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 drinking water ultraviolet disinfection.

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Carollo’s focus on municipal water and wastewater engineering combined with our investment in applied research sets us apart in the industry. An important example of our focus is our leadership position as an authority on drinking water UV disinfection process and design.

UV disinfection has emerged over the last 15 years as the best available technology for the inactivation of Cryptosporidium, Giardia, and other pathogens that are resistant to chemical disinfection. UV provides cost-effective pathogen inactivation without the formation of disinfection byproducts. Today’s UV technologies provide reliable operation with minimal maintenance and have been installed at hundreds of locations across North America.

A LEADER IN UV TECHNOLOGY

Carollo has contributed to the successful development and implementation of UV disinfection in North America by providing leadership in UV research, regulations, validation, and design. Highlights of our contributions include the following:

- **USEPA UV Disinfection Guidance Manual.** While the USEPA invited a number of consultants to work on the guidance documents associated with regulations and technologies for the Long-Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR), they selected Carollo to develop and write key sections of the USEPA UV Disinfection Guidance Manual (UVDGM), including UV fundamentals, validation, piloting, design, and operation.

- **Portland UV Validation Facility.** Recognizing the need for validation of commercial UV systems in North America, Carollo developed the Portland UV Validation Facility, which has successfully validated over 50 UV reactors at flows up to 70 mgd per reactor.

- **Dose Monitoring and Control.** The heart of a UV disinfection system is its validated dose monitoring and control algorithm. Through our Water Research Foundation (WaterRF) research, work on the UVDGM, and validation...
at the Portland facility, Carollo has developed new approaches for dose monitoring and control that have been adopted by the major UV equipment vendors, including WEDECO, Calgon, Trojan, and Aquionics.

**UV Disinfection Research.** Since 1990, the WaterRF has funded 38 projects on drinking water UV disinfection and advanced oxidation. Carollo is the principal or co-principal investigator for 13 of those projects and a Project Advisory Committee member or participant on three others. These projects define the state-of-the-art in drinking water UV disinfection.

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<th>Project Name</th>
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For our WaterRF UV Knowledge Base Project, Carollo conducted on-site evaluations of nine large-scale UV systems, including Victoria (top - 160 mgd) and Edmonton (bottom - 80 mgd). We apply the lessons learned from evaluating installed systems to enhance UV system design and operation.

Carollo leads the engineering consulting community in conducting WaterRF-sponsored research on drinking water UV disinfection.
WaterRF Practical Aspects of UV Disinfection. This was the first funded research project to address the practical aspects of UV disinfection for surface waters, creating industry-wide acceptance of the potential of UV.

New York City Computational Fluid Dynamic Peer Review. Recognizing Carollo’s UV expertise, New York City retained Carollo to provide expert peer review on Computational Fluid Dynamic (CFD)-based approaches for validating large-scale UV reactors for their 2,200-mgd Catskill/Delaware UV system.

UVXPT and UVCAT Performance Modeling Software. Carollo developed UVXPT software to provide CFD-based modeling of dose delivery by UV reactors and UVCAT software to provide performance and life-cycle costs assessments of UV system alternatives. These state-of-the-art tools provide a unique opportunity for WTPs to optimize and validate their UV system designs early in the design process.

**DESIGN EXPERIENCE**

Our expertise in applied UV research, validation, regulation, and modeling makes us the industry leaders on UV disinfection from concept design to startup. Our UV design projects include:

- **Los Angeles Department of Water and Power, CA** – 600-mgd design and construction, 650-mgd predesign.
- **Greater Cincinnati Water Works, OH** – 240-mgd design and construction.
- **Portland Water Bureau, OR** – 220-mgd design.
- **Denver Water, CO** – 180-mgd, 250-mgd, and 275-mgd concept designs.
- **Miami-Dade Water and Sewer Department, FL** – 225-mgd design.
- **Metropolitan Water District of Salt Lake and Sandy, UT** – 150-mgd design and construction.
- **Oklahoma City, OK** – 150-mgd conceptual design.
- **Washington Suburban Sanitary Commission, MD** – 120-mgd design and construction.
- **City of Tempe, AZ** – 50-mgd and 65-mgd design and construction.
- **Weber Basin Water Conservancy District, UT** – 32-mgd and 46-mgd design and construction.
- **City of St. George, UT** – 40-mgd design.
- **City of Tracy, CA** – 30-mgd design and construction.
- **Mountain House, CA** – 5-mgd and 20-mgd design and construction.

Carollo has designed and installed UV systems from: WEDECO (A - Point of Mountain, UT), Aquionics (B - East Bay MUD, CA), Calgon (C - Mountain House, CA), Trojan (D - Neenah Water Utility, WI)
Neenah Water Utility, WI – 18-mgd design and construction.
North Shore Water Commission, WI – 18-mgd predesign.
East Bay Municipal Utility District, CA – 8-mgd backwash water design and construction.
City of Flagstaff, AZ – 4-mgd design and construction.
City of Weiser, ID – 4-mgd design.
High Desert Power Project, CA – 3-mgd design.

In addition to externally-funded projects, Carollo conducts in-house research to enhance our understanding of UV disinfection. We have developed custom UV reactors that can be fitted with different types of UV lamps, quartz sleeves, and UV sensors. These reactors were used to evaluate the impact of lamp type on fouling rates for the City of San Francisco. We have also developed specialized instrumentation for conducting on-site assessments and commissioning of UV system performance.

Carollo actively promotes UV disinfection by sponsoring conferences and workshops across U.S., attended by academics, regulators, utilities, and manufacturers. As an example, Carollo authored five papers on UV disinfection at the 2012 Water Quality Technology Conference held in Toronto, Ontario.

The following pages provide additional detail regarding the projects that demonstrate our industry leadership in UV disinfection for drinking water treatment.

Through our WaterRF research and UV validation at Portland, Carollo has developed an innovative, low-cost approach for determining UV reactor dose distributions from MS2 biodosimetry data. The method has been proven by the accurate prediction of T1 phage inactivation with 15 commercial reactors. Using UV dose distributions determined from biodosimetry eliminates Reduction Equivalent Dose (RED) bias uncertainty and optimizes UV system sizing and operation by as much as 50 percent, depending on the reactor technology.
The project profiles on the following pages present highlights of Carollo’s key achievements in drinking water disinfection using UV technologies. 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.
As part of the Agreement in Principle for the Stage 2 Microbial and Disinfection Byproducts (M/DBP) Rules, UV disinfection was included in the regulatory toolbox for obtaining Cryptosporidium, Giardia, and virus inactivation credits. To support this decision, USEPA prepared a UV Disinfection Guidance Manual (UVDGM).

Due to its recognized leadership in UV disinfection, the USEPA contracted Carollo to write key sections of the UVDGM, including major portions of the sections on UV fundamentals, design and pilot testing, and all sections on UV reactor testing and validation. Carollo also supported stakeholder feedback on the manual by leading presentations and discussions at stakeholder meetings in New Orleans and Washington, D.C. In addition to UV disinfection, Carollo prepared sections of the Microbial Toolbox guidance on using chlorine dioxide, ozone, and demonstration of performance for earning inactivation/removal credits.
Validation of over 50 commercial UV reactor product lines from Calgon, Trojan, WEDECO, and Aquionics at flows up to 70 mgd in accordance with the USEPA’s LT2ESWTR.

