Carollo Engineers is an environmental consulting firm with more than 700 employees in 38 offices throughout the United States. All of our work is performed in the areas of water and wastewater, resulting in a level of understanding of key project issues that few can match. Carollo strives to maintain the tradition of using sound and proven engineering principles while moving progressively forward to keep abreast of changing times and new technologies.

This is a specialty Statement of Qualifications (SOQ) for Carollo detailing some of our experience and expertise in the field of water treatment specific to this topic.

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ARSenic occurrence IN THE UNItED StaTes

Arsenic has been spotlighted throughout history ranging from a common poison in classical Rome and the Broadway musical, “Arsenic and Old Lace,” to the high-tech electronics industry usage of gallium arsenide semiconductors. However, the recent adoption of a lower Maximum Contaminant Level (MCL) in drinking water by the Environmental Protection Agency (EPA) has brought this mineral to the forefront of the water industry. As a naturally occurring mineral in aquifer sediments, arsenic is primarily found in groundwaters of the Southwest, though isolated pockets exist in several Midwest and New England communities. Most known cases of elevated arsenic in drinking water sources stem from natural release of arsenic from sediments.

Considered a nutrient at “trace” levels and a chronic carcinogen at slightly higher levels, arsenic has been deemed by the EPA as a primary drinking water contaminant that needs more stringent regulation. Toxicological evidence in several Asian communities, South America, and even several western U.S. communities indicate that arsenic ingestion may cause several forms of cancer. Potential target organs include the heart, skin, bladder, endocrine system, and nervous system, just about every major system in the body.

By lowering the existing arsenic MCL from 50 µg/L to 10 µg/L, EPA estimates that at least 30 deaths a year will be prevented. While, at first glance, this may seem relatively small considering the U.S. population of 295 million, the risk factor used by the EPA in risk analysis has a very low tolerance. If more than 1 person in 1,000,000 die of a carcinogenic cause as a result of a contaminant in drinking water, the MCL is too high and needs to be lowered even further.
While it is not fully understood why arsenic is released into the groundwater in some places and not others, treatment processes have been studied extensively over the last decade. With an anticipated compliance cost (i.e., capital cost) with the Arsenic Rule as high as $600 million (Water Research Foundation estimate), there has been considerable time and money spent to better understand and optimize arsenic treatment processes. Carollo has been a player at all levels, from partnering with universities in research projects, to pilot testing of various processes, to full-scale design projects.

**ARSENIC TREATMENT**

The various types of arsenic treatment alternatives can be extensive, especially when considering all the commercially available arsenic-specific medias. The table below outlines different arsenic treatment technologies and associated advantages and disadvantages.

At Carollo, we have the capability to test all these processes at either the bench- or pilot-scale level. Furthermore, because we own the equipment, we know how to install it and start generating results in a very efficient manner. There is no need to go through several iterations of leasing agreements and startup delays with media vendors.

### Arsenic Removal Technologies

<table>
<thead>
<tr>
<th>Lower Cost Technology</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coagulation/Filtration (C/F)</td>
<td>• Effective, proven technology. • Moderate operator training.</td>
<td>• Process sensitive to pH. • Potential disposal issues of backwash waste.</td>
</tr>
<tr>
<td>Lime Softening (LS)</td>
<td>• Removal of multiple contaminants. • Treatment for high levels of As. • Relatively simple operational change (pH increase) for existing LS facilities.</td>
<td>• Process sensitive to pH. • May require additional treatment. • Sludge generation.</td>
</tr>
<tr>
<td>Oxidation/Filtration</td>
<td>• Also removes Fe and Mn. • Moderate operator training.</td>
<td>• Process sensitive to pH. • Addition of iron and oxidant may be required. • Potential disposal issues of backwash waste.</td>
</tr>
<tr>
<td>Activated Alumina (AA)</td>
<td>• High selectivity toward As$^{5+}$. • Effective in treating water with high TDS.</td>
<td>• Process very sensitive to pH. • High concentration of SeO$_4^{2-}$, F$^-$, Cl$^-$, and SO$_4^{2-}$ may limit arsenic removal. • Hazardous chemicals (acid and base) used to regenerate media.</td>
</tr>
<tr>
<td>Arsenic Specific Media (ASM)</td>
<td>• High selectivity toward As$^{5+}$. • No regeneration chemicals on site. • Minimal process upsets associated with start-stop operations.</td>
<td>• Proprietary media. (High O&amp;M costs for media) • Extended performance verification period.</td>
</tr>
<tr>
<td>Ion Exchange (IX)</td>
<td>• Removal of multiple contaminants (e.g., NO$_3^-$, ClO$_4^-$, and Cr$_6^{3+}$). • Proven technology (50 yrs. of experience). • High arsenic removal efficiency.</td>
<td>• Brine waste handling/disposal. • Leaching of NDMA or NDMA precursors from some IX resins. • Efficiency impacted by sulfate and other anions.</td>
</tr>
<tr>
<td>Membrane Filtration (MF/UF)</td>
<td>• High arsenic removal efficiency. • Removal of multiple contaminants.</td>
<td>• Waste disposal issue of membrane cleaning water • Pretreatment may be needed.</td>
</tr>
<tr>
<td>Membrane Filtration (RO/NF) and EDR</td>
<td>• High arsenic removal efficiency • Removal of multiple contaminants.</td>
<td>• Reject water disposal issues. • Poor production efficiency. • Pretreatment needed.</td>
</tr>
</tbody>
</table>
Design Considerations

Arsenic can be removed from water by a variety of processes (see “Arsenic Removal Technologies” table). Many of these processes have a common feature; water must pass through natural (e.g., sand) or man-made media (e.g., sorptive media) at some point in the process.

It is here that Carollo is able to provide a design feature that few engineering firms even mention, “media upgrade.” There are instances when arsenic-specific medias are the most cost-effective option. However, utilities are often apprehensive about locking themselves into a single system and not being able to competitively bid future upgrades. Carollo’s approach is to design the overall process (e.g., vessels, piping, controls) so that it can work using several types of media, thus allowing the media to be competitively bid. In this manner, more than one media supplier can bid on the project both during initial construction and afterwards when the media is replaced.

In some cases, we build flexibility into the design by allowing the system to be easily converted to a coagulation/filtration system if so desired at a later date. As the utility grows and becomes comfortable with operations, conversion from an arsenic-specific media to a coagulation/filtration system can often represent considerable cost savings in operations and maintenance. Other considerations Carollo carefully examines during design include:

- **Hydraulics** - “Will a treatment system negatively impact system hydraulics and require additional costs of a booster pump station?”
- **Chemical feed** - “Has chemical equipment been given appropriate space for current operations and maintenance efforts with room for expansion if needed?” “Is there enough clearance for installation of chemical service injection and a chemical storage/feed area?”
- **Flow control** - “How should filter backwashing be handled (i.e., storage tank vs. system supply vs. raw water?)”

Blending and Monitoring

One of the first options that should be examined in an arsenic evaluation study is the ability to use an alternate water source or blend sources. Because there are no in-line arsenic analyzers currently available, accurate flow monitoring and raw water characterization is a vital part of a blending plan.

Carollo, in conjunction with several universities, recently finished a project that developed a field kit for measuring low levels of arsenic.
Our experience with this particular method, other commercially marketed kits, and general laboratory methods provides us the tools to help utilities develop and implement their own process control measures. Part of this research project entailed visiting utilities, training operators on how to use the kit, and then asking them for their input to determine how the kit could be improved.

**Solids Handling**

With the advent of arsenic treatment came the issue of “hazardous waste management.” Every treatment process that removes arsenic, generates some form of concentrated arsenic waste stream. Handling and disposing of this waste can represent a significant portion of annual operating and maintenance costs. In the worst-case scenario, waste is classified as “hazardous,” resulting in significant permitting, handling, and disposal fees. It is for this reason that Carollo has been proactive and recently was awarded a Water Research Foundation project focusing on ways to minimize the production of arsenic waste residuals. Carollo was chosen for this project from 10 other proposing teams, making this one of the most competitive projects in Water Research Foundation history.

**ARSENIC PROJECT EXPERIENCE**

Carollo’s objective as an engineering design firm is to successfully integrate applied research and engineering to specific applications. A packaged arsenic treatment system may work just fine, but Carollo ensures that the process is the most cost effective one currently available and tailored to the specific needs of the utility while providing flexibility for future process adjustments. Many times, there are ancillary issues related to arsenic treatment (e.g., start-up water
disposal, waste disposal, or overall system integration) that require a “system approach.” Carollo has the expertise to provide technology-specific engineering skills, in addition to providing a big picture approach.

Since 1989, Carollo has been evaluating and designing arsenic treatment processes with over 25 projects completed or ongoing. We have worked with every major arsenic treatment process. As can be seen from the table on the next page, there has been an increased focus on this arsenic issue by utilities due to the January 2006 compliance deadline quickly approaching. Highlights of particular interest include:

► Evaluation and predesign work for the largest arsenic removal facility in the U.S. (600-mgd Los Angeles Aqueduct Filtration Plant, California).

