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Super-Critical Water Oxidation Special Study: Final Report

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& RISK REDUCTION

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Disclaimer

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorizing documents.

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The report evaluates the current state and proposed courses of action for the future disposition of the Super-Critical Water Oxidation (SCWO) systems located at the Blue Grass Chemical Agent Pilot Plant (BGCAPP). It provides factual data and potential courses of action to enable senior leadership at the Program Executive Office, Assembled Chemical Weapons Alternatives (PEO-ACWA), the Department of Defense, and other executive departments and agencies to determine the disposition of the SCWO systems. The best potential future application for the BGCAPP SCWO systems is the treatment of per- and polyfluoroalkyl substances (PFAS)/perfluorooctane sulfonate (PFOS) products and waste streams. Polyfluorinated compounds were identified as an emerging health and environmental threat when this study began, and the scope and magnitude of that threat have elevated to national crisis levels, gaining legislative and regulatory actions as a response. The breadth of design features with the BGCAPP SCWO that could be used for the treatment of PFAS/PFOS waste materials are unparalleled in commercial SCWO applications.

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PREFACE

The work described in this report was authorized under project no. PEO-ACWA WBS R.0048905.15.2.1. The work was started in April 2021 and completed in May 2023.

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EXECUTIVE SUMMARY

The U.S. Army Combat Capabilities Development Command Chemical Biological Center (DEVCOM CBC; Aberdeen Proving Ground, MD) recommends that the Program Executive Office, Assembled Chemical Weapons Alternatives (PEO-ACWA; Aberdeen Proving Ground, MD) begin the process outlined in Course of Action 9 (page 49 of this report) to disposition the Super-Critical Water Oxidation (SCWO) systems at the Blue Grass Chemical Agent Pilot Plant (BGCAPP). This course of action will remove the systems from the plant Resource Conservation and Recovery Act (RCRA) operating permit (as a partial closure action), identify the systems within the Plant Clearance Automated Reutilization Screening System (PCARSS), and enable the maximum flexibility to both the ACWA mission and potential future use of the SCWO systems, given current conditions.

The intent of the SCWO study and analysis and this report is to provide factual data and potential courses of action so that senior leadership at PEO-ACWA, the Department of Defense (DoD), and other executive departments and agencies have decision space within which disposition of the SCWO systems may have value for the investment made in their development and systemization. Ideally, a partnership within the Executive Branch would have enabled the full range of design features within the systems to be repurposed toward a mission requiring them.

Although contact, conversations, and site visits occurred with interested technical personnel at the U.S. Army Corps of Engineers (USACE), Department of the Army, DoD, the U.S. Environmental Protection Agency (EPA), and Heritage Environmental Services, as of May 2023, there is no commitment on the part of any government organization to take ownership or liability for the SCWO systems at BGCAPP. Discussion continues with government organizations regarding disposition of the SCWO systems in situ for use as a demonstration platform for PFAS treatment as described below and in the body of this report.

During the two-year period of this study, DEVCOM CBC contacted those private sector commercial groups that had previously been or were currently working in the SCWO area (General Atomics, Aquarden, Veolia North America, Heritage Environmental Solutions, Tetra Tech, AECOM, and Amentum). Companies like Fusion Tech, who were researching SCWO for possible application in geothermal technologies, were also contacted. The only group that showed sufficient interest to engage in a technical dialogue was Heritage Environmental Services (Indianapolis IN). Heritage Environmental Services continues to be engaged in conversation with potential DoD and EPA partners toward a possible disposition of the SCWO systems for future use.

From a technical standpoint, the best potential future application for the BGCAPP SCWO systems is the treatment of per- and polyfluoroalkyl substances/perfluorooctane sulfonate (PFAS/PFOS) products and waste streams. Polyfluorinated compounds were identified as an emerging health and environmental threat when this study began, and the scope and magnitude of that threat have elevated to national crisis levels gaining legislative and regulatory actions as a response. The breadth of design features with the BGCAPP SCWO that could be used for the treatment of PFAS/PFOS waste materials are unparalleled in commercial SCWO applications.

It is also abundantly clear that SCWO, as an operational capability, is at an economic disadvantage to other technologies for the treatment and disposition of most waste streams. Incineration, solidification/sequestration, and other legal, environmentally allowable capabilities are used to treat waste at a fraction of the estimated cost of operating SCWO systems. This situation is the most likely cause of reluctance on the part of government entities and commercial interests to engage meaningfully in a process to repurpose the systems.

The legal and regulatory response to the PFAS crisis has, in part, reduced this disadvantage by temporarily placing a moratorium on the incineration of PFAS/PFOS products and waste streams. The exact nature and extent of these actions remains under investigation, but draft contracting actions within the USACE reflect this moratorium.

Each course of action outlined in this report requires the initial steps being recommended for disposition of the SCWO systems. Defense Logistics Agency (DLA) processes[a] afford preference to governmental entities over commercial interests in the disposition of identified excess equipment. Beginning this process would serve as notification of disposition and opportunity for interested parties (government agencies, i.e., EPA; or industry, i.e., Heritage Environmental Services) to take action to secure the SCWO capabilities for future use.

[a] Deputy Assistant Secretary of Defense for Threat Reduction and Arms Control. *Assessment of Potential Transfer of Real Property, Equipment, and Facilities in the Assembled Chemical Weapons Alternatives Program.* Department of Defense, February 2021.

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SUPER-CRITICAL WATER OXIDATION SPECIAL STUDY: FINAL REPORT

1. INTRODUCTION

This study has been developed as an objective assessment of the SCWO system located at BGCAPP. All information was compiled from existing documentation, engineering, and technical reports on the system. This information was utilized to capture physical boundaries, interface points, operational requirements, and testing of the SCWO system within the overall infrastructure of the BGCAPP facility. In addition, this study assessed future use options for the system to leverage the investment the Army and PEO ACWA have made in this technology. A preliminary industry assessment was completed identifying industrial scale use of SCWO technology as a basis for potential future use of the system. General operation scenarios are identified consistent with industry practice, and testing requirements have been established for both bench scale and full-scale applications. The study, and its references, is intended to be a standalone document for all Phases outlined in the following sections.

As discussed in this study and the above paragraph, SCWO is a promising technology for destroying complex organic compounds and wastes that rapidly dissolve and mix with oxidants in a homogeneous reaction environment, eventually completely decomposing into harmless small molecules such as CO_2 and H_2O. It has high destruction and removal efficiencies (DRE>99%) in under 30 seconds at 600°C when destroying hazardous wet wastes.[85, 114, 115] Finally, there is sufficient evidence that the high temperature SCWO environment rapidly destroys fluorocarbons, however, in-depth studies are still required to optimize the SCWO reactor process.

2. SCOPE: PHASE I:

2.1. Objectives

The objectives of Phase 1 of the SCWO special study included:

- Review all ACWA/BGCAPP SCWO documents provided, tour facility, interview ACWA personnel to gain a working definition of what the SCWO system includes.

- Establish a baseline to define the current steady-state configuration and condition of the BGCAPP SCWO.

- Draft position on available decision space. What credible operation scenarios exist for SCWO path ahead?

- Begin collecting cost data for investment baseline.

- Begin collecting technical data from industry to analyze operational constraints and potential SCWO feed streams.

2.2. Key Milestones and Activities

Notable milestones and activities completed for Phase 1 were:

- **Facility Tour**
- **Data Gathering**
  - >200 Technical Documents Collected
  - >150 SCWO/SCWO Process Building (SPB) Pictures Collected
  - 8 years of ACWA SCWO Test and Development Prior to BGCAPP Award Cost Information Collected
  - 12 yrs. BGCAPP Cost Information Collected
- **Data Review (Sections 5, 6, and 7)**
  - Preliminary System Boundaries Identified
  - Preliminary Project Costs Reviewed
  - Utility Connections Beyond SPB Assessed
  - Control System Boundaries Identified
- **Market Research (Section 13)**
  - Existing SCWO Opportunities Identified
  - Potential Future Sources Researched
  - Identify Commercial Status of SCWO (Section 12)
- **Future SCWO Operations (Section 11)**
  - Four Operation Scenarios Identified
  - Government Advantages/Disadvantages Identified

3. SCOPE: PHASE II

3.1. Assessment for SCWO Future Use

Using the technical and cost information gathered for the BGCAPP SCWO system and the industrial uses of SCWO, the next step was to apply this information to seek external programs, waste streams or future users that may benefit from the investment made to date for the SCWO system. This information was used to develop a list of courses of action for SCWO future use. Further technical and cost analysis on these options provided a basis for comparison that may be used to make recommendations for next steps for the SCWO system. The following section addresses the objectives for Phase II.

3.2. Objectives

The objectives for Phase II of the SCWO Special Study included:

- Review cost data, identify historical narrative, identify gaps, finalize cost and investment position.
- Review technical data and industry experience. Contact industry facilities and/or operators as available/necessary to place potential feed streams into credible operation scenarios.
- Identify potential partners for future SCWO operations.
- Prepare "story board" of COA, options, decisions, and timeline for potential implementation.
- Draft cost and schedule estimates for available COA.
- (CBARR) Present credible COA's, options and decision space to ACWA in December of 2021.
- Review end state of BGCAPP compared with future use scenarios to make recommendations for maintaining operational fidelity of SCWO.

3.3. Key Milestones and Activities

Notable milestones and activities completed for Phase II were:

- **Review Cost Data**
    - Historical Narrative (Figure 2)
    - Identify Gaps

- Final Cost
- Investment Position (Table 4)

- **Technical Data Review and Industry Experience**
  - Contact Industry/Operators
  - Available Feed Streams
  - Credible Operational Scenarios (Section 11)
- **Potential SCWO Partners (Sections 13 and 15)**
- **Courses of Action (Section 15)**
  - Prepare Storyboards
  - Options/Decisions
  - Timeline
- **Cost and Schedule for COA (Sections 15 and 16)**
- **Present Credible COA**
  - Options
  - Decision Space
- **End State Review**

4. SCOPE: PHASE III/PHASE IV

4.1. COA Down Selection/Execution Support

Utilizing the list of courses of action for SCWO future use and the information gathered for the BGCAPP SCWO system, an assessment was made for the down selected COA's. Additional detailed assessments need to be performed on the final COA's to ensure operational compatibility with the SCWO process. The COA selection will be coordinated with potential partners.

Utilizing an ongoing review of COA viability, COA's naturally separated into likely and unlikely categories. This was utilized as the primary down selection process. Based on this COA down selection, the Draft SCWO Special Study, including the PFAS Demonstration Test Plan, was assembled and reviewed for technical accuracy.

4.2. Key Milestones and Activities

Notable milestones and activities completed for Phase III/IV were:

- **Outreach (Section 13)**
    - Industry/Government Partners
- **Detailed Assessment**
    - Corrosion Potential
    - Compatibility of Materials
    - BGCAPP SCWO Applicability
    - Variability of Feed
    - Operational Changes
- **Lab-Scale Testing – (Performed by Industry)**
- **Coordination**
    - Partners
- **Draft SCWO Special Study**

5. DATA REVIEWED

The initial effort to establish the design configuration of the SPB included a review of a variety of engineering documents to understand the configuration of the equipment, how the systems function together and separate, the various configurations of each system, and the utilities associated with them. There were several types of technical data available for each system. The latest published version of each was obtained and reviewed for applicability to this utility evaluation. The engineering documents that were utilized included:

- **System Design Descriptions.** These design descriptions provided for each system: scope and function; design requirements (electrical and I&C); process and utility interfaces; system description and major components; system parameters and performance characteristics. [1-9]

- **General Arrangement Drawings.** These arrangement drawings provided the location of specific pieces of mechanical equipment and their relative proximity to one another. Dimensions of various buildings were provided such that calculations (building square footage) could be performed.[10-14]

- **Process Flow Diagrams.** These flow diagrams provided an understanding of the sequence by which the process flows from one piece of equipment to the next. Equipment tag numbers and technical information about the equipment were also provided within the diagrams. Mass and Energy Balances (M&EBs) provided the process requirements for the process/utility in question.[15-21]

- **Piping and Instrumentation Diagrams (P&IDs) (Utility Distribution).** These diagrams were used to trace utility lines to and from the SPB. Tags at the end of lines provided information on where the utility came from or was going. In addition, they identified areas where the piping was entering or leaving the building.[22-31]

- **Turnover Packages.** The information contained in these documents included the entire set of P&IDs for the system. These P&IDs were assumed to be the latest engineering based on the turnover requirements.[30-31]

- **Foundation Location Plans.** These engineering drawings were necessary as external areas to the SPB required location and identification. The foundations for various pieces of equipment were typically marked on the drawings. In addition, these plans were utilized for the configuration of the equipment external to the SPB.[32-35]

- **Plant System Descriptions.** These documents provided technical data and pictures associated with the equipment and their utilities being discussed. In addition, process flow diagrams were available for each area of the SPB and utility system.[36-37]

- **Tests, Reports, and Standard Operating Procedures (SOP).** Configuration of the SCWO was identified in these documents and provided an understanding of some utilities and their engineering function. Changes that were made during testing were documented and allowed for insight into the SCWO configuration and changes made prior to operation.[38-43]

6. CURRENT DESIGN CONFIGURATION

In addition to the review of engineering documents, the current design configuration of the SPB, its surrounding equipment, and the utilities required for SCWO operations were reviewed for Phase 1. This effort documented the various types of engineering reviewed and provided a graphic depicting the boundary of the SPB and the equipment contained both within and outside of it. Utility boundaries which included the Utility Building (UB), Bulk Chemical Storage (BCS), and Yard were also addressed.

In addition, all utilities entering the SPB were documented along with their engineering characteristics. Equipment in the yard, which provided utilities to both the Main Plant (MP) and the SPB, were analyzed, and their application was established. The SPB was evaluated as if the MP was being demolished and the utilities shared were still required by the equipment located in the SPB.

6.1. SCWO Processing Building Configuration

An analysis was completed to identify the perimeter of the SPB as it exists today. Utilizing several General Arrangement Drawings [10-13], Utility Distribution Drawings[22-28], System Design Descriptions[5-8], P&IDs[29-31], and Foundation Location Plans[32-35] the current perimeter was established. Once the perimeter was understood, utility lines identified on P&IDs were traced from their origin to the SPB. In addition, several additional pieces of equipment were identified as part of the SCWO perimeter. Figure 1 identifies the various types of utilities that enter the SPB, and which system utilizes them. The systems contained inside the SPB include the:

- Aluminum Precipitation System (APS)
- Aluminum Filtration System (AFS)
- Super Critical Water Oxidation
- Reverse Osmosis (RO)[5-8]
- The systems and equipment located outside of the SPB include:
- SPB Storage Tank Area (8 tanks total)
- SPB Power
- Four High Pressure Process Air Compressors (includes three receivers)
- Two Carbon Filters
- Six Air Handling Units[32-35]

- Isopropyl Alcohol (IPA) and Acid Tanks (BCS)
- Truck Loading and Unloading Station (BCS)

In addition to the systems and equipment described above, the three identical SCWO trains (each consisting of a Feed Skid and a Reactor Skid) share the following common equipment:

- Acid Day Tanks and Pumps
- Blended Hydrolysate Feed Supply System
- Emergency Relief Tank and Transfer Pump
- Feed Additive Pumps, Tanks, and Conveyors
- Flush Water Heater
- Gas Effluent Duct Heater
- Off-Spec Effluent Tank and Transfer Pump
- High Pressure Air Compressor System[36]
- Facility Control System (FCS)/Facility Protection System (FPS) Control Systems

The utilities, as seen in Figure 1, come from three distinct areas: UB[14], BCS[37], and Yard. There are approximately 17 different utilities utilized in the SPB. The next section provides information, as available, about the various utilities used in the SPB.

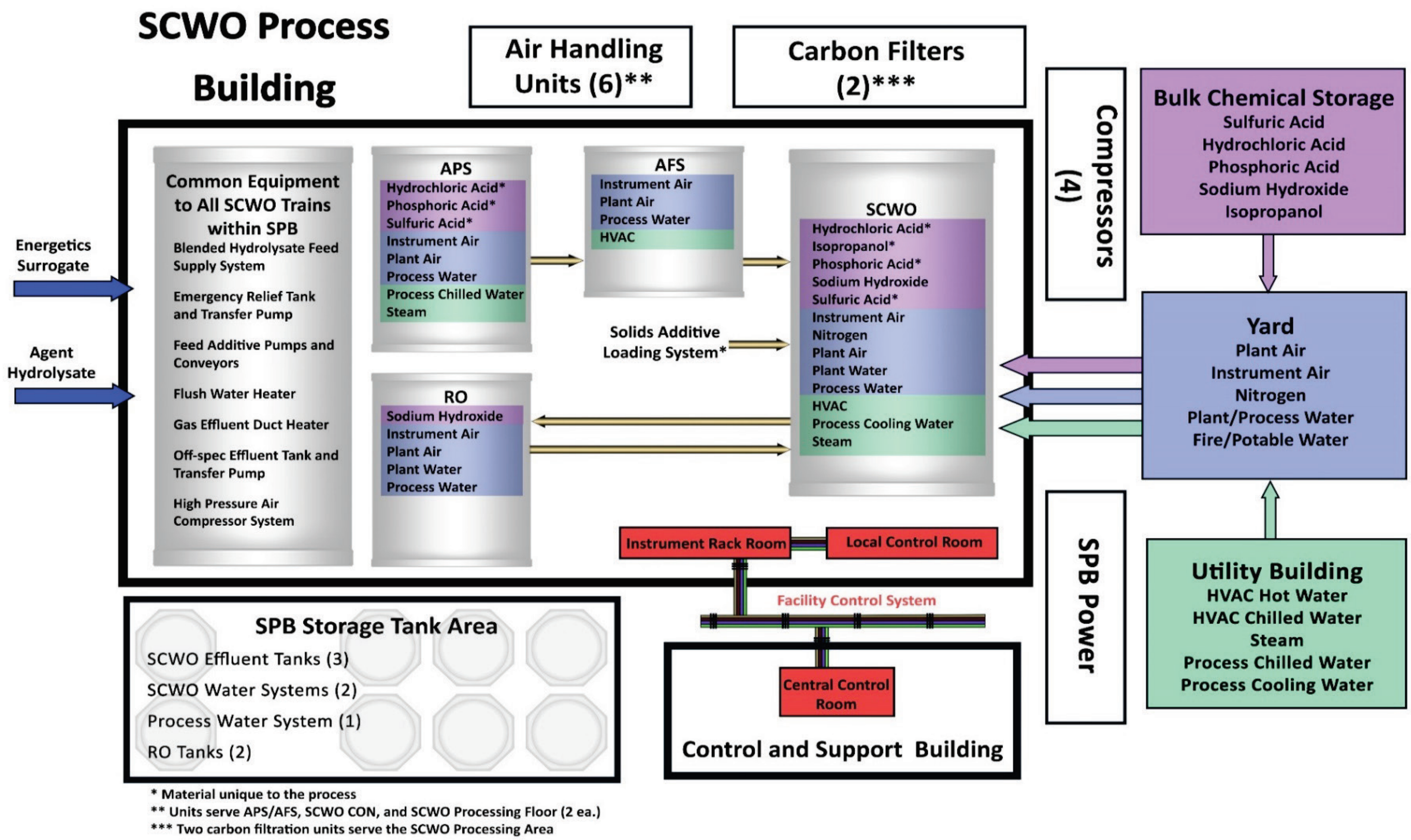

Figure 1. SCWO Design Configuration

6.2. Utilities

The following paragraphs provide a review of all utilities utilized in the SPB. This analysis includes utilities located in the UB, BCS, and Yard. The sizes of the facilities are provided to understand the amount of space which may need to be required if the SCWO trains were to be moved to a separate facility not located at BGCAPP.

