Capabilities for

Pilot and Bench-Scale Testing

carollo

Engineers...Working Wonders With Water®
Carollo Engineers is an environmental consulting firm with more than 1,050 employees in 44 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 Engineers detailing some of our experience and expertise in the field of water treatment specific to this topic.

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BACKGROUND

Carollo’s focus on municipal water and wastewater engineering, in concert with our investment in applied research and commitment to integrating conventional and innovative processes, sets us apart in the industry. As part of our dedication to customer service and continual commitment to quality, the Carollo Research Group (CRG) was founded in 1997. The CRG provides bench- and pilot-scale research, process evaluation, and plant optimization services in its ongoing effort to bridge the gap between fundamental research and practical, innovative, and reliable engineering solutions.

The CRG conducts studies as part of its applied research projects that are funded by associations such as the Water Research Foundation, the Water Environment Research Foundation, and our municipal clients. In order to provide these services, the CRG maintains a 2,500-square-foot process evaluation laboratory and over $3 million in custom-made, bench- and pilot-scale equipment, specifically designed to collect data representative of full-scale processes. We combine the use of bench- and pilot-scale testing capabilities to meet the specific objectives of each study, the locations of which are illustrated on the adjacent map.

A list of our current testing equipment is provided in the table on the following page. A detailed discussion of each piece of our equipment and our process evaluation laboratory is presented in the Testing and Optimization Capabilities section of this SOQ.

Carollo has conducted bench-/pilot-scale studies and demonstration/full-scale projects across the U.S.

ISSUES AND DIFFERENTIATORS • 1
Our laboratory and equipment, indicated above, has been used for projects all over the country. Brief descriptions of some of those key projects which highlight Carollo’s expertise with bench- and pilot-scale testing are provided below.

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<tr>
<td>Point of the Mountain WTP Pilot Study – Metropolitan Water District of Salt Lake and Sandy, UT</td>
<td>Carollo was selected to conduct pilot studies on three treatment trains to determine the most cost-efficient arrangement of unit processes for the new 70-mgd Point of the Mountain WTP.</td>
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*The Point of the Mountain pilot test received an Engineering Excellence Award in the area of Studies and Research from the American Council of Engineering Companies in 2003.*
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<td>Advanced Water Treatment of Estuarine Water Supplies for Improving Water Quality – Water Research Foundation and U.S. EPA</td>
<td>Carollo performed bench- and pilot-scale studies to fill in knowledge gaps with respect to treatment of estuarine supplies using existing and advanced technologies, as well as disinfectant combinations. <em>Estuarine water supplies pose numerous challenges when trying to meet today’s regulations.</em></td>
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<tr>
<td>Bench and Pilot Study for the Los Angeles Aqueduct Filtration Plant – Los Angeles Department of Water and Power, CA</td>
<td>Carollo conducted bench- and pilot-scale testing of process improvements for the 600-mgd Filtration Plant. Carollo tested enhanced coagulation under various conditions to evaluate the impact on finished water quality. <em>Carollo developed detailed design criteria from bench- and pilot-scale studies that will help LAAFP adding arsenic removal.</em></td>
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<td>Lake Pleasant Water Quality Study and Pilot Testing – City of Phoenix, AZ</td>
<td>Carollo completed a multi-phase study to determine the best method for providing treated water to northern Phoenix. In the 18-month pilot study, Carollo operated 8 different pilot trains at two different sites in the Phoenix. <em>Bench-scale testing helped to narrow down the number of treatment alternatives selected for pilot testing.</em></td>
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<td>Treatment of Perchlorate Contaminated Groundwater from the Saugus Aquifer – Castaic Lake Water Agency, CA</td>
<td>Carollo performed a preliminary design study. Pilot testing demonstrated that biological reactors can effectively reduce perchlorate and nitrate to below detection limits in relatively short contact times. <em>Pilot testing at Castaic Lake Water Agency showed that fixed-bed biological filtration is an efficient, robust process for removing perchlorate and nitrate from groundwater.</em></td>
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<tr>
<td>Comprehensive Everglades Restoration Program – U.S. Army Corps of Engineers, FL</td>
<td>Carollo performed pilot testing and engineering analysis of water treatment technologies on Lake Okeechobee. The alternatives proposed by Carollo applied the latest proven treatment technologies leveraged with a global analysis of all goals and constraints surrounding the project. <em>Carollo’s ozone pilot skid is flexible enough to treat even difficult waters like Lake Okeechobee (max TOC = 40 mg/L) and operate under harsh environments, such as the South Florida summer.</em></td>
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| **Granular Media Filtration Study**<br>for the Johnny G. Martinez WTP Expansion – City of Tempe, AZ | To alleviate taste and odor problems, the City elected to pilot test GAC as an alternate filter media. In addition to taste and odor control, pilot testing also evaluated the performance of GAC filtration for Total Organic Carbon removal for long-term disinfection byproducts compliance.  

*Carollo used its granular media filtration pilot skid to test various combinations of GAC for reduction of taste and odor-causing compounds and DBP precursors for the City of Tempe.* |
| **Innovative Reclaimed Water Treatment – WaterReuse Foundation, VA** | The study’s overall objective was to investigate the effectiveness of innovative treatment methods to inactivate, remove, or destroy biological and chemical constituents of concern that may be present in reclaimed water. Bench- and pilot-scale testing, was completed at a number of different reclaimed facilities using ozone/peroxide, UV/peroxide, UV, UV/peracetic acid, and titanium dioxide/UV.  

*Five pilot studies were conducted to determine system performance at full-scale and to develop accurate cost estimates.* |
| **Nova Ultrascreen Title 22 Validation Testing – Nova Water Technologies, FL** | Project includes the development and implementation of a test protocol to validate the performance of the Nova Water Technologies Ultrascreen in meeting the California Title 22 water recycling turbidity requirements at three times the loading rate of conventional filters. This testing resulted in the approval of Ultrascreen as a filter technology that can be used for Title 22 reclaimed water applications.  

*Two pilot studies were conducted to achieve Title 22 approval at hydraulic loading rates of up to 16 gpm/ft².* |
| **Ozone (with and without Hydrogen Peroxide) Certification for Reclaimed Water – APTwater, Inc., CA** | Conducted bench- and pilot-scale studies of the APTwater Inc. HiPox Ozone reactor (with and without hydrogen peroxide). This testing resulted in the HiPox system being approved as a disinfection technology that can be used for Title 22 reclaimed water applications  

*Not only was this ozone reactor demonstrated to effectively disinfect the reclaimed water but to provide significant microconstituent destruction.* |
| **Pasteurization certification for Reclaimed Water – Pasteurization Technology Group, CA** | Conducted pilot-scale studies of the Pasteurization APTwater Inc. HiPox Ozone reactor (with and without hydrogen peroxide). This testing resulted in Pasteurization being approved as a disinfection technology that can be used for Title 22 reclaimed water applications.  

