FINAL REPORT

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Project Title: Demonstrations of Holistic, Lower Cost/Energy Effluent Water Management Approaches for Coal-Fired Energy Plants

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EXECUTIVE SUMMARY

The project work conducted under DOE award DE-FE0031678 was comprised of three overarching project goals: (1) evaluate the performance of Saltworks' Flex EDR Selective process for treating wet flue gas desulfurization (FGD) wastewater, (2) conduct bench-scale testing of wastewater encapsulation as a byproduct management technology for the EDR generated brine, and (3) develop a dynamic water balance model encompassing the results of the aforementioned testing.

Saltworks' Flex EDR Selective system was offered as a technology that could improve water conservation at a low operational cost relative to competing water treatment technologies. Given its absence of soda ash use and high recovery rates, the system showed promise as a treatment technology to purge chlorides from FGD wastewater and allow increased cycles of concentration in the FGD scrubber.

The technology evaluation was organized as a two phased approach with Saltworks first operating a small bench-scale Flex EDR Selective unit on a FGD wastewater sample provided by the host site. This allowed Saltworks to tune key operational parameters at their facility prior to bringing the larger pilot-scale plant to the host site for treatment of a live water source.

After the bench-scale testing was completed, a pilot-scale Flex EDR Selective unit was deployed and operated at the coal-fired power plant host site for 61 days totaling 1,480 service hours. During that pilot run, the unit treated both a raw FGD wastewater and a concentrated FGD wastewater generated from a reverse osmosis system in an effort to provide representative data for two potential process configurations.

During this pilot study, a pairing of both process data and water chemistry data was collected to characterize the technology. This data was used to develop a technoeconomic analysis of the unit that provided estimated cost of ownership (CapEx and OpEx) for a full-scale installation based on data collected from the pilot demonstration. This analysis, in addition to the collected data and operational narrative, was recorded in OSTI report 1736265.

Concurrent to the Flex EDR Selective pilot testing was a bench-scale study investigating the disposal process of the resultant brine generated from the treatment system. This byproduct management testing focused on the encapsulation of the chloride-rich brine for safe, non-hazardous material disposal and demonstration of holistic water management.

As detailed in the OSTI report 1736239, the project team synthesized a series of monoliths from the pilot brine, fly ash from the host site and a host of chemical binders based on geochemical modeling results which identified the most favorable mix designs for constituent stabilization. The monoliths were then cured and subjected to chemical, leaching, physical, and mineralogical analysis for an in-depth characterization of these encapsulated monoliths.

Based on the results gathered from the bench-scale monolith study, two encapsulation mix designs were selected to be scaled up and cast as lysimeters at the host site. These lysimeters were filled with over 200 gallons of encapsulation paste and monitored to determine the quality and quantity of runoff and drainage water (leachate) that would result from exposure to the elements in a landfill. Using a congruent weather station to track the rainfall, a water balance around the lysimeters was developed using over a year of monitoring data to aid in forecasting full-scale landfill operations.

Throughout the Flex EDR and encapsulation testing, a dynamic water balance model was created using the statistical modeling platform GoldSim. During the first phase of the water balance work, a generic water balance model was designed to evaluate water and material balance outcomes of different industry-standard wet FGD treatment plant configurations based on historical data obtained from three coal-fired power plants each with distinct process configurations. While each of these power plants featured different coal sources and water management strategies, their commonalities were leveraged to create a generic process framework universal to each plant and customizable by a series of easily obtainable user-inputs. By building the model on the GoldSim™ framework and pairing it with thermodynamic metadata, probabilistic outcomes of water quantity and stream composition were calculable. OSTI report 1736241 was issued outlining the creation of this preliminary generic water balance model.

Once the generic model was developed and validated using the user-inputs derived from the previously obtained water balances, the project team incorporated the pilot and bench testing results from the Flex EDR Selective and encapsulation testing to add additional process technology modules to the generic water balance model that emulated a full-scale EDR system and encapsulation plant for subsequent byproduct management. These results and the development methods were documented in OSTI report 1736011. In addition to the findings from this phase of the project, the report also includes a copy of the updated model for public use and guidelines to model strategies for minimizing freshwater needs and reducing disposal volume.

ADDITIONAL FRONT MATTER

During the duration of the project, several key research findings were discovered as a result of the DOE award DE-FE0031678. These findings were documented in several publication and presentations from EPRI that were made publicly available. As mentioned in Section 1, four publications were produced as part of the project scope. These included the following reports:

1. FGD Wastewater Treatment Testing Using a Saltworks Flex EDR Selective (Electrodialysis Reversal System) Technology (OSTI report 1736265). This report can accessed online at no cost at https://www.epri.com/research/products/000000003002020092.
2. Studies on the Encapsulation of Brine Generated from a Process Using Selective Electrodialysis Reversal (OSTI report 1736239). This report can accessed online at no cost at https://www.epri.com/research/products/000000003002019595.
3. Topical Report on Water Balance Model Development and Initial Application (OSTI report 1736241, superseded by OSTI report 1736011). This report can accessed online at no cost at https://www.epri.com/research/products/000000003002017173.
4. Final Report on Water Balance Model Development and Initial Application (Report 1736011). This report can accessed online at no cost at https://www.epri.com/research/products/000000003002020284.

In addition to the aforementioned report, two presentations were made at NETL's Annual Project Review Meeting for Crosscutting, Rare Earth Elements, Gasification and Transformative Power Generation. This included a poster presentation in 2019 exploring preliminary learnings and a comprehensive project review presentation in 2020.

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1
INTRODUCTION

Background

Coal-fired power plants are being driven to reduce the concentrations of specific chemical contaminants from effluent/wastewater discharges. Existing technologies for treating challenging wastewater sources from coal-fired power plants can have limited capability due to periodic fluctuations in volumetric flow rate and/or frequent variation in concentrations of ions, metals, and other contaminants. Existing technologies that can handle these flow and concentration changes are often expensive and produce waste byproducts that require further handling for long-term environmental mitigation (i.e., more treatment processing and costs). Newer technologies are being developed to address the challenges of treating complex coal-fired effluent water, and a holistic approach (dealing with wastewater and byproducts from water treatment) is needed to support lower cost, reliable, and environmentally responsible electric power generation from coal-fired assets.

Project Objectives

The objective of this project is to evaluate a set of effluent water management technologies and strategies for coal-fired energy plants that yield clean water at lower cost and energy consumption than conventional systems while generating salts and solids that can be reused or disposed in non-hazardous waste landfills. The approach is holistic, addressing both water treatment and byproducts. Supporting objectives are to:

- Develop and use a statistical-based water mass balance model to identify opportunities for reducing water consumption and discharge treatment requirements;
- Demonstrate at pilot-scale a potentially highly effective, lower cost/energy technology for treating flue gas desulfurization (FGD) discharges; and
- Develop and test the encapsulation for safe disposal of solid byproducts that have no productive use.

The ultimate outcome of this project is a dynamic water and material balance tool that can be deployed with specific site conditions and simulate treatment of effluent water along with management of waste byproducts.

Project Structure

The Electric Power Research Institute, Inc. (EPRI) is the prime contractor for this project and is supported by Saltworks Technologies, Inc. and Golder Associates, Inc. as subcontractors.

