Osmotically-assisted Reverse Osmosis

- RO feed pressures increase with recovery rate because the osmotic pressure of RO permeate is negligible.
- However, if permeate is salty, then feed pressure is proportional to the difference between osmotic pressure of feed/brine and permeate.
- This is the phenomenon exploited by osmotically-assisted RO (OARO) to achieve ultra-high brine concentrations at relatively low feed pressures

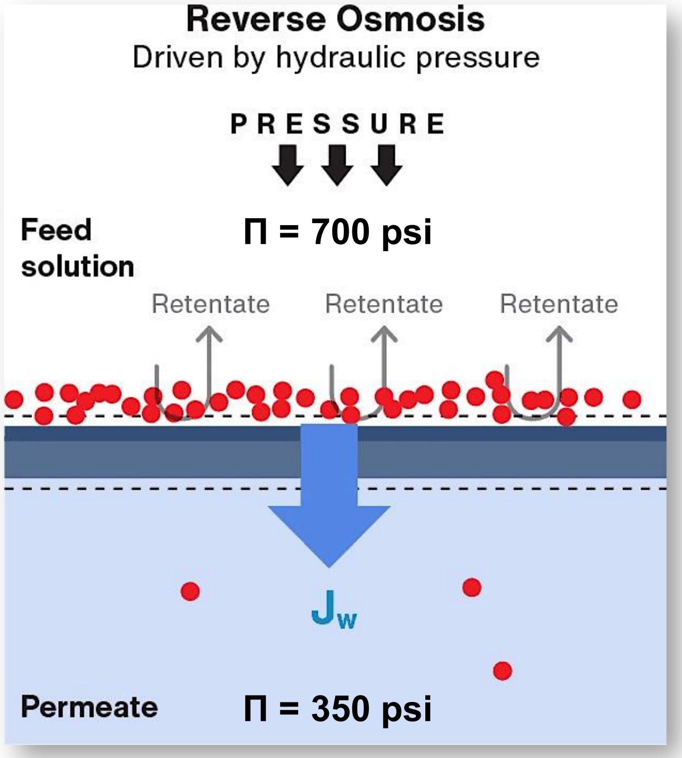
- **RO Driving force** = Feed pressure + permeate Osmotic Pressure (π) – Feed Osmotic Pressure

Example 1: Seawater Desal

- Feed TDS: 35,000 mg/L → Feed π: 350 psi
- Permeate π: ~0 psi
- Feed pressure: 700 psi
- **Driving force: 700 psi + 0 psi – 350 psi = 350 psi**

Example 2: OARO

- Feed TDS: 70,000 mg/L → Feed π: 700 psi
- Permeate π: ~350 psi
- Feed pressure: 700 psi
- **Driving force: 700 psi + 350 psi – 700 psi = 350 psi**



OARO Technology Process

Two ways of rising permeate salinity:
1. Using spiral membranes that permit high salt passage (Low salt rejection)
2. Directly, using hollow fiber membranes (Originally proposed by Sydney Loeb).

Option 1: Low Salt Rejection RO (LSRRO)

- FTSH2O, Porifera, Gradiant, Saltworks, HCON
- Membrane: low salt rejection, 1 inputs, 2 outputs
- Generally spiral wound membrane

Option 2: Osmotically-assisted RO (OARO)