*Pasteurization of reclaimed water provides a sustainable chemical free method of disinfection.* |
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<td>UV Certification Testing for Reclaimed Water – Various Clients (Aquionics, Calgon Carbon, Severn Trent, Trojan, and Wedeco)</td>
<td>Conducted pilot-scale validation testing of both in-vessel and in-channel UV disinfection systems. The results of this testing were used to garner approval of the UV disinfection reactor technologies for Title 22 reclaimed water applications.</td>
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<tr>
<td>Direct Fixed-Bed Biological Perchlorate Destruction Demonstration - U.S. Department of Defense, VA</td>
<td>Carollo was awarded a Department of Defense (DoD) Environmental Security Technology Certification Program (ESTCP) project designed to evaluate the efficacy of using FXB biological reactors to remove perchlorate from drinking water. The project emphasizes the demonstration of sustained removal capabilities, the identification and evaluation of process limitations and potential failure scenarios, and the development of realistic designs and cost estimates for full-scale drinking water fixed-bed biological perchlorate treatment.</td>
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*One of the UV reactors evaluated.*

*3D model of Carollo’s 25-gpm FXB biological treatment pilot skid.*
The project profiles on the following pages present highlights of Carollo’s key achievements in the 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.
Point of the Mountain WTP

Carollo led the effort to conduct a pilot study for the Metropolitan Water District of Salt Lake and Sandy. The purpose of the study was to evaluate three potential treatment trains for the new 70-mgd Point of the Mountain WTP:

- Treatment Train No. 1 - Low-pressure membrane filtration with conventional pretreatment.
- Treatment Train No. 2 - Low-pressure membrane filtration and granular activated carbon adsorption with presedimentation.
- Treatment Train No. 3 - Ozonation, biologically active filtration, and UV disinfection with conventional pretreatment.

Carollo conducted bench- and pilot-scale evaluations at a testing facility near the future site of the treatment plant. This involved the construction of a metal building close to the planned raw water intake location. This dedicated facility housed nine pilot skids and related equipment and included an onsite laboratory and office space for project meetings. Carollo maximized onsite testing capabilities to reduce external analytical costs during piloting.

For the pilot-scale evaluations, Carollo provided a new 7-gpm conventional treatment train, complete with pre- and intermediate ozonation, six granular media filters, and a 100-gpm pretreatment unit for the membrane systems.

Carollo used a combination of bench- and pilot-scale ozone evaluations to optimize testing costs. This involved refining viable ozone operating conditions at the bench-scale, such as dose and contact time, for subsequent pilot-scale tests. Carollo developed design criteria for the ozonation facilities, based on the results of the bench and pilot evaluations.

The piloting effort demonstrated that all three trains achieve the operational and finished water quality goals established for the Point of the Mountain WTP.

Carollo determined that Treatment Train No. 3, which included pre- and intermediate ozonation, was the most cost effective and robust to meet future challenges, such as taste and odor treatment and more stringent Disinfection By-Products (DBP) goals.
Pilot study to evaluate potential treatment options for an ASR project that included hundreds of wells.

Basis of design criteria and cost estimates for 1.5-bgd treatment system.

Cost-effective multi-barrier treatment alternative for the challenging water of Lake Okeechobee.

Comprehensive Everglades Restoration Program (CERP) Aquifer Storage and Recovery/Treatment Pilot Testing

Carollo was selected by the U.S. Army Corps of Engineers, in association with the South Florida Water Management District, to perform the first pilot testing and engineering analysis of water treatment technologies on Lake Okeechobee as part of the $8.4-billion CERP. The CERP presents a framework for Everglades restoration and contains 68 specific components to restore more natural flows of water and improve water quality in the South Florida ecosystem. The plan was designed to restore the habitat of threatened and endangered species and improve fresh water supply in the region. This study evaluated alternatives for treating Lake Okeechobee water prior to injection in Aquifer Storage and Recovery (ASR) wells. Pilot study results were used to develop design criteria and cost estimates for the 1.5-bgd ultimate capacity treatment facility.

Selection of the engineering team for this highly competitive project was based on qualifications as well as proposed treatment technologies. The alternatives proposed by Carollo apply the latest proven treatment technologies leveraged with a global analysis of all goals and constraints surrounding the project. The selected treatment train consisted of bank filtration (BF), ozonation, and UV disinfection. Bank filtration addresses microbial, total organic carbon, color, taste and odor, and turbidity goals cost-effectively with minimal operational and maintenance requirements. Ozonation provides additional treatment for microbial and organic contaminants and also substantially increases the UV transmittance, thereby reducing capital and operational costs of the UV disinfection process. UV disinfection provides a final barrier to pathogens, particularly disinfectant-resistant pathogens such as Cryptosporidium. The treatment train (BF/ozonation/UV) is robust and provides multiple barriers to target water quality impairments. As treatment may be applied at up to 300 individual sites across rural Central and South Florida, other key attributes of the treatment train include no waste stream disposal, minimal chemical delivery requirements, and low operational and maintenance requirements.
CONTRA COSTA WATER DISTRICT, CONCORD, CALIFORNIA/WATER RESEARCH FOUNDATION/USEPA

Advanced Water Treatment of Estuarine Water Supplies

Estuarine waters (fresh waters under tidal influence) are an important source of drinking water for millions of people. These waters pose a number of treatment challenges, including salt and bromide intrusions from seawater, as well as DBP precursors and anthropogenic chemicals from upstream discharges. Considering these challenges, successful treatment scenarios need to include a multiple-barrier approach.

The Water Research Foundation and the USEPA provided funding to the Contra Costa Water District, who then retained Carollo to study advanced water treatment of estuarine waters. The goal of this project was to fill knowledge gaps regarding treatment of estuarine supplies using existing and advanced technologies, as well as disinfectant combinations. The aim was to meet current and future regulations as well as water quality treatment goals. Project objectives included:

- Investigate the additive and synergistic effects of multiple disinfectants/oxidants, including: chlorine, chloramines, chlorine dioxide, ozone, potassium permanganate, and UV disinfection on disinfection efficacy and DBP formation.
- Investigate the ability of advanced technologies, such as enhanced coagulation, Powdered Activated Carbon (PAC), Granular Activated Carbon (GAC), MIEX® resin, and membranes, to remove Dissolved Organic Carbon (DOC), bromide, and taste and odor compounds prior to disinfection in estuarine waters.
- Investigate the impact of multiple disinfectants and advanced technologies on distribution system water quality, including DBP formation, nitrification, and microbial regrowth.
- Determine the threshold levels of source water quality and associated disinfection requirements; identify whether optimization, retrofit, or installation of advanced technologies may be required; and recommend the treatment levels necessary to achieve regulatory horizon targets.
- Determine practical operational conditions and limitations of the technologies tested, and propose alternatives and solutions to meet regulatory requirements.
- Provide a comparative cost analysis for the proposed solutions, including operating requirements.
CITY OF PHOENIX, ARIZONA

Lake Pleasant Water Quality Study and Pilot Testing

Carollo completed a multi-phase study to determine the best method for providing treated water to a growing area of northern Phoenix. The study defined water quality characteristics for the water sources for the proposed Lake Pleasant WTP: Lake Pleasant Water and Colorado River Water from the Central Arizona Project (CAP) Canal. Carollo also established finished water quality goals for the plant and evaluated the ability of current and new treatment process technologies to meet these stringent water quality goals.

The study included two phases developed to continually narrow bench- and pilot-scale investigations focusing on identifying those treatment technologies with the greatest potential to consistently and economically meet the new plant’s water quality goals. Bench-scale testing covered pre-oxidation, pretreatment, and advanced treatment processes for several key test waters, including taste and odor control. Pre-oxidation included ozone, chlorine dioxide, and perozone. Treatment processes included Dissolved Air Flotation (DAF), ballasted flocculation, and GAC filtration. Advanced treatment included a range of membrane options presently available. The testing focused on two primary parameters: removal of turbidity and DOC. Based on the bench-scale testing, Carollo developed select treatment options for pilot testing and constructed and operated six pilot plants:

1. Conventional pretreatment followed by filtration with monomedia anthracite or dual media anthracite/sand.
2. Conventional pretreatment followed by intermediate ozonation, then filtration with monomedia anthracite, dual media anthracite/sand, and monomedia Biologically Active Carbon (BAC).
3. Chlorine dioxide pre-oxidation, followed by conventional pretreatment and filtration with monomedia anthracite, dual media anthracite/sand, and monomedia GAC.
4. Conventional pretreatment followed by filtration with monomedia anthracite or dual media anthracite/sand.
5. No pretreatment followed by filtration via submerged hollow fiber membrane module.
6. No pretreatment followed by filtration via pressurized hollow fiber membrane module.