► Design and construction management of the largest arsenic removal facility built specifically for compliance with the Arsenic Rule (13-mgd City of Victorville plant, California).

► Participation in several research projects (Water Research Foundation and EPA funded) focused on important side issues - waste handling and process monitoring.

► Treatment evaluations on a variety of water qualities, from North Dakota to Southern California.
## Carollo’s Arsenic Experience

<table>
<thead>
<tr>
<th>Year</th>
<th>Client</th>
<th>State</th>
<th>Full-Scale Design</th>
<th>Bench/Pilot Study</th>
<th>Facility Plan/ Master Plan Update</th>
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</tbody>
</table>

1. Processes tested include: Coagulation/Filtration (Granular Media and Membranes), Oxidation Filtration, Ion Exchange, Activated Alumina, and Arsenic Specific Media (e.g., GFH, SORB 33).
2. Los Angeles Department of Water and Power (CA), City of Pomona (CA), Southern California Water Company (CA), La Puente Valley County Water Company (CA).
3. California Water Service Company (CA), City of Delta (UT), City of Hanford (CA), Eagle Mountain Water System (UT), Mesa Utilities Department (AZ), Metropolitan Water District of Salt Lake and Sandy (UT), Taylorsville-Bennington Improvement District (UT), Town of Gilbert (AZ), Truckee Meadows Water Authority (NV), United Water Idaho (ID).
The project profiles on the following pages present highlights of Carollo’s key achievements in arsenic treatment for drinking water. These examples illustrate our ability to:

- Implement innovative technologies to improve process design and performance.
- Integrate engineering and research to achieve practical solutions tailored to specific client needs.
- Involve project participants early in the process to “demystify” advanced technology and fully understand each other’s needs.
- Offer advanced solutions that are practical, affordable, and reliable.

We would be happy to provide client references that can attest to the quality and responsiveness of Carollo’s services upon request.
The Elsinore Valley Municipal Water District owns and operates several wells containing between 2 and 40 µg/L of arsenic. Carollo was retained to evaluate ways to mitigate arsenic in the wells, specifically focusing on the following:

- Evaluation of alternative treatment technologies (e.g., IX and AA).
- Pilot testing of the coagulation/filtration (C/F) process.
- Predesign for a 10-mgd C/F facility and two blending facilities for two of the three areas as part of the evaluation (2,300 gpm and 2,700 gpm).
- Design and construction management of all three facilities.
- Coordination and correspondence with State Water Board Division of Drinking Water (DDW) due to SRF funding for these projects.

Several “stress” tests were evaluated to help better understand the C/F process and how it could be properly integrated into the District’s system. We evaluated high filter loading rates (e.g., 8 gpm/ft²), the impacts of start-stop operation of the filters, and the benefits of acid pretreatment.

In predesign, it was determined that one set of wells (Machado Street Well, Lincoln Street Well, and Joy Avenue Well) could be centralized and use blending to meet compliance with the Arsenic Rule. At the other end of the distribution system, the second set of wells (Corydon Street Well and Cereal #1 Well) could also be blended, while the third set (Cereal #3 Well and Cereal #4 Well) would require treatment using the C/F process in order to meet compliance.

Detailed design and construction management focused on a pressurized filtration facility with pipe stub-outs with flanges to allow for addition of more filter vessels in the future.

Carollo offered engineering and start-up services during construction (Fall 2007 to Fall 2008).
The objective of the South Tahoe Public Utility District’s Arsenic Treatment Study was to select an arsenic treatment method that would meet water quality and operational goals and could be integrated into the existing site. The project included the following phases:

- Phase I - desktop evaluation of potential treatment technologies and development of a pilot testing program.
- Phase II - pilot testing of C/F and single-use sorptive media (SM).
- Phase III - site-specific preliminary design criteria, conceptual site layouts, and an economic analysis of C/F and iron-based adsorptive media. Iron-based adsorptive media was determined to be more economical over a 20-year period.
- Phase IV - development of prepurchase documents for the procurement of an iron-based adsorptive media treatment system and work on the DDW permit amendment.
- Phase V - design of a 1,000-gpm arsenic treatment facility.

The benefits to the District provided by these phases are as follows:

- A defensible selection of treatment technology and projected life-cycle costs.
- Confirmation of treatment efficacy in terms of arsenic removal and overall finished water quality (e.g., corrosivity).
- Appropriate strategy to integrate arsenic treatment into the existing site and treatment train (HiPOx - MtBE oxidation and chlorination disinfection).
- Early “buy-in” by DDW to help expedite well operation modifications permitting.
- A hands-on opportunity for operators to see and operate proposed treatment options.
- Development of preliminary design criteria to help reduce conservative safety factors.
- Refinement of cost estimates through each phase of the project for budgetary planning purposes.
- Prepurchase of the selected arsenic treatment technology to speed up final design and provide the District with a clean design (e.g., most operational flexibility and access) and smooth construction.
- Final design that integrates the arsenic treatment facility into the existing site.
Valley Vista Well Head Arsenic Treatment Facility

Carollo was retained by the Arizona Water Company to provide engineering design and bidding assistance for its Valley Vista Water Treatment Facility. The project consists of the design of a new 450-gpm wellhead arsenic treatment facility utilizing adsorptive media in a lead/lag vessel arrangement.

The existing Valley Vista site includes two wells and an existing pilot-scale adsorptive media system from Kinetico. The smaller of the two wells will be abandoned once the new treatment facility is operational. The pilot-system will be decommissioned as part of the work.

This project is divided into 5 phases as follows:

- Phase I - Selection of an adsorptive media supplier.
- Phase II - Development of preliminary design report, process schematics, and preliminary P&IDs.
- Phase III - Development of detailed engineering design plans, including mechanical and electrical/I&C integration and all applicable permitting and regulatory approvals required to complete the project.
- Phase IV - Support during bidding.
- Phase V - Construction management/inspection services where needed.

This project includes the installation of a new adsorptive media system in series configuration for a 450-gpm well. Adsorptive media in series was chosen to reduce maintenance, provide reliability, and have minimal impacts in a residential neighborhood. The treatment system included on-site backwash recovery and storage.
The Water Replenishment District of Southern California (WRD) selected Carollo to conduct a feasibility evaluation and permit acquisition for a future treatment facility to capture, treat, and re-inject the groundwater from 13 Caltrans dewatering wells into the Dominguez Gap Seawater Barrier recharge facilities. Currently, this water is being discharged to the ocean through the Los Angeles River following GAC treatment. Historic sampling results show the groundwater being contaminated with high levels of arsenic; TCE; cis-1,2 Dichloroethene; 1,2,3 TCP; iron; and manganese exceeding current established Title 22 MCLs, Notification Levels, and other advisory limits.

Because of the nature of the water, the DDW has classified the water from these wells as extremely impaired. This classification triggers the need for a DDW Policy memo 97-005. Blending and treatment strategies developed by Carollo were approved by DDW. The treatment strategy recommended to remove arsenic was an oxidation/filtration process. Carollo worked with WRD throughout the project providing detailed construction and O&M costs to help better understand the cost-benefit aspect of the project.

During the evaluation phase, Carollo completed the following tasks:

- Requirements of the initial four sections of DDW Policy Memo 97-005 (i.e., Raw Water Characterization, Source Water Assessment, Source Water Protection, and Treatment and Monitoring). The raw water characterization entailed the preparation of a DDW-approved sampling plan, sampling from the wells, and detailed analysis of water quality to evaluate blending strategies and treatment needs.

- Preliminary design of treatment equipment, pipelines, pump stations, and storage facilities.
  - Development of operational parameters including plant automation, equalization of water levels in dewatering wells, spent brine management, and monitoring and sampling requirements.
  - Analysis of blending scenarios to optimize treatment equipment sizing and selection.
  - Update of construction and O&M costs based on preliminary design layouts.
There is a need for new, cost-effective water treatment technologies for small systems in the U.S. and other parts of the world where minimal operational and maintenance resources are available. One such new technology is hydrogel-adsorbent media (produced using seaweed extracted biopolymer and iron) for the removal of arsenic and other anionic contaminants, such as selenium (Se) and chromium (Cr), from water and process wastewater. These oxyanions require cost-effective treatment because of the new and upcoming regulations.

This project evaluated the performance of hydrogel media in treating a wide range of water sources, including groundwater, surface water, IX brine, and reverse osmosis (RO) concentrate. The project compared the performance of the hydrogel media to three commercial media. In addition, the dehydration property of the hydrogel media was also investigated for waste disposal.

The goals of this project were to investigate the feasibility of the hydrogel media for cost-effective treatment of drinking water and for the minimization of brine or concentrate by utilizing the dehydration property of the media.