6.2.1. Utility Building Size

The UB and surrounding area house most of the utilities used in the SPB. The Utility Building is approximately 23,300 ft^2 (163' X 143') undercover[14] and has a total area of approximately 81,800 ft^2 (286' X 286')[12]. The area which is not undercover is approximately 58,500 ft^2.

6.2.2. Utility Building Utilities

The UB provides five separate utilities (refer to Figure 1) to the SPB. These utilities include:

- HVAC Hot Water
- HVAC Chilled Water
- Steam
- Process Chilled Water
- Process Cooling Water[36-37]

Table 1 provides termination points for all UB utilities such that the SCWO can be operational while the remainder of the Facility is being demolished. Termination points for each utility are described in the Termination Points Section of this document.

The power requirements for the UB (UPC-13) are as follows[9]:

- Two dry-type power transformers (A/B), 12.47-KV:480/277-V, delta-wye, 2.5/3.32 MVA, AA/FA, 80ºC rise (for UB)
- Switchgear (A/B): 480-V, 4,000-A, 65-kAIC (for UB)
- Two dry-type power transformers (A/B), 12.47-kV:4.16-kV, delta-wye, 5.0/6.65 MVA, AA/FA, 80ºC rise (outside of UB)
- Switchgear (A/B): 4.16-kV, 1,200 A, 22-kAIC (outside of UB)

The power distribution system is designed to provide a highly reliable source of power. Each process facility switchgear lineup provides a redundant power system with two main circuit breakers and one normally open tie breaker. This arrangement operates in such a way that if one of the two incoming lines is compromised or lost, the associated main breaker opens and the tie breaker closes. This transfer scheme connects loads on both sides of the tiebreaker to the other available incoming line.[9] This redundancy is maintained for the switchgear identified above.

Fuel oil and natural gas will also be required and will be stored near the UB. Natural gas is the primary and fuel oil is secondary fuel to operate the boilers.[37]

6.2.3. Yard Utilities

The yard provides seven known utilities (refer to Figure 1) to the SPB. The following utilities are provided:

- Plant Air
- Instrument Air
- Nitrogen
- Plant/Process Water
- Fire/Potable Water [36 37]

Like the utilities from the UB described above, each of these can be terminated to ensure SCWO operations without disruption (refer to Table 1).

6.2.4. Bulk Chemical Storage

The BCS delivers five chemical feeds (refer to Figure 1) to the SPB. These include:

- Sulfuric Acid
- Hydrochloric Acid
- Phosphoric Acid
- Sodium Hydroxide
- Isopropanol[36-37]

The Bulk Chemical Storage utilities require termination as well. Like the UB and Yard, these points are identified in Table 1.

6.2.5. SCWO Process Building Size

The square footage calculations below identify the various areas of the SPB.[11, 32-35] It should be noted that the exterior square footage has been measured from the "Area Limits" identified on the Foundation Location Plans.

- 5,535 ft^2 (Exterior Air Handling Units (AHUs))
- 10,744 ft^2 (Exterior Tanks)
- 15,314 ft^2 (Exterior Compressors and Carbon Filters)
- 14,034 ft^2 (Exterior Power)
- 26,569 ft^2 (Interior SPB)

Based on the calculations performed above, the total approximate square footage equals 72,200 ft^2 (both interior and exterior). Technical requirements for the SCWO will be identified once the utility configuration and usages are established.

6.2.6. SCWO Process Building Utilities

The power requirements for the SPB (UPC-10) are as follows[9, 44]:

- Two dry-type power transformers (A/B) 12.47-KV:480/277-V, delta-wye, 2.5/3.333 MVA, AA/FA, 80ºC rise
- Switchgear (A/B): 480-V, 4,000-A, 65-kAIC

Refer to power distribution narrative provided under UB section.

6.2.7. Termination Points

Table 1 identifies the termination points for the utilities that come from the UB, Yard and BCS.

Table 1. Utility Termination Points

Abbrev.	Utility	Termination
CHPR	Process Chilled Water Return	Rack
CHPS	Process Chilled Water Supply	Rack
CHR	HVAC Chilled Water Return	Rack
CHS	HVAC Chilled Water Supply	Rack
CWPR	Process Cooling Water Return	Rack
CWPS	Process Cooling Water Supply	Rack
FOS	Fuel Oil Storage	V199 in Yard
FWS	Fire Water System	Various Valves, V5001, V5090A, V8237, V5013
		Various Valves, V5024, V5025, V5032, V5037, V5073, PIV0005, PIV0006, V5077, PIV0007, V5076, V5033, PIV0016, PIV0017
		Various Valves, V5049, V5054, V5153, V5155
HCL	Hydrochloric Acid	N/A
HWR	HVAC Hot Water Return	N/A
HWS	HVAC Hot Water Supply	N/A
IA	Instrument Air	Rack
IPA	Isopropanol	N/A
NAHM	18% Caustic	Rack
NITG	Nirogen	Rack
NITM	Nitrogen	V577
PHOS	Phosphoric Acid	N/A
PLA	Plant Air	Yard Pipe Spool 3740 going to the CLA
PLW	Plant Water	N/A
POTT	Tempered Potable Water	N/A
PWS	Process Water	Rack, V159
SAS	Sulfuric Acid	Rack, V164
STM	Steam	Rack
STMC	Steam Condensate	Rack

The following definitions apply to the information contained in the "Termination Column" of the above table.

- Rack. The rack is identified as the pipe rack which runs from the UB to both the SPB and MP. Terminations in the rack would need to occur on the MP side of the identified utility (no valving available).

- Rack/Valve. Within the rack there is a valve for termination purposes of the utility prior to going to the SPB, UB and Waste Transfer Station.

- Various Valves. Identifies valve terminations required to ensure the utility is only provided to the SPB.

- Yard. There are terminations that occur outside of the rack, but also ensures the utility is only provided to the SPB.

- N/A. No termination is required of the utility prior to reaching the SPB.

7. DESIGN CAPABILITIES/FEATURES

As previously mentioned, there are four major systems located in the SPB to assist in the oxidation of all organic material contained in both Agent Hydrolysate (AH) and Energetics Hydrolysate (EH). These systems include the APS, AFS, SCWO, and the Water Recovery System (Reverse Osmosis) (WRS). A brief description of each is provided below:

- **APS.** The APS includes components and equipment designed to remove aluminum from EH via precipitation after acid addition. The process utilizes two aluminum precipitation reactors (APRs) measuring approximately 5' X 9' with a working capacity of 924 gal. Agitators are utilized to ensure proper mixing of the acids. The APS supports all three SCWO trains and can process 45,970 lbs./day of EH for the GB campaign and 57,600 lbs./day of EH for the VX campaign.[6]

- **AFS.** The AFS filters and removes precipitated aluminum salts from the neutralized EH received from the APS before the hydrolysate is transferred to the SCWO. The system includes two independent trains, each consisting of a feed tank, filter pump, and automatic pressure filter. It, like the APS, supports all three trains and processes enough neutralized EH to support the total SCWO blend feed rate of 3,000 lbs./hr.[5]

- **SCWO.** The SCWO system is used to oxidize all organic materials contained in agent and energetics hydrolysate as provided by upstream systems. Oxidation occurs at high temperature and pressure with supercritical water as a medium. Each SCWO train is designed to reach a nominal processing rate of 1,000 lbs./hr. of blended hydrolysate with AH provided by the ANS and EH by the AFS.[8] (21.4 lbs/hr of agent during the GB campaign and 47.4 lbs/hr of agent during the VX campaign)[112, 113]

- **WRS.** The WRS collects SCWO effluent and cooling water and steam-system blowdown, and produces RO permeate that recovers 70% of this water with a TDS maximum concentration of 500 mg/L. MPT Condensate that is not used by the SCWO System may also go to the SCWO effluent tanks. The RO permeate is used as quench water in the SCWO System.[7]

8. PERFORMANCE ISSUES AND RESOLUTION

The four SCWO status reports[64-67] from 2014 discussed below accurately captured the system status at the time with respect to data gaps/unresolved action items from previous testing and identified a path forward to resolution in the form of the 66 recommendations made. Of these, half were considered critical to resolve prior to the start of BGCAPP plant operations and half were considered non-critical (i.e., intended to optimize SCWO performance and/or improve efficiency, but not essential to operation). Over the period of pre-Systemization through Systemization and Shakedown testing, all the recommendations were addressed and closed except for those that could only be resolved during plant operation with real agent hydrolysate.

During Systemization and Shakedown testing, several additional issues related to system performance and safety were raised. After detailed review and evaluation by engineering staff, these issues have since been addressed, as outlined in Table 2.

Table 2. Issues Raised with SCWO during Systemization/Shakedown

Issue	Status	Resolution
SCWO Train 1 Quench Pump Failure	Pump repaired and future preventative maintenance program determined.	The quench pump on SCWO train 1 failed on 8 April 2020 after Shakedown testing. Analysis by the manufacturer concluded that one of the pump fluid cylinder tie studs was not properly torqued, causing fatigue failure of the stud and the pumping chamber to separate from the crank case with the resulting imbalance of forces.[75, 76] The manufacturer's analysis found no inherent defects or other factors that contributed to the failure. To address the problem, the manufacturer recommended 1) replacing the pump tie studs with new rolled thread studs having an improved fatigue resistance, and 2) including a periodic check on stud torque as part of the routine maintenance plan, proposed as the time corresponding to each reactor liner change (i.e., every 300 hours). The GFO report concurred with the results of the analysis and these recommendations.[77] The damaged pump was repaired and returned to BGCAPP with the new tie studs and new tie studs were installed in the other SCWO train quench pumps. With periodic checks on proper tie stud torque during future operation, the GFO report concluded that there is no further unaddressed risk with the quench pump that should prevent resumption of SCWO operation.[77]

Table 3. Issues Raised with SCWO during Systemization/Shakedown

Rupture Disc Ruptures	Unusual causes understood and actions taken to avoid future ruptures.	During SCWO Systemization and Shakedown testing, a total of eight (8) rupture discs ruptured during operation of the SCWO system.[78] Five of the eight rupture discs were associated with the high-pressure feed pumps. As documented in the Shakedown test report[73], the system was originally designed with pressure relief valves instead of rupture discs to protect the pumps, but the relief valves were replaced with rupture discs at BGCAPP. The impact of this change on the design was not recognized at the time. Some of the discs ruptured during normal SCWO system shutdowns because isolation valves downstream of the pumps shut before sufficient time had passed for the pumps to wind down and the line to depressurize. Unlike rupture discs, relief valves would have opened and reseated in these instances. To correct the problem, a two second delay on the isolation valve closures was added to the SCWO control software program, providing enough time for the line to adequately depressurize while still stopping the pumps immediately to maintain safety. The software change was proposed and implemented after considerable review and is intended to be permanent in order to accommodate the presence of the pump rupture discs in the design. After the time delay was instituted on 18 March 2020, no further pump disc ruptures occurred. Of the remaining rupture discs that ruptured, only one was associated with the reactor itself. This disc and another one downstream at the gas/liquid separator vessel ruptured in tandem due to operator error in handling a problem with the effluent heat exchanger cooling water temperature (note that operators were still being trained during the course of Shakedown testing). The remaining disc rupture was associated with the startup preheater. Its cause is unclear. The inclusion of the control program valve time delay and a fully trained operator staff should avoid further rupture disc ruptures. This projection is consistent with SCWO train 1 performance during the first of a kind (FOAK) testing, where there was one disc rupture during pre-operational FOAK equipment systemization and no disc ruptures over the subsequent six months of testing.

Table 4. Issues Raised with SCWO during Systemization/Shakedown

Number of System Shutdown Occurrences	Initially high number of shutdowns at start of Systemization decreases significantly to a more historically normal level as commissioning progresses and operators gain experience.	Measured from the very beginning of SCWO Systemization and the first attempt at ignition in December 2019 up through the first half of the Shakedown test in mid-February 2020, there were 103 planned and unplanned shutdowns.[79] The majority of the shutdowns occurred in the early part of Systemization as the operating crew was getting their first hands-on experience in operating the SCWO trains, which had either never been operated (train 3) or not operated in seven years since FOAK testing (train 1). As the staff began to learn proper operation and oversight techniques, the number of shutdowns decreased significantly. Of the 103 shutdowns, only 30 occurred during the first half of Shakedown testing[79]. Only 14 shutdowns occurred during the second half of Shakedown testing from mid-March 2020 through the end of March 2020.[80] As observed in earlier ACWA SCWO testing, the number of shutdowns would be expected to decrease further once system commissioning and operator training is completed.
Effectiveness of Lexan® Barriers	Lexan® panel thickness is sufficient to contain quench pump failure and designed to handle more serious failures.	Lexan® is the tradename given by General Electric to the polycarbonate thermoplastic resin that it manufactures in the form of sheets for safety enclosures. Lexan® panels are the industry standard for those in the worldwide SCWO community for research and industrial applications. The ¾ in. Lexan® thickness (in the form of two 3/8 in. thick panels with a gap in between) and relief panels used on both the BGCAPP SCWO Feed and Reactor skids were determined through calculations to specifically withstand the impact of both small fitting/debris projectiles[81] and the reactor contents in the event of a catastrophic release of system contents at pressure and temperature due to leak or rupture.[82] The scenarios captured in these calculations represent the most extreme or conservative (i.e., worst) cases that can be envisioned. As an example, the quench pump that failed on 8 April 2020 (and described above) contains much less fluid volume at a lower temperature than the reactor. Furthermore, the quench pump contains incompressible fluid (i.e., liquid water) with low potential energy. The quench pump failure was completely contained by the Feed skid Lexan® panels, causing only relatively minor scratches[77].

9. TIMELINE

ACWA identified SCWO as a suitable waste destruction process early in the program and supported development of the process specific to secondary waste for BGCAPP. SCWO was intended to be a means to address energetics and resultant chemical neutralization wastes that would be difficult to dispose of using existing conventional waste treatment. Throughout the development, there were decision gates at which SCWO continued to show acceptable performance for the BGCAPP processes. As the BGCAPP destruction processes were refined, the cost-benefit of SCWO changed and ACWA made a determination that it would not need to use SCWO to achieve their chemical agent destruction mission. The timeline described shows the path of development supporting the basis for the costs that are presented in the Cost section of this study.

The following is a brief description of SCWO development and testing in the ACWA program. Consult the indicated references for more details on any specific activity, event, or test program.

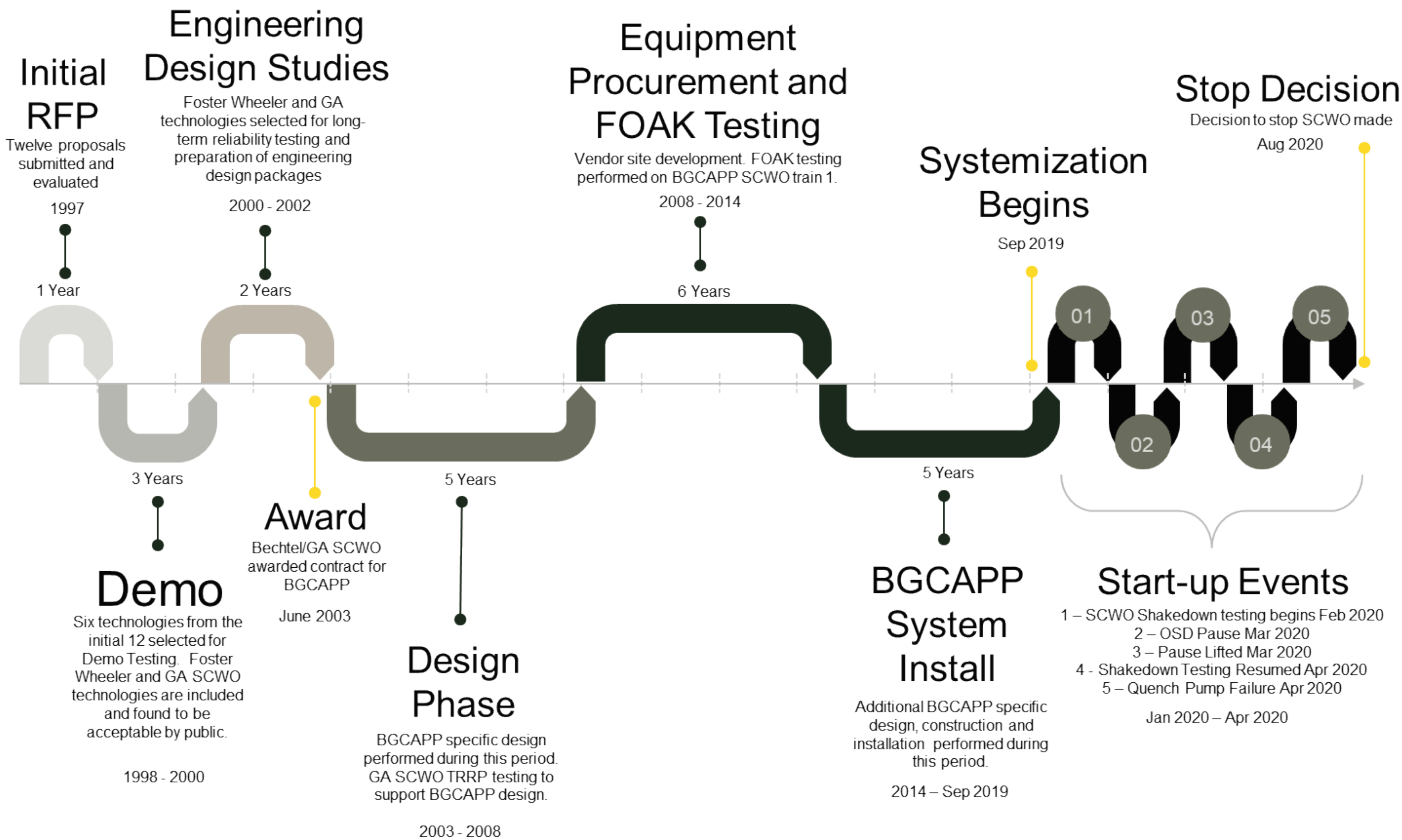

Figure 2. SCWO Timeline

9.1. Initial RFP

In response to an RFP issued in 1997, 12 proposals were received as potential alternatives to incineration, two involved SCWO technology. One was submitted by General Atomics (GA) and the other was submitted by a team that included Foster Wheeler (FW). Six of the 12 proposals (including the 2 that involved SCWO) were deemed of sufficient maturity to qualify for testing.

