ICL Industrial Products

Where needs take us

Br

Enhanced performance of membrane separated bromine based flow batteries using Bromine complexing agents

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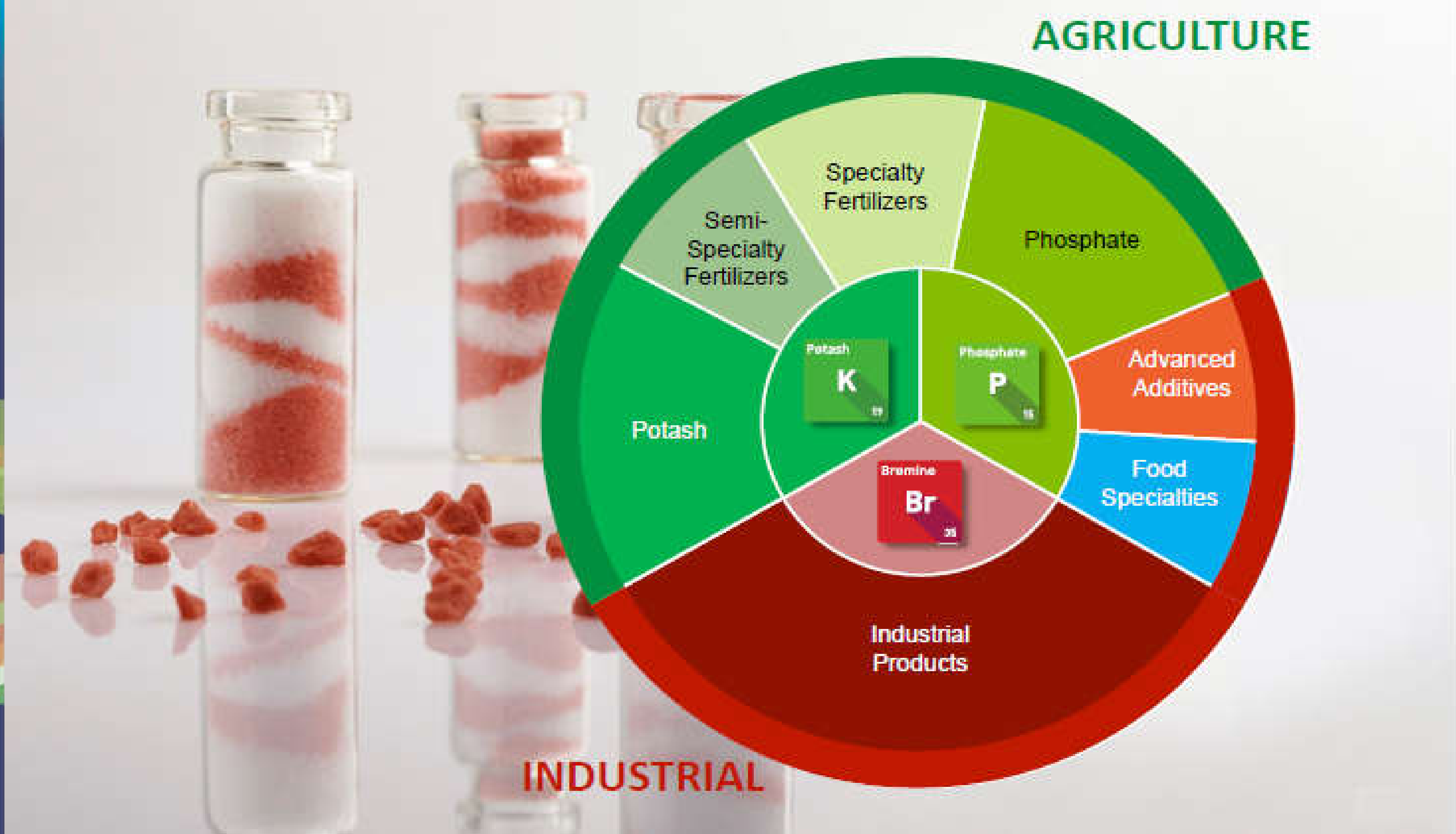
Outline

- About ICL
- Why Bromine?
- Bromine Complexing Agents
- BCA and Membrane interaction
- Wrap up

About ICL


AGRICULTURE
Specialty Fertilizers
Semi-Specialty Fertilizers
Phosphate
Potash
Advanced Additives
Food Specialties
Potash
K
Phosphate
P
Bromine
Br
Industrial Products
INDUSTRIAL

