1,400,000
100 gpm	$1,700,000	$1,200,000 - $2,600,000
500 gpm	$3,600,000	$2,500,000 - $5,400,000
2,000 gpm	$8,300,000	$5,800,000 - $12,000,000

5.3.3 O&M Costs

O&M costs were developed for 10, 100, 500, and 2,000 gpm WBA systems and included estimated annual costs for:

- Electricity,
- Chemicals,
- Resin and vapor-phase GAC replacement,
- Spent resin and backwash wastewater disposal,
- Other consumables (i.e. bag filters)
- Labor,

- Maintenance and spare parts, and
- Analytical costs.

O&M costs for each system size were developed for potential Cr(VI) MCLs ranging from 1 to 25 ppb (Table 5-1) and were based on the following assumptions:

- A utilization rate of 100% of the design flow was assumed for simplicity.
- Electricity was assumed to cost $0.102 per kilowatt hour (kWh).
- CO_2 costs were based on the estimated dose required to achieve pH 6.0 (calculated using design water quality; Table 5-6).
- Resin replacement costs were based on Cr(VI) breakthrough curves shown in Figure 4-5 and the estimated bed life for 1, 2, and 5 ppb MCLs listed in Table 4-1. The estimated bed life for 10 and 25 ppb Cr(VI) MCLs were assumed to be 260,000 and 480,000 bed volumes, based on the Phase III Demonstration testing breakthrough curves.
- WBA resin costs were based on quotes currently provided by Siemens for turn-key resin changeout, including $408/cf for fresh resin and $73.95/cf for resin preparation (cross regeneration pre-treatment) and delivery.
- WBA resin disposal costs were based on a $333/cf disposal cost for the spent resin as a non-RCRA hazardous and TENORM waste based on the most recent direct cost (November 2011) for resin disposal from the WBA Phase III demonstration system which was adjusted to 2012 dollars.
- Backwash wastewater disposal costs were based on discharge to the sewer without treatment at a cost of $3.06 per hundred cubic feet, plus a quarterly discharge fee of $918, which is adjusted based on the current costs for WBA wastewater disposal incurred at Glendale and is in 2012 dollars.
- Labor costs were estimated based on $102,000 per full time employee (FTE) per year (loaded), consistent with Glendale’s experience. Staff time to operate and maintain a WBA system was assumed conservatively to equate to a 0.5 FTE based on operator experience for the demonstration plant.
- Bag filters were assumed to require replacement every quarter at $16 per filter based on vendor quotes.
- VPGAC for aeration off-gas treatment was assumed to have carbon usage rates of 0.6, 6, 32 and 119 lb per day for 10, 100, 500 and 2,000 gpm systems, respectively, which were estimated by a manufacturer.

- Maintenance costs were estimated to be 1% of total installed equipment costs.
- Analytical costs were developed based on a water quality monitoring schedule updated from the Phase III Demonstration study and averages of quotes from two laboratories (details provided in Appendix T).

Figure 5-3 illustrates estimated annual O&M costs (in 2012 dollars) for WBA treatment for 10, 100, 500, and 2,000 gpm systems. The O&M costs are estimated separately for potential Cr(VI) MCLs of 1, 2, 5, 10, or 25 ppb to reflect the hypothesized cost difference due to different resin operational life. A full-scale WBA system would likely be operated at an average flow rate below the design flow (i.e., less than a 100% utilization rate). The O&M costs for a lower operational usage rate can be estimated by multiplying the costs in the figure by the expected utilization percentage.

Details of the O&M costs are provided in Appendix T. For the 500 and 2,000 gpm systems, the primary driver of WBA O&M costs is the WBA resin (12 to 33% of the annual operating costs) and spent resin disposal (8 to 22% of the operating costs) due to the relatively high prices of fresh resin and spent resin disposal as a non-RCRA and TENORM waste. For the smaller systems sizes (10 and 100 gpm), other fixed costs (i.e., labor, analytical costs) represent a more significant portion of the total annual operating costs, and the contribution of resin and disposal costs to the total is lower (less than 5% for 10 gpm and between 8% and 25% for 100 gpm).

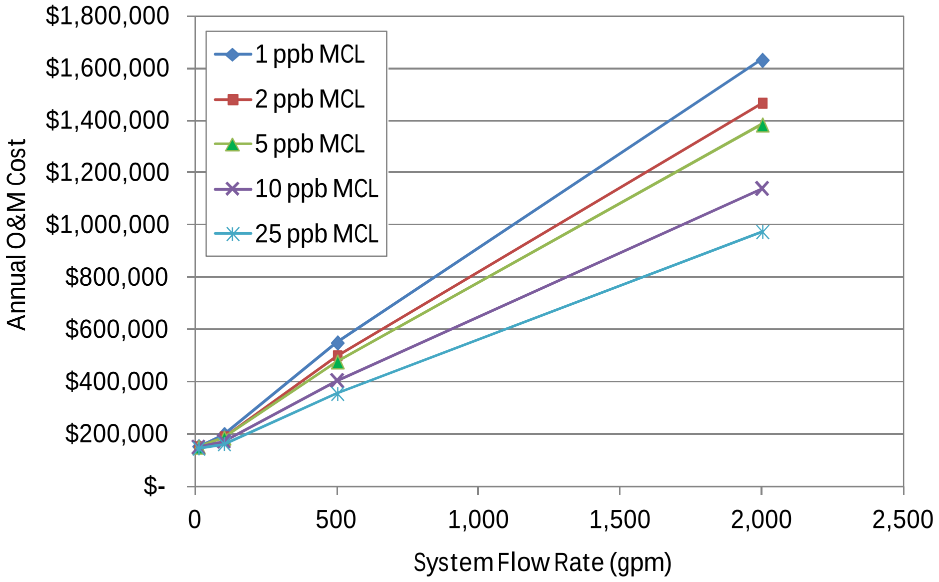

Figure 5-3: Estimated Annual O&M Costs for WBA Treatment Based on Cr(VI) Removal

5.3.4 20-Year Net Present Values

Table 5-11 provides the 20-year net present values (NPV) of WBA O&M costs for the four system sizes and five influent Cr(VI) concentrations rounded to two significant figures. Figure 5-4 illustrates the contribution of capital verses O&M costs to the 20-year life cycle costs at a 1 ppb Cr(VI) MCL (A) and a 25 ppb Cr(VI) MCL (B). For both potential MCLs, NPV O&M costs contribute 50% or more of the total life cycle costs regardless of system size and the target finished water Cr(VI) concentration (i.e., potential Cr(VI) MCL). At a 1 ppb MCL, NPV O&M costs contribute 65 to 77% of the total life cycle costs. The portion of costs from operating expenses is lower at a 25 ppb MCL, since resin could be replaced less frequently, reducing both resin replacement and disposal costs.

Table 5-11: 20-Year Net Present Values for WBA Treatment(1)

WBA System Size	Potential Cr(VI) MCL, ppb				
	1	2	5	10	25
10 gpm	$ 2,500,000	$ 2,500,000	$ 2,500,000	$ 2,500,000	$ 2,500,000
100 gpm	$ 3,300,000	$ 3,100,000	$ 3,100,000	$ 2,800,000	$ 2,800,000
500 gpm	$ 9,200,000	$ 8,400,000	$ 8,000,000	$ 6,700,000	$ 5,900,000
2,000 gpm	$ 27,000,000	$ 25,000,000	$ 23,000,000	$ 19,000,000	$16,000,000

(1) Capital and 20-year NPV O&M based on 2.5% inflation and a 4.5% discount rate
(2) In 2012 dollars

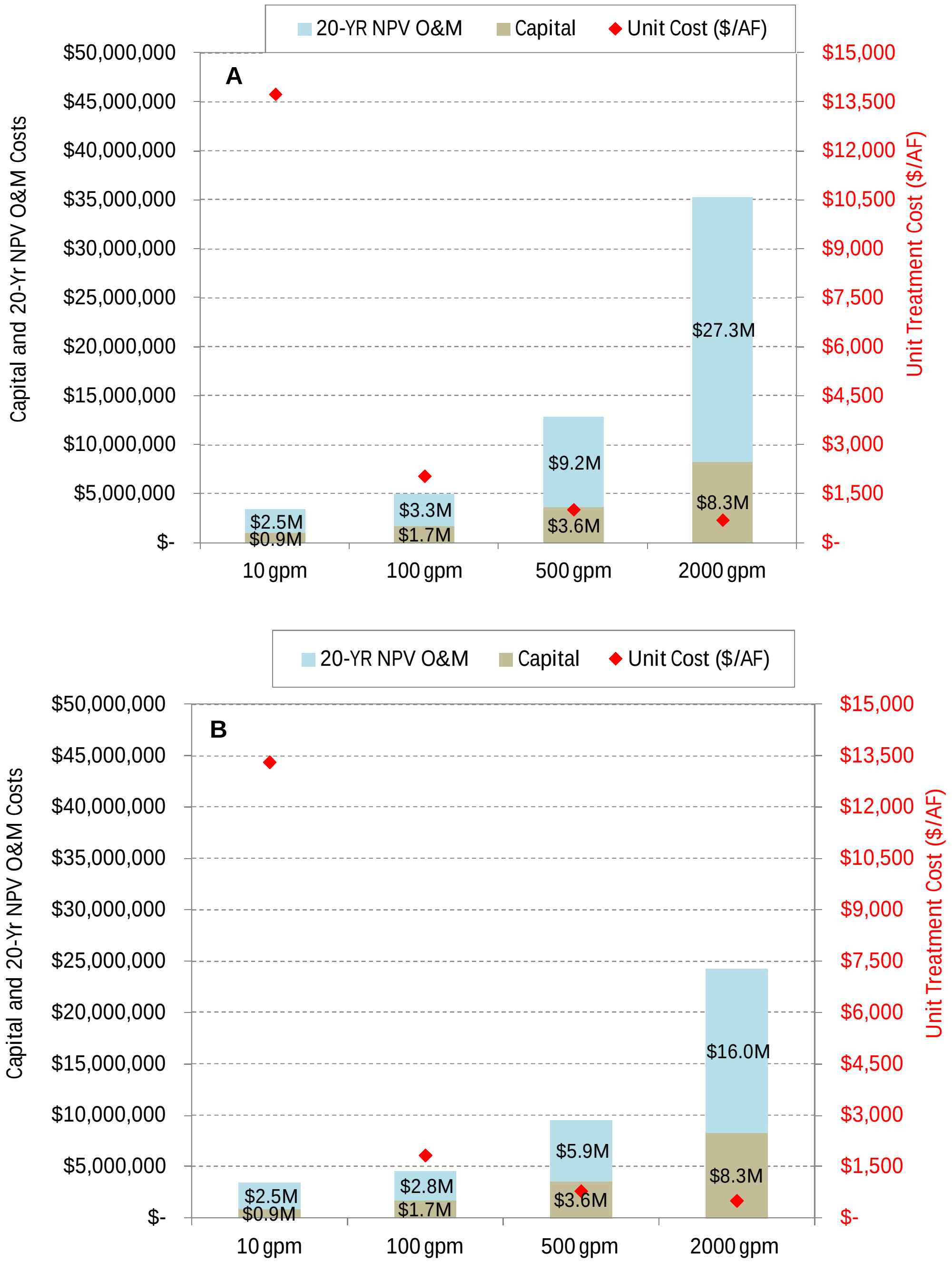

Figure 5-4: Contribution of Capital vs. O&M to 20-Year Life Cycle Costs (NPV) for WBA; A – 1 ppb Cr(VI) MCL, B – 25 ppb Cr(VI) MCL

5.3.5 Unit Treatment Cost ($/AF)

Figure 5-5 presents the estimated unit treatment costs in dollars per acre-foot ($/AF) for the four WBA systems with different target effluent Cr(VI) concentrations (i.e., potential Cr(VI) MCLs). For a 10-gpm system, the unit cost is approximately $13,000 per AF for different potential MCLs. The unit cost decreases dramatically for larger system sizes, reflecting significant 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 (serving 25 to 500 people, Table 5-2) would be particularly impacted by the cost to install WBA treatment.