In addition to project management and reporting conducted under Task 1, the project is organized around three technical tasks:

- **Task 2:** Water Balance Evaluations and Guidelines. Using a statistical software modelling platform and data from coal-fired energy plants, determine the fraction of power plant water needs that can be satisfied by advanced treatment technologies and, correspondingly, the discharge liquid and/or byproducts that still need to be managed. The initial evaluations will represent generic scenarios with traditional treatment processes, while the final evaluations will incorporate results from the advanced treatment and encapsulation studies in this project.
- **Task 3:** Advanced Water Treatment System Pilot Testing. Operate a small-scale bench test on FGD wastewater representative of coal-fired power plant wastewater. Complete a 60-day end-to-end pilot test operating 24/7 of the water treatment system optimized during bench testing.
- **Task 4:** Investigation of Byproduct Management Processes. Develop and test methods to encapsulate wastewater treatment brines/byproducts (obtained from the pilot test in Task 3) unfit for beneficial use to enable safe disposal as a non-hazardous material.
- **Task 5:** Pilot Treatment Demonstration Sample Analysis. Develop test plans for activities in Tasks 3 and 4, collect physical samples (water, byproducts, etc.) from Tasks 3 and 4 activities for certified laboratory analysis, analyze water samples from Task 3 and cured composite monolith samples from Task 4 activities, assemble all data gained throughout the project, and complete analyses of all data in support of each Task. Details of Task 5 are not included in this report due to the Task's role in supporting data collection and analysis. Relevant information related to this task is published in the following OSTI reports (1736011, 1736239, 1736241, 1736265).

Report Structure

The purpose of this report is to summarize all work performed in this project:

- Chapter 2 provides a summary of a generic dynamic water balance model that was created to support the evaluation of flue gas desulphurization (FGD) water blowdown handling systems and associated wastewater treatment options for coal-fired power plants.
- Chapter 3 provides a summary of an on-site advanced water treatment pilot-scale system operating on two different sources of FGD wastewater at the Water Research Center (located at Georgia Power Plant Bowen near Cartersville, Georgia).
- Chapter 4 provides a summary of laboratory testing, geochemical modeling, and mineralogical testing conducted to examine the efficacy of wastewater encapsulation using brine and waste byproducts from the pilot system.
- Chapter 5 provides a summary of the updated dynamic water balance model that incorporates results and learnings from the advanced water treatment system and encapsulation testing.
- Chapter 6 presents the main conclusions of the project in summary and a list of recommendations for future research/study based on the outcomes and learnings from the project effort.

2
WATER BALANCE EVALUATIONS

Static water balance information rarely captures the intricacies of wastewater treatment operations at coal-fired power plants. Wastewater treatment operators have little information and resources to rely on that addresses potential impacts of variable load caused by economics and other factors affecting the deployment of coal-fired power generating assets. Dynamic water balance tools are needed to support the type of analysis that can help decision-makers better understand operating in complex conditions. Using GoldSim[1] and OLI Studio software packages, a dynamic water balance model was created that is focused on flue gas desulphurization (FGD) water blowdown handling systems and associated wastewater treatment options for coal-fired power plants.

A detailed analysis of this task is presented in the project topical report under OST report 1736241 [1].

Methods and Approach

The generic model is designed to be dynamic. The model features three input modes: single point modes, stochastic mode, and time step mode. The single point mode executes a static water balance. The dynamic function of the model is based on the other input modes: stochastic and time step. The stochastic mode uses a probabilistic approach to analyze data. The time step mode allows data to be entered with time designations (e.g., daily, weekly, yearly, etc.). More details on the design of the input modes is summarized in OSTI report 1736241 [1]. A screenshot of the generic model input options is presented in Figure 2-1.

[1] GoldSim is a registered trademark of the GoldSim Technology Group LLC.

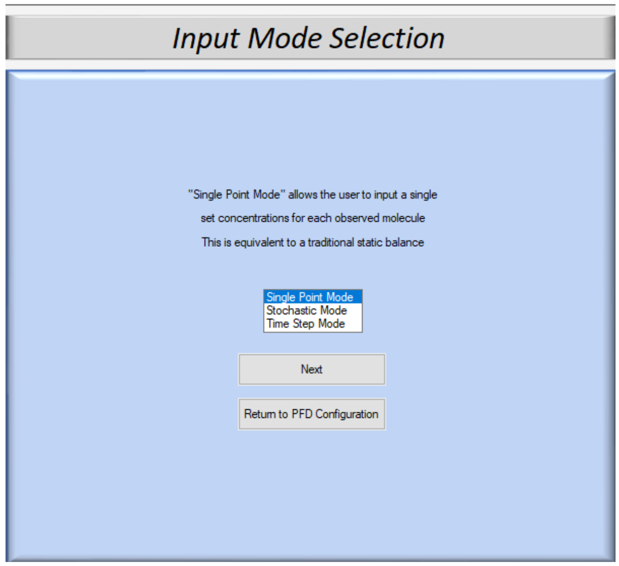

Figure 2-1
Screenshot from the generic model file showing the three input modes (taken from OSTI report 1736241 [1])

While the GoldSim framework can be used to study chemical systems, such as water treatment processes, it lacks capabilities to incorporate important thermodynamic principles that govern water chemistry. To incorporate a more accurate representation of the complexity in water treatment, the OLI Studio tool was used convert data on ions into molecular concentration data of various chemical species. The dynamic water balance tool accepts data on 16 chemical species to produce a more accurate mass balance. Examples of the configuration are provided in OSTI report 1736241 [1]. A screenshot of an example output stream file is presented in Figure 2-2.