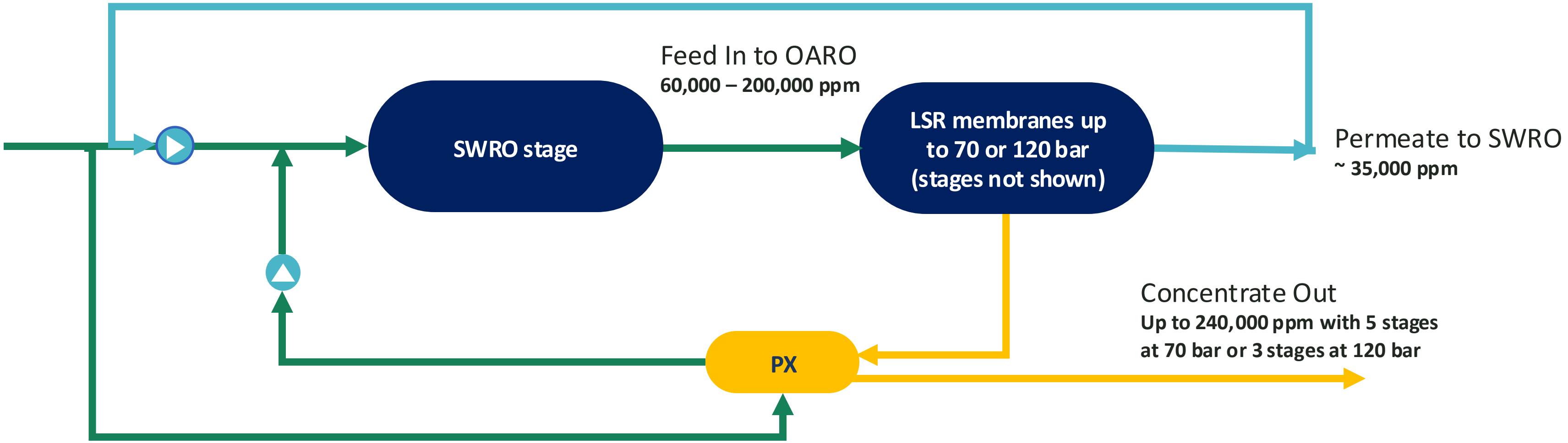
- Gradiant and HYREC
- Membrane: high salt rejection, 2 inputs, 2 outputs
- Generally Hollow fiber membrane

Note: these are simplified process flow diagrams that do not show all valves, connections, etc. and are not meant to cover all potential configurations of this technology.

Pressure Exchangers work with any OARO Process

Option 1 with ERD – Low Salt Rejection RO (LSRRO)

- Working with multiple process innovators to develop low energy solutions
- Pressure: Both conventional (<80 bar) and Ultra High Pressure (<120 bar) systems
- Membranes with long term stability are still the most significant challenge, but new spiral wound LSRRO membranes recently entered the commercial market



Note: these are simplified process flow diagrams that do not show all valves, connections, etc. and are not meant to cover all potential configurations of this technology.

Li Brine Mining Example 1: Early Commercial OARO

- Evaporation required years and yielded poor quality lithium bicarbonate
- Remote area of Tibet in the foothills of the Himalayas without a power supply
- Concentrated solar power (CSP) supply

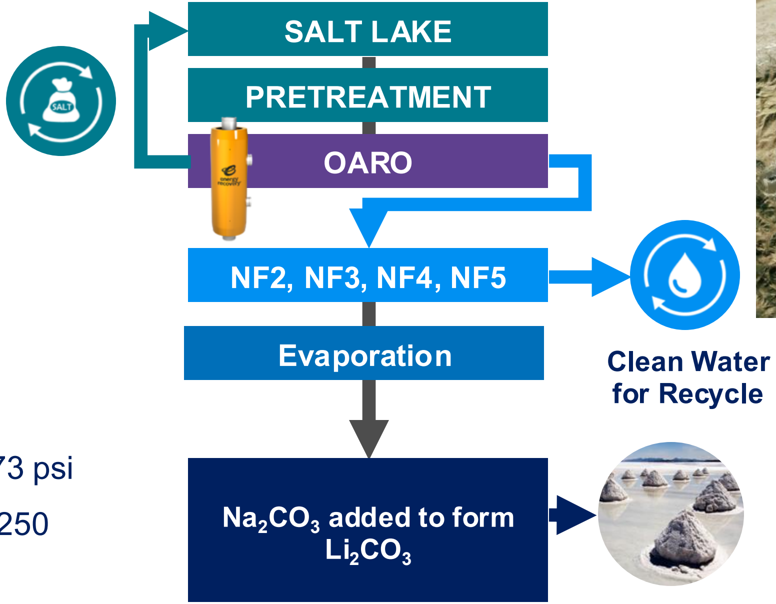
Lithium processing including membrane building	CSP power supply
	