Development of optimized validation techniques using MS2, T1UV, and T7 phage that accounts for the UV reactor’s dose distribution.

First full-scale validation of advanced oxidation using UV light and hydrogen peroxide.

Validation of 40-mgd UV reactors allows for accurate, bioassay validated scale-up from test site to installation.

**UV Disinfection Validation Facility**

To receive inactivation credits with UV disinfection, the USEPA requires that UV systems undergo validation testing. Before 2003, UV systems installed in the U.S. were validated either onsite or at a facility in Europe. Recognizing a need for a U.S. facility, Carollo developed the Portland UV Disinfection Validation Facility in Portland, Oregon. The facility is located near the groundwater pumping station of Portland’s South Shore Well Field. The wellfield can provide up to 90 mgd of chlorine-free, low UV-absorbance groundwater.

Carollo obtained funding for facility development from four UV system suppliers: Calgon Carbon Corporation, Trojan Technologies, WEDECO, and Aquionics. The design and construction of a 30-inch test train was completed in February 2003. A second 12-inch test train was added to the facility in December 2005. The facility was expanded in 2011 to provide validation at flows up to 70 mgd.

Carollo commissioned the site in March 2003 with the testing of a 40-mgd, medium-pressure (MP) UV system supplied by Calgon. Carollo has since tested over 50 commercial UV reactors for drinking water and reuse applications at flowrates ranging from 1 to 70 mgd and UV transmittance values ranging from 50 to 98 percent. Since facility startup, over 4,000 challenge tests using MS2, QB, T1UV and T7 coliphage and B. pumilis spores have been used to demonstrate UV doses ranging from 5 to 200 mJ/cm².

The test train provides highly accurate validation test results: (1) flow is controlled to within 1 percent of target flow, (2) UV transmittance (UVT) is controlled within 0.3 percent of target UVT, and (3) influent and effluent concentrations are typically measured with a standard deviation of 0.04 log. Through analysis of the validation data, Carollo has developed efficient and simple dose-monitoring algorithms that predict UV dose within ± 1 mJ/cm². The dose-monitoring algorithms are used by UV systems across North America and have been adopted by the UVDGM as a standard method for the UV industry.

The facility has also validated UV systems for UV advanced oxidation processes (AOP) applications. Carollo measured the destruction of methylisoborneol (MIB), geosmin, and caffeine as a function of UV dose, hydrogen peroxide concentration, and hydroxyl scavenger demand. Results were used to demonstrate scaleup of advanced oxidation from bench- to full-scale applications.
GREATER CINCINNATI WATER WORKS, OHIO

Demonstration Study and Final Design of UV System

Greater Cincinnati Water Works awarded Carollo, in partnership with another firm, a $3-million contract to design and construct a UV system for their 240-mgd Richard Miller Treatment Plant (RMTP). The RMTP is a surface water plant that uses conventional surface water filtration and post filtration granular activated carbon adsorption for organics removal. Carollo was responsible for 40 percent of the project and led tasks on process engineering, structural design, and demonstration testing.

Carollo used the cost-benefit model of the USEPA LT2ESWTR, customized for the RMTP to justify the selection of design criteria for pathogen log inactivation and UV dose. The analysis quantified the significant public health benefits to Cincinnati obtained by implementing UV disinfection for 2-, 3- and 4-log inactivation credit.

Carollo pre-qualified three UV vendors for the RMTP, prepared a Request for Information on UV system alternatives for 6-, 8-, 10- and 12-train systems, and used UVCAT software to evaluate and optimize the UV system alternates in terms of sizing, redundancy, dose monitoring and control, power consumption, operation and maintenance (O&M) costs, life-cycle costs, and validation. Carollo evaluated expansion options for the inactivation of emerging contaminants listed on the USEPA Unregulated Contaminant Monitoring Rule and the treatment of taste and odor compounds and micropollutants using UV light and hydrogen peroxide. The analysis was used to select the 8-train layout and define expansion for seasonal advanced oxidation for T&O compounds.

The project team completed the UV system design in 2010. Carollo provided structural design services and input on hydraulics, UV system layouts, electrical design, and controls. Carollo prepared UV system specifications and procurement documents and evaluated and ranked UV vendor bids. The project team selected a Calgon 48" Sentinel UV system, sized to provide 4-log inactivation of Cryptosporidium, based on a comparison of life-cycle costs.

Carollo has since worked with Calgon to define UV dose monitoring and control algorithm programming within the UV system’s PLC and conduct Factory Acceptance Testing to verify the programming. Carollo prepared documentation for UV system approval, including CFD-based UV dose modeling, to demonstrate that the UV installation piping provided UV dose delivery that agreed with validation. The UV system is currently under construction with startup anticipated in summer 2013. Future work will include UV system startup and warranty testing.
The Portland Water Bureau selected Carollo, in partnership with another firm, to evaluate and design UV disinfection for their 220-mgd Bull Run supply. UV disinfection would be implemented to achieve 2- to 3-log inactivation of Cryptosporidium as required for unfiltered systems under the LT2ESWTR. Key challenges included addressing fouling with unwiped UV systems, mercury release mitigation, impacts of power quality events on UV system off-spec performance, optimization of the UV system layout, and meeting the schedule requirements of the LT2ESWTR.

Carollo conducted a 1-year fouling study using UV reactors from Trojan, Calgon, and WEDECO. The fouling study evaluated the impact of seasonal water quality and upstream addition of chlorine on fouling rates. Fouling rates were quantified using UV sensor readings and measurements of quartz sleeve UV transmittance obtained using a custom optics bench. Fouling was observed only with the reactors equipped with MP UV lamps and only during the fall season when reservoir levels were low.

Based on the Basis of Design Report for the Bull Run Supply (10-percent design level), Carollo prepared UV system specifications to select the UV system. The specification provided detailed design and evaluation criteria for both MP and low-pressure high-output (LPHO) UV systems from three qualified UV vendors. Carollo evaluated proposed UV systems in terms of life-cycle costs, mercury release and mitigation, operation and maintenance, UV validation, and offspec performance. Based on the evaluation, the Portland Water Bureau selected a WEDECO K143 UV system consisting of five UV reactors, each with 11 rows of lamps expandable to 13 rows, and each validated up to 53 mgd.

Carollo developed five layout options for the UV system. CFD was used to compare the impact of inlet and outlet channels versus large diameter pipes on UV system flowsplit, headloss, and UV dose delivery. CFD was also used to optimize the lengths of straight pipe upstream of the reactor and determine the location of reactor inlet and outlet valves and flowmeters, thereby optimizing UV building footprint and capital costs. Carollo also evaluated options for UV system backup power. Carollo analyzed 14 months of power quality data for the plant, quantifying the levels of off specification performance expected with the UV system. Results were used to select the uninterruptable power supply (UPS) and generators required for the project.
Los Angeles Aqueduct Filtration Plant and Los Angeles Reservoir Ultraviolet Treatment Facilities

Carollo, in partnership with another firm, was selected to develop design criteria and prepare UV system drawings and specifications for the 600-mgd Los Angeles Aqueduct Filtration Plant and the 650-mgd Los Angeles Reservoir. The UV systems are designed to obtain *Giardia* and *Cryptosporidium* inactivation credit in accordance with LT2ESWTR, the UVDGM, and State Water Board Division of Drinking Water (DDW) requirements. Carollo was tasked with evaluating UV system hydraulics, electrical design, and UV system layouts including yard piping. Key challenges for UV implementation include the selection of design criteria for UV transmittance and fouling, selection of UV vendor technologies, addressing hydraulic constraints, and developing a UV system design and implementation strategy that met the overall project schedule with DDW approval.

