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While we wait…take a moment to **connect** with OCWD

@OCWaterDistrict

Squeezing the Last Drop: Using Enhanced-Recovery Reverse Osmosis to Improve Water Production

Before We Get Started

Attendees are muted to reduce background noise

Webinar is being recorded and will be published on OCWD's YouTube Channel

Use the Q&A box to submit questions on today's topic

Email info@ocwd.com for any follow-up questions

Meet Our Speakers

Han Gu, Ph.D.
Senior Scientist/Process Specialist
Orange County Water District

Alex Waite, P.E.
Senior Civil Engineer
City of Santa Monica

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OCWD Webinar

ORANGE COUNTY WATER DISTRICT
SINCE 1933

Han Gu, Ph.D.
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Senior Civil Engineer
City of Santa Monica

City of Santa Monica

August 7, 2024

Webinar Outline

- Utilization of high-recovery Reverse Osmosis (RO)
- OCWD’s pilot study results: Flow-reversal RO (FRRO), Closed-Circuit RO (CCRO) and Forward Osmosis RO (FO-RO)
- Santa Monica’s pilot study results: FRRO and CCRO
- Santa Monica’s full-scale FRRO implementation and lessons learned
- Q&A

OCWD R&D Piloting Experience with Recovery Enhancing RO Technologies: FRRO, CCRO, and FO-RO

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Han Gu, Ph.D.
Orange County Water District

August 7, 2024

Outline

- Utilization of high-recovery Reverse Osmosis (RO) for potable reuse
- Flow-reversal RO (FRRO) pilot study
- Closed-Circuit RO (CCRO) pilot study
- Forward Osmosis RO (FO-RO) pilot study
- Pros/Cons of three technologies piloted and cost comparison

Utilization of High-recovery RO for Potable Reuse

- **Conventional RO** removes dissolved solids, macro-molecules, and pathogens, but **recovery is limited**
- RO generates large volumes of **concentrated waste stream**, making concentrate management a challenge
- Economically feasible **high-recovery RO** technologies, such as **CCRO**, **FO-RO** and **FRRO**, may make potable reuse a more viable option
- **CCRO** pilot tested at PUB (2012-17), PDMWD (2016-17) and LACSD (2015-18), recovery range from 90-96%
- Singapore PUB implemented **FRRO** at full-scale (2.8 mgd) in NEWater plant from 2017-~22 (Recovery increased from 75% to 90%)
- Santa Monica recently began first municipal **FRRO** performance testing at full-scale facility

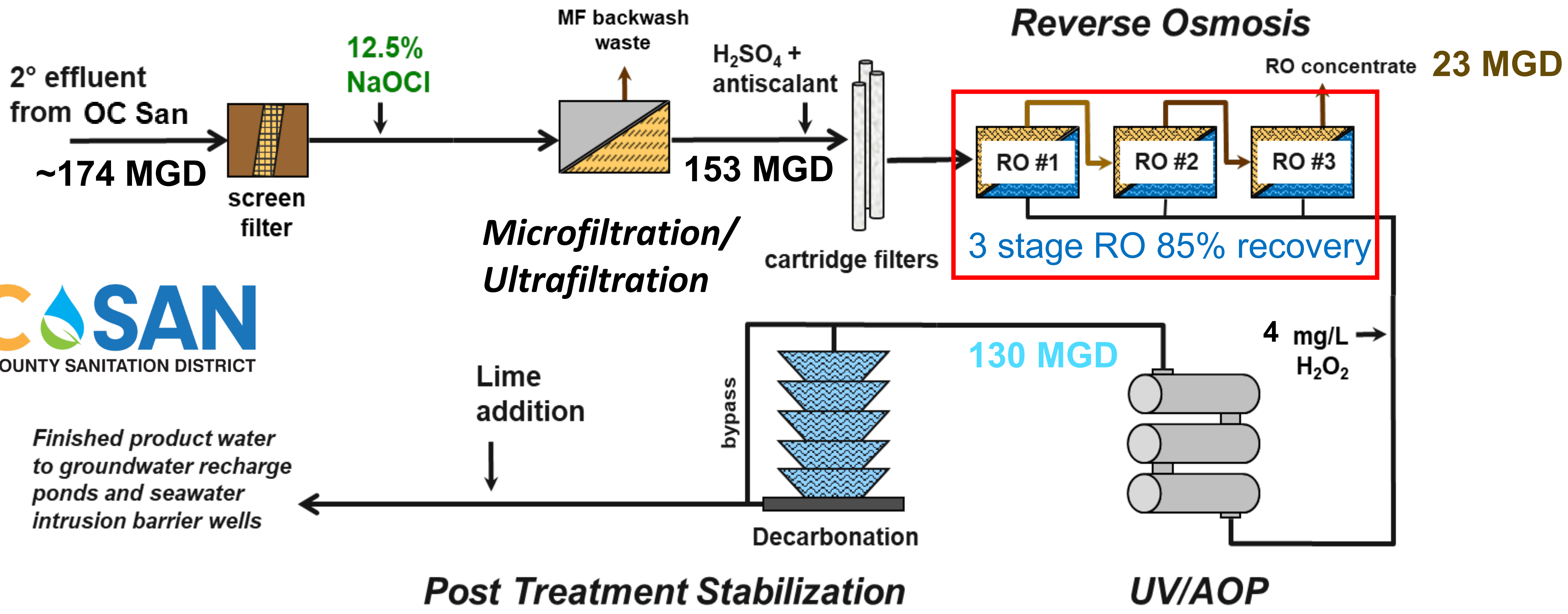
Singapore PUB – FRRO Retrofit

Full scale CCRO system

Advanced Water Purification Facility (AWPF) at OCWD's Groundwater Replenishment System (GWRS)

GWRS is the largest potable reuse facility in the world, producing up to 130 MGD of high purity water (after final expansion in 2023)

GWRS
GROUNDWATER REPLENISHMENT SYSTEM



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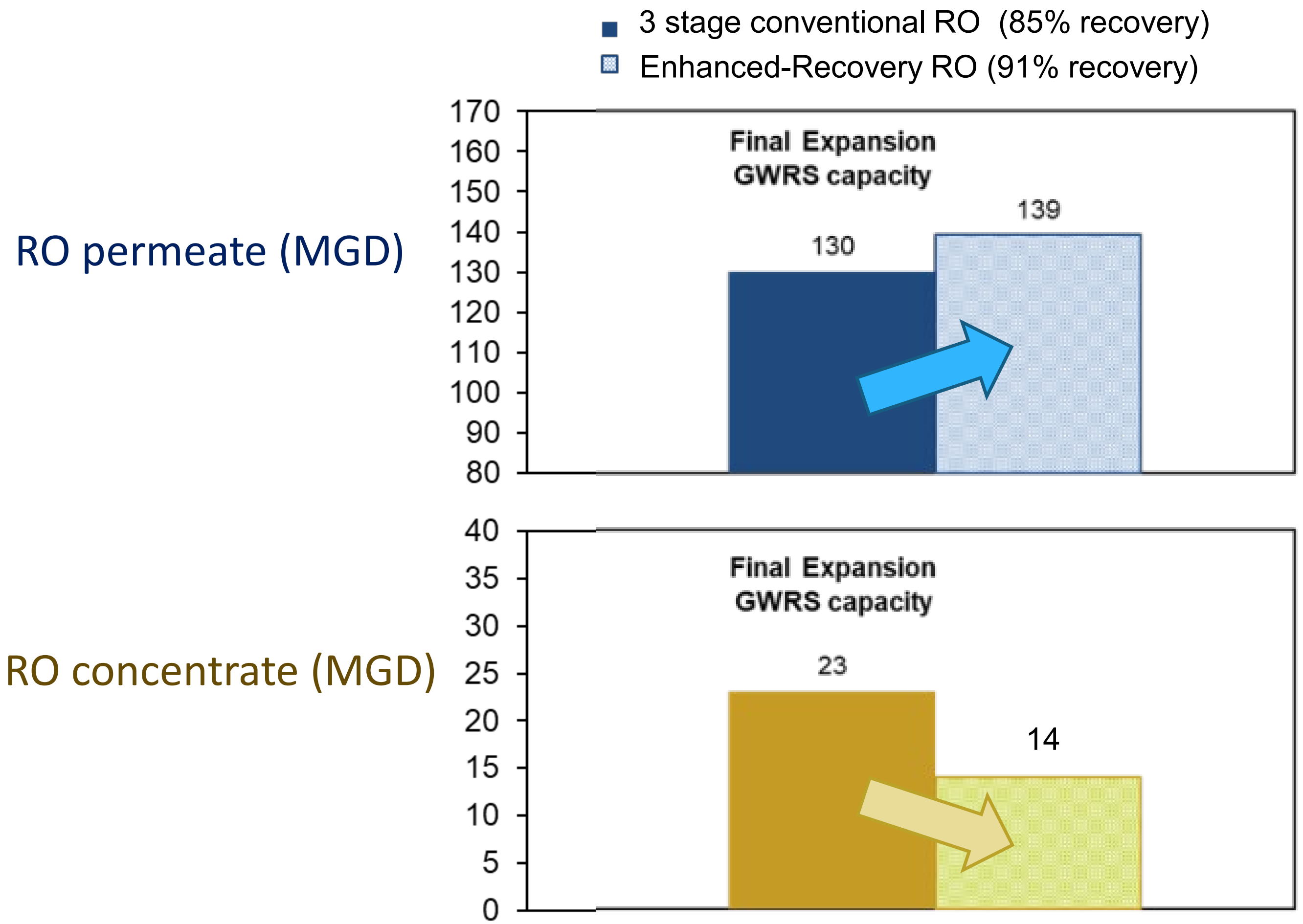
Benefit of Increasing the RO Recovery for GWRS

Increasing RO recovery would increase the overall GWRS production and lower the volume of reject water (currently discharged to ocean outfall)

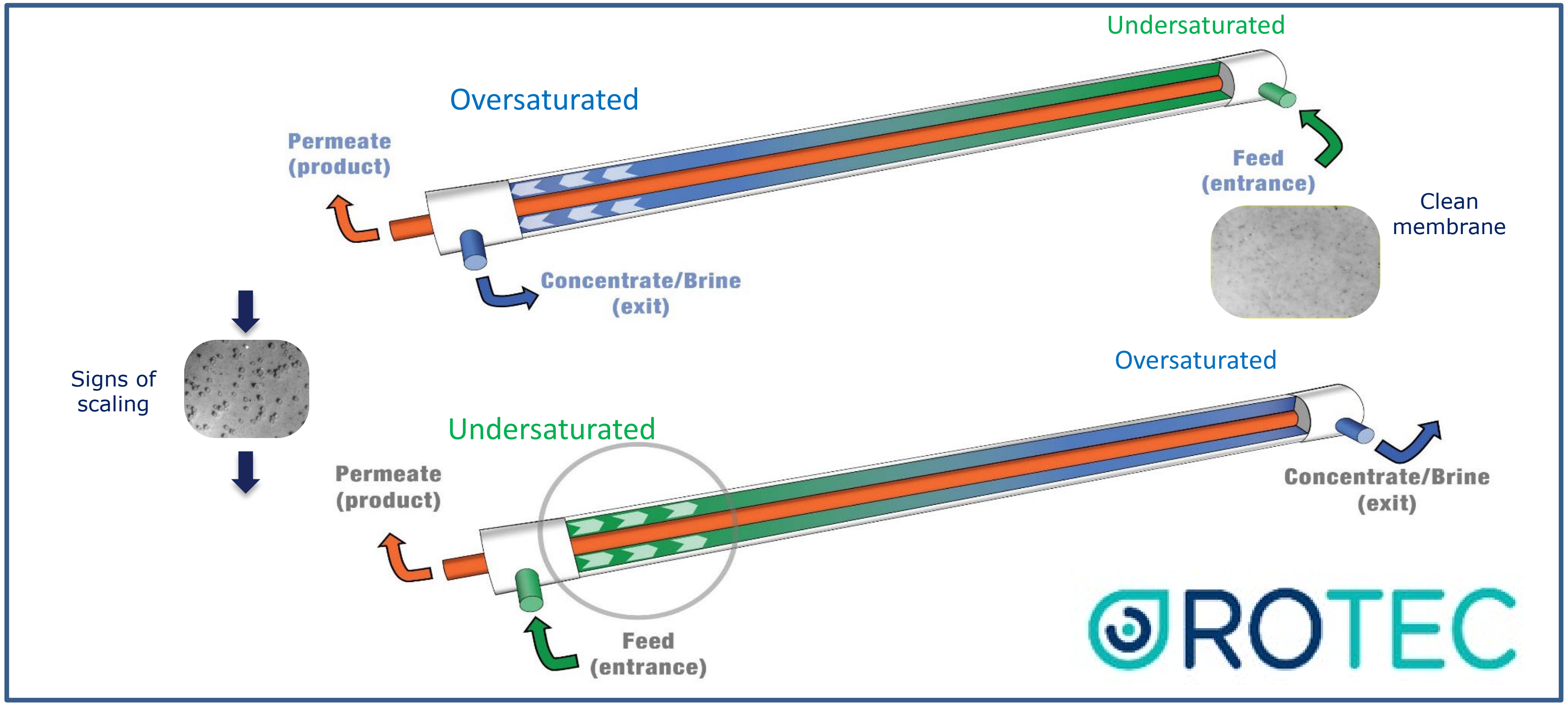
Main drivers for enhancing RO recovery:

1. Cost of imported water increases
2. Water conservation reducing source volume
3. Environmental stewardship



Flow Reversal RO (FRRO) Process Description

- Key features:
  - Feed side flow reversal (FR)
  - Block rotation (BR)
  - Proprietary FR/BR triggering system (based on crystallization induction time estimate)



Induction time: the time for a supersaturated solution to reach the onset of nucleation

OCWD FRRO Pilot Study – Overview

- Pilot study was conducted between 2021 to 2023 in collaboration with Chart/AdEdge and ROTEC
- Phase 1 (treating AWPF RO feedwater)
  - ➢ **Simulate full scale retrofit of a conventional primary RO with FR**
- Phase 2 (treating AWPF RO concentrate)
  - ➢ **Simulate RO brine concentrator**
- Phase 3 (treating AWPF final expansion RO feedwater)
  - ➢ **A repeat of Phase 1 to confirm performance on FE feedwater**