The effect of the potential Cr(VI) MCL is significant for larger systems installing WBA treatment, with a 70% difference in unit treatment costs based on a 1 versus a 25 ppb MCL. In contrast, the difference in unit treatment costs for treatment to a 1 versus a 25 ppb MCL for a 10 gpm system is estimated to be less than 5% ($13,307 versus $13,741 per AF), reflecting the significant contribution of fixed costs to install and operate a 10-gpm WBA system regardless of the target effluent Cr(VI) concentration.

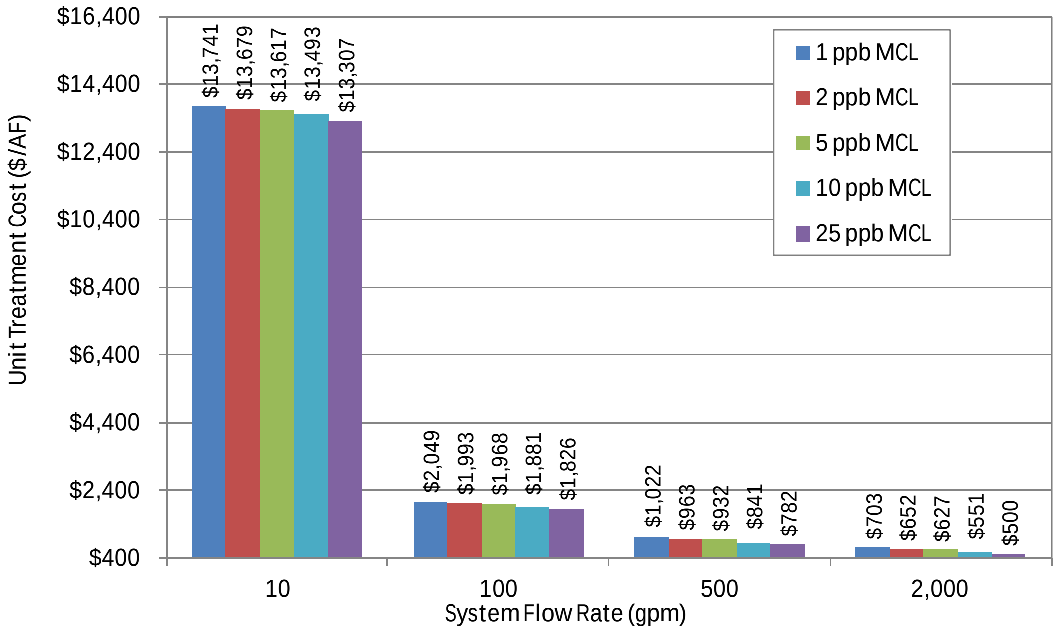

Figure 5-5: WBA Unit Treatment Costs Based on Cr(VI) Removal

5.3.6 WBA Costs Based on Total Chromium Removal

The WBA O&M costs described above are based on Cr(VI) removal. Previous testing suggests Cr(III) can be converted to Cr(VI) by disinfectant residual in the distribution system. Total Cr removal might be needed to meet a Cr(VI) MCL in the distribution system. Total Cr concentrations in WBA lag bed effluent were significantly higher than Cr(VI), especially 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 became similar when Cr(VI) reached 3 ppb.

Assume the same systems described in Section 5.3.2 would be used for total Cr removal (i.e. same capital costs but more frequent resin changeouts to meet total Cr removal targets). WBA O&M costs would be higher for chromium removal based on total Cr, especially for the potential MCLs equal to and below 2 ppb. Figure 5-6 shows the WBA O&M costs 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 based on total Cr removal are estimated to be approximately 10 to 22 times of the costs based on Cr(VI) removal (except 10 gpm). For a potential MCL of 2 ppb, annual O&M costs based on total Cr are approximately 2 to 4 times of the costs based on Cr(VI) removal (except 10 gpm). The higher O&M costs are due to more frequent resin replacements needed to meet total Cr removal targets. O&M cost details are included in Appendix T. Figure 5-7 shows the WBA unit treatment costs based on total Cr removal. To remove total Cr to 1 ppb, the unit costs are estimated to be $11,000 to $32,000 per AF for 10 to 2,000 gpm. To achieve total Cr removal to 2 ppb, the unit costs are estimated to be $2,000 to $16,000 per AF for 10 to 2,000 gpm.

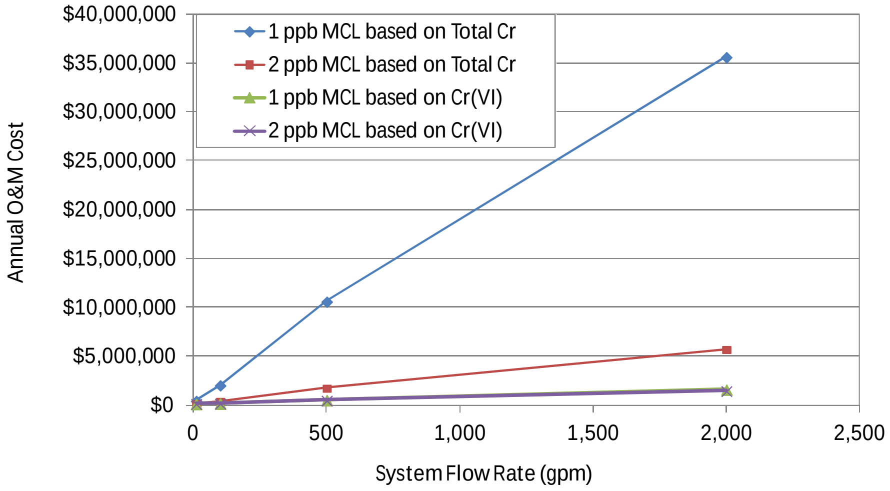

Figure 5-6. Estimated Annual O&M Costs for WBA Treatment Based on Total Cr Removal to 1 ppb and 2 ppb

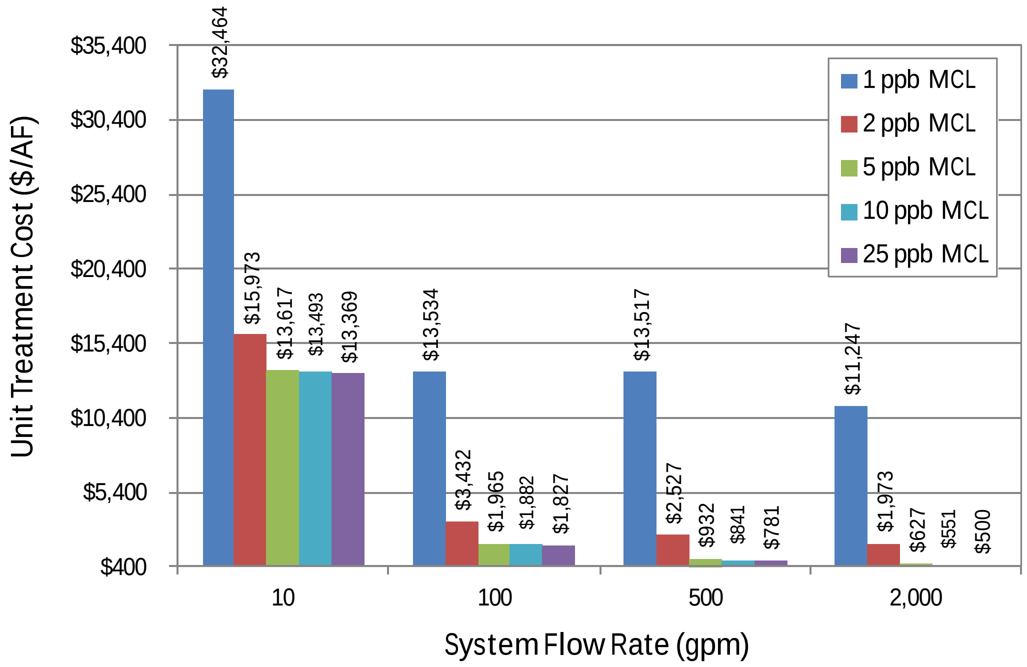

Figure 5-7. WBA Unit Treatment Costs Based on Total Cr Removal

5.4 Reduction/Coagulation/Filtration (Granular Media Filtration) Cost Estimates

This section describes the RCF costs for three system sizes (100, 500, 2,000 gpm) with different influent Cr(VI) concentrations (5, 10, 25 and 50 ppb).

5.4.1 Design Criteria

Table 5-12 presents the design criteria used for costing RCF treatment systems for the three system sizes. An influent Cr(VI) concentration of 50 ppb and an Fe:Cr(VI) ratio of 50:1 (i.e. ferrous dose of 2.5 mg/L) were used to size equipment as a conservative estimate, considering the ACWA residual study results (Appendix G) suggest a higher Fe:Cr(VI) dose might be necessary for lower influent Cr(VI) concentrations. A filter backwash flow rate of 18 gpm/sf and duration of 21 minutes were selected to conservatively size the backwash storage tank and residuals treatment system. The other items were the same as the demonstration-scale process tested at Glendale, California.

pH reduction is not expected to be needed for raw water pH below 7.7 for effective removal of Cr(VI) by RCF. Thus, no pH reduction and post-adjustment systems were considered in the RCF system design and cost estimates but may be necessary for utilities with higher pH values.

Table 5-12. RCF Design Criteria

Item	Design Criteria
Ferrous: Cr(VI) mass ratio	50:1
Required reaction time (reduction)	45 minutes
Reduction tank G value	60 s^{-1}*
Aeration air to water flow rate ratio	4:1
Polymer dose as coagulant aid	0.1 mg/L as active polymer
Polymer mixing time in tank	5 minutes ^
Dual media filtration rate	3 gpm/sf
Filter backwash flow rate	18 gpm/sf
Filter backwash duration	21 minutes
Polymer dose as solids settling aid to spent filter backwash water	1 mg/L as active polymer

*Estimated based on the operating conditions of demonstration-scale RCF at City of Glendale, CA.

^Note that the rapid mix contact time is based on the system at Glendale and may be too long; the optimal time period for rapid mix should be tested before facility design and construction.

5.4.2 Capital Costs

This section describes the RCF capital cost estimates for systems designed to treat flow rates of 100 gpm, 500 gpm and 2,000 gpm.

5.4.2.1 Assumptions

Capital cost development included the following assumptions:

- Equipment was sized for plant capacity (100 gpm, 500 gpm and 2,000 gpm). Excess capacity for redundancy was not included unless otherwise noted.
- Process sizing is not affected by potential Cr(VI) MCLs or treatment target levels.

- Raw water pump already exists and the pump pressure is sufficient to convey the water flow to RCF process. The water flow is carried through the treatment train by gravity until boosted by filter feed pumps. No intermediate pumping is provided.
- Pumps include a standby unit to ensure undisrupted service in the case of equipment breakdown.
- Progressive cavity pumps are used in the design and cost estimates as the filter feed pumps for all RCF systems. A progressive cavity pump was tested in the Phase III Demonstration study to minimize the break-up of iron and chromium floc. However, testing of other types of pumps may be warranted due to the high capital costs of progressive cavity pumps at high flow rates.
- Ferrous sulfate feed system was sized for influent Cr(VI) concentration of 50 ppb, Fe:Cr(VI) ratio of 50:1 (i.e. ferrous dose of 2.5 mg/L), and a chemical storage period of 14 days.
- Reduction equipment consists of three tanks in series, which provide a total of 45 minutes contact time (15 minutes per tank).
- Aeration is achieved by an aeration tank with a 5-minute contact time and coarse bubble diffusers. Aeration off-gas is treated by vapor VPGAC. For water sources with low VOCs concentrations, aeration off-gas treatment may not be needed.
- Polymer mixing is achieved by a rapid mixing tank with a mechanical mixer. Other mixing methods (e.g. inline mixers) may also be used, if tested effective.
- Filtration is achieved by pressurized granular media filters, which were tested at Glendale, California. Gravity filters and microfiltration may be used as alternatives, if tested effective.
- Filter backwash is supplied by stored treated water.
- Residuals treatment equipment was sized based on solids quantities estimated using mass balance, which was shown to be a conservative and reasonable approach for estimating residuals in the Phase III Demonstration study at Glendale, California (Appendix G).
- Supernatant from thickeners is recycled back to the head of the RCF process. Filtrate from SludgeMate containers are recycled back to the thickeners. Alternatively, they could be discharged to the sewer (resulting in sewer discharge fees) or stored onsite and hauled away (requiring a storage tank and disposal costs). Costs were developed for recycle.

