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Semi-batch reverse osmosis for home-scale desalination

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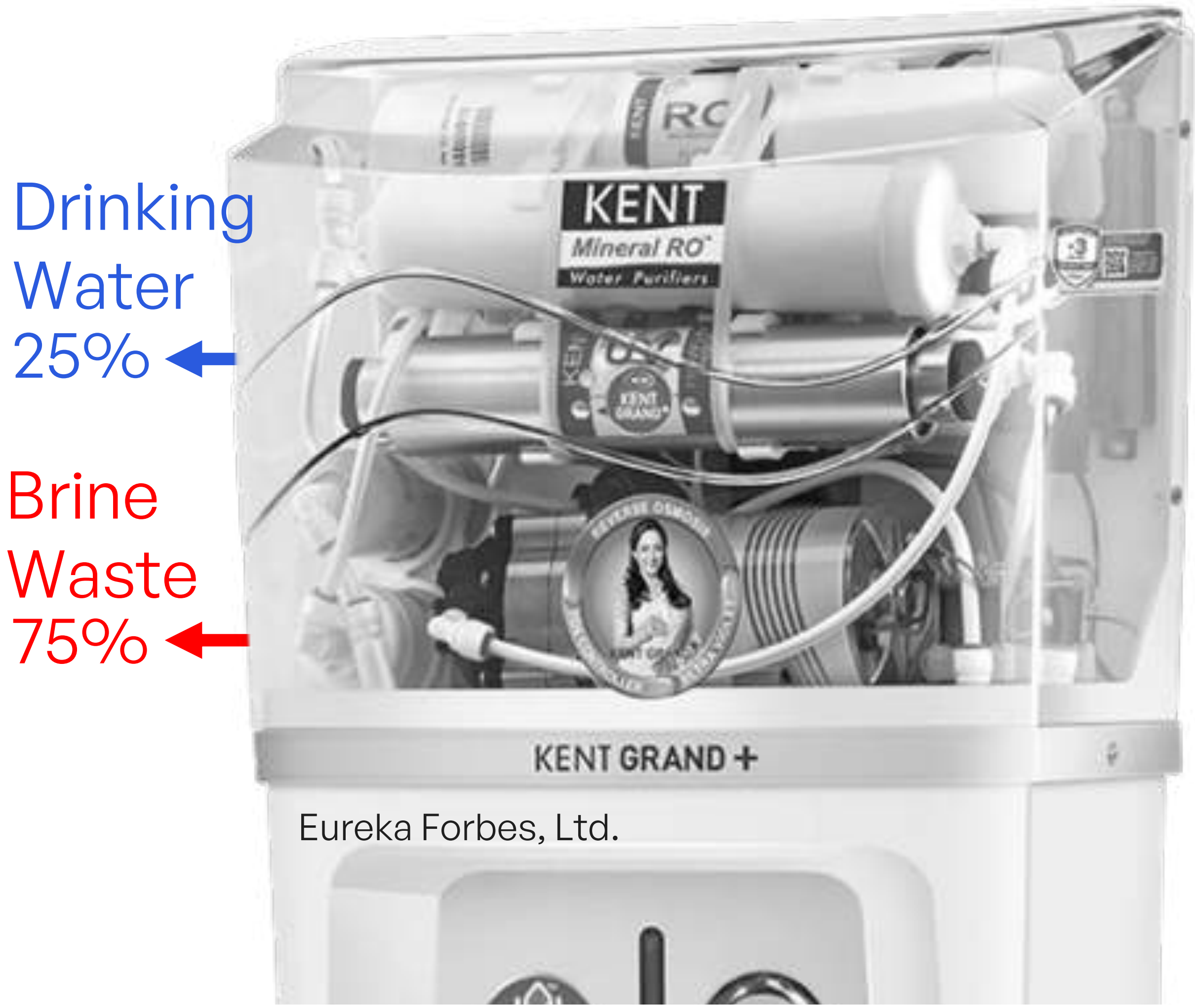
Agenda

- **Introduction** India’s home purifier market.
- **Theory** Semi-batch operation.
- **Methodology** Design of experiments.
- **Results** Operation parameters exploration.

Introduction

Families use Point-of-Use RO systems to purify water.



Eureka Forbes, Ltd.

But face the issue of low water efficiency (recovery).

Introduction

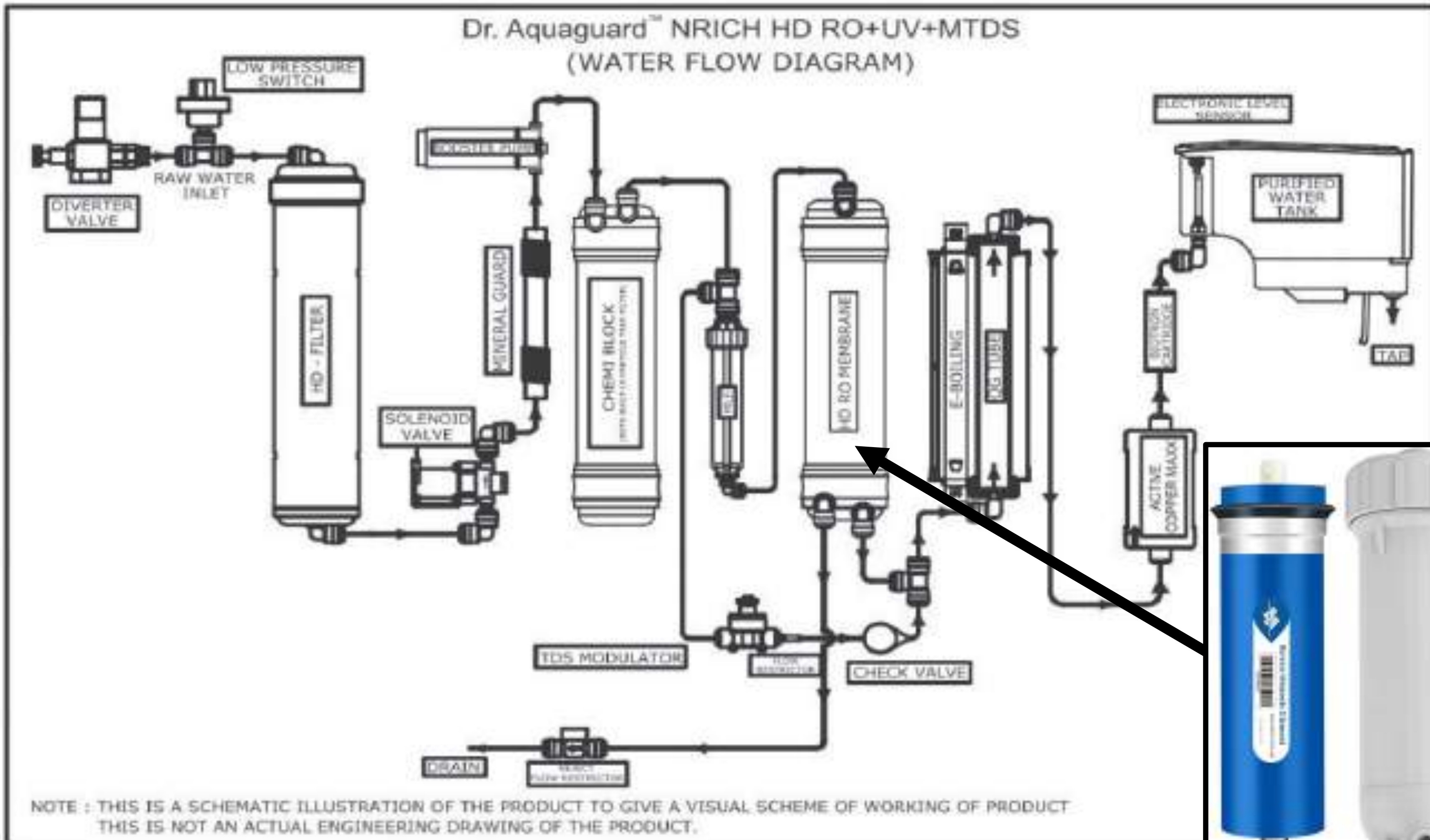
Drinking Water 60%

Brine Waste 40%

Eureka Forbes, Ltd.

National Green Tribunal aims to mandate a **minimum of 60% recovery,** increasing to 75%+