Hydrogel media were effective at treating high levels of arsenic, up to 300 µg/L, to concentrations below the detection levels from both the IX brine and the RO concentrate streams, with competing anions of 3 to 4 orders of magnitude higher than the concentration of arsenic.

Also, with an initial chromium concentration of 1.6 mg/L in the IX brine, the hydrogel media showed 50- to 94-percent reduction of Cr(VI) under the conditions tested, with a significant amount of other anions such as nitrate, sulfate, alkalinity, etc. The reduction of Cr(VI) using the commercial media was less effective, showing only 20- to 30-percent removal. As such, the reduction of chromium in the IX brine by hydrogel media can be a promising application. In addition to contaminant removal performance, the minimization of residuals showed significant potential for reducing the spent media volume up to 20 fold for effective residual management.
Identification of causes and impacts of pH variations on arsenic treatment processes.
Development of risk analyses and mitigation strategies for minimizing pH variations.

Unintentional pH Variation During Arsenic Removal

The objectives of this project were to evaluate the impact of pH and water quality variation on arsenic treatment processes and to conceptualize mitigation and operational strategies to prevent potential release of arsenic into the distribution system. A significant pH or water quality fluctuation may cause arsenic to leach and peak from the media vessels.

Among the arsenic treatment alternatives, single-use media adsorption provides the simplest approach for small-scale wellhead treatment. Media technology, however, is most prone to arsenic desorption due to pH or water quality variation in the feed water, because arsenic is retained in the media until the spent media are changed out. The risk of arsenic release should thus be evaluated thoroughly before the media adsorption technology is implemented at full scale.

As small utilities implement single-use media based treatment with pH control systems to increase the treatment capacity of media for arsenic adsorption, the potential for leaching arsenic from the media increases when unintentional pH increase occurs due to pH system failure. The bench- and pilot-column studies with several commercial media on the effects of pH and competing water quality parameters illustrated the conditions that may cause arsenic peaking from the media. Mitigation strategy concepts developed will help utilities identify alternatives to reduce the effects of unintentional pH or water quality variations on arsenic desorption from single-use media.

Findings from this study included the following:

- Arsenic spikes (desorption) due to increase in pH and/or competing ions.
- Magnitude of spike was dependent on type of media and level of saturation with arsenic.
- Competing ions that caused arsenic spikes when pH remained stable included bicarbonate, sulfate, phosphate, nitrate, and perchlorate.
- Manganese was released from some media in addition to arsenic.
- Spent media passed Toxicity Characteristics Leaching Procedure (TCLP) tests but failed Soluble Threshold Limit Concentration (STLC), Waste Extraction Test (WET), or Total Threshold Limit Concentration (TTLC) tests.
CITY OF VICTORVILLE, CALIFORNIA

Design of Infrastructure Improvements for Compliance with the Arsenic Rule

In April 2005, Carollo completed the preliminary design for two arsenic treatment facilities with a combined capacity of 21 mgd and over 4 miles of distribution system piping. These facilities used a combination of treatment and blending from area wells to allow the City of Victorville (formerly the Victor Valley Water District) to meet the new Arsenic Rule. After comparing various treatment technologies, IX and C/F were evaluated further. Based on the cost estimates and the potential issues of NDMA formation, C/F was selected as the preferred treatment technology. Pilot testing was conducted to confirm treatment efficiency and provide data for cost estimate development. The detailed preliminary design report included:

- Treatment process evaluation and selection.
- Hydraulic analysis.
- Site plan layouts.
- Cost analysis.
- Blending model development.
- Waste disposal options.

The two treatment plants (13.2 and 7.8 mgd) are located at separate sites and have a similar design. Design elements common to both treatment facilities included:

- Building enclosure for filter vessels and chemical storage.
- Metered bypass/blending line.
- Remote SCADA monitoring and control.
- On-site backwash recycle and sludge dewatering.
- Mechanical and structural design to accommodate plant expansion.

A prepurchase approach (filter vessels, instrumentation, and control equipment) was recommended by Carollo during the design phase in order to expedite construction. This fast-track design and construction helped the City to meet the Arsenic Rule compliance deadline while also receiving facilities that can be modified or expanded as needed in the future.
The City of Loma Linda has been experiencing water quality problems in four wells due to perchlorate contamination from the Potentially Responsible Party (PRP) since the late 1990s. In order to restore the lost production, the PRP equipped three replacement wells in an attempt to avoid treatment of wells for perchlorate.

The new wells, however, showed elevated levels of arsenic and fluoride. The PRP and the City developed a blending and treatment plan to deal with these new contaminants. Implementation of such treatment systems needed careful evaluation since the treatment of arsenic is often challenged by generation of a hazardous waste stream that will increase the overall cost of dealing with this contaminant. The presence of fluoride also complicated the selection of treatment options and treatment location.

The proposed blending and treatment plan by the PRP addressed the short-term issues with the contaminants of concern, but the plan must be carefully evaluated to ensure that the City does not incur major future costs if the water quality or regulations were to change in the coming years. In addition, the implementation of this plan needs to be evaluated for the City’s existing operations and equipment.

Carollo represented the City in developing a solution that provided long-term benefit for the City as part of this settlement. Based on the previous and current arsenic projects, Carollo’s team assisted the City in identifying potential issues, such as residual handling and treatment, hydraulic analyses, and blending analyses, to ascertain successful implementation of the granular ferric oxide treatment systems.
CITY OF HUGHSON, CALIFORNIA

Assessment of Arsenic Treatment Technologies

The City of Hughson’s water system serves a population of approximately 5,500 including residential, commercial, and industrial customers. The existing water system consists of four operating potable groundwater supply wells and various distribution/transmission lines. Water quality data indicated that naturally occurring arsenic levels in the well water ranged from 11 µg/L to 20 µg/L and exceed the new federal MCL of 10 µg/L.

Carollo conducted an evaluation of the City water system to determine if the City is required to install an arsenic removal system to meet the new standard and what current arsenic treatment technologies were best applied to the existing system. In determining preferred technologies, both capital and operation and maintenance costs were evaluated, along with site-specific concerns of waste disposal, size and location of treatment units, and staffing requirements for operation and maintenance.

The assessment report provided the City with a planning level evaluation of currently used arsenic treatment technologies appropriate for the existing City wells and preliminary cost estimates for implementation of arsenic treatment alternatives. Carollo worked with City staff and DDW to develop a programmatic approach for phased implementation of arsenic treatment to achieve compliance with the new federal arsenic standard.

Carollo worked with the City of Hughson to develop recommendations for removing arsenic at existing well sites.
The City of Hanford retained Carollo in 1989 and then again in 2004 to examine ways to reduce arsenic in the drinking water. Over the last decade, advances in ASM and more competitive pricing for membranes have opened up new options for arsenic treatment. In addition to developing cost data specific to the City’s treatment needs, non-economic criteria was also be developed in the event that one or more technologies appear equal in terms of costs. Carollo assessed treatment alternatives for 18 City wells. A final report was issued that included the following:

- Treatment design criteria.
- Process schematics (P&IDs).
- Operation and maintenance needs.
- Preliminary costs.
- Typical site layout.
- Project schedule and funding options.

Key findings during the technology selection study included:

- Eleven wells had to be treated, four were already in compliance, and three should be abandoned.
- Estimated construction cost is $15 million for the 11 wells requiring treatment.
- Wells requiring treatment were split between C/F (five wells) and sorptive media (six wells).
- Seven of the wells requiring treatment could utilize blending to reduce facility footprints. The remaining wells had raw water arsenic levels and flows so high that blending offered minimal if any advantages.
- Use of hypochlorite due to the presence of arsenite represented a potential drawback for IX due to potential for NDMA formation.
- Prioritization of wells provided for well improvements in three phases.
In 2004, Carollo developed design criteria for the City of Corcoran in anticipation of future compliance with the Arsenic Rule. After a desktop evaluation showed that coagulation/filtration (C/F) was a feasible technology, this process was pilot tested, with the following results:

- Ferric chloride coagulant (at 7 mg/L) was more effective than alum in reducing arsenic to below 10 µg/L.
- Oxidant (1 mg/L chlorine) was necessary to offset the impact of high arsenic wells (> 20 µg/L).
- Loading rates of 5 gpm/ft² provided up to 8 hours of filter run time.
- Two minutes of extended flocculation or 0.5 mg/L of cationic polymer reduced ferric chloride dose from 7 to 2 mg/L.
- System productivity was in excess of 95 percent when backwash duration was reduced from 10 to 5 minutes.
- Ferric backwash waste sludge approached limits of STLC for California hazardous waste classification. Alum sludge released significantly less arsenic during the CaWET procedure, resulting in lower STLC values.