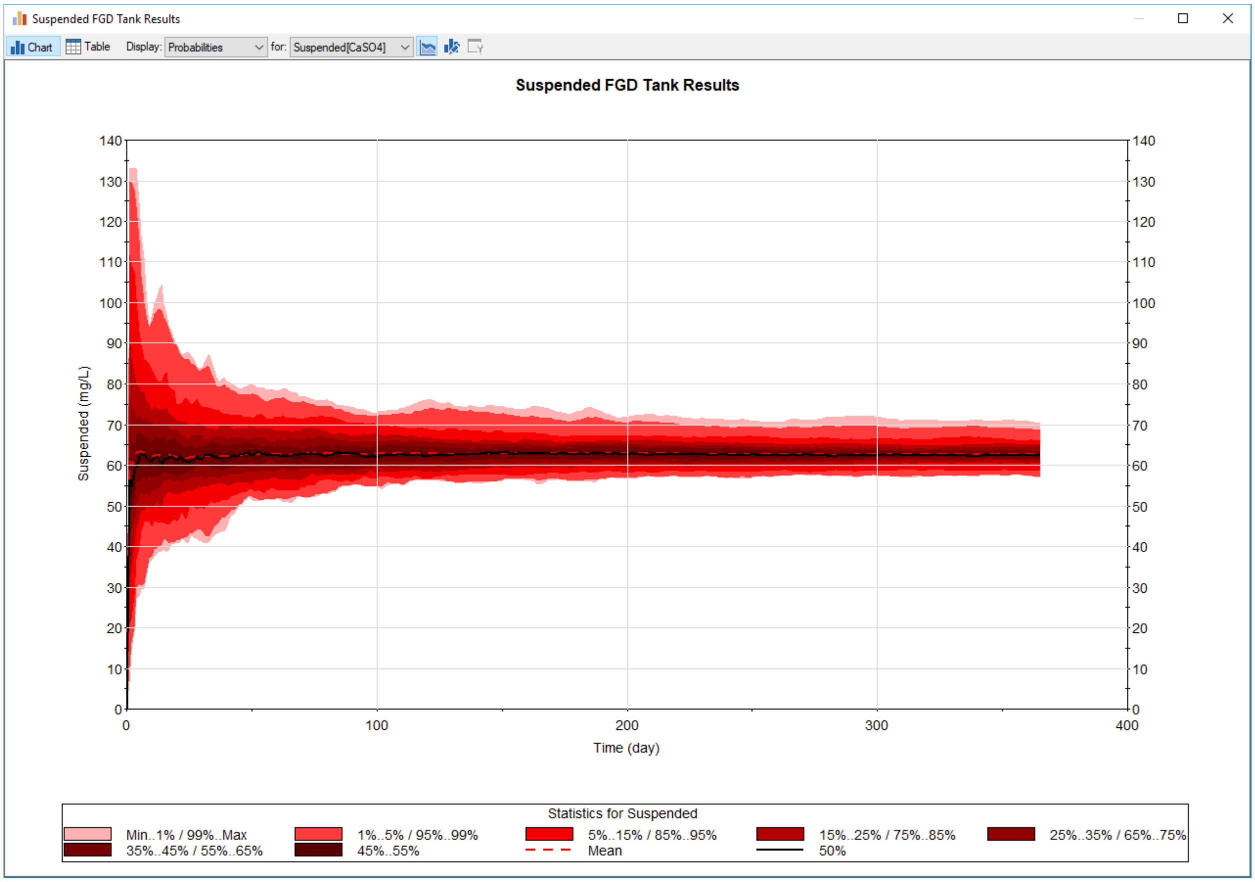

Figure 2-2
Example output stream data from the generic model (taken from OSTI report 1736241 [1])

Results and Discussion

The GoldSim tool allows for the creation of a Player file which is a user interface that does not require the use of licensed software. The GoldSim Player file contains the necessary information to run an analysis of site-specific conditions (as input by the user) but does not allow the user to alter the coding or design of the underlying conditions. Results that are generated by the Player file can be exported to other software applications for analysis (e.g., Microsoft Excel). For the generic model created in this project, the user is limited to changing only FGD blowdown water data, weather data, and select unit operations parameters. A screenshot of the Player file is presented in Figure 2-3. More details on the configuration of the GoldSim Player file are provided in OSTI report 1736241 [1].

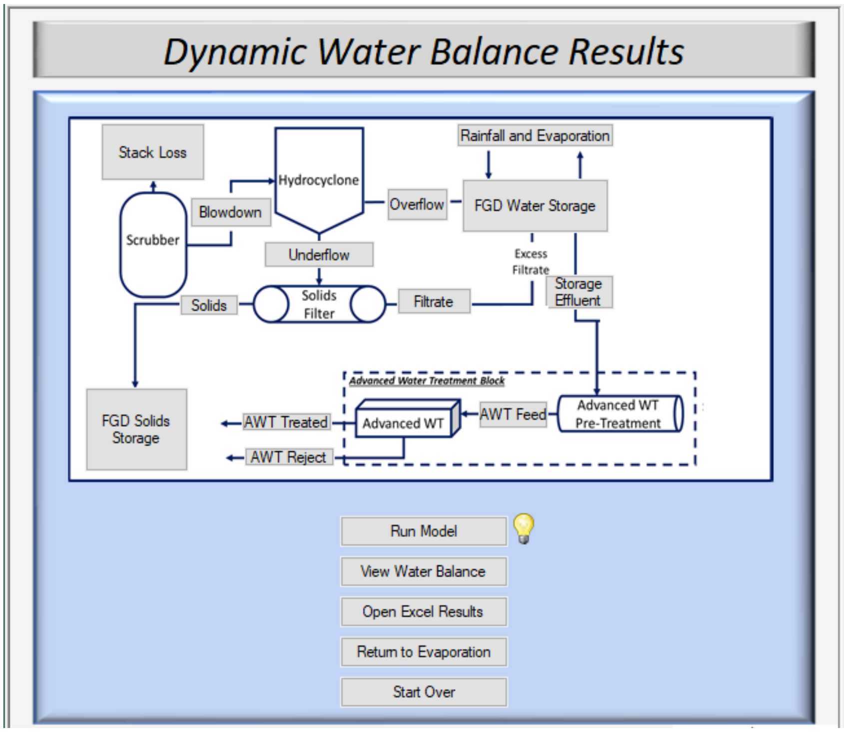

Figure 2-3
Generic model Player file screenshot (taken from OSTI report 1736241 [1])

The dynamic water balance model is designed with specific unit operations to incorporate major conditions impact FGD wastewater treatment systems:

- Physical water treatment
- Chemical water treatment
  - Settling via impoundment
  - Physical-chemical treatment
  - Advanced water treatment

Physical water treatment includes the use of hydrocyclones and solids filters as the unit operations. The primary controlling factors in this operation are the volumetric flow rate of the water and the concentration of suspended solids in the water. It is important that the user understand the governing conditions that determine the operating profile of these unit operations. For the hydrocyclone unit operation, two parameters control stream qualities and quantities: efficiency and percent fines in the overflow.

Chemical water treatment includes the use of open atmosphere impoundments for solids settling (along with water inflow resulting from the collection of precipitation), physical-chemical treatment which targets removal of suspended solids from water, and an advanced water treatment system which is studied in this project. The incorporation of an electrolyte thermodynamic tool such as OLI Studio is critical in establishing accurate representations of dynamic water treatment conditions. The manner in which various complexities are handled by the dynamic water balance tool are presented in OSTI report 1736241 [1].

Upon building the dynamic water balance tool, static water balance information from three different coal-fired power plants were incorporated as test subjects for the remainder of the project. This information was submitted to EPRI from existing coal-fired plant operators for use in this project. The profiles of the three plants are summarized in Table 2-1. Results from the dynamic water balance tool using Plant A configuration is provided in Figure 2-4.