Introduction



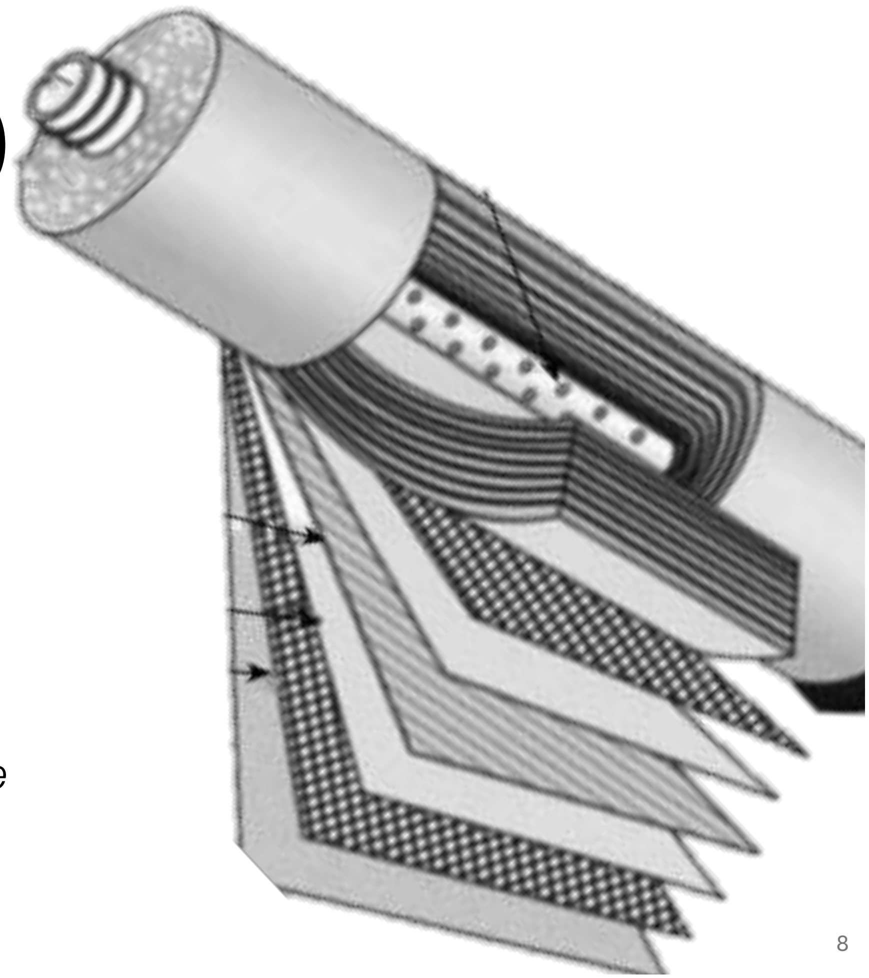
Theory

Max Pressure

$$Q_p = A_m * S\,(P_f - \pi)$$

Productivity

Scaling



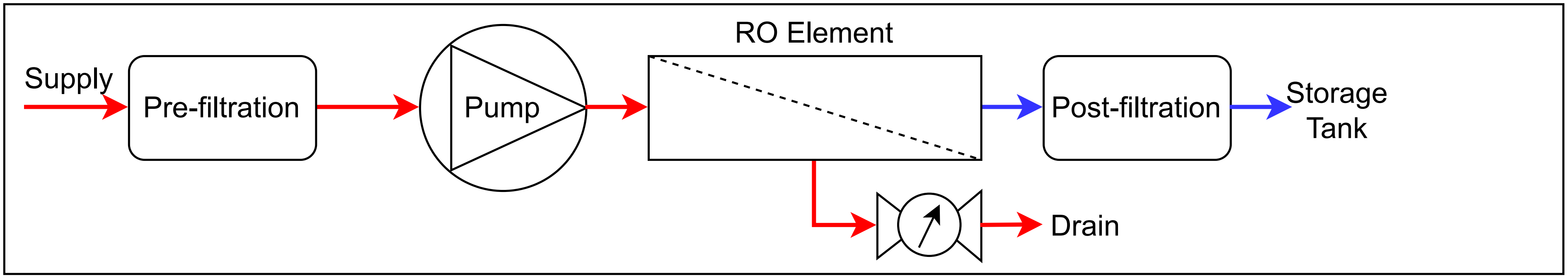
A_m range	2-6 LMH/bar
Q_p target	12-15 LPH
S	0.51 m^2 for Nano 75
π	20 psi, 1.38 bar
	100 ppm ~ 1 PSI osm. pressure

RO recovery ratio is limited by:

1) RO element specifications (pressure, flux)
2) Scale formation, exacerbated by intermittent operation in home-scale applications

Q_p < Max. product flow rate associated with maximum membrane pressure.

Continuous (Conventional)



Q_b > Min. required brine flow rate to avoid scaling

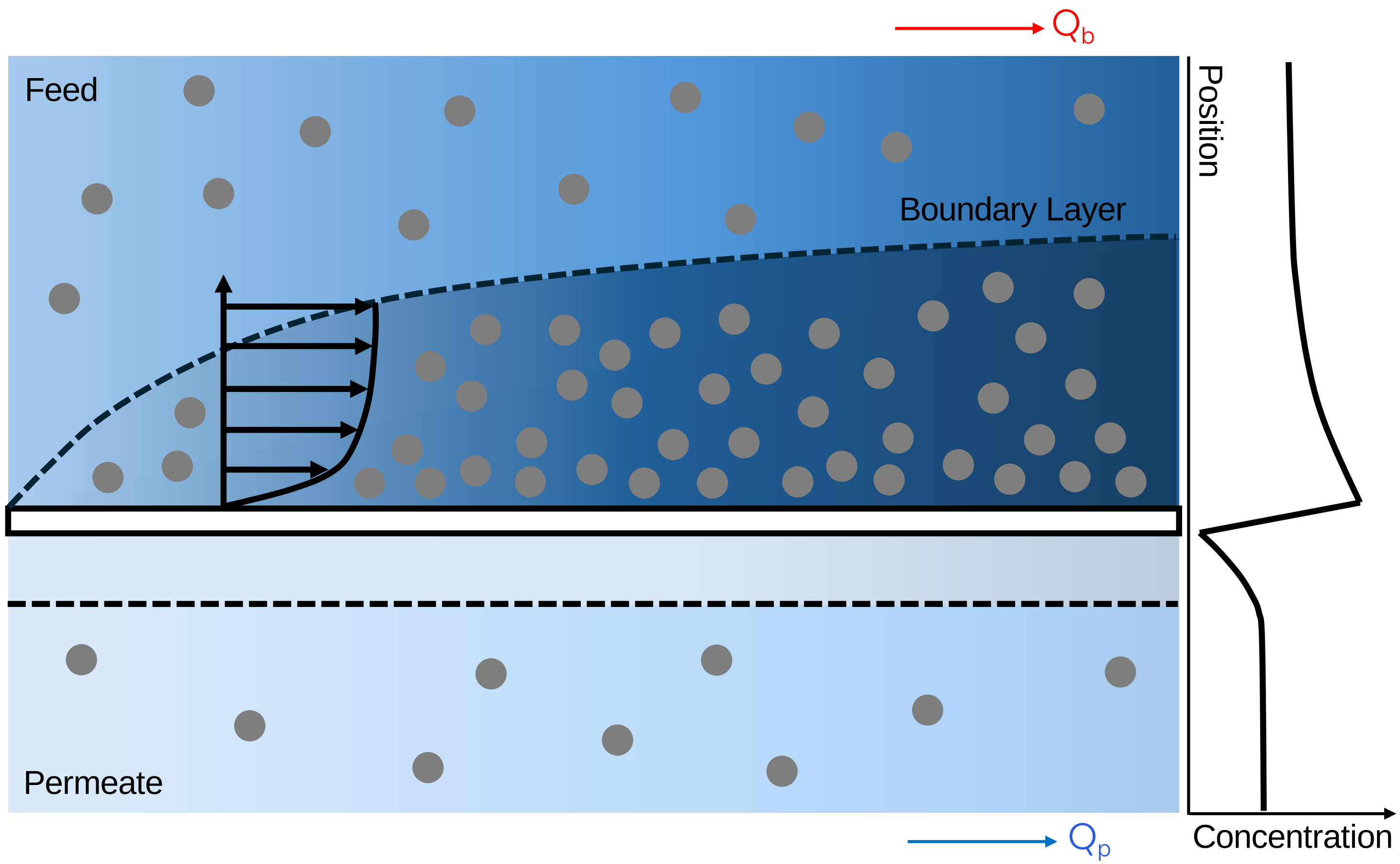
Alternative designs increase membrane area ($\uparrow S$) within an element (thus flux, $\uparrow$ Q_p)

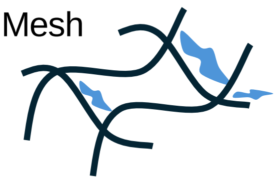
while keeping the throttle valve (brine, Q_b) the same,

resulting in higher recovery ratio.

Alt. design
Unilever Pureit

Introduction





What contributes to scale formation?

