Hexavalent Chromium Removal Research Supplemental Project Report

To the California State Water Resources Control Board – Division of Drinking Water

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

Report Prepared By
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February 28, 2013 (Project Report)
December, 2015 (Supplemental Project Report)

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Funding Partners

U.S. Environmental Protection Agency
State Water Resources Control Board –
Division of Drinking Water
Water Research Foundation
Los Angeles Dept. of Water and Power
City of Burbank
Metropolitan Water District of So.Cal.
National Water Resource Institute
North American Höganäs
Dow Chemical

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California Dept. of Water Resources
Association of California Water Agencies
City of Glendale
City of San Fernando
California Water Service Company
San Fernando Valley Industry
Evoqua / Siemans
Aqua Nano

Table of Contents

Tables

Figures

Appendices

Note that the Appendices are not attached to this report due their large size but are available upon request.

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 that time, little information was available on the ability of Cr(VI) treatment technologies to reach single parts-per-billion (µg/L, or microgram per liter) levels when the California Maximum Contaminant Level (MCL) for total chromium was 50 µg/L and the federal total chromium MCL was 100 µg/L. The research program began in order to test and identify treatment technologies for achieving low µg/L effluent chromium concentrations in drinking water supplies.

More detailed information on the scope of the research and research results was included in a Project Report dated February 28, 2013 and distributed to a wide group of recipients. The purpose of the Supplemental Report is to summarize research efforts from that date to the end of the overall research effort by December 31, 2015. This date is a requirement of the State Water Resources Control Board for Proposition 50 funding. Significant research occurred during this time frame. For clarification, in the original Project Report, Glendale worked closely with the California Department of Public Health (CDPH). Recently, the drinking water function of the California Department of Public Health was transferred to the State Water Resources Control Board. Much of the material included in the Supplemental Report continued to reference the California Department of Public Health, now called the WaterBoards Division of Drinking Water (DDW).

The contents of the Project Report was used by DDW to provide information on the technical feasibility and costs for setting the MCL for hexavalent chromium in drinking water supplies.

1.2 Organization of the Supplemental Report

The objective of the Supplemental Report is to document the research efforts subsequent to the original Project Report summarizing the various research results with the detailed material/reports included in the Appendices. New Table of Contents, Tables, Figures, and Appendices for the supplemental material were prepared. Additionally, there were a few sheets/pages from the Project Report that needed to be updated for inclusion in the Supplemental Project Report. The reader will notice that these errata sheets contain the original page number from the Project Report with identification at the bottom that this is a revised sheet “Original age number – rev.”).

1.3 Presentation of the Supplemental Project Report Material

The original Project Report was contained in a notebook that was sent to many individuals. The Supplemental Report is being sent to the same individuals via email notification that the supplemental report is located on the City’s website.

1.4 Errata Sheets from the Project Report

Errata sheets from the original Project Report are provided in the pages that follow.

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 (now the State Water Resources Control Board, Division of Drinking Water) 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; the San Fernando Valley Industry Group; and numerous vendors of various chromium removal systems. The costs for the 13 year study was $10.5 million.

(9 – rev.)

ERRATA SHEET

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) in water supplies and the regulatory process, 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 nationwide water industry.

1.5 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 Los Angeles Department of Water and Power (LADWP) and Awwa Research Foundation or AwwaRF (now Water Research Foundation or WaterRF). 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 2015),
- Michael De Ghetto, Assistant General Manager – Water, Glendale Water and Power (2015 to current), and
- Leighton Fong, Project Engineer (2003 to present).

(14 – rev.)

ERRATA SHEET

3. Summary of 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 ion exchange, adsorptive media, and RCF testing (Completed)
    - Phase IIIC - Pilot testing of new ion exchange resins (Completed)
    - Phase IIID – Enhanced demonstration testing of Reduction/Coagulation/Filtration (Completed)
- Phase IV – Implementation (Future)

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.

(17 – rev.)

ERRATA SHEET

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	• 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	• 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	• 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)	• 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 Additional Resin/Media/RCF Testing	• Test promising WBA and SBA resins & two adsorptive media • Compare technology effectiveness in two water qualities (Glendale and Livermore, California)	*Project Management: Glendale & California Water Service Company*

(18 – rev.)

ERRATA SHEET

Implementation Phase/ Cost/ Status	**Objective**	**Participants/ Financial Partners**
	• Project Report • Supplemental Project Report	City of Glendale, California California Water Service Company Water Research Foundation DWR/CDPH Proposition 50 North American Höganäs
Phase IIIC Pilot Testing of New Ion Exchange Resins	• Test one new WBA resin and one new WBA resin at pilot scale • Project Report	*Project Management: Glendale* AquaNano
Phase IIID Enhanced Demonstration Testing of Reduction/Coagulation/Filtration	• Test alternate pumping strategy for RCF • Evaluate effectiveness of less reduction time and use of chlorination for RCF • Develop preliminary designs for Cr(VI) treatment technologies • Update cost estimates for RCF, WBA, and SBA • Project Report	*Project Management: Glendale* Metropolitan Water District of Southern California CDPH/DWR Proposition 50

Total expenditure for Phase III - $9.3 million
Total expenditure for Phases I, II, and III - $10.5 million

(18 – rev.)

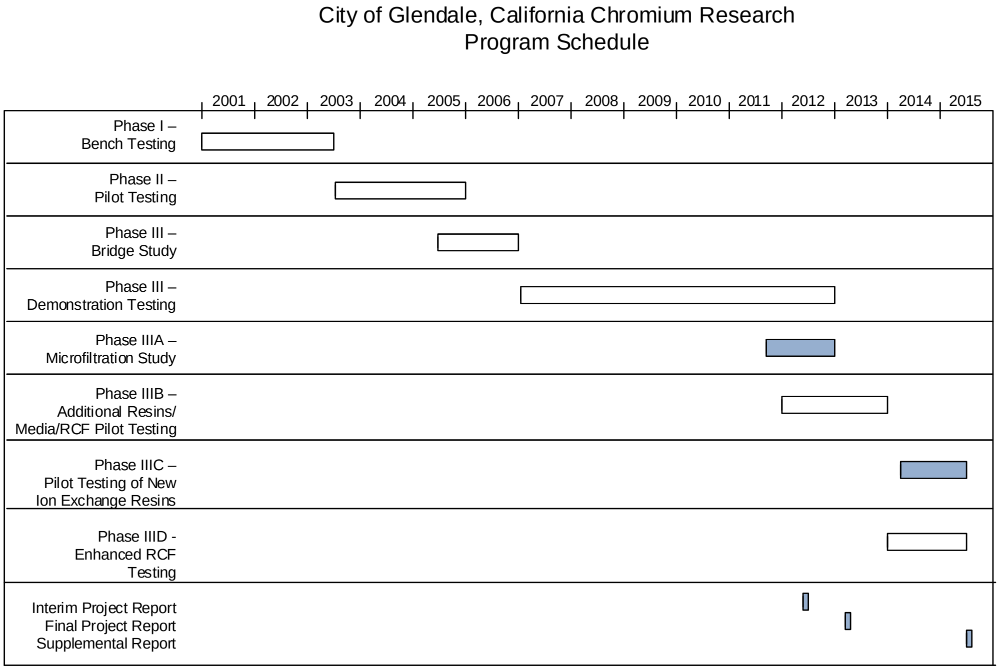

Figure 3-1. Overall Chromium Research Program Schedule

1.6 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, San Fernando, and the National Water Research Institute. 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 µg/L, and the mean total Cr was 8.2 µg/L. 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

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 µg/L) 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 µg/L).

3.5 Summary of Phase IIIB Additional Ion Exchange, Adsorptive Media, and RCF Pilot Testing

The Phase IIIB Additional Ion Exchange, Adsorptive Media, and RCF Pilot Testing study is described in the Water Research Foundation Report 4423. The study was conducted by California Water Service Company in partnership with the City of Glendale, California). An overview of the Phase IIIB study is in Section 4 of the Supplemental Report.

3.6 Summary of Phase IIIC Pilot Testing of New Ion Exchange Resins

The Phase IIIC Pilot Testing of New Ion Exchange Resins study is presented in the report to AquaNano, LLC, who contracted the work through the City of Glendale, California. An overview of the Phase IIIC study is in Section 5 of the Supplemental Report.

3.7 Summary of Phase IIID Enhanced Demonstration Testing of RCF

The Phase IIID Enhanced Demonstration Testing of RCF study is presented in the report the Metropolitan Water District of Southern California, who supported the study as part of the Foundational Actions Funding Program. An overview of the Phase IIID study is in Section 6 of the Supplemental Report.

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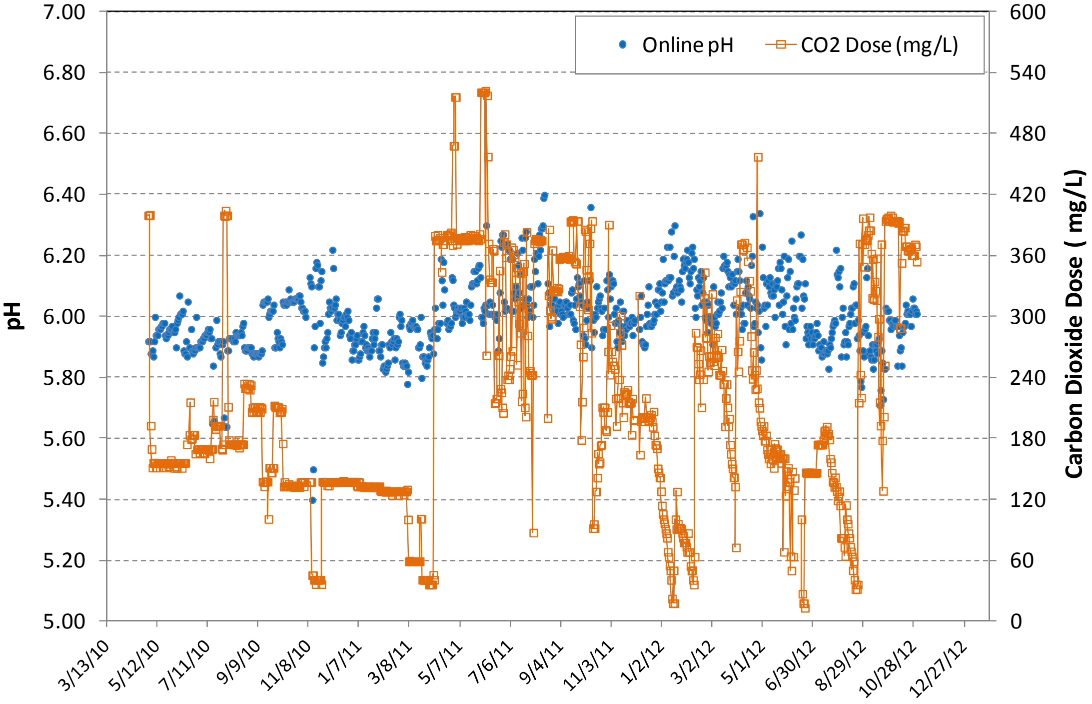


Figure 4-9. Carbon Dioxide Dose and pH Online Readings during WBA Demonstration Testing

(59 – rev.)

2. Update on Phase IIIA - WBA Resin Life of the Demonstration Facilities

The Phase IIIA demonstration WBA facilities were continuously operated after the original Project Report was finalized (dated February 28, 2013). A key finding during this extended operational period was regarding the WBA resin life. Since the startup in 2010, a total of three runs were tested (i.e. the initial resin installment and two resin replacements afterwards). The resin lead bed was replaced when the lag bed effluent Cr(VI) concentration reached 5 µg/L. The first and second runs were published in the original Project Report (Section 4.2), which indicated a resin life of 172,000 BVs and 364,000 BVs for the lead bed in the first and second runs, respectively. However, a significantly greater resin life, 566,000 BVs, was observed during the third run from December 2012 to August 2015. Figures 2-1 and 2-2 shows Cr(VI) concentrations in the lead and lag bed effluent from the startup of the demonstration facilities in 2010 to August 2015, respectively.

A few factors that can potentially affect the resin life were analyzed, including Cr(VI) concentration in the raw water (the WBA influent), raw water quality other than Cr(VI), and influent pH control. Influent Cr(VI) concentrations decreased significantly during the three runs as shown in Figure 2-1, with the exception of a spike in Cr(VI) levels during Run 3. The spike occurred during the same period when soil Cr(VI) remediation activities were performed by a third party at the site next to the well. The Cr(VI) spike was thought to be caused by the remediation activities. Except during that period, the lower influent Cr(VI) concentrations might have contributed to the greater resin life observed. The pilot study as a part of Phase IIIB (Blute et al., 2015) suggests that a greater resin life could be achieved with a lower raw water Cr(VI) concentration (e.g., at Livermore compared to Glendale).

Raw water quality other than Cr(VI) concentrations did not change significantly during the demonstration study period, including chloride, sulfate, nitrate, and total dissolved solids. Thus, the greater resin life is not likely attributed to other water quality changes. Another factor affecting WBA resin performance is pH. The operational experience at the demonstration facilities indicates a strong impact of pH on resin performance, whereby better pH control yielded lower resin effluent Cr(VI) levels. pH control and carbon dioxide dosing were improved over time. More consistent pH was achieved in Run 3, which likely contributed to the greater resin life in this run. In addition, the resin Cr(VI) capacity was greater in Run 3. The spent resin was estimated to contain Cr(VI) at approximately 10,300 mg/kg (1.03%), 10,600 mg/kg (1.06%), and 15,300 mg/kg (1.53%) for Runs 1, 2 and 3, respectively. More Cr(VI) was removed by the resin in Run 3, which could reflect resin product variability or improvement. A significant increase in uranium capacity was also observed in Run 3. Overall, resin product variability or improvement, better pH control, and lower influent Cr(VI) concentrations were proposed to be the key factors affecting the WBA resin life for Cr(VI) removal. For an influent Cr(VI) concentration of approximately 20 µg/L, the resin life at the demonstration facilities was shown to be greater than 566,000 BVs for a treatment goal of 5 µg/L in the lag bed effluent.