- Product water pumping and storage were not included.
- Land cost was not included.
- Equipment/operator building was not included.
- Concrete equipment pads were assumed to cost $1,275 per cubic yard.

5.4.2.2 100-gpm RCF system

Figure 5-8 shows a process flow diagram of a 100-gpm RCF system. The system consists of the following major equipment:

- A ferrous sulfate feed system consisting of a 100-gal chemical storage tank, metering pumps (one duty, one standby) and a static mixer. The system was designed for an influent Cr(VI) level of 50 ppb, a Fe:Cr(VI) ratio of 50:1 (ferrous dose of 2.5 mg/L) and ferrous sulfate solution of 5% as ferrous iron. For lower influent Cr(VI) concentration, a lower Fe:Cr(VI) ratio or a higher ferrous sulfate solution strength, the size of ferrous sulfate feed system may be reduced.
- Three 1,700-gallon reduction tanks in series with mixers,
- An aeration system consisting of a 700-gal aeration tank, diffusers, supply blower, exhaust blower, and two VPGAC vessels in series with a heater for aeration off-gas treatment,
- A 700-gal rapid mixing tank with mixer,
- Two progressive cavity pumps for filter influent pumping, one duty and one standby,
- Two 6.5-feet diameter pressurized filters, one duty and one standby,
- A polymer feed system for coagulation and filtration aid, which dilutes polymer before adding to the process (i.e. a batch system) due to the relatively low polymer dose and flow rate,
- A polymer feed system for solids settling,
- A 12,500-gal filter backwash storage tank with two backwash pumps (one duty, one standby), which is designed to store treated water for one filter backwash.
- A residuals treatment system consisting of two 13,000-gal gravity thickeners, two 6-CY SludgeMate passive filtration containers, recycle pumps and residuals pumps. This residuals treatment system is designed with a greater

residuals handling capacity than the Phase III Demonstration study, considering the operational constraints observed during the demonstration testing. SludgeMate passive filtration containers were used for cost estimates, as the same type of filtration container was tested effective in the Phase III Demonstration study at Glendale, California. Alternative dewatering equipment can be applied if tested and found to be feasible; for example, passive filtration containers similar to SludgeMate or mechanical dewatering such as centrifuges, plate and frame filter presses.

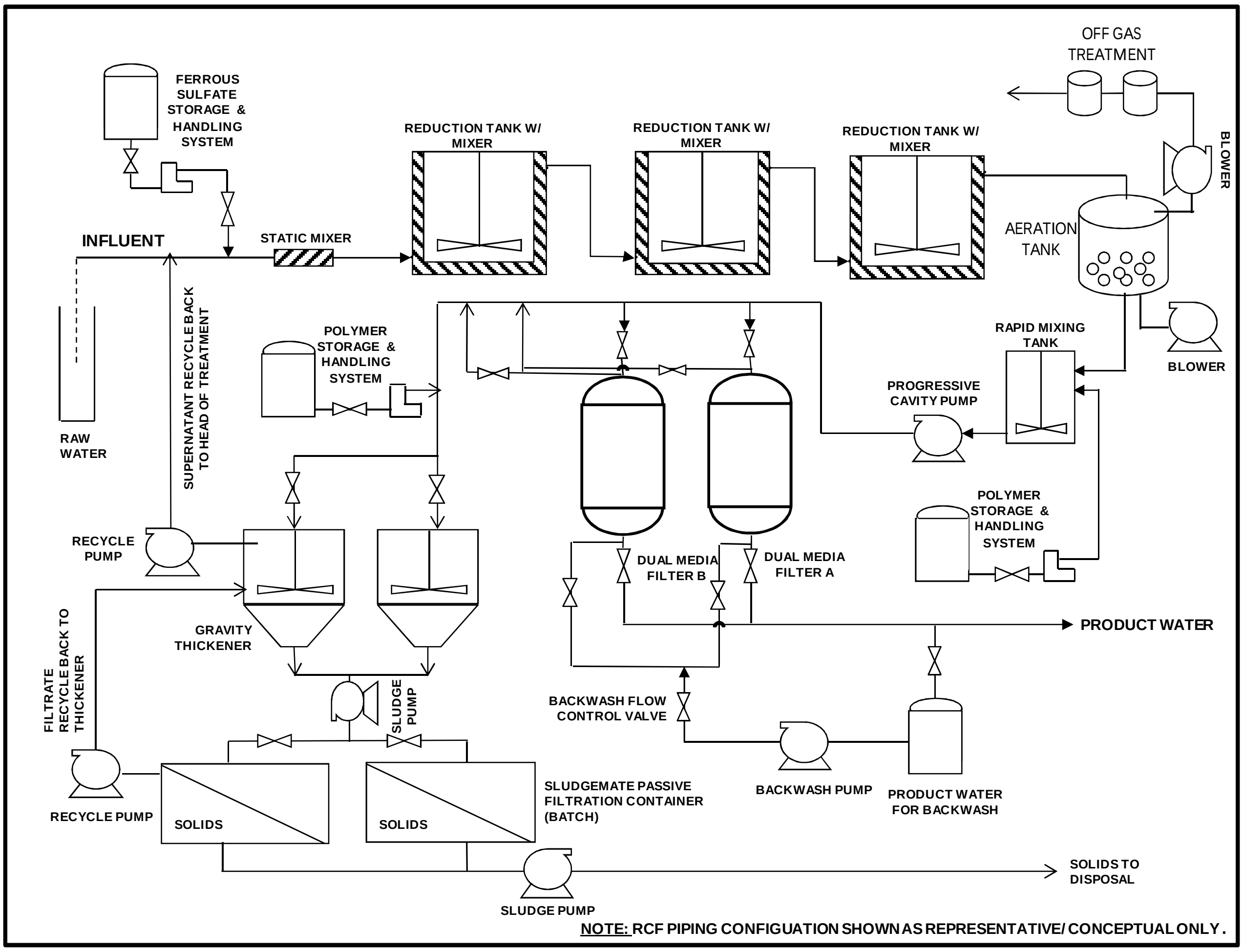

Figure 5-8. Process Flow Diagram of 100-gpm RCF System

5.4.2.3 500-gpm RCF system

Figure 5-9 shows a process flow diagram of a 500-gpm RCF system. The system consists of the following major equipment:

- A ferrous sulfate system consisting of a 500-gal chemical storage tank, metering pumps (one duty, one standby) and a static mixer,
- Three 8,000-gallon reduction tanks in series with mixers,
- An aeration system consisting of a 3,000-gal aeration tank, diffusers, supply blower, exhaust blower, and two VPGAC vessels in series with a heater for aeration off-gas treatment,
- A 3,000-gal polymer mixing tank with mixer,
- Two progressive cavity pumps for filter influent pumping, one duty and one standby,
- One 10-feet diameter and 24-feet long horizontal pressured filter, including three duty cells and one standby cell. The cells can be operated independently of each other. Alternatively, two horizontal filters (8 feet x 22 feet) were proposed by another vendor, which include one duty and one standby. A third alternative is to have four vertical filters, including three duty and one standby. The costs were based on an average of quotes for the first two alternatives.
- A polymer feed system for coagulation aid,
- A polymer feed system for solids settling,
- A 22,000-gal filter backwash storage tank with two backwash pumps (one duty, one standby),which is designed to store treated water for backwash one filter cell of 10 feet x 24 feet filters.
- A residuals treatment system, which consists of one 90,000-gallon equalization tank with mixer, one plate settler, three 15-CY SludgeMate passive filtration containers, recycle pumps and residuals pumps.

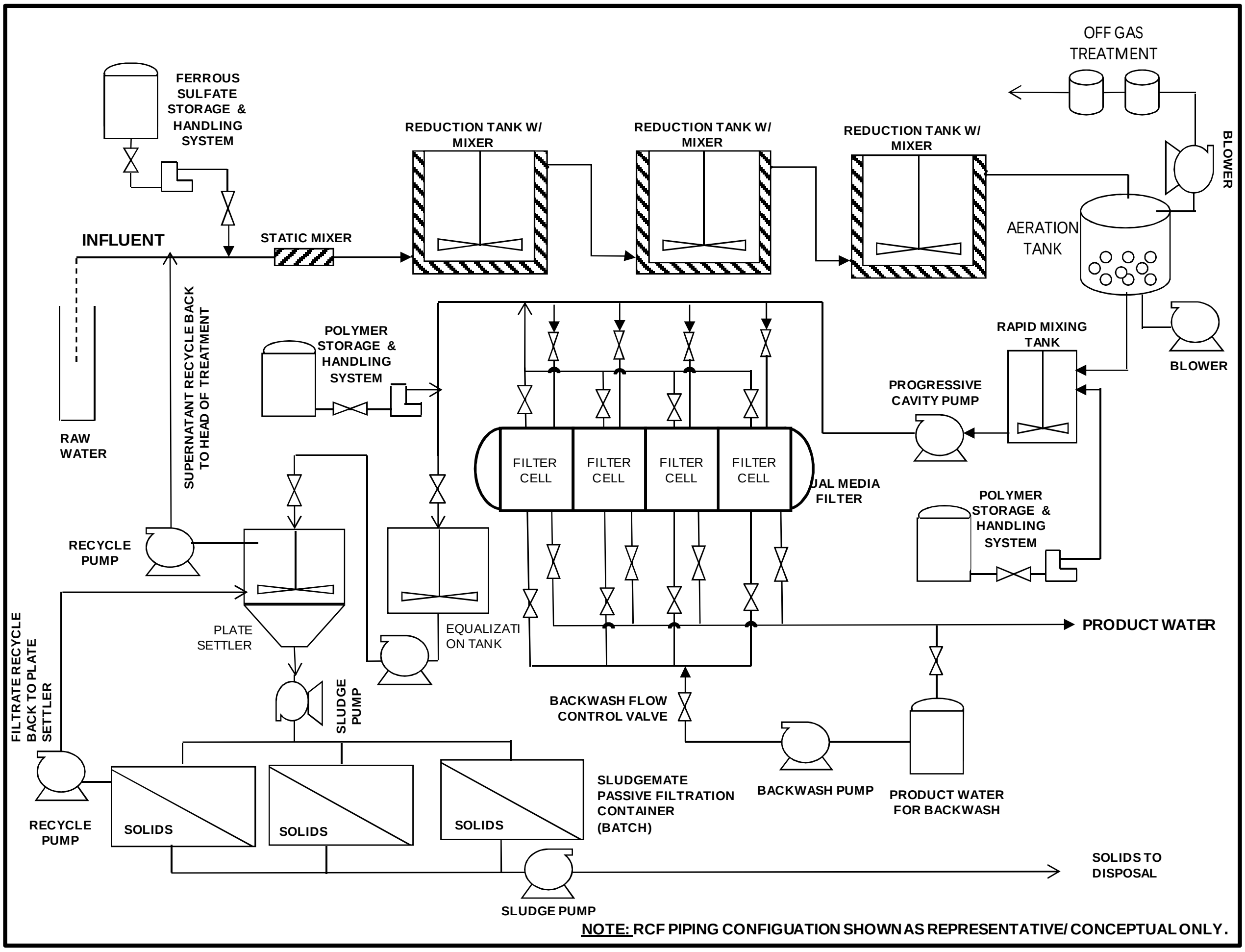

Figure 5-9. Process Flow Diagram of 500-gpm RCF System

5.4.2.4 2,000-gpm RCF system

Figure 5-10 shows a process flow diagram of a 2,000-gpm RCF system. The system consists of the following major equipment:

- A ferrous sulfate system consisting of a 2,000-gal chemical storage tank, metering pumps (one duty, one standby) and a static mixer.
- A concrete reduction tank consisting of three sub-tanks with shared walls and 2-feet freeboard,
- An aeration system consisting of a concrete aeration tank, diffusers, supply blower, exhaust blower, and two vapor phase GAC vessels in series with a heater for aeration off-gas treatment,
- A concrete polymer mixing tank with mixer,
- Three progressive cavity pumps for filter influent pumping, two duty and one standby,
- Two 10-feet diameter and 42-feet long horizontal pressured filters. Each filter consists of four cells, including three duty and one standby. The filter cells can be operated independently of each other. Alternatively, another vendor proposed four 10-feet diameter and 24-feet long filters, including three duty and one standby.
- A polymer feed system for coagulation aid,
- A polymer feed system for solids settling,
- A 30,250-gal filter backwash storage tank with two backwash pumps (one duty, one standby),which is designed to store treated water for backwash one filter cell of 10 feet x 42 feet filters, and
- A residuals treatment system, which consists of one 280,000-gallon equalization tank with mixer, one plate settler thickener, three 40-CY SludgeMate passive filtration containers, recycle pumps and residuals pumps.