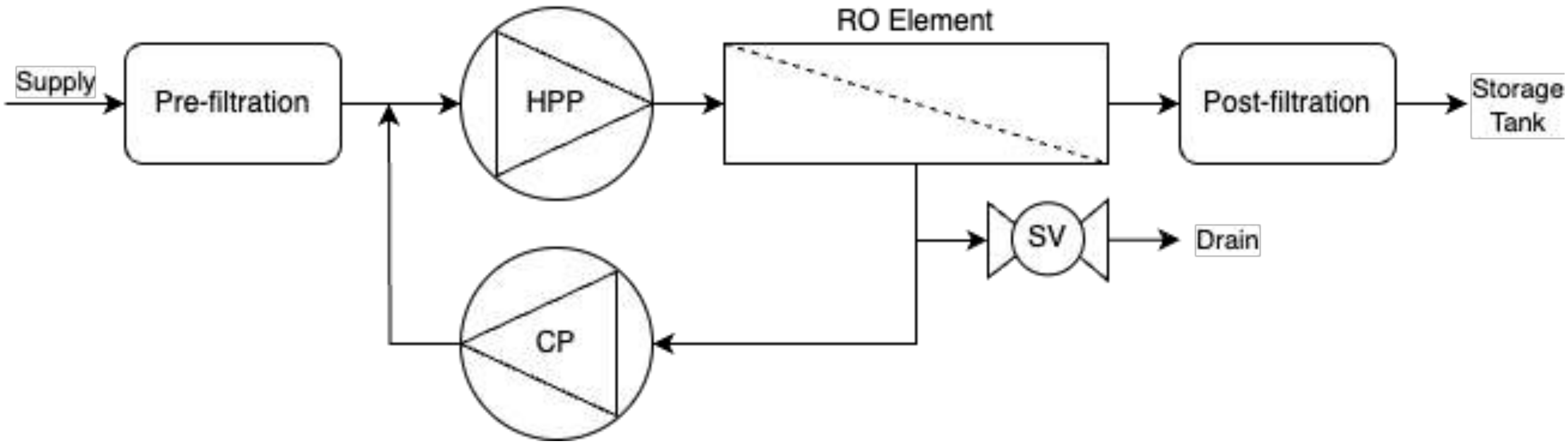
Induction time

- Flow rate
- Temperature
- Surface properties

Solution composition and concentration

Semi-batch (CCRO) Operation recirculates brine to increase recovery

HPP – High Pressure Pump

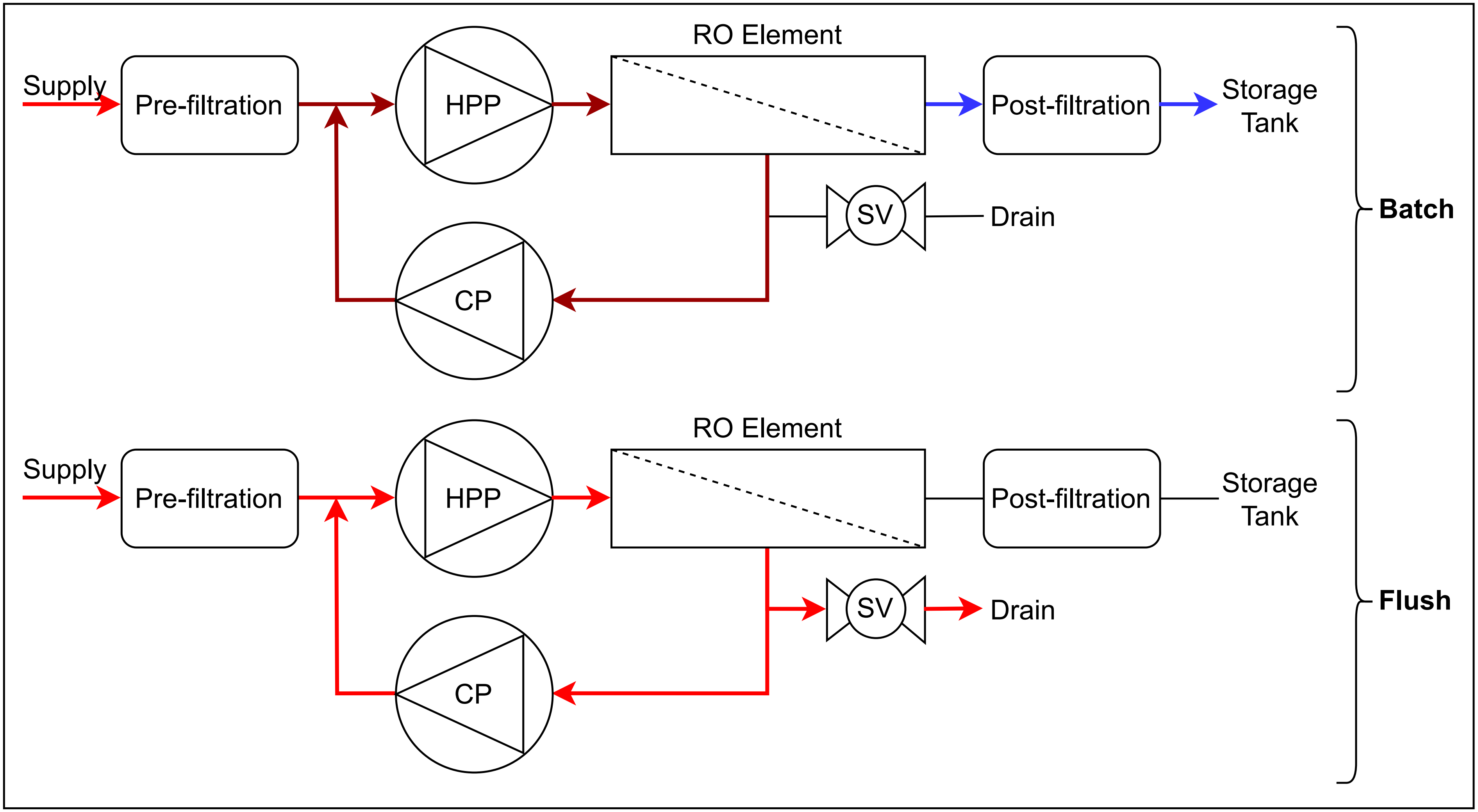


CP – Circulation Pump

Warsinger et al., 2016, “Energy Efficiency of Batch and Semi-Batch (CCRO) Reverse Osmosis Desalination,” Water Res.
Werber et al., 2017, “Can batch or semi-batch processes save energy in reverse-osmosis desalination?” Desalination, 402.
Swaminathan et al., 2019,“Practical aspects of batch RO design for energy-efficient seawater desalination.” Desalination, 470.
Wei et al., 2020, “Impact of Salt Retention on True Batch Reverse Osmosis Energy Consumption: Experiments and Model Validation,” Desalination, 479.
Lee et al., 2019, “Multi-Cycle Operation of Semi-Batch Reverse Osmosis (SBRO) Desalination,” J. Memb. Sci.

Theory

Semi-batch



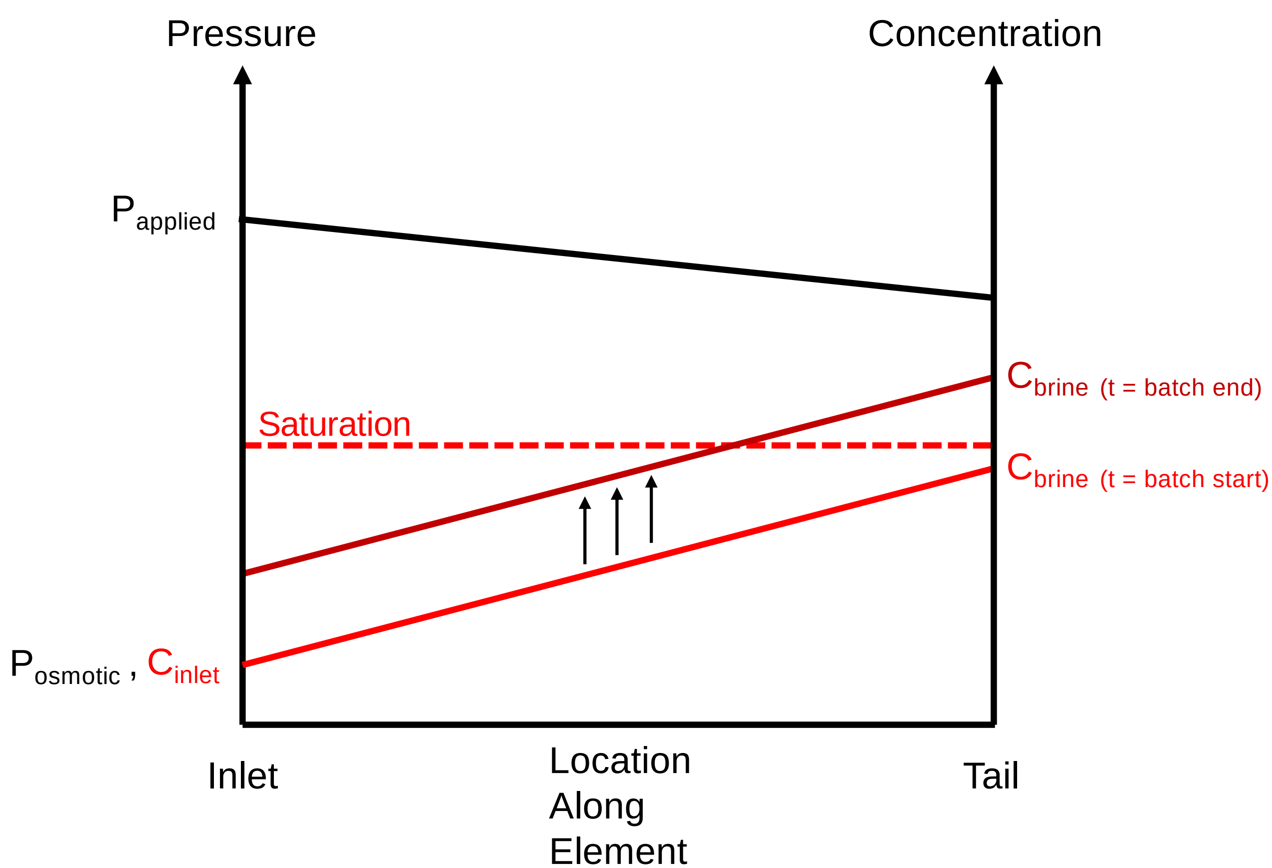
Where does scaling occur in semi-batch?

Feed pressure drops over the element

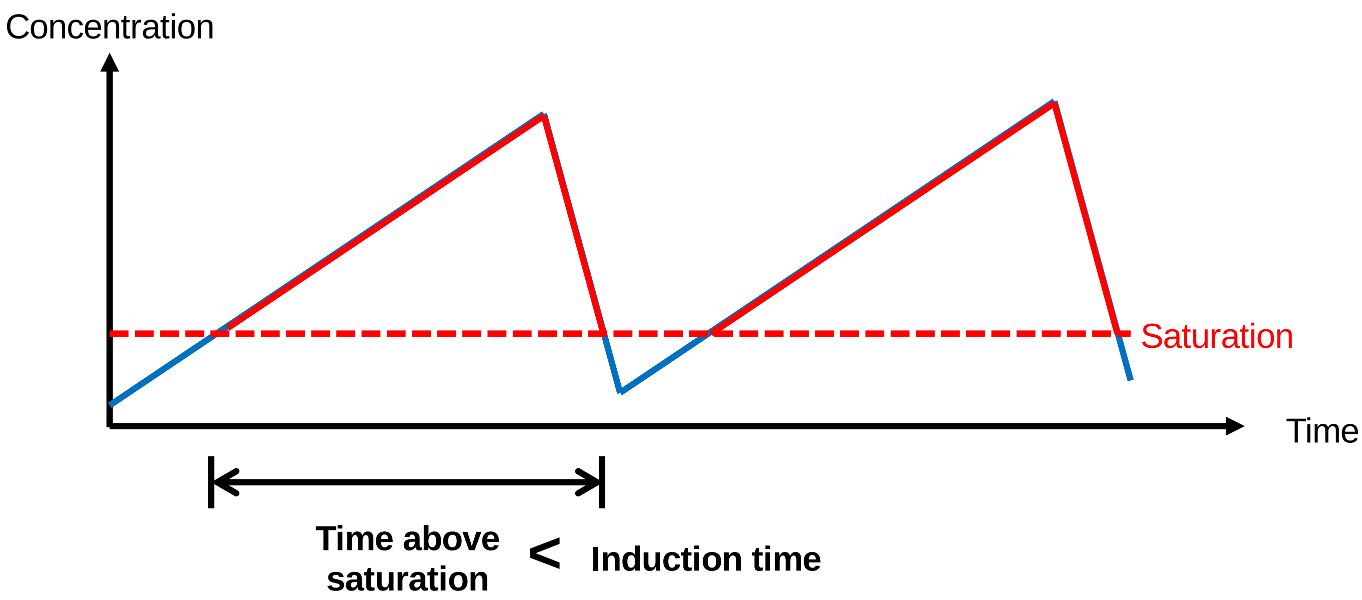
Increase in concentration (and thus, osmotic pressure) spatially, and temporally as a batch continues

Flux decreases towards the tail of the element and towards the end of the batch

Theory



Theory



Even above saturation, if we **operate under induction time** and clear salts during flush, we can prevent scaling.

Semi-batch RO

Value proposition

- Regulatory compliance (w/ recovery specification)
- Small modification to existing products, low-CAPEX change (SV, CP)
- Minimal retraining of providers
- Consistent user-experience & tech
- No increase in maintenance cost