ICL R&D Energy Storage Activity

Synthesis

Analytics

Energy Storage at ICL R&D

Electrochemistry

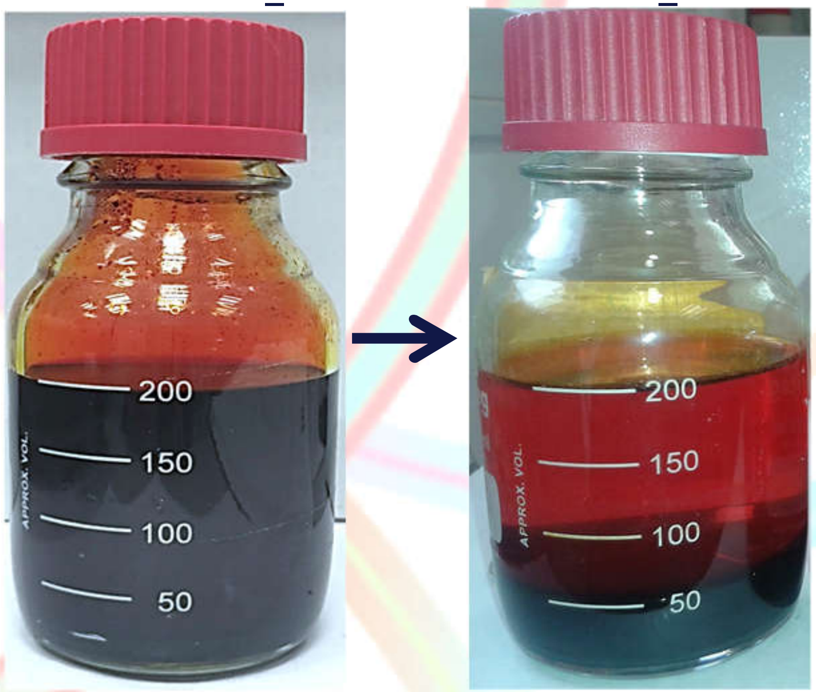
Corrosion

Why Bromine for Energy Storage?

- Liquid at room temperature
- Abundant and cost effective
- High energy density – High Br_2 loading
- High power density – Fast kinetics
- Electrochemical reversibility

How does BCA work?

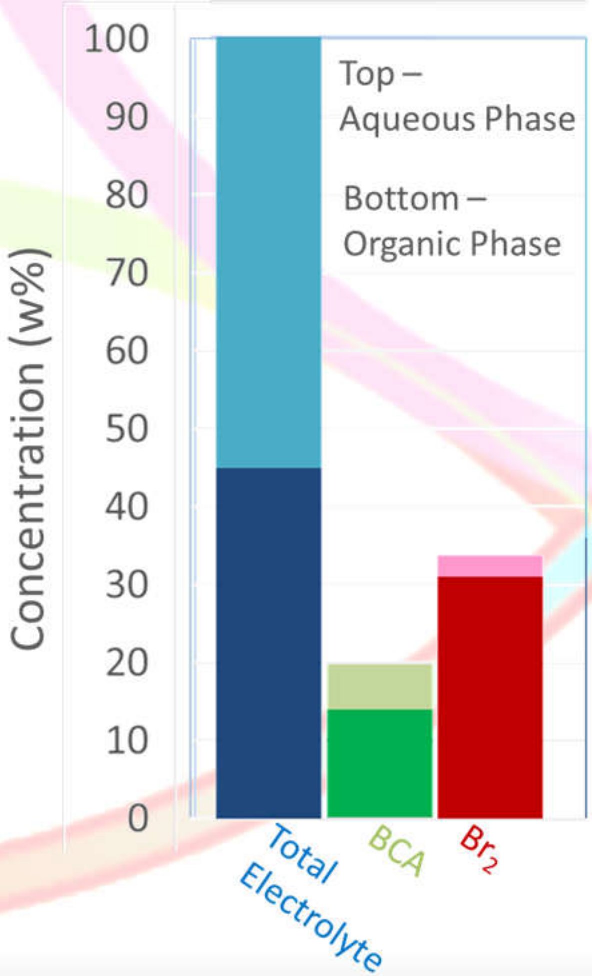
$HBr + Br_2$ → **$HBr + Br_2 + BCA$**



$HBr + Br_2$	$HBr + Br_2 + BCA$
Gas Phase High Br_2 Vapor	**Gas Phase** Reduced Br_2 Vapor
Aqueous phase Concentrate Br_2	**Aqueous phase** Diluted Br_2
	Organic phase Concentrated complexed Br_2

- Bromine vapor pressure is reduced significantly
- The complexed bromine (organic phase) is notably less reactive
- Cell materials are less subjected to Bromine oxidation

How does BCA work?