FRRO pilot deployed in the OCWD AWPF RO building

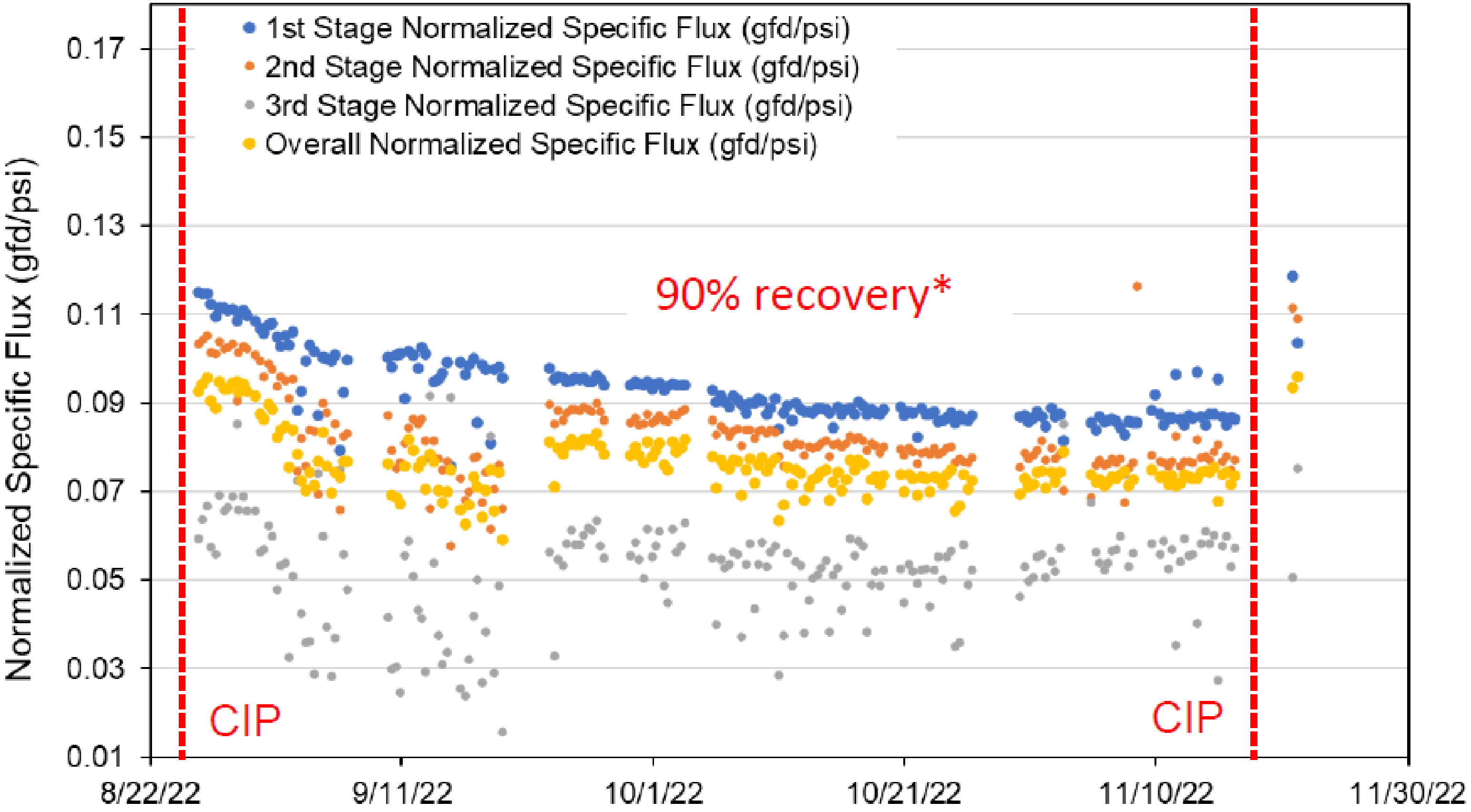
Single pass three stage RO system

30 gpm feed flow in 3 stage RO mode
15 gpm feed flow in 1 stage RO concentrator mode

ROTEC

FRRO Pilot Study: Summary of Findings

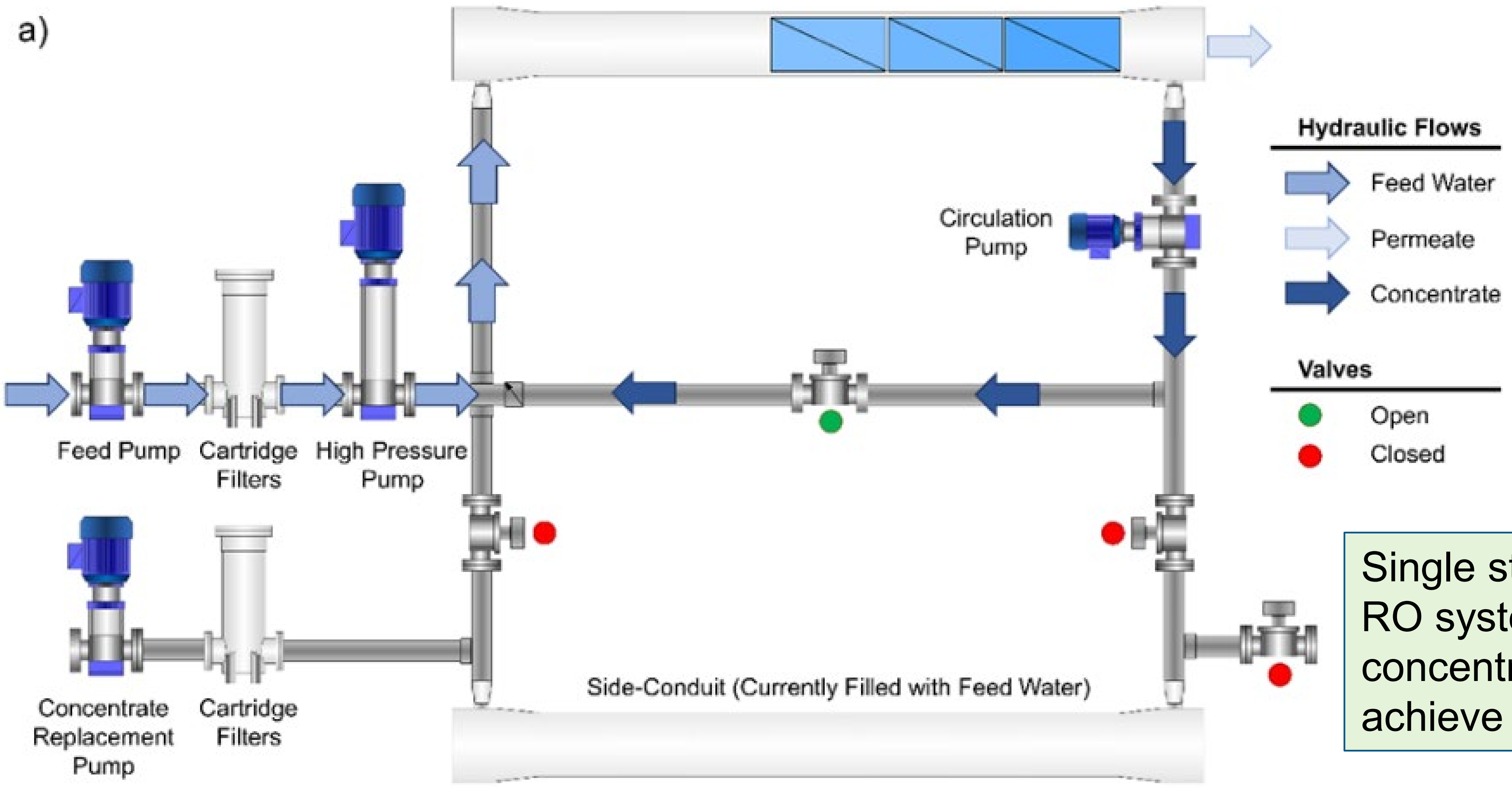
- Achieved ~89-90% stable recovery treating GWRS ROF
  - *No additional chemical needed*
  - *Re-confirmed after GWRS FE startup*
- Membrane cleaning approach was optimized: 3-mo between chemical cleanings (CIPs)
  - *GWRS RO CIP interval is 6-12 months*
- Treating RO concentrate directly with FRRO was ***not*** sustainable



3-month steady-state trial showing stable specific flux at 90% recovery. Block rotation and flow reversal every 40 min (1st and 3rd stage); 2nd stage flow reversal every 10 hr.

Closed-Circuit RO (CCRO) System Process Description

Step 1: Closed-Circuit Mode



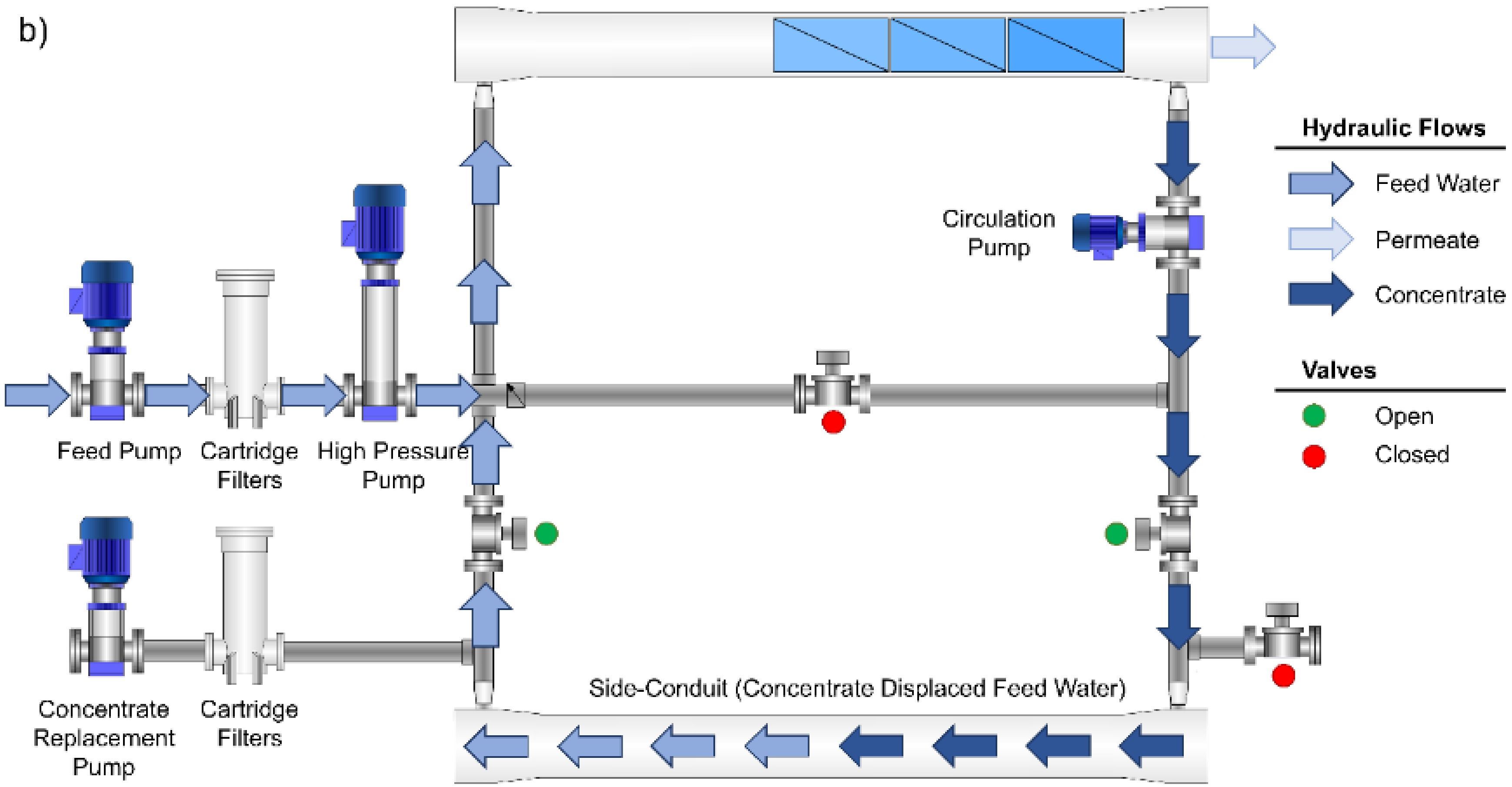
Single stage, semi-batch RO system, use complete concentrate recycling to achieve high recovery

Cross flow velocity can be adjusted independent of the overall recovery and permeate flux. All three are independently controlled set-points

Desalitech a DuPont brand

CCRO System Process Description

Step 2: Plug Flow (Purge) Mode

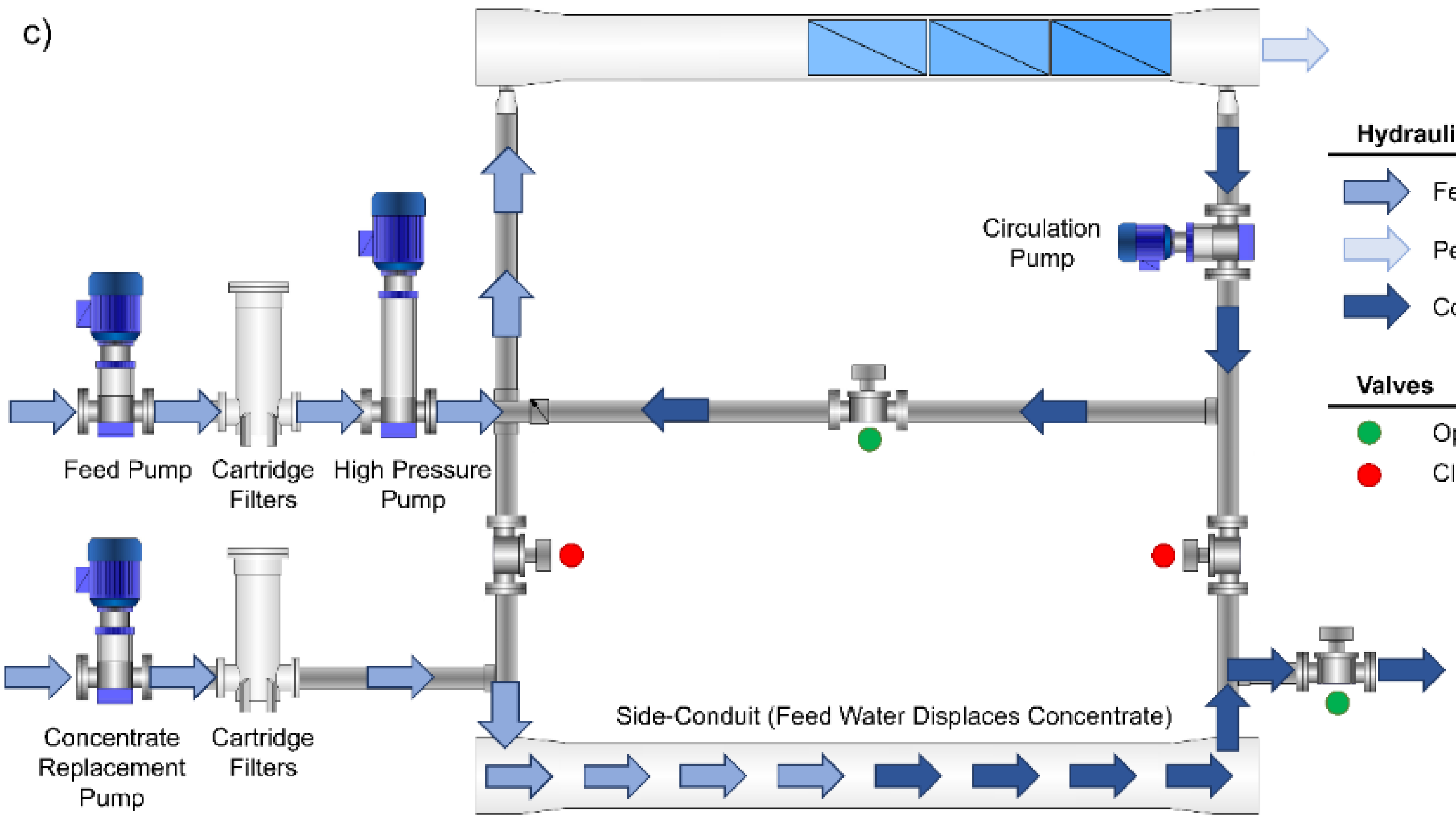


The pressurized CCRO concentrate is purged from the membrane array into the side conduit, which displaces the fresh feed to the front of the membrane array