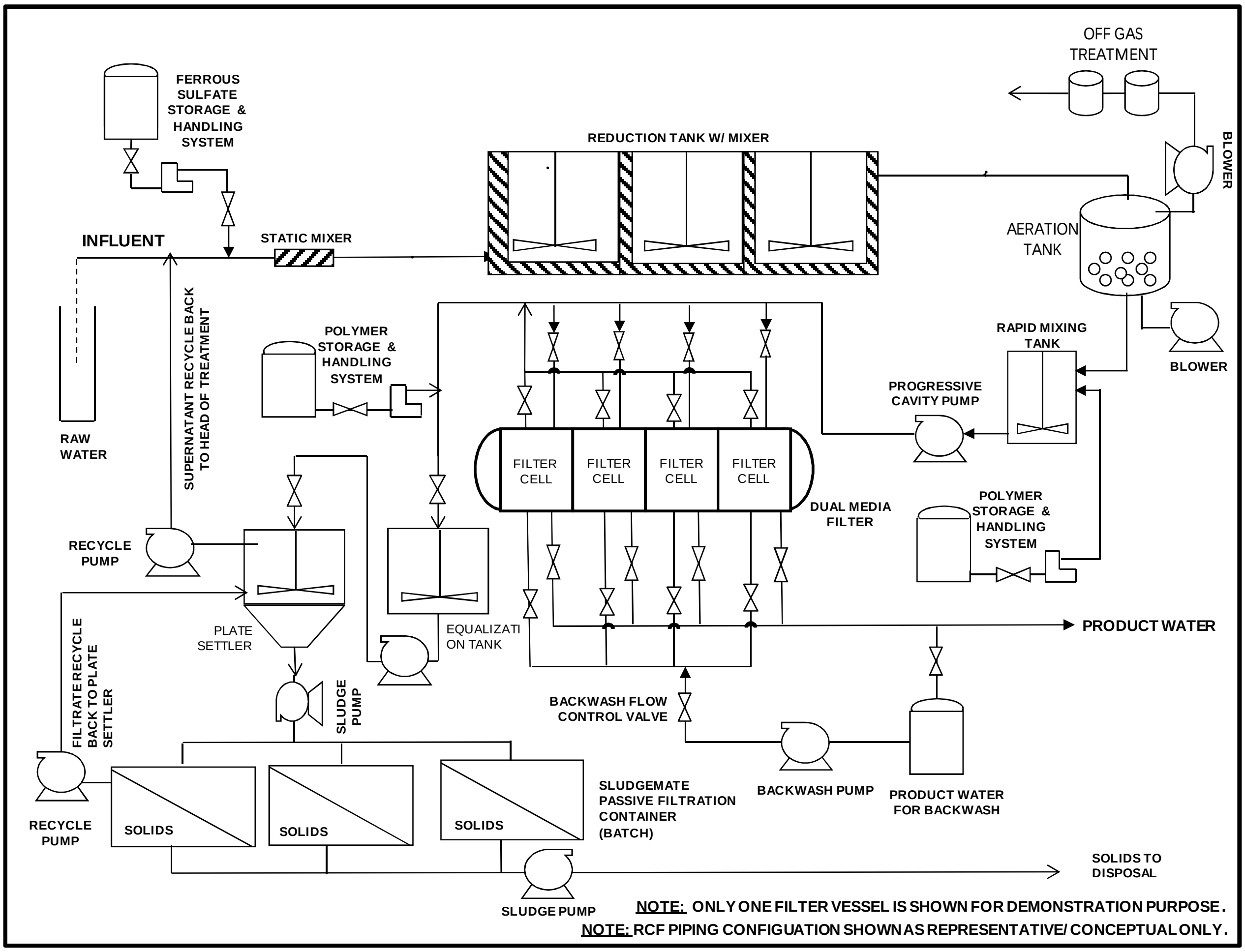

Figure 5-10. Process Flow Diagram of 2,000-gpm RCF System

Table 5-13 presents the capital costs developed for the three RCF system sizes rounded to two significant figures. Details are included in Appendix T.

Table 5-13. Capital Costs for RCF Systems

RCF System Flow Rate (gpm)	Capital Costs (in 2012 Dollars)	Level 5 AACE Accuracy Range (-30% to +50%)
100	$2,500,000	$1,700,000 to $3,700,000
500	$4,500,000	$ 3,200,000 to $6,800,000
2,000	$8,900,000	$ 6,200,000 to $13,000,000

5.4.3 O&M Costs

This section presents O&M cost estimates developed for the three RCF system sizes (i.e. 100, 500 and 2,000 gpm). Annual O&M costs were based on the following assumptions:

- A utilization rate of 100% of the design flow was assumed for simplicity.
- The 5% ferrous sulfate solution cost is $3.02 per gallon for orders in 5-gallon drums and $2.41 per gallon for orders in 55-gallon drums, which was the cost for the Phase III Demonstration study at Glendale, California and adjusted to 2012 dollars. Note that the Glendale supplier required a minimum order of 25 drums.
- The polymer cost is $23.67 per gallon, which was the cost for the Phase III Demonstration study at Glendale, California and adjusted to 2012 dollars.
- The electricity cost is $0.102/kWh.
- Labor costs are estimated based on $102,000 per FTE per year (loaded).
- Filter media is assumed to be replaced at a rate of 10% of the media volume in each filter every year, which reflects a usage life of 10 years.
- VPGAC for aeration off-gas treatment is assumed to have carbon usage rates of 0.6, 11 and 40 lb per day for 100, 500 and 2,000 gpm, respectively, which were estimated by a manufacturer.
- Maintenance costs are estimated as 1% of installed equipment costs.
- Spent filter backwash water accounts for 3% of the design flow rate, as determined in Glendale, California.
- Solid residuals quantities depend on influent Cr(VI) concentration and Fe:Cr(VI) ratio. An Fe:Cr(VI) ratio of 75:1 was assumed as a conservative estimate for influent Cr(VI) concentrations of 5 ppb and 10 ppb (ferrous dose of 0.375 and 0.75 mg/L, respectively). A Fe:Cr(VI) ratio of 50:1 was assumed as a conservative estimate for influent Cr(VI) concentrations of 25 ppb and 50 ppb (ferrous dose of 1.25 and 2.5 mg/L, respectively).
- Dewatered solid residuals have a moisture content of 85%, which was observed for the dewatered solids during the Phase III Demonstration testing of RCF.
- Dewatered solid residuals are non-RCRA hazardous wastes (in California).

- The landfill disposal cost for dewatered solid residuals is $1.58 per pound, based on drum disposal in the Phase III Demonstration study, which was adjusted to 2012 dollars. Bulk disposal in tons can result in cost savings.
- All liquid waste is recycled back to the RCF process, thus no liquid waste discharge costs are included in the O&M costs.
- Analytical costs were developed based on a water quality monitoring schedule updated from Phase III Demonstration study and averages of quotes from two laboratories (details provided in Appendix T).

Figure 5-11 presents the estimated annual O&M costs (in 2012 dollars) for RCF systems. The annual O&M costs were based on a utilization rate of 100% of the design flow 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. 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. Details are in Appendix T.

For a 100-gpm system, labor is the primary driver of the O&M costs, with electricity, analytical costs and residuals disposal also contributing significantly to costs. For a 500 gpm system, labor accounts for the biggest part of O&M, followed by electricity, residuals disposal, and analytical costs. For a 2,000-gpm system, labor or residuals account for the biggest O&M costs (depending on the influent Cr(VI) concentration), followed by electricity, media replacement and chemicals.

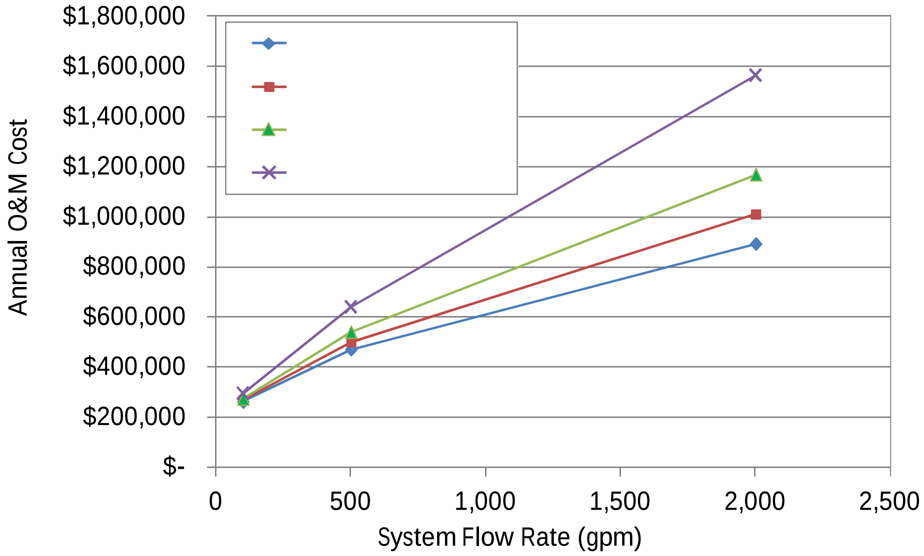

Figure 5-11. Annual O&M Costs for RCF Treatment

5.4.4 20-Year Net Present Values

Table 5-14 provides the 20-year net present values (in 2012 dollars) of RCF O&M costs for the three system sizes and four influent Cr(VI) concentrations, rounded to two significant figures.

Table 5-14. 20-Year Net Present Values of RCF O&M Costs(1)

100	$ 4,400,000	$ 4,500,000	$ 4,600,000	$ 4,900,000
500	$ 7,900,000	$ 8,400,000	$ 9,000,000	$ 11,000,000
2,000	$ 15,000,000	$ 17,000,000	$ 20,000,000	$ 26,000,000

(1) Capital and 20-year NPV O&M based on 2.5% inflation and a 4.5% discount rate

(2) In 2012 dollars

5.4.5 Unit Treatment Cost ($/AF)

Figure 5-12 presents the estimated unit treatment costs in dollars per acre-foot ($/AF) for the three RCF systems with different influent Cr(VI) concentrations. For a 2,000-gpm system, the unit treatment cost is significantly lower than the smaller systems due to economies of scale. In addition, a lower influent Cr(VI) concentration is estimated to result in a significantly lower unit treatment cost for the large system.