Carollo teamed with other consultants to complete the design of an 18-mgd C/F treatment plant. The project included a raw water blend tank, two backwash reclaim tanks, a chemical storage and chemical injection system, six 2,500-gpm feed pumps, two 1,700-gpm booster pumps, one 3,150-gpm backwash pump, a 3,250-gpm square foot operations building, and a new two-million gallon treated water reservoir.

Five horizontal pressure filters with a combined treatment of 12,500 gpm produce water with less than 10 µg/L of arsenic for the City of Corcoran.
Carollo was retained by the Lost Hills Utility District to evaluate feasible arsenic treatment processes and prepare documents necessary for the U.S. Department of Agriculture (USDA) funding review process. The District draws groundwater from one location containing arsenic at relatively high levels (35 ppb arsenic). The groundwater is relatively clean with only a high pH (~9.2) creating a potential treatment issue. Through a desktop analysis, it was determined that a C/F process would remove arsenic at less than $1.00 per gallon when complete.

Carollo completed the design for a 500-gpm arsenic removal water treatment plant including two 500-gpm pressure filters (duty and standby); filter booster pump station; chemical injection for sulfuric acid; sodium hypochlorite, ferric, and caustic backwash pumps; backwash tank; and sludge bed area. The design also included raw and treated water tanks and a distribution system booster pump station upgrade. The total construction cost was $2.2 million. The plant start-up was in January 2008.
Innovative Alternatives to Minimize Arsenic, Perchlorate, and Nitrate Residuals

Recent regulatory changes required the development and evaluation of technologies used to treat arsenic, perchlorate, and nitrate in drinking water. Currently, the most widely used and accepted treatment technologies for the removal of these contaminants involve the generation of a concentrated waste stream, which must be further treated or disposed. Carollo’s team, including Applied Research Associates, Environmental Engineering and Technology, and Caltech, was selected by the Water Research Foundation to investigate arsenic, perchlorate, and nitrate brine and concentrate treatment alternatives, which are critical waste management issues. The objectives of this proposed research were to:

- Identify different types of residuals generated and approaches required to meet overall arsenic, perchlorate, and nitrate treatment goals.
- Develop and evaluate processes to manage and treat concentrate waste streams.
- Review pertinent regulations and compare costs and implementation issues associated with various treatment and disposal scenarios.
- Describe the results of this work in a document that would serve as a tool to help utilities develop residuals minimization and handling strategies.

During this project, tests were performed to stabilize or treat sludge from conventional treatment, backwash water from filtration process, liquid brine from ion exchange, or concentrate from high pressure membrane.

This study demonstrated technologies that can be implemented for the treatment of various types of residuals. The final assessment provided a basis for utilities to evaluate overall contaminant management strategies and included evaluations of various residual management costs, discharge alternatives, and regulatory perspectives.
CITY OF CHANDLER, ARIZONA

Integrated Water, Wastewater, and Reclaimed Water Master Plan

Carollo was retained by the City of Chandler to develop master plans for water, wastewater, and reclaimed water systems. Part of the water master plan included an arsenic evaluation component due to the presence of arsenic above 10 µg/L in several of the City’s wells.

For the arsenic evaluation component, arsenic treatment technologies were compared side by side and costs were developed based on pilot testing. Results from these studies were used to update future projects for the City’s Capital Improvement Plans. Features of the field testing included:

- Testing of coagulation/media filtration, coagulation/membrane filtration, AA, and ASM ([e.g., GFH, Sorb33].
- ASM was found to process four times as much water before requiring replacement compared to AA.
- Different source waters have more of an impact on AA treatment performance compared to ASM.
- Coagulation/media filtration and coagulation/membrane filtration were comparable in terms of arsenic removal effectiveness. Both processes resulted in filtered water arsenic levels lower than 5 µg/L, using 3 to 5 mg/L of ferric chloride.

Coagulation/microfiltration was one of five arsenic treatment technologies evaluated for the City of Chandler over an 8-month period.
MAGNA WATER COMPANY, UTAH

Perchlorate and Arsenic Treatment Alternatives Study

Early before the Arsenic Rule was promulgated, Carollo worked with Magna Water Company to address inorganic removal at several area wells. Initial evaluation focused on Total Dissolved Solids (TDS), arsenic, and perchlorate removal. Several treatment scenarios were evaluated, including blending split-stream treatment and complete treatment of all wells.

Final recommendations included a long-term solution, wellhead treatment, and a short-term solution blending various water supplies. Treatment by EDR was pilot tested to validate the performance capabilities of the system for this particular water source.

In 2001, with the promulgation of the Arsenic Rule and several Best Available Technologies (BATs), Carollo conducted a follow-up investigation examining C/F. Two high rate C/F systems were piloted and it was shown that less than 5 mg/L ferric chloride would drop raw water arsenic from 13 µg/L to 5 µg/L in the filtered water. Filtration rates ranged from 5 to 10 gpm/ft².

With various performance and cost data generated from testing and modeling different treatment alternatives (e.g., centralized vs. wellhead), Carollo recommended an EDR process with centralized treatment. This would allow the following benefits:

- Simultaneous removal of three contaminants (arsenic, perchlorate, TDS).
- Environmentally friendly, bio-destruct process as the final perchlorate treatment step.
- Meet future demands by utilization of available water supplies.

Design and construction of a 15.4-mgd EDR facility was completed in 2008. Ancillary processes to the EDR process included bypass line, gas chlorine feed system, prefiltration system, and a booster pump station. The wastewater treatment facility (6.0 mgd) receives the EDR waste stream. This facility was upgraded with fixed-bed biological reactors to facilitate removal of the arsenic and perchlorate laden wastes.
CITY OF ST. GEORGE, UTAH

Gunlock Well Field Arsenic Evaluation

Carollo has worked with the City of St. George over the last several years to develop a drinking water supply consisting of both groundwater and surface water sources. Groundwater sources tend to have arsenic at levels ranging between 20 and 30 µg/L. Surface water sources require treatment for virus, Giardia, and Cryptosporidium removal credit. After reviewing different treatment options, Carollo recommended a C/F process using low-pressure (MF/UF) membranes.

During preliminary evaluation, Carollo provided a siting evaluation and bench-scale study to evaluate arsenic removal capabilities. Bench-scale testing provided the following useful design criteria:

- 5 mg/L ferric chloride resulted in arsenic levels dropping from 25 µg/L to 8 µg/L.
- pH optimization from 5.5 to 7.0 offered minimal benefits in terms of arsenic removal.
- All the arsenic that will be removed by the C/F process is removed in the first 10 minutes.
- Higher GT values for flash mixing and lower GT values for flocculation tended to result in an additional 2 to 4 µg/L of arsenic removal.

Carollo evaluated arsenic removal options for the City of St. George.
TOWN OF GILBERT, ARIZONA

Arsenic Mitigation Study

Carollo was hired by the Town of Gilbert to evaluate arsenic treatment options for several area wells and determine a plan that would ensure compliance with the Arsenic Rule. Historic water quality data from 1994 to 2003 was collected, evaluated, and summarized for each well site.

Arsenic levels ranged between 6 and 33 µg/L, indicating that some “cleaner” wells could be used as blending wells. Total production capacity for the wells examined was approximately 8 mgd. Groundwater supplies are critical to the Town of Gilbert in order to meet peak summer demands and also winter demand when surface water (from canals) is no longer available.

Wells were prioritized in terms of system flow and pressure requirements. Then, a desktop analysis was performed to determine the most appropriate arsenic mitigation option. Costs were developed for each well once a mitigation strategy had been selected. Strategies for arsenic mitigation ranged as follows:

- Well rehab (e.g., new casing and/or well depth).
- Blending of high arsenic wells with low arsenic wells.
- Complete wellhead treatment (e.g., C/F or ASM).

In 1992, Carollo provided design services to upgrade Well No. 14.
In 2003, Carollo followed up by providing site evaluation for this well and several other wells as part of the Arsenic Mitigation Study.
CUYAMA COMMUNITY SERVICES DISTRICT, CALIFORNIA

Arsenic Removal Project

Carollo was retained by the Cuyama Community Services District (CCSD) to evaluate feasible arsenic treatment processes and prepare documents necessary for the United States Department of Agriculture (USDA) funding review process. The CCSD draws groundwater from one location containing arsenic at relatively high levels, often approaching the previous arsenic MCL of 50 ppb arsenic. The groundwater also has moderate amounts of iron and a TDS level exceeding the secondary MCL of 500 mg/L.

The recommended process for the project was the coagulation/pressure filtration process. The project consisted of the construction of a 350-gpm arsenic removal water treatment plant, complete with 350-gpm pressure filters; filter booster pump; chemical injection for hypochlorite, ferric chloride, and sodium bisulfate; and a backwash tank and sludge bed area. The low bid was $896,000 (i.e., $1.8/gallon) for this 350-gpm system.