Desalitech
a DuPont brand

CCRO System Process Description

Step 3: Side-Conduit Refill Mode



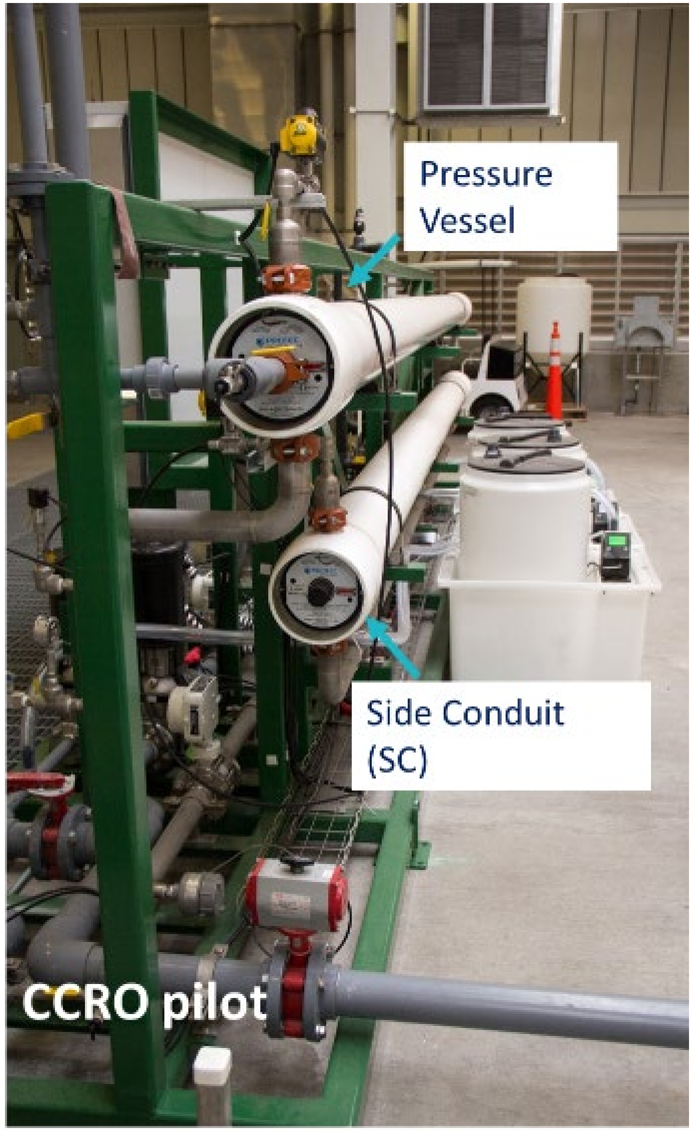
Concentrate flushing efficacy is key to maintain membrane performance

The side conduit is isolated, depressurized and flushed with fresh feed under low-pressure for the next sequence

Desalitech a DuPont brand

CCRO Pilot Testing at OCWD GWRS

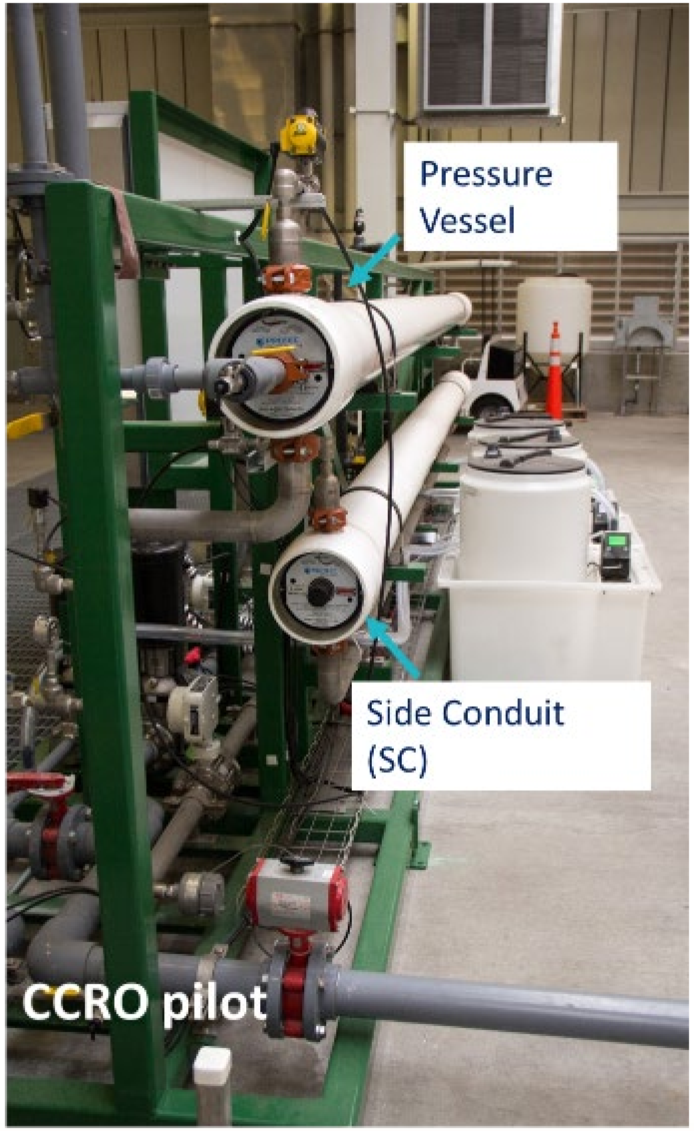
Dupont ReFlex Max CCRO Pilot at AWPF RO Building **(2017-2019)**



OCWD CCRO Pilot Study – Overview

Pilot study was conducted between 2017 to 2019 in collaboration with Dupont/Desalitech and Jacobs

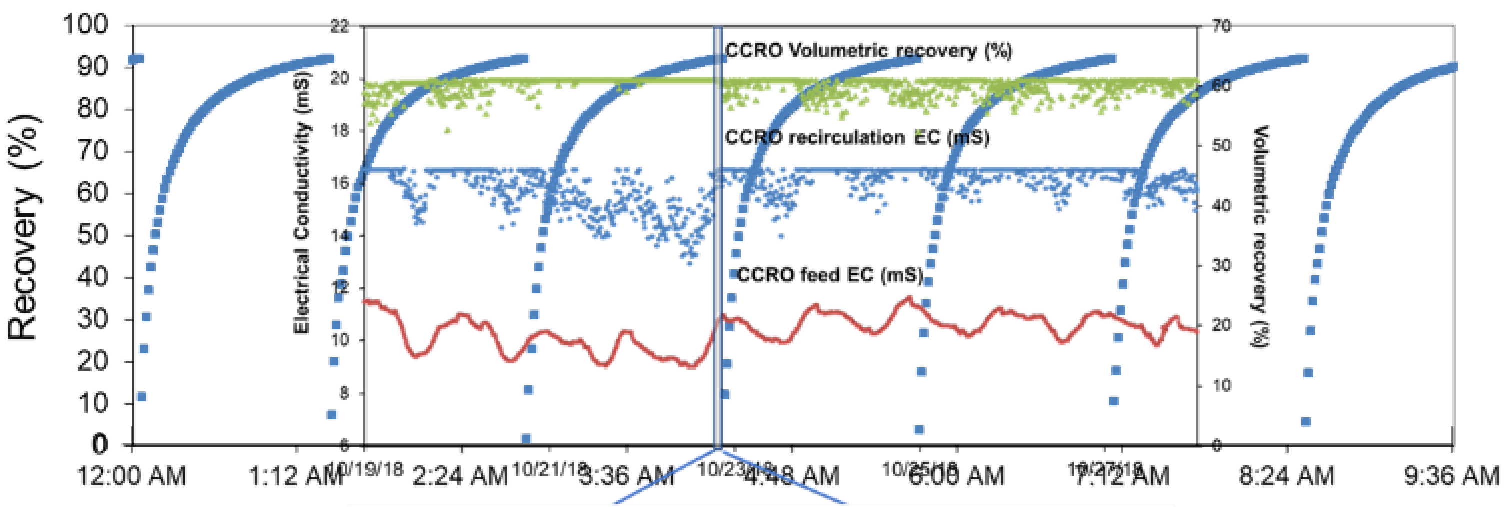
- Phase 1 (CCRO treating AWPF MF effluent)
  - **Simulate full scale CCRO (as primary RO)**
    - **Filling side conduit with MF effluent (ROF)**
- Phase 2 (CCRO treating AWPF RO concentrate)
  - **Simulate RO brine concentrator (4th stage RO)**
    - **Filling side conduit with AWPF ROC or ROF**



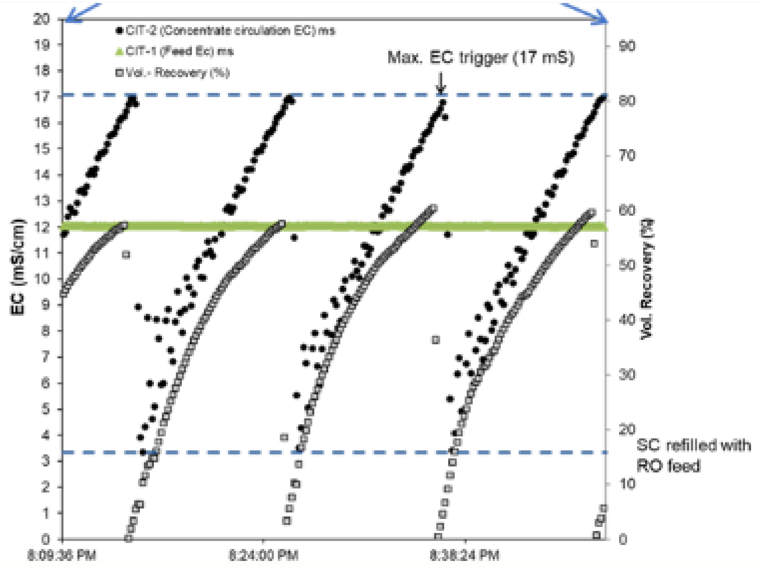
CCRO pilot study: Summary of Findings

- Achieved ~92% stable recovery treating GWRS AWPF MFE
- Achieved ~91% overall recovery treating RO concentrate (pilot was operated as a "fourth stage" RO)
  - Flush side conduit with ROF extended the interval between CIPs by more than two-fold
  - The pilot operated in adaptive variable recovery mode to cope with fluctuating feed water quality
- Membrane chemical cleaning was optimized: ~2-mo. between CIPs

Adaptive recovery rate control based on feed EC

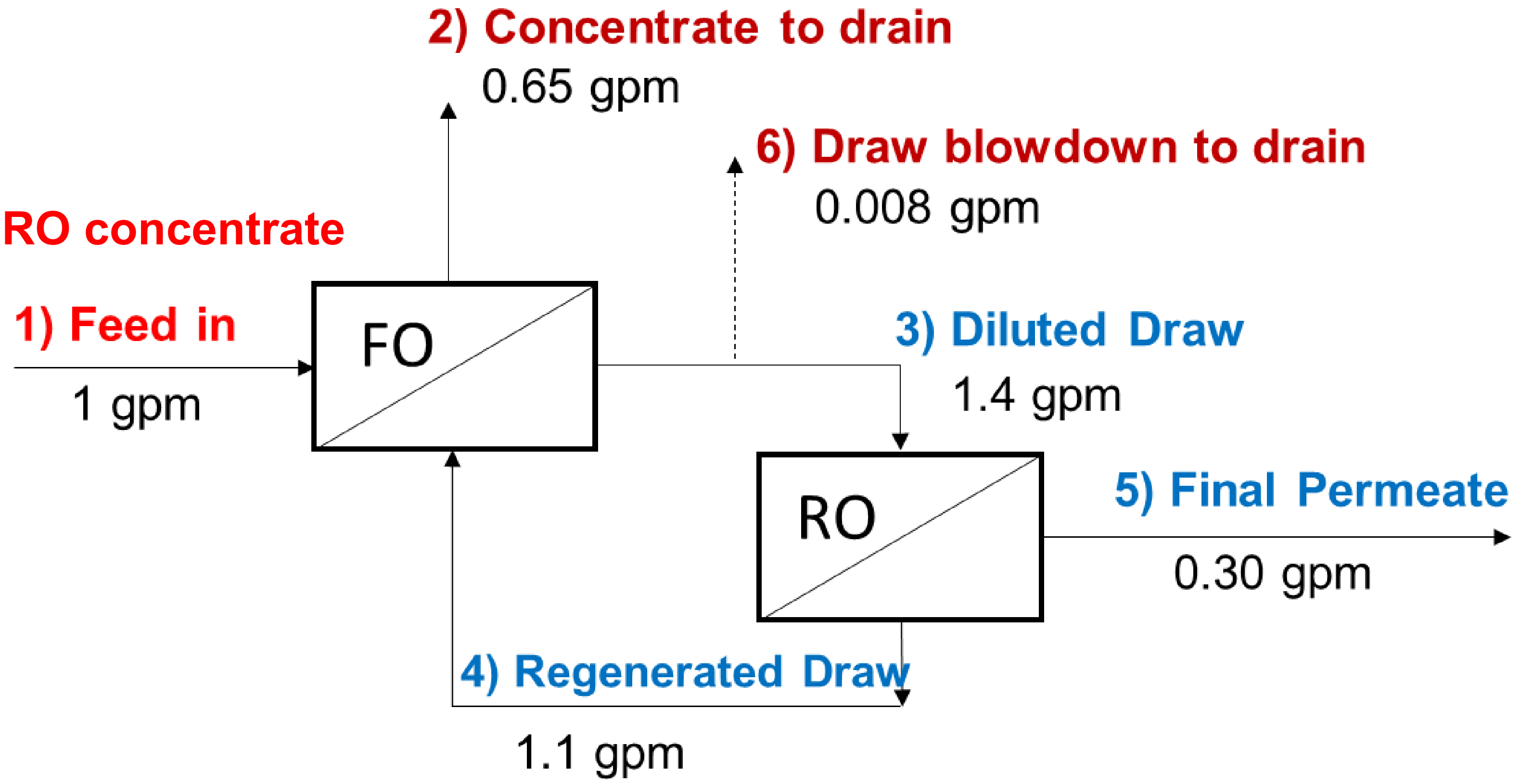


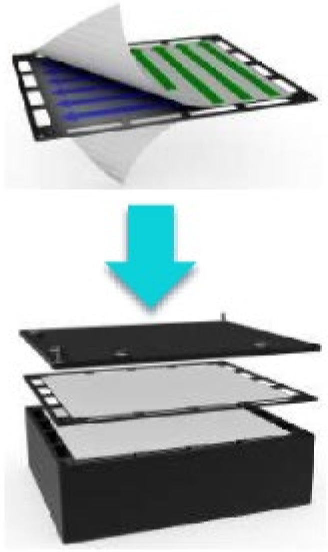
Triggering of CCRO cycles via max. EC threshold