Carollo used CFD to evaluate UV system layout alternatives, including inlet and outlet channels and bypass structures, to minimize headloss and optimize passive flowsplit with the UV system. The layouts also addressed geotechnical constraints, including known faults in the area of the UV facility, while minimizing excavation and yard piping costs.
Carollo was the lead consultant for the design and construction of the Point of the Mountain Water Treatment Plant (WTP) for the Metropolitan Water District of Salt Lake and Sandy, located near Salt Lake City, Utah. The plant was designed for an initial capacity of 70 mgd, expandable to 150 mgd. This greenfield project included flash mix, flocculation, sedimentation, intermediate ozone, biologically active filters, UV disinfection, and onsite chlorine generation. Other plant facilities included a finished water pump station, a 20-MG finished water reservoir, solids settling basins, a 6-megawatt standby power generation facility, and a maintenance facility. Total construction costs were $90 million (2004 dollars). Project construction was completed in Summer 2007.

Carollo conducted a $1.6-million bench and pilot study over 18 months to select and optimize process alternatives. Analysis showed that pre- and intermediate ozonation, biologically active filtration, and UV disinfection provided the most robust and cost-effective treatment to meet future challenges, including T&O events and the requirements of the LT2ESWTR and the Stage 2 DBP Rule.

Carollo designed the disinfection facilities to provide complementary use of ozone, chlorine, and UV disinfection. UV provided 2.5-log Cryptosporidium and Giardia inactivation credit. Ozone provided 0.5-log Giardia credit, T&O treatment, and process enhancement. Chlorine provided 2.0-log virus credit.

Carollo prepared UV specifications that provided a competitive bid between commercial LPHO and MP technologies. Based on an assessment of life-cycle costs and non-monetary factors, Carollo recommended the selection of a WEDECO K143 UV system.

While the UV system was designed to accommodate seven reactors, only four reactors are installed to treat an interim capacity of 70 mgd. With the optimization of UV validation using new test microbes, the implementation of the 2006 UVDGM, and the increase in UVT caused by ozonation, the four installed reactors have capacity to treat the 150-mgd design flow, thereby providing capital and O&M cost savings. Each UV reactor was validated for 40-mgd of flow capacity.
DENVER WATER, COLORADO

UV Disinfection Study and Conceptual Design for the Foothills, Marston, and Moffat WTPs

Denver Water selected Carollo to evaluate UV disinfection at three WTPs: the 300-mgd Foothills WTP, the 250-mgd Marston WTP, and the 210-mgd Moffat WTP. The project followed an aggressive 7-month schedule during which Carollo developed UV design criteria, established UV location alternatives, reviewed commercial UV technologies, and developed conceptual designs for each facility as well as an implementation plan for full-scale design. The evaluation also included an assessment of chlorella and control via UV seasonal T&O event mitigation with UV/H₂O₂.

Carollo’s approach for Denver Water addressed important issues that directly impact implementing UV disinfection in terms of costs, reliability, and ease of use. Carollo compared the costs and benefits of applying large-scale UV reactors (40 and 70 mgd) treating combined filter effluent to smaller scale reactors treating individual filter flows. Both the Marston and Moffat WTPs were headloss-constrained due to the earlier addition of chlorine contactors in the finished water reservoirs. To resolve this issue, Carollo developed a disinfection strategy for Denver Water using UV disinfection to achieve both Cryptosporidium and Giardia credit, thereby allowing chlorine contact time (CT) to be reduced to the level needed for 2.5-log virus credit. Combined with modifications of the yard piping and junction boxes, and the use of low headloss reactors, these changes would not only make combined filter effluent options feasible, but increase the water level in the finished water reservoirs.

Carollo used our UVCAT UV system cost and performance software to identify optimal UV system operational strategies and used cost-benefit workshops with Denver Water to rank and select the best UV system for each site. UVCAT was also used for risk analysis to evaluate the impacts of off-specification performance by the UV system and identify the need for back-up power using UPS systems.

“From the beginning of the project, Carollo showed they were above the competition in terms of qualifications, technical expertise, and customer focus.”

Martin Garcia, Project Engineer, Denver Water
UV Fouling Study for the Hetch Hetchy Supply

As part of planning efforts for San Francisco Public Utilities Commission’s (SFPUC’s) 315-mgd UV disinfection facility for the Hetch Hetchy supply, Carollo conducted a 6-month pilot study to evaluate fouling of UV reactors equipped with low-pressure high-output (LPHO) and medium-pressure (MP) UV lamp technologies. Carollo customized two UV reactors obtained from R-CAN Environmental to evaluate the lamp technologies. One reactor housed four non-amalgam and four amalgam LPHO lamps, while a second reactor housed a single MP lamp. Multiple sensor ports were installed to monitor fouling rates along the length and about the circumference of the quartz sleeves housing the UV lamps.

UV sensor readings were monitored over five test periods to determine UV lamp aging and quartz sleeve/sensor port fouling. Upon completion of each testing period, sleeves and sensor port windows were removed for direct measurement of fouling using Carollo’s custom optics bench. Sleeves were rinsed with acid solution to capture foulants for analysis by inductively coupled plasma/mass spectroscopy (ICP/MS) and then manually cleaned to restore UV transmittance.

The study showed significant sleeve and sensor port window fouling with both MP and LPHO lamp types. ICP/MS analysis showed that the primary constituents of the foulant were calcium, iron, silicon, and aluminum. The observed fouling rates were surprising because the Hetch Hetchy supply is an unfiltered source characterized by low hardness and alkalinity, low mineral content, and relatively high UVT. The study highlighted the need for careful evaluation of fouling potential prior to UV system selection and design. Based on these initial findings, SFPUC conducted further pilot testing to evaluate the effectiveness of the sleeve wiping mechanism prior to final selection of UV process equipment.
Carollo has completed the design of UV disinfection and onsite sodium hypochlorite generation facilities for the City of Tempe, Arizona’s 50-mgd South Tempe WTP and 65-mgd Johnny G. Martinez WTP. These upgrades were implemented to reduce DBPs, provide Cryptosporidium inactivation to meet the LT2ESWTR, and reduce public health risks associated with previously used gaseous chlorine.

The designs for both plants used large-scale UV reactors located in a dedicated building downstream of filtration. The Johnny G. Martinez design used four duty and one standby UV reactors, while the South Tempe Design used three duty and one standby. To simplify O&M, both plants used WEDECO K143 reactors, each equipped with seven rows of 12 LPHO lamps. The reactors were initially validated using MS2 phage at flows from 2 to 40 mgd and UVTs from 85 to 95 percent at the Portland UV Validation Facility.

Since the South Tempe Plant UV system had been commissioned in September 2005, the raw water quality at the South Tempe Plant dramatically changed, resulting in seasonal UVTs that dropped below the design UVT of the plant and below the validated range of the reactors. To resolve this issue, the UV reactors were re-validated using T1UV phage. The T1UV validation increased the capacity of the reactor to receive Cryptosporidium credit at lower UVTs and provided more efficient operation of the UV system under average conditions, thereby lowering O&M costs.