- Faster production & better quality
- 1.8-2.3 MW saved by including ERDs into membrane systems
- ~$10M USD CSP CAPEX ($4,500 / kW saved)

Li Brine Mining Example 1 Continued

Zabuye Salt Lake, Tibet Province, China; July 2024

Brine Mineral Content		
Parameter	**Units**	**Value**
Sodium	mg/L	160,000
Potassium	mg/L	60,000
Lithium	mg/L	15,300
Chloride	mg/L	120,000
CO_3	mg/L	90,000
Mg:Li	**Ratio**	**0.019**

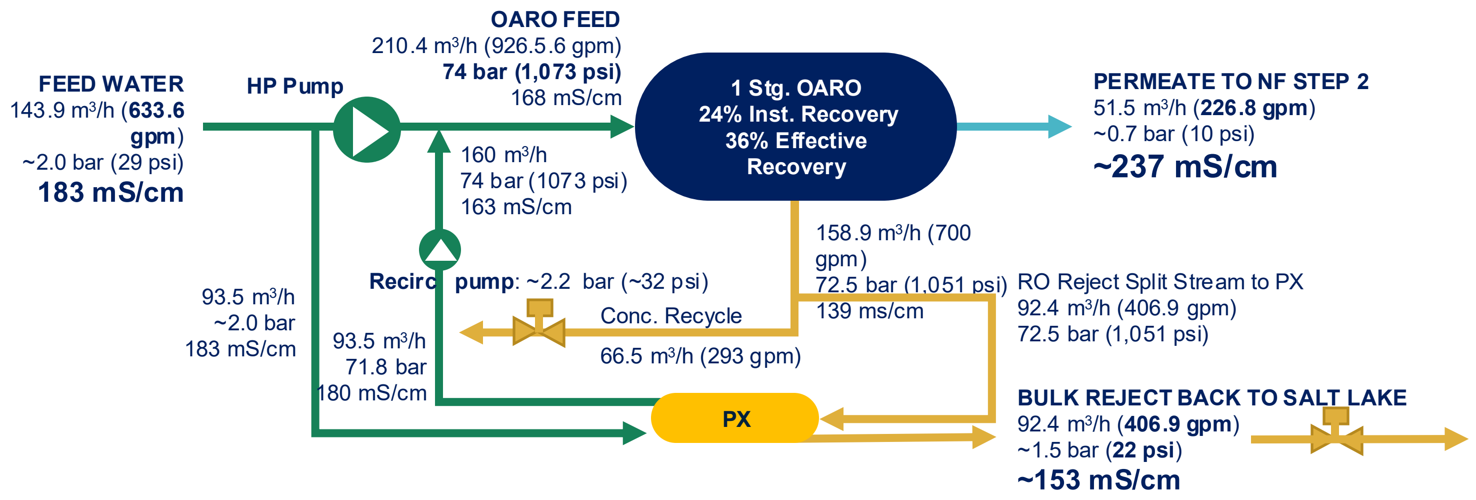


Design:

- ***OARO for Li***: 7 trains @ 1073 psi
- ***Polishing***: NF stages 2-5: <250 psi

Li Brine Mining Example 1 Continued

LSRRO Operating Parameters July 2024



Energy Recovery Device Economics					
Treatment Step	**RO System Design**	**ERD Model (Qty)**	**Without ERD (kWh/m^3)**	**With ERD (kWh/m^3)**	**Payback Period**
OARO	7 parallel trains; 1 stage @ 24% instantaneous recovery	2 PX 260 per train	**8.7**	**3.6**	<6 months w/o CAPEX savings