9.2. Demo

The Demonstration (Demo) testing was performed in two groups between 1998 and 2000. Demo I test results for GA SCWO were documented.[45, 46, 47] Demo II test results for FW SCWO were documented as well.[48] Total hours of SCWO operation on real hydrolysates or hydrolysate simulants for Demo testing and all subsequent ACWA sponsored tests are included in Table 3. The proposed technologies were evaluated by ACWA against 19 criteria covering process efficacy and performance, safety, human health and environment, and potential for implementation including public acceptability. The results of the evaluation of the GA and FW SCWO are documented in the Supplemental Reports to Congress covering Demo I and II test programs.[49, 50] The evaluations concluded that both SCWO technologies were part of viable total solutions for demilitarization of chemical weapons, which qualified them to move on to long term testing in the subsequent Engineering Design Studies (EDS).

Table 5. Total Hours of SCWO Operation on Hydrolysate or Hydrolysate Simulant Feeds During ACWA Test Programs

Test Program	GA SCWO (hours)	FW SCWO (hours)
Demonstration	272	261
Engineering Design Studies – Optimization	N/A	170
Engineering Design Studies - Operability	4,882	1,789
Technical Risk Reduction Project 07 and 08	334	N/A
Technical Risk Reduction Project 07 and 09	465	N/A
First of a Kind Testing	756	N/A
BGCAPP Shakedown	335	N/A
Total	**7,044**	**2,220**

9.3. Engineering Design Studies

The purpose of EDS testing was to investigate long term operating performance and to provide data for the technology providers to submit an engineering design package for PCAPP and/or BGCAPP. EDS testing was performed between 2000 and 2002. EDS SCWO tests consisted of multiple 500-hour tests for each feed corresponding to a proposed campaign at PCAPP or BGCAPP. Consistent with the proposed system design at the time, GA performed five 500-hour tests (one for each of three agent hydrolysates and two energetics hydrolysate/shredded dunnage combinations) plus additional corrosion tests with VX hydrolysate conducted jointly with Program Manager for Alternative Technologies and Approaches (PMATA) in support of the Newport project. EDS test results for GA SCWO were documented[51-56]. FW performed a preliminary set of short optimization tests and then three 500-hour tests corresponding to a different blended agent and energetic hydrolysate feed. EDS test results for FW SCWO were documented in reports by FW[57-58] and Focis Associates.[53, 59, 60]

9.4. Award

After EDS testing was completed, the Department of Defense in February 2003 announced that SCWO technology was as safe and cost effective as baseline incineration. Subsequently, with input and approval from the public, ACWA chose the combination of neutralization (hydrolysis)/SCWO as the technology to be used for BGCAPP.[111] After reviewing two proposals submitted to design, build, operate, and close the BGCAPP plant, a contract was awarded to the Bechtel Parsons Blue Grass Team Joint Venture (JV). This team included the GA SCWO design.

9.5. Design Phase

As part of the JV and in response to changing program requirements, GA modified its previous feeds for SCWO, dropping dunnage and adopting a blended agent/energetic hydrolysate feed approach. Two sets of Technical Risk Reduction Project (TRRP) tests between 2003 and 2004 focusing on SCWO were performed to confirm this new feed approach and supply necessary data for the BGCAPP plant design effort. Test results for both TRRP SCWO test programs were documented.[61-62]

9.6. Equipment Procurement and FOAK Testing

After completion of the BGCAPP design in 2008, fabrication of components began. The first of three replicate SCWO trains in the BGCAPP design was skid-assembled and ready for testing at GA’s facility in San Diego in 2012. FOAK testing of the SCWO train #1 was performed in 2012-2013. The purpose of the testing was to confirm operation of the BGCAPP SCWO system, confirm proper functioning of the control system and safety features, and examine methods to optimize corrosion rates and salt transport through the reactor. A final performance test of 100 hours in duration was performed with each of the three blended feeds corresponding to the expected agent campaigns at BGCAPP. Test results for SCWO FOAK testing are documented in a report by GA.[63] The remaining two SCWO trains were assembled and went through factory acceptance tests. At the conclusion of FOAK testing, all three SCWO trains were shipped to BGCAPP in late 2013.

9.7. BGCAPP System Install

The SCWO trains and support equipment were installed at BGCAPP between 2014 and 2019. During this time, ACWA requested Bechtel Parsons Blue Grass Team (BPBGT) to assemble a SCWO Working Group (SWG) to review SCWO status, discuss and resolve issues, and develop a plan to get to operation. The result of this effort was a series of four reports that summarized SCWO operating conditions[64], identified existing data gaps and open items from previous testing[65], established a series of 66 recommendations for addressing the identified data gaps and optimizing SCWO performance[66], and provided a schedule to implement recommendations through systemization in time to be ready for operation when needed.[67]

9.8. Systemization Begins

SCWO systemization at BGCAPP began approximately in September 2019. The Systemization Demonstration Procedure (SDP) was conducted on 2 January 2020 and 14-16 January 2020. The purpose of the SDP was to demonstrate startup, normal operations, and shutdown on water, auxiliary fuel (isopropanol), and air only, as well as selected abnormal and emergency operation responses. Verification of completion of all steps in the SDP program is contained in the completed SDP document.[68] Evaluation of the SDP results was included in reports by BPBGT[69] and the BGCAPP Government Field Office (GFO).[70-72]

9.9. Start-Up Events

SCWO Shakedown testing commenced after completing the SDP. The purpose of Shakedown testing was to demonstrate operation on GB hydrolysate simulant and energetics hydrolysate surrogate blended feed for a period of time up to the expected liner replacement time (about 300 hours). During this period, the intent was to demonstrate thermowell changeouts and replacement, liner changeout and replacement, feed batch preparation, RO operation, and other normal activities at their required times during SCWO operation over multiple shifts of operators to allow for operator training. Shakedown testing took place between 31 January 2020 and 31 March 2020. Testing was performed mostly on SCWO train 1 but also SCWO train 3. All objectives were successfully achieved/demonstrated. Test results for SCWO Shakedown testing are documented in a report by BPBGT[73] and the BGCAPP GFO.[74]

9.10. Stop Decision

Simultaneous to the ongoing testing with the SCWO, PEO ACWA was undergoing analysis of plant configuration and processes needed to give the program the best option to comply with the international treaty deadline for destruction of the agent stockpile. Revision of the rocket processing line, incorporation of explosive detonation technology for HD projectiles and the ability to pursue off-site shipment for industrial waste treatment of neutralization wastes were determined to provide the program with the best option. Therefore, the PEO ACWA made the decision to discontinue testing and pursuit of SCWO to be used for the Bluegrass stockpile. This decision was documented 28 August 2020.[110]

10. SCWO INVESTMENT

Total SCWO investment at both the ACWA program and BGCAPP project levels are found in the table below. (See Table 4)

Table 6. Cost and Investment/BGCAPP Project

SCWO Investment (MM$)		
ACWA SCWO Demo/EDS Subtotal	**68.5**	1997-2003
BGCAPP Investment Breakdown		
Design	12.3	-2009
SCWO Proc/Const		2010-2017
SCWO Equipment and Fabrication	80.5	
GA Pipe Mods	19.0	
Facility Construction	107.7	2010-2015
Systemization	18.6	2016-2021
Pre-Operational	3.4	2019-2021
BGCAPP Subtotal	**241.6**	
Total Investment in SCWO	**310.1**	

10.1. ACWA Program

In addition to BGCAPP Project Costs, ACWA has incurred costs related to SCWO development over the Demonstration (Demo) and EDS programs. These programs covered the years 1997-2002, prior to the BGCAPP contract award to the Bechtel/Parsons team. Before the award, ACWA tested two different types of SCWO systems that were part of two different teams: GA, which used a solid wall SCWO reactor, and FW, which had a transpiring wall SCWO reactor.

These costs were divided into Demo testing, EDS testing, preparation of an engineering design package (EDP) for Pueblo Chemical Agent Pilot Plant (PCAPP), and EDP preparation for BGCAPP. Testing costs were further broken down into those paid directly to GA or FW and those paid for test support. Test support included the cost of the host facility for testing, support contractor costs for oversight, and costs for hydrolysate preparation by Government agencies.

Costs were provided by resource management or prior ACWA management personnel familiar with the time frames required, 1997-2002.

10.2. BGCAPP Project

In order to establish the SCWO investment incurred by the BGCAPP Project, the JV's Contract Work Breakdown Structure (CWBS) was conducted to determine which control accounts (CAs) were related/potentially related to SCWO, from the Design phase through Operations phase. Then a search of the JV's Cost Control System (SOURCE) data files was performed to find the latest record of cost data relating to these control accounts.

Utilizing the SOURCE data files, the following steps were performed:

- Examined the work packages (WPs) in each of the CAs and verify which are applicable to SCWO.
- Listed the SCWO related WPs and record the total cumulative actual cost of work performed (ACWP) monetary value and hours of the completed work for each SCWO related WP (see summary below).
- Recorded the start and finish accounting month/year the work was executed for each SCWO related WP (see summary below).

Additionally, Contract Performance Report (CPR) Format 1 data was collected and the following steps were performed:

- Garnered the several applicable CPR Format 1 reports that document the cumulative actuals of the SCWO related CAs for each applicable phase of work.
- Identified the additional CAs that supported the total execution of all the CAs being executed for that phase of work (e.g., Project Services, Distribs, Bulk Materials, Misc. Engineering Support, Project Mgmt. Support, Business Mgmt. Support, Environmental Mgmt. Support, Systemization Engineering and Direct Support).
- Using ACWP costs, determined the total cost of all direct work (including the SCWO related CAs) for each applicable phase.

- Determined the Format 1 percentage ratio of each of the support CAs to the total direct work cost.

Based on the results of the above actions, the following steps were performed to achieve a summary level cost:

- For each phase, listed the SCWO related WPs with total cumulative ACWP dollar values and hours of the completed work, along with the start and finish accounting month/year the work was executed.

- Subtotaled the cost and hours.

- For each phase, added the Format 1 support CAs (and calculated percentages) below the subtotal line of the summary list of SCWO related WPs.

- For each phase, applied the calculated percentages of each support CA to the SCWO WPs subtotal cost to determine each of the support CAs dollar values.

- Subtotaled total direct SCWO related and support cost for each phase.

- Determined Grand Total.

11. OPERATION SCENARIOS

When assessing the viable decision space for SCWO opportunities in the future, four distinct operation scenarios were developed. These scenarios create distinct groups of courses of action (See Section 15) that can be expanded upon and fleshed out during a cost benefit analysis.

1. Operations Scenario: In Place – Blue Grass Army Depot (BGAD)

    a. New feed source identified for SCWO operations

    b. Perform additional design and modifications necessary for new feed

    c. Adequacy of infrastructure to support utility needs during operations.

    d. No disassembly required

    e. Remove (3) SCWO from lay-up status

f. Identify equipment needed for new process

g. Validate systems and electronic interfaces

h. Mobilize and train workforce to operate SCWO

i. Systemize/run surrogate trials if necessary

j. Operate as intended with new feed source

2. Operations Scenario: Total System Transfer

a. New feed source identified for SCWO operations

b. Perform additional design and modifications necessary for new feed

c. Remove all units from layup

d. Disassemble (3) SCWO units

e. Identify equipment needed for new process

f. Remove equipment/package/and transport

g. Facility in proper configuration to install equipment

h. FCS interfaces established

i. Mobilize and train workforce to operate SCWO

j. Systemize/run surrogate trials if necessary

k. Operate as intended with new feed source

3. Operations Scenario: Partial System Transfer

a. New feed source identified for SCWO operations

b. Perform additional design and modifications necessary for new feed

c. Remove some units from layup

d. Disassemble (1-2) SCWO Units

e. Identify equipment needed for new process

f. Remove equipment/package/and transport

g. Facility in proper configuration to install equipment

h. FCS interfaces established

i. Mobilize and train workforce to operate SCWO

j. Systemize/run surrogate trials if necessary

k. Operate as intended with new feed source

4. Operations Scenario: Modular Disposition

a. Identify Module

i. Feed Module

ii. Reactor Module

iii. Hydrolysate Blend Tanks and Pump Module

iv. Hydrolysate Holding Tank and Pump Module, Etc.

b. Disassemble Modules from each other

c. Remove/package for transportation as necessary

12. COMMERCIAL STATUS OF SCWO

The first company established to commercialize SCWO technology was started in 1980. In the roughly four decades since that time, there have been approximately 25 companies that have developed commercial SCWO designs. A list of past and present companies that have developed commercial versions of SCWO is found in Table 5. Today, there are at least nine (9) active companies with SCWO designs. Some are large companies where SCWO is just one of several technologies offered or lines of business (e.g., General Atomics, SRI, Hanwha, Battelle), while others are small companies started and/or focused exclusively on SCWO (e.g., SuperWater Solutions, SCFI, 374Water). Of the nine, approximately six are actively marketing SCWO systems to a variety of clients for different applications at the present time.

Table 7. Past and Present Companies in SCWO Commercialization[90-100]

Company (currently active in bold)	**Dates**	**Licensees or Partners**
MODAR, Inc.[1]	1980 - 1996	Organo Corp.
Oxidyne Corp.	1986 - 1991	-
MODEC (Modell Environmental Corp.)	1986 - 1995	Organo Corp., Hitachi Plant Engineering & Construction, Ltd., NGK Insulators, Ltd., NORAM Engineering and Constructors, Ltd.
EcoWaste Technologies, Inc.[2]	1990 – 2004	Chematur Engineering AB, Shinko Pantec (Kobelco)
General Atomics (GA)	1990 - present	Komatsu Ltd., Kurita Water Industries, Ltd., Abitibi-Price, Inc.
SRI International	1990 - present	Mitsubishi Heavy Industries, Ltd.
Organo Corp.	1991[5]– 2006[5]	-
Abitibi-Price, Inc.	1992 – 1997	General Atomics
Turbosystems Engineering	1992 – 2006	-
KemShredder, Ltd	1993 – 1996	-
Foster Wheeler Development Corp.	1993 – 2004[5]	Aerojet Gencorp Corp., Sandia National Laboratory
NORAM Engineering and Constructors, Ltd.	1994 – 2004	**-**
Hanwha Chemical	1994 – present	-
Chematur Engineering AB[3]	1995 – 2007	Johnson Matthey, WS Atkins, Stora-Enso, Feralco AB
HydroProcessing, L.L.C.	1996 – 2002	-
Komatsu/ Kurita Water Industries, Ltd.	1996[5] – 2005[5]	General Atomics[5]
Hydrothermale Oxydation Option (HOO)[4]	2000 – 2008[5]	-
Parsons	2003[5] – 2008[5]	-
Aquarden	2005 – present	Ariane Group
SuperWater Solutions	2006 – present	-
SuperCritical Fluids International (SCFI)	2007 – present	Parsons
Innoveox	2008 – Present	-
ENN Envirotech	~2008[5] – present	-
374Water	2013 – present	-
Battelle	2019 – present	-

(1) Acquired by General Atomics in 1995.
(2) Acquired by Chematur in 1999.
(3) SCWO business bought by SCFI in 2007.
(4) Succeeded by Innoveox.
(5) Nonattributable Information

Table 6 shows the commercial-scale SCWO plants in existence today. There are currently four (4) commercial-scale SCWO plants that are in operation (one being near-critical hydrolysis). All of these plants are in Europe or Asia. The system built by Aquarden is currently in operation destroying energetics and chemical agent for the French government. Another system based on the SRI International design is in the process of destroying a PCB stockpile in Tokyo and is scheduled to complete its mission in 2022. The other two are processing industrial chemical wastes. In addition to the four (4) active plants, there are three (3) mobile SCWO systems (by Battelle and SCFI) that are available and intended to be moved to a waste source to process on-site as needed. The other plants listed are either currently in fabrication, have completed operations, or are idle. Based on the number of companies marketing SCWO and the variety of active applications, SCWO remains a commercially viable and versatile technology with sustained interest from many customers.