Research Questions

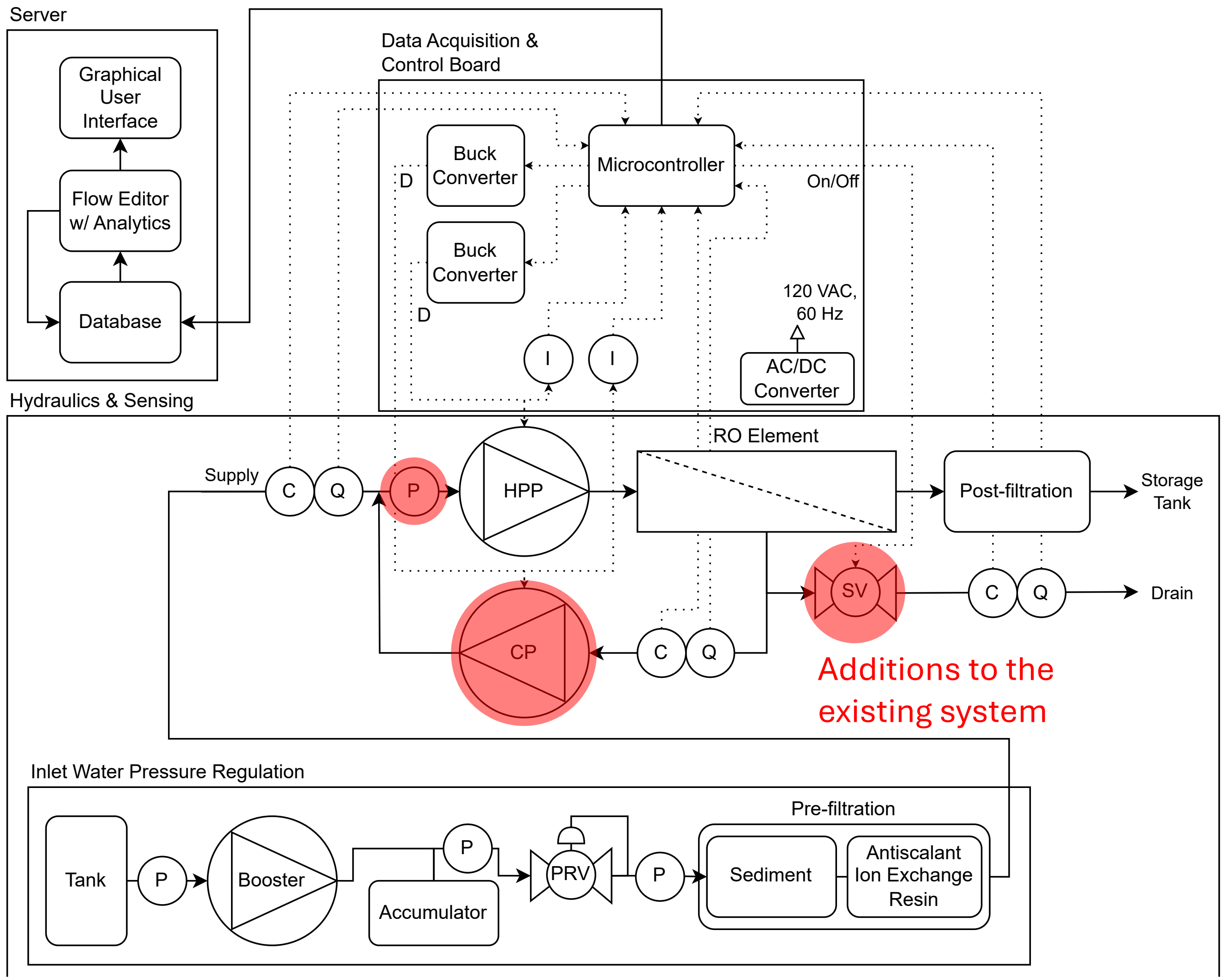
Semi-batch RO

Challenges

High-recovery semi-batch architecture

- What are the ideal control parameters & how do changing these affect performance?
- Does the system withstand **scaling** over time and meet the current system lifetime specs?

Methodology



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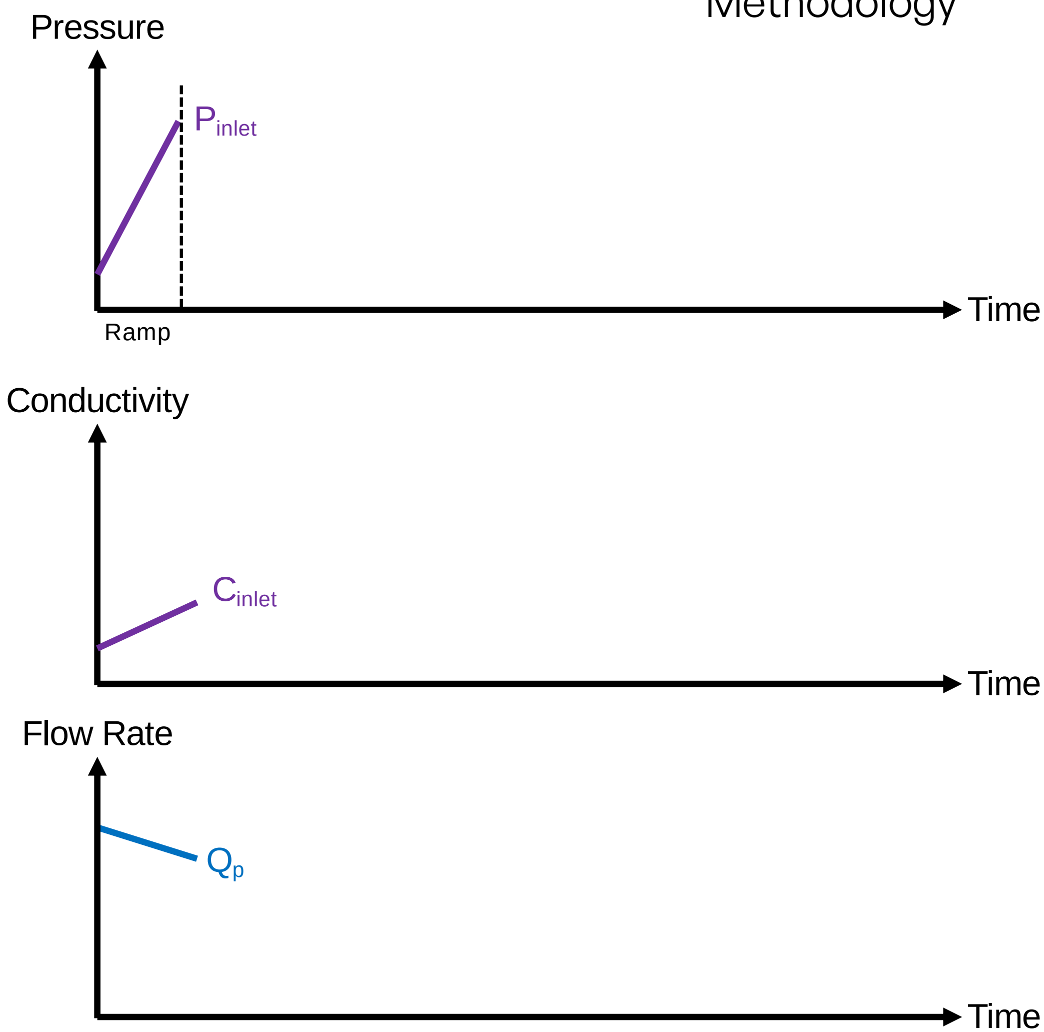