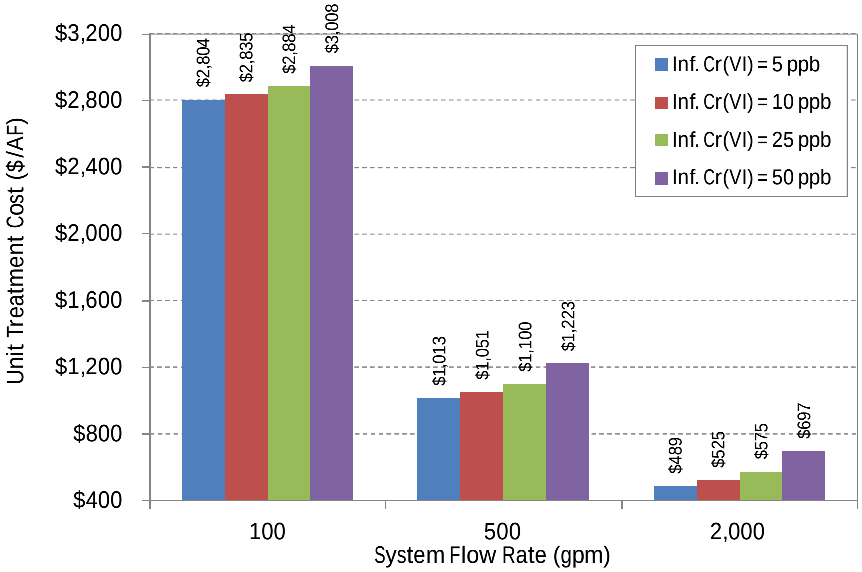

Figure 5-12. RCF Unit Treatment Cost

5.4.6 RC without Wastewater Recycle

With granular media filtration, filter backwash water accounts for approximately 3% of the total flow rate, based on the demonstration-scale RCF testing at Glendale. The costs described above include wastewater recycle and treatment, and solids disposal costs.

Alternately, the wastewater might be stored in a waste tank and discharged into the sewer, assuming this option is allowed by a utility's sewer discharge permit. Total Cr discharge limit vary at different cities. For City of Glendale, the limit for total Cr discharge to the sewer is 10 mg/L (10,000 ppb). During the Glendale testing, limited total Cr data was collected for spent filter backwash water; however, supernatant of the gravity thickener contained total Cr in the range of 27 – 7,400 ppb, with an average of 685 ppb, for low and high Cr(VI) influent water tested. Total Cr levels in the supernatant are expected to be lower than the levels in the spent filter backwash water, as some total Cr was precipitated and removed from the liquid. According to mass balance calculations and assuming 80 ppb of total Cr is completely removed by filter backwash, approximately 2.6 mg/L of total Cr would be present in the spent filter backwash water, which is below the sewer discharge limit of 10 mg/L. Without recycle, no wastewater recycle and treatment process would be needed, including polymer feed system for solids settling, residual treatment system. Instead, a waste water storage tank is needed to hold the water for discharge.

The capital costs for RCF without recycle were estimated based on the same assumptions in Section 5.4.2.1 only without solids dewatering and recycle. The major equipment described in Sections 5.4.2.2 through 5.4.2.4 is still applicable to the systems without recycle, except the following:

- No polymer feed system for backwash water solids settling,
- No residuals treatment system,
- A spent filter backwash storage tank is added with discharge pumps. The capacity is designed to store backwash water from all filters as a conservative approach. 21,000-gallon, 85,000-gallon and 286,000-gallon tank capacities are estimated for 100, 500 and 2,000 gpm systems, respectively.

Table 5-15 presents the capital costs developed for the three RCF system sizes rounded to two significant figures. Details are included in Appendix T.

Table 5-15. Capital Costs for RCF Systems without Recycle

RCF System Flow Rate (gpm)	Capital Costs (in 2012 Dollars)	Level 5 AACE Accuracy Range (-30% to +50%)
100	$2,200,000	$1,500,000 to $3,200,000
500	$3,600,000	$ 2,600,000 to $5,500,000
2,000	$8,100,000	$ 5,700,000 to $12,000,000

The O&M costs for RCF without recycle were estimated based on the same assumptions in Section **Error! Reference source not found.Error! Reference source not found.** and adjusted as the following:

- No polymer is needed for solids settling,
- No solid residuals need to be disposed,
- Wastewater is discharged to the sewer without treatment. The discharge cost is assumed as $3.06 per hundred cubic feet, plus a quarterly discharge fee of $918, which is adjusted based on the current costs for WBA wastewater disposal incurred at Glendale and is in 2012 dollars.
- Labor rates stay the same, but the labor time was reduced to reflect less equipment monitoring resulting from no residuals treatment system,
- The electricity consumption was adjusted to reflect no wastewater recycle and treatment,
- Analytical costs were adjusted to reflect no monitoring for wastewater treatment system.
- No value was assigned to the 3% water loss.

Figure 5-13 presents the estimated annual O&M costs (in 2012 dollars) for RCF systems of different sizes. The difference between different influent Cr(VI) concentrations is significantly reduced, as a result of no solid waste disposal as a hazardous waste. Details are included in Appendix T.

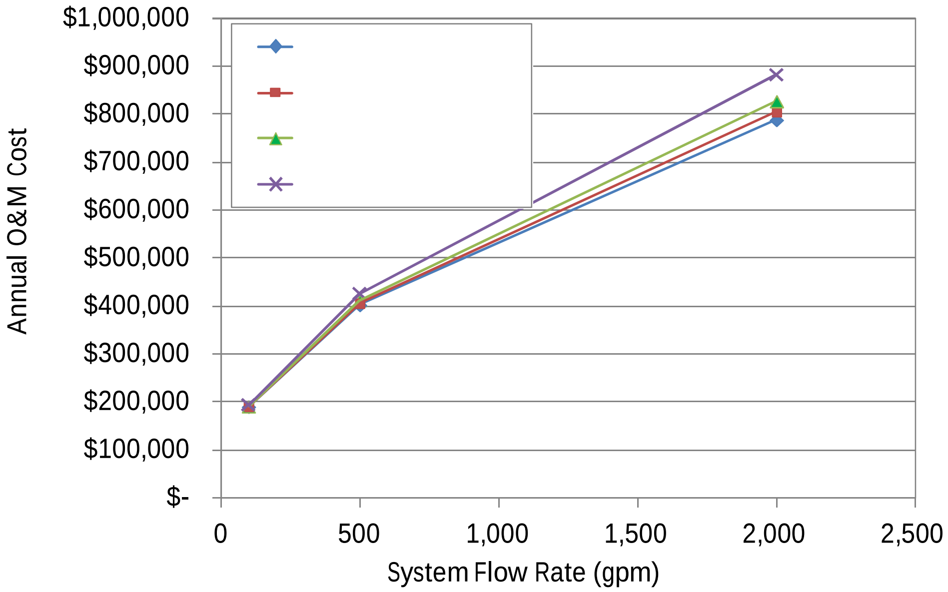

Figure 5-13. Annual O&M Costs for RCF Treatment without Recycle

Table 5-16 provides the 20-year net present values (in 2012 dollars) of RCF O&M costs without recycle for the three system sizes and four influent Cr(VI) concentrations, rounded to two significant figures.

Table 5-16. 20-Year Net Present Values of RCF O&M Costs without Recycle (1)

100	$ 3,200,000	$ 3,200,000	$ 3,200,000	$ 3,200,000
500	$ 6,700,000	$ 6,800,000	$ 6,900,000	$ 7,000,000
2,000	$ 13,000,000	$ 13,000,000	$ 14,000,000	$ 15,000,000

(1) Capital and 20-year NPV O&M based on 2.5% inflation and a 4.5% discount rate

(2) In 2012 dollars

Figure 5-14 presents the estimated unit treatment costs in dollars per acre-foot ($/AF) for the three RCF systems without recycle with different influent Cr(VI) concentrations. The unit treatment costs for different influent Cr(VI) concentrations with a same flow rate are similar, resulting from no solid waste disposal. The difference between different influent Cr(VI) concentrations is primarily caused by different ferrous doses.

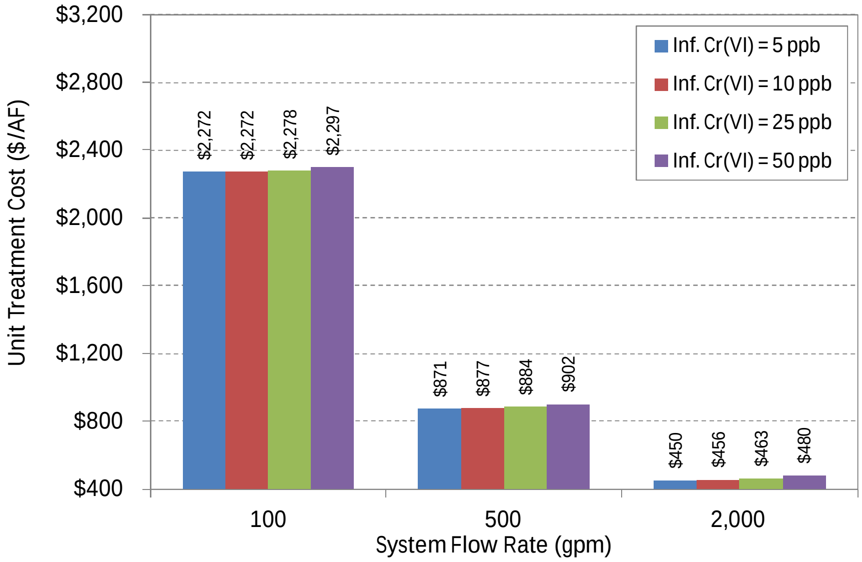

Figure 5-14. RCF without Recycle Unit Treatment Cost

5.5 RCF with Microfiltration Cost Estimates

This section describes costs for the RCF process with MF for three system sizes (100, 500, 2,000 gpm). In this iteration, MF replaces the granular media filtration in the RCF process described in Section 5.4 . Two types of MF membranes (vacuum and pressure) were considered for the cost estimates.

5.5.1 Design Criteria

In general, the RCF with MF process shares the same pre-treatment unit processes as the RCF with granular media filtration process (referred to as RCF for simplicity), including ferrous addition, reduction, and aeration with off-gas treatment (if necessary). Due to the potential impact of ferrous iron on membrane fouling, chlorination is added following aeration to oxidize remaining ferrous to ferric iron. MF pilot testing at the City of Glendale showed a small chlorine dose (added to the aeration effluent) based on the stoichiometric ratio of remaining ferrous to achieve a residual below 0.02 mg/L, did not re-oxidize Cr(III) to Cr(VI) to a significant extent. Specifically, Cr(VI) levels in membrane effluent were typically higher than in membrane influent by less than 0.5 ppb.

Aeration time might be reduced (or eliminated) if chlorination is shown to effectively oxidize ferrous at a higher level (e.g. the level in reduction effluent before aeration) without significantly oxidizing Cr(III) to Cr(VI). For the cost estimates, aeration with a 5-minute contact time is included in the RCF with MF process. It is also possible that reduction time could be decreased with the higher ferrous dose and the use of chlorination. Additional testing is needed to explore this potential optimization further.

For the RCF with MF process, the ferrous dose is assumed to be 2.0 mg/L, as tested in the Glendale pilot study. For RCF cost estimates in Section 5.4, the ferrous dose is assumed to be based on specific influent Cr(VI) concentrations and a Fe:Cr(VI) ratio of 75:1 for Cr(VI) concentrations of 5 and 10 ppb (ferrous dose of 0.375 and 0.75 mg/L, respectively), and a Fe:Cr(VI) ratio of 50:1 for Cr(VI) concentrations of 25 and 50 ppb (ferrous dose of 1.25 and 2.5 mg/L, respectively), which was based on previous pilot, demonstration-scale as well as jar testing of various water qualities. Ferrous dose is an important factor for RCF cost estimates due to its impact on residuals quantities and hence O&M costs. However, ferrous dose has a lesser impact on cost estimating for RCF with MF (other than chemical cost) as MF wastewater is assumed to be discharged to the sewer thus no solids residuals would be disposed.