Table 8. Active Commercial SCWO Companies – Full-Scale Plants[90-100]

Company	System Location	Capacity	Feed	Status			
				Operating	Built	Fabrication	Completed Operations
Aquarden, Denmark	France (Defense Department)	200 kg/hr[(1)]	Energetic wastes (pyrotechnics) and chemical warfare agents	x			
Battelle, US	Mobile unit	40-60 gpd	Per-and Polyfluoroalkyl substances (PFAS)	x			
	Mobile unit	300-500 gpd	PFAS	x			
ENN Envirotech, China	Nanjing, China	3	Sewage sludge (wet)		x		
General Atomics, US	TEAD	3 gpm	Energetics		x		
	BGCAPP	3 x 1000 lb/hr	Agent/energetics Hydrolysates		x		
	BGAD	10 gpm	Explosives		x		
	US Air Force	3 gpm[(1)]	Explosives				x[(1)]
	Republic of Korea	3 x 1.2 gpm[(1)]	Pink/Red water				x[(1)]
	Commercial client (France)[(1)]	2 x 3 gpm[(1)]	Waste cleaning solution[(1)]	x[(1)]			
	Commercial client (Japan)[(1)]	3 gpm[(1)]	Hazardous waste[(1)]		x[(1)]		
Hanwha, Korea	Huchems	2000 kg/hr	DNT prod. waste				x
	Samnam Petrochemical	5500 kg/hr	TPA prod. waste				x
	Namhae	35,000 kg/hr	Melamine prod. waste				x
	Korea Fine Chemical	20,000 kg/day	TDI residue (near critical hydrolysis)	x			
SCFI, Ireland	Valencia, Spain	6 tpd	Sewage sludge				x
	Mobile demonstration unit[(1)]	Unknown	Various	x[(1)]			
SRI, US	Tokyo, Japan	2000 kg/day	PCBs (transformer oil)	x			
374Water, US	Wastewater treatment plant	2 x 6 tpd[(1)]	Sewage sludge and biosolids			x	

(1) Nonattributable Information

13. MARKET RESEARCH

Over the course of two years, multiple electronic searches were conducted, and potential partners were identified and subsequently contacted to gauge interest. Based on those searches, CBC contacted those private sector commercial groups that had been found to previously be or were currently working in the SCWO area (General Atomics, Veolia North America, Heritage Environmental Solutions, Tetra Tech, AECOM, and Amentum). Companies like Fusion Tech who were researching SCWO for possible application in Geo-Thermal technologies, were also contacted. The only group that showed sufficient interest to engage in a technical dialogue, was Heritage Environmental Services.

14. ROM ESTIMATE ASSUMPTIONS

The following section of this study identifies eight (8) COA's and the activities required to complete each. In addition, ROM cost estimates are provided for each COA. Several assumptions were made during the development of these cost estimates. This section will review those assumptions in their entirety. They are as follows:

- PFAS @ BGAD (3 units) has the same ROM estimated cost and schedule as Aqueous Film-Forming Foam (AFFF) @ BGAD (3 units), Castalia @ BGAD (3 units), and Energetic Medium @ BGAD (3).
- PFAS @ EPA (3 units) has the same ROM estimated cost and schedule as Energetic Medium @ RSA (3 units).
- PFAS @ EPA (2 units) has the same ROM estimated cost and schedule as Energetic Medium @ Tooele Army Depot (TEAD) (2 units).
- PFAS @ EPA (1 unit) has the same ROM estimated cost and schedule as Energetic Medium @ TEAD (1 unit).
- Programmatic costs are not included in the ROM estimate.
- All BGCAPP engineering and drawings for the SCWO structures, utilities, and operational procedures will be provided to other facilities as directed.
- An allocation for parts and spares based on modifications due to the Engineering Review was $250,000 per site.
- All reactors at the various sites (3, 2, or 1) will be operational during SCWO processing.
- The SCWO, when utilized at BGAD, will operate as intended.

- Utilities at BGAD will be terminated to ensure Main Plant demolition does not interfere with SCWO Process Building (SPB) operations.

- Utility costs will be the same for all facilities (EPA, TEAD, RSA): Current ROM estimated to be $750,000.

- The interior building size for the SPB will be based on the current structure located at BGCAPP, which is 26,569 ft^2.

- The concrete around the SPB will be based on the current structure located at BGCAPP, which is 45,627 ft^2 (measurement taken from "Area Limits").

- The interior building size for the UB will be based on the current structure located at BGCAPP, which is 23,300 ft^2.

- When the units are transported, the building size interior of the SPB will be reduced by 65% for 1 SCWO unit and 50% of the concrete.

- When the units are transported, the building size interior of the SPB will be reduced by 40% for 2 SCWO units and 25% of the concrete.

- When the unit is transported, the building size interior of the UB will be reduced by 50% for 1 SCWO unit.

- When the units are transported, the building size interior of the UB will be reduced by 25% for 2 SCWO units.

- The SPB and UB at other facilities, excluding BGAD is estimated to cost $16/ft^2 to construct.

- The concrete at other facilities, excluding BGAD, is estimated to be $6/ft^2 to construct.

- The FCS for the BGAD SCWO is estimated to cost $500,000.

- There will be no reduction in cost for the FCS at the facilities.

- Development of the FCS is estimated to be 120 days.

- An estimate of $20,000 for both the loading and unloading areas at the facilities has been made.

- Quench water at all facilities will be available in support of the SCWO process.

15. COURSES OF ACTION

The following COA's are reviewed in this section of the SCWO Special Study. Each COA presented in the following section of this study includes:

- Feed
- Operations Scenario
- End User.

The COA's identify the various configurations of the SCWO and operational scenarios and its intended feed. The configuration also determines the end user. Various combinations are included in the COA's and are addressed accordingly. In addition, ROM estimates are provided along with companion schedules that can be found in Sections 15 and 16. A summary of duration to implement and complete, and the ROM estimate associated with each, can be found in Table 12.

It should be noted that a partial RCRA closure will be required for the SCWO. The SCWO is currently listed as a treatment unit which would no longer be the case due to the PFAS operations and not hydrolysate operations.

COA 1:

- Feed: Per- and Polyfluoroalkyl Substances (PFAS/AFFF)
- Operations Scenario: In place – BGAD
- End User: Army

COA 2:

- Feed: Per- and Polyfluoroalkyl Substances (PFAS/Water)
- Operations Scenario: In Place – BGAD
- End User: Army

COA 3:

- Feed: Per- and Polyfluoroalkyl Substances (PFAS)
- Operations Scenario: Total System Transfer – Cincinnati, OH
- End User: EPA

COA 4:

- Feed: Per- and Polyfluoroalkyl Substances (PFAS)
- Operations Scenario: Partial System Transfer – Cincinnati, OH
- End User: EPA

COA 5:

- Feed: Conventional Energetics Emulsion
- Operations Scenario: In Place – BGAD
- End User: Army

COA 6:

- Feed: Conventional Energetic Medium
- Operations Scenario: In Place – BGAD
- End User: Army

COA 7:

- Feed: Conventional Energetic Medium
- Operations Scenario: Partial System Transfer – TEAD
- End User: Army

COA 8:

- Feed: Conventional Energetic Medium
- Operations Scenario: Total System Transfer – Redstone
- End User: Army

COA 9:

- Feed: N/A
- Operations Scenario: Modular Disposition*

- End User: Government/Private industry

* Remove the modules through appropriate contractual disposition methods and from the plant's RCRA operating permit, identify within PCARSS, disassemble equipment, and prepare for shipping.

Each of these (COA 1-8) has a specific feed that could be processed through the SCWO to create inert material. It should be noted that SCWO was considered the primary destruction process for PFAS and a secondary for the Castalia and conventional demilitarization. The following sections look at the various COA's individually, as identified above, and provide activities to be performed for each and a cost estimate for executing each.

15.1 Per- and Polyfluoroalkyl Substances (PFAS)

15.1.1. Background

PFAS have been manufactured and utilized in a variety of industries since the 1940s[83]. PFAS are a family of chemicals that vary widely in their chemical and physical properties. These products have applications in the following industries:

- Aerospace
- Semiconductor
- Medical
- Automotive
- Construction
- Electronics
- Aviation

They can also be found in consumer products and materials used for firefighting applications[84]. The following COA's are being provided for discussion.

15.1.2. COA 1: AFFF Processed in the SCWO @ BGAD

One of the materials expected to be processed through the SCWO system is AFFF. AFFF has been used for 50 years for certain firefighting applications and associated training exercises. The vast majority of AFFF in use or stockpiled (millions of liters) contains fluorosurfactants, which are made up of PFAS. Many states have restricted or prohibited the use of AFFF due to the bio accumulative nature and adverse health effects of PFAS. Based on the research (Supercritical Water Oxidation as an Innovative Technology for PFAS Destruction; Case Study) that has been performed with AFFF, it is anticipated that SCWO can be utilized to destroy the PFAS (maybe requiring repeated treatments) contained in this material.[85]

The material would be received in a tanker truck, unloaded, and integrated into the SCWO process. Due to the possible presence of fluorine and sulfur (perfluorooctanesulfonic acid [PFOS] based AFFF), additional steps may be necessary to address formation of hydrofluoric and sulfuric acid[85] during processing. This could include identifying the proper materials of construction for both tanks, piping, and reactors and neutralization/dilution of the acid if warranted.

The material could be stored in blending tanks for neutralization/dilution and stored in a holding tank while awaiting processing. The material would then be transferred from the holding tank to the SCWO reactor. The SCWO processed AFFF would then be treated, if necessary, prior to being transferred to a loading area and shipped off site for final disposal.

The following activities will need to be performed for “AFFF Processed in the SCWO @ BGAD” (COA 1):

a. AFFF identified as feed source for SCWO operations at BGAD

b. Perform additional design and modification if necessary for AFFF feed

c. Ensure adequacy of infrastructure to support utility needs during operation

d. No disassembly required

e. Remove (3) SCWO units from lay-up status

f. Identify equipment needed for AFFF process

g. Develop control system

h. Mobilize and train workforce to operate SCWO

i. Operate as intended for AFFF

Based on ROM assumptions in Section 14 and the activities described above, Table 7 below provides the baseline estimate to prepare BGAD for the operation of the SCWO. This baseline estimate does not included costs associated with the processing of AFFF in the system. It should be noted that all three (3) SCWO trains are intended to be operational during COA 1.

Table 9. ROM Costs for Three SCWO Being Operated @ BGAD (COA 1, 2, 5, and 6).

Activity	Cost
Design Validation and Modifications Equipment Interfaces GA of Equipment Electrical Mechanical Civil FAWB Modifications Due to Engineering Review	$940,000
Establish Infrastructure Requirements Unloading Loading Building Design Utility Terminations	$241,000
Remove SCWO Unit from Layup Integrate Modules Ensure Equipment is Operational Establish Interfaces Integrate System Engineering	$846,000
Additional Equipment Identify Additional Process Equipment Procure Equipment Install Equipment Integrate Modules/Systems	$81,000
Control System Develop Control System Verify Operational Control Functional Test	$749,000
Mobilize and Train Workforce Control System Operator Training SCWO Operational Training Initial Testing of Process	$303,000
Operations (Systemization, Surrogate) Operations Manual Established Systemization Surrogate Trials	$602,000
	$3,762,000

15.1.3. COA 2: PFAS Contaminated Water Processed in the SCWO @ BGAD

Like the AFFF, the PFAS contaminated water (e.g., PFAS mixture resulting from filtration a/o treatment of water supplies) would be received in a tanker truck, unloaded, and integrated into the SCWO process. The material could be injected directly into the SCWO reactor from the holding tank. The processed water would be treated, if necessary. prior to being transferred to a loading area for shipment and final disposal.

The following activities will need to be performed for “PFAS Contaminated Water Processed in the SCWO @ BGAD” (COA 2):

a. PFAS identified as feed source for SCWO operations at BGAD

b. Perform additional design and modification if necessary for PFAS feed

c. Ensure adequacy of infrastructure to support utility needs during operation

d. No disassembly required

e. Remove (3) SCWO units from lay-up status

f. Identify equipment needed for PFAS process

g. Develop control system

h. Mobilize and train workforce to operate SCWO

i. Operate as intended for PFAS

Like COA 1, Table 7 was used to provide a baseline estimate to prepare BGAD for the operation of the SCWO. Once again, the estimate does not include costs associated with the processing of PFAS in the system. Just like COA 1, all three (3) SCWO trains are to be operational during COA 2.

15.1.4. COA 3: BGCAPP SCWO Relocated to the EPA

All SCWO unit(s), along with identified processing equipment deemed necessary for its intended use, will be removed from the BGCAPP SCWO Process Building and transported to a predetermined area by the EPA.

The following activities will need to be performed for “BGCAPP SCWO Relocated to the EPA” (COA 3):

a. New feed source identified by EPA for SCWO operations

b. Perform additional design and modification if necessary for new feed

c. Remove all units from layup

d. Disassemble 3 SCWO units

e. Identify equipment needed for EPA process

f. Remove equipment/package/and transport to EPA

g. EPA facility in proper configuration to install equipment

h. Develop control system

i. Mobilize and train workforce to operate SCWO

j. Systemize/run surrogate trials if necessary

k. Operate as intended by EPA

Based ROM assumptions in Section 14 and on the activities described above, Table 8 provides an estimate to disassemble three (3) SCWO trains and relocate them to an EPA site. This estimate includes the preparation of the EPA site for the operation of the SCWO. The estimate does not include costs associated with the processing of PFAS in the system. It should be noted that three (3) SCWO trains are intended to be operational during COA 3.

Table 10. ROM Costs for Three SCWO Being Operated @ EPA/RSA (COA 3 and 8).

Activity	Cost
Design Validation and Modifications Equipment Interfaces GA of Equipment Electrical Mechanical Civil FAWB Modifications Due to Engineering Review	$1,053,000
Remove SCWO Unit	$120,000
Dissassemble SCWO for Transportation Identify Modules to be Shipped Crate Modules for Transportation Transport SCWO Equipment Unpack Equipment	$129,000
Establish Infrastructure Requirements Unloading Loading SCWO Process Building Utility Building Utilities (including power)	$1,849,000
Install SCWO Unit Locate and assemble SCWO Integrate Modules Ensure Equipment is Operational Establish Interfaces Integrate System Engineering	$1,136,000
Additional Equipment Identify Additional Process Equipment Procure Equipment Install Equipment Integrate Modules/Systems	$370,000
Control System Develop Control System Verify Operational Control Functional Test	$715,000
Mobilize and Train Workforce Control System Operator Training SCWO Operational Training Initial Testing of Process	$236,000
Operations (Systemization, Surrogate) Operations Manual Established Systemization Surrogate Trials	$602,000
	$6,210,000

15.1.5. COA 4: BGCAPP SCWO Relocated to the EPA

One or two SCWO unit(s), along with identified processing equipment deemed necessary for its intended use, will be removed from the BGCAPP SCWO Process Building and transported to a predetermined area by the EPA.

The following activities will need to be performed for “BGCAPP SCWO Relocated to the EPA” (COA 4):

a. New feed source identified by EPA for SCWO operations

b. Perform additional design and modification if necessary for new feed

c. Remove some units from layup

d. Disassemble 1-2 SCWO units

e. Identify equipment needed for EPA process

f. Remove equipment/package/and transport to EPA

g. EPA facility in proper configuration to install equipment

h. Develop control system

i. Mobilize and train workforce to operate SCWO

j. Systemize/run surrogate trials if necessary

k. Operate as intended by EPA

Based ROM assumptions in Section 14 and on the activities described above, Table 9 provides an estimate to disassemble one (1) SCWO train and relocate it to an EPA site. This estimate also includes the preparation of the site for the operation of a single SCWO. Like the other courses of action, this estimate does not include costs associated with the processing of PFAS in the system. It should be noted that a single SCWO train will be operational during COA 4. Table 10 provides an estimate to disassemble two (2) SCWO trains and relocate them to an EPA site.

Table 11. ROM Costs for a Single SCWO Being Operated @ EPA/TEAD (COA 4 and 7).

Activity	Cost
Design Validation and Modifications Equipment Interfaces GA of Equipment Electrical Mechanical Civil FAWB Modifications Due to Engineering Review	$573,000
Remove SCWO Unit	$80,000
Dissassemble SCWO for Transportation Identify Modules to be Shipped Crate Modules for Transportation Transport SCWO Equipment Unpack Equipment	$108,000
Establish Infrastructure Requirements Unloading Loading SCWO Process Building Utility Building Utilities (including power)	$1,270,000
Install SCWO Unit Locate and assemble SCWO Integrate Modules Ensure Equipment is Operational Establish Interfaces Integrate System Engineering	$403,000
Additional Equipment Identify Additional Process Equipment Procure Equipment Install Equipment Integrate Modules/Systems	$81,000
Control System Develop Control System Verify Operational Control Functional Test	$608,000
Mobilize and Train Workforce Control System Operator Training SCWO Operational Training Initial Testing of Process	$129,000
Operations (Systemization, Surrogate) Operations Manual Established Systemization Surrogate Trials	$312,000
	$3,564,000

Table 12. ROM Costs for Two SCWO Being Operated @ EPA/TEAD (COA 4 and 7)

Activity	Cost
Design Validation and Modifications Equipment Interfaces GA of Equipment Electrical Mechanical Civil FAWB Modifications Due to Engineering Review	$938,000
Remove SCWO Unit	$120,000
Dissassemble SCWO for Transportation Identify Modules to be Shipped Crate Modules for Transportation Transport SCWO Equipment Unpack Equipment	$159,000
Establish Infrastructure Requirements Unloading Loading SCWO Process Building Utility Building Utilities (including power)	$1,519,000
Install SCWO Unit Locate and assemble SCWO Integrate Modules Ensure Equipment is Operational Establish Interfaces Integrate System Engineering	$823,000
Additional Equipment Identify Additional Process Equipment Procure Equipment Install Equipment Integrate Modules/Systems	$181,000
Control System Develop Control System Verify Operational Control Functional Test	$665,000
Mobilize and Train Workforce Control System Operator Training SCWO Operational Training Initial Testing of Process	$171,000
Operations (Systemization, Surrogate) Operations Manual Established Systemization Surrogate Trials	$459,000
	$5,035,000

15.2. Conventional Demilitarization

15.2.1. Background

The US military has a stockpile of approximately 400,000 tons of munitions. Munitions include projectiles, bombs, rockets, landmines, and missiles. A common disposal method for these munitions has been open burning/open detonation (OB/OD). Since approximately 2011, alternative methods have been considered and OB/OD has been minimized.[89] The following COAs are being provided for discussion.

15.2.2. Soukos Castalia Demilitarization System

15.2.2.1. Background

The Castalia uses a disruptive method and emulsion solution to dismantle various types of conventional munitions.[86] The system uses a series of proprietary processes to neutralize and exploit explosives contained in a wide range of conventional ammunition.[87] The following COA deals strictly with a conventional munition campaign utilizing the Castalia.

15.2.2.2. COA 5: BGAD Obtains a Conventional Demilitarization Mission

Conventional munitions processed in the Castalia are placed in an emulsion, that once the munition is processed, the emulsion will contain a low level of suspended solids, energetics, and other miscellaneous organic/inorganic constituents.[88] Based on the solids contained in the emulsion, a process will be needed to remove metallic materials prior to the SCWO. A filtration/separation system will need to be developed as a pre-treatment step to the SCWO process. This filtration/separation could be performed in the AFS/APS portion of the SPB.