The re-validated UV system was commissioned from January to March 2008 with the purpose of obtaining UV disinfection credit from the Maricopa County Environmental Services Department (MCESD). Commissioning included a detailed one-week startup test and training period led by Carollo, in partnership with the UV system manufacturer, followed by a 30-day operational test period conducted by the City’s personnel. The commissioning demonstrated that the UV system operated per regulatory requirements, resulting in MCESD approval of the UV system for 2.5-log Cryptosporidium and 3.0-log Giardia inactivation credit.
The Washington Suburban Sanitary Commission (WSSC) selected Carollo (teamed with another consultant) to design a new UV disinfection system for their 120-mgd Patuxent WTP expansion project. The Patuxent WTP was a conventional filtration plant using chlorine disinfection. UV disinfection was added to the treatment process to enhance multi-barrier pathogen control. The project also included design and construction services for conventional filtration and chlorine disinfection to increase the emergency capacity of the WTP from 80 to 120 mgd.

During preliminary design, Carollo identified and resolved issues that impacted the costs and ease of implementing UV disinfection. Because the WTP was originally designed to implement ozone upstream of filtration, locations between the filter effluent and the water reservoirs were headloss and space constrained. Carollo used UVCAT UV system simulation software and hydraulic analysis to compare life-cycle costs and headloss for the filter gallery and combined effluent locations. Because the combined effluent option was not feasible without costly intermediate pumping, the filter gallery option was selected.

Due to space constraints, the filter gallery option was limited to UV systems using MP UV lamps. UVCAT evaluated the dose monitoring and control strategies of MP UV system alternatives. The analysis showed that UV systems with high dose-delivery turndown were required to provide optimal dose pacing given the WTP’s highly variable flow and UVT. UVCAT was also used to evaluate the combined costs of filtration and UV disinfection as a function of the number of filters operating, allowing WSSC to select a filter operation strategy that provided the optimal balance between UV system costs and ease of use.

The project team selected a UV system consisting of 24” Calgon Sentinel reactors. Carollo used CFD to evaluate three options for installing the UV reactor within the filter gallery piping, which included locating the UV reactor upstream and downstream of a venturi flowmeter. The models were used to compare velocity profiles at the reactor inlet and outlet and UV dose delivery to that measured and predicted using validation piping. The models predicted slightly higher UV dose delivery with the UV reactor installed downstream of the venturi. Velocity profiles were confirmed once the UV reactor had been installed within the recommended layout.
Mountain House WTP Interim and Expansion Project

The Mountain House Community Services District (MHCSD) hired Carollo to evaluate their existing 2.5-mgd WTP and develop designs for a 15-mgd plant expansion. Because of tightening surface water regulations and rapid growth of the community, the owner required the new plant be designed and constructed in 21 months. The client also requested a capacity increase from 15 to 20 mgd without a time extension. To meet the fast-track delivery schedule required by the developer, Carollo partnered with Western Summit Constructors to provide design/build delivery of this 20-mgd $40-million facility.

Carollo performed a detailed evaluation of expansion alternatives, including conventional treatment with UV disinfection, ultrafiltration, and the expansion of the existing Trident filter system. Based on capital and operations costs, regulatory compliance, and system reliability, Carollo recommended a conventional treatment plant with UV disinfection and sludge drying bed for solids handling. Construction began in June 2005 and was competed in April 2007.

To provide treated water to the Mountain House community, the project was implemented in two phases. The interim expansion phase implemented a 5-mgd UV system using two pre-purchased Calgon 18" Sentinel reactors, each equipped with six MP lamps. The expansion phase implemented a 20-mgd UV system using two Calgon 36" Sentinel reactors, each equipped with nine MP lamps.

As part of the commissioning of the UV system, Carollo conducted startup testing to demonstrate that the installed UV system was sized to meet the UV dose requirements called for in the UV specification and that the PLC was programmed with the dose monitoring algorithm given in the UV validation report. Carollo also confirmed the accuracy of UV sensors and on-line UVT monitors, verified alarms indicating UV system operation outside the validated range, and confirmed that lamp aging, fouling, and power consumption met design criteria.

Carollo worked with the District and the UV equipment manufacturer to resolve issues identified during startup testing. Carollo also worked with the DDW to obtain disinfection credit for the UV system. Carollo documented UV system performance over a 6-month evaluation period with the interim project and prepared permitting documents that included the commissioning report, mercury response plan, and a UV system operating strategy.
WEBER BASIN WATER CONSERVANCY DISTRICT, LAYTON, UTAH

Davis North and Weber South WTPs

Carollo designed the expansions and upgrades for the Weber Basin Water Conservancy District’s Davis North and Weber South WTPs. Both plants use WEDECO K143 UV reactors equipped with LPHO lamps. The Davis North facility was the first UV system for potable water in Utah and one of the first large-scale drinking water UV disinfection systems installed in North America.

The Davis North project expanded the WTP’s capacity from 26 to 46 mgd and included the addition of new conventional flocculation and sedimentation basins, pre- and intermediate ozone for T&O control and enhanced particle removal, and UV disinfection for Cryptosporidium inactivation. The synergistic application of UV disinfection and ozone resulted in a facility cost reduction of approximately 50 percent compared to the next lowest cost alternative.

The Weber South project expanded the plant from 26 to 32 mgd and included primary disinfection using UV light, eight new dual media filters, a new chemical building, a backwash water pump station, and solids handling facilities.

**HIGHLIGHTS**

- UV installation at the Davis North WTP uses large-scale reactors equipped with LPHO lamps.
- CFD models helped to assess the impacts of inlet piping on hydraulics.
- One of the country’s first large-scale UV disinfection drinking water installations.

**Primary disinfection using UV light at design flows of 46 and 32 mgd.**

**First synergistic application of UV and ozone for drinking water treatment.**

**Conjunctive use of ozone and UV resulted in a facility cost reduction approximately 50 percent of the next-lowest-cost alternative.**
The Weber Basin Water Conservancy District (WBWCD) operates three WTPs that use WEDECO K143 UV reactors for Cryptosporidium and Giardia inactivation. The UV systems at the Davis North and South plants were installed in 2001 and 2002 and used early generation UV intensity-setpoint algorithms for UV dose monitoring developed before the publication of the UVDGM. The UV intensity setpoint algorithm provided a pass/fail indication of dose delivery that led to significant over-dosing by a factor of 2 to 3. In contrast, the UV system at the Weber South plant was installed 2009 and used a calculated dose algorithm based UV validation conducted in December 2007 in accordance with the 2006 UVDGM. The calculated dose algorithm predicts UV dose as a function of flow rate through the reactor, UVT of the water, UV sensor readings, and number of rows of operating lamps.

WBWCD selected Carollo to evaluate upgrading the UV dose monitoring and control algorithms at all three plants with the objective of obtaining disinfection credit with the Utah Division of Drinking Water (Utah DDW). Analysis showed that updating the algorithms would provide more efficient UV dose monitoring and control, thereby lowering UV system operating costs.

Carollo worked with the Utah DDW to develop a compliance plan for implementing the upgrades. A key concern with Utah DDW was the applicability of one validation report to all three UV systems, given differences in inlet piping and reactor design. Analysis of three validation reports showed that the K143 reactors provided similar UV dose delivery regardless of these differences. Based on this analysis, WBWCD chose to upgrade all three UV systems based on an updated validation report prepared by combining data from two validations. The combined data set extended the validated range to higher UVTs and provided the option to base UV dose monitoring on T1 REDs as opposed to MS2 REDs, thereby providing more efficient UV system operation.