Design of the arsenic treatment system was completed in November 2004. Construction began in April 2005. The project was completed in January 2006 to meet the January 2006 Federal compliance date. Resident inspection for this project was completed as a team effort by Carollo and the CCSD manager.
CITY OF DEVILS LAKE, SOUTH DAKOTA

Arsenic Treatment Bench-Scale Evaluation

Carollo conducted a bench-scale evaluation for the City of Devils Lake to determine baseline performance capabilities. The C/F process typically represents the lowest cost alternative for moderately sized facilities (e.g., >1 mgd). Equipment is readily available from a variety of suppliers eliminating the concern of “locking” yourself into a single supplier for the life of the equipment. Many of the proprietary media systems are appropriate for smaller systems and in situations where operator staffing is an issue. However, the limited number of proprietary media systems and their proprietary nature limit the ability of these systems to create a bid environment as competitive as standard C/F equipment.

The C/F process was tested on two groundwater wells from the City’s water supply. Both supplies were similar in water quality and indicated little variation in terms of the ability of a C/F process to remove arsenic. From bench-scale testing, the following results were discovered:

- Raw water quality included high hardness (>300 mg/L calcium carbonate), organics (>4.5 mg/L total organic carbon), manganese (0.8 mg/L manganese), and arsenic (30 to 35 µg/L).
- Competition from phosphates and organics along with a relatively high arsenic content resulted in an optimum coagulant dose of 20 to 35 mg/L ferric chloride, depending on the water source.
- Acidified ferric coagulant decreased optimum coagulant dose by 88 percent.
- Arsenic removed by the C/F process required less than 10 minutes of reaction time.
- Increasing flash mix intensity from 3,000 to 6,000 (GT value) provided an additional 40-percent removal of arsenic.

Bench-scale evaluations at Carollo’s Water Quality Laboratory provided important design criteria for a C/F process.
In 2001, the City of Garden City was faced with the task of treating two wells that had moderate levels of iron and manganese. Average concentrations of iron in Wells No. 5 and No. 10 were 0.6 and 0.2 mg/L, respectively. Average concentrations of manganese in Wells No. 5 and No. 10 were 0.3 and 0.2 mg/L, respectively. As a result of both constituents exceeding EPA’s secondary drinking water limits, the City experienced routine customer complaints regarding colored water, stained laundry, and stained plumbing fixtures. An important side issue was the presence of arsenic at trace levels in the groundwater.

Initially, Carollo conducted a desktop evaluation to narrow down the list of treatment options from four to one. Working with the City, Carollo recommended an oxidation, granular media filtration process that would meet the City’s needs. Carollo was also able to provide technical support to the City during this initial predesign stage when progress was slow due to permits required by various local agencies.

Carollo selected a prepurchase strategy to help reduce design and construction costs typically incurred when equipment selected by the contractor differs in size or layout from the engineer’s intent. After evaluating proposals for the prepurchase of filtration equipment, Carollo finished design and provided construction management services. Two facilities similar in layout and size (2,500 gpm each) were constructed. Carollo worked with the City to obtain temporary discharge permitting for the concentrated backwash waste. By controlling the accumulation of backwash waste, the City can slowly discharge waste every several weeks to the sanitary sewer and not upset plant operations at the wastewater facility. Total arsenic concentrations of the discharge waste are low enough so as not to create any issues with the land application of biosolids or plant effluent water quality.
Field Measurement Methods for Arsenic in Drinking Water

Utah State University and Virginia Tech University worked together to develop a low-cost arsenic field kit that would be portable and capable of detecting arsenic at the part-per-billion level. Currently, the arsenic kits offered commercially have detection limits above 10 µg/L and require special laboratory equipment and conditions. After reviewing the current field methods for measuring low levels of arsenic, researchers selected an existing technique (arsine hydride generation) and modified the analytical components and method. The detection limit of this modified field technique was determined to be 0.5 µg/L arsenic.

After development of the method, Carollo evaluated the technique in the field at six water utilities. Arsenic standards and groundwater samples were analyzed in the field and then sent to Utah State University for re-measurement using Hydride Generation Atomic Adsorption or Inductively Couple Plasma-Mass Spectroscopy, standard technologies that are used to detect low levels of arsenic. While there was good agreement between the field method and laboratory results for about one-third of the samples measured in the field, it was apparent that users needed practice with the method to ensure consistent results. At the end of field testing, each user completed a survey that was used to determine where the method could be streamlined and improved.
CITY OF LOS ANGELES DEPARTMENT OF WATER & POWER, CALIFORNIA

Evaluation & Preliminary Design of Enhanced Coagulation Facilities at the Los Angeles Aqueduct Filtration Plant

Carollo, in conjunction with another consultant, completed a 3-year project consisting of a bench- and pilot-testing program and preliminary design for Enhanced Coagulation (EC) facilities at the 600-mgd Los Angeles Aqueduct Filtration Plant (LAAFP). The project was conducted in two tasks: Task 1 - bench and pilot study to mimic existing and future 600-mgd plant, and Task 2 - preliminary design of EC and auxiliary facilities. Carollo was in charge of the preliminary design for electrical and instrumentation and controls and played a lead/support role in other tasks, including disinfection facilities, costing, permitting, hydraulic profile, process flow diagram, and solids management.

Carollo selected a treatment system (microsand enhanced sedimentation) that through its compact footprint was able to meet arsenic limits, decrease halogenated DBP formation, limit bromate formation, meet turbidity goals, and even limit algal growth potential. Additionally, Carollo was able to successfully incorporate the new facilities into the existing plant hydraulics and the current plant site, which was a challenge that had to be addressed during predesign.

The preliminary design phase of this project was completed in March 2007. Carollo delivered on time all of our deliverables, but in our capacity as subconsultant, we were not responsible for the overall schedule. There had been delays during predesign that were beyond Carollo’s control.

“Carollo responded exceptionally well to LADWP project and technical team advice to address the expectations [of] LAAFP operating staff.”

“Carollo was responsive in providing both labor and experimental apparatus. Carollo personnel worked well with LADWP staff under busy conditions to conduct experiments, handle, track, and report on sampling and laboratory analyses.”

– Gary Stolarik, Engineering Manager
In 2003, the Sandia National Laboratories launched a national Arsenic Water Technology Partnership and Pilot Demonstration Project with a $4-million congressional appropriation through the Department of Energy, Office of Science. The purpose of this program was to fund promising arsenic technologies to perform field pilot validation tests. The Water Research Foundation and WERC (a consortium for environmental education and technology development) also participated in additional phases of the project.

During this multi-year effort, technologies that were successfully demonstrated at the bench-scale level were selected and scaled up to pilot level at participating utilities that were planning to implement arsenic treatment systems. One of Carollo’s experts on arsenic has served as a member of the technology selection panel to review new arsenic treatment systems and recommend promising systems for further field demonstration. The majority of utilities impacted by the new arsenic rule are small and rural systems, and the technology selection during this project focused on such disadvantaged communities as the priority.

Sandia National Laboratories’ Arsenic Water Technology Partnership had three objectives according to the program guideline:

- Conduct research and develop innovative arsenic removal technologies with a focus on reducing energy costs and minimizing operating costs and quantities of waste.
- Demonstrate the applicability of these technologies to a range of water chemistries, geographic locales, and system sizes.
- Evaluate the cost effectiveness of these technologies and provide education, training, and technology transfer assistance to the user communities.
WASHOE COUNTY, NEVADA

South Truckee Meadows Water Treatment Facilities
Site Assessment and Preliminary Design

Washoe County retained Carollo in 2004 to evaluate local water supplies and feasibility of a new water treatment facility. During the initial phase of work (“Water Resource Characterization”), potential water supplies were evaluated both in terms of available water supply and quality. Key tasks included for this phase of work included:

- Quantify local groundwater and surface water supplies.
- Characterize water quality of surface water supplies based on withdrawal location along the creek reach.
- Outline operational strategies to offset changing water quality due to changes in flowrates and/or supply source.

Based on the initial review, it was determined that a new treatment facility capable of using surface or groundwater supplies would be required. Surface and groundwater rights of approximately 5 and 7 mgd respectively could be blended as necessary to meet consumer demands. It was recommended to use surface water supplies (two creeks) as primary supplies with groundwater supplies (four wells) retained as secondary sources when surface water was not available.

The new treatment facility sized at 6 mgd was estimated to operate at 65 percent of capacity on average. During low-demand periods, the facility would be operated closer to 33 percent of capacity. In addition to meeting various regulations associated with surface waters, the treatment process had to be capable of removing arsenic and antimony.

For several of the wells, elevated arsenic and/or antimony levels exceed the EPA’s MCL (Arsenic concentrations ranged between 5 and 93 µg/L). C/F can remove both arsenic and antimony. Coupled with the need to also treat surface waters, a coagulation/membrane filtration process was recommended. A sedimentation basin upstream of the membranes provided additional flexibility for operating and controlling plant performance. Previous bench-scale work had demonstrated that C/F (using membrane filtration) was an effective process, removing arsenic to below 10 µg/L with as little as 5 mg/L ferric chloride.