Gu et al. Desalination, Vol 518, 2021, 115300

(Forward Osmosis) FO-RO Pilot Process Description





Flat-sheet FO membrane

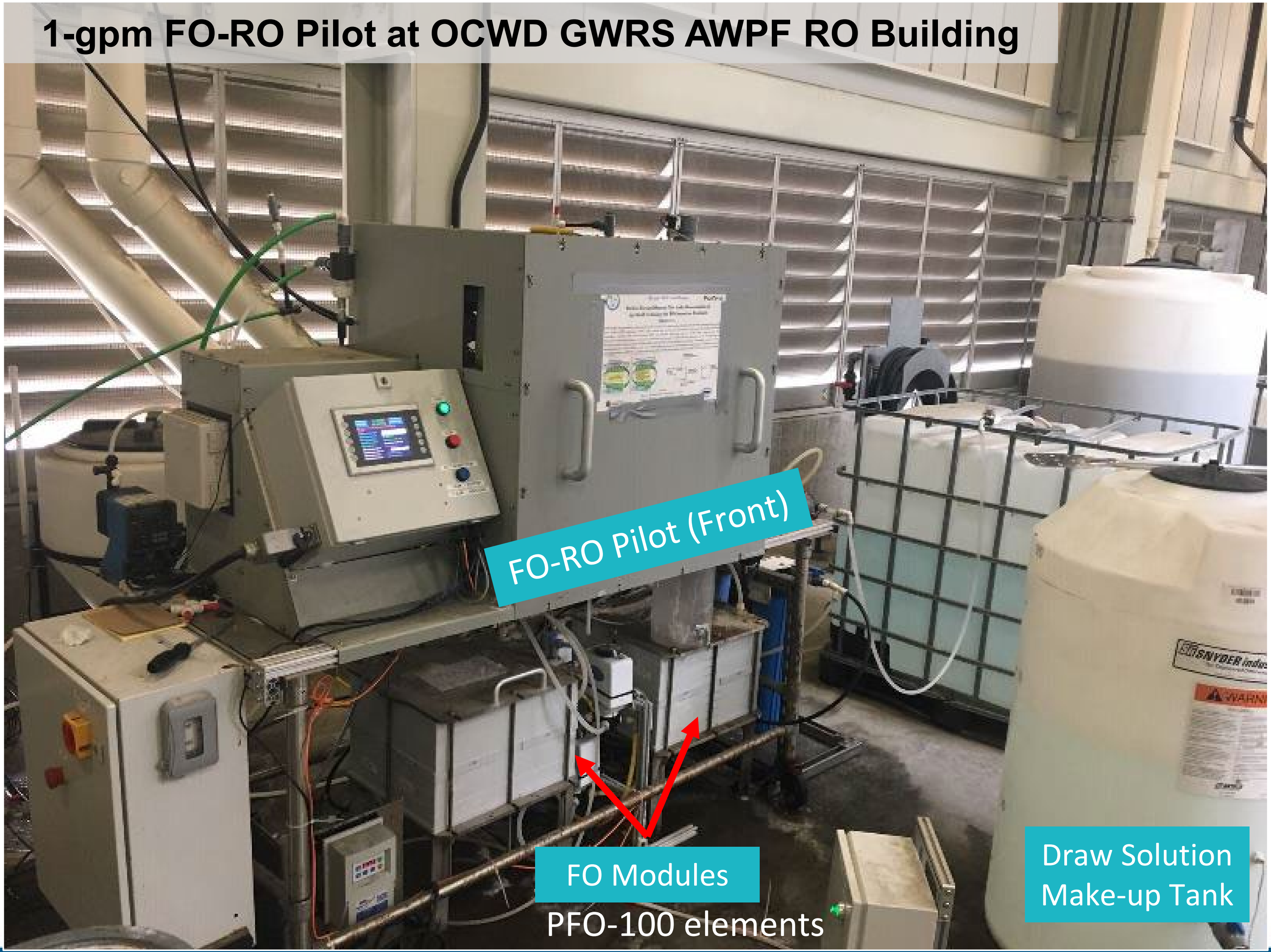
PFO-100 membrane module (14 m^2)

Hybrid membrane system, one pass, double barriers, draw solution (**NaCl**) required to separate permeate

The salt concentration in the draw solution is retained within the closed-loop

Porifera

(Forward Osmosis) FO-RO Pilot Testing (2018-2019)



RO Elements

Dupont SW30-2540

Porifera

FO-RO pilot study: Summary of Findings

- Pilot treated AWPF RO concentrate directly
- The system piloted at OCWD for about 18 months
- FO-RO system operated between 30-35% recovery (89.5-90.3% overall recovery)
- FO CIP frequency: every 3-4 weeks
- RO CIP frequency: every ~6 mo.

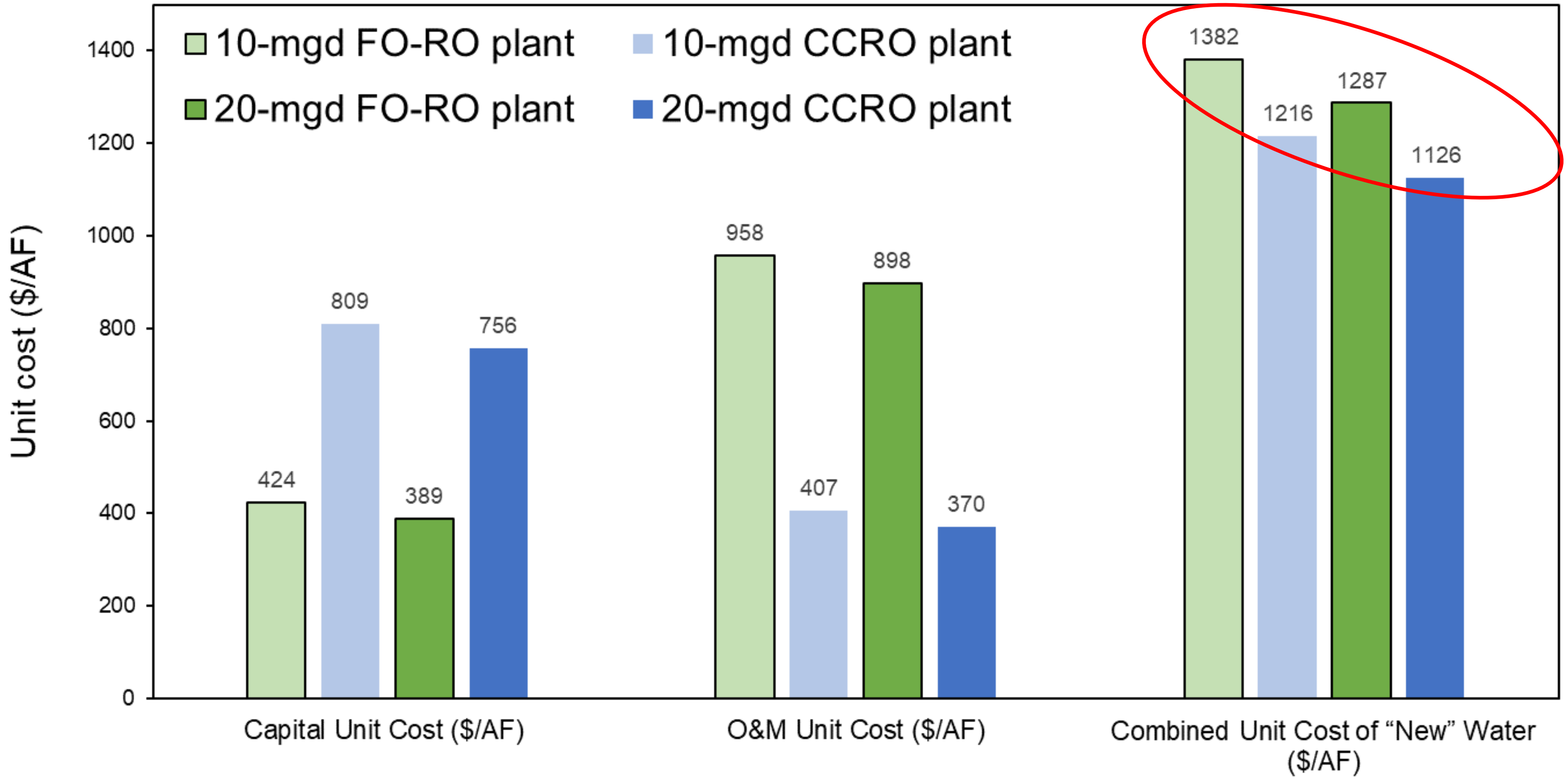
Operational Challenges

- ➢ Organic fouling and silica (silts/clay) scaling of the FO membrane
- ➢ FO membrane delamination due to rapid spikes in draw overpressure
- ➢ High draw solution usage

Porifera

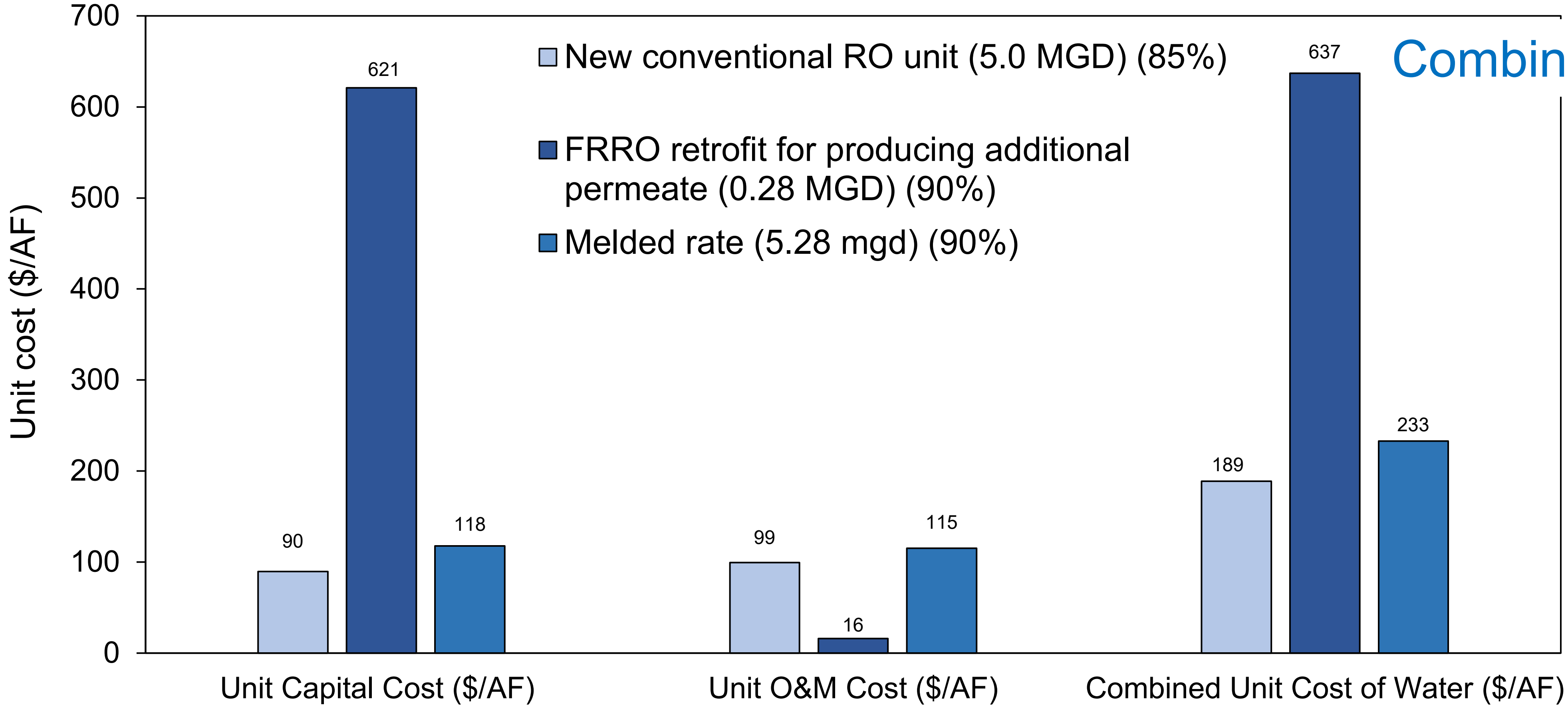
Preliminary Cost Evaluation for Full-Scale CCRO and FO-RO

Gu et al. Water Reuse (2023) 13 (3): 305–318.