This emulsion, once treated, could be stored in the blend tanks, transferred to the holding tank, and then to the SCWO reactor. In addition, spent decontamination solution and Pollution Abatement System (PAS) Condensate/Spent Caustic generated during the operation of the Castalia, will also be processed in the SCWO reactor (will require filtration as well).[88] The processed materials would then be transferred to a loading area and shipped off site for final disposal.

The following activities will need to be performed for “BGAD Obtains a Conventional Demilitarization Mission” (COA 5):

a. Castalia’s emulsion/additional liquids identified as feed source for SCWO operations at BGAD

b. Perform additional design and modification if necessary for emulsion/additional liquid feed

c. Ensure adequacy of infrastructure to support utility needs during operation

d. No disassembly required

e. Remove three (3) SCWO units from lay-up status

f. Identify equipment needed for Castalia's emulsion/additional liquid process

g. Develop control system

h. Mobilize and train workforce to operate SCWO

i. Systemize/run surrogate trials if necessary

j. Operate as intended for Castalia's emulsion/additional liquids

As utilized in COA 1 and COA 2, Table 7 provides a baseline estimate to prepare BGAD for the operation of three SCWO trains in COA5. Again, the estimate does not include costs associated with the processing of the energetic emulsion in the system. In addition, the estimate does not include the removal of the chemical agent from the munition and any preparation of the agent required for SCWO processing.

15.2.3. COA 6: BGAD Obtains a Conventional Demilitarization Mission

The demilitarization of conventional munitions requires the energetics to be destroyed. If the SCWO process is to be utilized for this mission, the energetics will need to be processed into a liquid suspension. An initial process to the SCWO would be required to ensure the energetics are in a liquid state. The energetic medium can now be processed through the SCWO reactor, and the processed medium can be transferred to a loading area for final shipment and disposal.

The following activities will need to be performed for "BGAD Obtains a Conventional Demilitarization Mission" (COA 6):

a. Energetic medium identified as feed source for SCWO operations at BGAD

b. Perform additional design and modification if necessary for energetic feed

c. Ensure adequacy of infrastructure to support utility needs during operation

d. No disassembly required

e. Remove three (3) SCWO units from lay-up status

f. Identify equipment needed for new process

g. Develop control system

h. Mobilize and train workforce to operate SCWO

i. Systemize/run surrogate trials if necessary

j. Operate as intended for energetic medium

Once again, Table 7 is used in COA 6 and provides a baseline estimate to prepare BGAD for the operation of three SCWO trains. The estimate does not include costs associated with the processing of conventional munitions in the system. In addition, the estimate does not include the removal of the energetics from the munition and any prep of the energetics (medium) required for SCWO processing.

15.2.4. COA 7: BGCAPP SCWO Relocated to TEAD

Like COA 6, the energetics found in conventional munitions will require an initial process to the SCWO to ensure the energetics are in a liquid state. The energetic medium can now be processed through the SCWO reactor, and then the processed medium can be transferred to a loading area for final shipment and disposal.

The following activities will need to be performed for "BGCAPP SCWO Relocated to TEAD (COA 7):

a. Energetic medium identified for SCWO operations at TEAD

b. Perform additional design and modification if necessary for energetic feed

c. Remove some units from layup

d. Disassemble 1-2 SCWO units

e. Identify equipment needed for new process

f. Remove equipment/package/and transport to TEAD

g. TEAD facility in proper configuration to install equipment

h. Develop control system

i. Mobilize and train workforce to operate SCWO

j. Systemize/run surrogate trials if necessary

k. Operate as intended for energetic medium

Like COA 4, Tables 9 and 10 are used in COA7 to provide an estimate to disassemble one or two SCWO trains and relocate them to TEAD. The estimates do not include cost associated with the processing of the energetic medium, removal of the energetics, or any prep of the energetics required for SCWO processing.

15.2.5. COA 8: BGCAPP SCWO Relocated to Redstone

Like COA 6, the energetics found in conventional munitions will require an initial process to the SCWO to ensure the energetics are in a liquid state. The energetic medium can now be processed through the SCWO reactor, and then the processed medium can be transferred to a loading area for final shipment and disposal.

The following activities will need to be performed for "BGCAPP SCWO Relocated to Redstone (COA 8):

a. Energetic medium identified for SCWO operations at Redstone

b. Perform additional design and modification if necessary for energetic feed

c. Remove all units from layup

d. Disassemble 3 SCWO units

e. Identify equipment needed for new process

f. Remove equipment/package/and transport to Redstone

g. Redstone facilities in proper configuration to install equipment

h. Develop control system

i. Mobilize and train workforce to operate SCWO

j. Systemize/run surrogate trials if necessary

k. Operate as intended for energetic medium

While performing conventional demilitarization, it is possible to come across agent filled munitions. The Explosive Destruction System can be utilized to process these munitions. A reagent is used after the detonation process to chemically treat the Explosive Destruction System's contents. Upon completion of the process and samples have been analyzed, the liquid is removed. This liquid waste can be transported to the SCWO and processed in the reactor. The processed liquid would be transferred to a loading area for final shipment and disposal.

Table 8 is used in COA 8 and provides an estimate to disassemble three (3) SCWO trains and relocate them to Redstone Arsenal. The estimate includes the preparation of the Redstone sight for the operation of the three SCWO trains. The estimate does not include costs associated with the processing of the energetic medium, removal of the energetics, or any prep of the energetics required for SCWO processing.

15.3. Modular Disposition

15.3.1. Background

While not originally envisioned as a stand-alone course of action, modular disposition includes the partial closure of the SCWO systems under the BGCAPP RCRA permit (removal from the operating permit), development and identification of SCWO subsystems as modules in the PCARSS, negotiating the disassembly and removal of those modules as part of the BGCAPP closure contract, and disposition of those modules through the Defense Logistics Agency excess property processes.[116]

Partial closure of the RCRA permit to remove the SCWO systems as treatment units is a necessary activity in every COA considered in this study. The costs associated with this action are programmatic costs borne by the BGCAPP project and are not included in the COA cost estimates.

Development and identification of SCWO subsystems as modules in the PCARSS would be a likely activity in every COA that involves the movement of SCWO modules to a new location although the details of the activity would vary.

The goal, in communicating with potential governmental partners and gaging both government and industry interest, was to recommend a more holistic course of action. As mentioned previously, the lack of a government organization with interest, authority, and funding has made modular disposition the recommended course ahead.

15.3.2. COA 9: Modular Disposition

This COA includes the disassembly of the SCWO modules and preparing them for shipment. The modules, however, will need to be removed through appropriate contractual disposition methods and from the facility's RCRA operating permit. The modules would then need to be identified in PCARSS. Upon completion of this effort, the modules can be disassembled and prepared for shipment. The cost of this effort ranges from $188,000 to $279,000 (as described in Tables 9 and 10). These values represent removal and all transportation associated costs.

15.4. ROM Summary Table

Table 11 summarizes the ROM estimate for each course of action.

Table 13. ROM Estimate Summary

Course of Action	ROM Estimate
COA 1, 2, 5, 6	$3,762,000
COA 3, 8	$6,210,000
COA 4, 7 (1 SCWO)	$3,564,000
COA 4, 7 (2 SCWO)	$5,035,000

15.5. Getting Started

Nine COA's have been identified within the body of this study. They have been repeated here for clarity:

- COA 1: AFFF Processed in the SCWO @ BGAD
- COA 2: PFAS Contaminated Water Processed in the SCWO @ BGAD
- COA 3: BGCAPP SCWO Relocated to the EPA (3 units)
- COA 4: BGCAPP SCWO Relocated to the EPA (1-2 units)
- COA 5: BGAD Obtains a Conventional Demilitarization Mission (Soukos Castalia)
- COA 6: BGAD Obtains a Conventional Demilitarization Mission (energetics disposal)
- COA 7: BGCAPP SCWO Relocated to TEAD (1-2 units)
- COA 8: BGCAPP SCWO Relocated to Redstone (3 units)
- COA 9: Modular Disposition

Each of the COA's identified above were viable at their initial inclusion in this report. Since then, however, some of the COA's are no longer recommended as a viable path for this effort or have been superseded by others due to due external factors and third-party interest. As PFAS became elevated to a national crisis (gained legislative and regulatory actions as a response), more of the selection efforts were geared towards COA 1 and COA 2. Conversely, the COA's that were identified to process conventional weapons were not given the same attention as those mentioned above (COA 5 – 8). These COA's were no longer recommended due to the very low likelihood of BGAD receiving a conventional weapons disposal mission or the ability for TEAD or Redstone to make energetic hydrolysate. It was even less likely that COA – 5 (Castalia) would have been selected if such a mission were to come to fruition since the Castalia has suffered performance issues during recent testing efforts, and the fact that there are well established disposal options that already exist for this process. As previously mentioned, there has been no commitment on the part of the government agencies to take ownership or liability for the SCWO systems at BGCAPP. Since the EPA fell within this category, COAs 3 – 4 cannot be recommended at this time.

Consequently, from a technical standpoint, the best potential future application for the BGCAPP SCWO system is private off-site treatment of AFFF/PFAS products and waste streams. Due to BGCAPP's success in its destruction mission leading to a reduced window of time for action, it is recommended that off-site treatment by private industry of PFAS/AFFF via COA 9 be pursued. It should be noted that the breath of design features with the BGCAPP SCWO that could be used for the treatment of AFFF/PFAS waste materials are unparalleled in commercial SCWO applications. The viability of this recommended COA may be limited by the timeframe remaining for decisions to be made before the BGCAPP mission is completed and the site is well into the closure phase.

It is important to note that all the COA's, at a minimum, require that the SCWO be excessed from the BGCAPP SC's contract through appropriate disposition methods, and removed from the RCRA permit through a partial closure effort. This would allow for other government authorities and agencies to transfer the SCWO system, in part or in total to their organization. If the SCWO ultimately becomes surplus to the government after the initial review cycles, then state government and private industry would have the opportunity to obtain the SCWO equipment, in part or in total through this same process.

16. SCHEDULE DURATIONS OF COA'S

The following schedules represent the duration of each COA based on the ROM estimate performed for each.

16.1. COA's 1, 2, 5, 6

Figure 3 identities the duration to implement and complete COA's 1, 2, 5, 6.

ID		Task Mode	Task Name	Constraint Date	Duration	Start	Finish
1			PFAS @ BGAD (3) SCWO	NA	338 days	Mon 1/2/23	Tue 12/5/23
2			Design Validation and Modifications	NA	180 days	Mon 1/2/23	Fri 6/30/23
3			Equipment Interfaces (existing w/new)	NA	30 days	Mon 1/2/23	Tue 1/31/23
4			General Arrangement of Equipment	NA	30 days	Wed 2/1/23	Thu 3/2/23
5			Electrical	NA	90 days	Wed 2/1/23	Mon 5/1/23
6			Mechanical	NA	30 days	Wed 2/1/23	Thu 3/2/23
7			Waste Feed Cutoffs (FAWB)	NA	60 days	Tue 5/2/23	Fri 6/30/23
8			Establish Infrastructure Requirements	NA	60 days	Mon 1/2/23	Thu 3/2/23
9			Unloading	NA	30 days	Mon 1/2/23	Tue 1/31/23
10			Loading	NA	30 days	Mon 1/2/23	Tue 1/31/23
11			Building Design	NA	60 days	Mon 1/2/23	Thu 3/2/23
12			Utilities (Termination)	NA	15 days	Mon 1/2/23	Mon 1/16/23
13			Remove SCWO Units (3) from Layup	NA	165 days	Mon 1/2/23	Thu 6/15/23
14			Integrate Modules	NA	15 days	Mon 1/2/23	Mon 1/16/23
15			Ensure Equipment is Operational	NA	60 days	Tue 1/17/23	Fri 3/17/23
16			Establish Interfaces	NA	30 days	Sat 3/18/23	Sun 4/16/23
17			Integrate Systems	NA	60 days	Mon 4/17/23	Thu 6/15/23
18			Engineering	NA	120 days	Mon 1/2/23	Mon 5/1/23
19			Additional Equipment	NA	76 days	Mon 1/2/23	Sat 3/18/23
20			Identify Additional Process Equipment	NA	15 days	Mon 1/2/23	Mon 1/16/23
21			Procure Equipment	NA	8 days	Tue 1/17/23	Tue 1/24/23
22			Install Equipment	NA	15 days	Fri 2/24/23	Fri 3/10/23
23			Integrate Modules/Systems	NA	8 days	Sat 3/11/23	Sat 3/18/23
24			Control System	NA	165 days	Sun 3/19/23	Wed 8/30/23
25			Develop Control System	NA	120 days	Sun 3/19/23	Sun 7/16/23
26			Verify Operational Control	NA	30 days	Mon 7/17/23	Tue 8/15/23
27			Functional Test	NA	15 days	Wed 8/16/23	Wed 8/30/23
28			Mobilize and Train Workforce	NA	38 days	Thu 8/31/23	Sat 10/7/23
29			Control System Operator Training	NA	15 days	Thu 8/31/23	Thu 9/14/23
30			SCWO Operational Training	NA	15 days	Fri 9/15/23	Fri 9/29/23
31			Initial Testing of Process	NA	8 days	Sat 9/30/23	Sat 10/7/23
32			Operations	NA	67 days	Sat 9/30/23	Tue 12/5/23
33			Operations Manual Established	NA	30 days	Sat 9/30/23	Sun 10/29/23
34			Systemization	NA	30 days	Mon 10/30/23	Tue 11/28/23
35			Surrogate Trials	NA	7 days	Wed 11/29/23	Tue 12/5/23

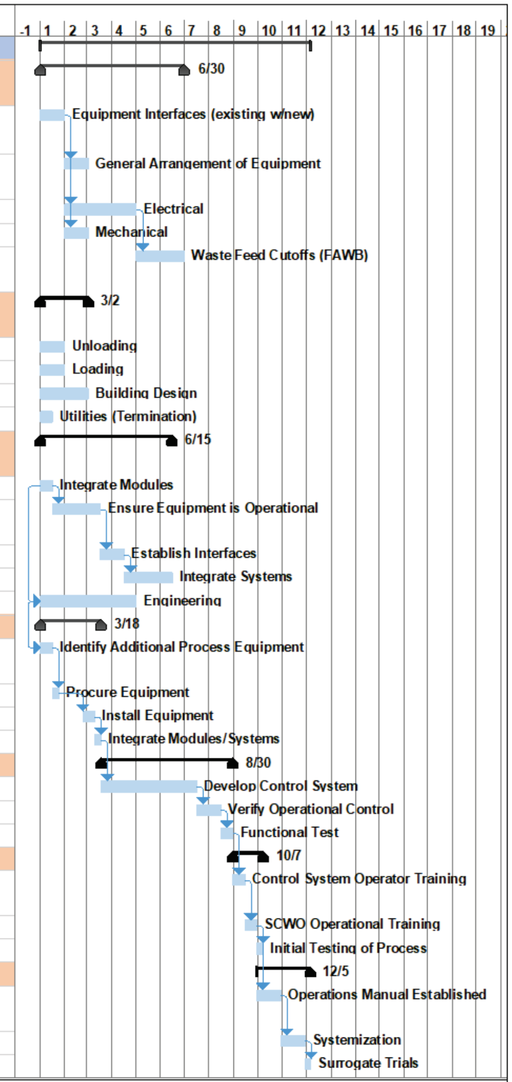

Figure 3. COA's 1, 2, 5, 6 Schedule Duration

16.2. COA's 3, 8

Figure 4 identifies the duration to implement and complete COA's 3 and 8.

ID		Task Mode	Task Name	Constraint Date	Duration	Start	Finish
1			PFAS @ EPA/RSA (3) SCWO	NA	772 days	Mon 1/2/23	Tue 2/11/25
2			Design Validation and Modifications	NA	180 days	Mon 1/2/23	Fri 6/30/23
3			Equipment Interfaces (existing w/new)	NA	30 days	Mon 1/2/23	Tue 1/31/23
4			General Arrangement of Equipment	NA	30 days	Wed 2/1/23	Thu 3/2/23
5			Electrical	NA	90 days	Wed 2/1/23	Mon 5/1/23
6			Mechanical	NA	30 days	Wed 2/1/23	Thu 3/2/23
7			Civil	NA	60 days	Fri 3/3/23	Mon 5/1/23
8			Waste Feed Cutoffs (FAWB)	NA	60 days	Tue 5/2/23	Fri 6/30/23
9			Remove SCWO Units (3) from Layup	NA	30 days	Fri 9/29/23	Sat 10/28/23
10			Remove	NA	30 days	Fri 9/29/23	Sat 10/28/23
11			Disassemble SCWO for Transportation	NA	43 days	Sun 10/29/23	Sun 12/10/23
12			Identify Modules to be Shipped	NA	3 days	Sun 10/29/23	Tue 10/31/23
13			Crate Module for Transportation	NA	15 days	Wed 11/1/23	Wed 11/15/23
14			Transport SCWO Equipment	NA	10 days	Thu 11/16/23	Sat 11/25/23
15			Unpack Equipment	NA	15 days	Sun 11/26/23	Sun 12/10/23
16			Establish Infrastructure Requirements	NA	180 days	Thu 6/1/23	Mon 11/27/23
17			Unloading	NA	30 days	Thu 6/1/23	Fri 6/30/23
18			Loading	NA	30 days	Sat 7/1/23	Sun 7/30/23
19			SCWO Process Building	NA	180 days	Thu 6/1/23	Mon 11/27/23
20			Utility Building (UB)	NA	90 days	Thu 6/1/23	Tue 8/29/23
21			Utilities (including power)	NA	90 days	Wed 8/30/23	Mon 11/27/23
22			Install SCWO Units	NA	225 days	Tue 11/28/23	Tue 7/9/24
23			Locate and Assemble SCWO (3)	NA	60 days	Tue 11/28/23	Fri 1/26/24
24			Integrate Modules	NA	15 days	Sat 1/27/24	Sat 2/10/24
25			Ensure Equipment is Operational	NA	60 days	Sun 2/11/24	Wed 4/10/24
26			Establish Interfaces	NA	30 days	Thu 4/11/24	Fri 5/10/24
27			Integrate Systems	NA	60 days	Sat 5/11/24	Tue 7/9/24
28			Engineering	NA	120 days	Sun 2/11/24	Sun 6/9/24
29			Additional Equipment	NA	120 days	Sat 1/27/24	Sat 5/25/24
30			Identify Additional Process Equipment	NA	30 days	Sat 1/27/24	Sun 2/25/24
31			Procure Equipment	NA	15 days	Mon 2/26/24	Mon 3/11/24
32			Install Equipment	NA	30 days	Tue 3/12/24	Wed 4/10/24
33			Integrate Modules/Systems	NA	45 days	Thu 4/11/24	Sat 5/25/24
34			Control System	NA	165 days	Sun 5/26/24	Wed 11/6/24
35			Develop Control System	NA	120 days	Sun 5/26/24	Sun 9/22/24
36			Verify Operational Control	NA	30 days	Mon 9/23/24	Tue 10/22/24
37			Functional Test	NA	15 days	Wed 10/23/24	Wed 11/6/24
38			Mobilize and Train Workforce	NA	37 days	Thu 11/7/24	Fri 12/13/24
39			Control System Operator Training	NA	15 days	Thu 11/7/24	Thu 11/21/24
40			SCWO Operational Training	NA	15 days	Fri 11/22/24	Fri 12/6/24
41			Initial Testing of Process	NA	7 days	Sat 12/7/24	Fri 12/13/24
42			Operations	NA	67 days	Sat 12/7/24	Tue 2/11/25
43			Operations Manual Establishe	NA	30 days	Sat 12/7/24	Sun 1/5/25
44			Systemization	NA	30 days	Mon 1/6/25	Tue 2/4/25
45			Surrogate Trials	NA	7 days	Wed 2/5/25	Tue 2/11/25

