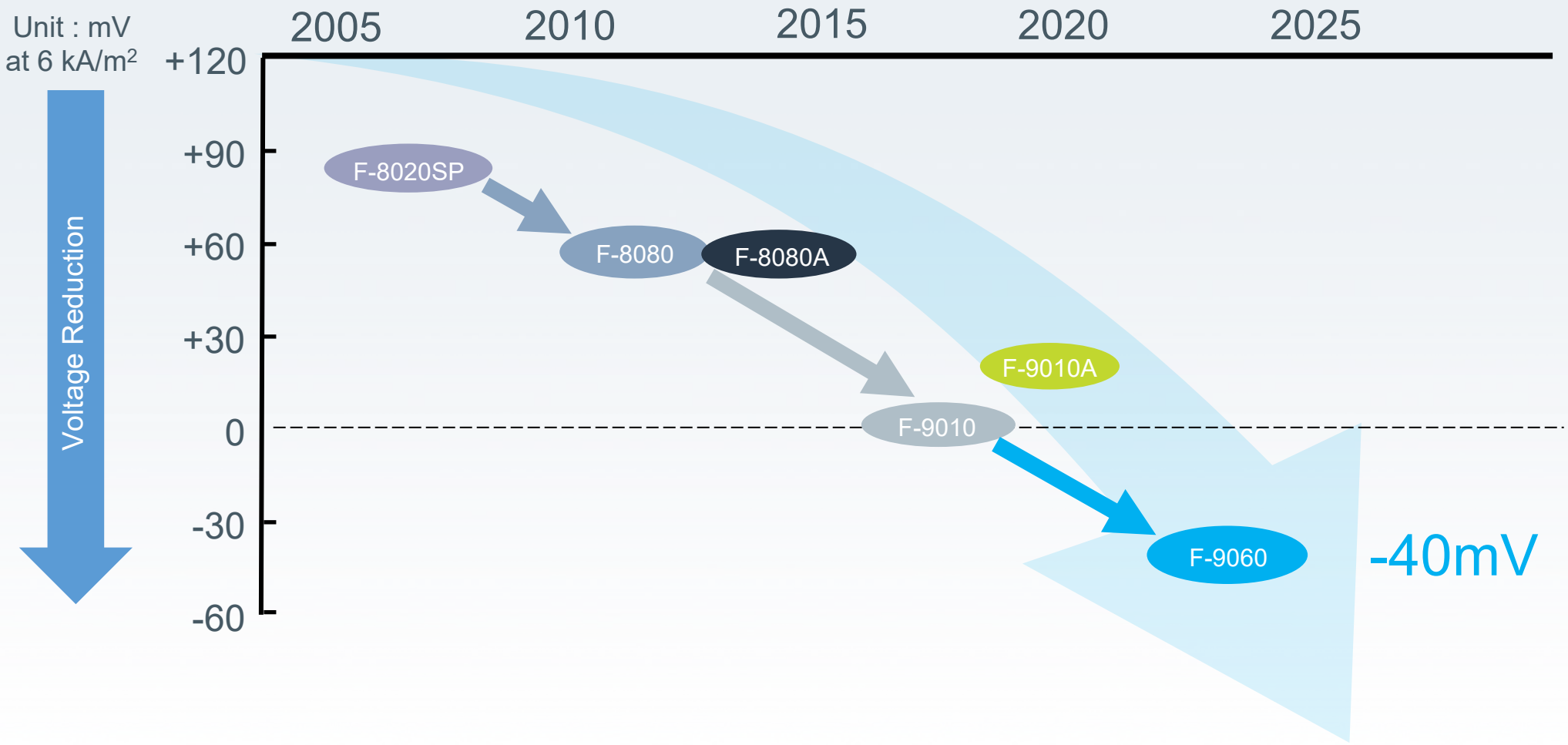
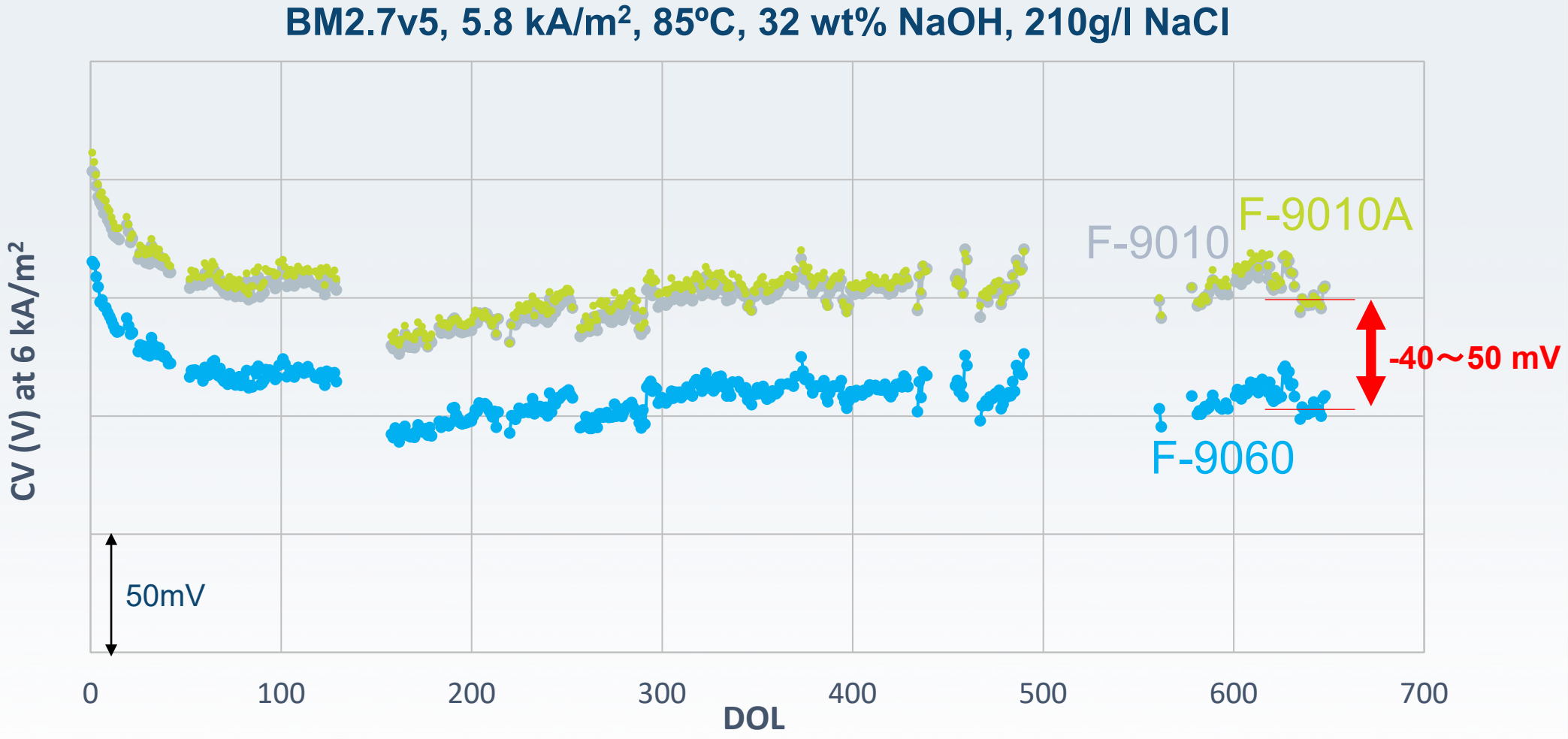
Introduction of FORBLUE™ FLEMION™ F-9060 Membrane