Li Brine Mining Example 1 Continued – Site Pictures

ALADYR

Zabuye Salt Lake

OARO & NF SKIDS

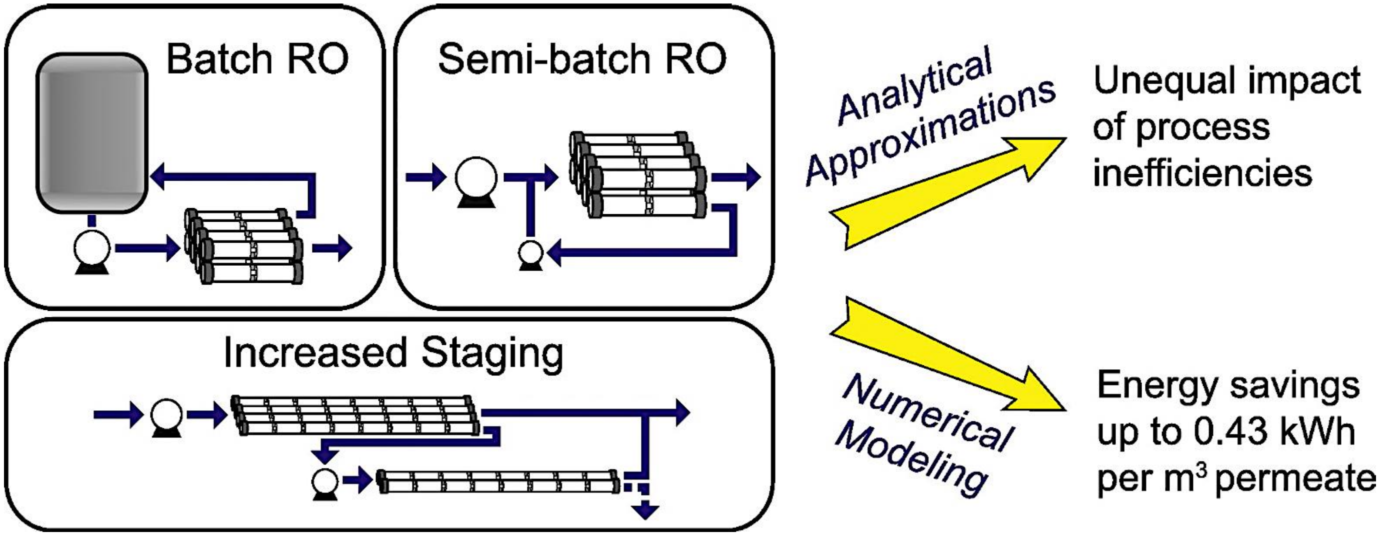
ERDs

energy recovery

Batch and Semi-batch RO Processes

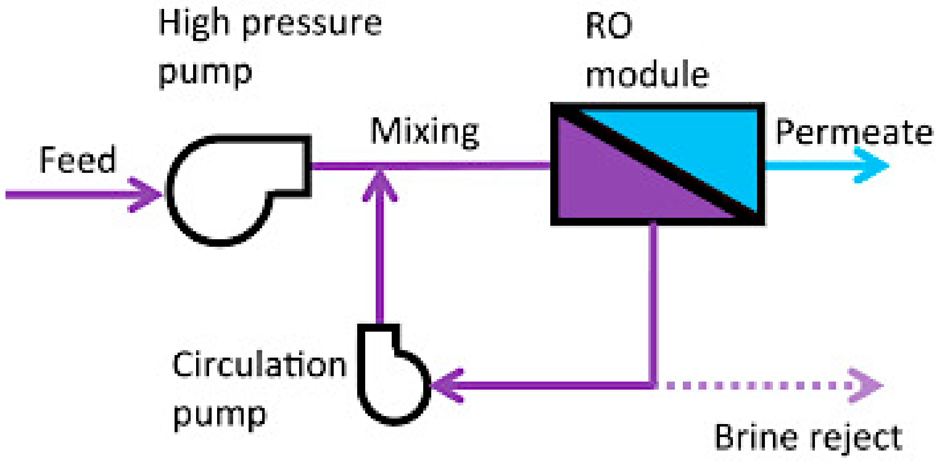
Batch and Semi-batch Processes Simulate Multiple Stages & De-couples Flux from Recovery to Reduce Energy and Fouling