Carollo completed this pilot plant work over the summers of 2000 and 2001. The new Lake Pleasant WTP was operational in 2007.
Evaluation and Preliminary Design of Enhanced Coagulation Facilities at the Los Angeles Aqueduct Filtration Plant

Carollo performed bench-scale and pilot-scale tests to evaluate process improvements for the 600-mgd Los Angeles Aqueduct Filtration Plant (LAAF). The plant treats water from two sources, the Los Angeles Aqueduct and the West Branch of California State Project Water. The plant employs high-rate direct filtration and preozonation to treat the water. However, treatment issues including arsenic, disinfection by-products, and turbidity had to be addressed as a result of more stringent regulations and an increased reliance on State Project Water. The project included:

- Bench and pilot study to mimic existing and future 600-mgd plant.
- Feasibility and efficiency of enhanced coagulation to meet new treatment goals.
- Arsenic reduction to meet new regulations and internal treatment goals.
- Bromate control for new water sources containing bromide.
- TOC reduction to meet Stage 2 of the Disinfectant/Disinfection By-Product Rule (D/DBP) MCLs and internal treatment goals.
- Phosphorus reduction to reduce potential for algae growth in open reservoirs and nitrification after the switch to chloramines.

Carollo tested enhanced coagulation under various conditions to evaluate the impact on finished water quality. A 9-week bench-scale testing program was completed, and the findings from the bench-scale program were used to design the pilot-testing program. Six blends of the three source waters were tested to address typical raw water conditions future and worst-case scenarios for arsenic, bromide, turbidity, and TOC.

The pilot-testing matrix included: 1) evaluating enhanced coagulation with the current direct filtration process at lower filtration rates and with a modified filtration configuration, and 2) evaluating conventional treatment with high rate filtration.

Carollo incorporated the results of the study into a preliminary design for new facilities at the plant.
WATERUSE FOUNDATION, VIRGINIA

Innovative Treatment on Reclaimed Water

This $750,000 research project is a collaborative effort with Carollo, Duke University, and the U.S. Department of Agriculture to survey a broad range of filtration and disinfection processes for pathogen and microcontaminant removal during reclaimed water disinfection and identify the most cost-effective technologies for a variety of treatment goals. Candidate treatment technologies were selected via a rigorous selection process based on agreed key criteria and were tested on the bench scale at Duke University and at four pilot sites in Florida, North Carolina, and California. These technologies included, on the bench scale, UV (low pressure [LP] and medium pressure [MP]), ozone (O$_3$), chlorine (free and preformed monochloramines), peracetic acid (PAA), advanced oxidation processes (AOPs) (LPUV/H$_2$O$_2$, LPUV/PAA, O$_3$/H$_2$O$_2$), and ultrafiltration.

The performance of these technologies was evaluated using bench-scale microbial inactivation tests on important indicator, surrogate, and pathogenic organisms (including indigenous total and fecal coliforms, indigenous aerobic spore-forming bacteria, spiked MS-2 bacteriophage, reovirus 3, coxsackievirus B5, and adenovirus 4). Removal and transformation of a suite of spiked microconstituents, including several potential endocrine disrupting compounds (EDCs) and pharmaceutical and personal care compounds, was evaluated using gas chromatography-mass spectrometry (GC-MS), and reductions in estrogenic activity following bench-scale treatment was measured using the yeast estrogen screen (YES) bioassay. Pilot-scale treatment technologies included: O$_3$, O$_3$/H$_2$O$_2$, TiO$_2$/UV, LPUV/H$_2$O$_2$, MPUV/H$_2$O$_2$, and MPUV/PAA. Reduction of indigenous coliform, spiked coliphage (MS2), spiked N-nitrosodimethylamine (NDMA), general hormonal activity (as measured by the YES bioassay), and background microconstituents was determined for the pilot tests.

WRF 02-009 started in January 2006 and was completed in January 2009. The final report will be published in early 2010.
CITY OF TEMPE, ARIZONA

Johnny G. Martinez WTP Expansion Granular Media Filtration Study

The City of Tempe, AZ, selected Carollo to expand the Johnny G. Martinez WTP. Currently, the plant utilizes conventional treatment with gravel/sand/anthracite filters to treat a mix of Salt and Verde River water conveyed through the Cross-Cut Canal.

As is often the case with many water treatment plants in Arizona, the Martinez plant experiences taste and odor excursions intermittently during the warmer months of the year. To alleviate this problem, Tempe elected to pilot test GAC as an alternate filter media. In addition to taste and odor control, pilot testing also evaluated the performance of GAC filtration for TOC removal for long-term disinfection byproducts compliance.

The pilot plant included three filter columns.
1. Column 1: 48 inches of virgin GAC and 12 inches of sand.
2. Column 2: 36 inches of virgin GAC and 12 inches of sand.

These media variations determined the optimal filter design for the expansion project as well as the estimated removal rates of taste and odor-causing compounds in the new full-scale filters.

In addition to the GAC evaluation, Carollo conducted a series of tests to evaluate various operational parameters of the filters. The first of these tests evaluated the treatability of the Filter Waste Washwater (FWWW) and helped define design criteria for chemical addition, flocculation, and clarification procedures. This testing was especially important at the Martinez plant because the treated FWWW is discharged to a “greenline” located in a public recreation area.

Carollo also completed full-scale filter evaluations as part of the overall study. This included core sampling, floc retention profile analysis, FWWW turbidity profiles, and turbidity breakthrough evaluations. The results of this full-scale filter evaluation allowed Carollo to evaluate the performance of the existing filter media, underdrain systems, and backwashing procedures to make recommendations to the City of Tempe.
California’s Sacramento-San Joaquin River Delta is a major estuarine drinking water supply for more than 3 million people in the San Francisco Bay Area, as well as approximately 19 million people in Southern California, via the California State Water Project aqueducts. Transport of the water through the aqueducts results in an estuarine water characterized by low turbidity (2 to 20 NTU), moderate organic matter concentrations (2 to 6 mg/L), and high bromide concentration (0.2 to 0.4 mg/L). This water tends to readily form chlorinated DBPs, especially when free chlorine is used as the secondary disinfectant. For some utilities, alternative disinfectants, such as chloramines, are not an attractive long-term option due to high temperatures, long distribution system residence times, and the need to feed ammonia at numerous (30 or more) entry points to the distribution system. The purpose of this study was to evaluate treatment options for this supply to comply with Stage 1 and 2 DBP regulations, while maintaining a free chlorine residual in the distribution system.