$$Q_p = A_m * S\,(P_f - \pi)$$

<u>Color Key</u>

Constraints

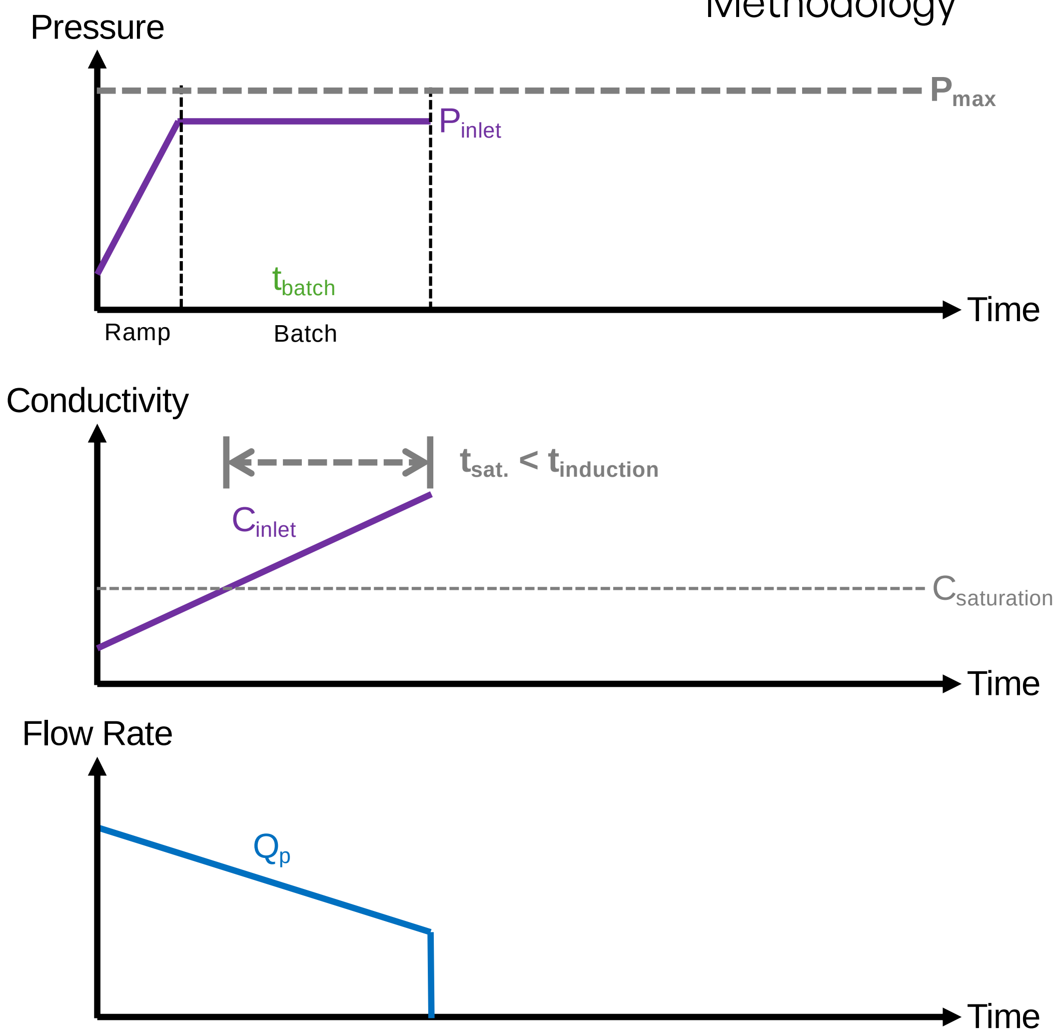
Operating parameters

Feed

Permeate

Brine

Methodology



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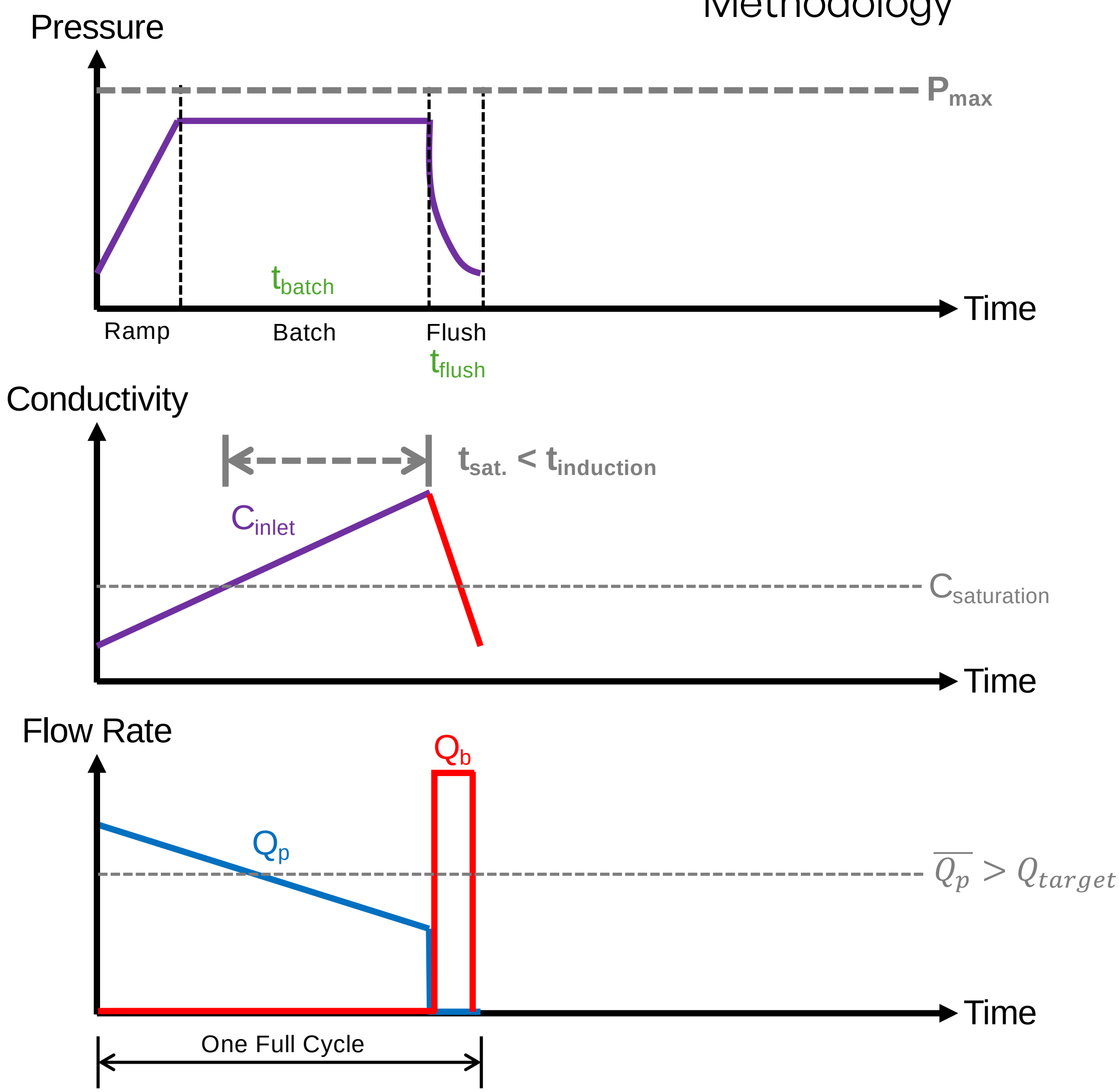

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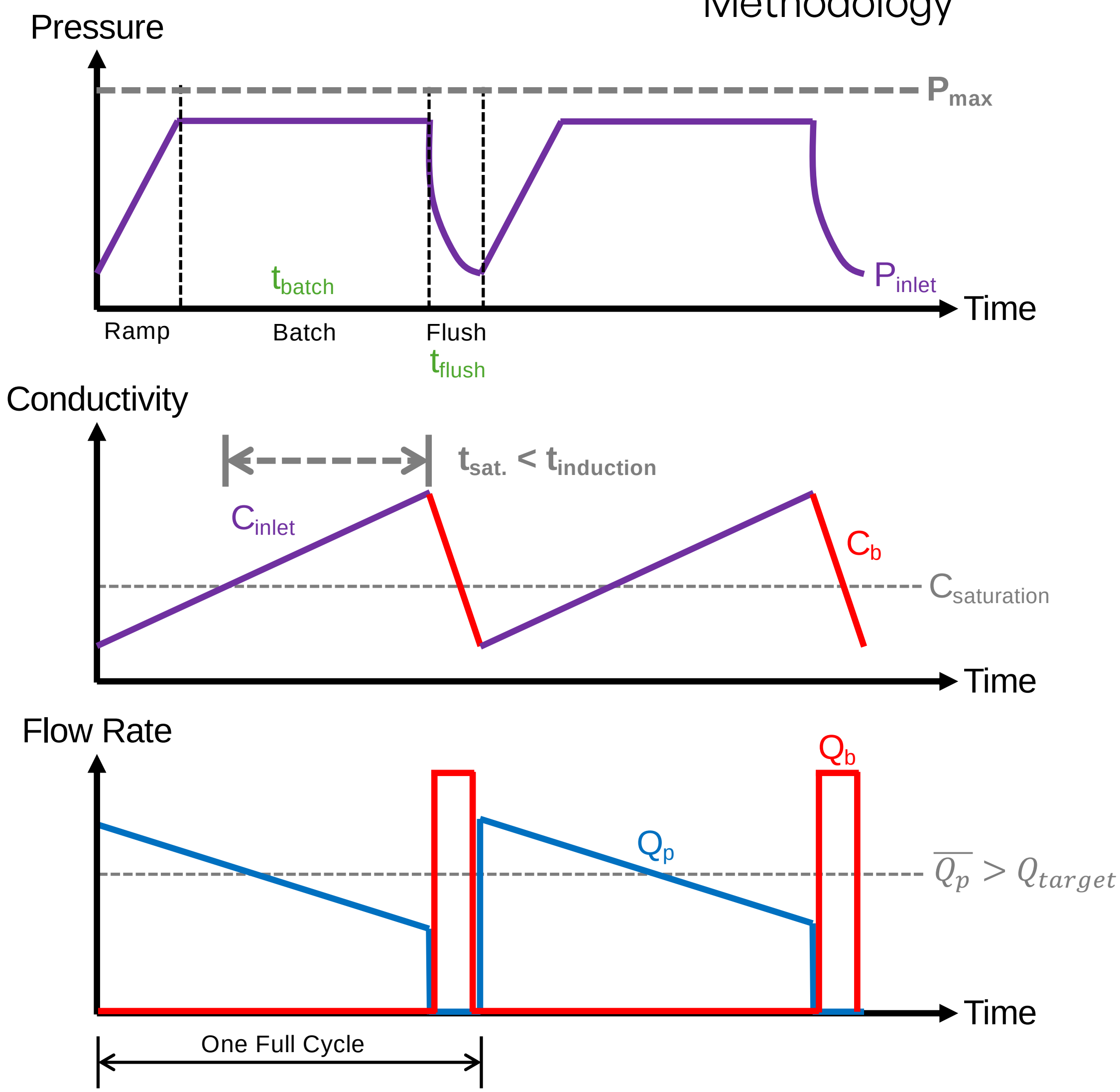

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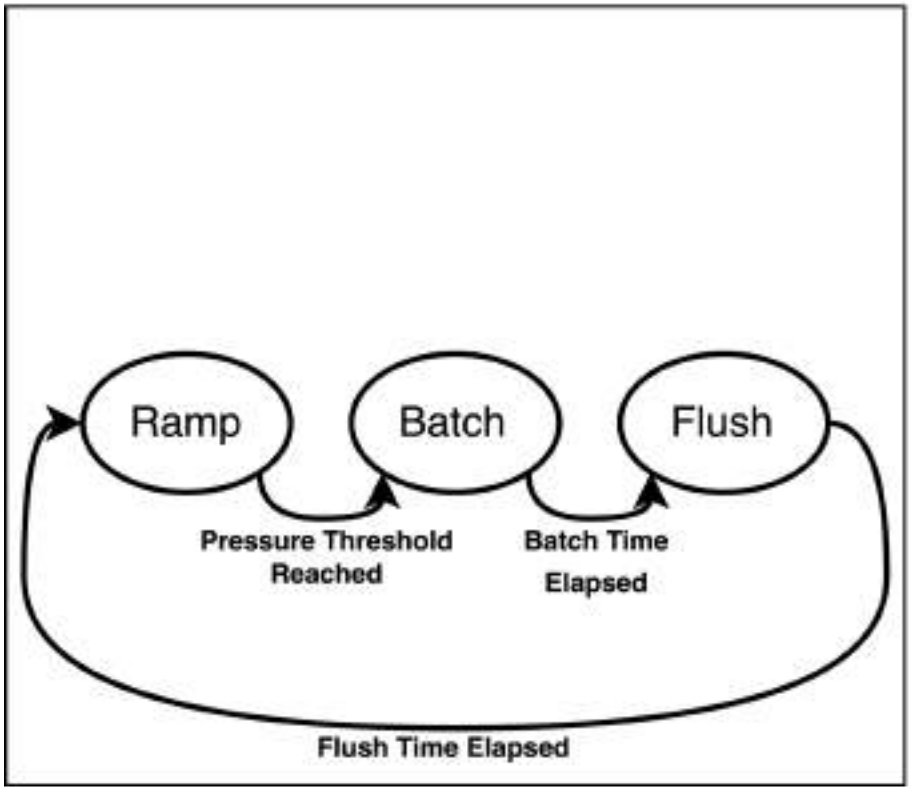
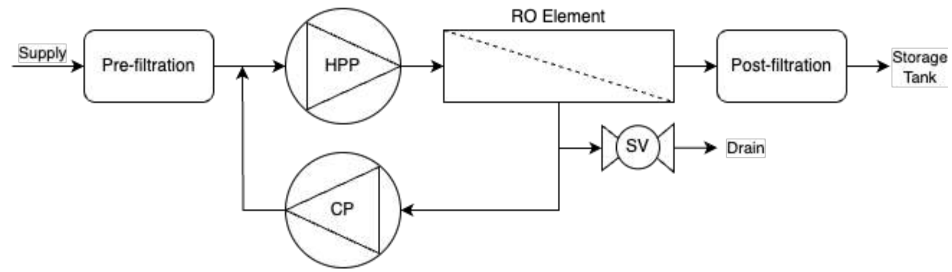
Methodology