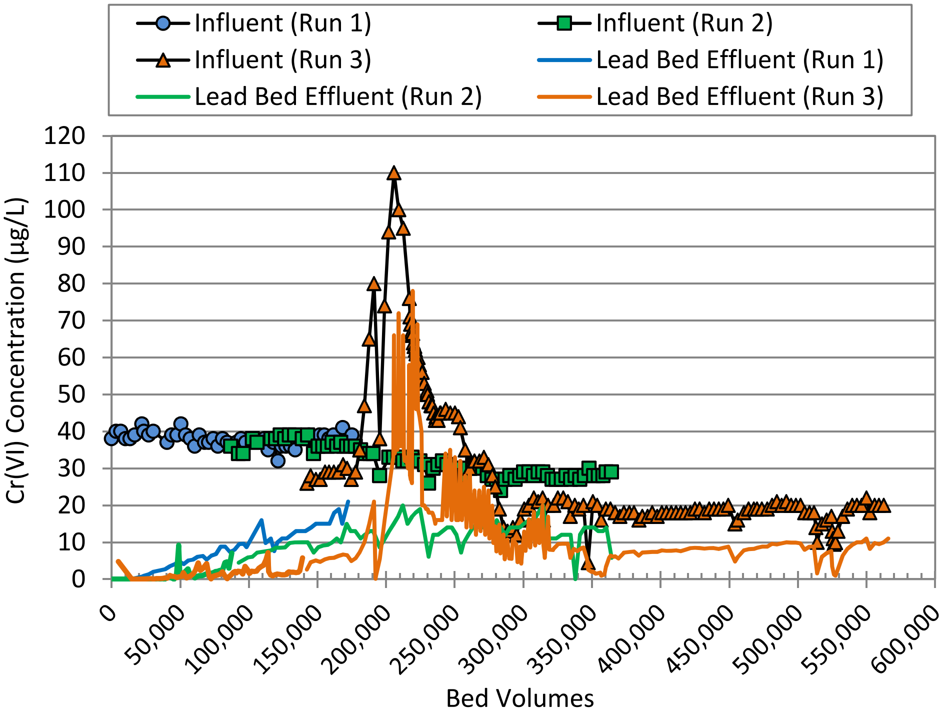


Figure 2-1. Cr(VI) Breakthrough Curves for Lead WBA Bed at Glendale's Demonstration Facilities

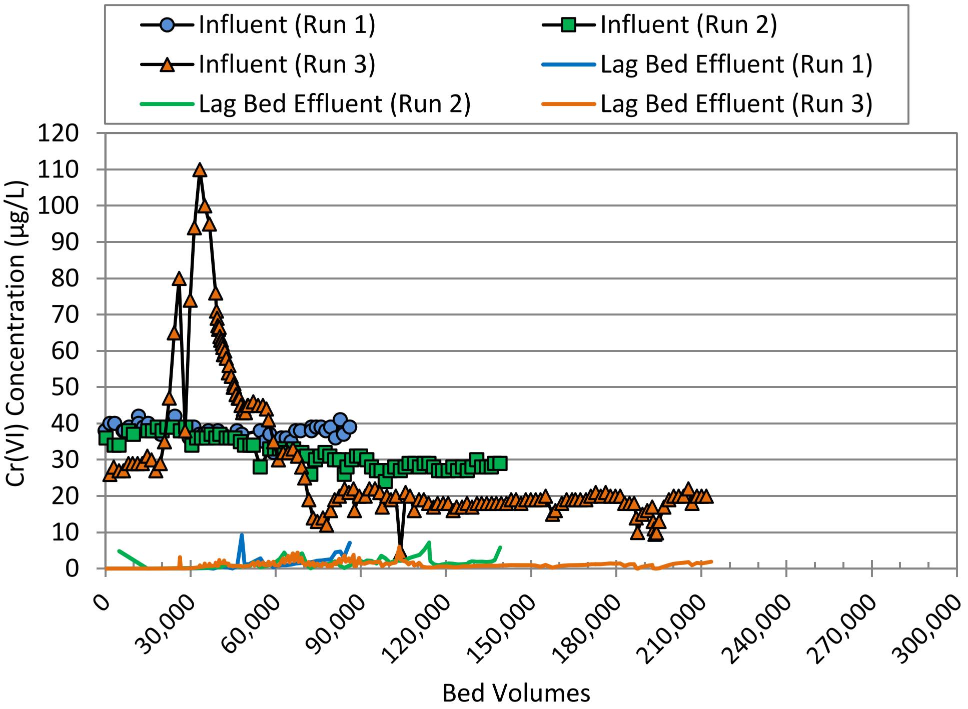


Figure 2-2. Cr(VI) Breakthrough Curves for Lag WBA Bed at Glendale's Demonstration Facilities

3. Phase IIIB Additional Ion Exchange, Adsorptive Media, and RCF Testing

This section describes pilot testing of resins and adsorptive media as part of the Water Research Foundation project 4423. The study was conducted under a cooperative agreement between the California Water Service Company (Cal Water) and the city of Glendale, California. The objectives of the study were to (1) determine the effectiveness of single-pass technologies for removal of Cr(VI) and co-occurring constituents in different water qualities, (2) assess the operational requirements for these treatment options, and (3) update costs estimates of treatment.

3.1 Approach

The initial concept for this project focused on testing of single-pass media for Cr(VI) removal, including two new WBA resins and three SBA resins with two different water qualities (Livermore and Glendale, California). In addition, one adsorptive media was planned to be tested at Livermore and one at Glendale. As the research proceeded, several challenges with the well were encountered at Livermore resulting in a delay of the WBA and adsorptive media testing. At the same time, new information became available from other research finding that water quality only has a minor impact on WBA resin performance, and that the RCF system could be modified to treat water with a smaller facility footprint.

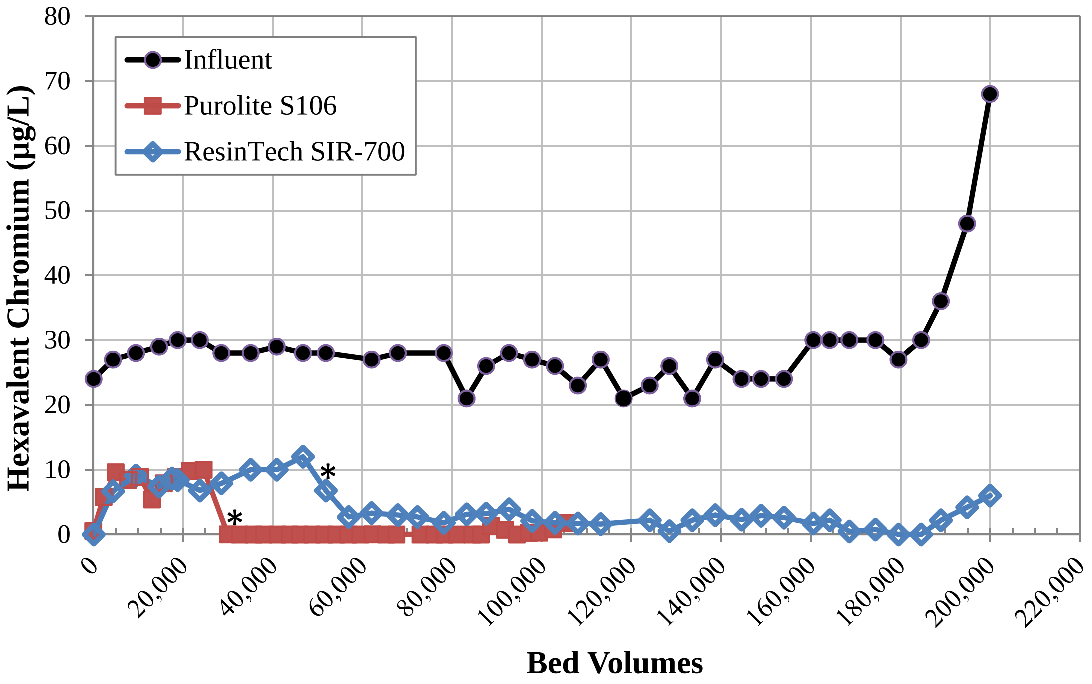
Therefore, the research scope was modified to include evaluation of RCF in place of extensive WBA and adsorptive media testing at Livermore. The revised approach included the following components:

- Pilot-scale testing of two WBA resins for comparison with the WBA resin being used in demonstration-scale testing at Glendale,
- Evaluation of resin preconditioning procedure effectiveness to minimize formaldehyde leaching from WBA resin,
- Pilot-scale testing of three SBA resins in single-pass mode at Livermore and Glendale,
- Demonstration-scale testing of RCF with decreased reduction times and chlorination replacing aeration, and
- Pilot testing of one iron-based adsorptive media.

3.2 Data Analysis

3.2.1 Weak-Base Anion Exchange

Pilot-scale testing of two new WBA resins (Purolite S106 and ResinTech SIR-700) was designed to evaluate the effectiveness of Cr(VI) removal and leaching of other constituents, with performance compared to previous testing with Dow PWA7. Testing showed that the two new resins have a high overall capacity for Cr(VI) and a long time to breakthrough, as seen in Figure 3-1. These findings are consistent with pilot testing results of the previously tested WBA resin (i.e., greater than 9 months of operation before breakthrough).



*Influent pH decreased from approximately 6.1 to approximately 5.8-5.9.

Figure 3-1. Cr(VI) Breakthrough Curves for WBA Resins at Glendale

Both of the new resins differed from the other resin Dow PWA7 in that they exhibited initial leakage of low levels of Cr(VI). The initial Cr(VI) and Total Cr breakthrough occurred at the same time during the first two months of pilot testing, for both resins. The potential that this breakthrough occurred as a result of inadequate pH control was considered, but initial leakage still occurred when pH was well-controlled. It was hypothesized that this impact was observed due to relatively elevated sulfate concentrations, since leakage was observed in another study with high sulfate (Chowdhury et al., 2015) and not in another with low sulfate (Najm et al., 2014). Additional testing demonstrated that the impact of this leakage on system design and operations can be minimized with a lead-lag configuration.

This study confirmed that the WBA resin used in Glendale demonstration-testing (Dow PWA7) is also effective in Livermore water, with a greater capacity that may be due to lower Cr(VI) concentrations.

Preconditioning of this resin with the cross-regeneration method developed by the manufacturer was effective at decreasing formaldehyde concentrations at the pretreatment facility, but leaching still occurred when the resin encountered the lower pH water necessary for Cr(VI) removal. Additional development and testing was later conducted with a new preconditioning procedure, resulting in a method to decrease formaldehyde below the Notification Level of 100 µg/L in California.

These two resins offer the advantage of not leaching constituents of concern above regulatory limits. Similar to Dow PWA7, both spent resins are likely classified as non-RCRA hazardous waste (hazardous in California) with uranium above the regulatory limit for radioactive material (if resin operational life is not controlled on purpose or absorbent material is not used in disposal, which could limit the uranium content of the resin to less than the radioactive threshold).

3.2.2 Strong-Base Anion Exchange

Pilot-scale testing of three SBA resins (Purolite A600E/9149, Dow SAR, and Envirogen HyperSorb A3-2-1) was designed to evaluate the effectiveness of Cr(VI) removal and leaching of other constituents at both Glendale and Livermore. The SBA resins showed a relatively short resin life of less than 5 days for all three resins (Purolite A600E/9149, Dow SAR, and Envirogen HyperSorb A3-2-1), with longer performance for Livermore’s water (approximately 10 days) to reach the influent concentration of 9-10 µg/L. The breakthrough curves for Glendale and Livermore are shown in Figures 3-2 and 3-3, respectively.

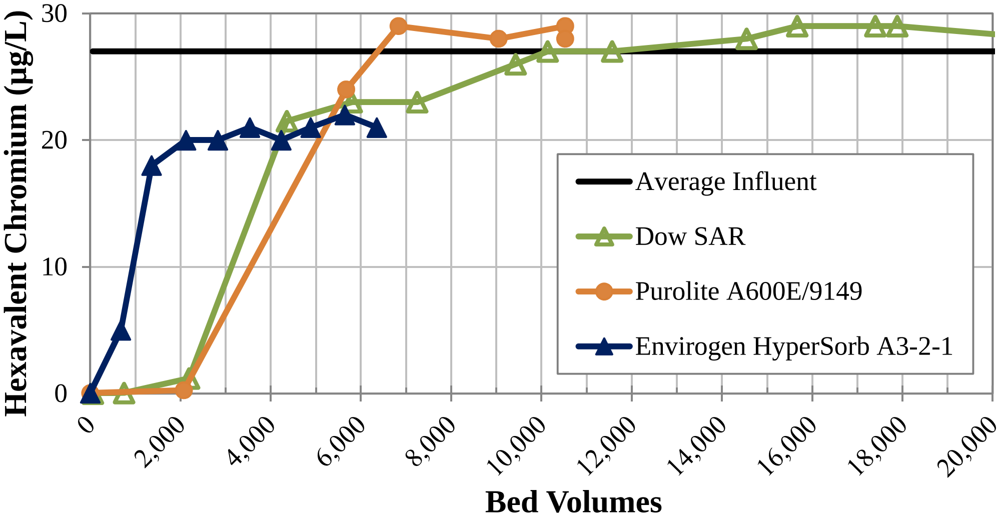


Figure 3-2. Cr(VI) Breakthrough Curves for SBA Resins at Glendale

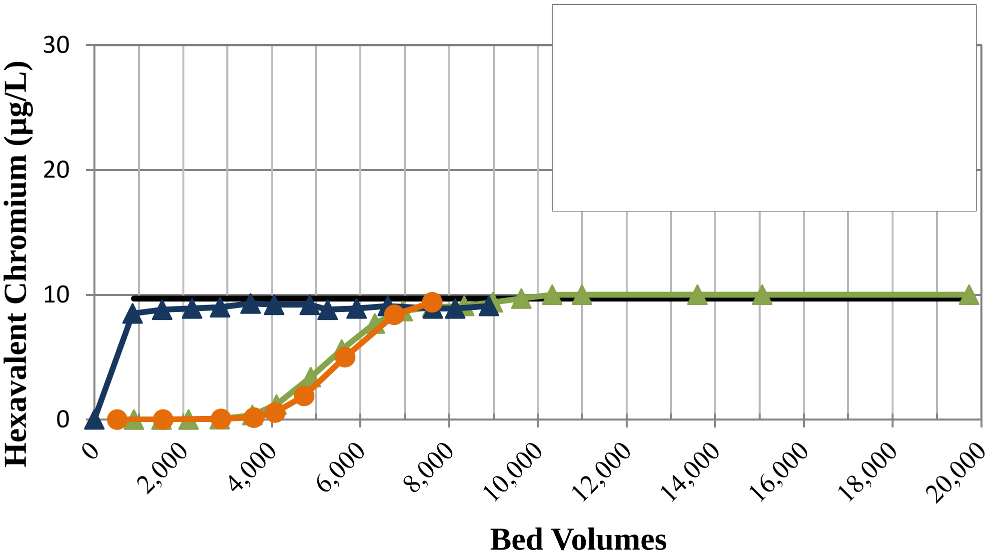


Figure 3-3. Cr(VI) Breakthrough Curves for SBA Resins at Livermore

Sulfate is known to impact Cr(VI) removal by SBA resins, which is consistent with this testing in which Livermore had half the sulfate concentration as Glendale. Simultaneous removal of other constituents, including nitrate, sulfate, and phosphate were observed by all three resins but with faster breakthrough than Cr(VI). Uranium was removed with a greater selectivity than Cr(VI), resulting in longer time to breakthrough. The results highlighted the importance of testing new resins before installation, as two resins lasted between three to five times longer than the other resin.

3.2.3 Reduction/Coagulation/Filtration

Demonstration-scale testing of the RCF process was conducted to determine if reduction time could be decreased and chlorine could be used to oxidize remaining iron before filtration. Results from this study indicate that the RCF process can be optimized on both accounts.