A preliminary feasibility study identified the following advanced treatment processes for DBP precursor removal: GAC adsorption, MIEX®, resin, and fixed-bed ion exchange. The goal of this project was to evaluate integration and potential synergies among the processes. The study determined the performance of combinations of these processes, regeneration frequencies, residuals disposal requirements, and costs to achieve compliance with the Stage 1 and 2 DBP Rules. Testing employed bench- and pilot-scale systems designed to simulate full-scale performance, with the following specific objectives:

- Characterize organic DBP precursors in raw and treated waters using size exclusion chromatography and XAD-8/-4 resin fractionation to fully evaluate performance.
- Determine practical operating conditions and limitations of the process combinations tested, and identify obstacles which may limit their ability to achieve DBP regulatory compliance.
- Develop practical design criteria and a comparative cost analysis for feasible process combinations.

Carollo completed the pilot study phase in mid-November 2004. The report was published in 2006.
High-Pressure RO Demonstration Plant

In an effort to improve system reliability, Collier County hired Carollo to demonstrate the use of a High-Pressure RO (HPRO) system to treat water from their high salinity Hawthorn wells. Carollo’s demonstration plant consisted of full-scale equipment that would typically be used in a seawater RO process. State-of-the-art and energy efficient technology was used to demonstrate that this high salinity water could be treated at a reasonable price. A high efficiency positive displacement pump and isobaric energy recovery device were used, and all the process equipment was selected so that the pilot data could be scalable to the full-scale plant.

Carollo also provided engineering services related to the operation of the demonstration scale plant. These services included:

- A test protocol, which included testing two membranes at 9 gfd, and 50-percent recovery to produce permeate with a TDS of 300 mg/L. 5 kWh/kgal of energy was required for the RO process.
- Progress monitoring and operational assistance.
- Weekly and final reporting.
- Cost estimates for a 2-mgd expansion to the NCRWTP using HPRO.

The County plans to proceed with the construction of two 1-mgd HPRO trains that will be located in the existing NCRWTP NF/BWRO building. Electrical motor controls will be fed from the existing transformer and switchgear (currently being upgraded), but are planned to be located in a new structure. Other ancillary facilities will also require upgrades, such as the degasifiers and chemical storage/feed systems.
Western Canal WTP Water Quality Sampling and Pilot Testing

The recently completed study demonstrated the feasibility of achieving 94 to 95-percent overall recovery on brackish surface water and groundwater using microfiltration surface water pretreatment skids, a primary RO system, an intermediate concentrate chemical stabilization (ICCS) reactor, a sand filter, and a secondary RO system. It demonstrates that the ultra-filtration is a feasible surface water pretreatment for RO. The two-stage primary RO system operated at 85-percent recovery and performed consistently well without a single CIP during the testing, equivalent to up to six month continuous run time.

During the groundwater testing, the foulant removals were sufficient to maintain a sustainable high RO recovery 94 percent. However, during the blended surface water/groundwater test phase, natural organic matter (NOM) and clay or soil content in the brackish surface water was believed to cause moderate to rapid membrane fouling on the secondary RO. Concentrate recycle was implemented in the secondary RO system in order to increase cross-flow velocity and reduce fouling. A membrane autopsy was performed on the lead- and tail-end elements of the secondary RO. The membrane surface and foulant scraped from the membrane surface of the autopsied membranes were analyzed using Scanning Electron Microscopic Analysis (SEM), Energy. Dispersive X-ray Analysis (EDX), Fourier Transform Infrared Spectroscopy (FTIR), and X-ray Diffraction (XRD). Results suggested that the observed membrane fouling during the surface water phase was caused by silica in the form of aluminum silicate.

The presence of amino acids (i.e., C-N bond and carboxyl group) was observed in the scraped material from the membrane surface, suggesting potential biological growth on the membrane. To assess the biological fouling potential, the source waters and RO concentrate before and after the ICCS were analyzed for assimilable organic carbon (AOC). The bacteria population density and the types of bacterial on the membrane surface were also assessed. Diverse bacteria populations were observed on the membrane surface at an approximate density of 10^8 colony forming unit (cfu) per square centimeter, causing a light degree of biological fouling during the groundwater/surface water blend testing. The inorganic content of the scraped material was around 55 percent by weight, leaving less than 45-percent organics and biomass.
Direct Fixed-Bed Biological Perchlorate Destruction Demonstration

Carollo was awarded a Department of Defense (DoD) Environmental Security Technology Certification Program (ESTCP) project designed to evaluate the efficacy of using FXB biological reactors to remove perchlorate from drinking water.

The project emphasizes the demonstration of sustained removal capabilities, the identification and evaluation of process limitations and potential failure scenarios, and the development of realistic designs and cost estimates for full-scale drinking water fixed-bed biological perchlorate treatment. Post-FXB treatment, which includes aeration, second stage biofiltration, and chlorination will also be tested.

While FXB bioreactors have been applied as a perchlorate treatment process for several years, no system has been tested at flow rates above ~2 gpm. As a result, scalability is not well understood. This project will address this issue by testing a FXB bioreactor at flow rates up to 24 gpm. Therefore, more realistic design and operating parameters will be developed, which will be used to develop facility layouts and more credible cost estimates. Additionally, process robustness and post-treatment requirements can be more fully characterized.

The major performance strengths of a FXB biological perchlorate-reducing process are as follows:

- Perchlorate is not concentrated, but rather is converted to innocuous chloride and oxygen.
- Multiple contaminants can be in a single reactor (e.g., perchlorate, nitrate, selenium, bromate, other oxidants, DBP precursors, chlorinated solvents).
- Design and operation of fixed-bed bioreactors are not complicated; they are comparable to the design and operation of conventional granular media filters.

Estimates indicate that capital costs for applicable fixed-bed bioreactors are substantially lower than capital costs of membrane-based perchlorate removal processes and are comparable to those associated with ion-exchange based perchlorate removal processes. The real cost benefit of FXB biological perchlorate treatment relates to the low O&M costs.
An 8-month pilot test was initiated in May 2007 (Riverside, CA) with the objective to evaluate the use of FXB biological treatment to remove nitrate from the RO by-pass water at the Arlington Desalter facility (nitrate currently limits the amount of water that can by-pass the costly RO treatment process). A second pilot test was performed from May-August 2008 to evaluate a polishing filter step to remove turbidity from the effluent of the nitrate-reducing bioreactor. Design parameters obtained during the two pilot tests are being used to develop the preliminary design for a 2.4-mgd biodenitrification facility that will treat RO by-pass water at the Arlington Desalter and distribute the blend as potable water. Below is a summary of the pilot testing results.

- Using an empty-bed contact time as low as 4 minutes, an acetic acid dose of 31 mg/L as carbon, and a phosphoric acid dose of 0.15 mg/L as P, 75 mg/L of nitrate was removed to below 5 mg/L. Nitrite accumulation was not observed.

- The raw water also contained perchlorate and dibromochloropropane (DBCP). Influent and effluent perchlorate concentrations were ~6 µg/L and non-detect (<4 µg/L), respectively. Influent and effluent DBCP concentrations were 0.025 µg/L and non-detect (<0.010 µg/L), respectively.

- When bioreactor effluent was dosed with a low molecular weight cationic polymer and treated through an equalization tank and then through a sand-anthracite polishing filter, system effluent turbidities were typically ≤0.1 NTU, monitored continuously.

- *E. coli* was not detected in the feed or effluent of the FXB bioreactors.

- Nitrate removal performance was minimally impacted by various planned process disturbances, including backwashing, raw water quality fluctuations, feed flow fluctuations, system shut-downs, and acetic acid shut-downs.