The World’s Lowest Voltage Membrane

FLEMION Continuous Development for Lower Voltage

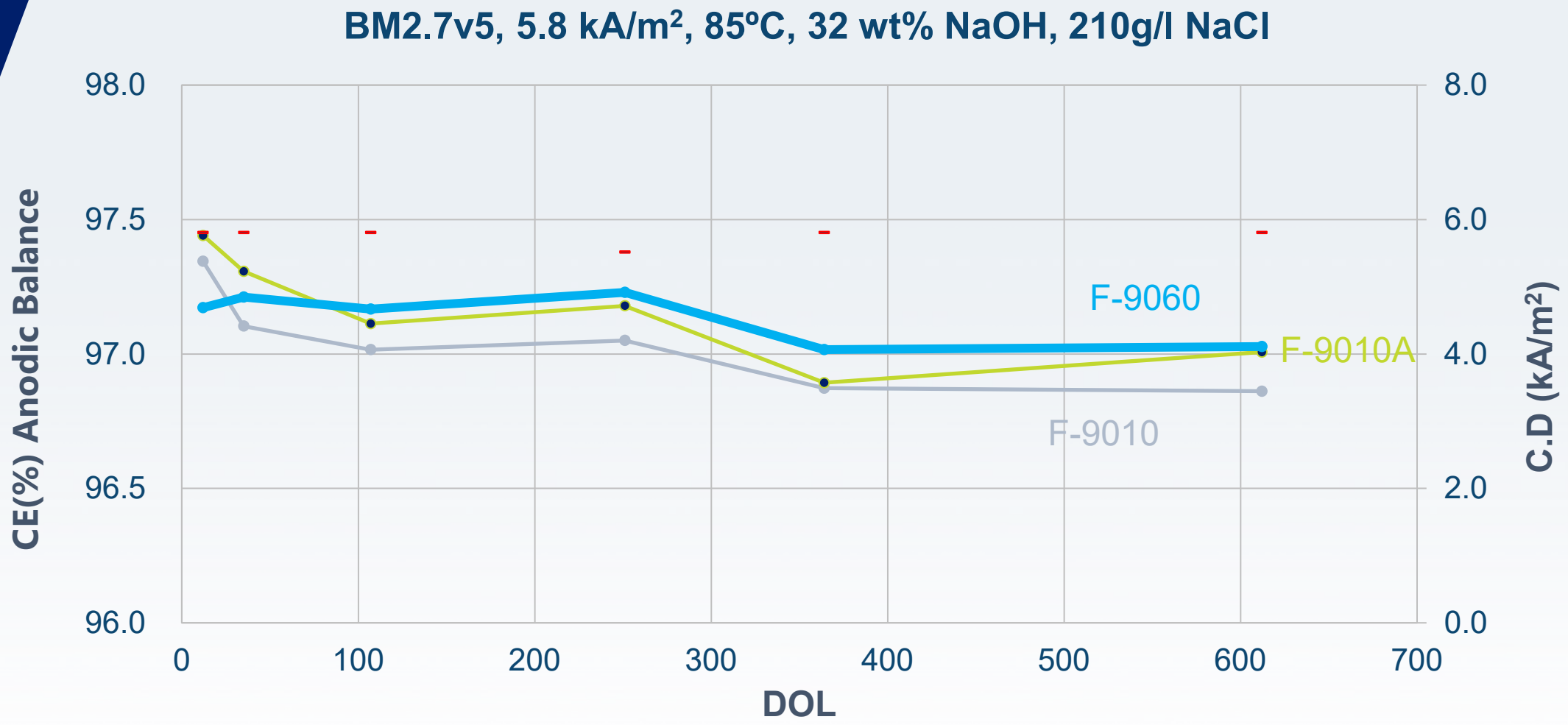


Voltage of F-9060 in AGC Commercial Plant



F-9060 holds stable, low voltage