Other major differences between the RCF with MF process and RCF include: 1) the RCF with MF process does not include polymer feed systems, as MF membranes generally do not tolerate with polymer; 2) MF backwash wastewater is assumed to be discharged to the sewer since recycling can have negative effects on membrane fouling; and 3) MF chemical recovery wastewaters (including maintenance cleans and CIPs) are neutralized before discharged to the sewer.

Table 5-19 summarizes the key design criteria for vacuum MF in the RCF with MF process for 100, 500 and 2,000 gpm, provided by GE/Zenon based on the pilot testing results at Glendale. The design recovery rate is 95% for all three systems, indicating that the volume of waste sent to the sewer is 5%. The design instantaneous flux is 45 gfd for 2,000 gpm. Lower fluxes were intentionally selected for 100 and 500 gpm systems to allow for membrane operations without daily maintenance cleans. Backwash is estimated to occur approximately every 63 and 57 minutes for 100 and 500 gpm, due to the lower fluxes. More frequent backwashing is expected for 2,000 gpm at a frequency of 31 minutes. All MF systems are designed to have CIPs once a month, using sodium hypochlorite, citric acid and hydrochloric acid. The vacuum MF system design is based on the Glendale water quality and the pilot testing results to provide basis for cost estimates. MF design is expected to change significantly for a different water quality, recovery rate and operational preferences. MF pilot testing and design should be conducted case by case with specific systems needs considered. This testing proved that the vacuum MF system is effective at achieving improved total chromium removals with realistic design criteria.

Table 5-17. Design Criteria for GE/Zenon Vacuum MF in the RCF with MF Process

Item	100 gpm	500 gpm	2,000 gpm
Design capacity (net) with all trains in service at 20 ºC, gpm	100	500	2,000
Membrane module	ZeeWeed® 1000	ZeeWeed® 1000	ZeeWeed® 1000
Membrane unit	Z-BOX™ S12	Z-BOX™ S18	Z-BOX™ L192
Design temperature range, °C	20 - 23	20 – 23	20 - 23
Recovery rate at design capacity	95%	95%	95%
Design net flux (all trains) at 20º C, gfd	27	30	38
Design instantaneous flux (all trains) at 20º C, gfd	29	32	45
Number of trains	1	3	2
Number of modules per train	12	18	84 plus 12 blank modules [#]
Total membrane area, sf	5,400	24,300	75,600
Backwash frequency per train (estimated)	Every 63 minutes	Every 57minutes	Every 31 minutes
Membrane integrity test	1/day/train	1/day/train	1/day/train
Maintenance clean frequency	Not applicable*	Not applicable*	1/day/train Sodium hypochlorite
Clean-in-Place (CIP) frequency	12/year/train Sodium hypochlorite followed by citric acid and hydrochloric acid[^]	12/year/train Sodium hypochlorite followed by citric acid and hydrochloric acid[^]	12/year/train Sodium hypochlorite followed by citric acid and hydrochloric acid[^]
Permeate turbidity, NTU	≤ 0.1 NTU for 95% of the time	≤ 0.1 NTU for 95% of the time	≤ 0.1 NTU for 95% of the time

[*] According to GE/Zenon, maintenance cleans are not expected necessary for the 100 gpm and 500 gpm systems due to lower design flux rates for the two systems and the low membrane fouling rates observed in pilot scale testing.

[#] Blank modules are included to fill blank module slots that are not needed for the design.

[^] This is the CIP procedures tested during the Glendale MF pilot study, which might be modified for improved membrane recovery.

Table 5-18 summarizes the key design criteria for pressure MF in the RCF with MF process for 100, 500 and 2,000 gpm, provided by Pall based on the pilot testing results at Glendale. The systems are designed based on a recovery rate of 95% and a maximum instantaneous flux of 70 gfd as a conservative approach, as higher recovery rate (97%) and flux (up to 90 gfd) were tested at the pilot scale. Backwash is estimated to be every 13 minutes for 100, 500 and 2,000 gpm. The backwash frequencies are based on the recovery rate of 95% and the membrane performance in pilot testing. CIPs are designed to be every 30 days with sodium hypochlorite followed by citric acid. Hydrochloric acid may be used to help reduce pH if needed. Maintenance cleans (also called enhanced flux maintenance, EFM, or chemically enhanced backwash, CEB), a procedure involving circulation of a chemical solution on a daily or weekly basis to control routine fouling, is not expected to be necessary based on the pilot testing results. However, EFMs could be conducted automatically if needed.

As with the vacuum system, MF pilot testing and design should be conducted case by case with specific systems needs considered. This testing proved that the pressure MF system is effective at achieving improved total chromium removals with realistic design criteria.

Table 5-18. Design Criteria for Pall Pressure MF in RCF with MF Process

Item	**100 gpm**	**500 gpm**	**2,000 gpm**
Design capacity (net) with all trains in service at 20 ºC, gpm	100 gpm	500 gpm	2,000 gpm
Membrane module	Microza^	Microza^	Microza^
Membrane unit	AP-3	AP-6	AP-6X
Design temperature range, °C	20	20	20
Recovery rate at design capacity	95%	95%	95%
Design net flux at 20º C, gfd	54	56	56
Design instantaneous flux (all trains) at 20º C, gfd	Maximum 70	Maximum 70	Maximum 70
Number of units	1	1	2
Number of modules per unit	5	24	48
Total membrane area, sf	2,690	12,912	51,648
Backwash frequency per unit (estimated)	Every 13 minutes	Every 13 minutes	Every 13 minutes
Membrane integrity test	1/day/unit	1/day/unit	1/day/unit
Enhanced flux maintenance frequency	Not applicable*	Not applicable*	Not applicable*
Clean-in-Place (CIP) frequency	Every 30 days. Sodium hypochlorite followed by citric acid	Every 30 days. Sodium hypochlorite followed by citric acid	Every 30 days. Sodium hypochlorite followed by citric acid
Permeate turbidity, NTU	≤ 0.1 NTU for 95% of the time	≤ 0.1 NTU for 95% of the time	≤ 0.1 NTU for 95% of the time

^Microza is the trade name of model UNA 620A.

*According to Pall, enhanced flux maintenance cleans are not expected to be necessary for the three systems, based on the low membrane fouling rates observed at pilot scale.

5.5.2 Capital Costs

This section describes the RCF with MF capital cost estimates for systems designed to treat flow rates of 100 gpm, 500 gpm and 2,000 gpm.

5.5.2.1 Assumptions

Capital cost development included the following assumptions:

- All assumptions for the RCF systems in Section 5.4.2.1 are applicable, except for the progressive cavity pump, ferrous sulfate feed system, polymer mixing, filtration, filter backwash and residuals treatment as described below.
- Progressive cavity pumps are not needed for RCF with MF systems. For vacuum MF systems, it is assumed the membrane tank(s) are filled by gravity. Process pump(s) for permeation and backwash are included in equipment provided by GE/Zenon. For pressure MF systems, it is assumed the feed tank(s) are filled by gravity. Membrane feed pump(s) are included in equipment provided by Pall.
- The same RCF ferrous feed systems are used in the cost estimates for RCF with MF. The systems for the RCF process are sized for a slightly higher dose (2.5 mg/L compared to 2.0 mg/L), thus, the chemical storage tank capacity is slightly greater than for the dose of 2.0 mg/L; however, the chemical pumps and static mixer would be the same. Therefore, the cost for the dose of 2.0 mg/L would be slightly lower than for the dose of 2.5 mg/L.
- Sodium hypochlorite systems are sized for a chlorine dose of 1.3 mg/L using 12.5% sodium hypochlorite solution, which is sufficient to oxidize 2.0 mg/L ferrous as a conservative design. Chemical storage is designed for 14 days.
- No polymer is added to RCF with MF process.
- Filtration is achieved via MF with the configurations listed in Tables 5-15 and 5-16.
- For vacuum MF systems, an equalization tank is included in the process prior to MF to accommodate flow variations due to membrane backwash. Equalization tanks were designed with sufficient volumes to equalize flow resulting from all trains in backwash at the same time, as a conservative approach. Maintenance cleans, CIPs and integrity tests are assumed to be conducted in low demand periods (e.g. during the night), such that additional equalization volume was not included.
- For pressure MF systems, feed tank(s) are included in equipment provided by Pall, which serve to equalize flow variations for one backwash for one unit (staggered unit backwash). For the 2,000-gpm system, an additional

equalization tank was included to handle flow variation when both trains were in backwash.

- MF backwash wastewater is collected in a waste storage tank and discharged to the sewer without treatment. The waste tanks were designed to store waste water from three backwashes as a conservative approach. Alternatives include recycling supernatant after settling the solids or using a second stage MF to concentrate solids so that the second stage MF permeate could be recycled back to the process. However, for this analysis, a conservative approach was taken in assuming backwash water could not be recycled in the MF systems due to accelerated membrane fouling. Potential problems with the recycle include accelerated membrane fouling rate to the primary MF systems. If recycle is desired, the option needs to be evaluated prior to full-scale design to ensure feasible and cost-effective O&M. The benefits and drawbacks of wastewater disposal/treatment approaches should be weighed by considering capital and O&M costs, labor requirements, impacts on MF membrane life cycle, and the long-term recovery goal for the utility.
- MF wastewater from maintenance cleans and CIPs are collected in waste storage tanks and neutralized before being discharged to the sewer. Sodium hypochlorite wastewater and citric acid wastewater are collected in separate waste tanks to avoid generation of chlorine gas. The chemical waste tanks are made of materials or have liners compatible with high chlorine or acid concentrations. If maintenance cleans or EFMs are needed, waste water can be stored in the sodium hypochlorite waste tank or citric acid waste tank, depending on the chemical used for maintenance cleans or EFMs. The waste tanks were designed to store waste from one CIP event, since CIPs are typically conducted on a monthly basis and can be scheduled at a low demand time (e.g. during the night). The tank capacities are estimated sufficient to hold waste from one maintenance clean or EFM.
- A building is included to house the MF equipment based on a unit cost of $250 per square feet, which is a moderate estimate for Southern California. The same building area was used for GE/Zenon and Pall systems for a same flow rate, as the space requirement for them are similar.

5.5.2.2 100-gpm RCF system

Figure 5-15 shows a process flow diagram of RCF with MF. For a 100-gpm flow rate, the system was assumed to consist of the following major equipment:

- The same ferrous sulfate feed system, reduction tanks and aeration system as for the 100-gpm RCF system in Section 5.4.2.2.
- A sodium hypochlorite feed system consisting of a 55-gallon chemical storage tank, metering pumps (one duty, one standby) and a static mixer,
- A 500-gallon equalization tank for the GE/Zenon system. A feed tank is included in the equipment provided by Pall, which serves as an equalization tank.
- MF membrane and ancillary equipment provided by the membrane manufacturer. The GE/Zenon major equipment include a strainer, a process skid (with two high density polyethylene (HDPE) membrane tanks, membrane modules, two backwash tanks, a process pump), an air compressor system, manual chemical dosing valves, chemical pumps, and programmable logic controller (PLC). No automatic control equipment for maintenance cleans is included. According to GE/Zenon, small package systems are not designed with automatic controls for maintenance cleans; adding customer engineered controls is possible, although could be costly. A typical approach for small systems is to increase membrane area to reduce the need for maintenance cleans. For the proposed membrane system, no maintenance cleans are expected to be necessary, as the MF system is designed with conservative flux compared to the pilot testing, according to GE/Zenon. Maintenance cleans could be performed manually if needed. Utilities should consider adding automatic controls if frequent maintenance cleans are determined to be necessary.
- For the Pall MF system, the major equipment include a skid (with a strainer, a feed tank, membrane modules, a feed pump with variable-frequency drive (VFD), a backwash tank and pump with VFD, an on-skid CIP system, a local control panel), an air compressor system, uninterruptable power supply (UPS), a EFM/CIP system, and a EFM/CIP/chemical transfer system.
- A backwash waste storage tank (1,250-gallon for the GE/Zenon system and 475-gallon for the Pall system) with discharge pumps,
- A chlorine waste tank (800-gallon for both GE/Zenon and Pall systems) with discharge pumps to store sodium hypochlorite waste from CIP or maintenance clean, which will be dechlorinated before being discharged.
- An acid waste tank (800-gallon for both GE/Zenon and Pall systems) with discharge pumps to store acid waste from CIPs, which will be neutralized before discharged.