The FXB biological process has key features that make it an attractive nitrate removal technology, including contaminant destruction, high efficiency, relatively low O&M costs, broad contaminant applicability (e.g., nitrate, perchlorate, VOCs), and process robustness. Pilot testing at the Arlington Desalter facility has confirmed these features of FXB biological nitrate treatment. Pertinent conditions of the DDW fixed-bed biological treatment technology approval letter have been addressed during these pilot studies. Design and permitting process for a ~2.4-mgd biotreatment facility at the Arlington Desalter is underway.
Pilot Testing of Zero Liquid Discharge Technologies for the Indian Wells Valley Water District

Carollo was selected by the Indian Wells Valley Water District to carry out the preliminary design of a new brackish water desalting facility. The Indian Wells Valley contains brackish groundwater that, apart from its moderate TDS levels, is also contaminated with a range of constituents including hardness (around 1,100 mg/L as CaCO₃), nitrate (over 200 mg/L), arsenic, selenium, iron, and manganese.

The first step in the project was a full characterization of the groundwater source to establish whether the groundwater contains any additional species of concern that may impact the selection of the treatment process - such as high levels of silica, for example.

The pilot facility was operated for a 7-month period and during this time, the RO unit was operated for a total of 4,400 hours (2,100 hours in conventional mode and 2,300 hours in reversible mode). A total of 1,600 hours of operation were achieved, which exceeded the initial goal of 1,000 hours. Long runtime and stable performance enabled a significant amount of data collection during the pilot study. This data allowed performance trends to be established and conclusions on system performance to be drawn.

The membrane processes (RO plus EDR) achieved an overall recovery of 92 percent and both produced a high-quality product removing 90 percent of the influent TDS. This removal resulted in a combined product TDS of 140 mg/L. All treated water goals were met (with the exception of boron) and the removal of more than 90 percent of many of the contaminants of concern (including As, Se, U, Fe, and Mn) was achieved. Ultimately, it was determined that a treatment train consisting of primary RO followed by RO concentrate treatment with EDR was the most cost-effective process train for the treatment of the groundwater sources. Data collected as part of the pilot testing program may be used for the design of a full-scale plant in the future, if required.

In addition, the project included establishing the DDW permitting requirements for the treatment system, as well as the Regional Water Quality Control Board requirements for the disposal of any waste streams from the process, including brine. After the completion of the Preliminary Design Report, Carollo worked with the District to design and construct a pilot testing facility for the testing of well water with the selected treatment process.
SAN ANTONIO WATER SYSTEM (SAWS), TEXAS

Brackish Groundwater Desalination Pilot Study

SAWS, TX, selected Carollo to develop and implement a multi-phase pilot study to achieve approval of a new 10-mgd inland brackish groundwater desalination plant by the Texas Commission on Environmental Quality (TCEQ). A preliminary evaluation determined that RO was the most viable option for treating this groundwater to potable water standards.

The membrane pilot study included four phases to evaluate RO membranes from three manufacturers, two recoveries, and multiple pretreatment options. At a minimum, the RO pretreatment for each phase included pH adjustment, antiscalant addition, and the normal cartridge filters upstream of each membrane pilot unit with additional pretreatment as follows:

- Phases I and II (85- and 90-percent recovery respectively). Operated in a closed configuration without additional pretreatment.
- Phase III (90-percent recovery) was operated with the addition of a raw water (RW) tank, which was open to the atmosphere.
- Phase IV (90-percent recovery) was similar to Phase III with the addition of a granular media filter after the RW tank to remove iron.

Autopsies of selected membranes were used to evaluate the organic, inorganic, radiological, and biological composition of membrane foulants.

Despite the relatively “clean” characteristics of the raw groundwater, which continuously had a silt density index of less than 2, the raw water constituents and pretreatment configuration had a significant impact on membrane performance. Some of these impacts included:

- Membrane fouling by biologically-produced zinc sulfide nanocrystals.
- Stabilizing conversion of iron (II) to iron (III) using air injected into the raw water.
- Significant iron fouling on the membrane despite its removal with granular media filters.
- Deterioration of the membrane surface resulting from radiological constituents co-precipitating with and adsorbing to an iron/silica foulant.

The membrane pilot study is expected to be complete in Summer 2010. Findings of this study will be submitted to the TCEQ.
Enhancing Aerobic Biofiltration to Achieve Sustained Removal of Multiple Organic and Inorganic Contaminants

The City of Arlington, TX, is faced with both operational and water quality complications at their John Kubala (JK) and Pierce-Burch (PB) water treatment facilities. Recently observed performance disruptions and the detection of endocrine disrupting compounds (EDCs) require that the City of Arlington evaluate their ozone/biofiltration systems to identify potential modifications to enhance process performance.

This study, part of a Water Research Foundation Tailored Collaboration project, focused on evaluating methods for restoring and enhancing the performance of the existing ozone/biofiltration process through nutrient supplementation. The work sought to comprehensively characterize, evaluate, and enhance filter biological activity.

The approach included an investigation of biological drinking water treatment process fundamentals (e.g., microbial ecology, bacterial metabolism, and contaminant removal mechanisms) to understand how: 1) DOC, MIB, geosmin, iron, and manganese can be efficiently removed; 2) biological clogging (filter headloss) can be minimized; and 3) overall process robustness can be improved. In addition, microbial tracking was performed throughout the project to gain a better understanding of the communities present in the biofilters, and how they shift under varying operating conditions. The study was conducted through 10 months of bench- and pilot-scale testing that evaluated biofilter nutrient supplementation.

The biological filter feed at typical water treatment facilities has non-detectable amounts of phosphorus (<0.01 mg/L), due to removal through enhanced coagulation and general source water limitation. As phosphorus is an essential nutrient for biological growth and health, its limitation may be detrimental to biofilter operation. Low concentrations of phosphoric acid (0.015-0.20 mg/L as phosphorus) were dosed to a pilot-scale biological filter to identify the critical ratios of carbon to phosphorus for improved microbial activity. The findings from this study showed that phosphorus supplementation greatly enhances biological filter hydraulic and treatment performance over baseline. These sustainable benefits over the control included longer filter run times (>20 percent), improved taste-and-odor reduction (>50 percent), improved manganese removal (>50 percent), and lower effluent DOC (>80 percent).
Cater WTP Advanced Treatment Solutions Pilot Testing

Although the City of Santa Barbara complies with all current primary drinking water standards, meeting regulations related to DBPs and T&O have been challenging for the City. Stage 2 D/DBP rule promulgated in 2006 required the City to meet DBP requirements at individual sites rather than in the distribution system as a whole. In addition, familiarity with chlorine as a residual disinfectant and cross connections between neighboring utilities make conversion to chloramines an undesirable alternative.

Removal of TOC through conventional means at the Cater WTP is difficult since TOC is not amenable to enhanced coagulation. Through bench-scale studies, Carollo assisted the City in obtaining a waiver from DDW for the practice of enhanced coagulation. Given the difficulty in removing TOC from the water through conventional means, the City needed to find alternative ways to remove TOC and meet DBP requirements. Treatment has become even more challenging as TOC levels have increased over 50 percent because of a recent fire in the watershed. The City retained Carollo to conduct a series of desktop evaluations and bench and pilot scale studies to identify and evaluate alternatives to meet water quality regulations.

The current chemical treatment scheme was evaluated and bench tests were conducted to determine how alternative coagulants affected water quality and subsequent DBP levels. These studies were also used to test alternative coagulants (polyaluminum chloride, ferric chloride, ferric sulfate) as well as PAC. GAC was tested as a filter media as well as downstream of filtration for TOC removal.