in AGC commercial plant for almost 2 years.

CE of F-9060 in AGC Commercial Plant



F-9060 also shows stable high CE.

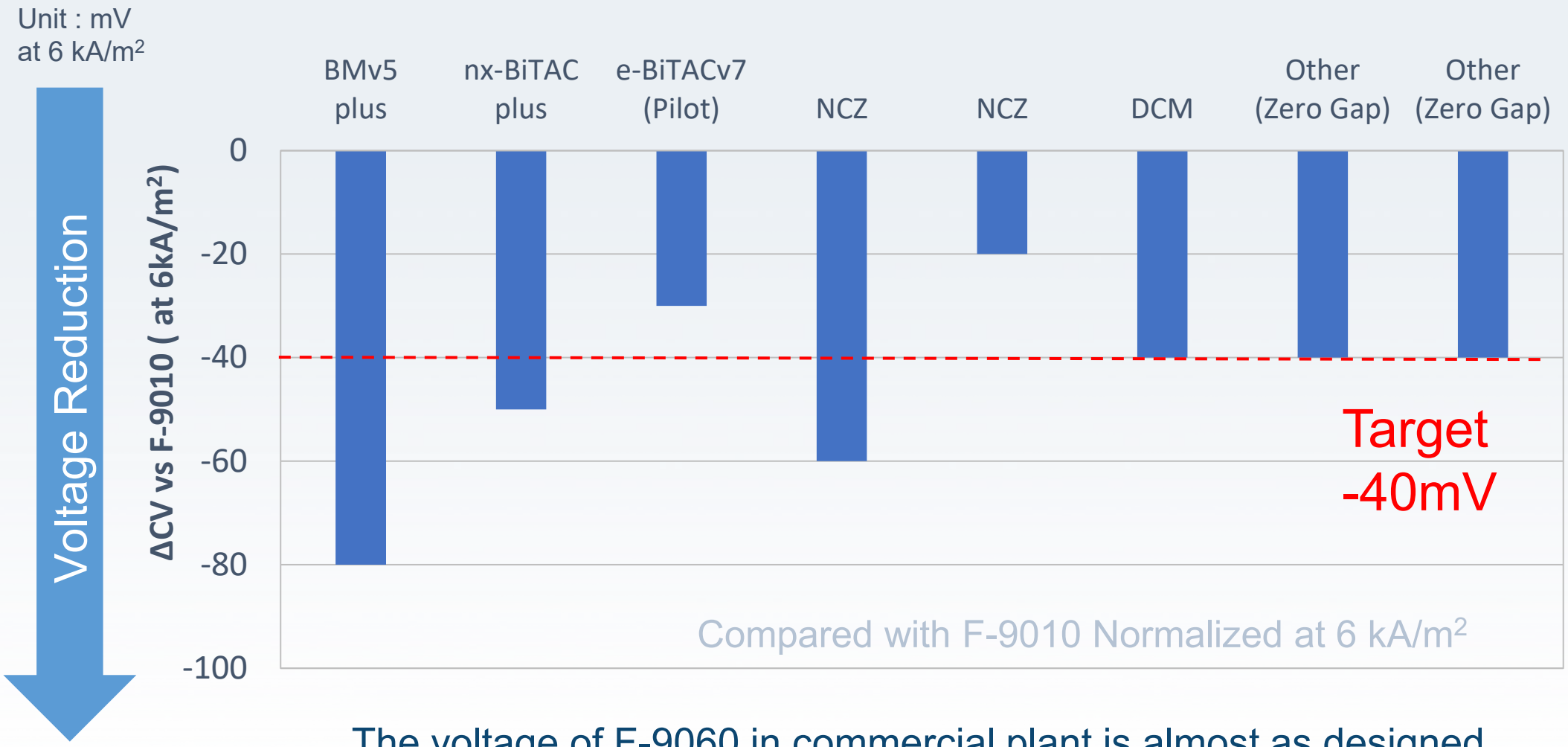
Table of Initial Performance in Laboratory Cell