Carollo developed design drawings for a new treatment facility including ancillary buildings (e.g., chemical storage and feed, administrative). Extensive coordination between local, regional, and state interest groups was necessary due to the number and type of water supplies proposed for use. Public meetings and workshops with the County helped direct the final design phase of this project.
Arsenic Mitigation of Water System

The City of Delano provides water to customers via the local groundwater supply. Of the 11 wells owned by the City, 9 wells are above the new arsenic MCL of 10 µg/L arsenic, with values ranging from 11 µg/L to 42 µg/L. Carollo developed a mitigation report that examined various methods to bring these wells into compliance and included the following options:

- Develop a new water supply.
- Blend high arsenic wells with low arsenic wells.
- Treat high arsenic wells.
- Rehabilitate existing high-arsenic wells and drill additional wells to maintain production capacity.

Treatment and new wells were the most feasible options and were examined in greater detail to determine planning-level costs. Three options were pre-selected based on predominance in the industry and overall cost effectiveness: C/F, IX, and SM.

After collection and review of water quality data, it was determined that treatability for each well could be focused on several key parameters. Total arsenic, turbidity, sulfides, and reduced arsenic (i.e., arsenite) were at levels in the wells that could impact the effectiveness of each treatment option. The C/F process was recommended for those wells high in turbidity and low in arsenic and when sulfides were present. The SM process was recommended for those wells high in arsenic and those wells that had frequent start-stop cycles. In general, the added cost and complexity of a separate oxidation/de-oxidation (to minimize NDMA formation) step for IX precluded this process from being cost effective compared to C/F and SM.

Although a treatment option was recommended for each well, the rehabilitation/new well option was the most cost effective. Based on a hydrogeologic review of the area, the aquifer between 500 and 900 feet below ground surface contains arsenic less than 10 µg/L. Thus, rehabilitating existing wells and building new wells, so that intake screens are between 500 and 900 feet, is a potential mitigation option. Pilot wells were recommended to verify water quality specific to each well’s location before constructing a full-capacity well.

The final recommendation for mitigating arsenic in the City’s water system was the rehabilitation of existing wells and construction of five new wells. This option was approximately $4.5 and $10 million lower in cost compared to wellhead treatment for the initial construction and present-worth costs, respectively.
TREATMENT PROCESS MODELS

Numerous technologies are available to remove arsenic from drinking water, and the selection of the most appropriate technology can be complex due to the number of variables that must be considered. Many times, Carollo can narrow down the list of potential technologies based on previous experience and desktop models, thus saving testing costs. Screening technologies at the desktop level helps to focus only on those technologies truly feasible from a process performance and cost perspective. Site-specific issues considered in this initial screening typically include:

- Finished water arsenic goal.
- Raw water quality.
- Waste discharge regulations and proximity of discharge point.
- Arsenic waste characterization/classification.
- Footprint and other site constraints.

One tool Carollo can utilize during preliminary screening is our Split-Stream Treatment Model shown on the next page. Raw water quality, well flow rates, and finished water arsenic goals serve as input variables. With these inputs, the model then determines the bypass flow around treatment so that the final blended water meets the finished water arsenic goal. A split-stream treatment or blending approach such as this may offer cost savings. Overall benefits offered by desktop models include:

- Sensitivity analysis based on “what-if” scenarios for changes in raw water quality or well production.
- Dynamic spreadsheet useful for group discussions and consensus building.
- Broad application to similar inorganic contaminants (e.g., nitrate, perchlorate, or vanadium).

Another important tool developed by Carollo for applications where waste management could be a limiting factor is our Hazardous Waste Model.
Groundwater Management Tool for Arsenic Treatment and Blending

Generated from model output, the graph below shows the range of operating conditions that would result in an arsenic waste sludge failing the Total Threshold Limit Concentration (TTLC) test, thus being classified as a California hazardous waste. This type of model has been developed specifically for utilities in California that are required to test waste sludges using California-specific standards.

Results from the model show that, under most typical operating conditions, the waste sludge would contain more arsenic than allowed for by the TTLC (i.e., 500 mg arsenic/kg waste). By understanding this early on in the project, Carollo can focus bench- or pilot-testing efforts in areas that will favor production of a non-hazardous waste, minimizing permitting requirements and costs. This model can be tailored for each individual application, depending on the type of coagulant used, amount of arsenic to be removed, and climate conditions for sludge drying.

Bench-Scale Equipment

Our bench-scale testing capabilities can be tailored to our clients’ needs providing a cost-effective means to evaluate and optimize various treatment processes. We use innovative bench-scale tools developed to minimize time-consuming and expensive pilot studies. Bench-scale tools that are readily available in Carollo’s water quality lab include jar testing and filtration equipment (granular media and...
testing and optimization capabilities

membrane), column testing for IX, AA, or arsenic-specific media, and a bench-top RO unit. The use of these bench-scale tools provides preliminary design criteria and useful start-up conditions for pilot testing, reducing the time (and, thus, cost) spent in early stages of piloting.

PILOT-SCALE EQUIPMENT

At times, pilot testing is necessary in order to more fully develop bench-scale design criteria and provide more accurate performance information. More detailed design criteria allow for more accurate equipment sizing and costing. More detailed performance data also provides overall assurance that the best possible process has been selected. Carollo owns a fleet of pilot-scale equipment used to test the following arsenic removal processes:

- Ozonation for pre-oxidation.
- Flocculation, sedimentation, and granular media filtration.
- Ion exchange, activated alumina, and arsenic specific media contactor.
- Low-pressure membrane filtration (microfiltration [MF] and ultrafiltration [UF] with coagulation).
- High-pressure membrane filtration (nanofiltration [NF] and RO).

In addition to these systems, Carollo tests and validates UV reactors from several UV suppliers. State-of-the-art data acquisition and process control units are used on all our pilot systems. These units are designed to operate multiple pilot plants side-by-side to log hydraulic performance and water quality data. Data can be accessed remotely to monitor pilot operation and allow project stakeholders to access real-time data. A detailed description of our pilot-scale equipment is included in the following sections.

Rapid Small-Scale Column Testing

Carollo maintains Rapid Small-Scale Column Testing (RSSCT) equipment for evaluating the removal of contaminants by a range of adsorptive media. This equipment can be used to determine performance and cost data for adsorptive media, such as ion exchange resins, activated alumina, and arsenic specific media (e.g., granular ferric hydroxide). Column testing is used to study several areas of treatment, including arsenic removal, natural organic matter removal (for reduction of disinfection by-products), and removal of other key inorganics (i.e., nitrate, perchlorate).

Scaling equations, which are used to design the RSSCT tests, are based on a dimensional analysis that normalizes the results with the
testing and optimization capabilities

For example, grinding the media to a particular size or reducing the contact time in the bed provides a breakthrough curve (i.e., one complete production cycle) 10 to 20 times faster than a pilot-scale study.

The RSSCT columns are made of glass with inner diameters in the range of 4 to 15 millimeters. The media are carefully installed in the columns to avoid packing the media too densely and to prevent the formation of air spaces within the bed. The media are supported with either glass beads or glass wool. The test water is pumped through the column in a down-flow mode at a specified flow rate. The effluent water from the RSSCT column is sampled for various parameters. Typically, the target contaminant is measured at a frequency ranging from once per day to once per week to monitor when contaminant breakthrough finally occurs.

For a given application, Carollo prepares a testing plan at the start of the study. We then design the small-scale columns to simulate a range of possible full-scale designs. Typically, a 50- to 200-gallon batch of test water is collected as the feed water for the RSSCT system. Water quality parameters (e.g., pH) in the batch may be adjusted to reflect historical values. Testing can normally be completed in 2 to 6 weeks. The ability to run several resins or media side by side provides a powerful comparative tool that allows assessments in one-quarter of the time it takes for pilot-scale units.

Ozone Equipment (Bench-Scale)

In instances where multiple contaminants require oxidation (e.g., Fe, Mn, and As), ozone is one possible option. Not only does ozone provide the necessary oxidation power to convert arsenite (AsIII) to arsenate (AsV), which is easier to remove, but ozone can also enhance the performance of the flocculation process.

Information required to develop design criteria for ozone facilities includes ozone demand, ozone decay, and screening of ozone application points. Traditionally, this information has been developed using pilot-scale units, semi-batch bench-scale testing units, or modeling techniques. However, semi-batch reactors and the use of mathematical models have limitations, especially when extrapolating design criteria to full-scale systems. The major drawbacks of ozonation pilot studies include the tendency to overestimate the hydraulic efficiency and the added time and cost to mobilize equipment. To address these drawbacks, Carollo has developed a continuous-flow bench-scale ozone-testing unit, which combines the
reliability of pilot-scale testing and cost-effectiveness of bench-scale methods.