- CCRO system is expected to have lower annual operation and maintenance (O&M) cost but higher capital cost than the FO-RO system (FO-RO system exhibit the reverse trend)
- Assuming a 30-year loan period at a fixed annual interest rate of 5%, the unit cost of new water produced by the CCRO system is slightly lower than FO-RO system

Preliminary Full-Scale FRRO Retrofit Cost Estimate



Combined Cost

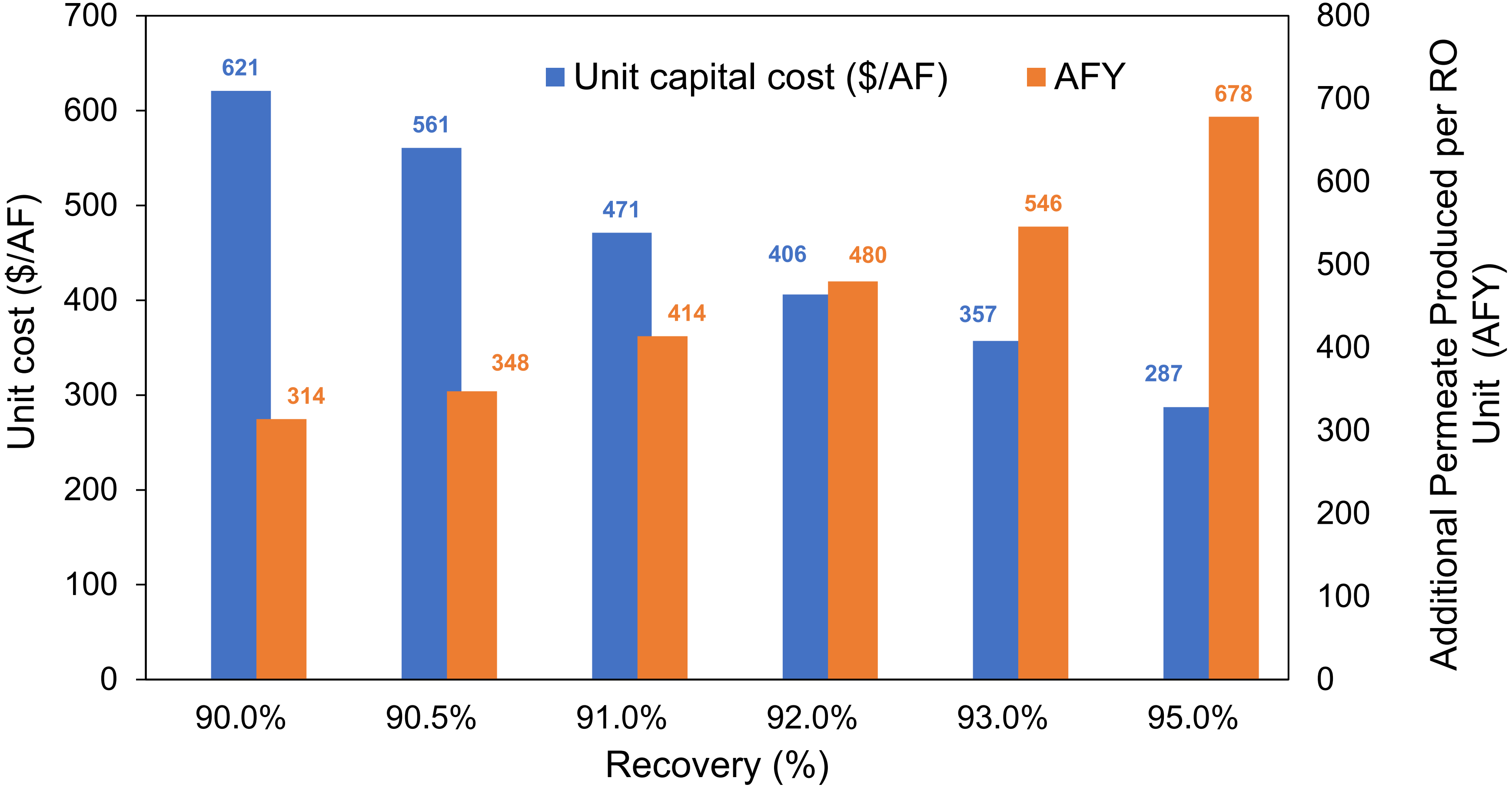
OCWD site specific cost number

The melded rate: RO unit + retrofit cost

The O&M cost is higher due to more frequent cleanings and higher electrical power consumption (due to membrane fouling)

Preliminary Full-Scale FR Retrofit Cost Estimate

Unit capital cost for retrofit



Capital cost for retrofit heavily contingent on % recovery, i.e., additional permeate produced (AFY). If advancements in FR technology, antiscalant, or membrane performance led to increased recovery, the unit capital cost will greatly reduce.

"Squeeze out the last drop of water"

Relative Pros/Cons of Three High Recovery RO Technology

Technology	Pros	Cons	Test Duration	Pilot configuration and max recovery
FRRO	Able to retrofit an existing RO *CIP interval: ~3-mo.* *Salt and organic rejection similar to conventional RO*	Concentrator mode was unsuccessful *Recovery reduced during FR/BR transition*	2021-2023	Primary RO mode at 89-90% overall recovery
CCRO	Work well in both primary RO and concentrator mode *Variable cycle recovery mode, adaptive to feed EC*	Concentrator mode requires ROF for SC flushing *Permeate quality vary with time (cyclic behavior)*	2017-2019	Primary RO mode at ~92% overall recovery, or RO concentrator at ~91% overall recovery
FO-RO	Internal salt retention min. concentrate reject salinity *Better organic and virus rejection than CCRO*	CIP interval: 3-4 weeks *FO membrane integrity issues* *High draw solution usage*	2018-2019	RO concentrator at 89.5-90% overall recovery

Conclusions

- The unit cost of additional permeate from full-scale FR retrofit is lower than that of CCRO and FO-RO system. If higher percent recovery is achieved, $/AF will drop significantly
- All pilots produced high quality permeate that could be blended with the existing primary RO permeate to increase overall production

Acknowledgements

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Andrew Huang

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BUREAU OF RECLAMATION

CCRO and FO-RO pilot study
FRRO pilot study

SCSC Southern California Salinity Coalition

FRRO pilot study

STATE OF CALIFORNIA ENERGY COMMISSION
CALIFORNIA ENERGY COMMISSION

FO-RO pilot study

City of Santa Monica

Squeezing the Last Drop: Using Enhanced-Recovery Reverse Osmosis to Improve Water Production

Alex Waite

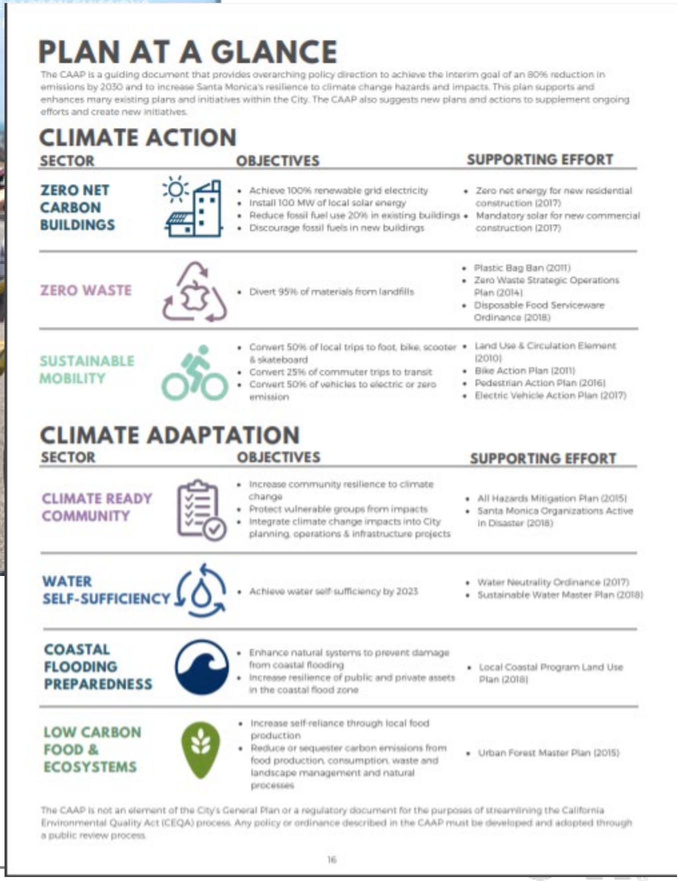
August 7, 2024

Goals of the City’s Sustainable Water Master Plan

Diverse, sustainable, & drought resilient water supply to support a sustainable community

Energy footprint reduction to support carbon reduction goals for the City

Long term cost benefits for rate payers



PLAN AT A GLANCE

The CAAP is a guiding document that provides overarching policy direction to achieve the interim goal of an 80% reduction in emissions by 2030 and to increase Santa Monica's resilience to climate change hazards and impacts. This plan supports and enhances many existing plans and initiatives within the City. The CAAP also suggests new plans and actions to supplement ongoing efforts and create new initiatives.

CLIMATE ACTION

SECTOR	OBJECTIVES	SUPPORTING EFFORT
ZERO NET CARBON BUILDINGS	• Achieve 100% renewable grid electricity • Install 100 MW of local solar energy • Reduce fossil fuel use 20% in existing buildings • Discourage fossil fuels in new buildings	• Zero net energy for new residential construction (2017) • Mandatory solar for new commercial construction (2017)
ZERO WASTE	• Divert 95% of materials from landfills	• Plastic Bag Ban (2011) • Zero Waste Strategic Operations Plan (2014) • Disposable Food Serviceware Ordinance (2018)
SUSTAINABLE MOBILITY	• Convert 50% of local trips to foot, bike, scooter & skateboard • Convert 25% of commuter trips to transit • Convert 50% of vehicles to electric or zero emission	• Land Use & Circulation Element (2010) • Bike Action Plan (2011) • Pedestrian Action Plan (2016) • Electric Vehicle Action Plan (2017)

CLIMATE ADAPTATION

SECTOR	OBJECTIVES	SUPPORTING EFFORT
CLIMATE READY COMMUNITY	• Increase community resilience to climate change • Protect vulnerable groups from impacts • Integrate climate change impacts into City planning, operations & infrastructure projects	• All Hazards Mitigation Plan (2015) • Santa Monica Organizations Active in Disaster (2018)
WATER SELF-SUFFICIENCY	• Achieve water self sufficiency by 2023	• Water Neutrality Ordinance (2017) • Sustainable Water Master Plan (2018)
COASTAL FLOODING PREPAREDNESS	• Enhance natural systems to prevent damage from coastal flooding • Increase resilience of public and private assets in the coastal flood zone	• Local Coastal Program Land Use Plan (2018)
LOW CARBON FOOD & ECOSYSTEMS	• Increase self-reliance through local food production • Reduce or sequester carbon emissions from food production, consumption, waste and landscape management and natural processes	• Urban Forest Master Plan (2015)

The CAAP is not an element of the City's General Plan or a regulatory document for the purposes of streamlining the California Environmental Quality Act (CEQA) process. Any policy or ordinance described in the CAAP must be developed and adopted through a public review process.

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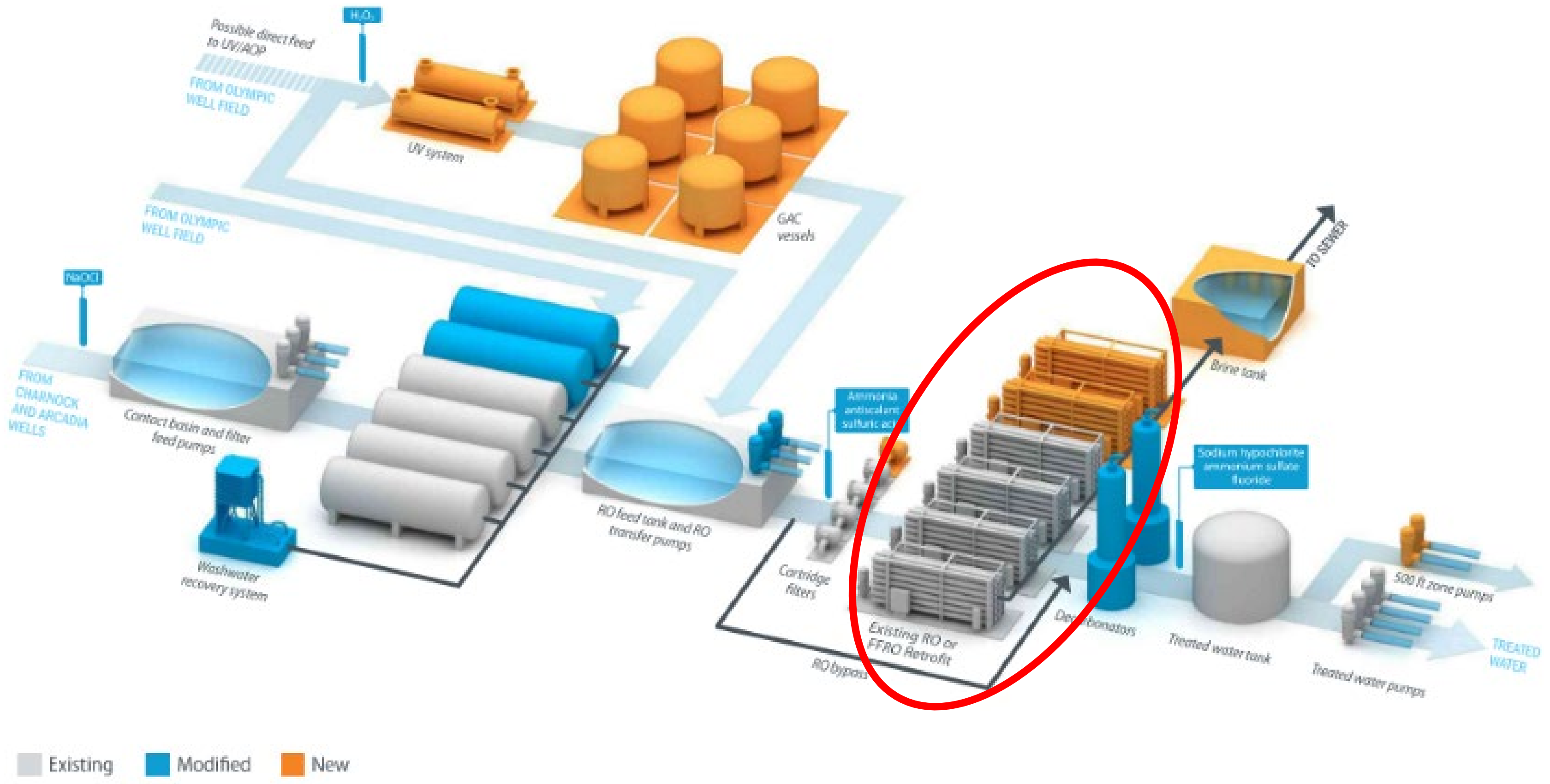
Olympic Well Field Restoration and Arcadia WTP Production Expansion Project



- Increase capacity from 10 mgd to 13 mgd
- Retrofit existing RO skids to achieve >90% recovery

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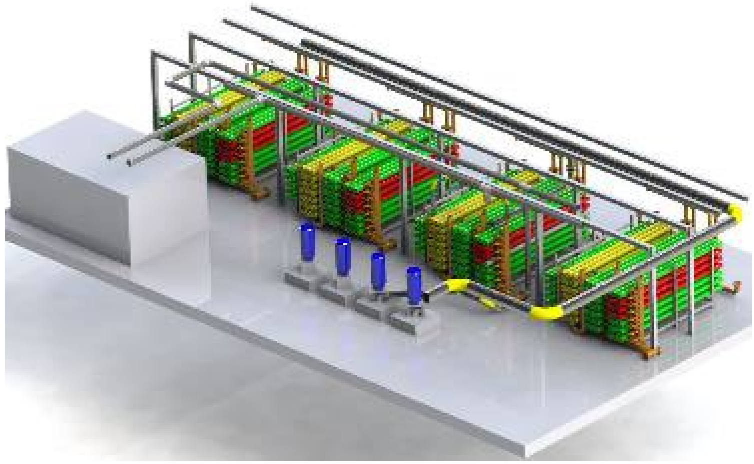
Is the RO Concentrate Worth the Squeeze?