AGC lab cell, 6 kA/m², 90ºC, NaOH 32 wt%, NaCl 200 g/l

	CE	⊿CV	Features
F-8080	≧96.0	+50mV	Previous standard membrane
F-8080A	≧96.5	+50mV	Higher CE than F-8080 suitable for zero gap technology.
F-9010	≧96.8	0mV	Standard Membrane suitable for zero gap technology
F-9010A	≧97.0	+20mV	Higher CE than F-9010 with CV increase suitable for zero gap technology
F-9060	≧97.0	-40mV	the lowest voltage & the highest CE suitable for zero gap technology

F-9060 has both the lowest voltage and the highest CE.

F-9060 Performance Feedback from Customers' Commercial Plants



The voltage of F-9060 in commercial plant is almost as designed.

Impact of F-9060 on Electricity Cost Saving

Voltage

Compared with F-9010 at 6 kA/m^2

Electricity Cost Saving

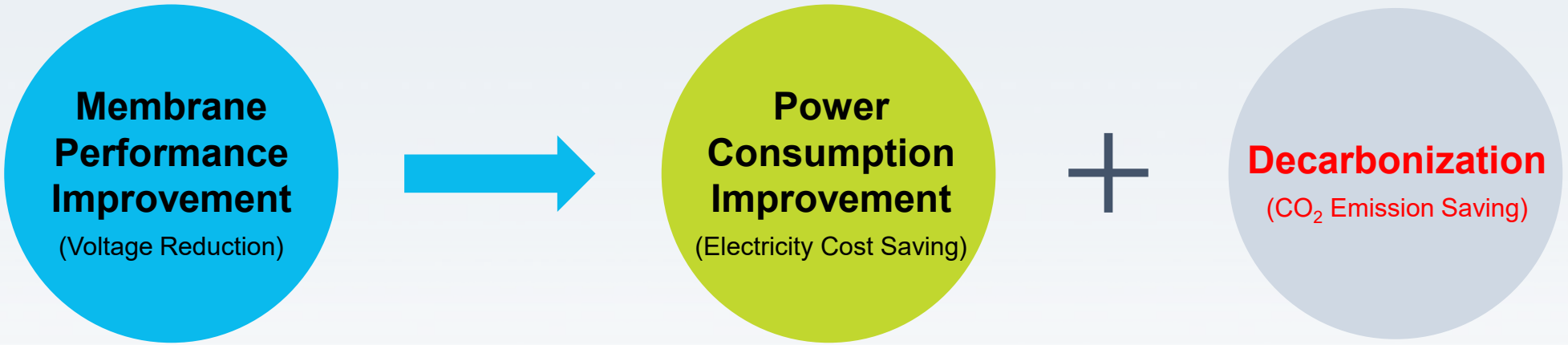
$2.8 M/y

(28 GWh/year)

Plant scale: 1 million ton / year
electricity price : 0.1 $ / kWh

*Values are based on AGC's own calculation and estimation
they are NOT intended for performance guarantee

Contribution of Membrane Performance Improvement



Further development of membrane would contribute not only economical value but also environmental value.