RCF post-reduction data shows that the 5 minute reduction time is effective for Cr(VI) removal below the 10 µg/L limit using chlorination and higher iron dose. The RCF filter effluent data shows slightly higher Cr(VI) values, primarily due to the oxidation of Cr(III) to Cr(VI) by chlorination. It should be noted that in the control (30 minute reduction time and aeration), Cr(VI) concentrations were low except one data point of 68 µg/L. Considering the corresponding Cr(VI) in the reduction effluent was 0.097 µg/L and aeration does not significantly oxidize Cr(III) to Cr(VI) in these time frames, the result of 68 µg/L Cr(VI) was considered an anomalous data point. The RCF filter effluent data is shown in Figure 3-4.

The initial reason why aeration was used to oxidize the remaining iron was concern that chlorine could oxidize Cr(III) to Cr(VI). This phenomenon was observed in testing, with the magnitude of this reoxidation varying. Cr(III) re-oxidation is hypothesized to be affected by free chlorine residual, chlorine contact time, and Cr(III) concentration. The chlorine residual in the chlorine tank effluent greatly varied from the target residual. Efforts were made to control the chlorine dose; however, high chlorine residual levels were still noted occasionally, which might have contributed to some of the high Cr(VI) levels in the filter effluent. Results indicated that tight controls would be necessary if chlorine is used for oxidation of ferrous iron to minimize oxidation of Cr(III) to Cr(VI). Additional testing of this approach was conducted in Phase IIID.

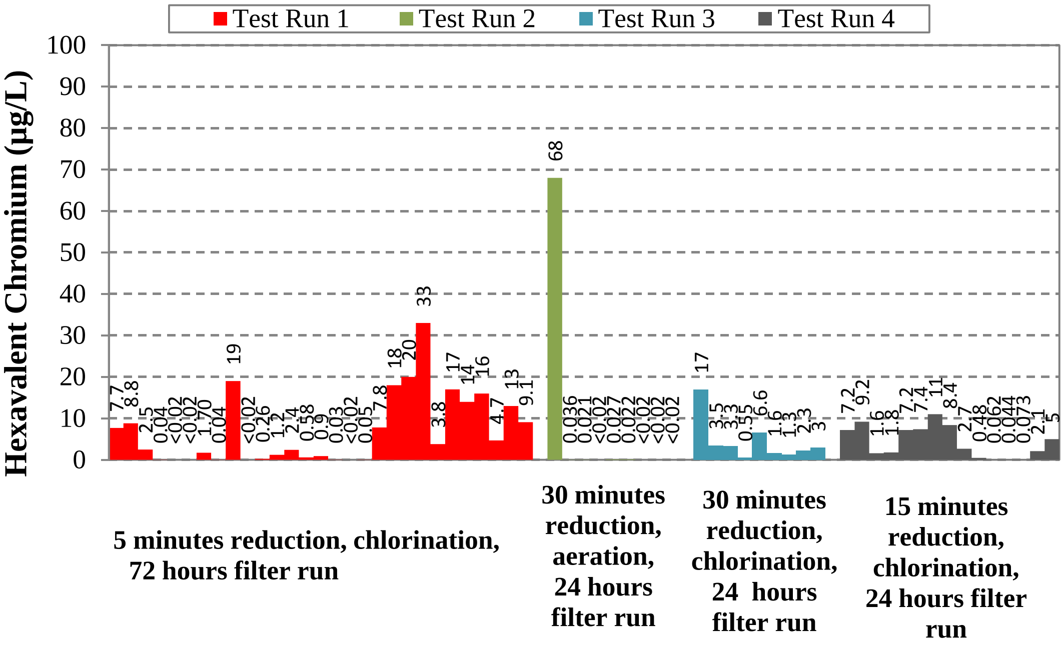


Figure 3-4. RCF Filter Effluent Cr(VI) Concentrations

Results of this testing showed that effective filter backwash is critical for Total Cr removal, as poor Total Cr removal was occasionally observed when filter backwash was insufficient to clean the bed due to challenges with wastewater disposal at the site. In this study, Total Cr removal was improved when backwashing occurred every 24 hours instead of every 72 hours.

3.2.4 Adsorptive Media

Pilot testing was conducted of iron-based adsorptive media (North American Hogänäs Cleanit®), building on Phase I bench scale testing that showed high capacities of some iron-based media for Cr(VI). Adsorptive media testing at Glendale showed removal of Cr(VI) and Total Cr with breakthrough occurring at a throughput similar to SBA resin (Figure 3-5). A much longer contact time was necessary for the adsorptive media (minimum of 15 minutes) compared with SBA (approximately 2 minutes), and iron treatment downstream is necessary due to high levels leaching from the media into the water. Testing also showed that while pH adjustment was not necessary, the media experienced calcium carbonate precipitation, which was overcome by adding polyphosphate to the raw water.

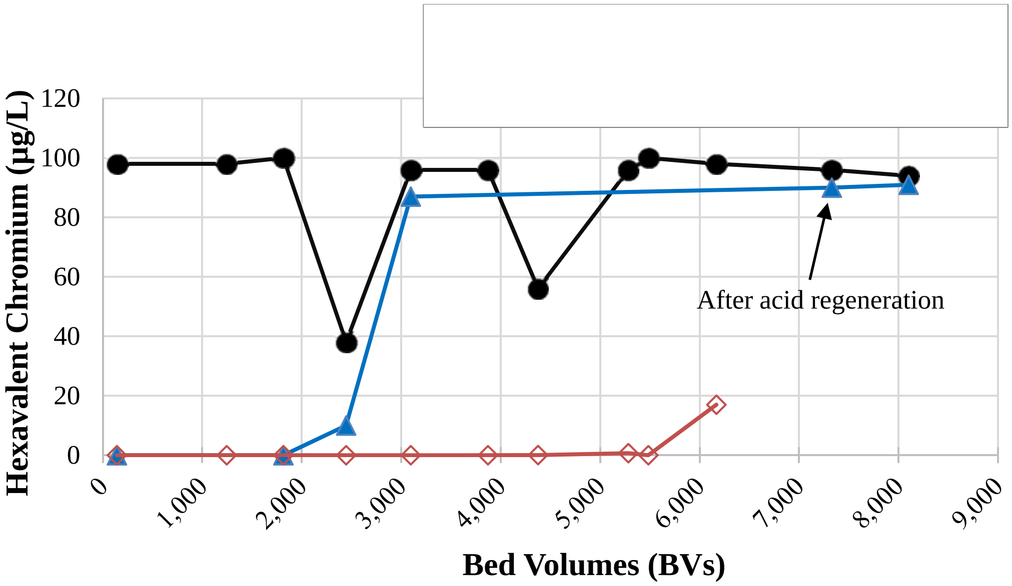


Figure 3-5. Adsorptive Media Cr(VI) Breakthrough (15-min EBCT)

Other constituents were tested and it was found that nitrate, uranium and potentially silica were removed by Cleanit® media for a short period of time. Iron is the primary constituent that must be addressed in the Cleanit® media effluent, due to the nature of the permeable iron composite Cleanit® material. Post-treatment for ferrous and total iron removal would be needed in a full-scale application.

Two types of residuals are generated by the Cleanit® process, including backwash water and spent media. The spent backwash water and the Total Cr concentration were similar in quality to the raw water, indicating that chromium particles were not significantly flushed from the bed during backwash. The spent media was classified a non-RCRA hazardous waste in California. The uranium concentration was below the regulatory limit and likely classifies the media as a TENORM waste.

Overall, adsorptive media will have a larger footprint, which makes it less attractive than SBA unless removal of co-occurring constituents like nitrate are desired and brine disposal is difficult. Additional pilot testing would be necessary to understand long term performance of the media and identify ways to overcome formation of other potentially problematic by-products. This testing worked through operational challenges with the new adsorptive media and provided high level proof-of-concept testing.

3.3 Cost Estimates of Treatment

Cost estimates were updated in this study from the prior work conducted in Phase III. Details of the estimates for the two WBA resins and the modified RCF system are available in the report. Estimates were further refined in Phase IIID, which is where the reader should look for the final estimates from the research program.

3.4 Summary and Conclusions

Key findings from Phases IIIB include:

- WBA and SBA were both effective at Cr(VI) removal in different water qualities from Glendale and Livermore.
- Two SBA resins showed higher Cr(VI) capacity than a third resin, demonstrating the need to test new resins prior to installation. SBA resin capacity was dependent on water quality.
- A new pre-treatment procedure to reduce formaldehyde leaching from the original resin was found to be successful. Two new WBA resins were identified that do not leach formaldehyde.
- Adsorptive media for Cr(VI) removal showed a similar capacity as SBA but required scale formation control and downstream iron treatment. Additional development testing is necessary for adsorptive media.
- RCF showed promise for optimization in reduction time and oxidation approach.

4. Phase IIIC Pilot Testing of New Ion Exchange Resins

This section describes pilot testing of two new resins developed by AquaNano LLC, and funded by the manufacturer through the City of Glendale, California with third-party oversight by Hazen and Sawyer. The objectives of the study were to (1) determine the effectiveness of the new resins for removal of Cr(VI) compared to other resins, and (2) assess potential chemical leaching and spent resin characteristics for disposal.

4.1 Approach

The two new AquaNano resins were tested using a pilot skid that has been successfully used for previous resin testing. The WBA resin (AQ208-WB) was tested with 2-minute EBCT for six months and then reduced to 1-minute EBCT to maximize bed volumes during the remaining 3 months. The SBA resin (AQ60-MP) was tested with 2-minute and 4-minute EBCT as a single pass without regenerations until breakthrough.

4.2 Data Analysis

4.2.1 Weak-Base Anion Exchange

Results of this study showed that the new WBA resin had a high Cr(VI) capacity (Figure 4-1). Cr(VI) in the new WBA resin effluent was < 0.02 µg/L until approximately 92,000 BVs. At that time, the EBCT was decreased from 2 minutes to 1 minute to maximize the bed volumes during the 9 month test period. The effluent Cr(VI) concentration slightly increased after the EBCT change and fluctuated in the range of <0.02 – 1.5 µg/L. At the end of the field testing, Cr(VI) in the WBA resin effluent was 0.36 µg/L at approximately 198,600 BVs. Cr(VI) in the 50% port samples was 6.4 µg/L at approximately 397,000 BVs. The results suggest initial breakthrough occurred at approximately 98,200 BVs, which was possibly accelerated by the shorter EBCT, considering the slow rate of Cr(VI) removal by WBA in general.

Compared with the other two WBA resins tested at Glendale in the Phase IIIB study, the new WBA resin did not show an initial Cr(VI) leakage observed with the others. The influent Cr(VI) concentration was slightly lower than as for the other resin tests, although it was the same water source. The impact of influent Cr(VI) level on resin life has not been quantified. The Phase IIIB study indicates a lower influent Cr(VI) likely contributes to a greater resin life. However, a Water Research Foundation study suggests the impact of Cr(VI) concentration on WBA resin life was minor (Najm et la., 2014). Glendale’s study results suggest the new WBA resin likely has a greater Cr(VI) capacity compared with Purolite S106 and ResinTech SIR-700 as well as Dow PWA7.

Formaldehyde was not detected in water treated by the AQ208-WB as observed with PWA7. As with the other three WBA resins, the spent AQ208-WB resin tested in this study was characterized as a non-RCRA hazardous waste likely TENORM or radioactive waste, depending on disposal methods.

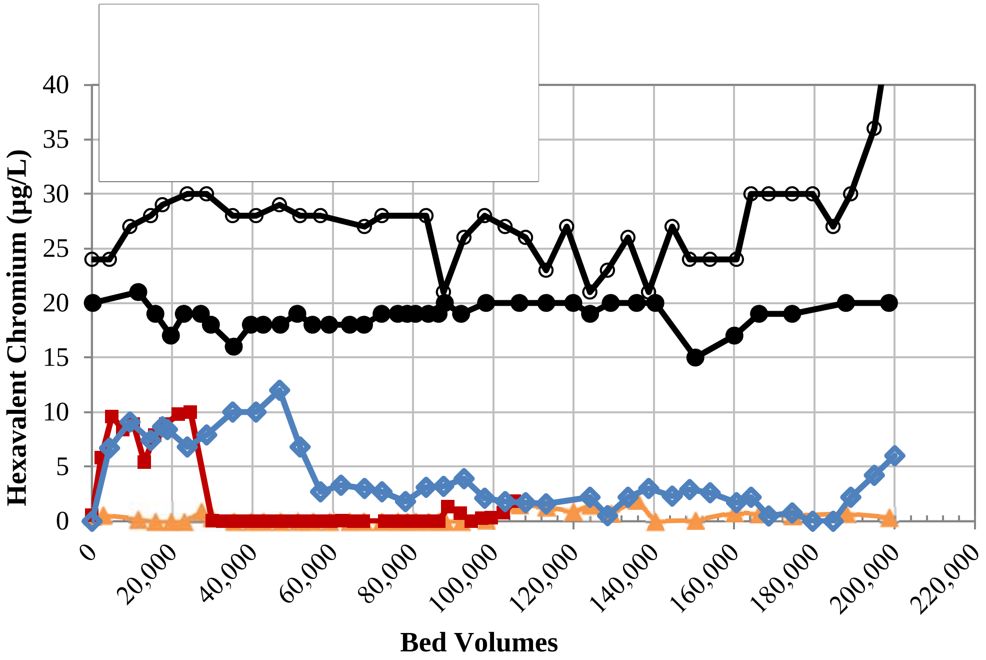


Figure 4-1. Cr(VI) Breakthrough Curves for WBA Resins including AQ208-WB

4.2.2 Strong-Base Anion Exchange

The SBA results suggest significantly greater Cr(VI) capacity compared with other SBA resins tested at Glendale in Phase IIIB as well as other previous studies (Figure 4-2). The test water contained relatively high sulfate (110 – 120 mg/L), which is expected to negatively impact SBA resin life. Resin effluent Cr(VI) reached 8 µg/L at approximately 12,000 to 14,000 BVs (for the two columns tested), which is about 17 to 19 operational days with a 2-minute EBCT. By comparison, the other SBA resins had operational life of 4 to 5 days when tested with the same water. A greater EBCT (4 minutes) did not show improved Cr(VI) capacity or resin life for the new SBA resin.