HBr + Br_2+ BCA

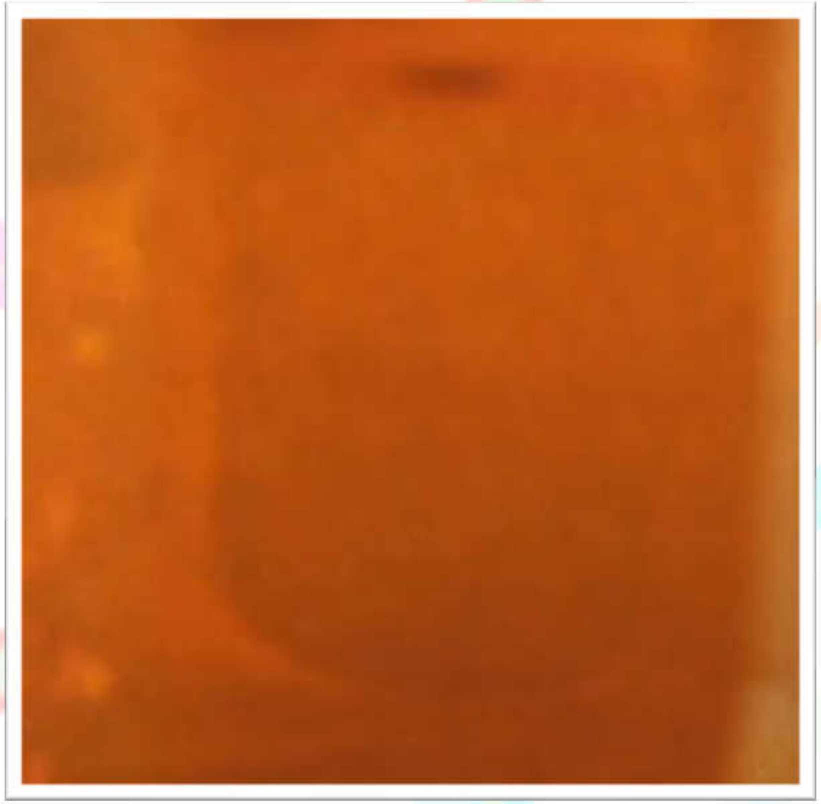
Gas Phase
Reduced Br_2 Vapor

Aqueous phase
Diluted Br_2

Organic phase
Concentrated complexed Br_2

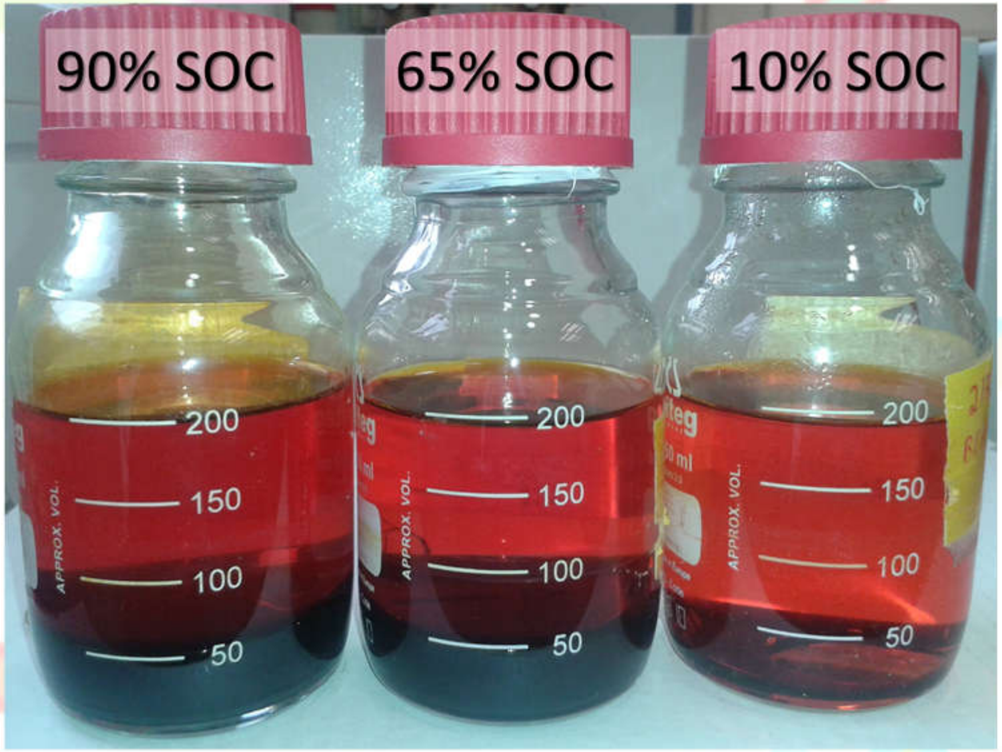
How does BCA work?

Electrochemical HBr oxidation on rotating electrode



Electrolyte components distribution

State of Charge [SOC %]	100	90	65	10	0
HBr [M]	1	1.67	3.35	7	7.70
Br_2 [M]	3.35	3.00	2.20	0.34	0
BCA[M]	1.1	1.1	1.1	1.1	1.1



- No Bromine vapor is observed
- High Br2 loading = High Energy density
- Br2 is stored safely in its complexed phase
- Available Bromine concentration in the aqueous phase is low and stable