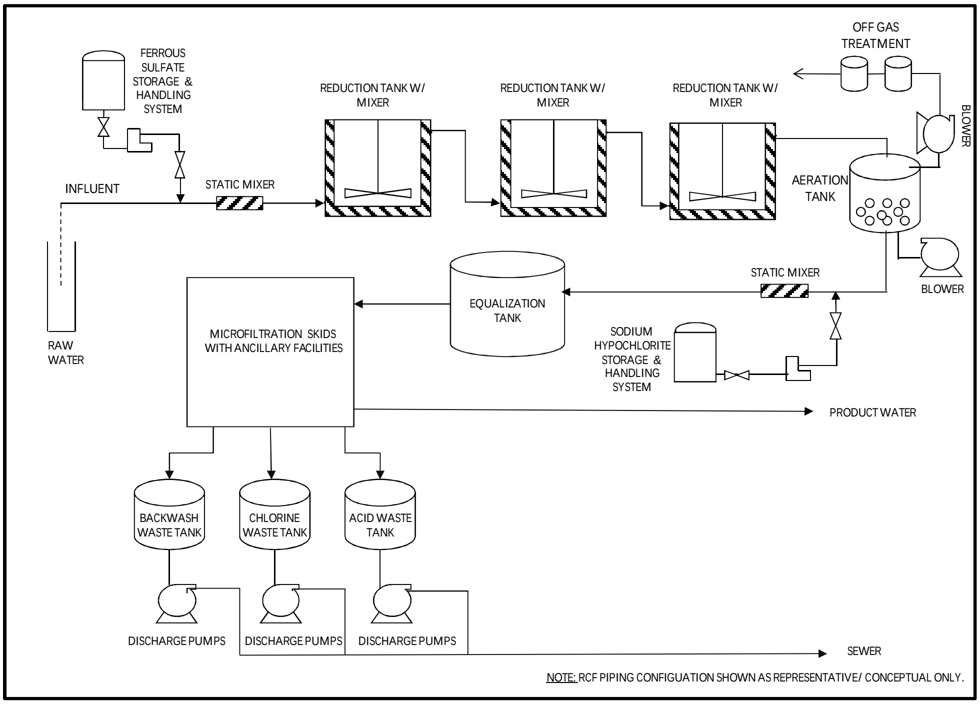

Figure 5-15. Process Flow Diagram of RCF with MF System (100, 500 and 2,000 gpm)

5.5.2.3 500-gpm RCF system

For 500-gpm, the system was assumed to consist of the following major equipment:

- The same ferrous sulfate feed system, reduction tanks and aeration system as for the 500-gpm RCF system in Section 5.4.2.3.
- A sodium hypochlorite feed system consisting of 115-gallon chemical storage tank, metering pumps (one duty, one standby) and a static mixer,
- A 3,000-gallon equalization tank for GE/Zenon system. A feed tank is included in the equipment provided by Pall, which serves as an equalization tank.
- MF membrane and ancillary equipment provided by membrane manufacturer. The GE/Zenon major equipment include a strainer, three process skids (each skid with three HDPE membrane tanks, membrane modules, three backwash tanks, a process pump), an air compressor system, manual chemical dosing valves, chemical pumps, and PLC. No automatic control equipment for

maintenance cleans is included as described for the Zenon100-gpm system. Maintenance cleans could be performed manually if needed. Utilities should consider adding automatic controls if frequent maintenance cleans are determined to be necessary.

- For Pall MF system, the major equipment include a skid (with a strainer, a feed tank, a membrane skid with membrane modules, feed pump with variable-frequency drive (VFD), a backwash tank and pump with VFD, an on-skid CIP system, a local control panel), an air compressor system, uninterruptable power supply (UPS), a EFM/CIP system and a EFM/CIP/Chemical Transfer system.
- A backwash waste storage tank (2,000-gallon for the GE/Zenon system and 1,500-gallon for the Pall system) with discharge pumps,
- A chlorine waste tank (1,100-gallon for the GE/Zenon system and 3,000-gallon for the Pall system) with discharge pumps to store sodium hypochlorite waste from CIP or maintenance clean, which will be dechlorinated before being discharged.
- An acid waste tank (1,100-gallon for the GE/Zenon system and 3,000-gallon for the Pall system) with discharge pumps to store acid waste from CIP, which will be neutralized before being discharged.

5.5.2.4 2000-gpm RCF system

For 2,000-gpm, the system was assumed to consist of the following major equipment:

- The same ferrous sulfate feed system, reduction tanks and aeration system as for the 2,000-gpm RCF system in Section 5.4.2.4.
- A sodium hypochlorite feed system consisting of 475-gallon chemical storage tank, metering pumps (one duty, one standby) and a static mixer,
- A 10,300-gallon equalization tank for the GE/Zenon system. Two feed tanks are included in the equipment provided by Pall, which serve as equalization tanks. In addition, a 3,000-gallon equalization tank is added to the Pall system.
- MF membrane and ancillary equipment provided by membrane manufacturer. The GE/Zenon major equipment include a strainer, four stainless steel membrane tanks, membrane modules, a backwash tank, a process pump skid, an air compressor system, a CIP skid with a CIP tank, automatic chemical feeding systems and PLC. Maintenance cleans and CIPs can be performed automatically with the equipment supplied.

- For the Pall MF system, the major equipment include two skids (with a strainer, two feed tanks, membrane modules, feed pumps with variable-frequency drive (VFD), two backwash tanks and pumps with VFD, an on-skid CIP system, a Master control panel), an air compressor system, uninterruptable power supply (UPS), a EFM/CIP system and EFM/CIP/Chemical Transfer system.
- A backwash waste storage tank (5,050-gallon for the GE/Zenon system and 3,000-gallon for the Pall system) with discharge pumps.
- A chlorine waste tank (3,500-gallon for the GE/Zenon system and 4,000-gallon for the Pall system) with discharge pumps to store sodium hypochlorite waste from CIP or maintenance clean, which will be dechlorinated before being discharged.
- An acid waste tank (3,500-gallon for the GE/Zenon system and 4,000-gallon for the Pall system) with discharge pumps to store acid waste from CIP, which will be neutralized before being discharged.

Table 5-19 presents the capital costs developed for the three RCF with MF system sizes rounded to two significant figures. Details are included in Appendix T. Capital costs were similar for RCF with vacuum MF and pressure MF.

Table 5-19. Capital Costs for RCF with MF Systems

System Flow Rate (gpm)	RCF with Vacuum MF		RCF with Pressure MF	
	Capital Costs (In 2012 Dollars)	Level 5 AACE Accuracy Range (-30% to +50%)	Capital Costs (in 2012 Dollars)	Level 5 AACE Accuracy Range (-30% to +50%)
100	$1,900,000	$1,400,000 to $ 2,900,000	$2,300,000	$1,600,000 to $3,400,000
500	$3,900,000	$2,800,000 to $5,900,000	$3,500,000	$2,500,000 to $4,400,000
2,000	$8,100,000	$5,700,000 to $11,000,000	$7,700,000	$5,400,000 to $11,500,000

5.5.3 O&M Costs

This section presents O&M cost estimates developed for the three RCF with MF system sizes (i.e. 100, 500 and 2,000 gpm). Annual O&M costs were based on the following assumptions:

- The same assumptions for utilization rate, ferrous sulfate pricing, electricity, labor, VPGAC, maintenance costs in Section 5.4.3 are applied to MF cost estimates.
- The cost of 12.5% sodium hypochlorite is $6.15 per gallon for orders in 5-gallon drums and $4.23 per gallon for orders in 55-gallon drums.
- Costs are $8.25 per gallon for 50% citric acid, $10.78 per gallon for 33% hydrochloric acid, $7.75 per gallon for 50% sodium hydroxide and $8.05 for 38% sodium bisulfate for orders in 5-gallon drums since relatively small quantities will be needed. Hydrochloric acid is assumed to be used for pH reduction in CIPs for Zenon systems. Phosphoric acid could be used instead if desired.
- For vacuum MF systems, no maintenance clean chemicals are included in the O&M costs for 100 and 500 gpm system sizes, as maintenance cleans are not expected necessary based on the pilot testing results and conservative design fluxes, according to GE/Zenon. For 2,000 gpm, it is assumed that sodium hypochlorite will be used for maintenance cleans, according to GE/Zenon. However, alternative chemicals such as citric acid might be used instead, if found to be effective in subsequent testing. It is suspected that citric acid may be more effective than sodium hypochlorite for controlling/recovering membrane fouling for groundwater.
- For pressure MF systems, no EFM chemicals are included in the O&M costs for 100, 500 and 2,000 gpm systems, as EFMs are not expected necessary based on the pilot testing results and the design fluxes, according to Pall. Citric acid or sodium hypochlorite can be used for EFMs if needed.
- Wastewater accounts for 5% of the total flow rate, as the MF design recovery rate is 95%. All wastewater is discharged to the sewer in these cost estimates. Chemical waste water is neutralized or dechlorinated before discharge.
- Total chromium in wastewater is assumed to meet the sewer discharge permit requirement without treatment. During the Glendale pilot testing, all wastewater tested contained total chromium below 1.1 mg/L for the low Cr(VI) water source. For the high Cr(VI) water source (approximately 80 ppb), wastewater contained total chromium with an average of 3.9 mg/L and a maximum of 7.2 mg/L. Glendale has a sewer discharge limit of 10 mg/L for total chromium.
- Energy consumption required for MF membrane operations was provided by GE/Zenon and Pall, including process pumps and air compressor operation.

- Annual membrane replacement costs were estimated based on a membrane life of 10 years and an interest rate of 5%.
- Analytical costs were developed based on a water quality monitoring schedule updated from the Phase IIIA pilot study and averages of quotes from two laboratories (details provided in Appendix T).

Figure 5-16 presents the estimated annual O&M costs for RCF with MF systems. The annual O&M costs were based on a utilization rate of 100% of the design flow 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. Details are provided in Appendix T. For a 100-gpm system, labor is the primary driver of the O&M costs, followed by analytical costs and electricity. For 500 and 2,000 gpm systems, labor followed by electricity and chemicals accounts for the biggest O&M cost components.

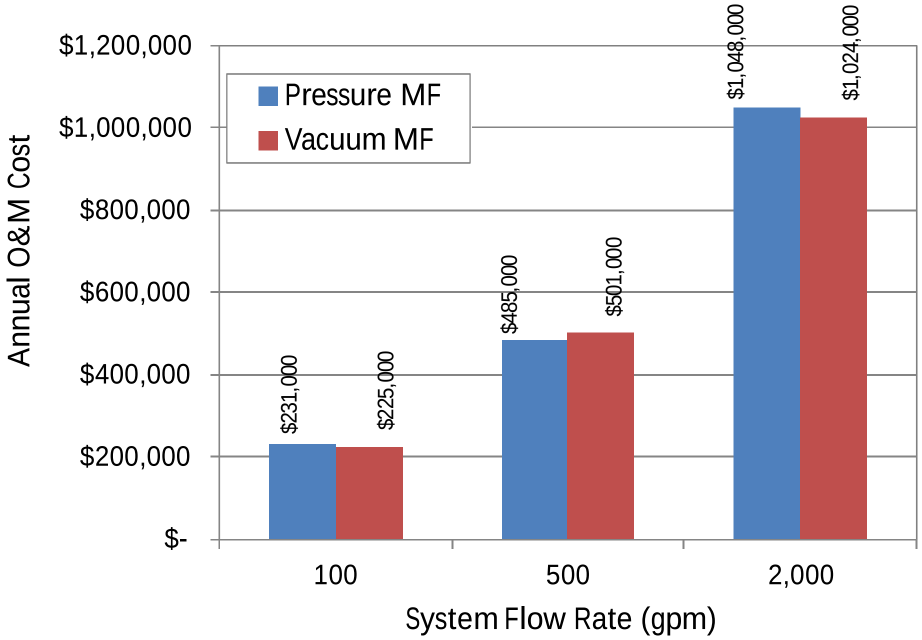

Figure 5-16. Annual O&M Costs for RCF with MF Treatment

5.5.4 20-Year Net Present Values

Table 5-20 provides the 20-year net present values of RCF with MF O&M costs for the three system sizes, rounded to two significant figures.