The UV system upgrades were implemented in February 2012. Carollo audited the upgrades at each plant, showing that the PLC software code matched the validation report algorithms. Results were submitted to Utah DDW for UV system approval.
Carollo provided preliminary and final design for the East Bay Municipal Utility District’s Walnut Creek WTP Improvements Project. The project’s primary objective was to increase plant capacity to 120 mgd through $85 million in planned improvements, including: new chemical storage/feed facilities; new filters totaling 40 mgd; a new backwash water treatment facility; new 5- and 16-MG clearwell tanks; plant control instrumentation upgrades; and measures to improve work space, plant security, and landscaping.

Construction of the facilities involved significant neighborhood issues and required a phasing plan to keep existing facilities in operation during construction.

The project included implementing UV disinfection for the filter backwash water handling system and designing an optional addition for the main treatment process. The backwash water UV system met the State of California’s requirement to achieve 3-log inactivation of Cryptosporidium and Giardia using a design dose of 40 mJ/cm² at 8 mgd. Carollo performed bench-scale studies to identify the optimal backwash treatment process using equalization, coagulation, sedimentation, and UV. Results provided a basis for defining a design UV transmittance for UV system sizing.

The client-engineer project team chose an MP Aquionics system based on availability of UV validation data, reliability considerations, and site constraints.
John Jones WTP Expansion

Carollo approved design and construction services for the John Jones WTP Expansion. The project increased the plant flow to 30 mgd with the addition of new flocculation/sedimentation basins, washwater basins, and chemical addition facilities. UV disinfection was implemented to address current and pending regulatory requirements for the inactivation of Giardia and Cryptosporidium. UV disinfection also provided fewer hydraulic impacts and lower capital and O&M costs than other technologies, such as ozone.

Carollo evaluated the life-cycle costs (capital and O&M), reactor validation experience, and installation and operating history of these proposed UV system alternatives and selected a WEDECO K143 system consisting of seven rows of 12 LPHO lamps.

Commissioning confirmed that the UV system was properly sized per the design criteria and used the dose monitoring algorithm provided in the validation report. Commissioning also verified UV sensor accuracy, power consumption, response to changing flow and UVT, and alarms.

To optimize lamp replacement and cleaning schedules, Carollo provided the City with a software tool that calculates the combined aging and fouling factor from the measured UV intensity. Carollo also provided software tools to calculate UV sensor calibration ratios to maintain regulatory compliance.

To obtain regulatory credit for the UV system, Carollo served as liaison between the City and DDW, conducted workshops with DDW on the performance of the UV system, and prepared all documents associated with the permitting process, including commissioning report, mercury response plan, and UV system operating strategy.

<table>
<thead>
<tr>
<th>Cost Summary</th>
<th>Vendor A</th>
<th>Vendor B</th>
<th>Vendor C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equipment</td>
<td>$713,600</td>
<td>$805,100</td>
<td>$608,900</td>
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<tr>
<td>Structural/Mechanical</td>
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<td>$542,000</td>
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<tr>
<td>Total Capital Cost</td>
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<tr>
<td>Annual O&amp;M Cost, $/year</td>
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<td></td>
</tr>
<tr>
<td>Power</td>
<td>$24,400</td>
<td>$35,200</td>
<td>$10,500</td>
</tr>
<tr>
<td>Replacement</td>
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<tr>
<td>Labor</td>
<td>$700</td>
<td>$600</td>
<td>$1,700</td>
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<tr>
<td>Total Annual O&amp;M Cost ($/year)</td>
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<td>$55,300</td>
<td>$26,800</td>
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<tr>
<td>Total O&amp;M (w/patent), $/year</td>
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<td>$55,300</td>
<td>$26,800</td>
</tr>
<tr>
<td>O&amp;M NPV, $</td>
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<td>$634,300</td>
<td>$307,400</td>
</tr>
<tr>
<td>Total NPV of UV System</td>
<td>$1,705,600</td>
<td>$1,981,400</td>
<td>$1,692,900</td>
</tr>
</tbody>
</table>

Carollo used an evaluated bid approach, which included capital costs, life-cycle costs, and non-monetary factors to help select the preferred UV system for the City of Tracy.
Oklahoma City Water Utilities Trust commissioned Carollo to perform a study to expand the treatment process at the Draper WTP from 90 to 150 mgd. Due to increased concerns over Cryptosporidium and the production of chlorinated DBPs, Carollo evaluated the feasibility of a new 150-mgd UV disinfection facility. This evaluation included establishing preliminary UV design criteria; identifying implementation issues; evaluating different equipment alternatives; presenting estimates for capital, operation, and life-cycle costs; and providing recommendations for UV system implementation.

A hydraulic audit of the Draper WTP indicated significant available hydraulic driving force between the gravity filters and the clearwells. As a result, Carollo proposed using flow-splitting weirs to control the flow to the UV reactors, thereby simplifying system operation and eliminating the need for valves and flow metering.

As part of the study, Carollo performed a life-cycle cost analysis for both MP and LPHO systems from several different manufacturers, and developed preliminary layouts of both systems. Carollo used its experience in the design, evaluation, and implementation of both types of systems, as well as manufacturers’ quotations for equipment, the estimated life of consumables, the estimated utility cost, and compliance with the draft UVDGM, as a basis for the life-cycle cost analysis. Due to the high costs of power and the costs to expand electrical capacity at the Draper plant, an LPHO UV system presented the most cost-effective alternative.
As part of the $8.4-billion Comprehensive Everglades Restoration Program (CERP), the U.S. Army Corps of Engineers and the South Florida Water Management District selected Carollo to perform the first pilot testing and engineering analysis of water treatment technologies on Lake Okeechobee. This pilot study provided the basis for design and cost estimates for treatment systems with an ultimate capacity of approximately 1.5-billion gallons per day (bgd).

The CERP presents a framework for Everglades restoration and contains 68 specific components to restore natural water flows and improve water quality in the South Florida ecosystem. The plan will 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.

Because of the high organic content of the Lake Okeechobee water, the remote location, and issues with chemical supply and residuals disposal, Carollo proposed an innovative approach using bank filtration, ozonation, and UV disinfection. Carollo conducted a pilot study to evaluate and optimize the proposed treatment process. The study found that ozonation upstream of UV significantly increased water UV transmittance, thereby reducing UV system costs. The optimized process offered significant synergies in terms of cost and reliability compared to using any one technology alone. Pilot study results provided a basis for developing a full-scale conceptual design with capital and O&M cost estimates.
Carollo completed the WaterRF Tailored Collaboration (TC) Project, *Practical Aspects of UV Disinfection*. This project was funded through the WaterRF TC program and was jointly sponsored by the North Shore Water Commission, the Electric Power Research Institute, and the Energy Center of Wisconsin. This was the first funded research project in the U.S. to address the practical implementation issues associated with applying UV disinfection to surface water supplies.

As part of this research, Carollo conducted 1-year pilot studies on four UV reactors:

- MP UV reactors provided by Calgon Carbon.
- LPHO reactors provided by WEDECO.
- Low-pressure and LPHO reactors provided by Ideal Horizons.

Pilot studies involved collecting and analyzing water quality data, monitoring UV reactor performance, and conducting MS2 challenge testing. Carollo conducted challenge studies using live *Cryptosporidium* with the WEDECO system. Carollo analyzed all data, including fouling, wiper performance, temperature impacts, sensor performance, and power consumption. Results provided a basis for cost estimates for full-scale implementation of UV disinfection.