Potential Benefits: Less energy, higher cross-flow velocity & potential for higher RO recovery because concentrate can be discharged from system prior to scalant induction time



Source: https://www.sciencedirect.com/science/article/abs/pii/S0011916416306312?via%3Dihub

What is Semi-Batch Without an ERD?: Simple PFD

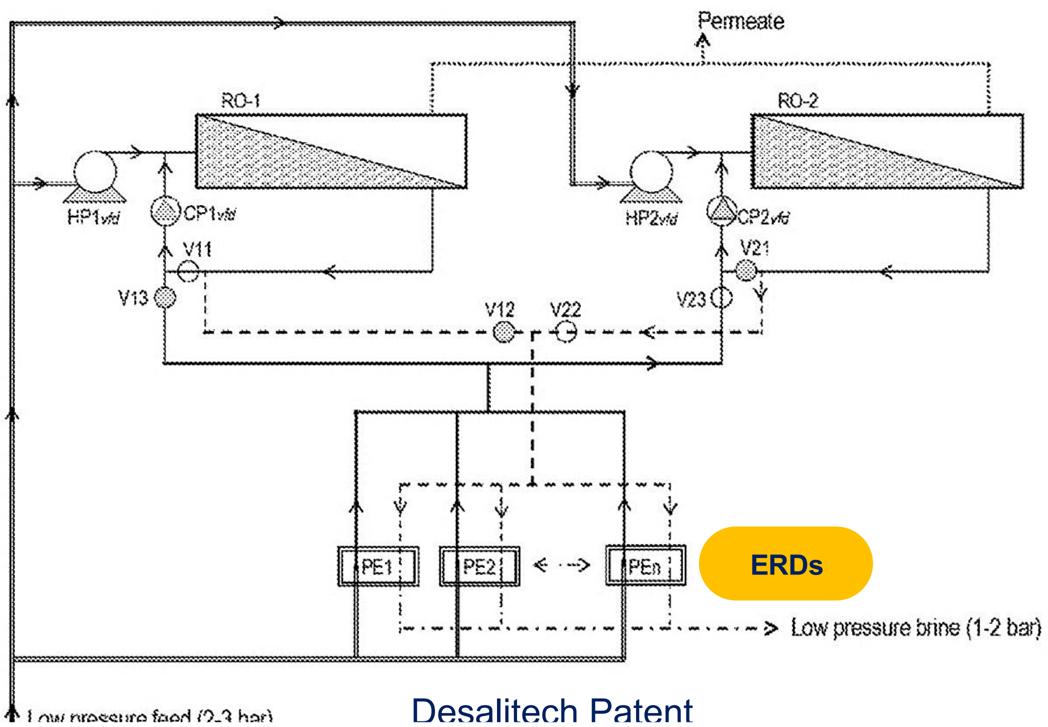


Schematic diagram of a closed-circuit reverse osmosis system. Feed continuously enters the system, but brine is rejected only at the end of the cycle. Pressure gradually increases over time. Dotted lines represent flows present only between cycles.

Source: Energy efficiency of batch and semibatch (CCRO) reverse osmosis desalination. The MIT Faculty has made this article openly available. Citation: Warsinger, David M., Emily W. Tow, Kishor G. Nayar, Laith A. Maswadeh, and John H. Lienhard V. "Energy Efficiency of Batch and Semi-Batch (CCRO) Reverse Osmosis Desalination." Water Research 106 (December 2016): 272-282. As Published: http://dx.doi.org/10.1016/j.watres.2016.09.029 Publisher: Elsevier. Persistent URL: http://hdl.handle.net/1721.1/105441