Existing RO System

Closed Circuit RO (CCRO)



Flow Reversal RO (FRRO)

- Increase RO system recovery to ≥90% to increase local water supply
- Side-by-side pilot testing of CCRO vs FRRO

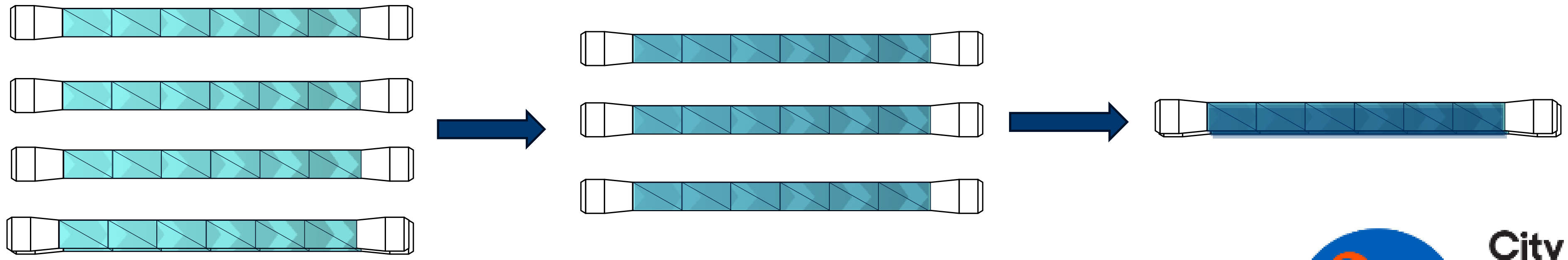
City of Santa Monica

FRRO's Block Rotation for Multi-Stage System

RO system staged in a series of blocks that are cycled through a rotation where each block takes a turn as the last stage of the system.

Last stage block rotates switches back into first stage based on induction timer and replaced with new block.

Flow is reversed and fed with undersaturated feedwater which dissolves scale particles before proliferating.



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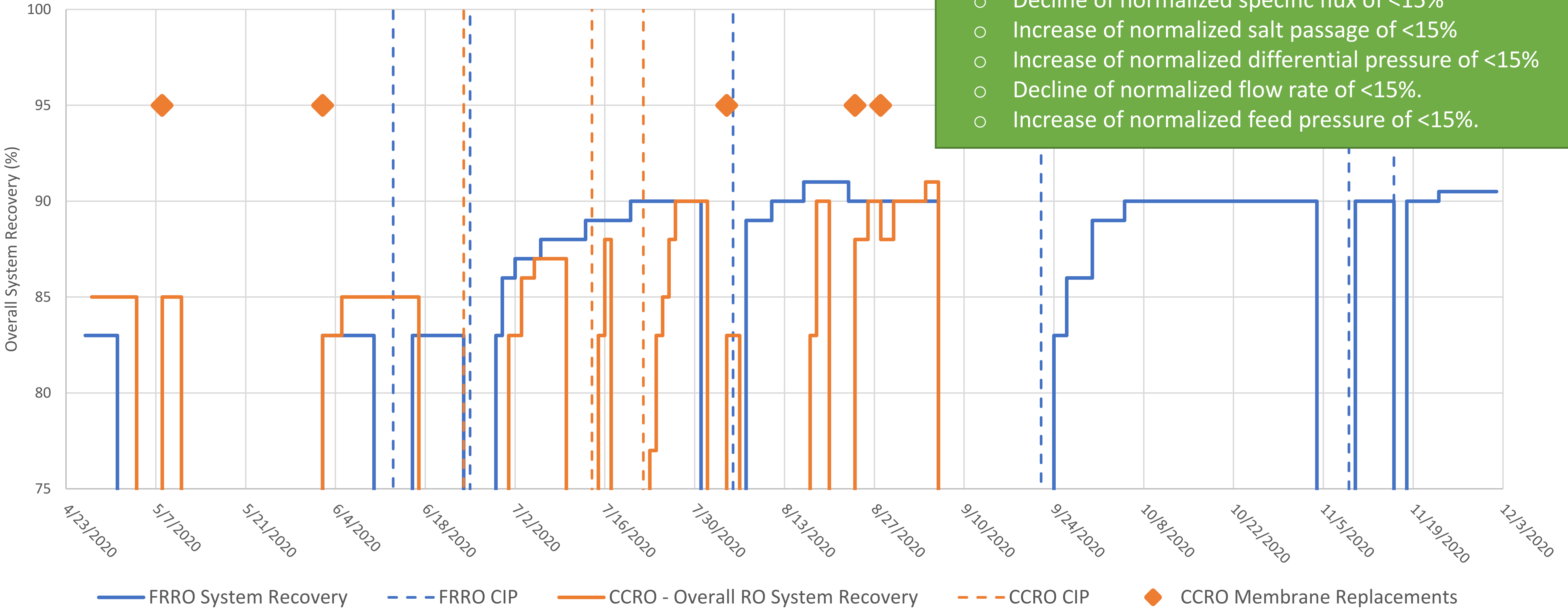
FRRO/CCRO Pilot Summary

Success Criteria:

- Operate at >88% recovery for at least 4 months
- CIP no greater than every 1 month, triggered by:
  - Decline of normalized specific flux of <15%
  - Increase of normalized salt passage of <15%
  - Increase of normalized differential pressure of <15%
  - Decline of normalized flow rate of <15%.
  - Increase of normalized feed pressure of <15%.



Pilot Performance Summary

Pilot	FRRO	CCRO
Operations	Primary RO in High Recovery Mode	Concentrate minimization system = 62% greensand filtrate/38% RO concentrate
Membrane / Average Flux	• Toray TML10D • 11.7 – 12.8 gfd	• FilmTec BW30XFRLE-400/3 • 8 – 9 gfd
Online Time	• Total online time of 144 days • ~106 days at 89% or greater recovery • 15 consecutive days at 91% recovery	• Total online time of 86 days • ~22 days at 89% or greater overall recovery • <5 non-consecutive days at 91% overall recovery
CIPs and Membrane Replacement	• Five CIPs • Membranes never replaced • Typical pilot operation between CIP events was over 30 days, longest operation was 42 days	• Three CIPs • Membranes replaced five times • No typical pilot operation between CIP events or membrane replacements
Chemical Consumption	• pH of 6.3 (depressed from 7.5) • Antiscalant dose of 1 ppm of AWC A-119 antiscalant or 2.5-3.0 ppm of Avista Vitec-4000	• pH of 6.8 (depressed from 7.5) • Antiscalant dose of 3 ppm of AWC A-119 antiscalant + antiscalant present in RO Concentrate

Cost Competitiveness of FRRO

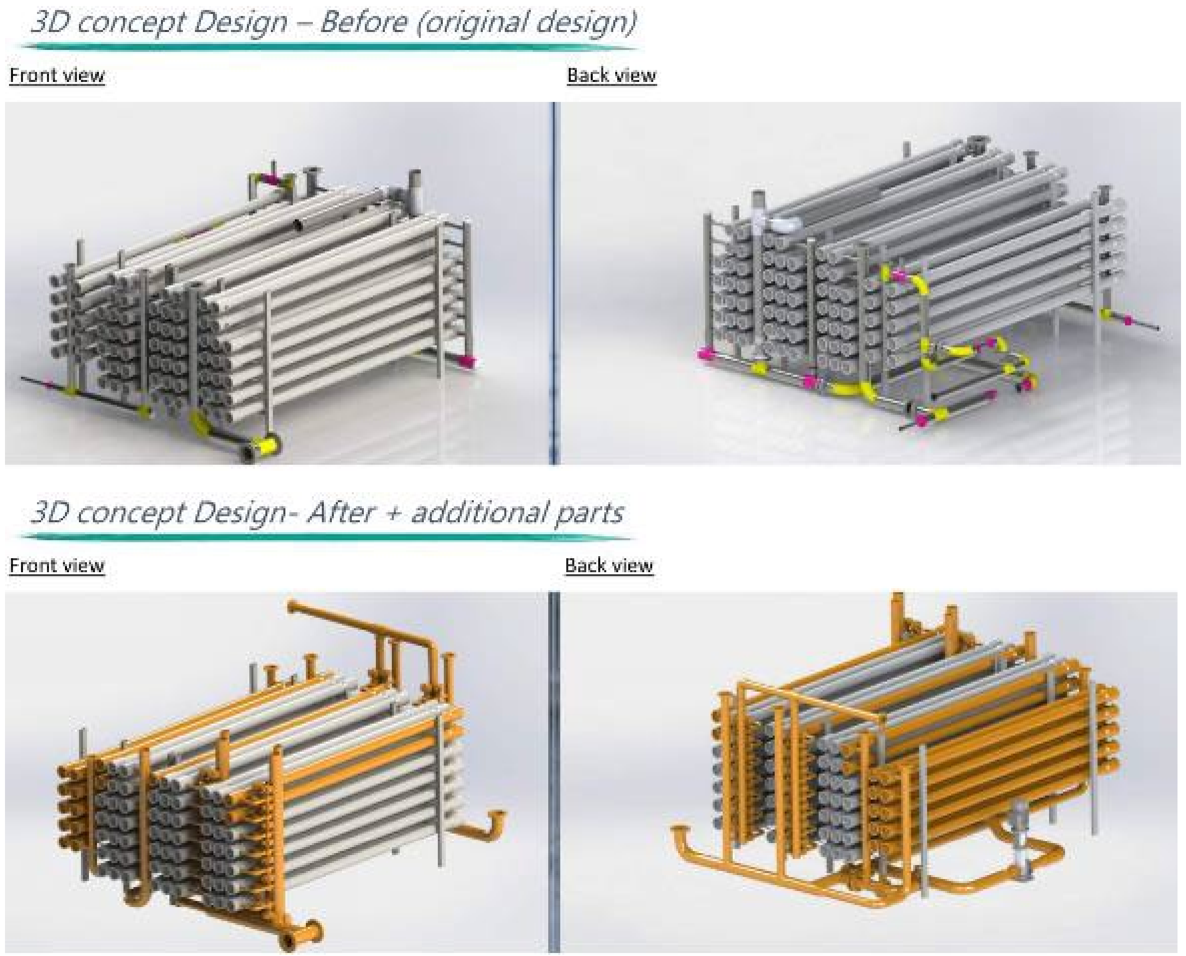
Design Condition	Cost* ($/AF)
4 FRRO Train Retrofit + 0 Standby	$1,068
4 FRRO Train Retrofit + 1 New FRRO Train as Standby	$1,515
Add 2 CCRO Trains (No Standby)	$1,794
Imported Water**	$1,015

*Cost for added production (0.78 mgd) made possible by FRRO (does not include existing RO permeate production cost)
**Costs based on 2018 rates

City of Santa Monica

Benefits of FRRO For Santa Monica

- Stable operations at high recovery ≥90%
- Ability to retrofit existing RO skids
- Lower operation and life-cycle cost
- Funding flexibility
- Operation flexibility
- Relatively lower risk profile



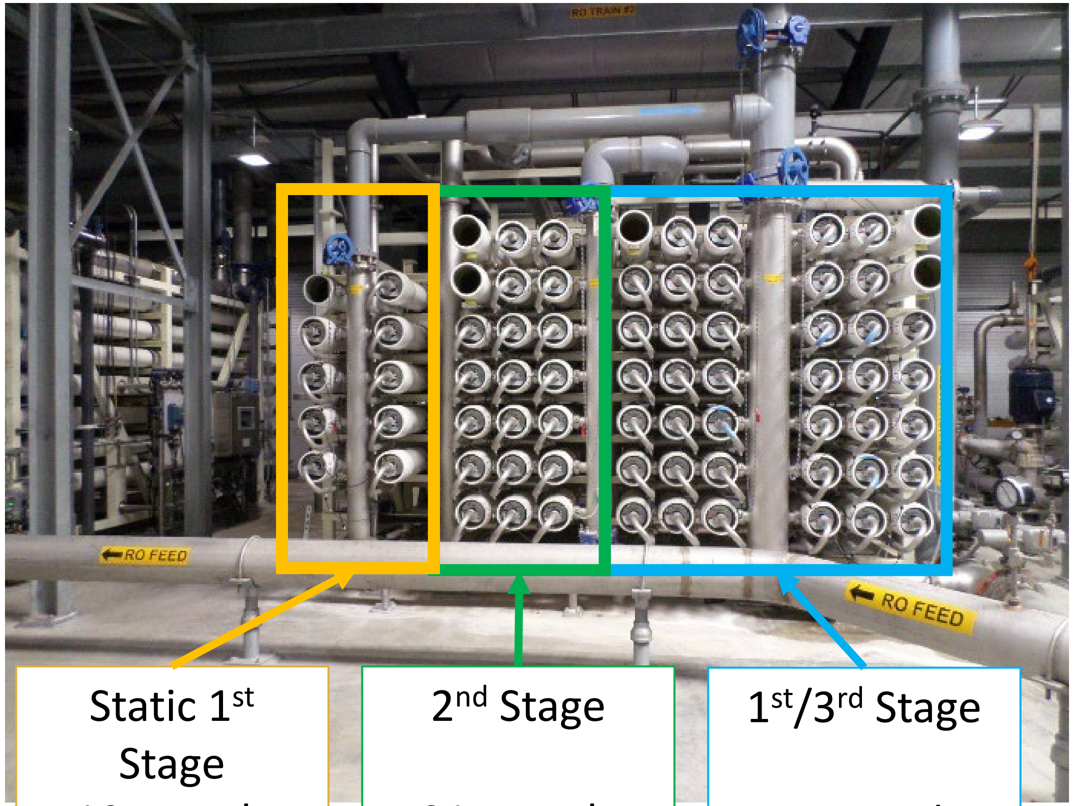
First municipal application of FRRO in the United States!