Table 2-1
Profiles of three coal-fired power plants used to evaluate the dynamic water balance tool (taken from OSTI report 1736241 [1])

Plant Designation	Capacity (MW)	Fuel Characteristics	FGD process description
A	3,000	Blends high sulfur and low sulfur coal	Hydrocyclone, belt filter, and physical-chemical FGD treatment system designed to reduce total suspended solids
B	3,500	High sulfur coal	Hydrocyclone, belt filter, and a settling pond
C	3,500	Low sulfur coal	FGD gypsum pond

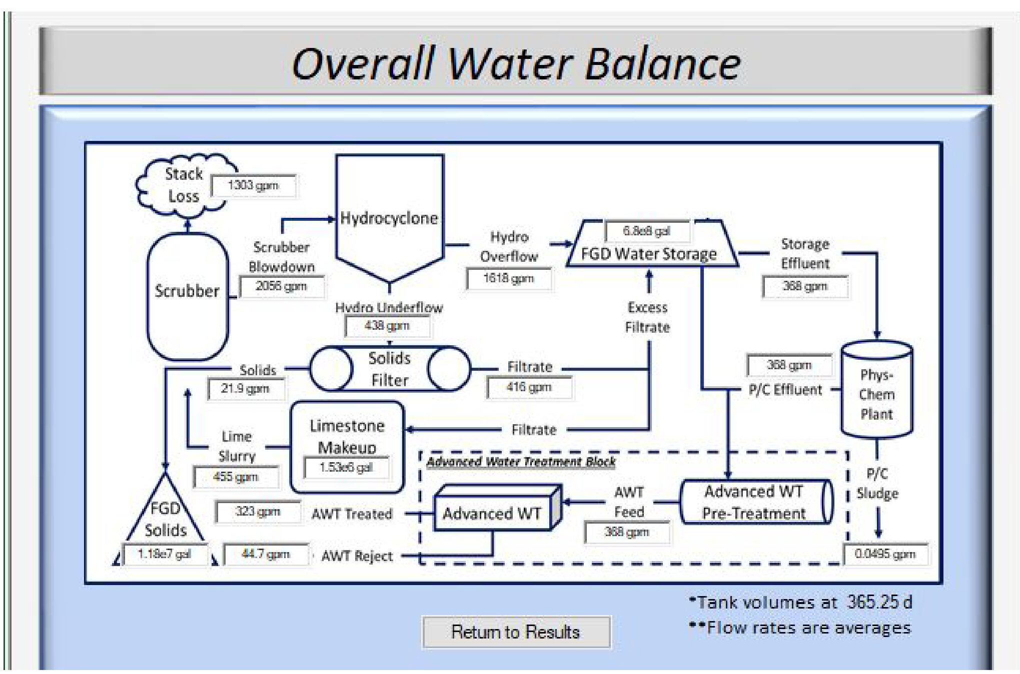

Figure 2-4
Overall water balance for Plant A generated by the dynamic tool (taken from OSTI report 1736241 [1])

3
ADVANCED WATER TREATMENT SYSTEM PILOT TESTING

Saltworks Technologies, Inc. (Saltworks) offers desalination technologies in a variety of markets. The advanced water treatment system studied in this project is a novel concept in water and wastewater management. Prior/separate studies led by Saltworks and EPRI suggested the treatment process could result in >90% water recovery and byproducts for reuse or co-disposal with other coal combustion residuals (CCRs). The main objectives for the Saltworks processes are to eliminate soda ash softening (an expensive reagent), increase system water recovery to minimize additional treatment, and minimize overall residual waste, especially hazardous waste, if any.

When treating FGD wastewater, which is highly scaling, Saltworks achieves these goals by first passing the water through a pH adjustment pretreatment step to precipitate low solubility scaling compounds; no soda ash is used in this process. The pretreated water is then sent to the Flex EDR Selective system, an electrodialysis reversal (EDR) unit fitted with Saltworks' proprietary IonFlux monovalent anion selective anion exchange membranes (mAEM) that has 98% selectivity for monovalent anions, such as chlorides, while rejecting multivalent anions, such as sulfates. The system is operated with a proprietary process and control to remove ionic scaling limits. Specifically, the Salt Splitter process separates calcium ion and sulfate ions responsible for scaling into a high solubility sodium sulfate (Na_2SO_4) rich stream.

The Flex EDR Selective technology is based on monovalent electrodialysis reversal. As shown in Figure 3-1, monovalent chlorides are removed from the feed water while rejecting sulfates into a brine stream. This brine stream is composed primarily of calcium chloride with a low risk of scaling which, notably, is accomplished without the use of soda ash softening as a pre-treatment step before the Flex EDR Selective technology.

A detailed analysis of this task is presented in the project topical report under OSTI report 1736265 [2].

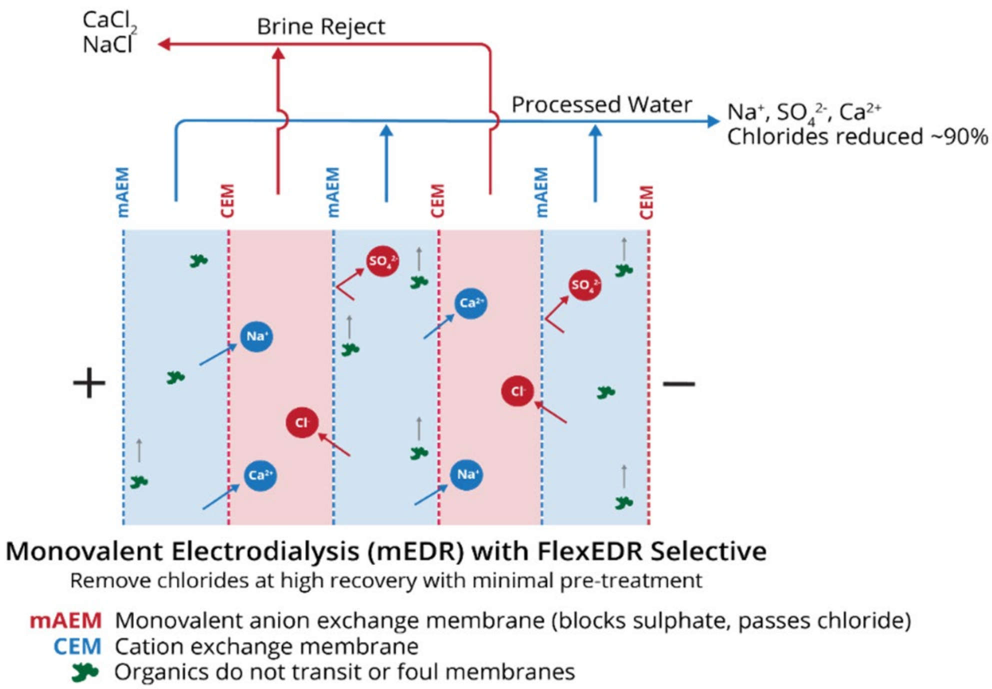

Figure 3-1
Simplified Flex EDR Selective diagram (taken from OSTI report 1736265 [2])

Methods and Approach

Planning

The planning work consists of (1) developing a site implementation plan including a power plant host site-acceptable safety plan and space, utility, raw water supply and brine/solids discharge needs; (2) completing the bench and pilot test plan, including coordination with all project partners and the power plant host site; and (3) finalizing the mobilization/demobilization/pilot operations plan.

Bench-Scale Testing

Saltworks operated a bench-scale test of the advanced water treatment system using FGD wastewater obtain from the Water Research Center (WRC). The bench plant was operated in advance of setting initial process conditions and of making changes to the pilot to identify easily and at low cost/risk optimized process settings, controls, and cleaning procedures.