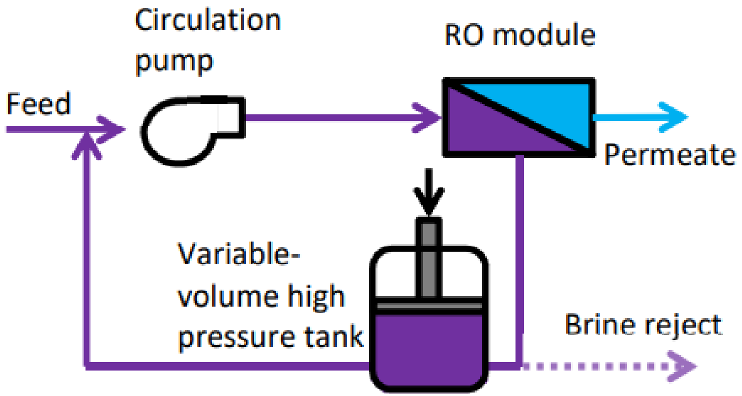
Semi-batch with an ERD; Desalitech CCRO Patent Example

Fig. 4



Desalitech Patent

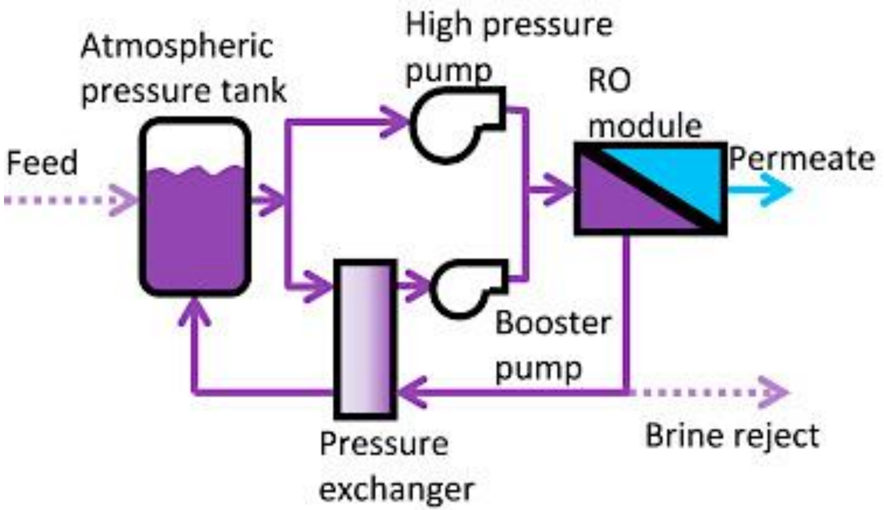
What is Batch RO Without an ERD: Simple PFD



Schematic diagram of a batch RO system with a high pressure, variable-volume tank. In each cycle, the system is initially filled with feed, which is then circulated and concentrated over time. Brine is finally rejected at atmospheric pressure. Dotted lines represent flows present only between cycles.

Source: Energy efficiency of batch and semibatch (CCRO) reverse osmosis desalination. The MIT Faculty has made this article openly available. Citation: Warsinger, David M., Emily W. Tow, Kishor G. Nayar, Laith A. Maswadeh, and John H. Lienhard V. "Energy Efficiency of Batch and Semi-Batch (CCRO) Reverse Osmosis Desalination." Water Research 106 (December 2016): 272-282. As Published: http://dx.doi.org/10.1016/j.watres.2016.09.029 Publisher: Elsevier. Persistent URL: http://hdl.handle.net/1721.1/105441

MIT Batch RO Example with Isobaric ERD



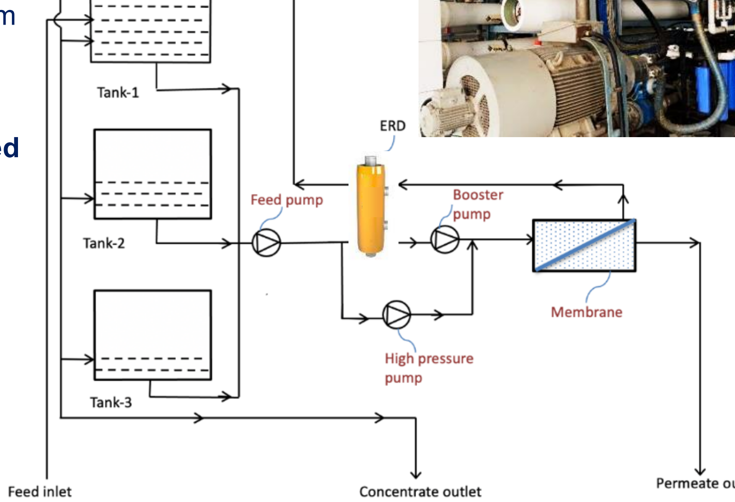
Alternative batch RO design, in which a pressure exchanger is used to reduce the pressure of the recirculating stream so that a standard, low-pressure tank can be used.