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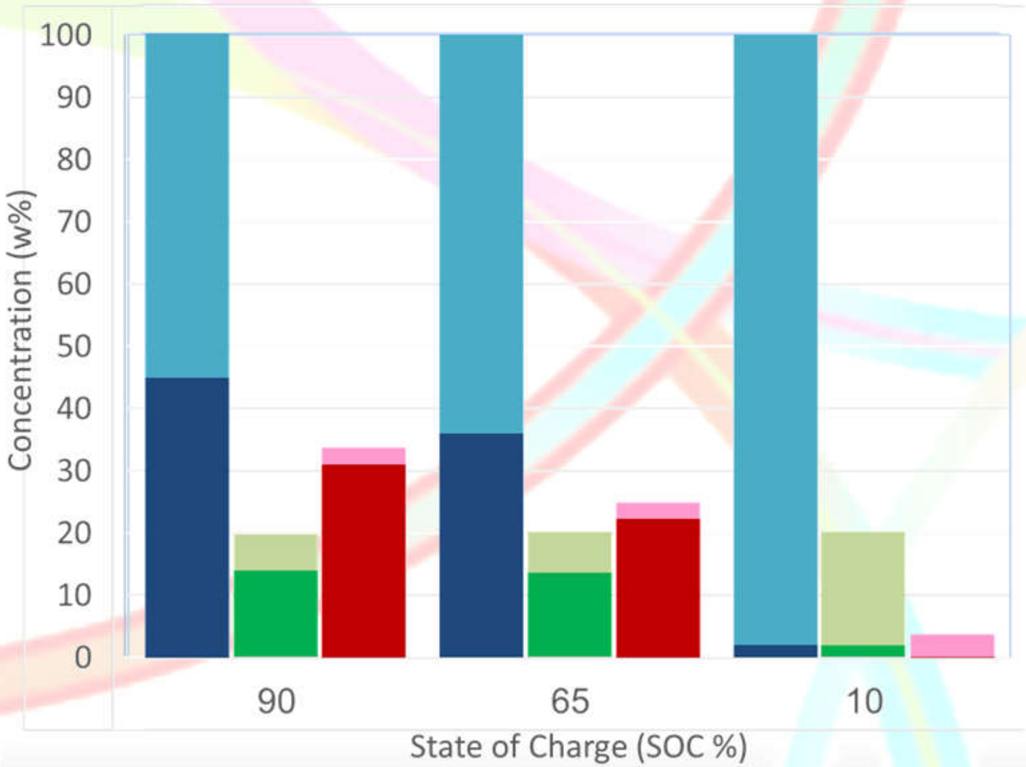

- No Bromine vapor is observed
- High Br2 loading = High Energy density
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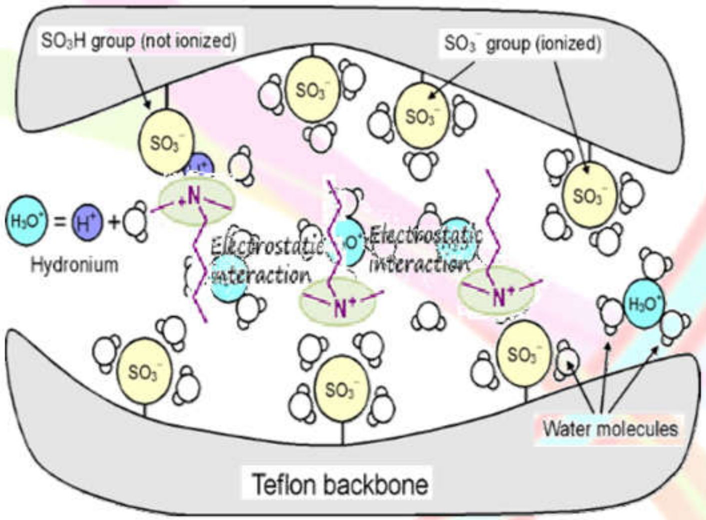
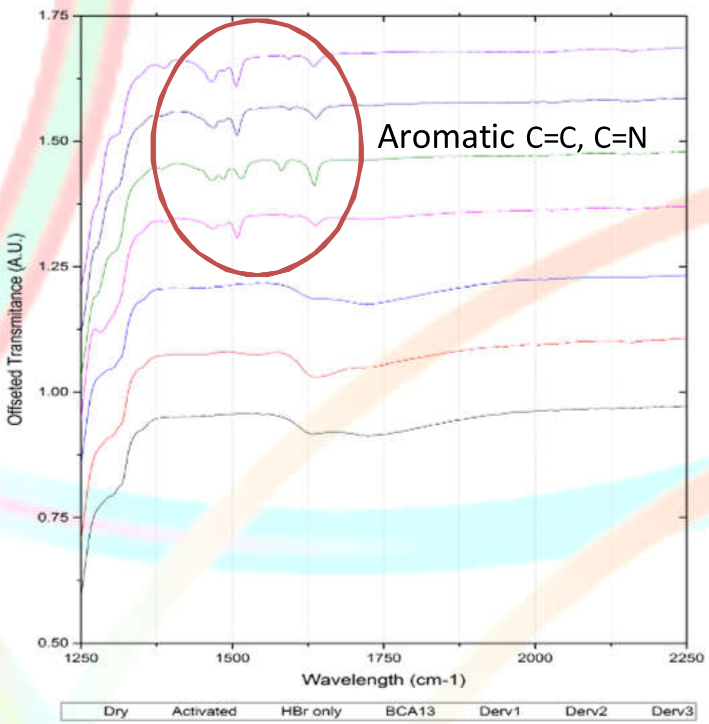
Case Study: BCA PEM Interaction