State Machine



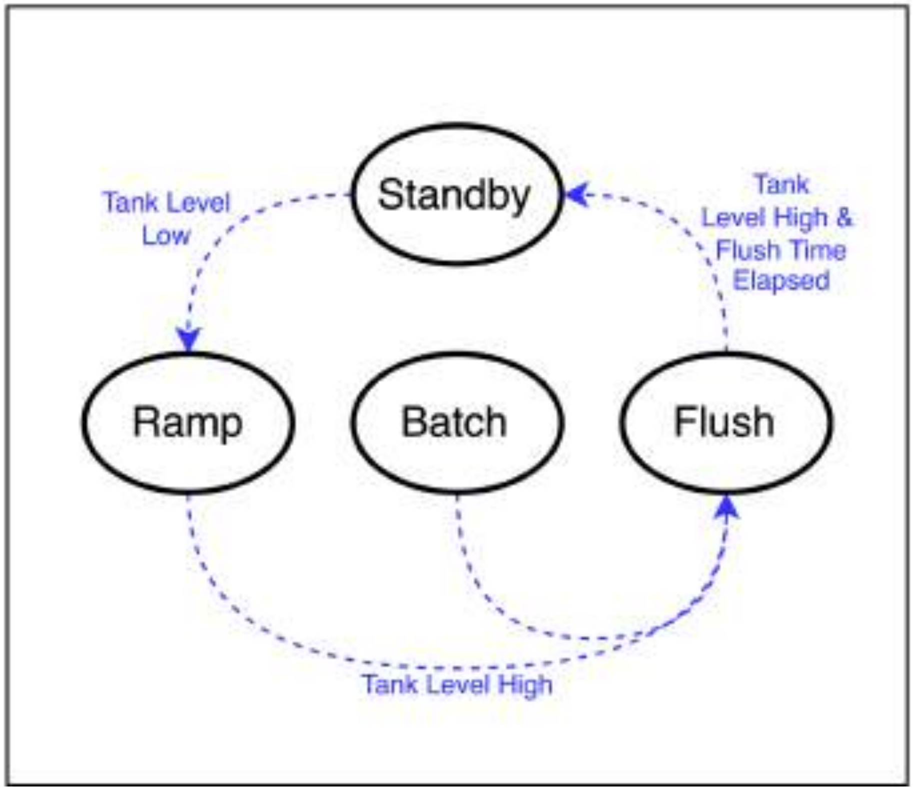


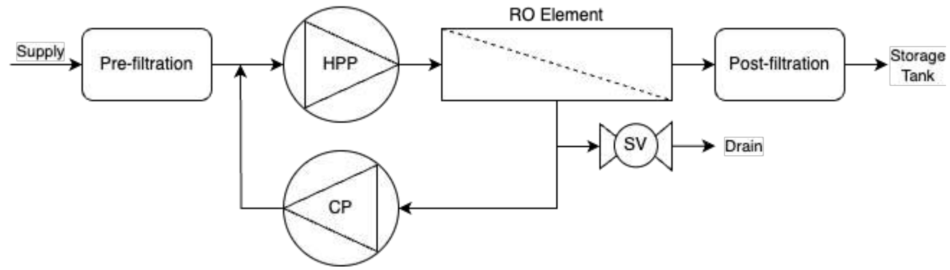
State Descriptions

Actuators	Ramp	Batch	Flush	Standby
HPP	On	Regulated	On	Off
CP	On	On	On	Off
SV	Closed	Closed	Open	Closed

Methodology

State Machine





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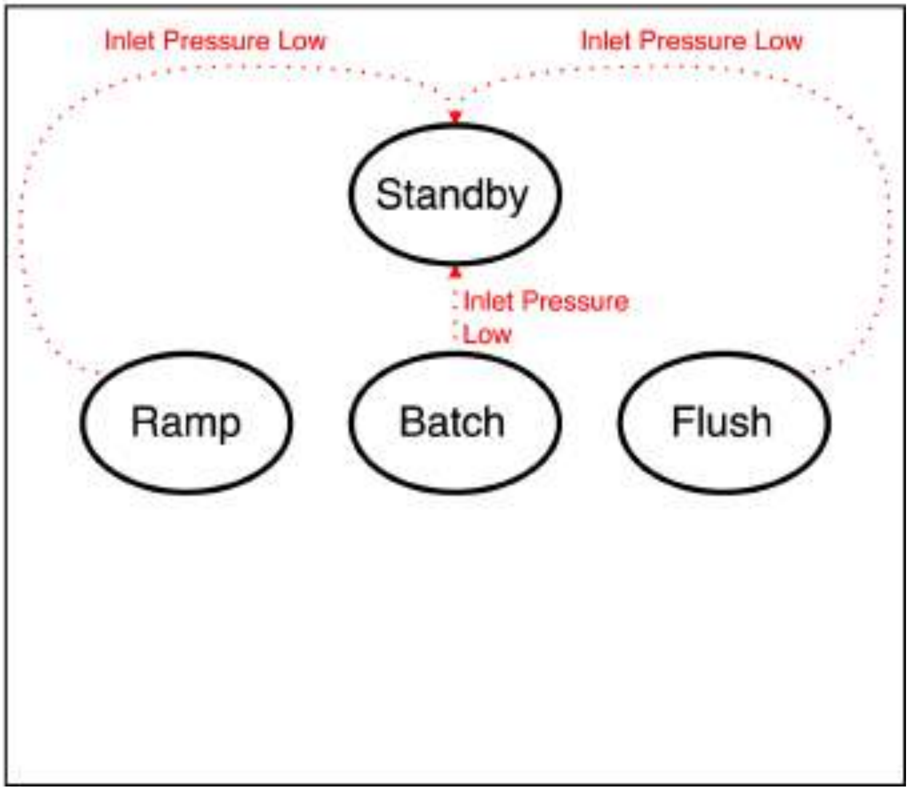

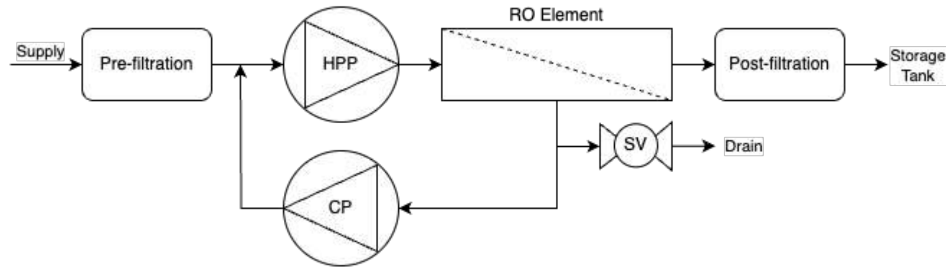

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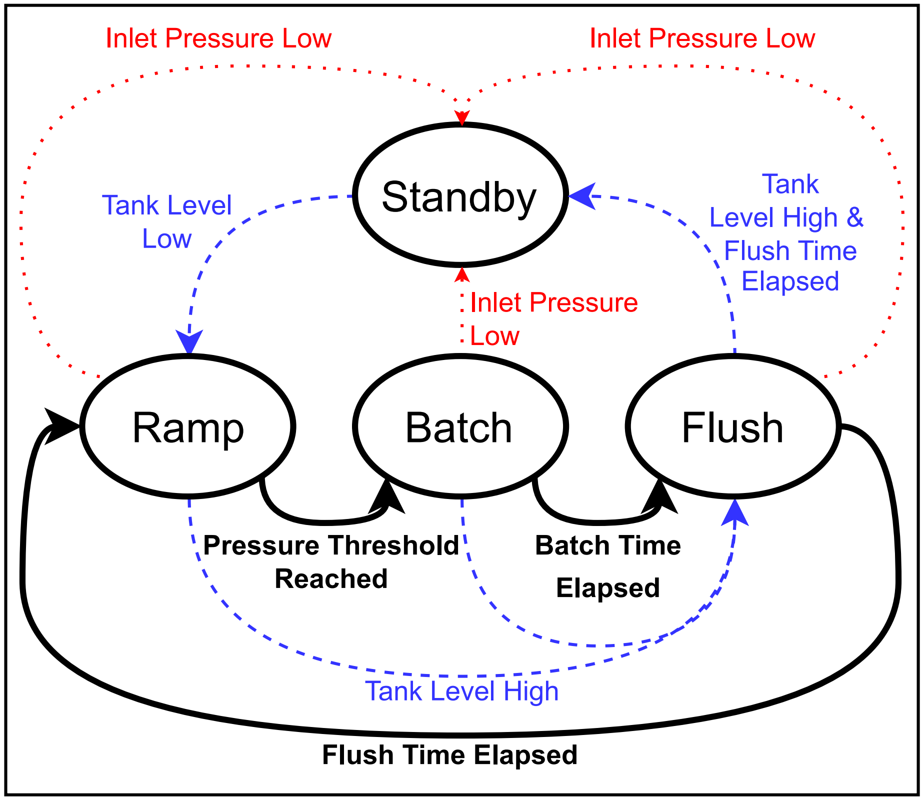