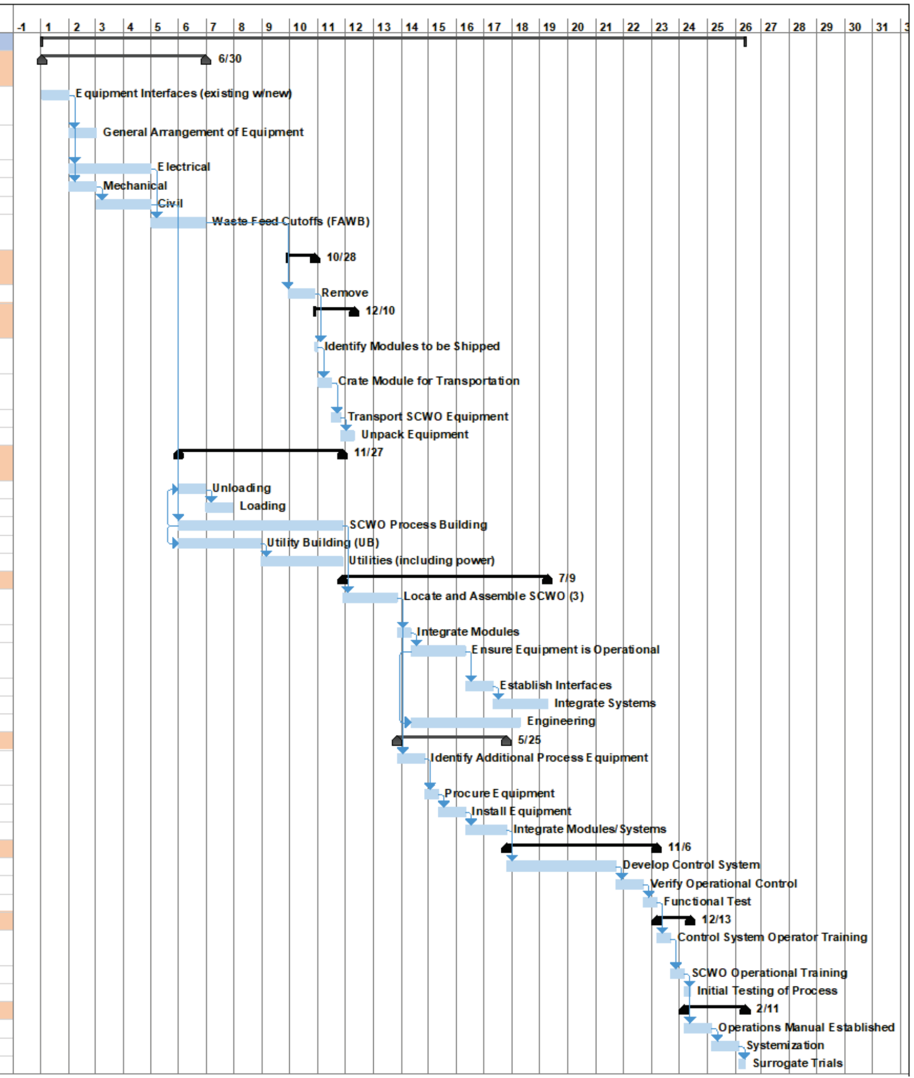

Figure 4. COA's 3 and 8 Schedule Duration

16.3. COA’s 4 and 7 Duration with One (1) SCWO

Figure 5 identifies the duration to implement and complete COA’s 4 and 7 with only one (1) SCWO relocated to each facility (EPA/TEAD).

ID		Task Mode	Task Name	Constraint Date	Duration	Start	Finish
1			PFAS @ EPA/TEAD (1) SCWO	NA	503 days	Mon 1/2/23	Sat 5/18/24
2			Design Validation and Modifications	NA	75 days	Mon 1/2/23	Fri 3/17/23
3			Equipment Interfaces (existing w/new)	NA	15 days	Mon 1/2/23	Mon 1/16/23
4			General Arrangement of Equipment	NA	15 days	Tue 1/17/23	Tue 1/31/23
5			Electrical	NA	30 days	Tue 1/17/23	Wed 2/15/23
6			Mechanical	NA	15 days	Tue 1/17/23	Tue 1/31/23
7			Civil	NA	30 days	Wed 2/1/23	Thu 3/2/23
8			Waste Feed Cutoffs (FAWB)	NA	30 days	Thu 2/16/23	Fri 3/17/23
9			Remove SCWO Unit from Layup	NA	18 days	Tue 5/2/23	Fri 5/19/23
10			Remove	NA	18 days	Tue 5/2/23	Fri 5/19/23
11			Disassemble SCWO for Transportation	NA	31 days	Sat 5/20/23	Mon 6/19/23
12			Identify Modules to be Shipped	NA	3 days	Sat 5/20/23	Mon 5/22/23
13			Crate Module for Transportation	NA	9 days	Tue 5/23/23	Wed 5/31/23
14			Transport SCWO Equipment	NA	10 days	Thu 6/1/23	Sat 6/10/23
15			Unpack Equipment	NA	9 days	Sun 6/11/23	Mon 6/19/23
16			Establish Infrastructure Requirements	NA	120 days	Fri 3/3/23	Fri 6/30/23
17			Unloading	NA	30 days	Fri 3/3/23	Sat 4/1/23
18			Loading	NA	30 days	Sun 4/2/23	Mon 5/1/23
19			SCWO Process Building	NA	120 days	Fri 3/3/23	Fri 6/30/23
20			Utility Building (UB)	NA	60 days	Fri 3/3/23	Mon 5/1/23
21			Utilities (including power)	NA	60 days	Tue 5/2/23	Fri 6/30/23
22			Install SCWO Units	NA	120 days	Sat 7/1/23	Sat 10/28/23
23			Locate and Assemble SCWO	NA	30 days	Sat 7/1/23	Sun 7/30/23
24			Integrate Modules	NA	30 days	Mon 7/31/23	Tue 8/29/23
25			Ensure Equipment is Operational	NA	15 days	Wed 8/30/23	Wed 9/13/23
26			Establish Interfaces	NA	15 days	Thu 9/14/23	Thu 9/28/23
27			Integrate Systems	NA	30 days	Fri 9/29/23	Sat 10/28/23
28			Engineering	NA	60 days	Wed 8/30/23	Sat 10/28/23
29			Additional Equipment	NA	46 days	Mon 7/31/23	Thu 9/14/23
30			Identify Additional Process Equipment	NA	15 days	Mon 7/31/23	Mon 8/14/23
31			Procure Equipment	NA	8 days	Tue 8/15/23	Tue 8/22/23
32			Install Equipment	NA	15 days	Wed 8/23/23	Wed 9/6/23
33			Integrate Modules/Systems	NA	8 days	Thu 9/7/23	Thu 9/14/23
34			Control System	NA	150 days	Fri 9/15/23	Sun 2/11/24
35			Develop Control System	NA	120 days	Fri 9/15/23	Fri 1/12/24
36			Verify Operational Control	NA	15 days	Sat 1/13/24	Sat 1/27/24
37			Functional Test	NA	15 days	Sun 1/28/24	Sun 2/11/24
38			Mobilize and Train Workforce	NA	37 days	Mon 2/12/24	Tue 3/19/24
39			Control System Operator Training	NA	15 days	Mon 2/12/24	Mon 2/26/24
40			SCWO Operational Training	NA	15 days	Tue 2/27/24	Tue 3/12/24
41			Initial Testing of Process	NA	7 days	Wed 3/13/24	Tue 3/19/24
42			Operations	NA	67 days	Wed 3/13/24	Sat 5/18/24
43			Operations Manual Establishe	NA	30 days	Wed 3/13/24	Thu 4/11/24
44			Systemization	NA	30 days	Fri 4/12/24	Sat 5/11/24
45			Surrogate Trials	NA	7 days	Sun 5/12/24	Sat 5/18/24

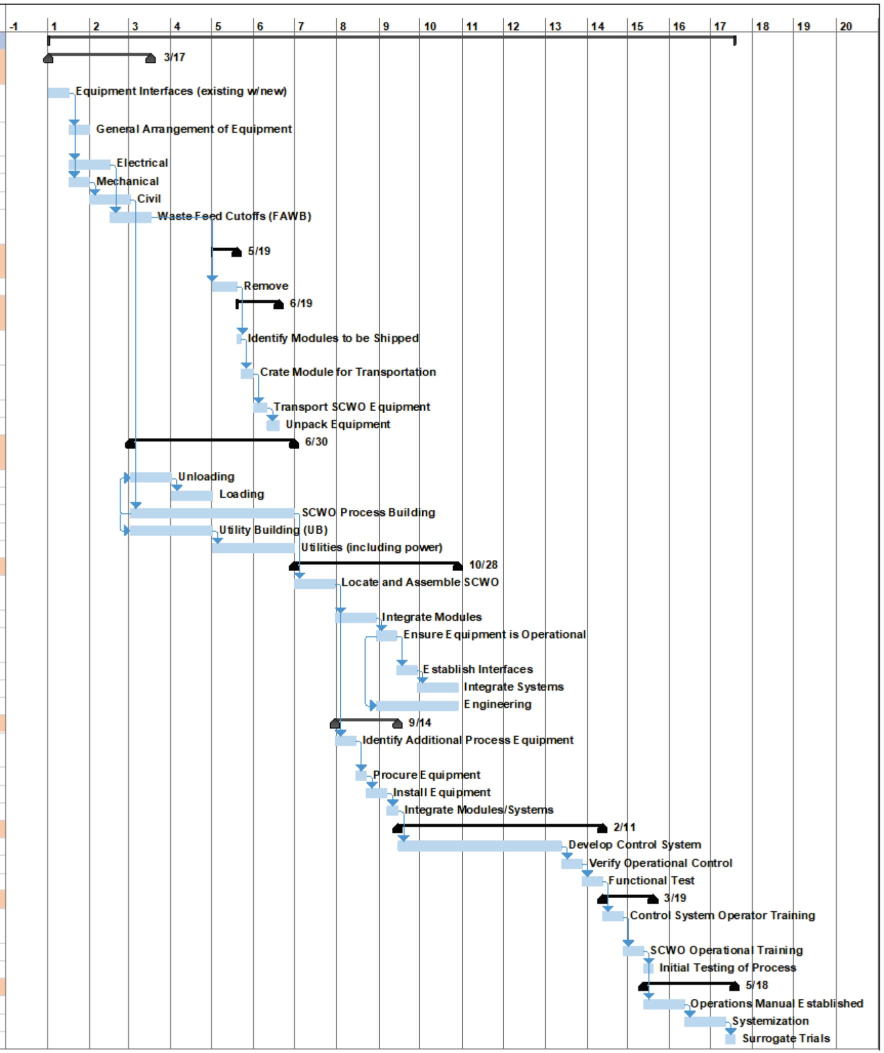

Figure 5. COA's 4 and 7 Schedule Duration with a Single SCWO Relocated

16.4. COA's 4 and 7 Schedule Duration with Two (2) SCWOs

Figure 6 identifies the duration to implement and complete COA's 4 and 7 with two (2) SCWOs relocated to each facility (EPA/TEAD).

ID		Task Mode	Task Name	Constraint Date	Duration	Start	Finish
1			PFAS @ EPA/TEAD (2) SCWO	NA	616 days	Mon 1/2/23	Sun 9/8/24
2			Design Validation and Modifications	NA	165 days	Mon 1/2/23	Thu 6/15/23
3			Equipment Interfaces (existing w/new)	NA	30 days	Mon 1/2/23	Tue 1/31/23
4			General Arrangement of Equipment	NA	30 days	Wed 2/1/23	Thu 3/2/23
5			Electrical	NA	90 days	Wed 2/1/23	Mon 5/1/23
6			Mechanical	NA	15 days	Wed 2/1/23	Wed 2/15/23
7			Civil	NA	60 days	Thu 2/16/23	Sun 4/16/23
8			Waste Feed Cutoffs (FAWB)	NA	45 days	Tue 5/2/23	Thu 6/15/23
9			Remove SCWO Units (2) from Layup	NA	30 days	Mon 7/31/23	Tue 8/29/23
10			Remove	NA	30 days	Mon 7/31/23	Tue 8/29/23
11			Disassemble SCWO for Transportation	NA	37 days	Wed 8/30/23	Thu 10/5/23
12			Identify Modules to be Shipped	NA	3 days	Wed 8/30/23	Fri 9/1/23
13			Crate Module for Transportation	NA	12 days	Sat 9/2/23	Wed 9/13/23
14			Transport SCWO Equipment	NA	10 days	Thu 9/14/23	Sat 9/23/23
15			Unpack Equipment	NA	12 days	Sun 9/24/23	Thu 10/5/23
16			Establish Infrastructure Requirements	NA	150 days	Mon 4/17/23	Wed 9/13/23
17			Unloading	NA	30 days	Mon 4/17/23	Tue 5/16/23
18			Loading	NA	30 days	Wed 5/17/23	Thu 6/15/23
19			SCWO Process Building	NA	150 days	Mon 4/17/23	Wed 9/13/23
20			Utility Building (UB)	NA	75 days	Mon 4/17/23	Fri 6/30/23
21			Utilities (including power)	NA	75 days	Sat 7/1/23	Wed 9/13/23
22			Install SCWO Units	NA	195 days	Thu 9/14/23	Tue 3/26/24
23			Locate and Assemble SCWO (2)	NA	45 days	Thu 9/14/23	Sat 10/28/23
24			Integrate Modules	NA	30 days	Sun 10/29/23	Mon 11/27/23
25			Ensure Equipment is Operational	NA	15 days	Tue 11/28/23	Tue 12/12/23
26			Establish Interfaces	NA	30 days	Wed 12/13/23	Thu 1/11/24
27			Integrate Systems	NA	60 days	Fri 1/12/24	Mon 3/11/24
28			Engineering	NA	120 days	Tue 11/28/23	Tue 3/26/24
29			Additional Equipment	NA	60 days	Sun 10/29/23	Wed 12/27/23
30			Identify Additional Process Equipment	NA	15 days	Sun 10/29/23	Sun 11/12/23
31			Procure Equipment	NA	15 days	Mon 11/13/23	Mon 11/27/23
32			Install Equipment	NA	15 days	Tue 11/28/23	Tue 12/12/23
33			Integrate Modules/Systems	NA	15 days	Wed 12/13/23	Wed 12/27/23
34			Control System	NA	159 days	Thu 12/28/23	Mon 6/3/24
35			Develop Control System	NA	120 days	Thu 12/28/23	Thu 4/25/24
36			Verify Operational Control	NA	24 days	Fri 4/26/24	Sun 5/19/24
37			Functional Test	NA	15 days	Mon 5/20/24	Mon 6/3/24
38			Mobilize and Train Workforce	NA	37 days	Tue 6/4/24	Wed 7/10/24
39			Control System Operator Training	NA	15 days	Tue 6/4/24	Tue 6/18/24
40			SCWO Operational Training	NA	15 days	Wed 6/19/24	Wed 7/3/24
41			Initial Testing of Process	NA	7 days	Thu 7/4/24	Wed 7/10/24
42			Operations	NA	67 days	Thu 7/4/24	Sun 9/8/24
43			Operations Manual Establishe	NA	30 days	Thu 7/4/24	Fri 8/2/24
44			Systemization	NA	30 days	Sat 8/3/24	Sun 9/1/24
45			Surrogate Trials	NA	7 days	Mon 9/2/24	Sun 9/8/24

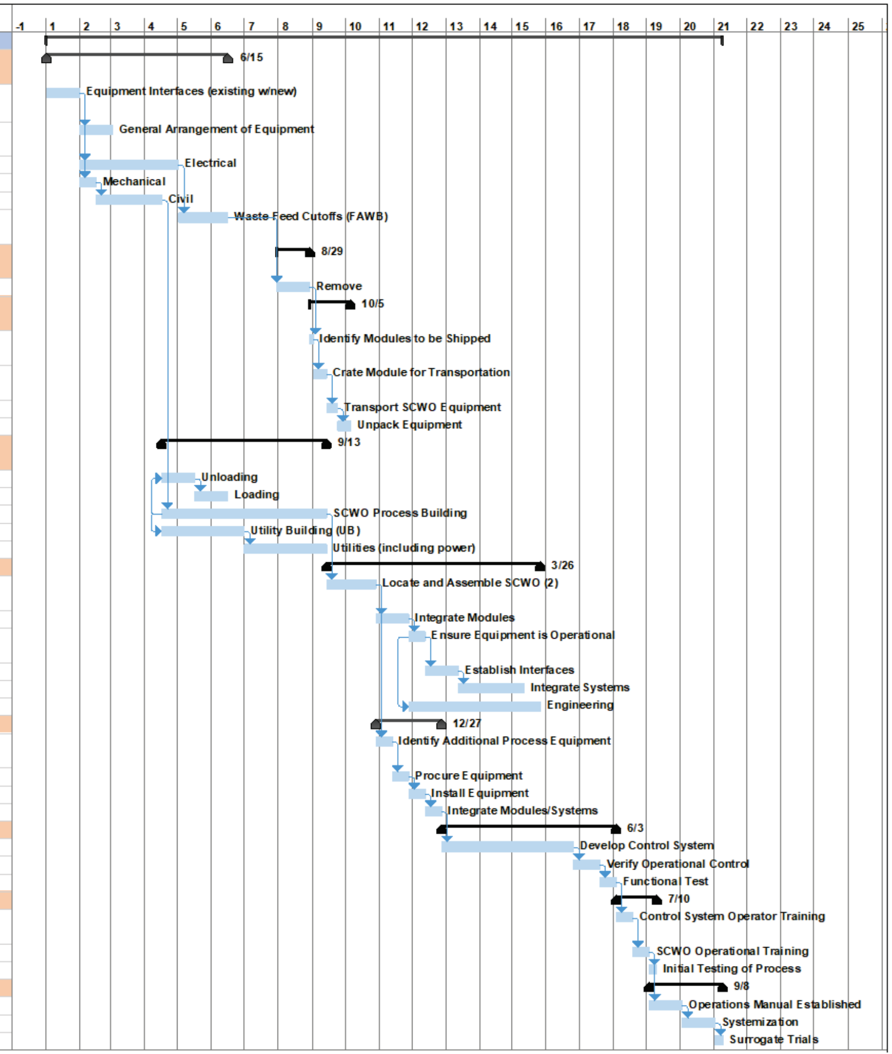

Figure 6. COA's 4 and 7 with Two (2) SCWOs Relocated

16.5. ROM Cost and Schedule Summary

Utilizing the data from Section 15 of this technical paper and the schedules provided above, a summary chart for cost and schedule was made. Table 12 summarizes as follows:

Table 14. ROM Cost and Schedule for COA's

Courses of Action	Schedule Duration	ROM Estimate
COA 1, 2, 5, 6	11.1 months	$3,762,000
COA 3, 8	25.4 months	$6,210,000
COA 4, 7 (1 SCWO)	16.5 months	$3,564,000
COA 4, 7 (2 SCWO)	20.3 months	$5,035,000

17. DEMONSTRATION TEST PLAN

The following section of this Study outlines a possible Demonstration Test that could be performed using a single SCWO train at BGCAPP. It provides background information on PFAS, test objectives, and facilities required to execute the test. The content of this sample test plan is an execution strategy for planning purposes, including assumptions, approaches, and methodology.