Information from the bench and pilot scale studies was used to assess potential changes in the distribution system, including changing the residual disinfectant from chlorine to chloramine. The City distribution system is challenging, as it is large with long hydraulic residence times in tanks and distribution lines. This results in areas of high DBP formation and potential nitrification if chloramines are used in lieu of chlorine. Localized treatment with GAC and blending with groundwater was evaluated for these locations.

Resultant water quality was compared and treatment alternatives evaluated economically (capital and O&M costs) to select the most beneficial, lowest cost technology that will provide potable water that meets water quality regulations while staying on free chlorine. Currently, the project is on schedule to meet the Stage 2 requirements for 2012.
PILOT TESTING EQUIPMENT

Reverse Osmosis/Nanofiltration - Demonstration-Scale Pilot Plant

Carollo’s demonstration-scale RO and NF pilot plant is designed to simulate full-scale system operation and water quality. The demonstration plant is used to develop full-scale design criteria and operation costs. Membrane replacement frequency, chemical cleaning frequency, and membrane life are also determined through demonstration-scale testing with this equipment. Additionally, this pilot can be used to verify the accuracy of RO models that predict feed pressure and permeate water quality.

The demonstration-scale pilot plant is configured in a 2:1 array with seven 4-inch-diameter elements per pressure vessel. This configuration can be used to simulate the operating conditions for brackish water treatment and membrane softening applications at a product water recovery of up to 85 percent.

Instrumentation

The pilot system is equipped with a Programmable Logic Controller (PLC) system capable of controlling feed water pH, total permeate water flow, and permeate flow balance between stages. Flow balance can be controlled by either an inter-stage booster pump or by throttling permeate pressure in the first stage. The system is also equipped with a data acquisition system that logs pertinent data automatically and is accessible by remote telemetry.

Process Operation and Sampling

Feed water is delivered through a low-head booster pump and then a cartridge filter. Pretreatment chemicals (e.g., acid and scale inhibitor) are then added. A static mixer blends the pretreatment chemicals and feeds the water to a high-pressure RO pump. High-pressure RO feed water passes through the RO membrane array while gauges and sensors monitor various parameters at critical locations. Flow
is metered at the following process locations: first-stage permeate, system permeate, and concentrate. A sample tap panel is provided to gather water samples from all points throughout the process. Manual flow measurements can also be taken from every pressure vessel and at points where flow is metered electronically to verify meter calibration.

**Reverse Osmosis/Nanofiltration - Single-Element Pilot Plant**

Carollo’s single-element RO/NF pilot plant provides a fast, cost-effective way to screen membranes and pretreatment chemicals. This pilot plant requires only one membrane element for each test, in contrast to the demonstration-scale pilot equipment which requires 21 membrane elements. For screening tests, where the results are not certain, the cost of the membranes and the rental fee for the two-stage demonstration-scale equipment may not be justified. Cost-effective screening is accomplished with this pilot by using one membrane element and simulated full-scale operational settings such as hydraulics and recovery.

**Instrumentation**

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. The pilot plant is equipped with a PLC system capable of controlling feed water pH, permeate water flow (i.e., flux), and recovery. Full-scale crossflow 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 accessible by remote telemetry.

**Process Operation and Sampling**

A low-head feed water booster pump is provided, operating at approximately 5 gpm at 30 to 60 psi. As water flows through the pilot plant, pretreatment chemicals (e.g., 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 metering permeate water flow rate and varying the speed of the high-pressure pump Variable Frequency Drive (VFD). 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 this pilot plant to screen membranes and to develop initial design criteria in Florida, Kansas, Missouri, South Carolina, and Utah. It is sufficiently flexible in design to be housed in filter galleries, maintenance sheds, and temporary storage trailers. An operations and maintenance (O&M) manual and a standard operating procedures (SOP) manual are available. Data spreadsheets are also available to generate report-quality graphics.

**Custom Membrane Pilot Plants**

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 designed the CMPPs to accommodate a wide range of pressurized membrane modules.

Carollo has used the CMPPs in the evaluation of membranes of various surface area, configuration, 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 are also used to optimize backwashing procedures to minimize backwash wastewater production. These investigations include:

- Backwash chemical dosing strategy.
- Backwash flow rates and durations for both air and water.
- Recovery.

The CMPPs have also been used to evaluate various chemical cleaning strategies. Important considerations with respect to chemical cleaning include the cost of the chemicals and disposal requirements. Chemical cleaning optimizations involve the examination of:

- Sequence of chemical addition.
- Chemical dosages.
- Temperature.
- Duration of each phase of cleaning.

**Instrumentation**

The CMPPs are equipped with Remote Data Acquisition and Control (RDAC) systems, which include a PLC and data logging system to monitor operational 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 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.

**Pre-Oxidation, Flocculation, and Sedimentation Skid**
Carollo’s 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 six 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.

**Instrumentation**
The skid includes continuous measurement of the following treatability parameters: raw water pH, temperature, turbidity, and settled water turbidity, along with chemical dosages. The data may be collected using Carollo’s RDAC system or recorded manually.

**Pre-oxidation**
The head of the pilot plant includes two parallel 8-inch-diameter columns, which are typically used for pre-ozonation. The columns provide a 5-minute contact time at 6 gpm, and hydraulics representative of full-scale preozonation facilities. These columns may also be used to evaluate and optimize other alternative pre-oxidation chemicals.
**Flash Mix and Flocculation**

A chemical mixer provides flash mixing, with G values in the range of 500 to 1,000 s\(^{-1}\). Three stages of flocculation are provided so that mixing energy can be tapered and optimized in successive flocculation stages. The skid provides five chemical feed systems that include storage tanks and peristaltic pumps which maximize the turndown ratio. All chemical feed pumps use the same pump head and drive. This reduces the size and complexity of the spare parts inventory and simplifies repairs and maintenance. The pumps are controlled with VFDs to easily adjust the chemical dosage. Easy-to-use optical level sensors on the chemical feed tanks minimize mechanical hardware.

**Sedimentation**

Sedimentation is provided with plate settlers for overall process performance representative of full-scale facilities. Sludge is removed from the sedimentation basin via a manual valve and peristaltic pump arrangement. This system provides the best control of the sludge removal rate while eliminating plugging of the blow down tubing.

**Ozone Skid**

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 intermediate ozonation. 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 transport.

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 onboard, water-cooled PCI Wedeco GLS-3 provides up to 3 lbs/day of ozone generation capacity. This generator allows a full range of ozone dosages (i.e., 0.2 to 20 mg/L) so that various applications may be examined.

Ozone Contacting
The three ozone contactors are 8 inches in diameter and 13 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 byproduct 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 byproduct 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 onboard PLC. Ozone residual is monitored at the effluent of the second ozone contactor, although multiple ports are available to monitor residuals at other locations.

Ozone Quenching
The skid includes a low-pressure UV reactor (Wedeco-Ideal Horizons) for quenching ozone in order to avoid carry-over of ozone residuals to downstream processes.

Granular Media Filtration Skids
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 onboard 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 eight 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 head loss. Each skid includes a backwash water storage tank to allow optimization of the chemical dosing strategy of the backwash water (e.g., chlorination, polymer addition, etc.).

**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 head loss development during filter runs.

Data may be acquired using Carollo’s RDAC system, or using an onboard RDAC. This system stores and handles data in convenient formats for easy download and analysis.