Source: Energy efficiency of batch and semibatch (CCRO) reverse osmosis desalination. The MIT Faculty has made this article openly available. Citation: Warsinger, David M., Emily W. Tow, Kishor G. Nayar, Laith A. Maswadeh, and John H. Lienhard V. "Energy Efficiency of Batch and Semi-Batch (CCRO) Reverse Osmosis Desalination." Water Research 106 (December 2016): 272-282. As Published: http://dx.doi.org/10.1016/j.watres.2016.09.029 Publisher: Elsevier. Persistent URL: http://hdl.handle.net/1721.1/105441

Example: Batch RO Pilot on Textile Waste; Tirupur Region, Tamil Nadu, India

Project Drivers

- **100 m³ feed / day batch RO system with ERD (patent pending).**
- Batch feed is collected continuously in a dedicated tank.
- Batch feed is supplied to RO in pass1. Permeate is removed from RO and pass1 brine is collected in tank 1.
- Tank 1 is feed for RO pass2; Pass2 brine is collected in Tank 2.
- **Process is repeated in subsequent passes to achieve desired batch recovery. This project included 3 tanks per batch.**



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Example Continued: Batch RO Benefits & Data For Textile MLD

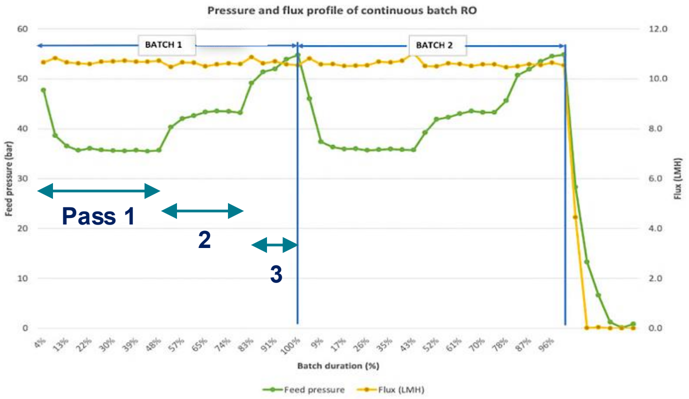
Batch Process Benefits

- **ERDs have quick payback at operating pressures & recovery**
- **Operating flux independent of batch recovery.**
- Improved scaling & biofouling data vs. traditional RO
- Capital cost is competitive with traditional multistage RO
- Stable flux achieved over 18 months
- **Operational flexibility**

Comparison with Existing Continuous RO

Parameter	Units	Continuous RO	Batch RO
Feed TDS	g/L	17	25
Reject TDS	g/L	25	**57**
Recovery	%	32%	**56%**
Flux	LMH	12.5 – 13	10 – 10.5

Pressure and Flux Profile of Continuous Batch RO



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Conclusions

- Isobaric energy recovery devices such as pressure exchangers can be fully integrated in OARO processes helping to reduce the size and energy consumption of the main HPP.
- Isobaric ERD’s can work with any OARO configuration.
- OARO technology is applicable to ZLD processes, mineral extraction (e.g Lithium), brine mining, etc.
- Isobaric ERD can benefit semi-batch RO processes by recovering the wasted energy during the flushing sequences of the process and allowing flushing the system with feedwater.
- Isobaric ERD can benefit batch RO processes by eliminating the need for a high-pressure variable-volume tank, and allowing an atmospheric low pressure tank to be used instead while recovering energy from the high-pressure recirculating stream.

Muchas Gracias!

ALADYR

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