Full-Scale Implementation

Retrofit of Full-Scale System

Conventional 3-Stage RO

39:19:9 3-Stage Array, 83% Recovery



Static 1st Stage
10 vessels

2nd Stage
21 vessels

1st/3rd Stage
42 vessels

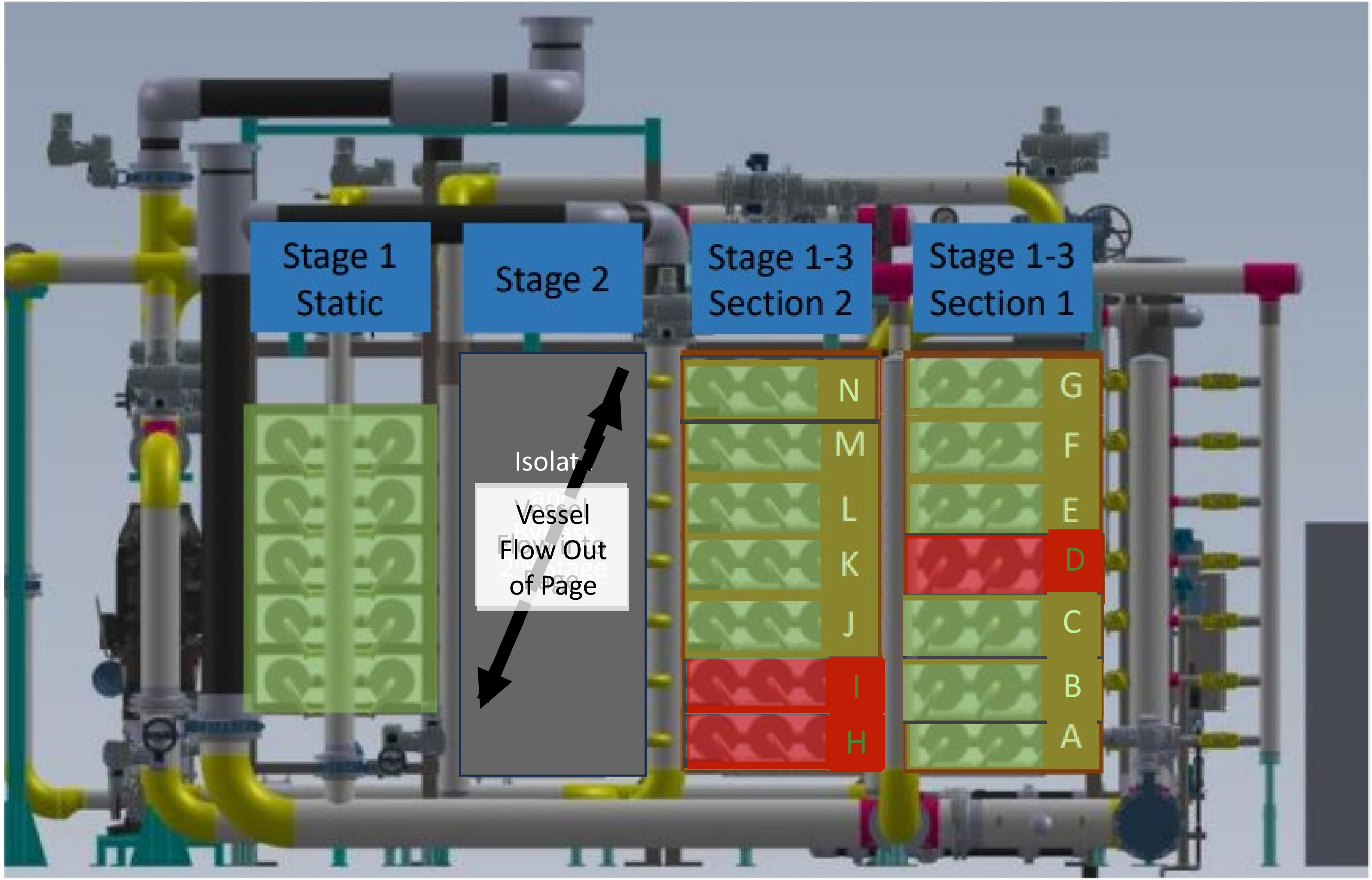
FRRO 3-Stage Retrofit

43:21:9 3-Stage Array, 90% Recovery

Changes from Conventional to FRRO

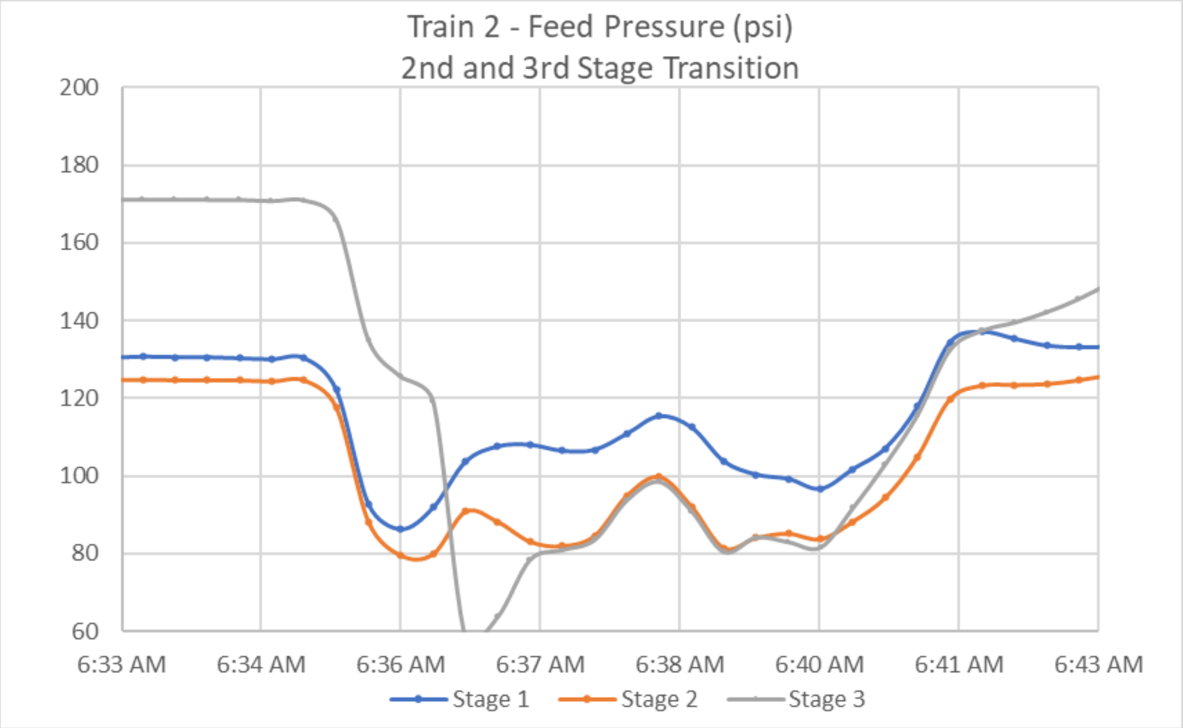
Parameter	Original	Retrofitted
PV Stage Configuration (1^{st}:2^{nd}:3^{rd})	39:19:9	43:21:9
Membrane	Toray TMG20D-440	Toray TMG20D-440**SR**
Maximum Recovery	85% (true operating max of 83%)	90%+
Design Flux	13.5 gfd	12.8 gfd
Interstage Booster	2^{nd} stage booster only	Replaced 2^{nd} stage and new 3^{rd} stage with inline vertical centrifugal pumps
Rotating Block Configuration	Static	• 10 static 1^{st} stage vessels • 14 rotating blocks of 3 vessels each "A" thru "N" for 1^{st}/3^{rd} stage operations • 21 2^{nd} stage vessels rotating as one
Instrumentation	Existing typical instrumentation	Existing plus new pressure transmitters, flow meters, and permeate/conductivity probes
Controls	Existing PLC and train RIO	New PLC, existing train RIO plus new RIO cabinet

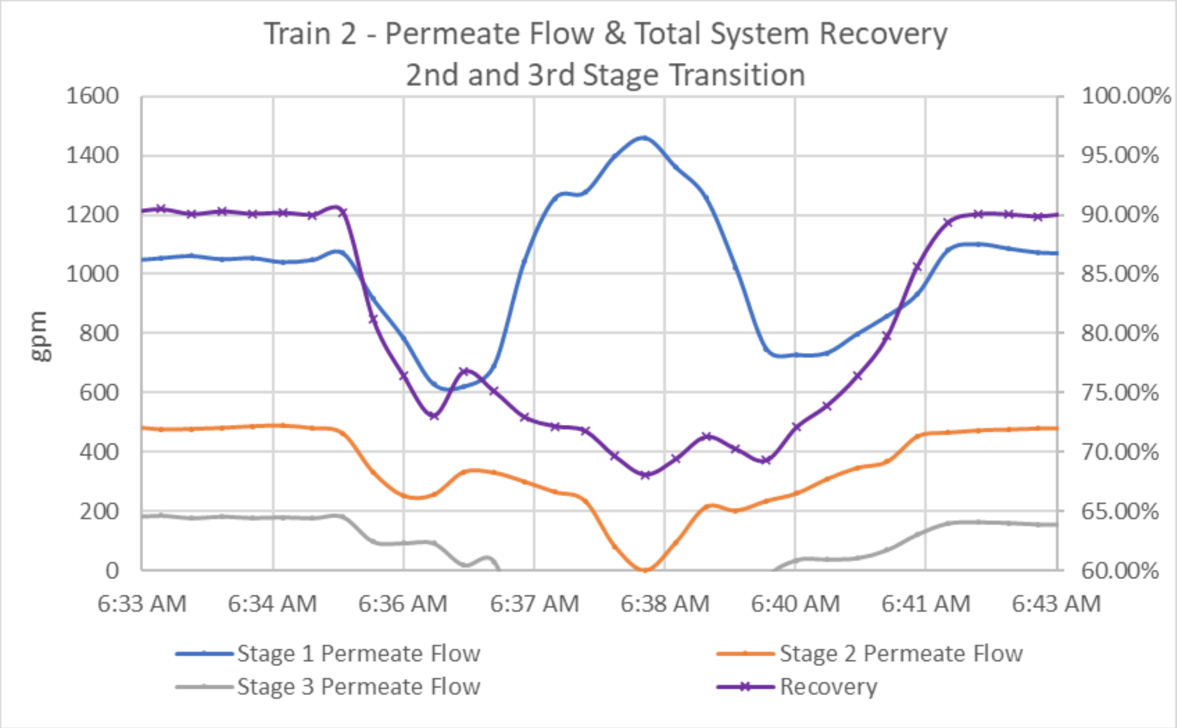
Full-Scale Transition Process



1. Isolate next 1st stage blocks for rotation
2. Open closed blocks to 3rd stage flow
3. Open 2nd stage bypass valve, and close 2nd stage inlet/outlet
4. Open 2nd stage inlet/outlet in opposite direction
5. Isolate original 3rd stage blocks
6. Open closed blocks to 1st stage flows
7. Stabilize and begin operations

Transition Process and Effect on Overall Recovery





Stage 2 and 3 booster pumps cease during flow-reversal

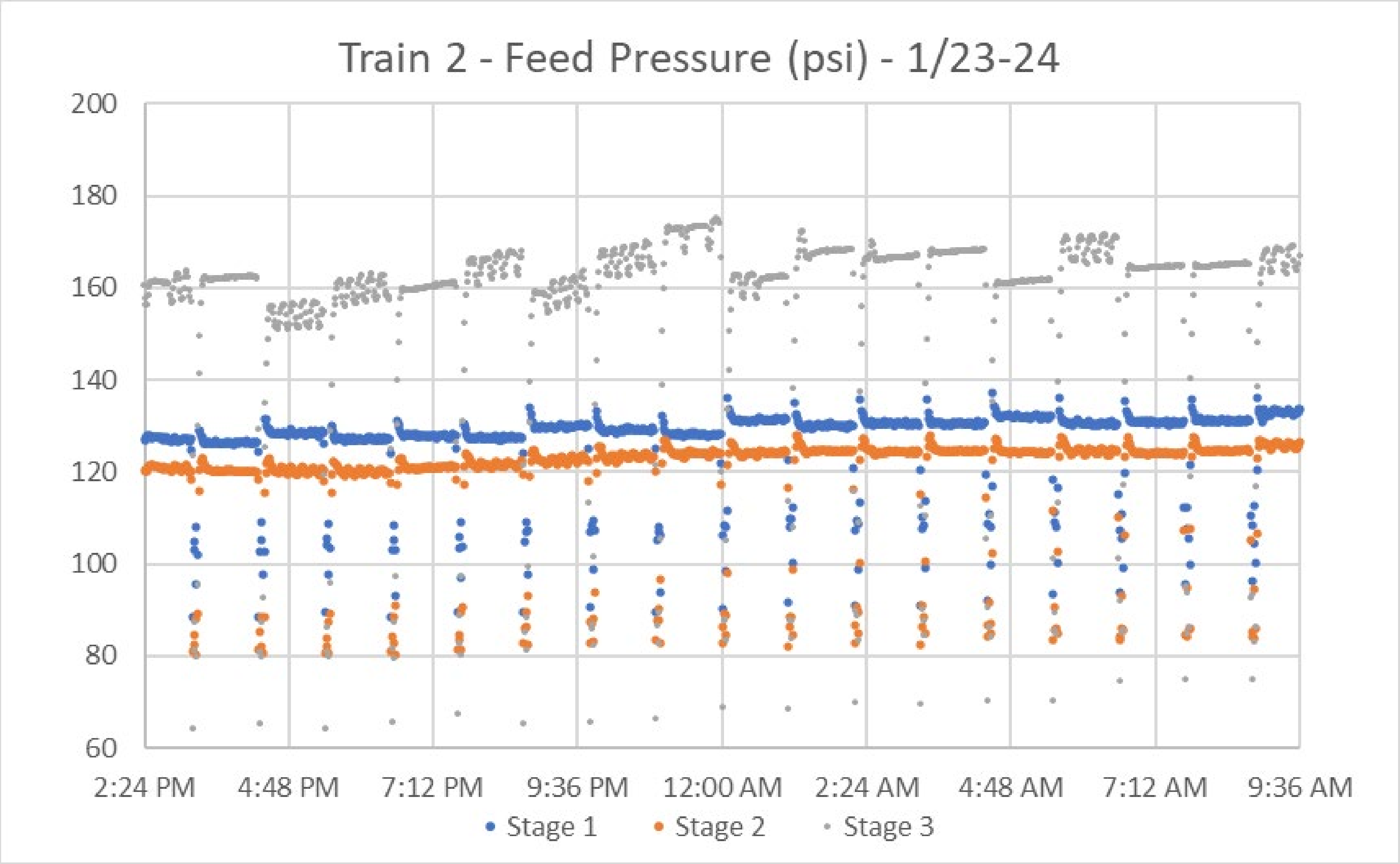
- Increase in pressure in 1st stage
- Utilize 1st stage transient pressure for remaining system