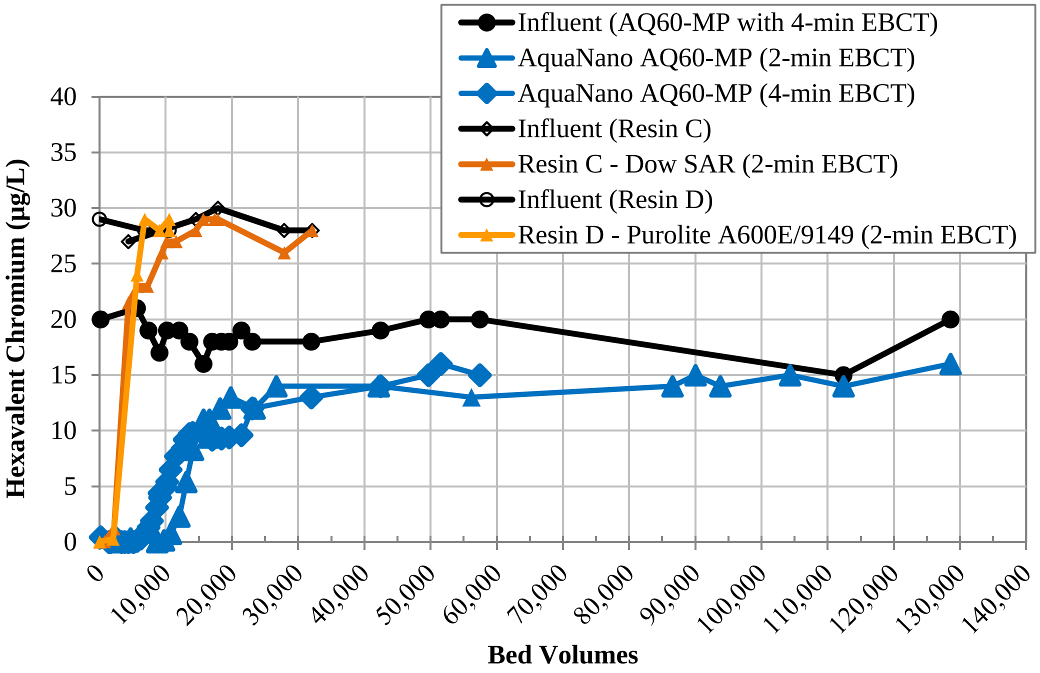


Figure 4-2. Cr(VI) Breakthrough Curves for SBA Resins including AQ60-MP

4.3 Summary and Conclusions

Key findings from Phases IIIC include:

- New SBA resin developed by AquaNano had a higher capacity for Cr(VI) than the resins tested in Phase IIIB.
- New WBA resin developed by AquaNano showed a high capacity like other WBA resins without formaldehyde leaching or initial leakage of Cr(VI) that two of the resins exhibited.

Next steps for AquaNano resins include testing of SBA resin regeneration to assess long term operational effectiveness.

5. Phase IIID Enhanced Demonstration Testing of Reduction/Coagulation/Filtration

This section describes RCF demonstration testing funded by Metropolitan Water District of Southern California and California Department of Water Resources, Proposition 50. The objectives of this study were to (1) optimize reduction time and iron dose of the RCF process, (2) test an alternative RCF pumping approach for potential cost savings, (3) evaluate cost competitiveness of enhanced RCF compared with WBA and SBA, (4) develop technology site layouts and preliminary design drawings for enhanced RCF compared with WBA and SBA, (5) and identify opportunities for water system blending to achieve compliance with the Cr(VI) MCL.

5.1 Approach

Jar testing was conducted first to identify effective combinations of iron dose and reduction time for Cr(VI) removal. Based on the jar testing results, the demonstration-scale RCF process at Glendale was tested with two iron doses and three reduction times for a total of six runs. Next, alternative pumping (a centrifugal pump) was tested in place of progressive cavity pumping using the effective iron doses and reduction times identified.

Treatment costs for the enhanced RCF process were developed based on the demonstration test results in this study. WBA costs in Phase IIIB were updated to 2015 dollars. SBA costs were developed using the same methodology to provide a direct comparison with optimized RCF and WBA. Site layouts and preliminary design drawings for enhanced RCF, WBA and SBA were developed for the Glendale RCF demonstration site.

Opportunities for using blending to achieve Cr(VI) MCL compliance were evaluated by comparing treatment costs for scenarios with and without blending for RCF, WBA, and SBA. Glendale’s groundwater quality was used as a baseline. Effects of water quality and Cr(VI) treatment goal on the comparison of blending versus non-blending were also evaluated.

5.2 Data Analysis

5.2.1 Reduction/Coagulation/Filtration with Progressive Cavity Pumping

Demonstration-scale testing of the RCF process was conducted to further optimize iron dose and reduction time based on the Phase IIIB results. Inline chlorine injection (instead of a chlorine contact tank) was also evaluated in this testing. The granular media filters were backwashed every 24 hours.

RCF results at the post-reduction point show that Cr(VI) was effectively reduced to below or close to 1 µg/L with an iron dose of 2 or 3 mg/L and a reduction time of 5 or 15 minutes. Chlorine residuals were maintained below 0.4 mg/L (except several occasions) to minimize Cr(III) reoxidation. For a reduction time of 5 or 15 minutes, Cr(VI) concentrations in RCF filter effluent were slightly higher than at post-reduction by up to 1.5 µg/L, indicating a little Cr(III) reoxidation to Cr(VI). The RCF filter effluent data are shown in Figures 5-1 and 5-2. For an iron dose of 2 or 3 mg/L and a reduction time of 5 or 15 minutes, treated Cr(VI) and total Cr concentrations were generally below 3 µg/L.

A reduction time of 1 minute was not sufficient for complete Cr(VI) reduction by a ferrous iron dose of 2 or 3 mg/L. More significant Cr(III) re-oxidation to Cr(VI) by chlorine was observed (up to 4.8 µg/L), although chlorine residual levels were similar as in the other runs. Consequently, Cr(VI) and total Cr concentrations in the filtered water were much higher than in the other runs (up to 11 µg/L). The results indicate that reduction time plays a role in Cr(VI) reaction with ferrous iron and Cr(III) re-oxidation by chlorine, when chlorine residuals were maintained below 0.4 mg/L most of the time.

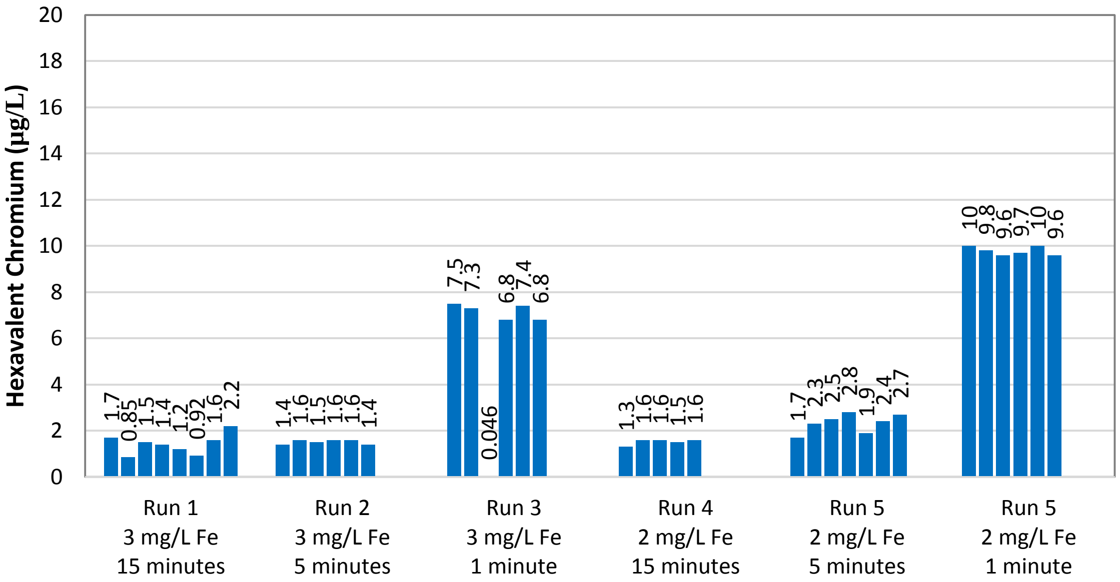


Figure 5-1. RCF Cr(VI) Filter Effluent Concentrations with Progressive Cavity Pumping

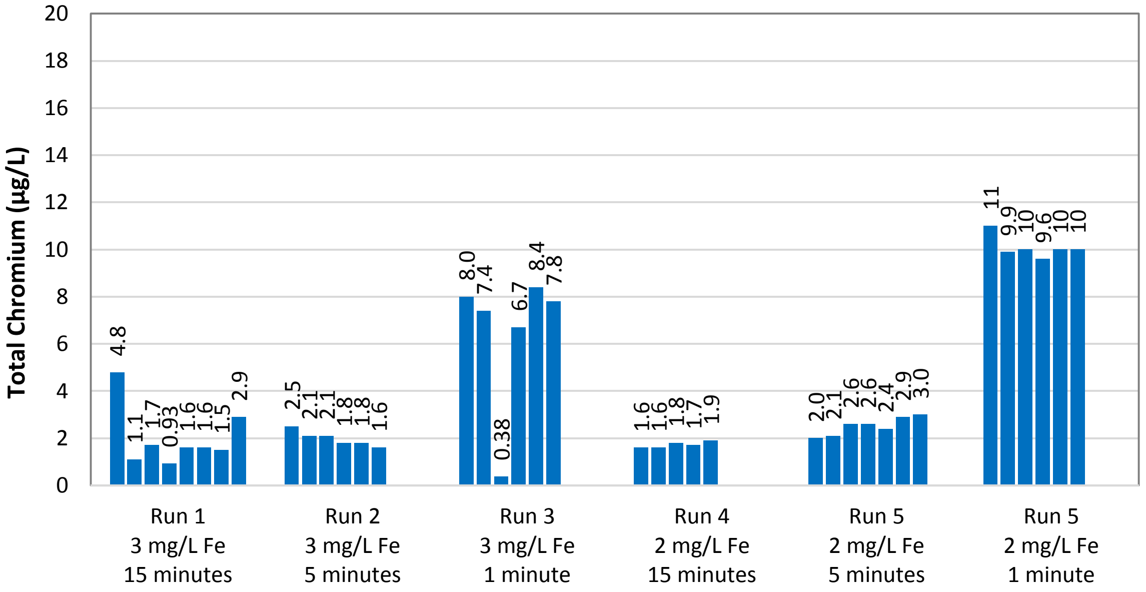


Figure 5-2. RCF Total Cr Filter Effluent Concentrations with Progressive Cavity Pumping

5.2.2 Reduction/Coagulation/Filtration with Alternative Pumping

Based on the demonstration results with progressive cavity pumping, two ferrous iron doses (2 and 3 mg/L) and two reduction times (5 and 15 minutes) were selected for the demonstration testing with centrifugal pumping. The other operational conditions (chlorine residual target, polymer dose and filter backwash) were kept the same as the demonstration testing with progressive cavity pumping.

The test results with centrifugal pumping confirm that an iron dose of 2 or 3 mg/L with a reduction time of 5 or 15 minutes was effective for Cr(VI) reduction to below 3 µg/L. Chlorine injected inline effectively oxidized excess ferrous iron post reduction. Slight Cr(III) re-oxidation to Cr(VI) was observed (< 1.3 µg/L). The RCF filter effluent data are shown in Figures 5-3 and 5-4. Cr(III) particles were effectively removed by granular media filtration with centrifugal pumping and the filtered Cr(VI) and total Cr concentrations were below 3 µg/L. The results are similar to the results for the progressive cavity pumping tests, suggesting that centrifugal pumping could replace progressive cavity pumping for cost savings without significantly deteriorating Cr removal.

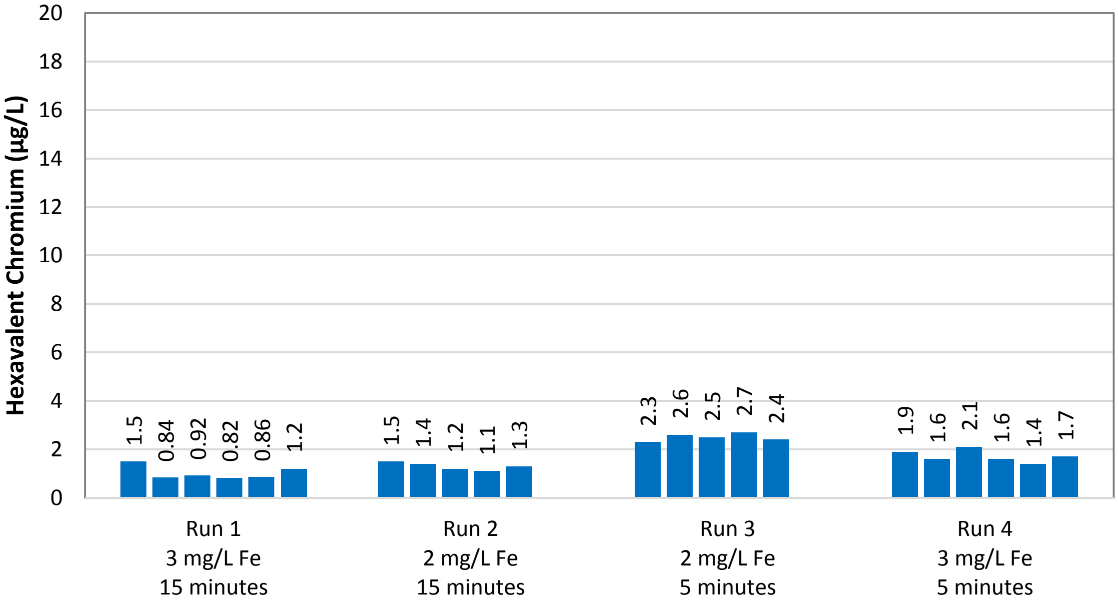


Figure 5-3. RCF Cr(VI) Filter Effluent Concentrations with Centrifugal Pumping

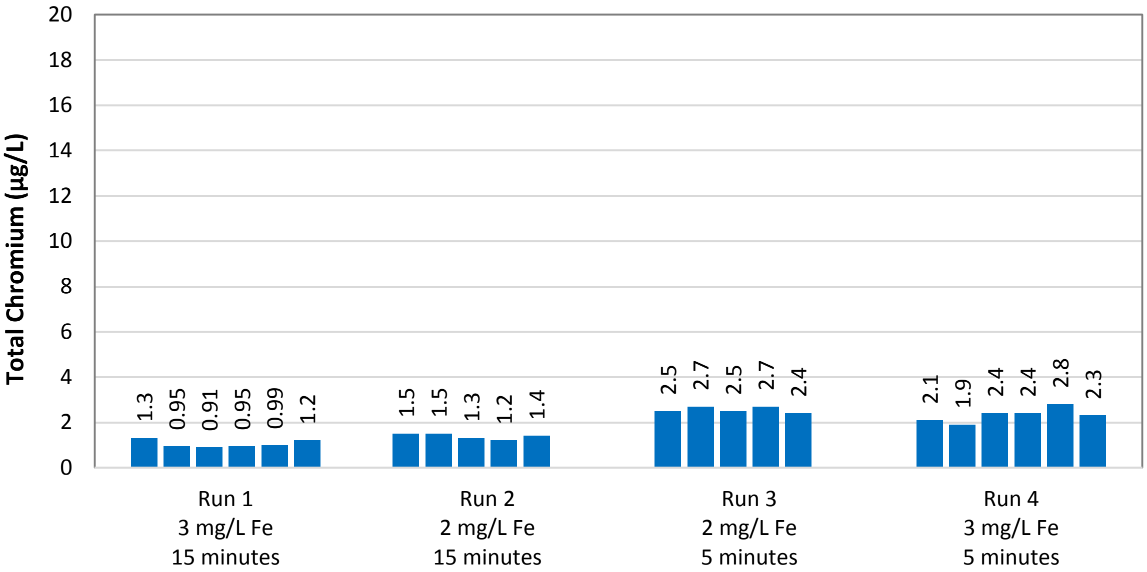


Figure 5-4. RCF Total Cr Filter Effluent Concentrations with Centrifugal Pumping

5.3 Cost Estimates of Treatment

Cr(VI) treatment costs were developed for WBA and RCF in Phase III and were updated in Phase IIIB. In this study, RCF costs were further updated based on the findings from the demonstration testing described in Section 5.2. WBA costs in Phase IIIB were updated to 2015 dollars to provide a direct comparison with RCF. In addition, SBA cost estimates were developed using the same methodology as for RCF and WBA. Detailed costs are provided in the Phase IIID Report.