Pilot-Scale Testing

The Flex EDR Selective system was commissioned at the WRC and operated on FGD water provided by the host power plant. Process data (process changes, operational events, maintenance requirements as well as calibration confirmation and visual checks of the instruments and equipment) were collected and logged daily by the pilot system operators. Current, voltage, conductivities, pressures, temperature, flow rates, and tank volume collected by the data acquisition system were stored on the pilot plant's computer hard-drive. Samples of the raw inlet, RO permeate, any other clean water streams, usable byproduct streams, and brines were collected at least twice per week and sent to a third-party analytical laboratory for analysis. The process data were be analyzed daily and the processes were adjusted as needed to optimize performance or meet new targets. Significant changes and/or issues were discussed with the project partners before any operational changes were implemented.

The objectives of the pilot-scale testing were:

- Demonstrate Flex EDR Selective operations under site conditions for 60 days.
- Evaluate Flex EDR Selective performance to reduce chloride concentration to less than 1,500 mg/L.
- Collect data to determine OpEx (energy and chemicals) and CapEx (membrane flux) for full-scale plant design and economics.

The original test plan for the pilot-scale study assumed a water quality (i.e., range of concentrations for key species) would be present throughout the timeframe of the project. However, host-site-specific factors resulted in feed water which lower concentrations of chemical species. The first 995 hours of testing were conducted on the raw FGD wastewater, and the remining 485 hours of the study used brine from a VSEP membrane unit that was already commissioned at the WRC. More details on the aspects of the feed water quality are covered in OSTI report 1736265 [2].

Results and Discussion

Following testing using a bench-scale process and water provided by the WRC, the Saltworks pilot system was commissioned for testing. A simplified process flow diagram of the system is shown in Figure 3-2.

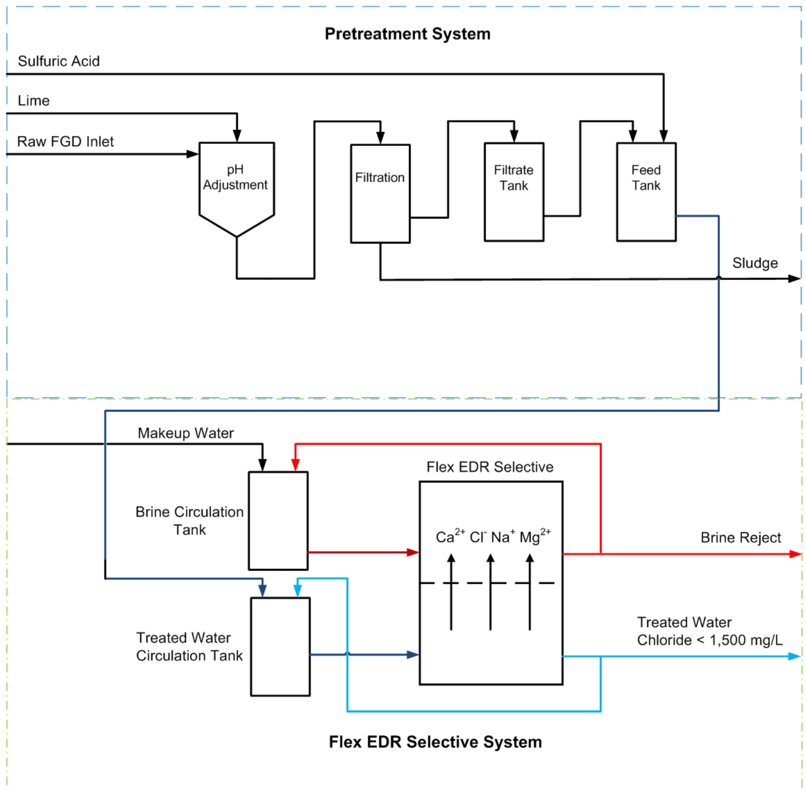

Figure 3-2
Simplified Process Flow Diagram for Flex EDR Selective with Pretreatment (taken from OSTI report 1736265 [2])

Pretreatment

FGD wastewater from an open impoundment was sent to the pilot-scale system at the WRC. Pretreatment of the water included elevating the pH to 11 using calcium hydroxide (lime) to facilitate the precipitation of manganese, silica, and fluoride which cause fouling and scaling on membrane surfaces. Filtration after pH adjustment led to the removal of precipitated compounds (suspended solids) which could plug the EDR treatment unit. Following filtration, the water was treated with sulfuric acid to reduce the pH to 3. This adjustment was made to minimize carbonate scaling inside the EDR unit.

Advanced Water Treatment

The primary treatment process consists of the Saltworks Flex EDR Selective system. The pilot equipment used in this study is rated with a treatment capacity of 1 to 3 m^3/day (dependent on the total dissolved solids [TDS] concentration in the feed water). The pilot system is configured in a semi-batch arrangement due to the smaller capacity – full-scale systems would operate in a continuous treatment mode. For this study, the system is configured to achieve a chloride concentration of approximately 1,500 mg/L. This value was defined by the host site as an estimate for water quality that could either be recycled back to the FGD or sent to additional purification steps for other water reuse applications.

The unit operated with a 98% up-time over a period of 61 days. Water recovery (measured as the amount of clean water produced divided by the feed water) averaged 93% for the entire study. Other process parameters such as the EDR stack resistance, cleaning frequency and duration, contaminant removal effectiveness, and chemicals consumption were evaluated throughout the study.

EDR stack resistance data provide an indication of membrane scaling within the unit. The pretreatment process proved to be sufficiently robust to where no EDR scaling occurred during the study. See data trends in Figure 3-3.

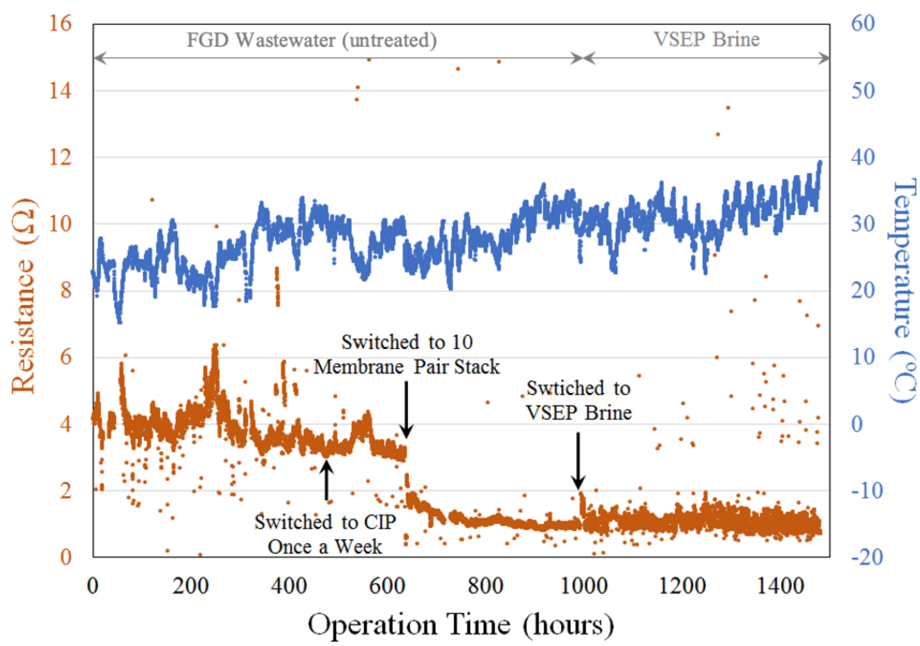

Figure 3-3
Flex EDR Selective stack resistance measured during the pilot-scale study (taken from OSTI report 1736265 [2])

A clean-in-place (CIP) process for the EDR system is incorporated and operated in the event that the pretreatment process is unable to manage the removal of scalants. For this pilot study, the CIP process used a solution of 1% sodium chloride (NaCl) which has proven to be effective in other testing conducted by Saltworks. The entire CIP processes was programmed to run for 30 minutes and frequency of CIP increased from once every two days to once per week approximately halfway into the study.