17.1 Background

Various industries have produced and used per- and polyfluoroalkyl substances (PFAS). They are found in both consumer and industrial products, including non-stick coatings, waterproofing materials, and as a manufacturing additive. PFAS compounds are stable and resistant to natural destruction in the environment, leading to their pervasive presence in groundwater, surface waters, drinking water, and other environmental media (soil).[103]

A significant source of PFAS found in the environment is due to the use of AFFF. Used to extinguish fuel and other flammable liquid fires, AFFF is widely used at airports, military sites, chemical plants, and above-ground petroleum storage tank facilities. Many fire departments use AFFF for training and emergency response. There have been instances of AFFF contaminating groundwater after being used to extinguish vehicle fires. When AFFF is used, runoff may enter sewers or contaminate soil and groundwater. Due to its pervasive and toxic nature, the EPA has established drinking water health advisories: 0.004 ppt for PFOA and 0.02 ppt for PFOS.[104]

After decades of PFAS use in industrial manufacturing and firefighting applications, regulations are rapidly being adopted and enforced to establish strict cleanup standards and to phase out several notable PFAS compounds, including PFOS and PFOA. Incineration of PFAS-rich wastes is currently the industry standard for disposal but is being phased out in many locations due to concerns over toxic emissions of short-chain PFAS molecules and volatile organic fluorocarbons (VOFs) damaging to the environment (greenhouse gases) and human health.[102] In addition, incineration is not a permissible option for DoD (a temporary moratorium on incineration is cited in the National Defense Authorization Act {NDAA} FY 22).[105]

17.2. Description

Based on the information documented within this SCWO Study, it is most likely that COA 1: "AFFF Processed in the SCWO @ BGAD" would be demonstrated to obtain information regarding the destruction of PFAS (PFOS and perfluorooctanoic acid (PFOA)) in AFFF. The demonstration would be performed utilizing a single SCWO train located in the SPB. The intent of the demonstration test would be to evaluate the efficacy of AFFF/PFAS destruction and maximize the throughput. The question of whether the SCWO can efficiently destroy the PFAS has been or would be answered during bench-scale testing. Therefore, it can be assumed that the SCWO technology works to destroy PFAS at the parameters established during the testing. The question this demonstration test would be intended to inform is: is it feasible, at an industrial scale, to effectively treat PFAS-containing streams, specifically concentrated AFFF in the BGAD SCWO.[101]

The efficacy of the performance would be evaluated based on destruction and mineralization rates for PFAS as a function of feed rate, temperature, and residence time. Determining the destruction and mineralization of legacy AFFF formulations for each design case is identified above (specific objectives can be found in this Demonstration Test Plan in Section A.3 of this Study).[102]

COA 1 (a single SCWO train) was selected for the following reasons:

- There are no requirements to transport the single SCWO train to another facility; expected that the control system may be used as designed.
- A single reactor demonstration minimizes the effort required to prepare the train for operations.
- AFFF, as a waste stream, can be obtained for testing purposes.
- The SCWO technology has been identified by the scientific community and federal agencies as an acceptable technology for PFAS/AFFF treatment.
- Bench scale testing has proven that the SCWO technology can effectively destroy PFAS/AFFF.
- The destruction results of PFAS have been documented (>99.99% destruction efficiencies for PFSA and PFCAs at T>600 C and residence time of approximately 30 sec) and published in several scientific literature.

- While AFFF formulation is more complex than neat PFAS, limited-scope studies suggest that SCWO is also effective in treating complex PFAS matrices.[102]

17.3. Demonstration Test

A demonstration test would be held at the BGAD to demonstrate high-volume treatment of PFAS (PFOS and PFOA) contained in AFFF/contaminated waste and/or concentrated legacy AFFF stock in the SCWO facility. The test would consist of treating PFAS and AFFF/contaminated waste in a single reactor train and establishing the efficacy of various operational conditions.

The intent of this demonstration would be to maximize the throughput of the PFAS while monitoring destruction efficiency. It is assumed that SCWO technology works to destroy PFAS based on previous bench-scale efforts and demonstrations. The intent would be to evaluate, at an industrial scale, if PFAS-contaminated stream destruction (including legacy AFFF stock) is possible using the existing BGAD SCWO facilities.[101]

Two methods can be tested to help address the above question. They are as follows:

- The initial design limits for the BGAD SCWO are 1,000 lbs/hr of feed and 188 lbs/hr of fuel. During the demonstration, the AFFF flow rate would be ramped incrementally from a predetermined starting point until the design limit parameters (reactor temperature and residence time) are achieved (flow rate depends upon residence time).

- After AFFF's maximum feed is achieved, reactor temperature would be reduced in 20-50° increments from 650°C using fuel flow rate while collecting liquid effluent and gas exhaust for analysis.

Note: For purposes of this testing, a single manufacturer of AFFF would be utilized due to the inconsistency of concentration standards and lot variations across the industry. This allows the concentration level of PFAS in AFFF, by lot, to be the same when performing all testing.

The characterization includes destruction and mineralization rates of PFAS and legacy AFFF for each design case identified above[102]. Refer to the "Objectives" section of this Demonstration Test Plan for more detailed objectives related to the general information provided above.

17.4. Facility Activities

Before the demonstration test is performed, the following activities would need to be completed to prepare the SPB and SCWO equipment for PFAS-contaminated waste and AFFF stock testing and processing. These activities include, but are not limited to:

- SCWO Facility and Process Equipment: A multi-disciplinary review would be performed to evaluate the SCWO system prior to its operation.

- Modify Facility and/or Process Equipment: These modifications, if required, would be based on the multi-disciplinary review previously performed.

- Utility Termination: Utilities coming into the SCWO process building (SPB) would have to be isolated from those going to the MDB.

- Integrate Modules/System: Once the SCWO is taken out of lay-up, the various modules/systems would require integration.

- Establish Interfaces: The SCWO modules would require their interfaces to be established once modules are integrated.

- Identify Additional Systems and Procure/Install: If the demonstration testing requires equipment currently unavailable at the SPB, it would be procured/installed as required.

- Perform Functional Test (Control System): This test would be required to ensure the control system is fully operational and the software will function as designed.

- Initial Testing of the Process: Initial testing would be performed to ensure all equipment and software are functional and the SCWO is fully operational.

- Systemization: This is the start of processing material through the SCWO.

17.5 Objectives

The following objectives and their corresponding implementation plans provide a reasonable approach for the execution of this demonstration test.

1. Evaluate and adjust various parameters of the SCWO (SCWO design limits and operational temperature envelop) to maximize the throughput of the PFAS-containing stream and take measurements and samples as described in objectives 2 and 3 for each configuration.

2. Determine the destruction and mineralization rates of AFFF as a function of temperature and residence time. The liquid effluent and gas samples of organic and inorganic intermediates will be analyzed.

3. Determine the destruction and mineralization of legacy AFFF formulations (2-3 formulations to be evaluated).

17.6. Implementation

The following, listed by objective, are descriptions of what is required to implement the above tasking. Requirements for each include:

17.6.1. Objective 1

- **SCWO Design Limitations:** This test requires understanding the SCWO's existing operational characteristics. Currently, the design limitations for the SCWO are 1,000 lbs/hr of solution and 188 lbs/hr of fuel. A test may be performed at these conditions unless it is determined that a lower flow rate starting point is required.[101] In this case, the flow rate would be started at a predetermined value and increased to reach maximum throughput limited by reactor operating temperature and allowable HF level in the effluent (flow rate depends upon residence time).

- **Temperature Adjustments:** This test requires an understanding of the processing of AFFF at the SCWO's maximum feed. Once the maximum feed has been achieved at a reactor setting (T~ 650°C), the reactor's temperature would be lowered by predetermined increments while monitoring reactor effluent for organic and inorganic Fluorine and intermediate products of oxidation.[101]

- **Analysis:** It should be noted that the configuration of conditions found in Objectives 2 and 3 would have to be established depending on the testing performed and the materials utilized for the tests in Objective 1. In addition, initial testing and final testing samples of the fluid would be required for comparative purposes with the processed liquid to calculate Destruction Removal Efficiency (DRE) and ensure there is no carryover.

17.6.2 Objective 2

For each design parameter identified for the demonstration test, the following analysis would be performed, and several samples would be taken for each.

DRE should be measured using qualitative Mass Spectrometry (MS) methods for organic Fluorene analysis (Liquid Chromatography (LC)/Mass Spectrometry (MS) or Time-of-Flight (TOF/Mass Spectrometry (MS)). The mineralization rate can be measured by Ion Chromatography (IC) or Ion-selective Electrode (ISE), or other methods according to EPA approved method (e.g., Draft Metod 1633)[106] (refer to the implementation of Objective 3).

It is anticipated that approximately 75 samples would be collected to determine the destruction and mineralization rates for AFFF.[107] Liquid effluent, organic and inorganic gas samples will be retrieved and evaluated.[102] The liquid effluent samples would be evaluated using EPA approved methods, while the organic and inorganic gas samples would be evaluated using Gas Chromatography (GC)/Mass Spectrometry (MS) or possibly Fourier-Transform Infrared Spectroscopy (FTIR). The gas samples could be collected into Tedlar bags, Adsorbent traps, or into a solvent for analysis according to an approved method (e.g., OTM-45).[106]

The following temperatures and residence times would be utilized to determine the destruction and mineralization rates of AFFF:

- 500-650 C (3-5 temperatures): 5 conditions.
- 10s, 30s, 60s (3 residence times): 3 conditions.
- 5 samples for each of 15 conditions.[107]

Some or all of the conditions identified above may be used during the demonstration test (Objective 1). It is assumed that the test outlined in Objective 2 has already been performed during bench-scale testing.

17.6.3 Objective 3

For each design parameter identified for the demonstration test, the following analysis would be performed, and a number of samples would be taken for each.

It is anticipated that approximately 135 samples, for each formulation, would be collected for analysis. The analysis of the samples for the destruction and mineralization of legacy AFFF formulations would be performed by measuring the inorganic F (fluoride) via IC or F ISE. The fluoride measurements would be compared with the analysis of organic fluorene by LC/MSor other methods according to EPA methods (e.g., Draft Method 1633).[108] Sample analysis can be performed by a certified Third-Party Laboratory.

Generalization of the SCWO reactor operation for energetic PFAS streams includes mixing fuel into the PFAS stream (e.g., EtOH, IPA, or glycol in different proportions). This would determine how much the SCWO reactor can tolerate before its temperature can no longer be controlled and flaming combustion begins. This is a known concern based on industry input when treating PFAS. Problems with system control and material limits are likely to occur.[106]

The following temperatures and residence times would be utilized to determine the destruction and mineralization rates of legacy AFFF formulations (containing glycols)

- 550-650 C (3 temperatures): 3 conditions[109]
- 10s, 30s, 60s (3 residence times): 3 conditions.
- 1X – 20X (3 dilutions): 3 conditions[109]
- 5 samples for each of 27 conditions.

Some or all of the conditions identified above may be used during the demonstration test (Objective 1). It is assumed that the test outlined in Objective 3 has already been performed during bench-scale testing.

17.7. Summary

Various industries have produced and used PFAS. A significant source of PFAS in the environment is the use of AFFF. AFFF is widely used at airports, military sites, chemical plants, and above-ground petroleum storage tank facilities. The EPA has established drinking water health advisories: 0.004 ppt for PFOA and 0.02 ppt for PFOS.[104]

The intent of this demonstration test would be to maximize the throughput of the PFAS while monitoring destruction efficiency. It is assumed that SCWO technology works to destroy PFAS based on previous bench scale efforts and demonstrations.[101] The characteristics of the demonstration test would include destruction and mineralization rates of PFAS and legacy AFFF for each of the design cases identified in the body of this Demonstration Test Plan.[102]

Several tests could be performed, and samples would be retrieved for evaluation. The two demonstration tests would include SCWO Design Limitations and Temperature Adjustments. The question this demonstration test would be intended to address is: is it feasible, at an industrial scale, to operate/process PFAS through the BGAD SCWO.[101]

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REFERENCES

1 Bechtel Parsons, General Atomics, *System Design Description for Aluminum Filtration System*, Rev. 7, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 20-May-2010.

2 Bechtel Parsons, *System Design Description for Aluminum Precipitation System (APS),* Rev. 2, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 21-Jul-2009.

3 Bechtel Parsons, *System Design Description for Water Recovery System*, Rev. 5, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 24-Feb-2020.

4 Bechtel Parsons, *System Design Description for Supercritical Water Oxidation System*, Rev. 4, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 21-May-2010.

5 Bechtel Parsons, General Atomics, *System Design Description for Aluminum Filtration System*, Rev. 10, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 28-Mar-2016.

6 Bechtel Parsons, *System Design Description for Aluminum Precipitation System (APS)*, Rev. 3, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 18-Feb-2016.

7 Bechtel Parsons, *System Design Description for Water Recovery System*, Rev. 5, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 25-Feb-2020.

8 Bechtel Parsons, General Atomics, *System Design Description for Supercritical Water Oxidation System*, Rev. 7, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 26-Feb-2020.

9 Bechtel Parsons, *System Description for Power Distribution System*, Rev. 3, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 20-Sep-2019.

10 Bechtel Parsons, *SCWO Process Building Ground Floor Plan*, 24915-10-A1-00-00001, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 29-Mar-2007.

11 Bechtel Parsons, *SCWO Process Building General Arrangement Overall Floor Plan*, 24915-10-AE-00-00001, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 29-Mar-2007.

12 Bechtel Parsons, *Construction Facilities Layout Temporary 480V Distribution Power Plan*, 24915-00-C2K-00-00001, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 8-Jun-2013.

13 Bechtel Parsons, *SCWO Process Building General Arrangement Overall Floor Plan,* 24915-10-AE-00-00001, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 3-Dec-2009.

14 Bechtel Parsons, *Utility Building General Arrangement Overall Floor Plan*, 24915-13-AE-00-00001, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 24-Aug-2009.

15 Bechtel Parsons*, Aluminum Filtration System Process Flow Diagram*, 24915-10-M5-AFS-00001, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 15-May-2017.

16 Bechtel Parsons, *SCWO Processing Building Aluminum Precipitation Process Flow Diagram*, 24915-10-M5-APS-00001, 1 of 3, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 15-May-2017.

17 Bechtel Parsons, *SCWO Processing Building Aluminum Precipitation Process Flow Diagram*, 24915-10-M5-APS-00001, 2 of 3, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 15-May-2017.

18 Bechtel Parsons, *SCWO Processing Building Aluminum Precipitation Process Flow Diagram*, 24915-10-M5-APS-00001, 3 of 3, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 15-May-2017.

19 Bechtel Parsons*, SCWO Processing Building SCWO Process Flow Diagram*, 24915-10-M5-SCWO-00001, 1 of 7, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 13-Dec-2019.

20 Bechtel Parsons, *SCWO Processing Building SCWO Process Flow Diagram*, 24915-10-M5-SCWO-00001, 2 of 7, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 13-Dec-2019.

21 Bechtel Parsons, *SCWO Processing Building SCWO Process Flow Diagram*, 24915-10-M5-SCWO-00001, 3 of 7, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 13-Dec-2019.

22 Bechtel Parsons, *Site Utility Systems Distribution Piping, Piping & Instrument Diagram*, 24915-03-M6-UTIL-00001, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 16-Jul-2019.

23 Bechtel Parsons, *Site Utility Systems Distribution Piping, Piping & Instrument Diagram*, 24915-03-M6-UTIL-00002, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 16-Jul-2019

24 Bechtel Parsons, *Site Utility Systems Distribution Piping, Piping & Instrument Diagram*, 24915-03-M6-UTIL-00003, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 16-Jul-2019.

25 Bechtel Parsons, *Site Utility Systems Distribution Piping, Piping & Instrument Diagram*, 24915-03-M6-UTIL-00004, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 16-Jul-2019.

26 Bechtel Parsons, *Site Utility Systems Distribution Piping, Piping & Instrument Diagram*, 24915-03-M6-UTIL-00005, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 16-Jul-2019.

27 Bechtel Parsons, *Site Utility Systems Distribution Piping, Piping & Instrument Diagram*, 24915-03-M6-UTIL-00006, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 16-Jul-2019.

28 Bechtel Parsons, *Site Utility Systems Distribution Piping, Piping & Instrument Diagram*, 24915-03-M6-UTIL-00007, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 16-Jul-2019.