The expected level of accuracy for the cost estimates presented in this chapter is classified by the Association for the Advancement of Cost Engineering International (AACE) as an International Class 5 estimate. 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 expected accuracy range of estimates.

5.3.1 Reduction/Coagulation/Filtration

The design criteria used for estimating RCF costs are summarized in Table 5-1. Based on the demonstration test results in this study, a fixed ferrous iron dose of 2 mg/L and 5-minutes of reduction time were selected. Inline chlorination with a chlorine dose of 1.3 mg/L was assumed based on the chlorine results in this study. The filter run cycle was assumed to be 24 hours as tested in this study. Centrifugal pumping was assumed for feeding the filters. The other design criteria remain the same as for the previous cost estimates. Costs were developed/updated for RCF with and without recycle.

Table 5-1. RCF Design Criteria Used for Cost Estimates

Specifications	Design Criteria
Ferrous Iron Dose (mg/L)	2
Required Reaction Time (reduction) (minutes)	5
Chlorine Dose (mg/L)	1.3
Chlorine Injection	Inline
Polymer Dose as Coagulant Aid (mg/L as active polymer)	0.1
Polymer Mixing Time in Tank (minutes)	$5^{\wedge}$

Specifications	Design Criteria
Dual Media Filtration Rate (gpm/sf)	3
Filter Run Cycle (hours)	24
Filter Backwash Flow Rate (gpm/sf)	18
Filter Backwash Duration (minutes)	21
Polymer Dose as Solids Settling Aid to Spent Filter Backwash Water (mg/L as active polymer)	1
Filter Pumping	Centrifugal Pumping

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

RCF capital and O&M costs are summarized in Tables 5-2 and 5-3, respectively. Both capital and O&M costs for RCF without recycle are significantly lower than RCF with recycle. Compared with the previous costs in Phase IIIB, the updated costs in this study reflect cost savings in the range of $0.1 to $0.6 million for capital and $0.1 to $0.5 million for annual O&M. The cost savings are a result of the optimized RCF conditions (i.e. centrifugal pumping, inline chlorine injection, less reduction time and a lower ferrous dose), which reduced both equipment cost and system footprint.

Table 5-2. RCF Capital Costs

Treatment System Size	RCF without Recycle	RCF with Recycle
100 gpm	$1,648,000	$2,015,000
500 gpm	$2,621,000	$3,631,000
1,000 gpm	$3,640,000	$4,521,000
2,000 gpm	$5,578,000	$6,714,000

Accuracy range is -30% to +50%. In 2015 dollars.

Table 5-3. RCF Annual O&M Costs

Treatment System Size	RCF without Recycle	RCF with Recycle
100 gpm	$186,000	$296,000
500 gpm	$262,000	$467,000
1,000 gpm	$343,000	$663,000
2,000 gpm	$599,000	$1,127,000

In 2015 dollars.

Unit treatment costs ($/AF) for RCF are shown in Figure 5-5. The estimates reflect cost savings by $86/AF to $312/AF for RCF without recycle and $141/AF to $164/AF for RCF with recycle (except for 100 gpm), compared with the costs in Phase IIIB.

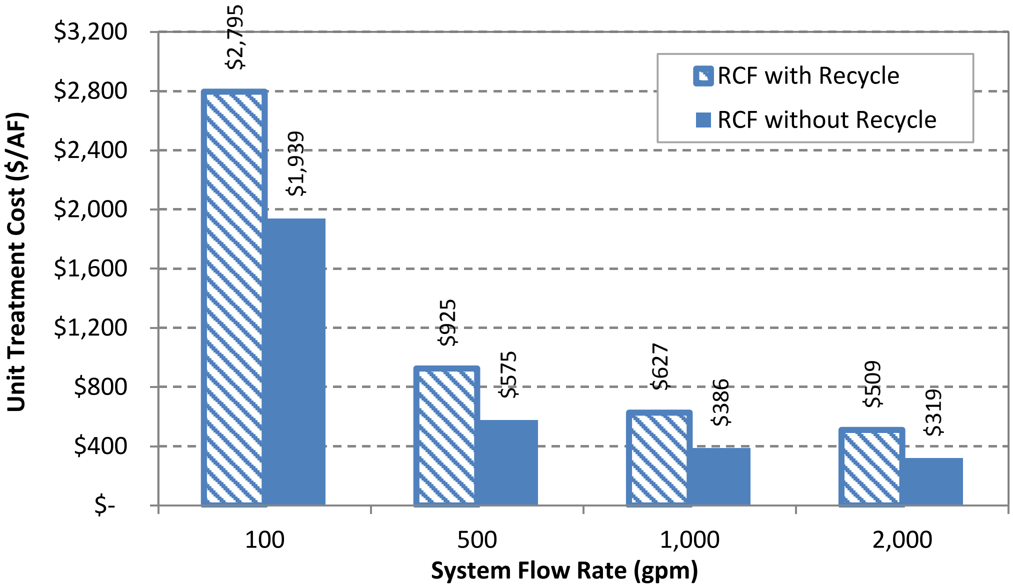


Figure 5-5. RCF Unit Treatment Costs

5.3.2 Strong-Base Anion Exchange

The SBA process consists of bag filters, ion exchange vessels, a regeneration system and a residual treatment system. The regeneration procedure typically consists of backwash, brine regeneration, slow rinse and fast rinse. In this study, the regeneration procedure was assumed to include one bed volume of backwash, four bed volumes of 12% brine, one bed volume of slow rinse and 2.5 bed volumes of fast rinse. To minimize residuals volumes, it was assumed that three out of four bed volumes of used brine is recycled, while the remaining one bed volume containing a high Cr(VI) concentration is sent to treatment. Slow rinse waste was assumed to be reused by being added back to the recycled spent brine and make up the one bed volume. Alternatively, spent brine and slow rinse waste could be treated and disposed of, if preferred. Spent brine requires treatment to remove Cr(VI) before disposal. The treatment process was assumed to include ferrous iron addition, polymer addition, aeration and settling. Treated brine contains high TDS concentrations above typical sewer discharge limits, and therefore was assumed to be trucked off site for disposal. Backwash and fast rinse wastewaters are not expected to contain high Cr(VI) or TDS concentrations, and were assumed to be discharged to the sewer.

The design criteria used for estimating SBA costs are summarized in Table 5-4. SBA vessels were designed in parallel with two or more service vessels and one regeneration/standby vessel. Parallel configuration allows blending of treated water from the different vessels to alleviate nitrate peaking and/or maximize resin life. Alkalinity is typically removed by SBA resin and results in a lower pH for a short period of time when regenerated resin is put back in service. It was assumed the vessels can be operated in a staggered mode to alleviate the effects of alkalinity removal. No post pH adjustment was included in this cost estimate but should be considered on a case-by-case basis by water agencies.

Table 5-4. SBA Design Criteria Used for Cost Estimates

Specifications	100 gpm	500 gpm	1000 gpm	2000 gpm
SBA Resin	Purolite A600E/9149	Purolite A600E/9149	Purolite A600E/9149	Purolite A600E/9149
IX Vessel Configuration	Two service in parallel, plus one regen/standby	Two service in parallel, plus one regen/standby	Two service in parallel, plus one regen/standby	Three service in parallel, plus one regen/ standby
Total Number of Vessels	3	3	3	4
Vessel Diameter (ft)	3.5	6	8	10
Resin per Vessel (cf)	20	100	201	267
Surface Loading Rate (gpm/sf)	5	8.9	10	8.4
HLR (gpm/cf)	2.5	2.5	2.5	2.5
EBCT per Vessel (minute)	3	3	3	3

HLR – Hydraulic Loading Rate

EBCT – Empty Bed Contact Time

SBA capital and O&M costs are summarized in Tables 5-5 and 5-6, respectively. SBA capital costs were comparable to the capital for RCF without recycle and were generally lower than RCF with recycle (except for 2,000 gpm where economies of scale were realized for RCF). Sulfate is a key water quality parameter that affects resin regeneration frequency, and therefore O&M costs. Two raw water sulfate levels, 50 mg/L and 110 mg/L, were used for O&M cost estimates. The SBA O&M costs for both sulfate levels are comparable to those for RCF without recycle and significantly lower than the costs for RCF with recycle.

Table 5-5. SBA Capital Costs

Treatment System Size	SBA
100 gpm	$1,492,000
500 gpm	$2,609,000
1,000 gpm	$3,978,000
2,000 gpm	$7,026,000

Accuracy range is -30% to +50%.

In 2015 dollars.

Table 5-6. SBA Annual O&M Costs

Treatment System Size	Sulfate = 50 mg/L	Sulfate = 110 mg/L
100 gpm	$189,000	$197,000
500 gpm	$233,000	$249,000
1,000 gpm	$289,000	$314,000
2,000 gpm	$408,000	$456,000

In 2015 dollars.

Unit treatment costs ($/AF) for SBA are shown in Figure 5-6. Overall, the differences in unit costs between the two sulfate levels are relatively small, especially for system flow rates of 1,000 gpm or above. The estimated costs also show significant economies of scale for SBA treatment. The unit costs for the higher sulfate level are close to the unit costs for RCF with recycle.

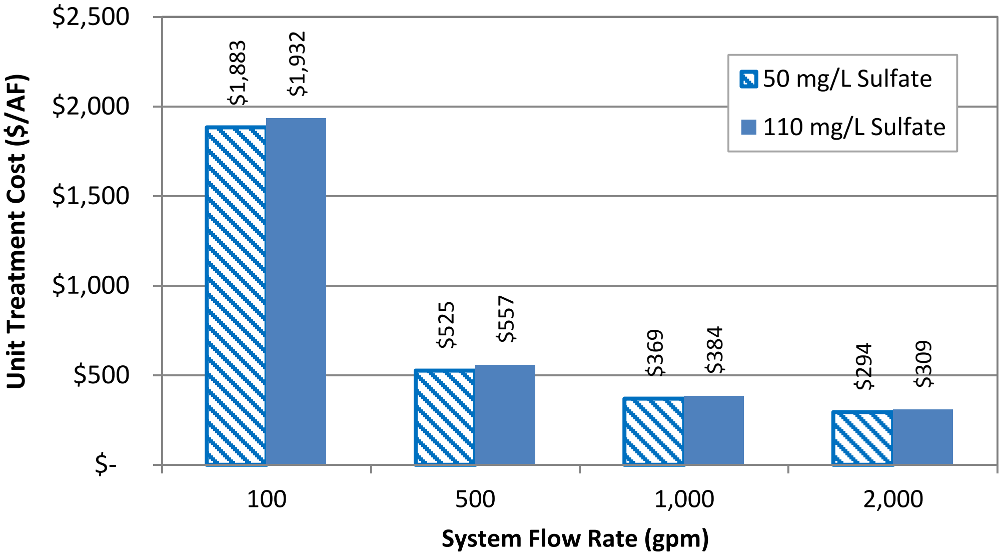


Figure 5-6. SBA Unit Treatment Costs

5.3.3 Weak-Base Anion Exchange

The WBA design criteria are summarized in Table 5-7, for which capital and O&M costs were developed and updated. The WBA process used in the cost estimates consists of bag filters, pre-pH adjustment using CO_2, ion exchange vessels in a lead-lag configuration, and post-pH adjustment using aeration. Alternatively, acid and caustic soda can be used for pre- and post-pH adjustment. Aeration off-gas treatment was included at Glendale as its water contains VOCs that require off gas treatment using vapor phase GAC. However, for water sources without VOCs, aeration off gas treatment is not needed. Therefore, the capital and O&M costs in this study did not include aeration off gas treatment.

Table 5-7. WBA Design Criteria Used in Cost Estimates

WBA System Specifications	100 gpm	500 gpm	1,000 gpm	2,000 gpm
IX Vessel Configuration	1 lead/lag train	1 lead/lag train	1 lead/lag train	2 lead/lag trains
Total Number of Vessels	2	2	2	4
Vessel Diameter (ft)	4	8	12	12

WBA System Specifications	100 gpm	500 gpm	1,000 gpm	2,000 gpm
Volume of Resin per Vessel (cf)	50	250	500	500
Total Resin Volume for First Fill (cf)	100	500	1,000	2,000
Surface loading rate (gpm/sf)	8.0	9.9	8.8	8.8
HLR (gpm/cf)	2.0	2.0	2.0	2.0
EBCT per Vessel (minute)	3.74	3.74	3.74	3.74
Operating pH	6.0	6.0	6.0	6.0

HLR – Hydraulic Loading Rate

EBCT – Empty Bed Contact Time

WBA capital and O&M costs are summarized in Tables 5-8 and 5-9, respectively. The O&M costs were based Purolite S106 resin. Costs estimated in Phase IIIB for three WBA resins (DOW PWA7, Purolite S106 and ResinTech SIR-700) are generally comparable. The WBA capital costs are close to the SBA capital costs, except for 2,000 gpm (significantly lower than SBA). The WBA O&M costs are lower than SBA costs for 100 and 500 gpm, but higher than SBA costs for 1,000 and 2,000 gpm. For systems above 1000 gpm, SBA system has greater economies of scale based on resin regeneration and spent brine treatment unit processes.

Table 5-8. WBA Capital Costs

Treatment System Size	Purolite S106
100 gpm	$1,433,000
500 gpm	$2,887,000
1,000 gpm	$3,645,000
2,000 gpm	$6,172,000

Accuracy range is -30% to +50%. In 2015 dollars.

Table 5-9. WBA Annual O&M Costs

Treatment System Size	Purolite S106
100 gpm	$113,000
500 gpm	$221,000
1,000 gpm	$356,000
2,000 gpm	$655,000

In 2015 dollars.

Figure 5-7 shows the unit treatment costs for WBA. Figure 5-8 compares the unit treatment costs for RCF, SBA and WBA. For 100 gpm, WBA has the lowest unit treatment cost among the three technologies. For 500, 1,000 and 2,000 gpm, SBA with 50 mg/L of sulfate has the lowest unit treatment costs; however, the differences between SBA, WBA and RCF without recycle are small. RCF with recycle is higher because additional infrastructure and operations is necessary, although water savings are offered by recycling compared to RCF without recycle.