Contaminant removal effectiveness was primarily evaluated based on the treated stream chloride concentration target of 1,500 mg/L. During the initial stages of the study, field measured conductivity and lab analyses for chloride concentration were compared to determine the extent to which field conductivity could be used as a proxy to the chloride concentration.

Consumption of all chemicals used in the pilot study was documented and analyzed after the testing was completed. The chemicals used for pretreatment were lime and sulfuric acid, and the chemicals used in the Flex EDR Selective process were sodium chloride, sodium sulfate, and a biocide. The amount of chemical consumption compared to the volume of water treated is summarized in Table 3-1.

Table 3-1
Chemicals consumption from the pilot-scale study (taken from OSTI report 1736265 [2])

Process Unit	Chemicals	FGD Wastewater (untreated)	VSEP Reject
Pretreatment	Lime (kg/m^3)	1.1	3.6
	98% H_2SO_4 (kg/m^3)	0.16	0.77
Flex EDR Selective	NaCl (kg/m^3)	0.32	0.51
	Na_2SO_4 (kg/m^3)	0.13	0.19
	Biocide (kg/m^3)	0.001	0.001

Economic Analysis

Economic analysis of two full-scale plants was completed by Saltworks. The analysis is based on water composition of two different FGD wastewater samples represented by the data in Table 3-2. The concentrations in these two analyses differ from the study, but are representative of an operating coal-fired facility. These compositions were used as the basis of the analysis because the concentrations of key chemical species were lower than originally anticipated.

Table 3-2
Design basis water chemistry (taken from OSTI report 1736265 [2])

Parameter	FGD Wastewater Chemistry #1	FGD Wastewater Chemistry #2
Units:	mg/L	mg/L
pH	7.00	7.02
Total Dissolved Solids	14300	8280
Total Hardness (as CaCO3)	9590	5920
Total Organic Carbon	-	6
Alkalinity (as CaCO3)	60	48
Aluminum	0.032	<0.25
Antimony	<0.0025	<0.025
Arsenic	0.002	<0.005
Barium	0.502	0.276
Beryllium	<0.00025	<0.0025
Bicarbonate (as CaCO3)	60	48
Boron	181	94.7
Bromide	27.4	14.1
Cadmium	0.0829	0.0434
Calcium	2730	1840
Carbonate (as CaCO3)	<1	<1
Chloride	5990	3380
Chromium	0.0054	<0.025
Cobalt	0.00225	0.0028
Copper	0.0032	<0.025
Fluoride	8.6	5.5
Hydroxide (as CaCO3)	<1	<1
Iron	<0.02	<0.1
Lead	<0.00025	<0.0025

Parameter	FGD Wastewater Chemistry #1	FGD Wastewater Chemistry #2
Units:	mg/L	mg/L
Lithium	0.123	0.058
Magnesium	674	322
Manganese	2.97	1.69
Mercury	0.0016	0.0091
Molybdenum	0.0462	0.016
Nickel	0.29	0.14
Nitrate (as N)	19.8	10.6
Nitrite (as N)	<0.05	<0.05
Nitrate + Nitrite (as N)	19.8	10.6
Phosphorus	18	1.5
Potassium	17.9	7
Selenium	0.12	0.071
Silica (Reactive)	31.2	16.8
Silicon	13.4	7
Silver	<0.001	<0.010
Sodium	91	28
Strontium	15.3	10.6
Sulfate	1290	1090
Thallium	0.0035	0.0028
Tin	<0.00025	<0.0025
Titanium	<0.005	<0.05
Uranium	0.0412	0.0343
Vanadium	<0.005	<0.05
Zinc	1.36	0.87

The economic analysis, presented in Table 3-3, assumes a full-scale system representative of the treatment process studied in this project. The volumetric flow rate of FGD wastewater to be treated is 258 gpm (1,407 m^3/day). The operating parameters used to develop the economic analysis incorporate the system performance and design factors of the pilot-scale system. The economic analysis excludes installation, brine management, disposal and labor costs. Capitalization is assumed for 20 years, 8% interest, and 90% uptime. Labor is projected to be one full-time equivalent with electrical and mechanical maintenance as required (not dedicated).

Table 3-3
Summary of Full Scale Plant Economic Analysis (+/- 40% and all in USD) (taken from OSTI report 1736265 [2])

		Flex EDR Selective Chemistry #1 @ 8280 mg/L TDS		Flex EDR Seletive Chemistry #2 @ 14300 mg/L TDS	
Total Plant Inlet Flow (FGD + Make up Water)	GPM		258		258
	m^3/day		1,407		1,407
FGD Wastewater Inlet Flow	GPM		250		250
	m^3/day		1,361		1,361
FGD Wastewater Inlet TDS	mg/L		8,280		14,300
Reject Brine Flow	GPM		5		17
	m^3/day		28		91
Reject Brine Outlet TDS	mg/L		130,000		130,000
Treated Water Flow	GPM		253		241
	m^3/day		1,379		1,316
Treated Water Discharge TDS	mg/L		6,210		6,210
Treated Water Discharge Chlorides	mg/L		1,500		1,500
Membrane System Treated Water Recovery	%		98.0%		93.6%
Capital Cost[1]	**$**	**$**	**1,843,792**	**$**	**5,064,691**
	$/$m^3$ inlet	**$**	**0.42**	**$**	**1.15**
Lime	$/$m^3$ inlet	$	0.57	$	0.83
Soda Ash (Na_2CO_3)	$/$m^3$ inlet	$	-	$	-
Hydrochloric Acid (31% HCl)	$/$m^3$ inlet	$	0.24	$	0.36
Biocide	$/$m^3$ inlet	$	0.002	$	0.002
Sodium Chloride (NaCl)	$/$m^3$ inlet	$	0.21	$	0.27
Sodium Sulphate (Na_2SO_4)	$/$m^3$ inlet	$	0.06	$	0.06
Total Chemical Cost	**$/yr**	**$**	**486,406**	**$**	**680,592**
	$/$m^3$ inlet	**$**	**1.09**	**$**	**1.52**
Energy Requirement[2]	kWh/m^3 inlet		8.03		25.84
Energy Requirement	kW		455		1,465
Energy Cost	**$/yr**	**$**	**215,312**	**$**	**693,037**
	$/$m^3$ inlet		**$0.48**		**$1.55**
Membrane Replacement	**$/yr**	**$**	**45,048**	**$**	**97,671**
	$/$m^3$ inlet	**$**	**0.10**	**$**	**0.22**
Annual Operating Cost[2]	**$/yr**	**$**	**746,765**	**$**	**1,471,300**
	$/$m^3$ inlet	**$**	**1.67**	**$**	**3.29**
Total Cost of Ownership (excludes install, labor)	**$/$m^3$ inlet**	**$**	**2.09**	**$**	**4.45**
	$/kgal	**$**	**7.92**	**$**	**16.84**