Carollo’s bench-scale unit consists of a six-stage ozone contactor with three chambers operating in counter-current flow for ozone transfer and three chambers operating without gas transfer for ozone contacting. The volume of each chamber available for ozone contacting is adjustable to achieve detention times ranging from 3 to 40 minutes. The ozone concentration in the feed gas is monitored by UV light absorption spectrophotometer. Ozone residuals in the liquid phase are analyzed from grab samples collected at the effluent of each column.

**System Hydraulics**

In order to ensure the applicability of the results, we have designed this system so that the hydraulics are characterized with a $T_{10}/T$ ratio of 0.6 to 0.7. This hydraulic behavior is modeled by seven to nine Completely Stirred Tank Reactors (CSTR) in series, corresponding to Peclet numbers of 12 to 16, respectively. This hydraulic characteristic is also maintained in Carollo’s pilot-scale ozone system.

**Ease of Mobilization**

The ozone system resides in a shipping container for ease of transportation. Associated equipment includes ozone contactors, rotameters for measuring liquid and gas flow rates, valves and tubing, and sample taps. This unit also includes a 0.08 lb/day ozone generator. Other equipment required to perform ozone evaluations, such as a feed water pump, UV spectrophotometer, and ozone residual measurements kit, is shipped with the system.

Mobilization and testing can begin within a half-day of arrival on-site. Only a small sample volume (approximately 5 gallons) is required in order to develop design data, such as ozone demand and decay relationships, by-product formation, and ozone quenching alternatives.

**Ozone Equipment (Pilot-Scale)**

Carollo’s standard ozone skid may be operated independently, or easily integrated with other skids to evaluate the impact of ozonation on other treatment processes. This type of skid is generally used to evaluate ozonation at intermediate steps in the treatment process. The rugged metal outer frame of the skid is polymer coated to provide a durable finish and prevent corrosion. The three ozone columns can be easily disassembled and crated for transportation.

The ozone contact columns provide a theoretical contact time of 10 minutes at a flow rate of 6 gpm. The skids come fully equipped for complete ozone evaluations, including the following components:
Air compressors to provide feed gas.

Complete air preparation, including drying and filtration.

Ozone generation equipment.

Ozone contacting.

Ozone quenching.

Off-gas ozone destruction.

Instrumentation and control.

**Ozone Generation**

The on-board, water-cooled PCI Wedeco GLS-3 provided up to 3 lbs/day ozone generation capacity. This generator allows a full range of ozone dosages (i.e., 0.2 to 20 mg/L) so that various applications can be examined. At the end of the process (i.e., after the contactors), residual ozone can be quenched using a low-pressure UV reactor (Wedeco-Ideal Horizons). This helps avoid carry-over of ozone residuals to downstream processes.

**Ozone Contacting**

The three ozone contactors are 8 inches in diameter and 8 feet in height. Carollo has specifically designed the columns to match full-scale ozone contactor hydraulics with a T_{10}/T ratio in the range of 0.6 to 0.7. Matching full-scale hydraulics is important for developing proper design criteria for ozone system sizing and to accurately determine ozone demand and by-product formation, such as bromate or assimilable organic carbon. Fine bubble diffusers, common in full-scale design practice, provide ozone transfer within the columns. Multiple sample ports allow detailed analysis of ozone residual, ozone decay kinetics, and disinfection by-product formation.

**Instrumentation**

The gas feed flow rate, the ozone concentration in the gas, and the water flow rate through the system are continuously monitored. The transferred ozone dose can be calculated directly by Carollo’s Data Acquisition and Control (DAC) system or using an on-board Programmable Logic Controller (PLC). Ozone residual is monitored at the effluent of the second ozone contactor, although multiple ports are available to monitor residuals at other locations.

**Pre-Oxidation, Flocculation, and Sedimentation Equipment**

Carollo Engineers’ pre-oxidation, flocculation, and sedimentation skid is part of a series of modular pilot equipment that is fully compatible and can be combined to form an integrated treatment train. Our standard pre-oxidation, flocculation, and sedimentation pilot plant offers a flexible and cost-effective solution for evaluating a
wide range of conventional pretreatment alternatives. This skid has a nominal treatment capacity of 6 gpm, although the variable-speed feed pump has a maximum capacity of 10 gpm. This skid features a rugged metal outer frame that is polymer coated to provide a durable finish and to prevent corrosion. The frame facilitates crating and therefore protects process components during transportation.

The head of the pilot plant includes two parallel 8-inch-diameter columns, which can be used for pre-ozonation. The columns provide a 5-minute contact time at 6 gpm and hydraulics representative of full-scale pre-ozonation facilities. These columns may also be used to evaluate and optimize other alternative pre-oxidation chemicals. The pilot unit is capable of feeding five different chemicals, providing a full range of testing conditions and scenarios. Operating conditions for chemical flush mixing, filtration, and sedimentation can all be adjusted to further optimize the process.

Filtration and Sorptive Media Equipment

Carollo’s granular media filtration skids may be operated independently to evaluate the filtration process or integrated with other pilot units to evaluate a complete conventional treatment train. The filter skids feature a rugged metal outer frame, which is polymer coated to provide a durable finish to minimize corrosion. The frame also facilitates crating, transport, and set up.

Filter Columns

Carollo’s standard skid includes three filter columns, which are 4 inches in diameter and 14 feet tall. The column height allows the flexibility to operate in gravity-feed filtration mode or in pressure filtration mode using the on-board feed pumps. The 4-inch column diameter provides performance representative of full-scale filters, while minimizing the volumetric flow of the water required. Carollo designed the filter skids to test a wide range of hydraulic loading rates (i.e., in the range of 2 to 17 gpm/ft²). The filters are flanged at approximately the middle of the column to allow convenient disassembly for transport.

The columns allow a wide range of filter media types and depths (as high as 8 feet) to be evaluated. A media retention plate is used for media support to eliminate the inconvenience of a gravel support system and also to be more representative of full-scale underdrain systems. The backwash protocol may include both air and water at a wide range of flow rates to optimize backwashing conditions and to ensure restoration of appropriate clean bed headloss. Each skid
includes a backwash water storage tank to allow optimization of the chemical dosing strategy of the backwash water (i.e., chlorination, polymer addition, etc.).

The filter columns may also be used as contacting beds (rather than filtration beds) when testing arsenic removal medias, such as ion exchange, activated alumina, and arsenic specific medias. All of Carollo’s pilot equipment is designed for operator-friendly data collection and system operation. For this particular unit, three separate media can be evaluated in side-by-side comparisons.

**Instrumentation**

The filter effluent turbidity is monitored by dedicated turbidimeters on each filter column. Filter effluent particle counts are monitored by a single particle counter, which samples the three filters in sequence via a sampling manifold with solenoid valves. Samples are automatically collected from each filter effluent, based on an adjustable timing scheme. Because a single particle counting instrument is used, data variability among instruments is eliminated. Another benefit of this approach is that all relevant data are collected with the minimum amount of instrumentation. This approach also reduces maintenance requirements on the skid and provides greater reliability. A pressure transducer is used to monitor headloss development during filter runs.

Data may be acquired using Carollo’s Remote Data Acquisition and Control (RDAC) system or using an on-board RDAC. This system stores and handles data in convenient formats for easy download and analysis.

**MF/UF Membrane Equipment**

Coagulation/filtration represents one of the most cost-effective treatment processes for arsenic removal. Providing filtration by means of a low-pressure membrane offers the following advantages:

- Consistent and complete rejections of arsenic solids.
- Log removal credit for virus and Giardia/Cryptosporidium in instances where surface water (with arsenic) is being treated.
- Inherently more capabilities for automation with remote control/monitoring capabilities (compared to granular media filtration).

Carollo’s Custom Membrane Pilot Plants (CMPPs) provide a unique means of evaluating low-pressure (MF and UF) membrane
modules operating in a dead-end mode from multiple membrane manufacturers. Carollo has used the CMPPs in the evaluation of membranes of various surfaces, configurations, and flow patterns. The CMPPs are often used to develop design criteria for a range of membrane modules in order to identify the most cost-effective solution. Design criteria in these evaluations include optimization of the permeate flux and the system recovery.

The CMPPs offer the following advantages:

- The pilot unit can accept full-scale membrane modules from multiple suppliers.
- Clean-in-Place (CIP) and backwash strategies can be optimized using three different types of chemicals.
- Pilot systems can be operated and monitored remotely, offering significant cost savings in regards to staffing requirements.

**Instrumentation**

The CMPPs are equipped with RDAC systems, which include a PLC and data logging system to monitor operations parameters at user-defined intervals. Critical operating parameters, such as flow rates, flux, transmembrane pressure, and temperature, are displayed in real time in a graphical format using a Human-Machine Interface (HMI), or they are accessed remotely. In addition, water quality data, such as permeate turbidity and particle counts, are also continuously measured. All data, control functions, and operating parameters can be monitored or adjusted remotely via a website-based or dial-up connection.