**25-gpm Fixed-Bed Bioreactor Pilot**

A 3D model and a process flow diagram for the 6-25 gpm bioreactor pilot are provided below. The skid, which is contained in a 40'x8'x8' trailer, includes three 24” diameter pressure vessels that are 8’ tall and constructed from epoxy-coated steel. Effluent from the bioreactor can travel directly to the biofilter or to an interstage aeration/degasification column ahead of the biofilter. Effluent from the biofilter will be pumped into a backwash tank (two cylindrical
500-gallon polyethylene tanks) and then a chlorine contact tank (one cylindrical, 500-gallon polyethylene tank).

The skid is also equipped with automatic backwash capabilities, chemical dosing systems for electron donor, hydrogen peroxide, polymer, and chlorine addition, and in-line monitoring and data logging for flow rates, headloss, dissolved oxygen and nitrate. The trailer houses a Dionex 800 ion chromatograph, which can be used to analyze grab samples for perchlorate. In addition to feed and effluent sample ports, all pressure vessels include depth-wise sample ports that will allow for the simultaneous evaluation of several empty-bed contact times. These sample ports protrude 3 inches into the bed to ensure that representative samples are taken (i.e., eliminate wall effects). Six 3-inch by 12-inch windows run the length of each pressure vessel that enable the operator to view the media bed during production and backwash. The skid includes a touch screen human-machine interface to monitor and control pilot operations. It can also be connected to the internet, so that pilot operations can be monitored and data downloaded from remote locations.

6-gpm Fixed-Bed Bioreactor Pilot

Carollo owns a second fixed-bed bioreactor pilot system. This skid contains three 12” columns that are 10’ tall and are operated in series at between 2 and 6 gpm (2.5-7.6 gpm/ft²). The first column serves as the FXB bioreactor; the second column is an open basin, which can be used for flocculation or degasification; the third column served as the polishing filter. Effluent from the bioreactor could also be routed to bypass the flocculation/degasification column (i.e., direct filtration mode). The skid is equipped with automatic backwash capabilities, chemical feed systems for electron donor, nutrient, and nitrate/perchlorate dosing, and on-line monitoring and data logging for monitoring flow rates, head loss, DO concentrations, and nitrate concentrations. The pilot skid is also equipped with a data acquisition and control (DAC) system, which stores and manages data. The DAC continuously logged date/time, flow, headloss, DO concentration, nitrate concentration, and turbidity. The skid includes
a touch screen human-machine interface to monitor and control pilot operations. It was also connected to the World Wide Web, so that pilot operations could be monitored and data downloaded remotely.

**DATA ACQUISITION AND CONTROL SYSTEMS**

Carollo’s DAC systems store and manage data in a useful way to optimize pilot study data interpretation. Ease of pilot plant control and convenience of data storage and access are factors that determine the efficiency and usefulness of pilot studies. These DAC systems allow the maximum number of conditions to be tested within the time available for conducting the pilot study.

The DAC may be integrated into an existing pilot to allow stand-alone operation of that particular skid. This approach minimizes the amount of space required for the pilot study, while providing a convenient and meaningful way to control the pilots and collect data. Alternatively, Carollo can provide the DAC system as a separate skid, which provides additional benefits. This skid offers a touch screen HMI to monitor and control pilot operations. It also offers additional connectivity, such as access to the World Wide Web for data storage and download from any remote location. A phone line connection is also available for data transfer and pilot control.

This skid also serves as the central power supply for other pilot skids. The other skids may be plugged into the DAC skid, therefore necessitating only a single source of power for the entire system. This power configuration simplifies pilot study mobilization and eliminates the need for installation of multiple electrical connections.

Data that are typically acquired during a pilot study include water quality data (e.g., pH and temperature), flow rates, pressures, and alarms. Process control functions include chemical feed system regulation, flow rate modifications, and automated valve actuation sequences.

Remote access capabilities allow the engineer in charge of the study to monitor performance daily and make real-time changes to testing conditions as necessary. Web-based access to data allows stakeholders such as equipment vendors to monitor the performance of their system. Data for individual systems may be password-protected to maintain the integrity of the study, while sharing the results. In a competitive situation, this approach provides a non-controversial communication tool and gives equipment vendors the opportunity to quickly respond to challenges encountered during the study.

The DAC skid is supported by a rugged polymer-coated, metal frame for protection during transport. Carollo has used these systems in

**IN-HOUSE PROCESS EVALUATION CAPABILITIES**

Carollo maintains process evaluation laboratories to support process evaluations, predesign studies, and applied research activities. These facilities serve three main functions:

- Provide adequate laboratory space for conducting bench-scale studies and performing basic water quality analyses.
- House offices and workstations for data analysis and interpretation of results.
- Provide space for storage and maintenance of testing equipment and pilot plants.

The laboratories have a broad range of equipment to optimize a wide range of drinking water and wastewater treatment processes:

- A continuous flow bench-scale ozone system is used to develop ozone demand and decay relationships, contaminant oxidation efficiency, optimization of taste and odor removal, and byproduct formation.
- Rapid small-scale column tests are provided for granular activated carbon evaluations, and to develop design criteria for other sorptive media such as ion exchange resins. Carollo also maintains capabilities for natural organic matter characterization and molecular weight fractionation.
- Annular reactors are used to perform bench-scale distribution system evaluations, and to quantify regrowth potential and pipe corrosion.
- Microbial inactivation studies and UV dose-response relationships are developed using a UV collimated beam apparatus.
- An Optics Bench is used to evaluate UV lamp output, quartz sleeve and UV sensor window UV transmittance, and UV sensor measurement properties.
- Custom UV reactors can be configured to evaluate lamp aging, fouling, microbial disinfection, and advanced oxidation using UV light and hydrogen peroxide.

This testing equipment is described in further detail in the pages that follow.
Carollo maintains analytical instrumentation for those parameters that require a rapid turn-around time during process optimization studies. For example, a total organic carbon analyzer is used to measure total and dissolved organic carbon concentrations in order to evaluate the effectiveness of enhanced coagulation, and to quantify DBP precursor removal. We also maintain spectrophotometers which operate in both visible and UV light. UV absorbance and transmittance scans are used to develop design criteria for UV disinfection systems and also to develop correlations with other water quality parameters.

Carollo conducts these process evaluations and analytical testing using equipment that is specifically designed to be portable. Therefore, studies can be conducted within our laboratory facilities or at a treatment plant, at a well pump house, or at a raw water source for onsite testing analysis and problem solving.

**Continuous-Flow Bench-Scale Ozone System**

The 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 facilities, semi-batch bench-scale testing units, or modeling techniques. The major drawbacks of ozonation pilot studies include the tendency to overestimate the hydraulic efficiency and the high cost and time commitment required to mobilize the equipment. Semi-batch reactors and the use of mathematical models do not provide sufficiently reliable data for extrapolation to full-scale design. 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 three to 40 minutes. The ozone concentration in the feed gas is monitored through a UV light absorption spectrophotometer. Ozone residuals in the liquid phase are analyzed by collecting grab samples at the effluent of each of the columns.

**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 maintained in Carollo’s pilot-scale ozone systems.

**Ease of Mobilization**

The ozone system resides in a shipping container for easy transport to various sites for ozone testing. 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 measurement kit, is shipped with the system.

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

**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 GAC, ion exchange resins, activated alumina, and granular ferric hydroxide.

Applications include the removal of natural organic matter to minimize byproduct formation during downstream chlorination, and arsenic removal optimization studies.