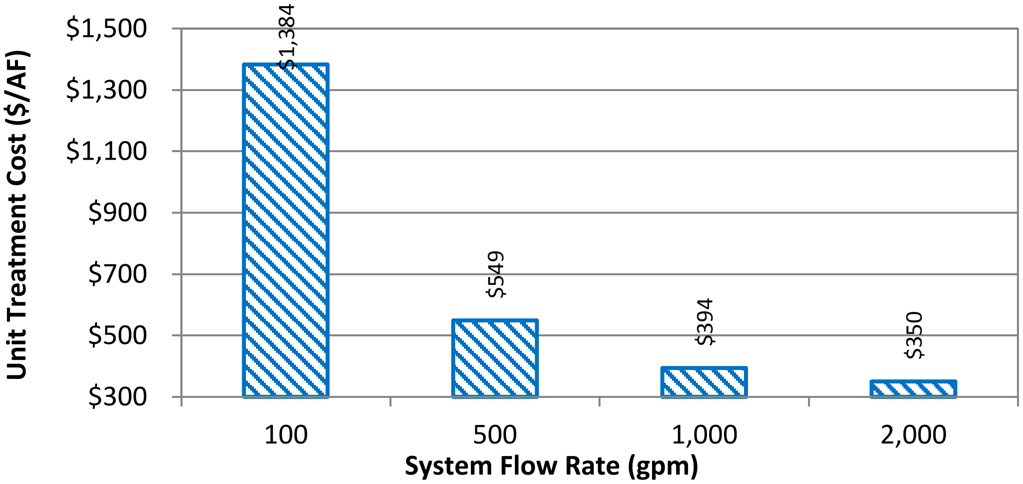


Figure 5-7. WBA Unit Treatment Costs

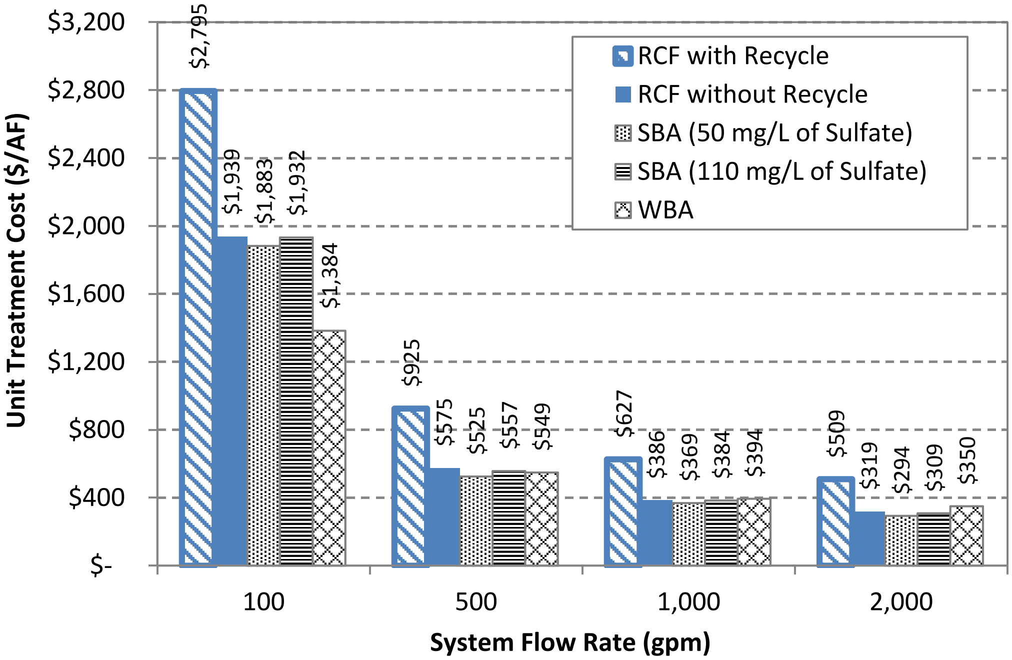


Figure 5-8. RCF, SBA and WBA Unit Treatment Costs

5.4 Site Layouts and Preliminary Design Drawings

Site layouts and preliminary design drawings were developed for RCF, SBA and WBA for a 1,000 gpm system to compare the required footprints. Glendale's RCF demonstration process site was used as the site for the layouts and drawings as an example.

5.4.1 Reduction/Coagulation/Filtration

Site plans and equipment layouts were developed for RCF without recycle and RCF with recycle. Figures 5-9 and 5-10 show the site plan and equipment layout for RCF without recycle. The estimated total equipment footprint is 1,455 sf. The minimum site footprint is 6,677 sf. Figures 5-11 and 5-12 show the site plan and equipment layout for RCF with recycle. The estimated total equipment and site footprints are 3,385 sf and 13,060 sf, respectively. Thus, RCF with recycle would require much more space for equipment and a larger site than RCF without recycle but offers water savings if that is of primary concern to water agencies.

5.4.2 Strong-Base Anion Exchange

The SBA site plan and equipment layout are shown in Figure 5-13 and 5-14 for SBA with on-site regeneration and brine treatment. The estimated total equipment and site footprints are 1,715 sf and 11,140 sf, respectively. The equipment footprint is slightly bigger but comparable to RCF without recycle. The site footprint is comparable to RCF with recycle.

5.4.3 Weak-Base Anion Exchange

The WBA site plan and equipment layout are shown in Figures 5-15 and 5-16. The estimated total equipment and site footprints are 1,070 sf and 6,426 sf, respectively. The equipment footprint is significantly smaller than SBA or RCF without recycle.