1: Excludes install, brine management, disposal. Capitalization assume 20 years, 8% interest, 90% uptime

2: Excludes labour and disposal costs. Labour projected to be 1 FTE + Electrical/Mechanical maintenance as required

4

INVESTIGATION OF BYPRODUCT MANAGEMENT PROCESSES

Long-term isolation of wastewater treatment byproducts, from traditional and advanced water treatment technologies, is a necessary component of a holistic approach to wastewater management. A water treatment approach that produces a solid salt residual for disposal is not an ideal final product. Landfill disposal of salt wastes can pose a significant risk to landfill systems as they, over time, will re-dissolve back into the landfill leachate where they will have to be re-treated. Additionally, this high strength leachate could compromise landfill liners and pose a risk to groundwater quality [3]. Therefore, the fourth task in this project is to delve further into these approaches by first evaluating the unique opportunity presented by the Saltworks technologies' ability to segregate byproducts into distinct streams; this was accomplished by performing a full analysis of the materials, including chemical and physical properties. Depending on the quality of these byproducts, reuse markets could exist.

For the final constituent-laden concentrated waste stream unfit for reuse, the team developed and tested brine encapsulation. This is a new area of focus for the industry, and much is to be learned: geochemistry of encapsulated materials, long term fate of constituents of interest, physical properties, leaching properties, etc. In previous work, EPRI and Golder Associates have achieved successes in experiments of processes that mix concentrated brines that are unfit for reuse with reagents to induce mineralogical reactions that chemically bind salts, trace elements, and excess water, essentially encapsulating them and rendering them impervious to leaching. Onsite byproducts such as fly ash can be utilized for encapsulation, helping to reduce the overall cost. Expanding the range of materials that can be encapsulated for safe disposal will increase the industry's and regulators' confidence that such byproducts can be disposed safely as a non-hazardous material, greatly reducing costs and liabilities.

A detailed analysis of this task is presented in the project topical report under OSTI report 1736239 [4].

Methods and Approach

Bench Testing: Encapsulation Mixture Development

To develop encapsulation mixes, the project team first characterized the ingredient materials (dry and wet) for each mix. These index properties were input to an existing geochemical model (built in the publicly available United States Geological Survey [USGS] geochemical modeling code PHREEQC) for brine encapsulation. The team used the model to predict the theoretical formation of known mineralogies that chemically bind halides, trace metals, and water, and used the results, combined with their prior experience, to create various mix designs for bench-scale evaluation.

The mix designs were evaluated first for transportability (rhetorical properties) using a rheometer. Material was then mixed, cured, and subjected to chemical, leaching, physical, and mineralogical analysis for a bench-scale performance evaluation of these encapsulated monoliths. Seven mix designs were developed for the bench testing and represented different mixtures of fly ash, brine, and additives. The results of this testing were used to select the two designs used in a larger field study.

Lysimeter Testing

Two field lysimeters were used to study two different mix designs and produce encapsulated material from the Flex EDR Selective brine. The lysimeters were exposed to atmospheric conditions at the WRC to determine the quality and quantity of runoff and drainage water (leachate) that would result from exposure to precipitation and other climate conditions. A drawing of the lysimeter design is shown in Figure 4-1.

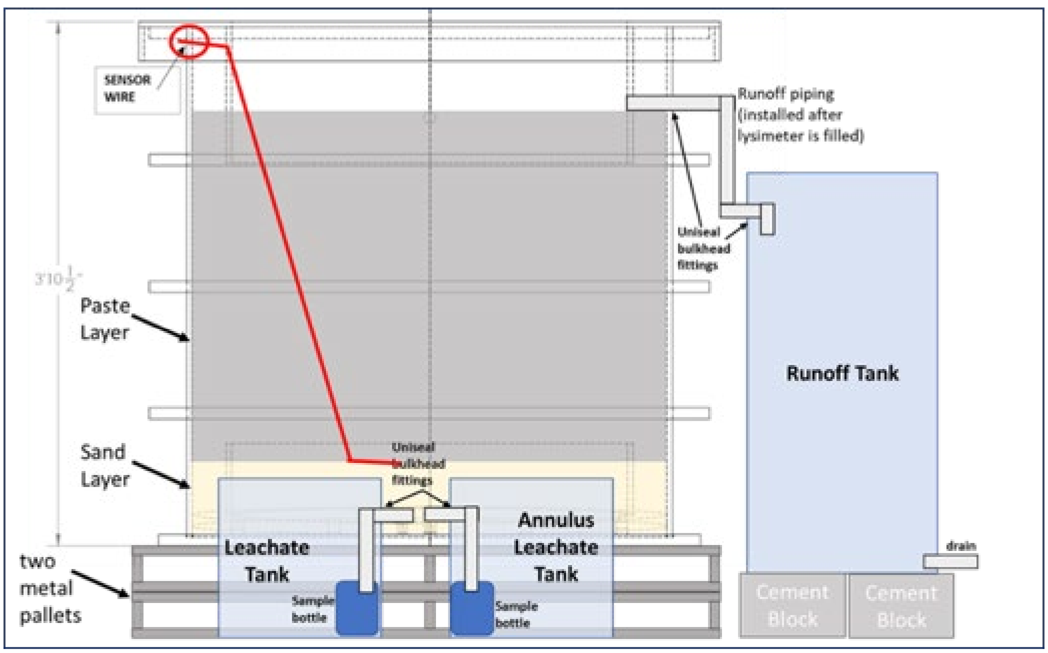

Figure 4-1
Lysimeter layout drawing showing the final setup with drainage layer, encapsulated material, and leachate and runoff water collection tanks (taken from OSTI report 1736239 [4])

The field lysimeters were placed outside and exposed to naturally occurring environmental conditions. The project team actively monitored the condition of each lysimeter for six months after hardening. Monitoring activities included visual inspections of the material and structural aspects of the lysimeters. The lysimeters remain intact at the host site for potential continued exposure to the ambient environment. As a separate activity not related to this project, EPRI intends to revisit the condition of the lysimeters after longer exposure.

Geochemical Model Validation

The project team used the chemical, physical, and mineralogical data from the bench tests along results from lysimeters to validate the geochemical model. Once validated, this model can be used for future encapsulation work, potentially reducing the number of bench-scale evaluations needed. It can also provide the geochemical reactions required to predict contaminate fate and transport through landfills (although this is not part of the project scope).

The main evaluations conducting in the geochemical model validation focused on qualitative and quantitative factors. The qualitative portion seeks to predict the presence secondary mineral phases that are likely to form based on the mix design (present or not present). This prediction is compared to results from x-ray diffraction (XRD) analysis of the encapsulated products to determine the accuracy of the model capabilities.

The quantitative portion provides the weight percentages of secondary mineral phases. The three most common secondary minerals across all six mix design samples were calcite (calcium carbonate), ettringite, and Friedel's salt.