~~Dis~~functional Proton Exchange Membrane



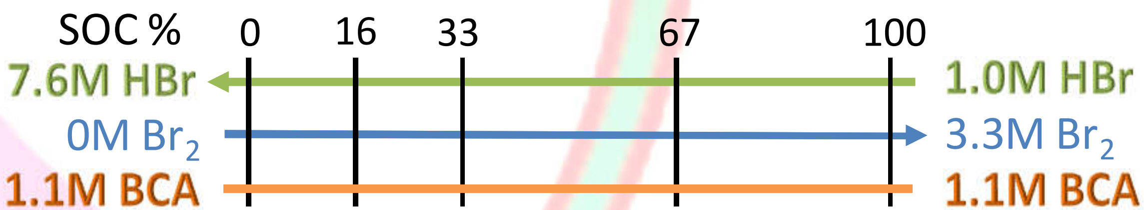
ftIR transmittance mode spectra



BCA quaternary amine cations bond to negatively charged sulfonic groups

Experimental setup

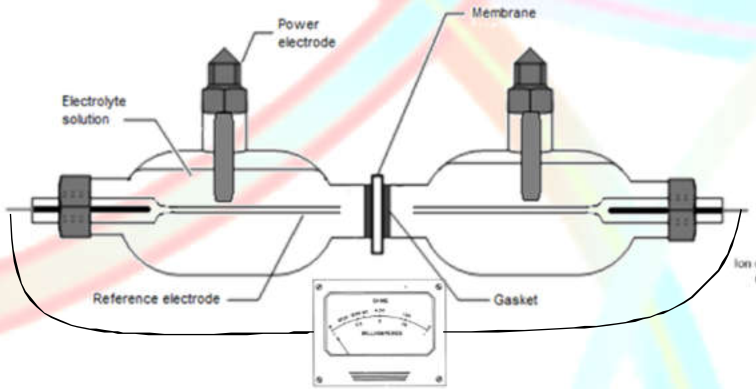
Chemical composition of HBr/Br_2 electrolyte solution



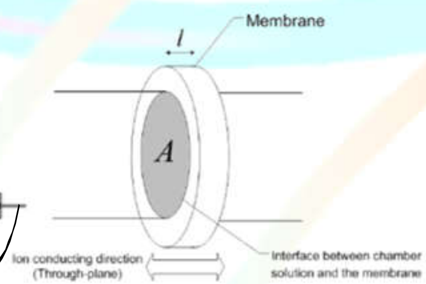
Electrochemical impedance spectroscopy (EIS)