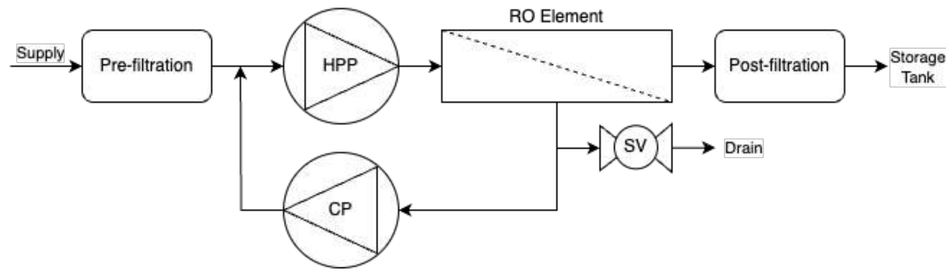

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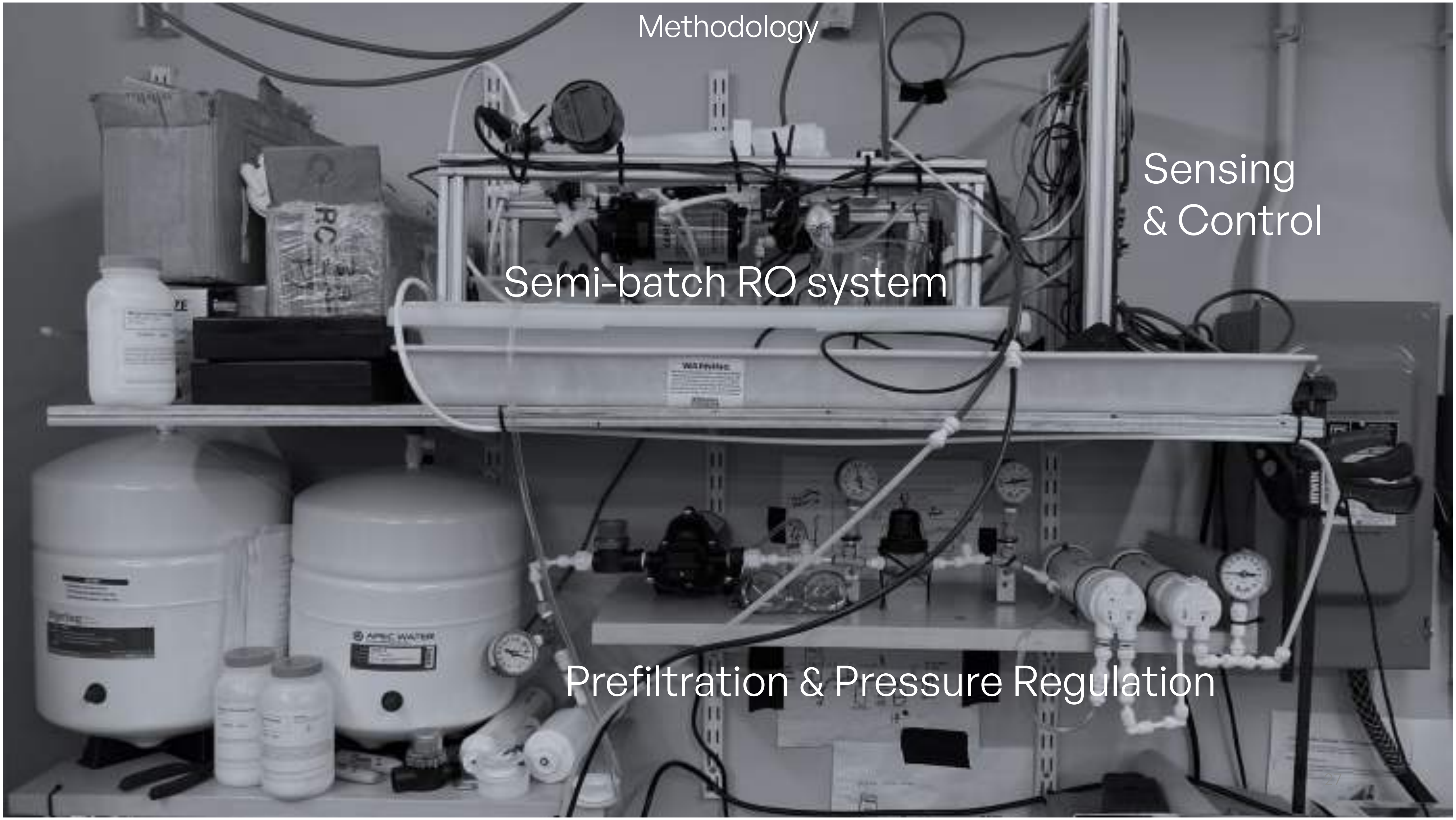
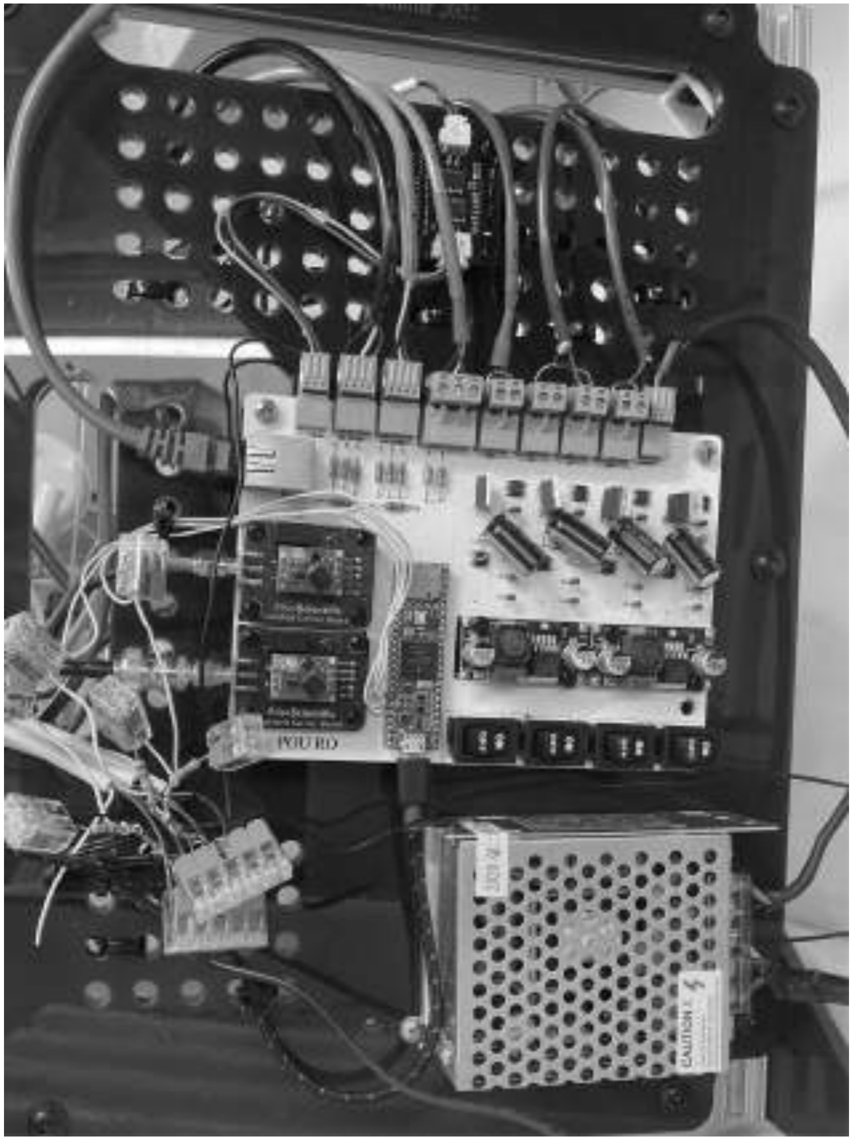

Methodology
Semi-batch RO system
Sensing
& Control
Prefiltration & Pressure Regulation



Teensy 4.1
Import Packages
MQTT/Ethernet Init.
Read Sensors
State Machine Control
PID on Pressure within Batch State
Export Sensor Data

Methodology

Server

InfluxDB & Node-Red

Parametric Exploration (DOE)

IV

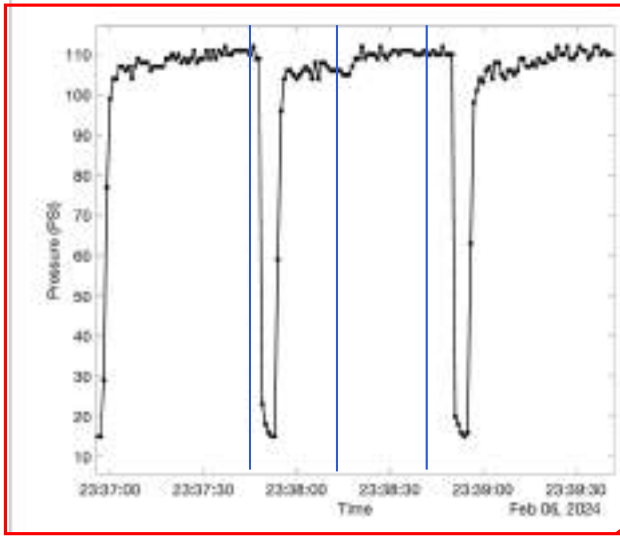
- HPP, CPP max duty
- Operating pressure & hysteresis
- Flushing time
- Batch time

DV

- Diluate, Brine volume → Recovery, Production rate
- Diluate, Brine conductivity → Scaling propensity

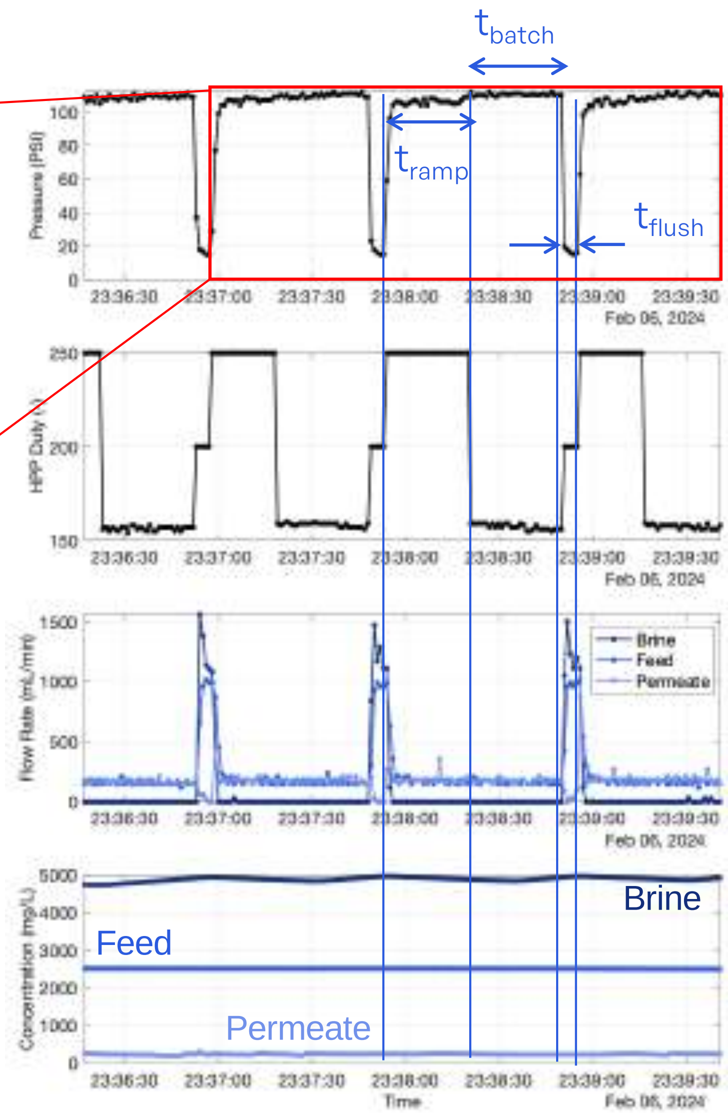
	Recovery	**Production Rate**	**Scaling Propensity**	**Virtual Cond. & Mem. Sensing**
Flush Time ↑ Batch Time ↓	↓	↑	↓	↓
Flush Time ↓ Batch Time ↑	↑	↓	↑	↑

Results



A typical cycle

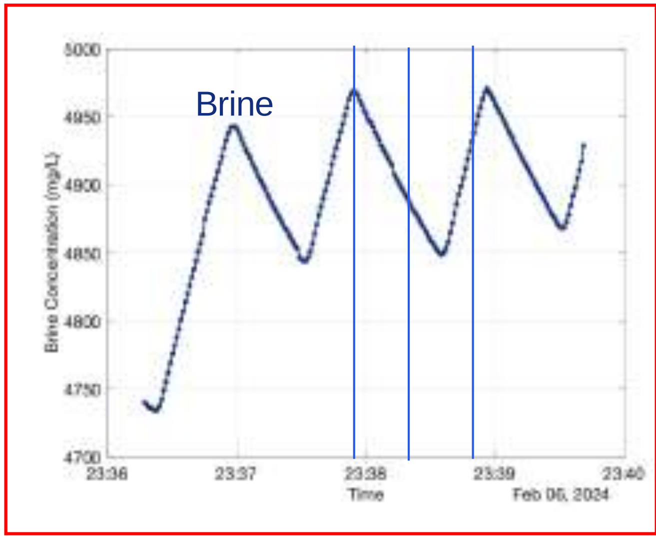
- Pressure increases (ramp)
- Is regulated (batch)
- And drops (flush)