![Image of UV reactor installation](image-url)
Bridging Pilot-Scale Testing to Full-Scale Design of UV Disinfection Systems

Carollo was the co-principal investigator on the research team conducting the WaterRF Project, Bridging Pilot-Scale Testing to Full-Scale Design of UV Disinfection Systems. Involving an internationally recognized team and a budget well over $1 million, this project represented the most comprehensive evaluation of UV disinfection for drinking water performed to date.

As part of this research, Carollo completed 1-year pilot studies on five UV reactors:

- MP reactors provided by Trojan Technologies.
- LPHO reactors provided by WEDECO.
- MP reactors provided by Calgon Carbon.
- MP reactors provided by Aquionics.

Pilot studies involved collecting water quality data, conducting MS2 challenge tests, monitoring on-line sensors, assessing fouling and cleaning, and evaluating aging, degradation, and failure of system components. Carollo analyzed all data from these pilot studies and used the results to develop UV design concepts for the Metropolitan Water District of Salt Lake and Sandy’s 150-mgd Little Cottonwood WTP and an 80-mgd water treatment facility for Central Utah Water Conservancy District.
WATER RESEARCH FOUNDATION AND THE NEW YORK STATE ENERGY RESEARCH AND DEVELOPMENT AUTHORITY (NYSERDA)

Optimization of UV Disinfection

Carollo was the Principal Investigator for the joint WaterRF/NYSERDA Project, Optimization of UV Disinfection. This $600,000 project, co-sponsored by New York City, Tacoma, and Phoenix, developed and demonstrated new tools and approaches for validating, designing, and operating UV disinfection systems.

The project identified Qβ and T7 phage as better microbes for validating UV reactors for Cryptosporidium and Giardia credit, and SuperHume™ as a better UV absorber for validating MP UV reactors. These new validation tools significantly reduce, if not eliminate, the experimental uncertainty with UV validation methods, thereby reducing the need to apply conservative safety factors to UV system design and operation.

The project also evaluated the impacts of non-uniform lamp aging on UV dose delivery and monitoring. UV dose models based on CFD identified UV sensor placement within UV reactors that minimize over- and under-dosing that can occur with non-uniform lamp aging. The study also completed a 1-year pilot testing of UV systems equipped with LPHO and MP UV lamps at the John P. Buckley WTP in Troy, New York. The pilot study quantified the impacts of operational factors such as on/off cycling and operating power level on the efficiency and performance of UV lamps.

The project evaluated the cost benefits of using NaS batteries, a new technology developed in Japan. NaS batteries can be charged at night when power costs are low and used to power the UV system during the day when power costs are high, thereby reducing the overall power costs associated with UV system operation. They can also be used as a UPS system to minimize UV system off-spec performance.

Finally, the project developed the UV system optimization tool, UVCAT. UVCAT simulates the day-to-day operation of a UV system using the UV system’s validated dose monitoring and control strategy and the utility’s flow and UV transmittance. The tool predicts how many reactors and lamps are required over time to deliver the required UV dose. The results can be used to assess UV system sizing, redundancy, power consumption, dose monitoring efficiency, off-spec performance, and public health protection. By simulating UV system operation, UVCAT lets the user evaluate and optimize UV system alternates before they are selected and installed at the utility.
The National Institute of Standards and Technology’s Spectral Comparator Facility is used to calibrate all UV sensor measurement standards for U.S. The Optical Division of NIST worked with Carollo to develop UV sensor guidelines. Carollo completed the WaterRF Project, Design and Performance Guidelines for UV Sensor Systems. This $580,000 project quantified the capabilities and limitations of commercial UV sensors, evaluated the impacts of UV sensor properties on dose monitoring, and developed guidelines for UV sensors and dose monitoring with stakeholder buy-in. The project team included the Veterinärmedizinische University in Vienna, Austria; the National Institute of Standards and Technologies in Maryland; nine North American and nine European utilities; and eight UV system and UV sensor manufacturers.

Field and laboratory studies showed significant variability with UV sensor performance, especially with UV sensors used with MP UV systems. In particular, the data analysis showed that spectral and angular response criteria specified by current guidance can be a significant cause of variability. UV sensor accuracy can be significantly improved by controlling the angular orientation of sensors within the sensor port, field calibration of duty sensors using the average reading of three reference sensors, and calibrating MP reference sensors using polychromatic light.

Using dose delivery models based on CFD, the team analyzed how UV sensors are used for UV dose monitoring. New approaches were developed for analyzing UV validation data obtained using MS2 phage that predict UV dose distributions. The new approaches eliminate the need to apply a RED bias uncertainty factor to the sizing and operation of UV systems, thereby significantly reducing the capital and operating costs of UV disinfection.
UV disinfection has evolved considerably over the last 10 years in terms of regulations, commercial technologies, design and operation, and fundamental understanding. Thus, utilities, engineers, and regulators see UV disinfection as an emerging technology and have questions that include: How much lamp aging and fouling occurs? Are UV systems properly sized? How reliable are UV systems? How much do they cost in terms of capital and O&M? Is mercury release an issue? How do they comply with guidance and regulations? What are the lessons learned implementing UV disinfection?

To answer these questions, WaterRF and ten utilities across North America funded WaterRF Project 3117, Development of a UV Disinfection Knowledge Base. This $720,000 project collected and analyzed data on the design, validation, performance, costs, and lessons learned from installed UV systems across North America. Data was stored within a MS Access database and can be evaluated using software tools specifically designed to answer questions on the application of UV disinfection. The project team also conducted onsite evaluations of UV system performance at nine UV installations representing the four top UV vendors. At each site, Carollo evaluated the UV dose monitoring and control algorithm, and the performance of UV system components including lamps, ballasts, quartz sleeves, UV sensors, and UVT monitors using a custom optics bench and instrumentation. Results from those evaluations were used to develop standard methods for evaluating and troubleshooting UV system performance. Finally, Carollo conducted a pilot study to evaluate mercury release following breakage events with MP and LPHO lamps. The results were used to develop approaches utilities can take to minimize the risk and impact of lamp breakage events with UV system operation.
Evaluation of CFD as Cost-Effective Tool for Assessing UV System Performance

UV dose models based on CFD provide a fundamental understanding of UV dose delivery and monitoring that compliments empirical data obtained through validation. For example, Carollo uses CFD-based models to develop validation test plans and provide confidence that the UV system will provide the validated performance at the water treatment plant.

To provide confidence in CFD-based models, the WaterRF awarded this project to Sandia National Laboratories, teamed with Carollo to develop CFD as a tool for implementing UV disinfection at WTPs. Carollo and Sandia modeled three commercial UV systems and compared results to validation. The team also conducted sensitivity studies to identify how model parameters impact predicted results and developed new approaches for model calibration. Based on these studies, guidance was developed to assist regulators and utilities in using CFD modeling to demonstrate compliance with applicable regulatory metrics and the UVDGM.

Carollo developed advanced UV dose models that account reflection of UV light from the reactor walls.