Membrane resistance measurement setup

4 electrodes conductivity cell

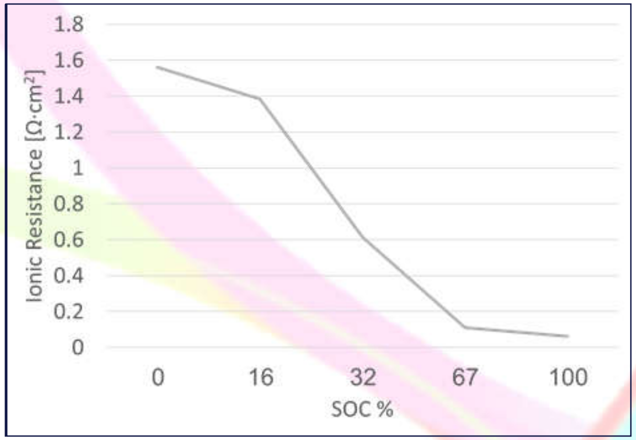


Membrane cross section

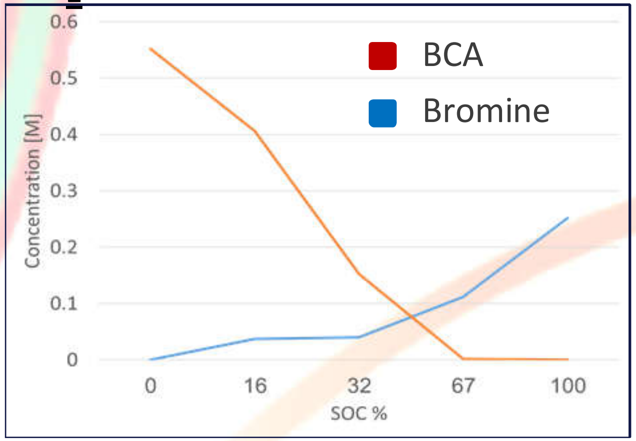


State of Charge effect

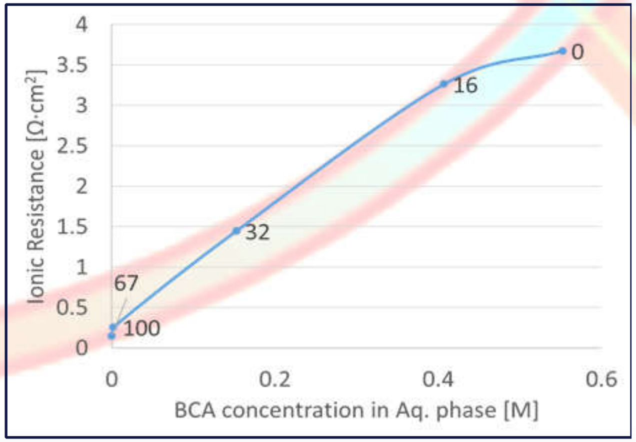
Membrane ionic resistance



Br_2 and BCA conc. in Aq. phase



Resistance vs. BCA concentration

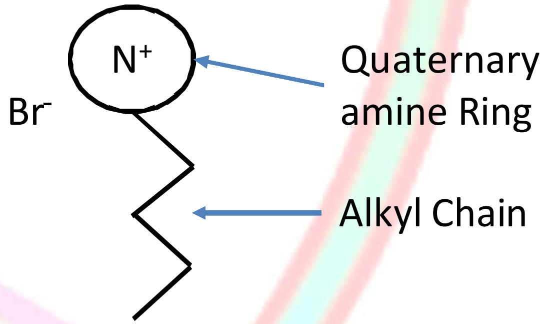


- Resistance decreases as SOC increases.
- BCA concentration in Aq. phase decreases as SOC increases.
- The resistance is positively depends on BCA concentration

=>Switching to hydrophobic BCA

BCA – Structure & Function

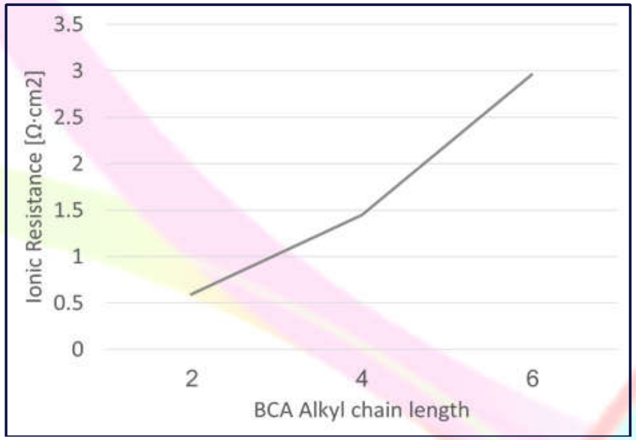
Complexing agent illustration



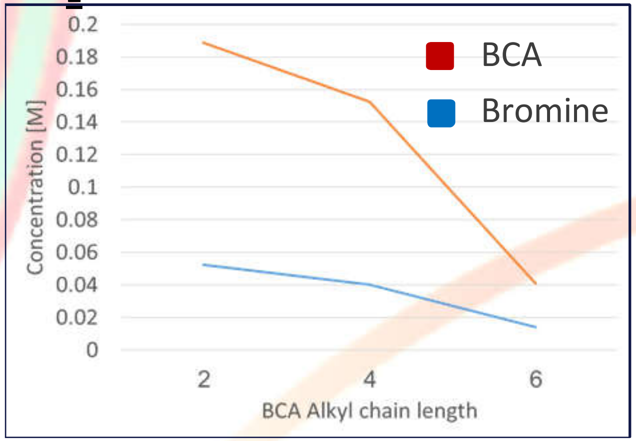
Same electrolyte, different complexing agent

BCA Alkyl Chain effect

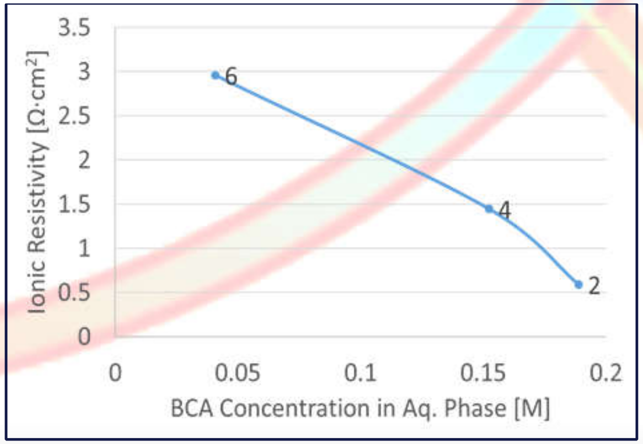
Membrane ionic resistance



Br_2 and BCA conc. in Aq. phase



Resistance vs. BCA concentration

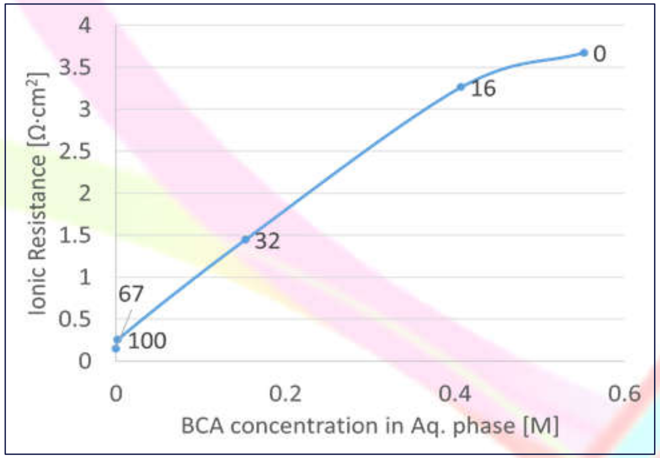


- The longer the chain the higher the resistance.
- BCA and Br2 concentration in Aq. phase decreases as chain length increases.
- The resistance is negatively depends on BCA concentration.