Results and Discussion

The geochemical model was successful in predicting the presence of most mineral phases in mix design samples, which was also confirmed by the XRD results. For the three most common secondary minerals (that is, calcite, ettringite, and Friedel's salt) that formed during the encapsulation process, the quantitative comparison with the XRD weight percent of formation has shown that the model generally underpredicted weight percent of formation, with the reactivity of the ash and brine likely accounting for this discrepancy.

A key objective in this study was to understand the encapsulation mechanism responsible for the entrapment of the chloride ion from the $CaCl_2$ brine. The model helped with a fundamental understanding by differentiating between a cementitious and pozzolanic reaction mechanism responsible for the formation of chloride minerals.

Overall, this study has shown the value that geochemical modeling can add in terms of the fundamental chemical understanding and predictive capabilities for complex mix designs involving cementitious, pozzolanic, and hypersaline brine systems.

5
DYNAMIC WATER BALANCE MODELING

The dynamic water balance model was further expanded to incorporate the findings from Tasks 3 and 4 on wastewater treatment and byproduct encapsulation. The model was then used to compare traditional and advanced treatment cases. The revised model could help power plants assess and select strategies for maximizing water reuse, obtaining value from water treatment byproducts, and reducing waste disposal costs and risks.

A detailed analysis of this task is presented in the project topical report under OSTI report 1736011 [5].

Methods and Approach

The generic model developed in Task 2 was modified to account for the Saltworks Flex EDR Selective treatment process. This process was handled as a standalone unit operation block and was developed using thermodynamic modeling to represent chemical changes in the water. Developing an integrated thermodynamic approach into the GoldSim platform required a unique approach to representing the likely effluent qualities of the water treatment system. This block development was largely derived from a coupling of GoldSim and OLI Studio to simulate the piloted treatment system performance.

Based on the analytical results generated during the pilot study, the same ions modeled in the FGD wastewater stream (calcium, magnesium, sodium, potassium, silica, chloride, and sulfate) were collected for the pretreatment effluent, treated effluent, and chloride purge water and imported into OLI Studio.

Results and Discussion

The model can be used to draw insights from performance results summarized from the suite of simulations. These insights include:

- Water recycle performance;
- Projected landfill water totalizer;
- Projected water quality;
- Produced solid waste volume; and
- Encapsulation additive usage rates.

Upon completing the modifications to the dynamic water balance model, the project team evaluated its effectiveness against the three plant profiles obtained from supporting organizations. The model was executed to account for each site's unique processes, water treatment scenario, and operational factors. A summary of the outputs from each plant is provided in Table 5-1.

Table 5-1
Summary of model performance results (taken from OSTI report 1736011 [5])

Plant Conditions	Plant A	Plant B	Plant C
Percent Blowdown to Recyclable Water	82.9%	84.5%	86.7%
Average Treated Chloride (mg/L)	174.3	3347.2	123.0
Landfill Disposal Water (m^3/yr)	385,354.9	108,679.2	278,189.9
Landfill Volume of Mix 2 Paste (m^3/yr)	856,403	241,490	618,033
Landfill Volume of Conditioned Ash (m^3/yr)	1,304,000	367,713	941,067

Three major assumptions are made to simplify the model to a point that the dynamic water balance tool can be used as a water balance modeling framework:

1. No reactions take place outside of the Flex EDR Selective treatment process (includes pretreatment operations).
2. Only 11 molecular species are formed via major ions and tracked.
3. The Flex EDR Selective treatment process can be modeled using flow factors, and the pilot-study results are representative of a variety of water chemistries.

To improve the model's efficacy, additional testing on different water chemistries at a variety of operating conditions would be necessary to expand the model's envelope and enable the development of a more encompassing tool. Without this additional testing, the model will continue to extrapolate performance based on a limited amount of data but the flexibility of the existing format makes it more powerful than static methods.

6
CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The objective of this project was to evaluate water management technologies and develop strategies for coal-fired power plants to generate clean water at lower cost and energy consumption than conventional systems while simultaneously treating the byproduct stream for non-hazardous waste landfill disposal. The holistic approach studied both the water treatment technology and the resultant byproduct management associated with this zero liquid discharge solution, while also creating a dynamic water balance to model these process changes.

The project began in October 2018 and ended in September 2020. The activities were organized into three core tasks. The first task developed a generic water balance model which was used to create a dynamic tool that incorporates learnings from the entire project. The second task facilitated testing of a novel water treatment process designed to improve water recovery and reuse while producing waste byproducts that are easier to manage for long-term applications. The major third task investigated various byproduct management techniques and solutions to examine methods for minimizing environmental impacts.

Four technical reports were published documenting the findings from this project. These reports were published on EPRI's website for public access and included technical findings from the water treatment testing, encapsulation testing, and water balance modeling. In addition to these four technical reports, two presentations were delivered providing project updates at NETL's 2019 and 2020 Annual Project Review Meeting for Crosscutting, Rare Earth Elements, Gasification and Transformative Power Generation. Project updates were given via presentations to EPRI members, which included representatives from NETL, two times per year throughout the project. There were no patent applications, inventions, or licenses created as a result of this project. Many examples of technology transfer are possible. The EPRI team have since brought technical learnings to the U.S. DOE Energy-Water Nexus Desalination Hub planning discussions.

Recommendations

The following recommendations represent areas of potential future studies based on results and learnings throughout the project. These recommendations are described in greater detail in the relevant project topical reports.

Dynamic Water Balance Model

- Additional evaluations of site-specific properties and conditions could provide certainty on broad deployment of the model. Power plants have many operational and design variables and these variables create complexities that require careful observation.
- The model could be evaluated and tested using water and solid waste properties that are different than the scenarios used in this project.
- With fixed site properties in place, a variety of operating conditions could be considered to support the expansion of the model's envelope. Without this additional testing, the model will continue to extrapolate performance based on data collected during this project.
- Additional water treatment and water and solid waste management processes could be incorporated into the model's capabilities to expand its applicability to a broader number of power plant conditions. In doing so, the primary chemical species and operating parameters could be adjusted accordingly.

Advanced Water Treatment

- Testing of the Saltworks Flex EDR Selective process on various water compositions could provide a more robust analysis of opportunities for deploying innovative water treatment technologies. While the exact composition of water quality from FGD processes is unique to each site, the same predominant chemicals species tend to be present at many sites.
- While the pilot study was able to test and observe characteristics of the EDR process, the breadth of testing was limited by site-specific conditions. For example, future testing could further evaluate the relationship between voltage and current density under various chemical compositions.
- Economic analysis could be conducted on a variety of site conditions and characteristics to better understand the impacts of treatment requirements. This effort could be especially important in developing details for operational costs with varying chemical consumptions, flow rates, and other variables.

Byproduct Encapsulation

- Byproduct encapsulation provides opportunities for long-term management of waste material but is subject to site-specific conditions. Additional testing using geochemical models, especially with modifications identified in this project, and field testing could help expand the deployment of encapsulation across multiple locations.

- Understanding long-term materials properties requires additional testing and studies with robust analysis of mix design properties, geochemistry properties, and field deployment considerations.
- Future studies could examine scale-up of encapsulation processes that support various landfill designs and plant operation characteristics.

7
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