Table 5-20. 20-Year Net Present Values of RCF with MF O&M Costs(1)

100	$ 3,800,000	$ 3,900,000
2,000	$ 17,000,000	$ 18,000,000

(1) Capital and 20-year NPV O&M based on 2.5% inflation and a 4.5% discount rate
(2) In 2012 dollars.

5.5.5 Unit Treatment Cost ($/AF)

Figure 5-17 presents the estimated unit treatment costs in dollars per acre-foot ($/AF) for the three RCF with MF systems. For a 2,000-gpm system, the unit treatment cost is significantly lower than the smaller systems due to economies of scale. Pressure or vacuum MF systems were estimated to have similar unit treatment costs for a same flow rate.

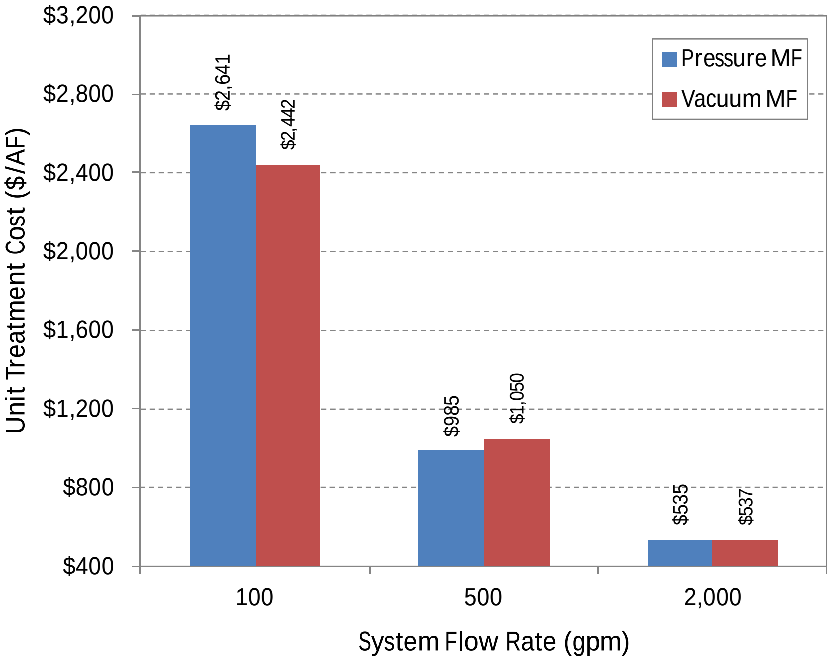

Figure 5-17. RCF with MF Unit Treatment Cost

5.6 Summary Cost Ranges

Figure 5-18 provides a graphical representation of the treatment cost ranges for:

- WBA treatment to achieve a 5 ppb treatment goal for total Cr (and costs also reflect treatemtn to less than 1 ppb for Cr(VI))
- RCF treatment with granular media filtration and backwash water treatment to allow recycle to the head of the plant – to achieve less than 1 ppb Cr(VI) and 5 ppb total Cr
- RCF treatment with granular media filtration and backwash water sent to the sewer without treatment – to achieve less than 1 ppb Cr(VI) and 5 ppb total Cr
- RCF treatment with microfiltration and backwash water sent to the sewer without treatment – to achieve less than 1 ppb Cr(VI) and total Cr

In general, the RCF process for granular media filtration with sewer discharge is lowest cost at higher flow rates. RCF becomes more expensive than WBA as flow rates increase. The high ends of the RCF ranges reflect the use of MF rather than granular media filtration. Granular media filtration with recycle to minimize water losses (and in case sewer dicharge is not a feasible option) was charaacterized by costs between the other two RCF options. Note that this figure does not include the uncertaintly ranges of -30% to +50% and assumes 100% utilization of treatment.

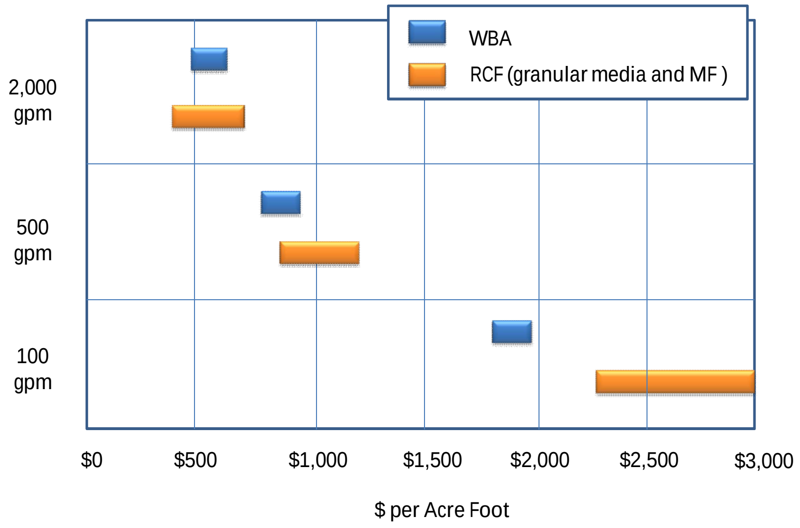

Figure 5-18. Summary of Cost Estimate Ranges for Chromium Treatment (Assuming Potential MCLs of 5 ppb or Higher)

6. Summary and Conclusions

Nearly a decade of research on Cr(VI) treatment technologies has significantly advanced the state of knowledge about the capabilities and limitations of different approaches. The research program, which has been led by the City of Glendale in partnership with other utilities, has been supported by funding from state, federal, and private organizations, which highlights the importance of this work across many sectors. The program began with Phase I, a bench testing program to screen promising technologies. Phase II honed in on seven of the most mature and feasible technologies at that time, with three emerging as frontrunners – reduction/coagulation/ filtration (RCF), weak base anion exchange (WBA), and strong base anion exchange (SBA). An Expert Panel convened to guide the research effort into Phase III, the demonstration study, recommended proceeding with the RCF and WBA processes rather than SBA due to limitations in brine disposal options for Glendale.

The Phase III Demonstration study confirmed the effectiveness of both the WBA and RCF processes for Cr(VI) and total Cr removal to less than 5 ppb (i.e., the initial treatment goal). The RCF process was able to remove Cr(VI) to less than 1 ppb and total Cr to less than 5 ppb, but consistent removal to less than 1 ppb for total Cr was not achieved as in the pilot testing. Operational conditions found to be most effective included a 25:1 Fe:Cr(VI) ratio for an influent concentration of 75-80 ppb (and 50:1 for a lower influent concentration around 10 ppb), aeration, and 48 to 72 hours of filter run time. Water recovery rates also vary, with the RCF process having a water loss of about 3% for granular filtration and 5% for MF, compared with less than 1% for WBA.

The breakthrough curves for the WBA process mirrored those from pilot testing, showing a high capacity (approximately 172,000 bed volumes, or 1 year of operation, for the lead bed before the lag bed reached 5 ppb breakthrough). Even longer operation was observed for the lag bed, and the next changeout will verify the steady-state number of bed volumes of water treated for the resin. The tested WBA resin, Amberlite™ PWA7, was found to leach formaldehyde during startup. Levels were decreased to below the California Notification Level using the cross regeneration pre-treatment procedure on the resin, but this procedure was not consistently effective and additional research is underway by the resin manufacturer.

A significant consideration for the technologies is the generation of treatment by-products, or residuals waste, due to cost and labor. Residuals generation and disposal options were studied in detail in the Phase III Residuals study. All three processes – RCF, WBA, and SBA - generate a waste that is classified as hazardous in the State of

California by the Waste Extraction Test (WET) but often non-hazardous according to the Federal Toxicity Characteristic Leaching Procedure (TCLP). Due to its high capacity and long life, WBA resin can also accumulate other anions, including uranium, which can trigger additional disposal considerations. For the RCF process, it may be possible to dispose of backwash water to the sanitary sewer, but water losses must be considered and compared with the costs of backwash water treatment and recycle.

A detailed cost evaluation of treatment options was prepared as part of the Phase III Demonstration study, including generation of cost curves for different flow rates, influent concentrations, and potential MCL treatment goals. The cost estimates revealed that the WBA treatment systems ranged from approximately $500/AF to $703/AF for a 2,000 gpm system, $782 to $1,022/AF for 500 gpm, $1,826 to $2,049/AF for 100 gpm, and $13,307 to $13,741/AF for 10 gpm. These ranges reflect treatment to potential Cr(VI) MCLs ranging from 25 to 1 ppb, as a lower treatment goal would result in more frequent resin changeouts. Capital and O&M cost details are included in the report. If potential MCLs are based on total Cr removal, the WBA treatment costs would increase dramatically for 1 and 2 ppb potential MCLs, due to more frequent resin replacements thus increased O&M costs. Capital costs are not expected to be affected unless more resin vessels are installed to reduce resin disposal frequency. For 1 ppb, the cost estimates are approximately $11,247/AF for a 2,000 gpm system, $13,517/AF for 500 gpm, $13,534/AF for 100 gpm and $32,464/AF for 10 gpm. For 2 ppb, the costs estimates are approximately $1,973/AF for 2,000 gpm, $2,527/AF for 500 gpm, $3,432/AF for 100 gpm and $15,973/AF for 10 gpm. For potential MCLs equal to or above 3 ppb, the treatment costs based on total Cr are similar to these based on Cr(VI) removal. Details are discussed in Section 5.3.6.

RCF treatment system costs with granular media filtration and backwash water treatment and recycle ranged from $489 to $697/AF for 2,000 gpm, $1,013 to $1,223/AF for 500 gpm, and $2,804 to $3,008/AF for 100 gpm. Costs for granular media filtration without backwash water treatment ranged from $450 to $480/AF for 2,000 gpm, $871 to $902/AF for 500 gpm, and $2,272 to $2,297/AF for 100 gpm. The ranges for RCF costs reflect variable influent Cr(VI) concentrations ranging from 5 to 50 ppb, due to higher chemical doses and residuals quantities for higher influent Cr(VI) concentrations. RCF treatment system costs with microfiltration ranged were estimated $535/AF (pressure membrane) and $537/AF (vacuum membrane) for 2,000 gpm, $985/AF (pressure membrane) and $1,050 (vacuum membrane) for 500 gpm, and $2,641/AF (pressure membrane) and $2,442 (vacuum membrane) for 100 gpm. All costs include the assumption of 100% utilization rate, which means that unit costs will be higher if processes are not used throughout the year. No blending options were included in the cost analysis but could bring down costs of treatment for systems not treating an impaired source.

For utilities requiring Cr(VI) treatment, key considerations in technology selection include: co-occurring contaminants requiring removal, water quality that may impact technology effectiveness, facility sizing needs and space availability, operational requirements, residuals handling and disposal options, and cost.

Significant opportunity to decrease the footprint and cost for the RCF process was identified in the RCF demonstration testing studies, whereby a small chlorine dose might be used in place of aeration and less reduction time may be sufficient. Both details require additional testing at the pilot or demonstration scale, but this work indicated that both items have merit.

Several additional technologies not studied thoroughly in this research program beyond bench testing hold promise for Cr(VI) treatment, including reverse osmosis, adsorptive media, and biological treatment. Studies are underway to investigate the improved chromium removals that can be achieved with adsorptive media and additional ion exchange resins (Phase IIIB), and biological treatment. The research program led by the City of Glendale provides the foundation for identifying effective technologies, and follow-on studies are needed to test the their application for other utilities, to identify the next generation of technological approaches to overcome limitations of existing technologies, and optimization to reduce costs.

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