=>Opposite effect

Ionic resistance vs BCA concentration

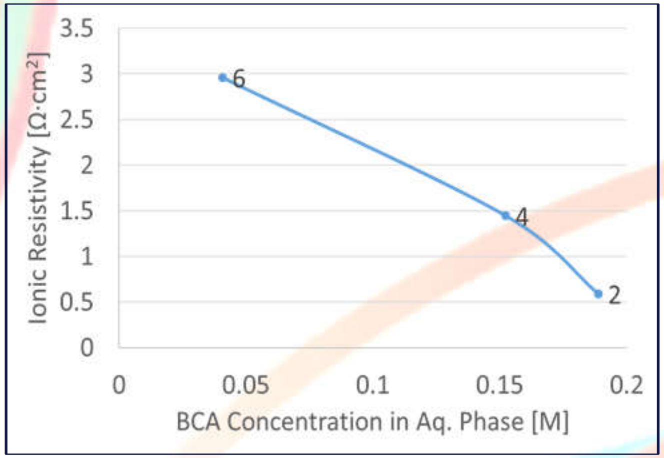
<u>State of Charge Response</u>



The membrane resistance
increases
as BCA concentration in aqueous phase increases

VS.

<u>Alkyl chain length Response</u>

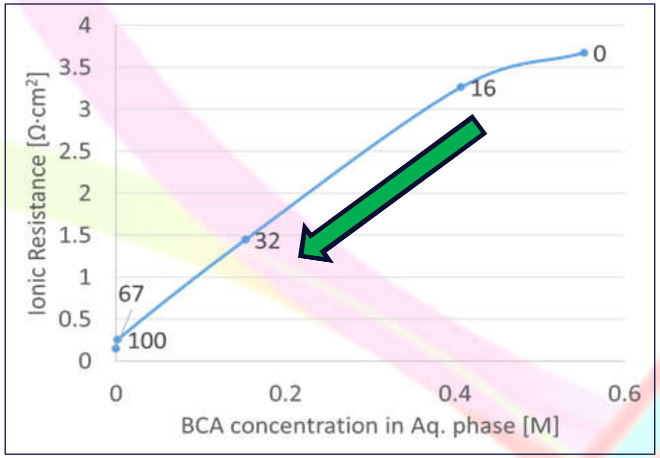


The membrane resistance
decreases
as BCA concentration in aqueous phase increases

Complex Bromine Organic Phase ⇄ BCA + Br_2 aqueous phase ⇄ BCA + PEM interaction Membrane

Ionic resistance vs BCA concentration

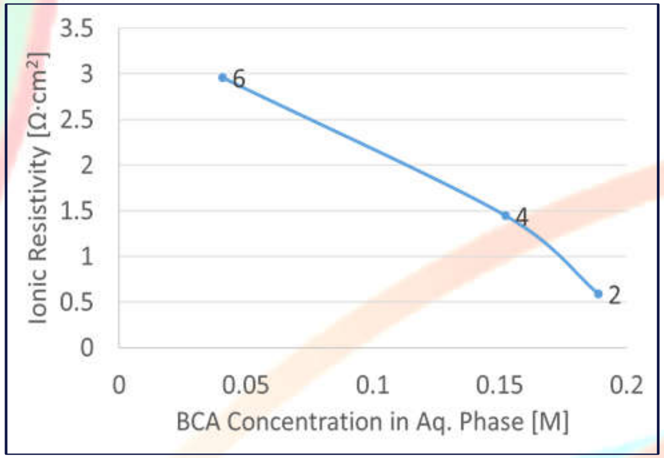
State of Charge Response



The membrane resistance **increases** as BCA concentration in aqueous phase increases

vs.

Alkyl chain length Response

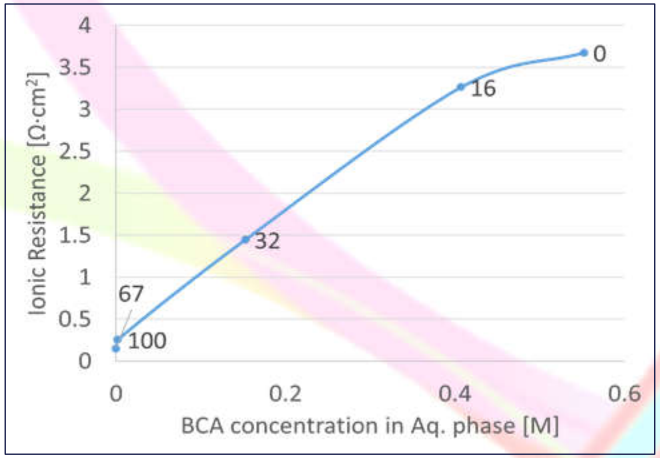


The membrane resistance **decreases** as BCA concentration in aqueous phase increases