Carollo’s CFD-based UV dose models provide highly accurate predictions of UV reactor performance.
Guidance Document for Testing Medium-Pressure UV Systems

The Groundwater Rule states that there are no adequate methods (surrogates or procedures) for assessing the capabilities of UV systems to achieve 4-log virus inactivation. In this work, the UV dose-response of adenovirus, rotavirus, other UV-resistant pathogens, and candidate validation test microbes were measured using a tunable UV laser and a MP collimated beam equipped with bandpass filters. The wavelength response data is being used as inputs to proven CFD-based UV dose models for commercial MP UV reactors developed by Carollo through previous WaterRF projects. The models will be used to quantify the impact of the wavelength response on UV dose monitoring and control, accounting for differences in spectral lamp output, sleeve UVT, and UV sensor spectral response seen with commercial UV systems and differences in water UV absorbance spectra observed during validation and at the utility. The results of the model will be used to develop UV dose monitoring and validation strategies for UV systems operating for adenovirus credit that account for these differences. The project deliverable will be a guidance document with input and consensus from UV academics, regulators, consultants, utilities, and UV vendors.

“Our team used a tunable UV laser provided by the National Institute of Standards and Technologies to measure the wavelength response of waterborne pathogens and validation test microbes.”
The Carollo Research Group (CRG), founded in 1997, provides research, process evaluation, and plant optimization services. Early in the design process, CRG often performs testing to develop design criteria for new treatment facilities. CRG also conducts evaluations as part of our applied research projects that are funded by associations such as the Water Research Foundation.

The adjacent map presents locations across the United States where Carollo has conducted bench, pilot and full-scale evaluations of UV disinfection for research, validation, design, and startup projects. A description of our UV-related capabilities is provided below.

**DESKTOP EVALUATIONS**

**UVXPT - CFD-Based UV System Performance Modeling Software**

Carollo has developed UVXPT, a software package for modeling UV system dose delivery. Computational Fluid Dynamics (CFD) provides a detailed description of microbe trajectories through UV reactors that takes into account short-circuiting and eddy zones. Dose delivery is calculated by integrating the UV intensity experienced by the microbes over time as they follow the predicted trajectories through the UV reactor. UV intensity fields are modeled either for monochromatic low-pressure or for polychromatic medium-pressure UV lamps. UV intensity sensor measurements are also modeled to allow simulation of a UV reactor’s dose monitoring system.
Carollo uses UVXPT in the design and implementation of UV systems for drinking water, wastewater, and reclaimed wastewater applications, including:

- Optimizing UV reactor inlet/outlet and baffle design for enhanced dose delivery and reduced headloss.
- Scaling validation data as a function of flow rate, water UV transmittance, and reactor size.
- Comparing hydraulic conditions obtained with an installation to those conditions used with validation.
- Evaluating UV reactor designs.

**UVCAT-UV SYSTEM PERFORMANCE AND COST ANALYSIS SOFTWARE**

Carollo developed the UV simulation tool, UVCAT, to provide comprehensive evaluations of UV system performance and costs with drinking water and wastewater applications. UVCAT was developed in 2004 for the Water Research Foundation-NYSERDA project entitled *Optimization of UV Disinfection* and has since been enhanced to provide simulations of emerging pathogen inactivation, advanced oxidation using UV light and hydrogen peroxide, and UV system cost-benefit modeling based on the USEPA's risk model.

<table>
<thead>
<tr>
<th>Client</th>
<th>UV Reactors</th>
<th>Application of CFD and UVXPT</th>
</tr>
</thead>
<tbody>
<tr>
<td>USEPA, DC</td>
<td>Hanovia Cross Flow Hanovia PMD WEDECO K143 6/12</td>
<td>Evaluate and develop recommendations for the RED bias, polychromatic bias, and inlet piping for the USEPA UV Disinfection Guidance Manual.</td>
</tr>
<tr>
<td>Greater Cincinnati Water Works, OH</td>
<td>All vendors</td>
<td>Developed inlet structures to optimize flow split and inlet velocity profiles upstream of the UV reactors.</td>
</tr>
<tr>
<td>New York City, NY</td>
<td>WEDECO K143</td>
<td>Evaluate UV intensity fields and UV sensor readings as part of the peer review for the CFD modeling of UV reactors for New York City.</td>
</tr>
<tr>
<td>Washington Suburban Sanitation Community, MD</td>
<td>Calgon 36&quot; Sentinel Trojan 24&quot; UVSwift</td>
<td>Evaluate impact of filter gallery inlet piping alternatives on UV reactor performance.</td>
</tr>
<tr>
<td>City of Tempe, TX</td>
<td>WEDECO K143 8/12</td>
<td>Compare validation and installation hydraulics and dose delivery for State approval.</td>
</tr>
<tr>
<td>East Bay MUD, CA</td>
<td>Aquionics (Berson)</td>
<td>Compare validation and installation hydraulics and dose delivery for State approval.</td>
</tr>
<tr>
<td>Water Research Foundation, CO</td>
<td>Trojan 24&quot; UVSwift WEDECO K 6/12 Hanovia PMD</td>
<td>Results used to assess dose delivery and monitoring as part of Water Research Foundation project <em>Design and Performance Guidelines for UV Sensor Systems</em>.</td>
</tr>
<tr>
<td>Water Research Foundation, CO</td>
<td>Trojan 30&quot; UVSwift Calgon 12&quot; Sentinel IDI 20&quot; In-line</td>
<td>UV dose delivery and sensor readings predictions compared to validation data for the Water Research Foundation project <em>Evaluation of Computational Fluid Dynamics as a Cost-Effective Tool for Assessing UV System Performance</em>.</td>
</tr>
</tbody>
</table>
UV Disinfection. UVCAT provides simulations of UV system operation as a function of time using the UV system’s validated dose monitoring and control algorithm. Typically, several years of daily or even hourly flow and UVT data is used as inputs to evaluate the impact of seasonal and year-to-year changes in water quality on UV system sizing, dose delivery, redundancy, and power consumption. UVCAT quantifies the inactivation of regulated and emerging pathogens, which can be used to justify UV system sizing and expandability. UV system O&M costs are determined by integrating power consumption and component replacement, accounting for lamp aging and sleeve fouling expected with the application. Power quality data measured at the water treatment plant can also be used to quantify and evaluate the impact of UV system off-spec performance on public health protection and identify the need for backup power.

Advanced Oxidation. Many utilities implementing UV disinfection are also exploring using UV light with hydrogen peroxide for the advanced oxidation of taste and odor (T&O) compounds and micropollutants such as pesticides and endocrine disruptors. While the sizing and operation of UV disinfection systems are well defined by dose monitoring algorithms developed through full-scale UV validation testing, the design and operation of advanced oxidation systems using UV light and hydrogen peroxide currently rely on proprietary algorithms defined by UV vendors. Electrical energy per order (EEO), defined in units of kWh per 1000 US gallons per log removal, has been proposed as a figure of merit that can be used to size UV peroxide systems. However, EEO values are site specific because they depend on the UVT and concentration of hydroxyl scavenger species in the water (e.g., TOC, alkalinity), and equipment specific because they depend on the dose distribution delivered by the reactor and the electrical-to-UV energy conversion efficiency of the lamp and ballast.