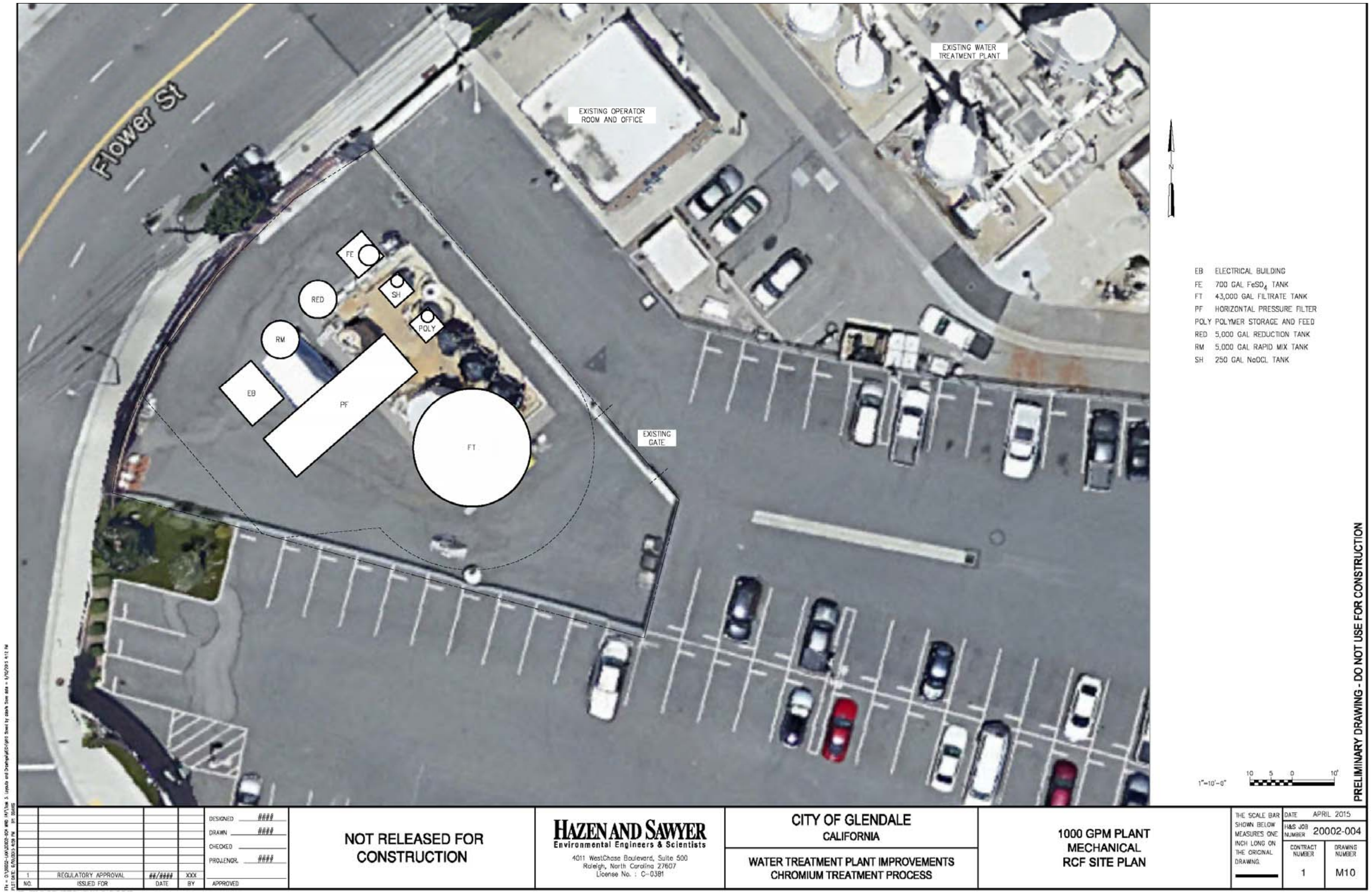


Figure 5-9. RCF without Recycle Site Plan

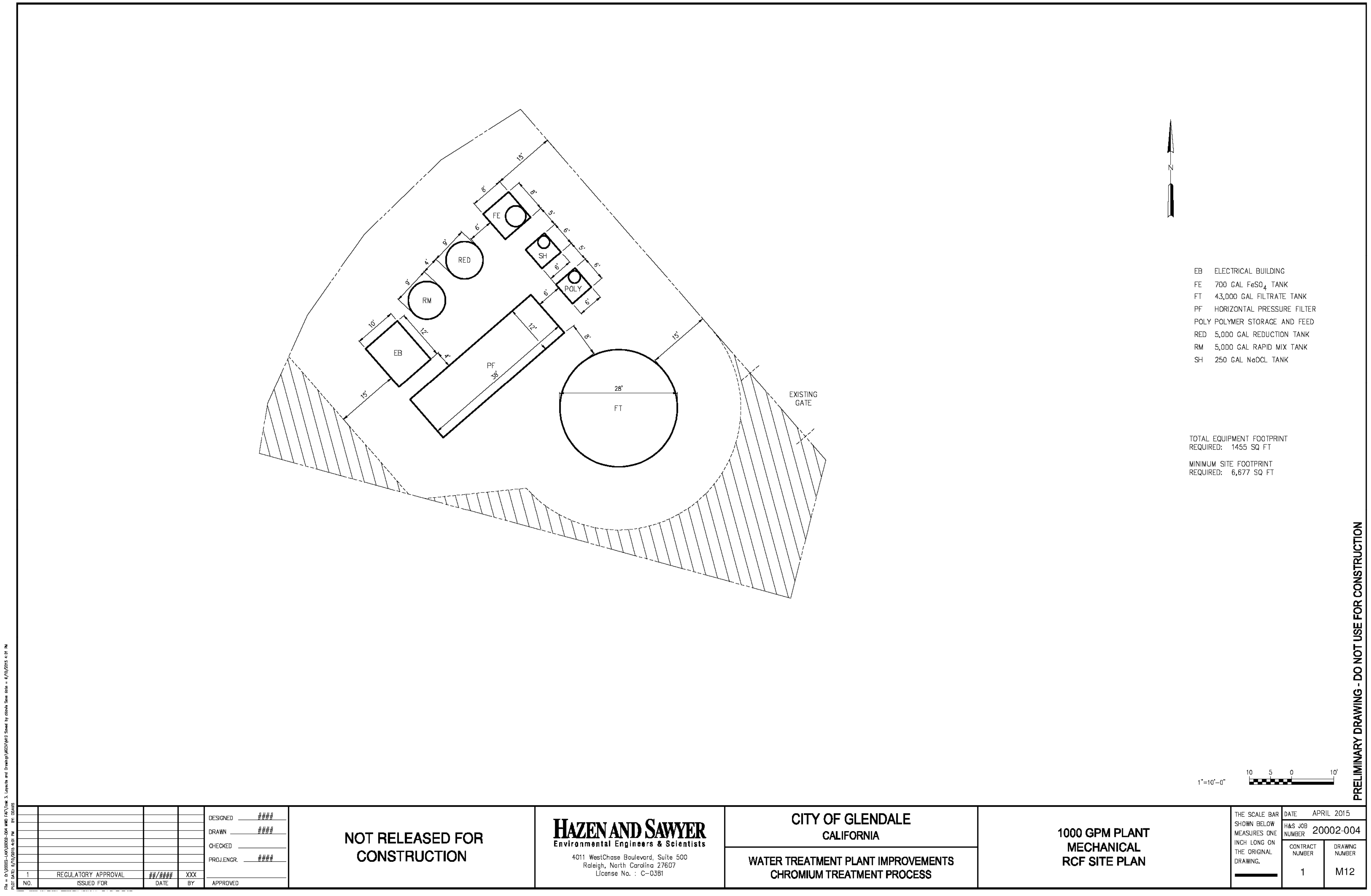


Figure 5-10. RCF without Recycle Equipment Layout

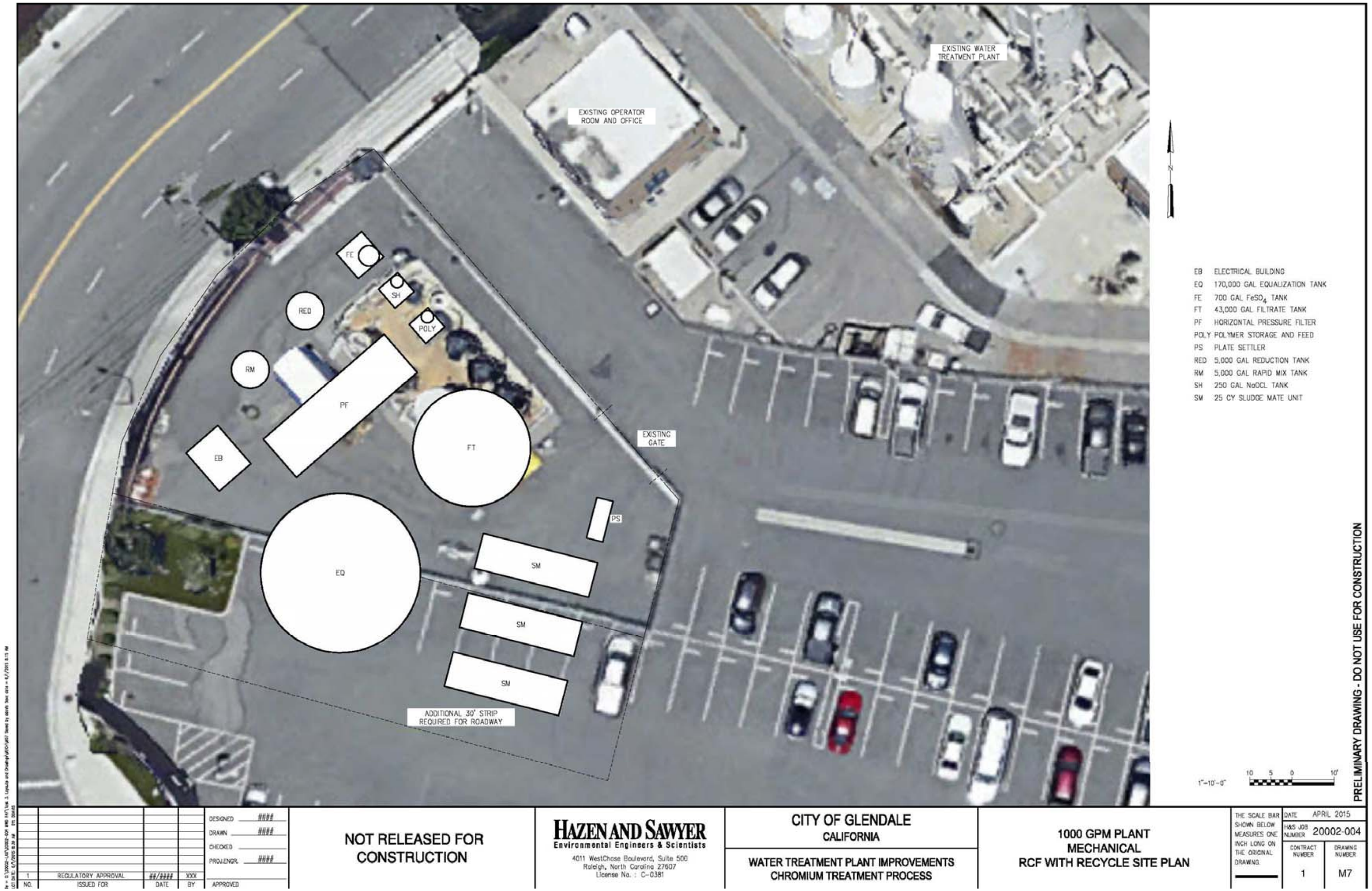


Figure 5-11. RCF with Recycle Site Plan

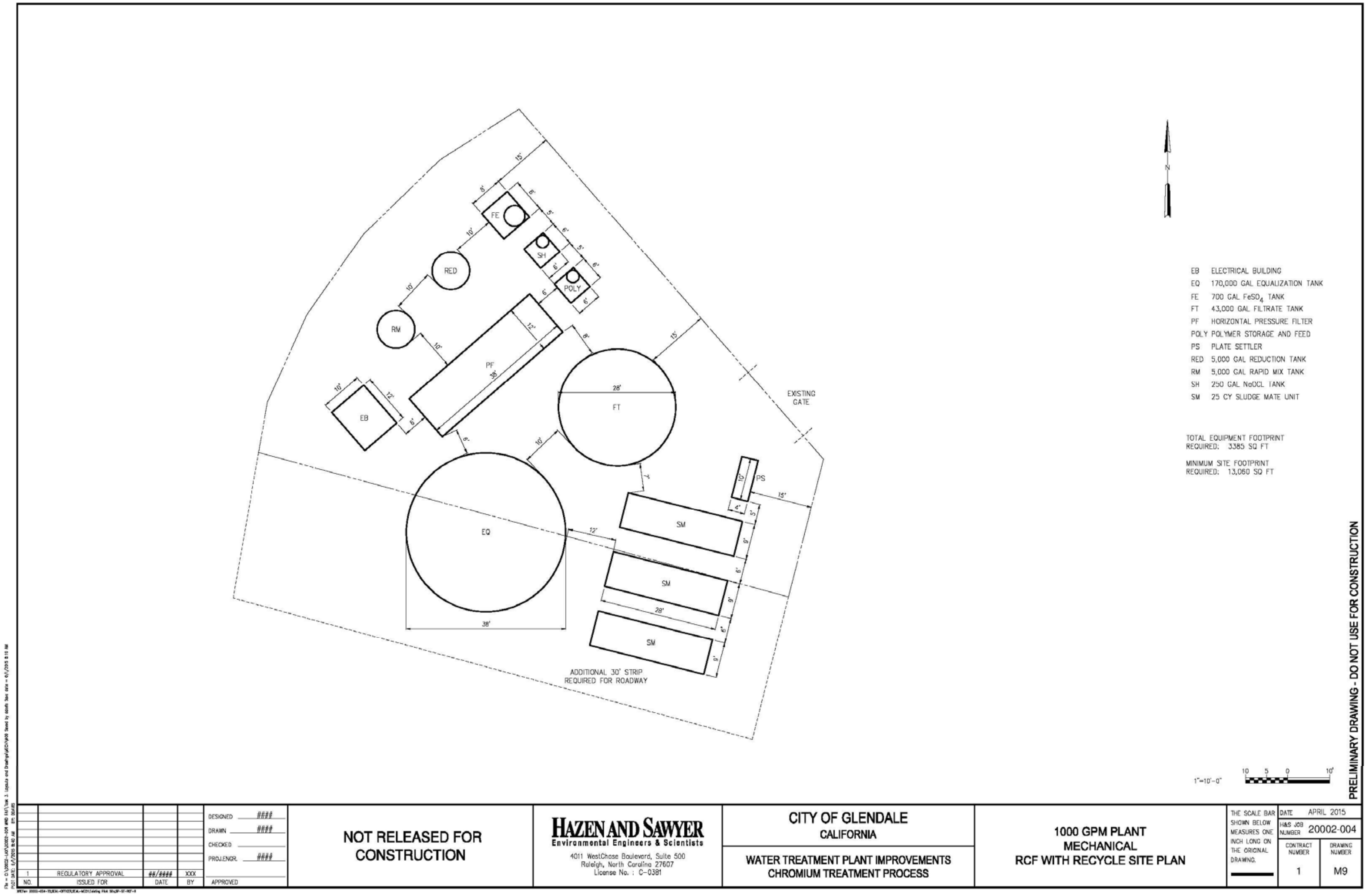


Figure 5-12. RCF with Recycle Equipment Layout

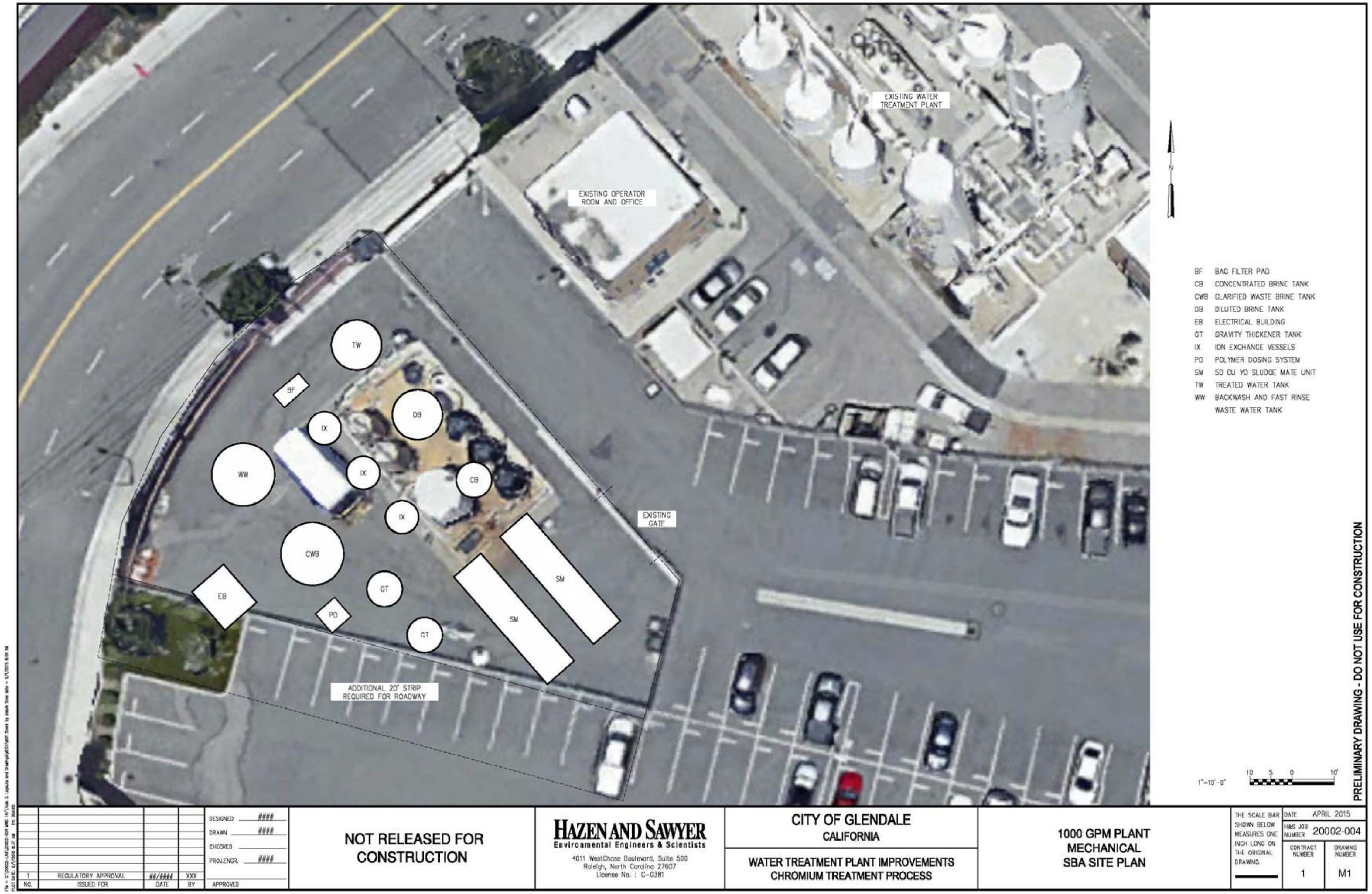


Figure 5-13. SBA Site Plan

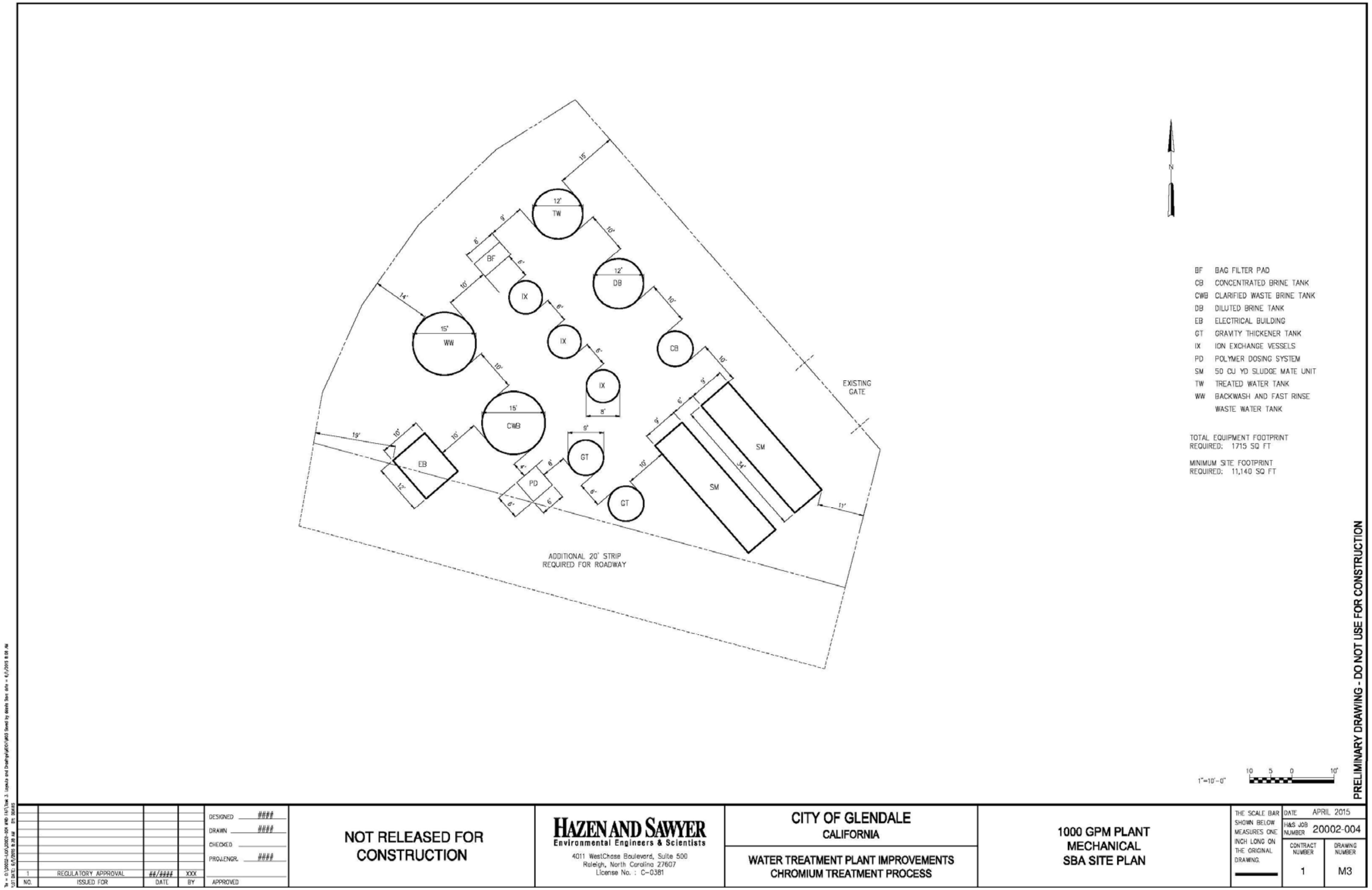


Figure 5-14. SBA Equipment Layout

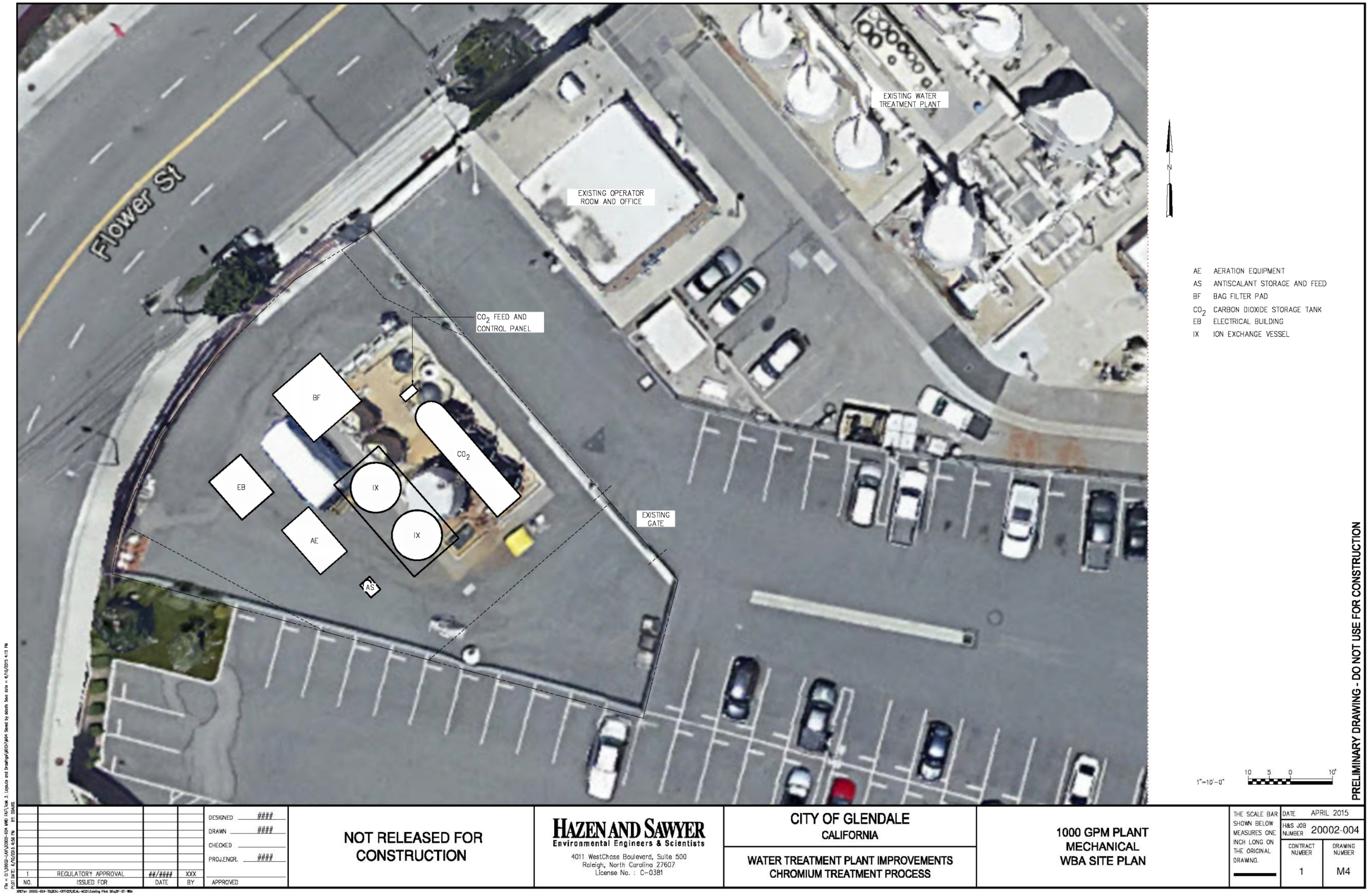


Figure 5-15. WBA Site Plan

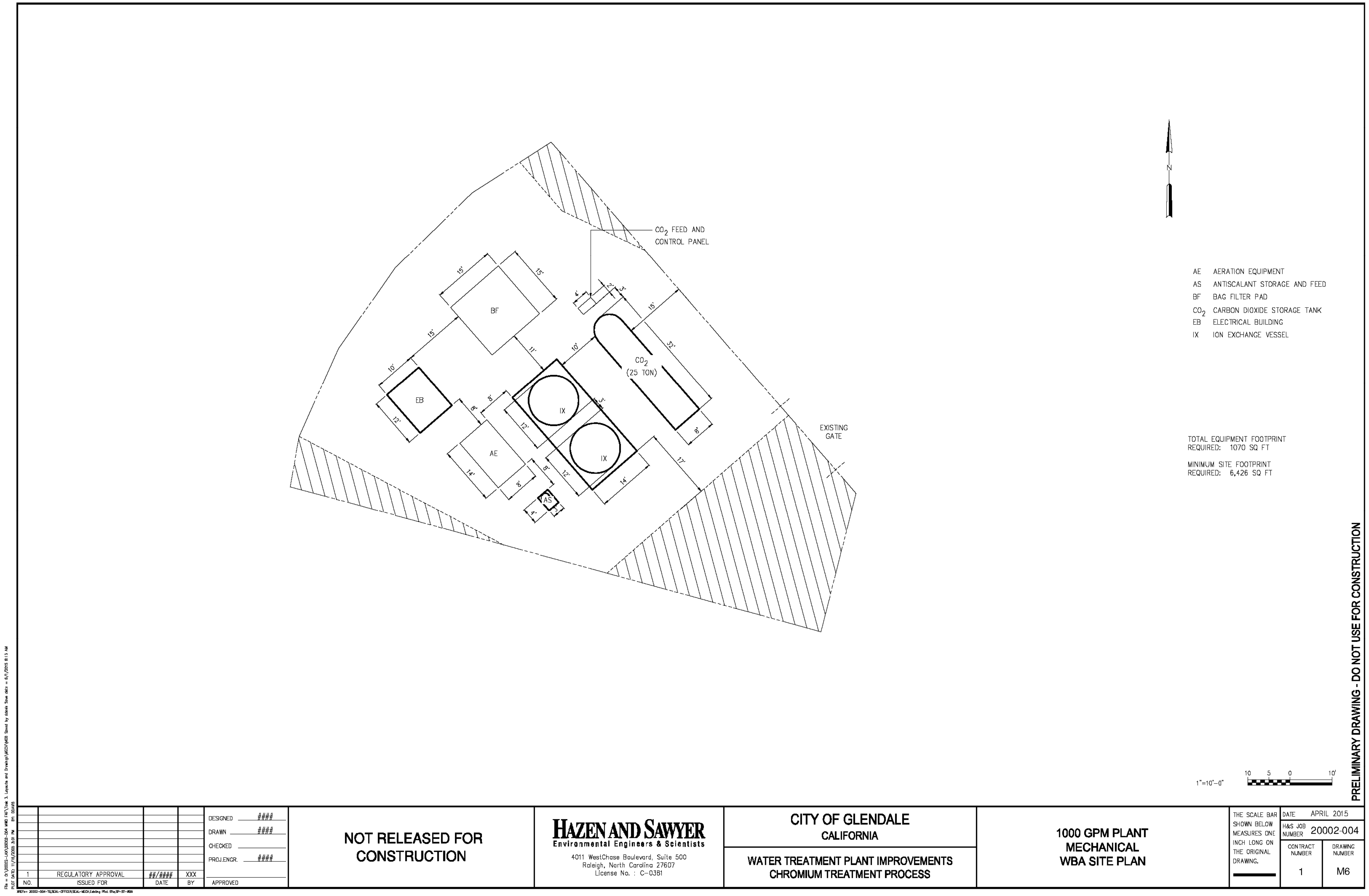


Figure 5-16. WBA Equipment Layout

5.5 Using Blending with Treatment to Achieve Compliance

When Cr(VI) treatment is needed for compliance with the MCL, the treatment process can be designed to treat the whole flow or only a portion of the flow and then blend the treated water with bypass to achieve the Cr(VI) treatment goal. The advantage of the blending approach is that the treatment system size is smaller and lower in capital cost. However, the Cr(VI) treatment goal is lower to allow blending of the treated flow with the bypass flow to achieve compliance. This section evaluates the cost benefits of using blending with treatment to comply with the Cr(VI) MCL.

Three scenarios were developed for comparison. A baseline scenario evaluated the treatment costs for RCF, WBA, and SBA with blending compared to without blending to achieve treated Cr(VI) of 8 µg/L. The second scenario evaluated the impact of key water quality parameters on treatment costs with blending compared to without blending. For WBA, the key water quality parameter affecting treatment costs is alkalinity. Two alkalinity levels of 250 and 100 mg/L as $CaCO_3$ were evaluated in this scenario. For SBA, the key water quality parameter affecting treatment costs is sulfate. A total of three sulfate concentrations (20, 50 and 110 mg/L) were evaluated in this analysis. RCF treatment costs are not significantly affected by water qualities and were not evaluated further. The third scenario evaluated the impacts of Cr(VI) treatment goal on treatment costs with blending compared to without blending. The Cr(VI) treatment goal affects the resin life for WBA and SBA both with and without blending, and also affects the water quantities to be treated with blending for RCF, WBA and SBA. Three treatment goals were evaluated, including 8, 6, and 4 µg/L.

Capital and O&M costs were estimated based on the costs summarized in Section 5.3. Unit treatment costs were used to compare the costs for blending versus non-blending, which incorporated both capital and O&M costs. Unit treatment costs were calculated based on a 20-year life cycle and a 5% interest rate.

For all scenarios, a system flow rate of 1,000 gpm was used. For the non-blending approach, the treatment flow rate is 1,000 gpm. For the blending approach, the treatment flow rate was calculated based on the Cr(VI) concentrations in raw water, the Cr(VI) treatment target after blending and the assumed Cr(VI) concentration in the treated water using mass balance. It was assumed WBA and SBA can effectively remove Cr(VI) to below 2 µg/L, while RCF can effectively remove Cr(VI) to below 5 µg/L.

The results for Scenario 1 are shown in Figure 5-17. For all technologies, the unit treatment costs for the blending approach (blending treated water with bypass) are significantly lower than the non-blending approach (i.e. treating the whole flow). SBA is the most cost effective, followed by WBA, RCF without recycle, and RCF with recycle. The Scenario 2 results indicate that blending would generate a lower unit treatment cost than non-blending for WBA regardless of the alkalinity level and for SBA regardless of the sulfate level. The Scenario 3 results indicate that blending would be more cost effective than non-blending for RCF, WBA and SBA regardless of the Cr(VI) treatment goal, although the difference of unit treatment cost for blending versus non-blending becomes smaller when the treatment goal is lower.

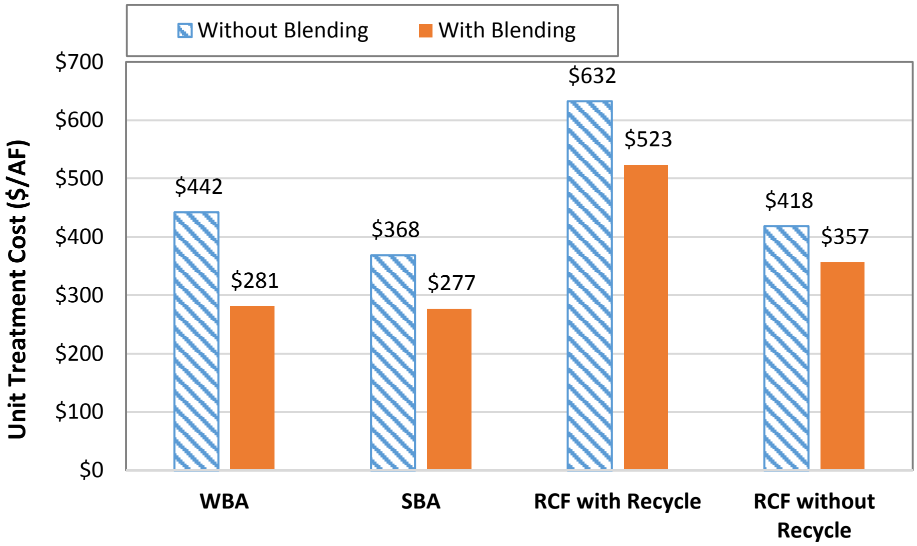


Figure 5-17. Treatment Costs for Blending versus Non-Blending

5.6 Summary and Conclusions