Complex Bromine Organic Phase ⇌ BCA + Br_2 aqueous phase ⇌ BCA + PEM interaction Membrane

Ionic resistance vs BCA concentration

State of Charge Response



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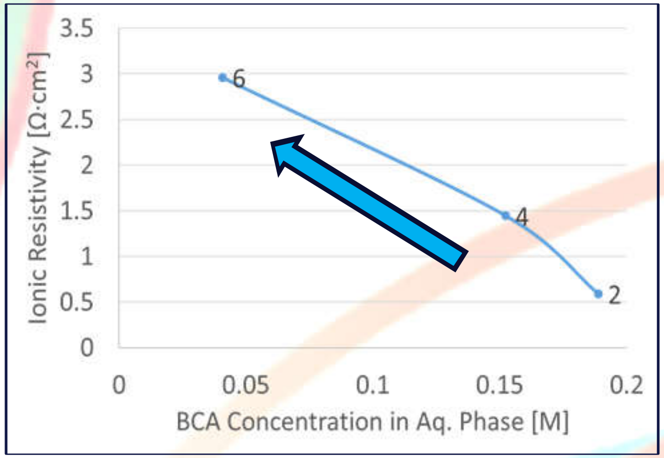
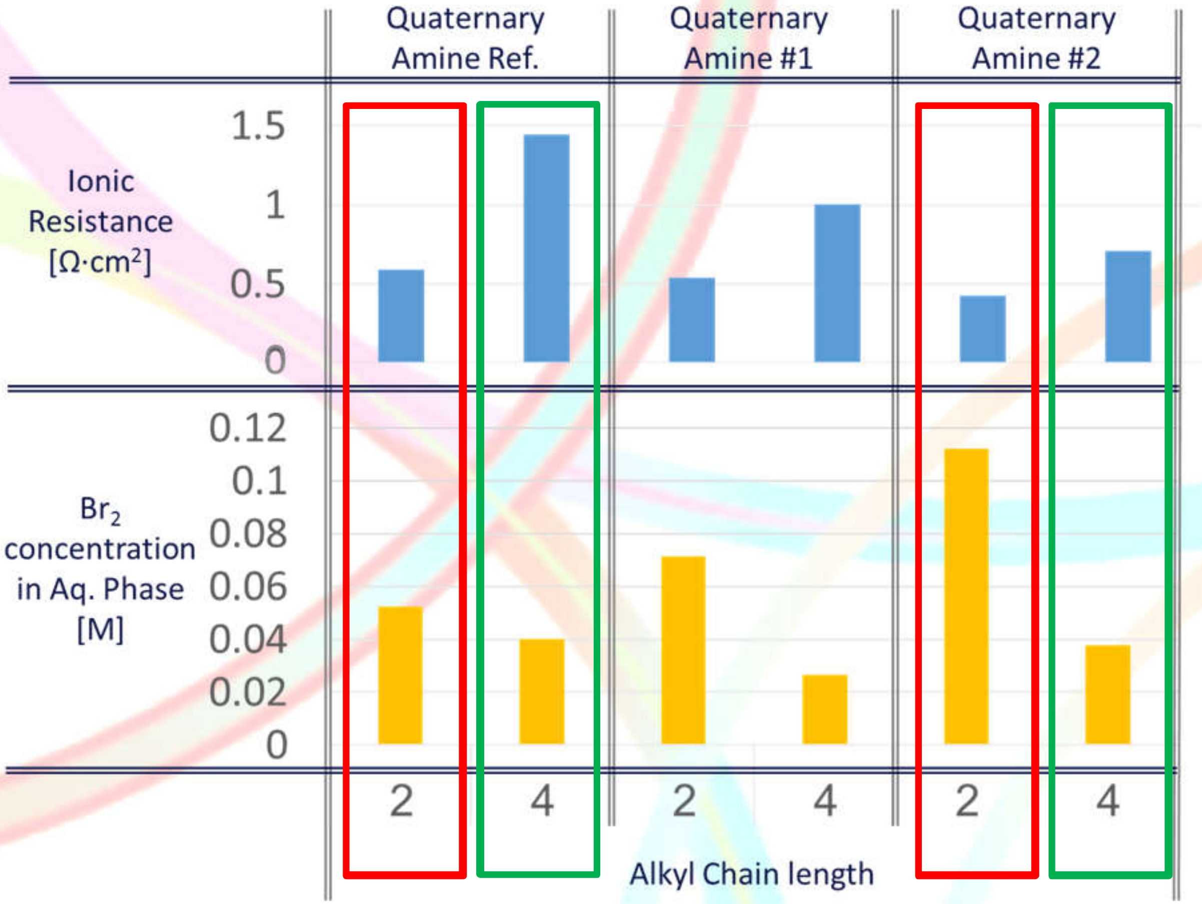


The membrane resistance **decreases** as BCA concentration in aqueous phase increases

Complex Bromine Organic Phase ⇄ BCA + Br_2 aqueous phase ⇄ BCA + PEM interaction Membrane

Effect of quaternary amine type



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