Scaling equations, which are used to design the RSSCT tests are based on a dimensional analysis which maintains similitude with the full-scale process. In the case of GAC testing, carbon for the small-scale columns is obtained by grinding GAC from the full-scale application to a smaller size. Specific techniques are used for grinding, sieving, and washing the media to provide a uniformly ground GAC with a low-fines content. In the proportional diffusivity design approach, the ratio between the full-scale and the small-scale contact times equals the scaling factor. The ground GAC is typically 1/10 to 1/20 the size of the full-scale carbon. Therefore, the length of time required to develop a breakthrough curve at the small-scale is 10 to 20 times shorter than at the pilot- or demonstration-scales.

The RSSCT columns are made of glass with inner diameters in the range of 4 to 15 millimeters. The media is 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 is supported with...
either glass beads or glass wool. The test water is pumped through the
column in a down-flow mode at the specified flow rate for the given
conditions of contact time and temperature. 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. The effluent contaminant concentration data
are plotted to monitor breakthrough as the study progresses. Samples
may be collected to determine the potential downstream formation of
byproducts.

For a given application, Carollo prepares an experimental testing
matrix and sampling and analysis 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 in the batch may be adjusted to reflect historical values.
Testing can normally be completed in 2 to 6 weeks.

**Bench-Scale Annular Reactors**

Carollo maintains BioSurface Technologies annular reactors for
conducting distribution system studies. These reactors have the
unique capability of allowing separate control of the detention
time and shear stress within the system. The reactors consist of
a rotor inside a stationary outer cylinder. Hydraulic conditions
within the reactor, such as shear stress and water velocity, depend
on the rotational speed of the rotor. A rotational speed of 50 rpm
is commonly used in drinking water studies, as it creates a shear
stress of 0.25 N/m² at the outer wall, which corresponds to a flow of
approximately 1 foot per second (0.3 meters per second) in a 4-inch-
diameter (100 mm) smooth pipe. Four draft tubes inside the inner
cylinder enhance liquid mixing.

The reactors allow the collection of both water samples and coupons
from which biofilm growth and the extent of corrosion may be
determined. Polycarbonate coupons are often used to evaluate biofilm
growth without the presence of corrosion or corrosion byproducts.
Coupons manufactured from common pipe materials such as ductile
iron may also be used. The influent flow rate determines the water
residence time inside the reactor, simulating the residence time in the
distribution system.

In most bench-scale experiments, the reactor is assumed to
approximate a finite section of a distribution system. A common
setup for drinking water experiments consists of pumping the test
water into the annular reactor. Test waters may be augmented
by adjusting water quality parameters such as pH or the level of
background organic material, or seeded with specific consortia
of microorganisms. Additional nutrients, disinfectants, corrosion
inhibitors, or other constituents may also be pumped into the reactor depending on the specific experimental objectives.

Annular reactors may also be used in combination with batch incubation bottles to differentiate the effect of the pipe wall from the effect of water age. For batch incubation, a clean bottle is filled with reactor influent water. The bottle is kept under the same conditions of temperature and darkness as the reactors. After a period of time equivalent to the reactor residence time, water is sampled from the incubation bottle and from the reactor effluent. A comparison of the results allows the impact of biofilm growth and corrosion at the pipe wall to be distinguished from the effect of water age.

The reactors are readily transportable, and can be shipped along with other required equipment such as a feed water pump, chemical dosing pumps, and instrumentation for basic water quality parameters.

Carollo has used the annular reactors to evaluate the effectiveness of scale inhibitors for preventing scale formation in a RO brine disposal pipeline. These reactors have also been used to evaluate biofilm formation and regrowth in distribution systems with varying levels of available biodegradable organic matter. Carollo has also used the annular reactors to study the formation and decay of specific DBPs in distribution systems for various water quality conditions.

Collimated Beam Apparatus

Carollo’s collimated beam apparatus provides rapid and accurate determination of microbial and contaminant UV dose-response.

The collimated beam apparatus can be equipped with either a low- or medium-pressure mercury lamp to assess the impact of monochromatic light (i.e., UV at 254 nm) or polychromatic light (i.e., UV from 200 to 300 nm). Small sample volumes (between 25 and 100 mL) are placed under the collimating tube and exposed to UV light for a controlled period of time. The UV intensity incident on the samples is accurately measured using an International Light radiometer with a NIST traceable calibration. UV transmittance of the sample is measured using a spectrophotometer. UV dose delivered to the sample is calculated using the measured intensity, exposure time, and UV transmittance. UV dose-response curves are obtained by plotting microbial inactivation or the photochemical response as a function of dose.

Applications of the collimated beam apparatus include:

- Determining the UV dose response of indicator microbes for UV system sizing.
- Determining the UV dose-response of heterotrophs in biologically-active filter effluents.

- Developing inactivation data for nuisance species such as the algae *chlorella*.

- Evaluating the impact of water quality on microbial UV dose-response.

- Evaluating the advanced oxidation of T&O compounds or micropollutants using UV light and hydrogen peroxide.

- Quantifying the formation of DBP such as nitrates and aldehydes with medium-pressure UV systems.

**Optics Bench**

As part of our Water Research Foundation Project *Design and Performance Guidelines for UV Sensor Systems*, Carollo developed a UV Optics Bench for the evaluation of UV lamp output, quartz sleeve and UV sensor window UV transmittance, and UV sensor measurement properties.

Similar to the collimated beam apparatus, the Optics Bench uses either a low- or medium-pressure UV lamp to produce monochromatic or polychromatic light. Apertures and filters control the UV intensity, spectra, and beam width of the light emitted from the UV source. UV light from the lamp is quantified using a research grade International Light radiometer with NIST-traceable calibration.

The Optics Bench was used to quantify sleeve and UV sensor port window fouling at nine installed UV systems for the Water Research Foundation Project *Development of a UV Disinfection Knowledge Base*. The Optics Bench was also used to quantify UV sensor measurements properties for the Water Research Foundation Project *Design and Performance Guidelines for UV Sensor Systems*, and to quantify UV reactor fouling with LP and MP pilot reactors for the City of San Francisco’s Hetch Hetchy water supply.

**Custom UV Reactors**

Carollo has developed custom UV reactors that can be fitted with different types of UV lamps, quartz sleeves, and UV sensors. The UV reactors can be configured to evaluate lamp aging, fouling, microbial disinfection, and advanced oxidation using UV light and hydrogen peroxide. As an example, the reactors were recently used by San Francisco PUC to compare lamp sleeve and UV sensor window fouling with LPHO, amalgam, and MP lamp types. Because the reactors are customized for the application, they provide cost effective evaluations of different UV system component technologies with minimal footprint and setup time.
Full-Scale Testing

Portland, OR, UV Validation Facility

The USEPA requires that UV systems undergo performance validation testing in order to receive inactivation credit. Recognizing the need for a large UV validation facility in the U.S., Carollo developed and commissioned the Portland UV Validation Facility in 2003. The facility has since validated over 30 commercial UV technologies at flows up to 40 mgd, all in accordance with the USEPA UV Disinfection Guidance Manual. A more comprehensive description of the test facility and Carollo’s responsibilities is provided in the Key Achievements section of this Statement of Qualifications.
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SELECT BENCH- AND PILOT-SCALE STUDIES PUBLICATIONS/PRESENTATIONS - OTHER


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 86-year history, Carollo has successfully completed more than 25,000 projects for public sector clients. Carollo is currently ranked within Engineering News Record’s (ENR) top 500 design firms. More importantly, ENR’s annual Source Book ranks Carollo among the top 10 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 1,050 employees, including more than 500 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.
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. 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 principals 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.

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 Research Group (CRG). The relationship between our design engineers and the CRG 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 80 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.