29 Bechtel Parsons, *Startup Release to Operations Turnover Package SCWO Processing Building HVAC (SHV)*, 24915-OPS-572-00-00047, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 21-Aug-2018.

30 Bechtel Parsons*, Startup Release to Operations Turnover Package Reverse Osmosis Unit System (RO)*, 24915-OPS-572-00-00056, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 17-Apr-2020.

31 Bechtel Parsons, *Startup Release to Operations Turnover Package Supercritical Water Oxidation System (SCWO)*, 24915-OPS-572-00-00057, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 17-Apr-2020.

32 Bechtel Parsons, *SPB Area Foundation Location Plan - SH 2 Area 10-10*, 24915-10-DB-00-00047, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 19-Apr-2010.

33 Bechtel Parsons*, SPB Area Foundation Location Plan - SH 3 Area 10-11 & 10-12*, 24915-10-DB-00-00048, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 5-Jun-2015.

34 Bechtel Parsons*, SPB Area Foundation Location Plan - SH 5 Area 10-15 & 10-16*, 24915-10-DB-00-00049, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 12-Nov-2019.

35 Bechtel Parsons, *SPB Area Foundation Location Plan - SH 4 Area 10-13 & 10-15*, 24915-10-DB-00-00050, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 12-Nov-2019.

36 Blue Grass Chemical Agent-Destruction Pilot Plant, *Plant System Description*, Rev. 3, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 1-Mar-2016.

37 Blue Grass Chemical Agent-Destruction Pilot Plant, *Plant Systems Description for Maintenance*, Rev. 2, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 1-May-2016.

38 Bechtel Parsons*, Test Report for Supercritical Water Oxidation (SWCO) First-of-a-Kind (FOAK) Test,* Rev. 0, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 1-Sep-2013.

39 Bechtel Parsons, *Supercritical Water Oxidation (SCWO) Shakedown Plan*, Rev 0., Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 19-Nov-2019.

40 Bechtel Parsons, *Supercritical Water Oxidation (SCWO) Shakedown Final Report*, Rev. 0, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 8-May-2020.

41 Bechtel Parsons, *Systemization Test Procedure/Systemization Demonstration Procedure for the Supercritical Water Oxidation (SCWO) System*, Rev. 0, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 8-Nov-2019.

42 Bechtel Parsons, *BGCAPP Systemization Demonstration Procedure (SDP) Test Summary Report for Supercritical Water Oxidation System*, Rev. 0, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 28-Feb-2020.

43 Bechtel Parsons, *Standing Operating Procedure for Supercritical Water Oxidation (SCWO) Reactor Operations Working Copy*, Rev. B, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 22-Oct-2019.

44 Bechtel Parsons, *SCWO Processing Building (SPB) Utility Power Center 10-UPC-101 Equipment Layout Plan*, 24915-10-EA-00-10002, Blue Grass Chemical Agent Destruction Pilot Plant Project (BGCAPP), 28-Mar-2013.

45 General Atomics, *ACWA Draft Test Technical Report - Volume 1*, General Atomics, 30-Jun-1999.

46 General Atomics, *ACWA Draft Test Technical Report - Volume 2 Appendices,* General Atomics, 30-Jun-1999.

47 Arthur D. Little, Inc., *Summary of General Atomics Demonstration Testing - ERH, DSHS, and SCWO*, Arthur D. Little, 23-Mar-2001.

48 Arthur D. Little, Inc., *Testing Milestone Report of Foster Wheeler's Supercritical Water Oxidation (SCWO) System*, Arthur D. Little, 13-Nov-2000.

49 Assembled Chemical Weapons Assessment, *Supplemental Report to Congress*, Department of Defense, 30-Sep-1999.

50 Assembled Chemical Weapons Assessment, *Supplemental Report to Congress*, Department of Defense, 23-Jun-2005.

51 General Atomics, *Engineering Design Studies, Final Test Report, Volume II - Supercritical Water Oxidation*, General Atomics, Jul-2002.

52 General Atomics, *Engineering Design Studies, Final Test Report, Volume II - Supercritical Water Oxidation Appendices*, General Atomics, Jul-2002.

53 Marrone, Philip A., Darren W. Dalton, *Testing of Solid Wall and Transpiring Wall SCWO Systems for Demilitarization of Chemical Weapons*, *Ind. Eng. Chem. Res.*, 44, 9030-9039, 2005.

54 Arthur D. Little, Inc., *Summary of General Atomics Engineering Design Study I - Supercritical Water Oxidation (SCWO) Testing,* Arthur D. Little, 1-Apr-2002.

55 Focis Associates, *Summary of General Atomics Engineering Design Studies I - Energetics Rotary Hydrolyzer (ERH) and Supercritical Water Oxidation (SCWO) Process Testing (Hydrolysates of GB, VX, and Comp B/M28), Final Technical Report*, Volume 1 of 2, Focis Associates, 10-Dec-2002.

56 Focis Associates, *Summary of General Atomics Engineering Design Studies I - Energetics Rotary Hydrolyzer (ERH) and Supercritical Water Oxidation (SCWO) Process Testing (Hydrolysates of GB, VX, and Comp B/M28), Final Technical Report*, Volume 2 of 2, Focis Associates, 10-Dec-2002.

57 Foster Wheeler Development Corporation, *EDS II TW-SCWO Optimization Report*, Foster Wheeler Development Corporation, 6-Jul-2001.

58 Foster Wheeler Development Corporation, *TW-SCWO Operability Test Summary Report*, Foster Wheeler Development Corporation, 10-Jan-2003.

59 Focis Associates*, Summary of Foster Wheeler Engineering Design Studies II Supercritical Water Oxidation (SCWO) Testing, Final Technical Report*, Volume 1 of 2, Focis Associates, 31-Jan-2003.

60 Focis Associates, *Summary of Foster Wheeler Engineering Design Studies II Supercritical Water Oxidation (SCWO) Testing, Final Technical Report*, Volume 2 of 2, Focis Associates, 31-Jan-2003.

61 General Atomics, *Technical Risk Reduction Project (TRRP) 07 and 08: Report on Supercritical Water Oxidation Accelerated Blended Feed Tests*, Rev. 2, 24915-00-GQY-GGEN-00014, Bechtel Parsons Blue Grass Team, 23-Jan-2006.

62 General Atomics, *Technical Risk Reduction Project (TRRP) 07 and 09: Report on Supercritical Water Oxidation Blended Feed Performance Tests*, Rev. 0, 24915-00-GQY-GGEN-00034, Bechtel Parsons Blue Grass Team, 5-May-2005.

63 General Atomics, *Test Report for Supercritical Water Oxidation (SCWO) First-of-a-Kind (FOAK) Test*, Rev. 0, 24915-00-GQY-GGEN-00094, 24-Sep-2013.

64 Bechtel Parsons Blue Grass Team, *Characterization of Supercritical Water Oxidation (SCWO) Operating Requirements*, Rev. 0, 24915-00-30R-SCWO-00001, 25-Sep-2014.

65 Bechtel Parsons Blue Grass Team, *Identification of SCWO Knowledge, Experience, and Potential Performance Gaps*, Rev. 0, 24915-00-30R-SCWO-00002, 24-Sep-2014.

66 Bechtel Parsons Blue Grass Team, *Recommendations for Correcting Potential Gaps in Supercritical Water Oxidation (SCWO) Knowledge, Experience, and Performance*, Rev. 0, 24915-00-30R-SCWO-00003, 27-Oct-2014.

67 Bechtel Parsons Blue Grass Team, *Supercritical Water Oxidation (SCWO) Working Group (SWG) Systemization Planning Report,* Rev. 0, 24915-00-30R-SCWO-00004, 17-Dec-2014.

68 Bechtel Parsons Blue Grass Team, *Systemization Test Procedure/Systemization Demonstration Procedure for the Supercritical Water Oxidation (SCWO) System*, Rev. 0, 24915-SYS-5FD-SCWO-00001a01, 8-Nov-2019.

69 Bechtel Parsons Blue Grass Team, *BGCAPP Systemization Demonstration Procedure (SDP) Test Summary Report for Supercritical Water Oxidation System*, Rev. 0, 24915-SYS-5FD-SCWO-00001A02, 28-Feb-2020.

70 Blue Grass Government Team, *Blue Grass Government Team Field Report: SCWO Blend Tank SDP,* FR--B-3660-2020, Blue Grass Government Team, 10-Jan-2020.

71 Blue Grass Government Team, *Blue Grass Government Team Field Report: SCWO Reactor SDP*, FR--B-3669-2020, Blue Grass Government Team, 22-Jan-2020.

72 Blue Grass Government Team, *Blue Grass Government Team Field Report: SCWO SDP Additional Observations*, FR--B-3675-2020, Blue Grass Government Team, 27-Jan-2020.

73 Blue Grass Government Team, *Supercritical Water Oxidation (SCWO) Shakedown Final Report*, Rev. 0, 24915-00-GQY-GGEN-00156, Blue Grass Government Team, 8-May-2020.

74 Blue Grass Government Team, *GFO Review of SCWO Shakedown Period*, FR-B-3706-2020, Blue Grass Government Team, 11-May-2020.

75 Mierau, Jeff, ClydeUnion Pumps, *Engineering Report: Reciprocating Power Pump Failure Analysis*, PL100388B-1, ClydeUnion, 21-May-2020.

76 Vojcak, Edward D., SGS Msi, *Investigative Summary: Metallurgical Report on Failed HP Quench Water Pump*, Report No. 296304, SGS Msi, 5-May-2020.

77 Blue Grass Government Team, *SCWO Rx1 Quench Pump Failure*, FR-B-3710-2020, Blue Grass Government Team, 1-Jun-2020.

78 Glenn Hong, *SCWO Rupture Disk Observations*, 6-Aug-20.

79 Bechtel Parsons Blue Grass Team, *BGCAPP SCWO Reactor Shutdowns During Systemization*, Bechtel Parsons, 8-Jun-2020.

80 Bechtel Parsons Blue Grass Team, *SCWO Shutdowns 03-13-2020 Through Current*, Bechtel Parsons Blue Grass Team, 22-Jun-2020.

81 Bechtel Parsons Blue Grass Team, *SCWO Safety Panel Sizing Calculation*, 24915-10-M6C-SCWO-00049, Bechtel Parsons Blue Grass Team, 15-Apr-2014.

82 Bechtel Parsons Blue Grass Team, *SCWO Reactor Compartment Relief Panel Sizing*, 24915-10-M6C-SCWO-80036, Bechtel Parsons Blue Grass Team.

83 Environmental Protection Agency, *PFAS Strategic Roadmap: EPA's Commitments to Action 2021-2024,* EPA 2021.

84 Interstate Technology Regulatory Council, *History and Use of Per- and Polyfluoroaklyl Substances (PFAS) Found in the Environment,* ITRC, Aug-2020.

85 Krause, Max J., Eben Thoma, Endalkachew Sahle-Damesessie, Brian Crone, Andrew Whitehall, Erin Shields, and Brian Gullet, *Supercritical Water Oxidation as an Innovative Technology for PFAS Destruction*, ASCE, 23-Nov-2021.

86 CB&I and VG Associates, *Elimination System Evaluation: Summary Report,* 31-Dec-2016.

87 Soukos Robotics, *Un-Manned Air Platform for Multiple Purposes*, Soukos, 2022.

88 *Controlled Hazardous Substance Research, Development and Demonstration Permit Application for the Castalia Waste Munitions Demilitarization System, Aberdeen Proving Ground, Volume 1,* July-2021.

89 National Academies of Science, Engineering, and Medicine, *Alternatives for the Demilitarization of Conventional Munitions,* Washington DC: The National Press Academies Press. 2019.

90 Aquarden, *Defense Industry*, Aquarden.

91 Battelle*, PFAS Annihilator Destruction Technology*, Battelle.

92 Xu, Donghai, Shuzhong Want, Xdingying Tang, and Yanmeng Gong, *Design of the first pilot scale plant of China for supercritical water oxidation of sewage sludge*, ResearchGate, 1-Feb-12.

93 General Atomics, *industrial Sueprcritical Water Oxidation (iSCWO)*, General Atomics.

94 Scfi, *Supercritical Water Oxidation & Water Treatment (LIFE + Lo2x)*, Scfi.

95 Treatment Plant Operator, *EU Project Brings Innovative Wastewater Treatment Technology to Spain*, Treatment Plant Operator, 16-Sep-14.

96 Kart, Jeff, *Cleantech Company 374Water Touts PFAS-Eliminating Technology that 'Makes Toxic Sludge Turn to Water'*, 374Water, 21-Jul-21.

97 374Water, *Supercritical Water Oxidation: AirSCWO*, 374Water.

98 374Water, *Supercritical Water Oxidation: AirSCWO*, 374Water.

99 Marrone, Philip A., *Supercritical Water Oxidation - Current Status of Full-scale Commercial Activity for Waste Destruction*, Environmental Protection Agency.

100 Adar, Elanur, Mahir Ince, and Mehmet Sinan Bilgil, *Evaluation of Development in Supercritical Water Oxidation Technology, Desalination and Water Treatment*, 18-Apr-19.

101 Coughlin, Mark*, PFAS Demonstration Test Plan - BGAD SCWO Email*, 15-Nov-22.

102 Novosselov, Igor V., *Defluorination of PFAS-containing Wastes in Supercritical Water Oxidation Environment*, 2022.

103 EPA Office of Research and Development, *Potential PFAS Destruction Technology: Supercritical Water Oxidation*, Environmental Protection Agency, Jan-21.

104 American Association for the Advancement of Science, *What We Know: Per- and Polyfluoroalkyl Substances (PFAS)*, AAAS EPI Center, Jul-22.

105 Cramer, Paul D., *Temporary Prohibition on Incineration of Materials Containing Per- and Polyfluoroalkyl Substances (PFAS)*, Office of the Assistant Secretary of Defense, 26-Apr-22.

106 Novosselov, Igor V., *Re: Additional Questions Email*, 9-Nov-22.

107 Novosselov, Igor V., *Re: Final Questions Email*, 10-Nov-22.

108 Novosselov, Igor V., *Re: Four Additional Questions Email*, 8-Nov-22.

109 Novosselov, Igor V., *Re:Re: Email*, 29-Nov-22.

110 Abaie, Michael, *Program Executive Officer's (PEO) Decision Memorandum for the Supercritical Water Oxidation (SCWO) System,* Program Executive Office Assembled Chemical Weapons Alternatives, 28-Aug-2020.

111 Program Manager Assembled Chemical Weapons Assessment Public Affairs, *Alternative Technology Chosen to Destroy Kentucky Chemical Weapons Stockpile,* Department of Defense, 12-Feb-2003.

112 Bechtel Parsons Blue Grass, *System Design Description for Agent Collection and Neutralization*, Bechtel Parsons Glue Grass, 26-Mar-13.

113 Blue Grass Chemical Agent-Destruction Pilot Plant, *Participant Guide Supercritical Water Oxidation System Training Course*, 24915-00-G8L-GGG-00329 Rev. 5, Blue Grass Chemical Agent-Destruction Pilot Plant.

114 Li, J., et al., *PFOS Destruction in a Continuous Supercritical Water Oxidation Reactor*, 451, p. 139063, Chemical Engineering Journal, 1-Jan-23.

115 McDonough, J.T., et al., *Validation of Supercritical Water Oxidation to Destroy Perfluoroalkyl Acids*, 32, p. 75-90, Remediation Journal, 22-Feb-22.

116 Deputy Assistance Secretary of Defense for Threat Reduction an Arms Control, *Assessment of Potential Transfer of Real Property, Equipment and Facilities in the Assembled Chemical Weapons Alternatives Program,* Department of Defense, Feb 2021.

ACROYNMS AND ABBREVIATIONS

ACWP	Actual Cost of Work Performed
AFFF	Aqueous film-forming foams
AFS	Aluminum Filtration System
AH	Agent Hydrolysate
AHU	Air Handling Units
APR	Aluminum Precipitation Reactor
APS	Aluminum Precipitation System
BCS	Bulk Chemical Storage
BGAD	Blue Grass Army Depot
BGCAPP	Blue Grass Chemical Agent Pilot Plant
BPBGT	Bechtel Parsons Blue Grass Team
CA	Control Accounts
CBARR	Chemical Biological Applications & Risk Reduction
COA	Courses of Action
CPR	Cost Performance Report
CWBS	Contract Work Breakdown Structure
DLA	Defense Logistics Agency
DoD	Department of Defense
DRE	Destruction Removal Efficiency
DEVCOM CBC	U.S. Army Combat Capabilities Development Command Chemical Biological Center
EDP	Engineering Design Package
EDS	Engineering Design Studies
EH	Energy Hydrolysate
EPA	U.S. Environmental Protection Agency
F	Fluoride
FAWB	Functional Area Workbook
FCS	Facility Control System
FOAK	First of a Kind
FPS	Facility Protection System
FTIR	Fourier-Transform Infrared Spectroscopy
FW	Foster Wheeler
GA	General Atomics
GFO	Government Field Office
GS	Gas Chromatography
IO	Ion Chromatography
IPA	Isopropyl Alcohol
ISE	Ion-selective Electrode
JV	Bechtel Parsons Blue Grass Team Joint Venture
LC	Liquid Chromatography
M&EB	Mass and Energy Balances
MP	Main Plant
MS	Mass Spectrometry
OB/OD	Open Burn/Open Detonation

P&ID	Piping and Instrumentation Diagrams
PAS	Pollution Abatement System
PCAPP	Pueblo Chemical Agent Pilot Plant
PCARSS	Plant Clearance Automated Reutilization Screening System
PEO-ACWA	Program Executive Office, Assembled Chemical Weapons Alternatives
PFAS	Per- and polyfluoroalkyl substances
PFOA	Perfluorooctanoic Acid
PFOS	Perfluorooctane Sulfonate
PMATA	Project Manager for Alternative Technologies and Approaches
RCRA	Resource Conservation and Recovery Act
RO	Reverse Osmosis
SCWO	Super-Critical Water Oxidation
SDP	Systemization Demonstration Procedure
SOP	Standard Operating Procedures
SPB	SCWO Process Building
SWG	SCWO Working Group
TEAD	Tooele Army Depot
TOF	Time of Flight
TRRP	Technical Risk Reduction Project
UB	Utility Building
USACE	U.S. Army Corps of Engineers
VOF	Volatile Organic Fluorocarbons
WP	Work Packages
WRS	Water Recovery System

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