<table>
<thead>
<tr>
<th>Client</th>
<th>Application of UVCAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greater Cincinnati Water Works, OH</td>
<td>UVCAT was used to provide a cost-benefit analysis of UV sizing for 2-, 3-, and 4-log Cryptosporidium credit. UVCAT compared dose delivery, redundancy, emerging pathogen inactivation, O&amp;M costs of 6, 8, 10 and 12 train UV system alternatives from three UV vendors. UVCAT also evaluated seasonal and continuous application of UV/peroxide for the reduction of MIB, geosmin, atrazine, and ethynylestradiol.</td>
</tr>
<tr>
<td>Washington Suburban Sanitation Community, MD</td>
<td>UVCAT evaluated O&amp;M costs for Calgon and Trojan UV systems identifying the need for enhanced UV system turndown to provide optimum O&amp;M costs. UVCAT analysis also evaluated and ranked UV system alternatives during procurement.</td>
</tr>
<tr>
<td>Denver Water, CO</td>
<td>UVCAT evaluated combined filter effluent and filter gallery UV system alternatives from four UV vendors at three large-scale WTPs.</td>
</tr>
<tr>
<td>City of Tempe, AZ</td>
<td>UVCAT quantified public health and cost benefits of UV system re-validation using T1 phage.</td>
</tr>
</tbody>
</table>
To provide utilities a better cost justification for selecting advanced oxidation, Carollo modified UVCAT to simulate continuous and seasonal application of UV/peroxide. UVCAT uses a kinetic approach for simulating UV/peroxide that uses UV dose as opposed to EEO and accounts for the seasonal impacts of radical scavenger species such as alkalinity and TOC. Life-cycle costs are estimated by integrating UV system power consumption, UV component replacement, and peroxide and quenching agent consumption over time, and can be minimized by optimizing the UV and peroxide dosing for the utility’s water quality profile.

**BENCH- AND PILOT-SCALE TESTING**

Carollo supports UV process evaluations, predesign studies, and applied research activities using bench- and pilot-scale equipment that includes a UV collimated beam apparatus, optics bench, custom UV reactors, and specialized optical and electronic instrumentation. Carollo also works with UV system suppliers to provide pilot-scale evaluations of commercial UV systems for disinfection and advanced oxidation applications.

**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*, used to quantify UV sensor measurements properties for the Water Research Foundation Project *Design and Performance Guidelines for UV Sensor Systems*, and 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.

On-Site Validation

Although the Portland UV Validation Facility is designed and equipped to test UV reactors under a wide range of hydraulic configurations and UV transmittance ranges, there are circumstances that may require a reactor to be validated on-site at the utility, such as site-specific piping and special water quality characteristics. In those instances, Carollo has the necessary expertise and equipment to perform UV reactor validations on location. As an example, Carollo conducted the on-site validation of the 206-mgd Calgon Sentinel UV system installed at the City of Winnipeg, Manitoba’s Deacon Pump station.

UV System Commissioning and Troubleshooting

UV systems contain a vast array of complex components that may not always operate correctly or that may have difficulty in meeting the vendor’s claims. A few of the parameters that could be out of line with expectations include:

- Lamp output.
- Quartz sleeves transmittance.
- UV sensor accuracy and drift.
- Fouling rates.
- Cleaning mechanism effectiveness.
- Power consumption.
- Dose monitoring and control.
Carollo’s UV experts have many years of experience assessing UV system performance at locations across North America. This expertise comes not only from our current full-scale projects, but also from our numerous research projects, which cover such topics as:

- Field verification of UV reactor dose monitoring and control algorithms.
- Field verification of UV sensor and UVT monitor performance.
- Quantification of lamp aging and fouling.
- Optimization of UV system performance and O&M costs.
- UV system troubleshooting and operator training.
- Reporting and regulatory approval.
- Development of mercury response plans.

Carollo’s combined expertise in UV research, regulations, validation, design, and startup uniquely qualifies us for assisting utilities identify and resolve operations, maintenance, and design issues with their UV systems. The project descriptions in the Key Achievements section of this Statement of Qualifications provides further details on those services.
UV DISINFECTION PUBLICATIONS - PEER REVIEWED


UV DISINFECTION PUBLICATION/PRESENTATIONS - OTHER


16. Wright, H. “UV Disinfection and the UVDGM.” Presented at the UV Ballast Water Workshop, Hamburg, Germany, November 22, 2011.


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 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.** 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, non-proprietary, non-packaged pilot plant unit, which has been successfully tested in Kansas City, MO.
Engineering the fast-paced design/build expansion of the Palm Coast, FL, reverse osmosis (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 electrodialysis reversal (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.

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

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 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, some of which are highlighted in the table below.

<table>
<thead>
<tr>
<th>Client/Project</th>
<th>Project Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Representative Water Treatment Projects</strong></td>
<td>Capacity (million gallon/year)</td>
</tr>
<tr>
<td>Southern Nevada Water Authority, Las Vegas, Nevada - Southern Nevada Water System Improvements Project</td>
<td>624</td>
</tr>
<tr>
<td>City of Phoenix, Arizona - Val Vista Water Treatment Plant</td>
<td>220</td>
</tr>
<tr>
<td>City of Phoenix, Arizona - Union Hills Water Treatment Plant</td>
<td>160</td>
</tr>
<tr>
<td>City of Sacramento, California - E.A. Fairbairn Water Treatment Plant</td>
<td>160</td>
</tr>
<tr>
<td>City of Sacramento, California - Sacramento River Water Treatment Plant</td>
<td>160</td>
</tr>
<tr>
<td>Metropolitan Water District of Salt Lake City and Sandy, Utah - Point of the Mountain Water Treatment Plant</td>
<td>150</td>
</tr>
<tr>
<td>City of Oklahoma City, Oklahoma - Draper Water Treatment Plant</td>
<td>150</td>
</tr>
<tr>
<td>East Bay Municipal Utility District, California - Walnut Creek Water Treatment Plant</td>
<td>120</td>
</tr>
<tr>
<td>Santa Clara Valley Water District, California - Santa Teresa Water Treatment Plant</td>
<td>100</td>
</tr>
<tr>
<td>Santa Clara Valley Water District, California - Rinconada Water Treatment Plant</td>
<td>75</td>
</tr>
<tr>
<td>City of Arlington, Texas - Pierce-Burch Water Treatment Plant</td>
<td>68</td>
</tr>
<tr>
<td>City of Arlington, Texas - John F. Kubala Water Treatment Plant</td>
<td>65</td>
</tr>
<tr>
<td>Santa Clara Valley Water District, California - Penitencia Water Treatment Plant</td>
<td>42</td>
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<tr>
<td>City of Vallejo, California - Fleming Hill Water Treatment Plant</td>
<td>42</td>
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<tr>
<td>Town of Gilbert, Arizona - Gilbert Water Treatment Plant</td>
<td>30</td>
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<tr>
<td>City of Peoria, Arizona - Greenway Water Treatment Plant</td>
<td>16</td>
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<tr>
<td>Upper Trinity Regional Water District, Texas - Tom Harpool Water Treatment Plant</td>
<td>16</td>
</tr>
<tr>
<td>Brazos River Authority, Texas - Brazos River Authority Water Treatment Plant</td>
<td>15</td>
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<tr>
<td>City of Lake Forest, Illinois - Lake Forest Water Treatment Plant</td>
<td>14</td>
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<tr>
<td>City of Neenah, Wisconsin - Neenah Water Treatment Plant</td>
<td>12</td>
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<tr>
<td>United Water Missouri - United Water Missouri Treatment Plant</td>
<td>8</td>
</tr>
<tr>
<td>City of South Bend, Washington - South Bend Water Treatment Plant</td>
<td>2</td>
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</table>