**Sample Collection**

For quality assurance and control purposes, pressures, temperatures, and flows can all be manually checked and compared to transmitter readings on the pilot plant. Sample taps located on the pilot plant also provide access to feed, permeate, and backwash water for quantification of water quality parameters. Waste streams from the cleaning process may also be collected for pH adjustment prior to disposal.

**NF/RO Membrane Equipment**

There are two types of high-pressure membrane filtration units: a single-element and a demonstration-scale unit.

**Single-Element Unit**

- Quick and cost-effective approach to screen membranes and pretreatment chemicals.
- Only one membrane element required (approximately 5 gpm production flow).
- Full-scale operation (e.g., cross-flow velocity, flux, and recovery) is simulated relatively well.

**Demonstration-Scale Unit**

- Accurate determination of cleaning frequency, membrane life, and permeate water quality.
- More accurate sizing (and costing) data.
- Useful verification tool for RO models predicting feed pressure and permeate water quality.

Critical to the successful screening of membranes and pretreatment chemicals is an accurate simulation of the full-scale design conditions. Flux, recovery, and cross-flow velocities are important parameters in these evaluations and must represent full-scale conditions to provide an appropriate evaluation. Both pilot plants are equipped with a PLC system capable of controlling feed water pH, permeate water flow (i.e., flux), and recovery. Full-scale cross flow conditions are created through concentrate stream recirculation, which provides adequate flow into and out of the membrane element. The system is also equipped with a data acquisition system that is accessible by remote telemetry.

As water flows through the pilot units, pretreatment chemicals (i.e., acid and scale inhibitor) are added and the water is passed through cartridge filters. Cartridge filtered water is mixed with recycled concentrate water, and the pressure is boosted using a high-pressure RO feed pump. Flows and pressures are metered at all critical locations. The permeate flow rate is controlled by a Variable Frequency Drive (VFD) high-pressure pump. The recovery is controlled by metering concentrate flow rate and adjusting it with a control valve. A sample tap panel is provided to gather water from all points throughout the process. Manual flow measurements can be taken to verify electronic meter calibration.

Carollo has used these pilot plants to screen membranes and to develop initial design criteria in several states, including: Florida, Kansas, Missouri, South Carolina, and Utah. The pilot units are sufficiently flexible in design to be housed in filter galleries, maintenance sheds, or temporary storage trailers. O&M manuals and Standard Operating Procedures (SOP) are available. Data spreadsheets are also available to generate report-quality graphics.
SELECT ARSENIC PUBLICATIONS – PEER-REVIEWSED


SELECT ARSENIC PUBLICATIONS/PRESENTATIONS - OTHER


CAROLLO has engineered water projects across the country.

WATER AND WASTEWATER EXPERTS

Carollo is an environmental engineering firm specializing in the planning, design, and construction of water and wastewater facilities and infrastructure. Carollo’s reputation is based upon client service, a continual commitment to quality, and technical leadership.

During our 82-year history, Carollo has successfully completed more than 20,000 projects for public sector clients. Carollo is currently ranked within Engineering News Record’s top 500 design firms. More importantly, ENR’s annual Source Book ranks Carollo among the top 20 firms for water and wastewater treatment plant design. Unlike many of our competitors, Carollo provides only water and wastewater engineering services.

With our focus on water and wastewater, we recruit nationwide and hire technical staff who have the extensive background and training specific to this field. For that reason, the quality and professional standing of our core group of water and wastewater professionals equals or exceeds that provided by some of the largest engineering firms in the U.S.

Resources

Carollo’s staff numbers more than 700 employees, including more than 325 registered engineers. We are a full-service water and wastewater engineering company with the experience and qualified professionals to successfully manage projects of any size. Our staff includes civil, sanitary, electrical, environmental, mechanical, chemical, structural, instrumentation, and corrosion control engineers, as well as architects, planners, and specialists in other areas. These individuals perform work solely on water and wastewater related facilities.
Carollo’s state-of-the-art computer network allows us to effectively communicate between offices and interface with almost any engineering software on the market today.

Carollo provides only water and wastewater engineering services, resulting in a level of understanding of key project issues that few can match.

**MANAGEMENT PHILOSOPHY**

Carollo’s management philosophy and the success of our company are founded on simple precepts:

- **Seek out, hire, and hold onto the best people in the business.** We recognize that the most critical element for a successful project is the project team. Carollo aggressively recruits the top candidates from the leading engineering schools across the country. We train and mentor these engineers to become the next generation of leaders for Carollo and the industry. This long-term commitment to developing excellent engineers has resulted in a depth of talent unmatched by other consulting firms.

- **Specialize in the planning, design, and construction management of water and wastewater projects.** This is our business. Our success hinges solely upon our ability to provide responsive service to our municipal clients.

- **Commit our partners to an active role in every project.** This provides our clients with top management interest, clear accountability, responsiveness, and talent—and helps to ensure that the necessary staff and resources are committed to each assignment.

- **Focus on client service.** Carollo knows the value of listening to our clients and recognizes that successful projects result from the combined expertise of our staff and the client’s staff. This commitment to understanding client needs and valuing their input is one of the cornerstones of Carollo’s success.

**LEADERS IN WATER ENGINEERING**

Carollo has provided design and construction management services for more than 100 water treatment plants with a total capacity of more than 3.5 billion gallons per day, more than 1,000 miles of water pipeline ranging in size from 6 to 108 inches in diameter, and more than 100 water pumping stations with capacities as high as 600 mgd. We have recently completed or are performing ongoing water projects for many of the country’s major municipalities or special districts. A few examples of Carollo’s achievements include:

- Conceiving and developing the custom design approach for low-pressure membrane water treatment plant design. Carollo developed our own custom, nonproprietary, non-packaged pilot plant unit, which has been successfully tested in Kansas City, MO.
Our client list includes the following:

- City of Phoenix, AZ
- East Bay Municipal Utility District, Oakland, CA
- Metropolitan Water District of Southern California
- Sacramento Regional County Sanitation District, CA
- City of San Diego, CA
- City and County of San Francisco, CA
- City of Sacramento, CA
- Denver Water Department, CO
- City of Minneapolis, MN
- Kansas City, MO
- City of St. Louis, MO
- City of Las Vegas, NV
- Southern Nevada Water Authority, NV
- City of Arlington, TX
- City of Austin, TX
- Upper Trinity Regional Water District, TX

- Engineering the fast-paced design/build expansion of the Palm Coast, FL, RO water treatment plant from 3.2 to 9.6 mgd. Carollo completed preliminary design and obtained all permits just eight weeks after beginning work to help facilitate successful completion of this project in just 15 months.

- Conducting the first U.S. testing and evaluation of EDR for perchlorate treatment.

- Achieving leadership in ultraviolet (UV) disinfection, first for wastewater applications in the western United States and now for UV drinking water applications. Carollo was the primary author of the USEPA UV Disinfection Guidance Manual. We also developed and operate the world's largest UV validation facility in Portland, OR.

- Designing the preozonation and intermediate ozonation at two water treatment facilities for the City of Arlington, TX, using our computational fluid dynamic (CFD) modeling to optimize ozone contactor design. Carollo also conducted a joint research project with various utilities in the Phoenix, AZ, area to evaluate ozonation and biological filtration to meet long-term finished water quality goals, leading to design and construction of ozonation facilities in Gilbert and Peoria, AZ.

- Designing, in a joint venture, the world’s largest ozone generation system at a water treatment facility in Las Vegas, NV.

**FORMULA FOR SUCCESS**

Much of our success as an industry leader is based on our ability to offer advanced solutions that are practical, affordable, and reliable. We strive to maximize the use of existing infrastructure whenever possible, promote environmental conservation, and make the best technologies available at a competitive cost.

A major factor in maintaining Carollo’s ability to integrate new technology is the Carollo Water Research Group (CWRG). The relationship between our design engineers and the CWRG is unique in the industry and serves as a company-wide resource for evaluating water quality and treatability data, performing pilot studies, developing design criteria, tailoring design solutions to water quality issues, and addressing regulatory compliance concerns.
Our firm takes pride in the large number of clients with whom we have maintained continuing working relationships. We have worked with some clients for more than 70 years — a clear indication of the quality of our work, our control of costs, and our ability to meet schedules. This dedication to quality has resulted in a long list of successful projects and satisfied clients, some of which are highlighted in the table below.

### Representative Water Treatment Projects

<table>
<thead>
<tr>
<th>Client/Project</th>
<th>Capacity (mgd)</th>
<th>Conventional Treatment</th>
<th>Membranes</th>
<th>Ozone</th>
<th>UV Disinfection</th>
<th>Automation</th>
<th>Solids Handling</th>
<th>Chemical Handling</th>
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<td>City of Sacramento, California - E.A. Fairbairn Water Treatment Plant</td>
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