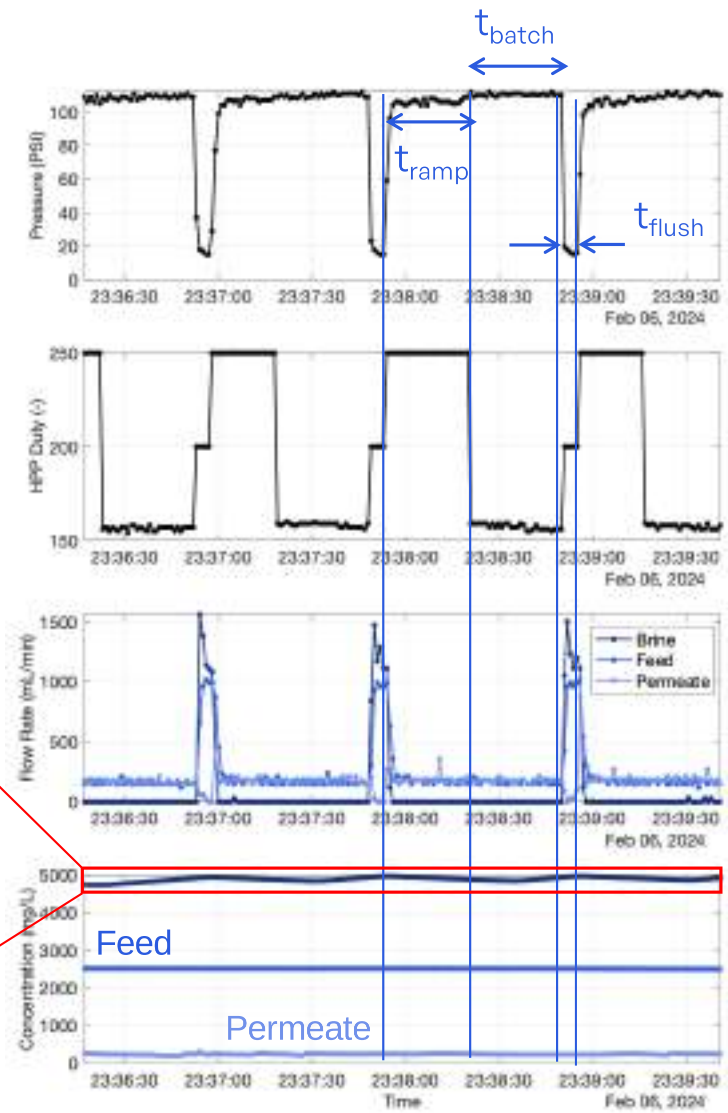


Results

A typical cycle

- Permeate flow decrease gradually over time
- Conductivity increases over time (ramp & batch)
- Conductivity drops (flush)





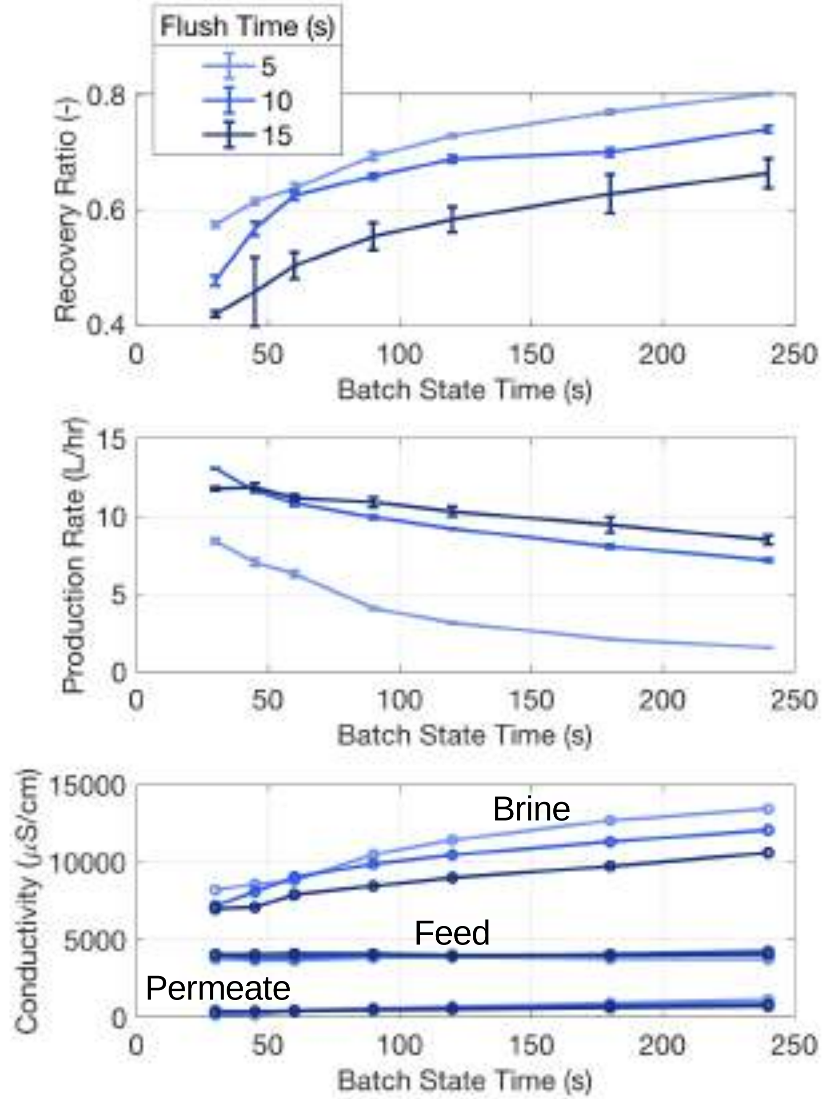
Results

Non-linear tradeoffs

Changing batch time:

- diminishing return on higher recovery
- steep drop in production rate
- higher recirc. loop conductivities

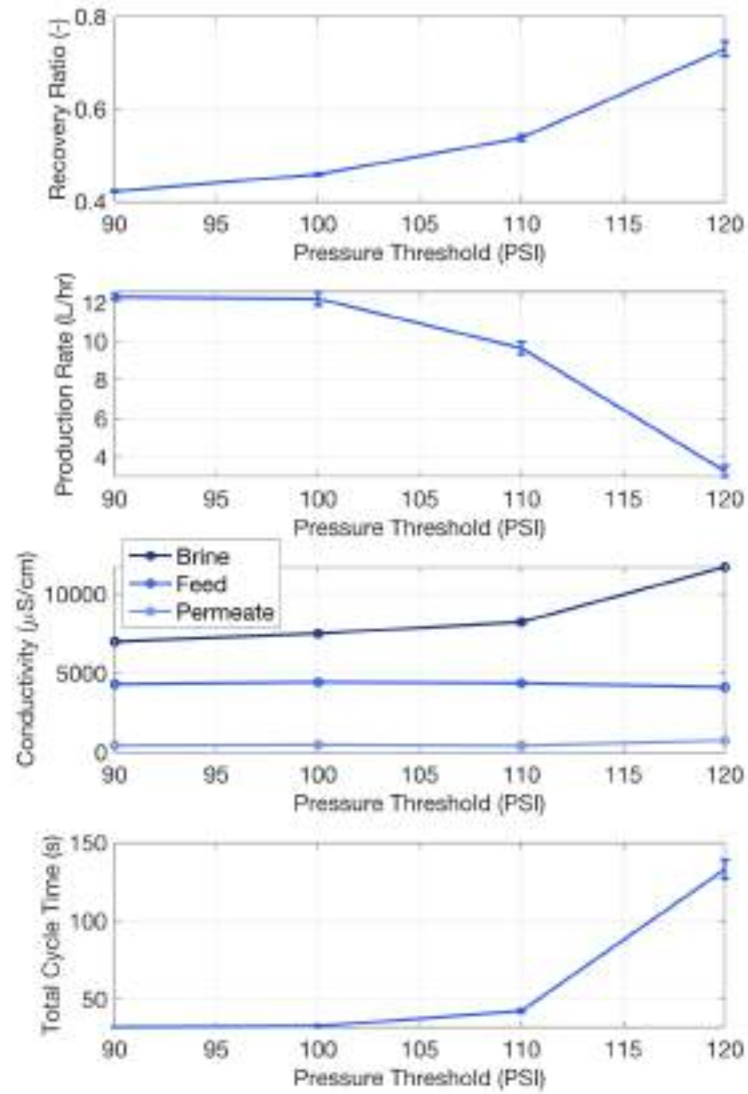
Recall, we want high recovery, high production rate, low recirc. conductivity



Non-linear tradeoffs

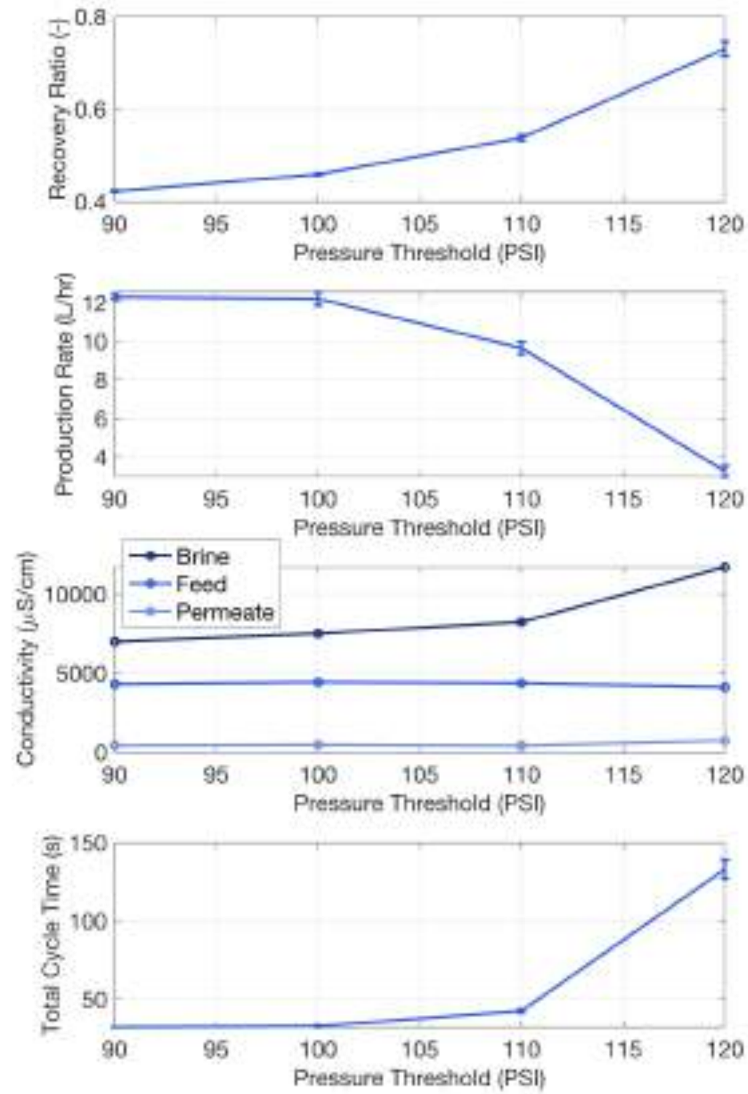
Changing pressures:

- High recovery
- steep drop in production rate (due to longer batches)
- higher recirc. loop conductivities



Takeaway

- Performance from batch/flush time ratios are relatively coupled, but we want fast batches so lower overall is better.
- There's a sweet spot in batch:flush time (10:1) and operating pressure (~110 PSI)



Conclusions

High-recovery semi-batch architecture

- Relationship between control parameters & performance? 
- Withstand scaling & fouling over time? 

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