In this study, the RCF operational conditions were optimized to 2 mg/L of iron dose, 5-minutes of reduction time, inline chlorine injection and centrifugal filtration pumping, which result in significant cost savings and reduce the system footprint. Cost analysis suggests that SBA has the lowest treatment cost for 500 gpm and above, while WBA has the lowest cost for 100 gpm. RCF with recycle generally requires a higher cost due to the additional infrastructure and operations necessary for recycling wastewater. However, the cost differences between SBA, WBA, and RCF without recycle are not dramatic. Other factors, such as site space, sewer access and operational preference, must also be considered. Preliminary design for 1,000 gpm shows WBA requires the smallest footprint, followed by RCF without recycle, SBA with on-site regeneration and brine treatment, and RCF with recycle. Blending analysis based on treatment of a 1,000 gpm well indicated that blending (i.e., treating a portion of the flow and then blending the treated water with untreated bypassed water) is more cost effective than treating the whole flow for RCF, WBA and SBA, for a range of water quality and Cr(VI) treatment goals.

6. Supplemental Report Overall Summary and Conclusions

More than 14 years of research has been completed in this program, forming a foundation of knowledge on Cr(VI) treatment for water agencies and the State of California. The previous work described in the Project Report (Blute et al., 2013) identified technologies for Cr(VI) removal, including testing from the bench scale through demonstration operations. The work presented in this Supplemental Report provides findings from Phases IIIB, IIIC, and IIID, which all investigated potential optimization opportunities for best available technologies.

One of the simplest solutions for Cr(VI) treatment is single-pass ion exchange – either SBA or WBA. In Phase IIIB, two new WBA resins were demonstrated to be effective alternatives to the one previously tested, without formaldehyde leaching that had been problematic with the first WBA resin. The manufacturer of the first resin developed a method to decrease formaldehyde leaching from that resin, and tests showed that new procedures can minimize this effect so the resin can be used more effectively. SBA resins offer another treatment option, possibly in a single-pass mode of operation if sulfate levels are low and costs are reasonable. Iron-based adsorptive media continues to hold promise in Cr(VI) removal as shown by this testing, but additional study is needed on regeneration and iron removal prior to implementation to allow comparison to the other technologies for evaluation of cost effectiveness. As in prior studies, this testing demonstrated the importance of pilot testing new media, as reported performance was not always achieved in practice.

In Phase IIIC, one WBA and one SBA resin in the laboratory development stage were provided by AquaNano for similar testing as other resins. Both of these AquaNano resins showed better performance compared to other resins already in the marketplace, including higher Cr(VI) capacity (for SBA) and no leaching of formaldehyde or initial leakage (for WBA). It is recommended that the promising AQ60-MP SBA resin be evaluated with regeneration to compare longer term performance with other resins.

Phase IIID included optimization of the RCF process for cost and footprint savings, including less reduction time, use of chlorination for oxidizing remaining iron, and use of a less expensive pumping strategy. Testing identified that conditions could be optimized on each of these variables. This project also provided an update of treatment costs for RCF, WBA, and SBA based on findings from Phases IIIB and IIID. Several case studies were developed that analyzed a partial treatment and blending strategy for minimizing cost, finding benefit from this approach compared with whole flow treatment.

Overall, the additional studies conducted in Phases IIIB, IIIC, and IIID provided significant opportunities for treatment optimization, including new resins and smaller facilities for removing Cr(VI) from water supplies.

7. References

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