36 hours to cycle through every block combination

- 90% recovery for 60 min during plug-flow mode
- ~75% recovery for 5.5 min during transition
- **Total recovery is 89.1%**

Operational Data and Lessons Learned

FRRO Typical Operating Data



- Variation in block performance
- Cyclical swing in operations during reversal sequence
- Important to focus on the time between cycles for the purpose of analyses

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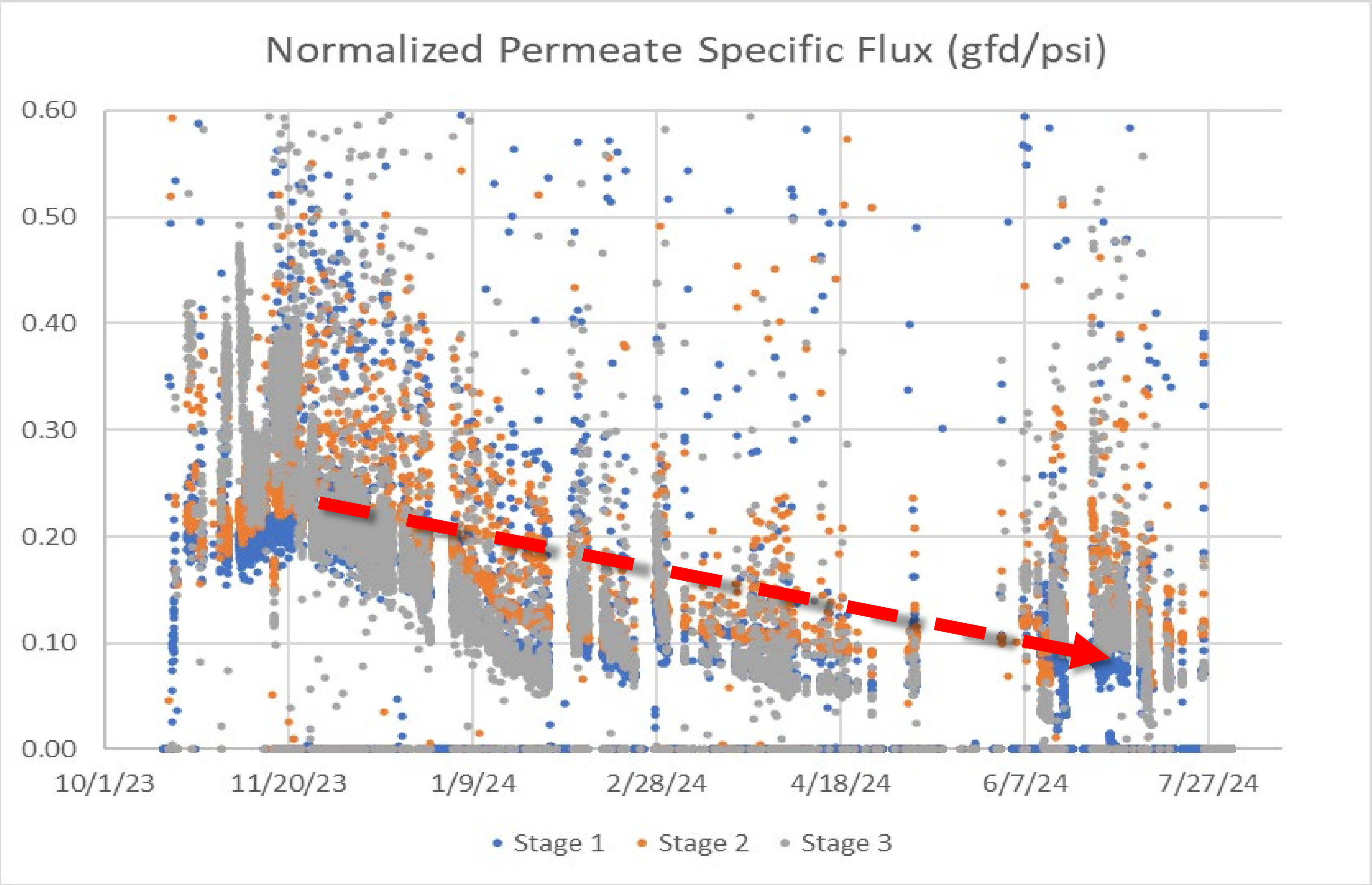
Specific Energy Consumption Compared to Conventional System



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On closer inspection…

Methods to Prevent Scale Formation

- ☑ Limit turbulence in brine holding tank by maintaining higher level
- ☑ Remove opportunities for CO2 off-gassing and air entrainment
- Move air gap as close as possible to point of dilution
- ☑ Increase flush duration
- ☑ Increase RO feed antiscalant dose (Avista Vitec 4000 from 3.5 to 4.5-5 mg/L)
- Add acid to brine
- Add proprietary cleaners or acid to flush cycle to remove scale
- **Change antiscalant**

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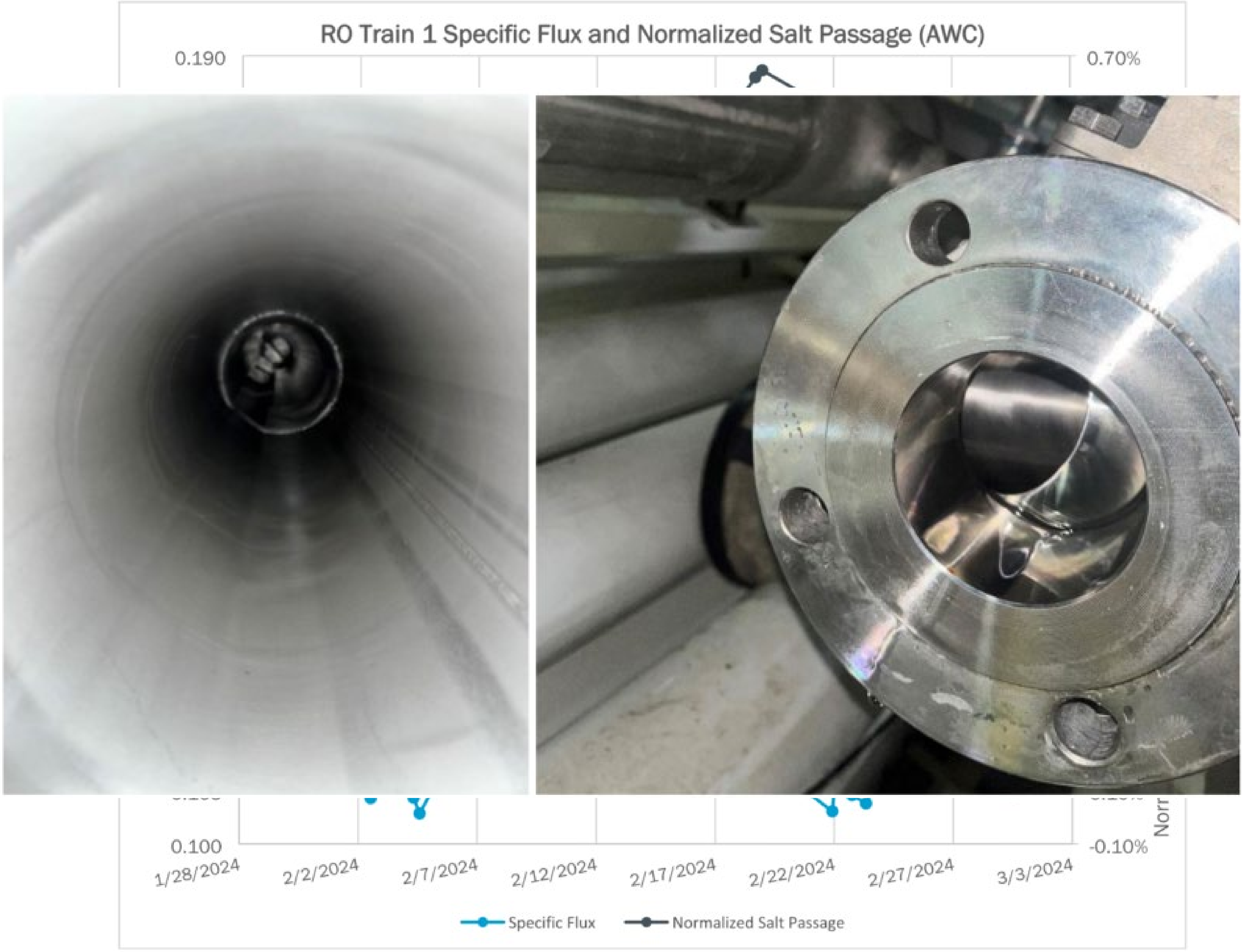
Antiscalant Challenge Test – AWC vs Avista



- Changed antiscalant from Avista Vitec-4000 to AWC A-119
- Tested for one month of continuous operation and compared to previous results
- Significant improvement in performance
- Estimated savings of $88k annually with AWC compared to Avista

Avista Vitec-4000	AWC A-119
4.5 mg/L	2.9 mg/L
6.6 pH	6.8 pH

Other Full-Scale Design Considerations

- Many MANY pneumatic valves
  - Position indicators and feedback are key
  - Check pneumatic throttling valves
  - Set preventative maintenance schedule early
- Maintain higher pneumatic air pressure for more optimized valve closure times
- Set your shims – proper membrane loading is critical
- Retrofit vs. New Skid

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Construction/Commissioning Schedule Considerations

- General contractor versus OEM procurement and/or construction
- Build in extra time for unknowns during commissioning, especially for retrofit
- No 0 to 100 - step wise increase in recovery
  (82 → 85 → 88 → 90%)
- Lock-in your performance guarantee
  - Expected influent water quality (e.g., pH, ORP, TDS, etc.)
  - 90% recovery in flow-reversal mode for 60 days without CIP

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Next Steps

- Finalize permit amendment for Olympic Well Field Restoration
- Continue 2-month full-scale contractual testing period to prove out performance guarantee
- Optimize FRRO to reduce transition time and increase overall recovery
  - 2nd stage rotation every other cycle
  - Decrease valve closure times
  - Increase plug-flow mode duration between transitions

Acknowledgements

CALIFORNIA WATER BOARDS
State Water Resources Control Board

CALIFORNIA DEPARTMENT OF WATER RESOURCES

THE METROPOLITAN WATER DISTRICT OF SOUTHERN CALIFORNIA

WALSH

Brown AND Caldwell

GHD

RCS RICHARD C. SLADE & ASSOCIATES LLC
CONSULTING GROUNDWATER GEOLOGISTS

BLOIS Construction Inc.

TETRA TECH

City of Santa Monica

Thank you!

Questions?

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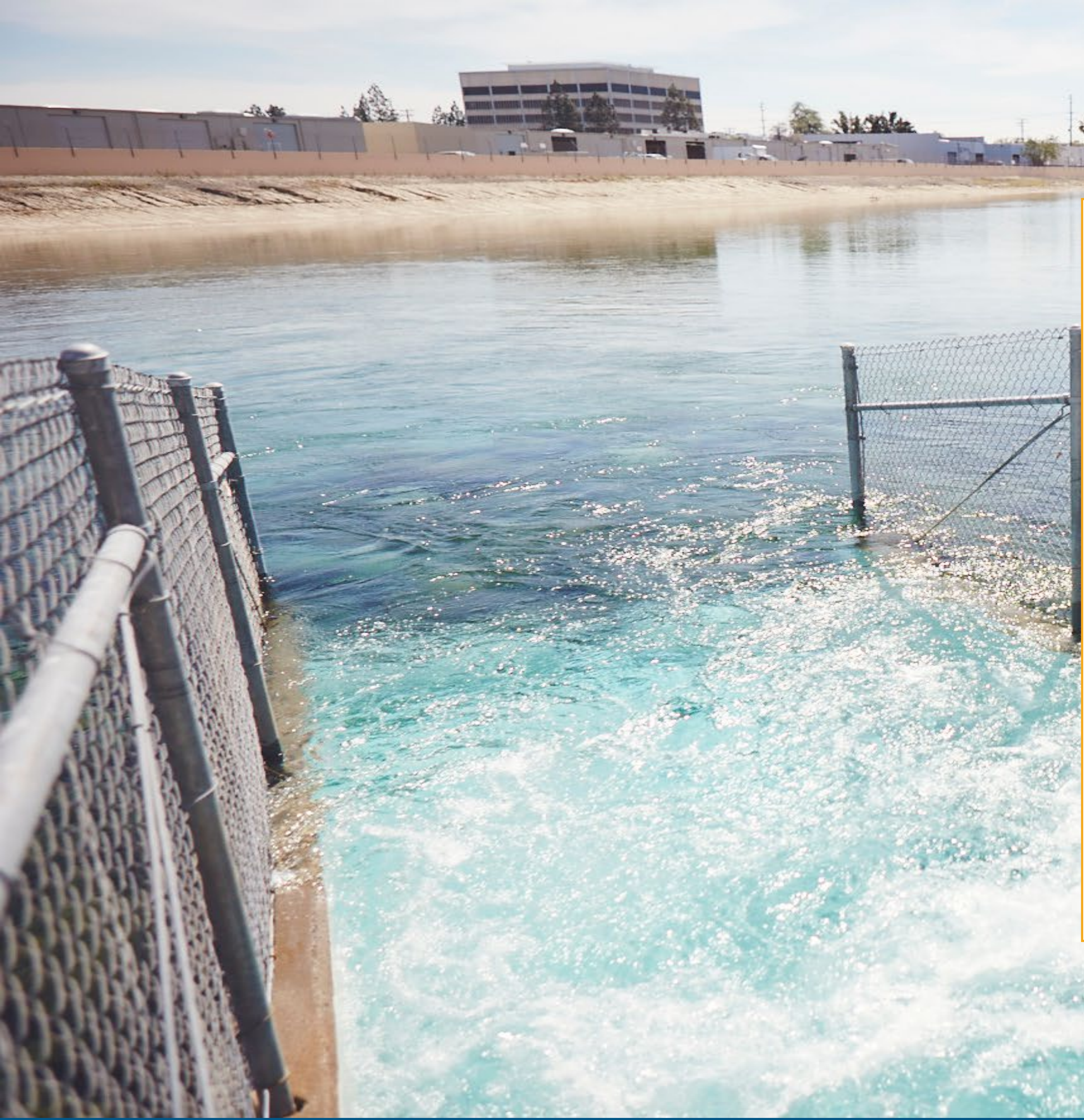

Thank You!

Webinar recording will be posted on OCWD’s YouTube channel

Please send follow up questions to: info@ocwd.com

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