Impact of F-9060 on CO2 Emission Saving

Voltage

-40 mV

Compared with F-9010 at 6 kA/m^2

CO_2 Emission Saving

$1.8 M/Y

(17 kton-CO2/y)

Plant scale: 1 million ton / year
EPA's non-baseload emission factors (Mar, 2023):
0.00061 t-CO_2/kWh (US average)
ETS price: € 93.3 /t-CO_2, €1=$1.12 (14th Jun, 2023)

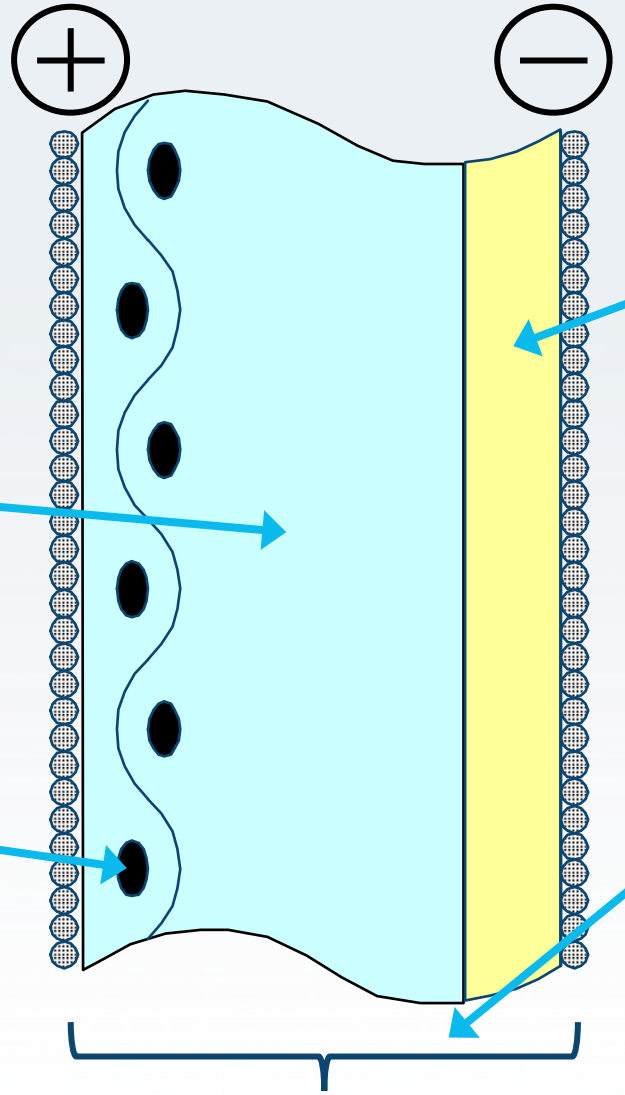
*Values are based on AGC's own calculation and estimation they are NOT intended for performance guarantee

Concept of Next Generation Membrane F-9060

Keyword in Market	Main Required Features	Key Technology
Rising Electricity Cost & Decarbonization Society	Low Voltage	**New** S-Polymer
High Current Density Operation	High Durability against Brine Impurities	**New** Ion Channel
Zero Gap Electrolyzer	Wider Operational Range	**New** Layer Configuration
	High CE Stability in Zero Gap	Advanced Cloth (as well F-9010)

F-9060 is the latest membrane based on further evolution and development of the technology of F-9010 series.

Key Technology of F-9060



New Ion Channel
Wider Operational Range &
High CE Stability in Zero Gap

New Sulfonic Polymer
Low Voltage

Advanced Cloth as F-9010
Same Mechanical Strength

New Layer Configuration
High Durability against Brine Impurities

Concept of Next Generation Membrane F-9060

Keyword in Market

High Current Density Operation

- Increment of Cell Voltage
- Increment of Mass Flow
- Fluctuation of Anolyte and Catholyte Concentration

Zero Gap Electrolyzer

- Less Flow of Anolyte/Catholyte at Membrane Surface
- High Membrane Temperature
- Direct Contact with Cathode

Main Required Feature

- Low Voltage
- High Durability against Brine Impurities
- Wider Operational Range
- High CE Stability in Zero Gap

Concept of Next Generation Membrane F-9060

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High Current Density Operation

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Main Required Feature

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- Wider Operational Range
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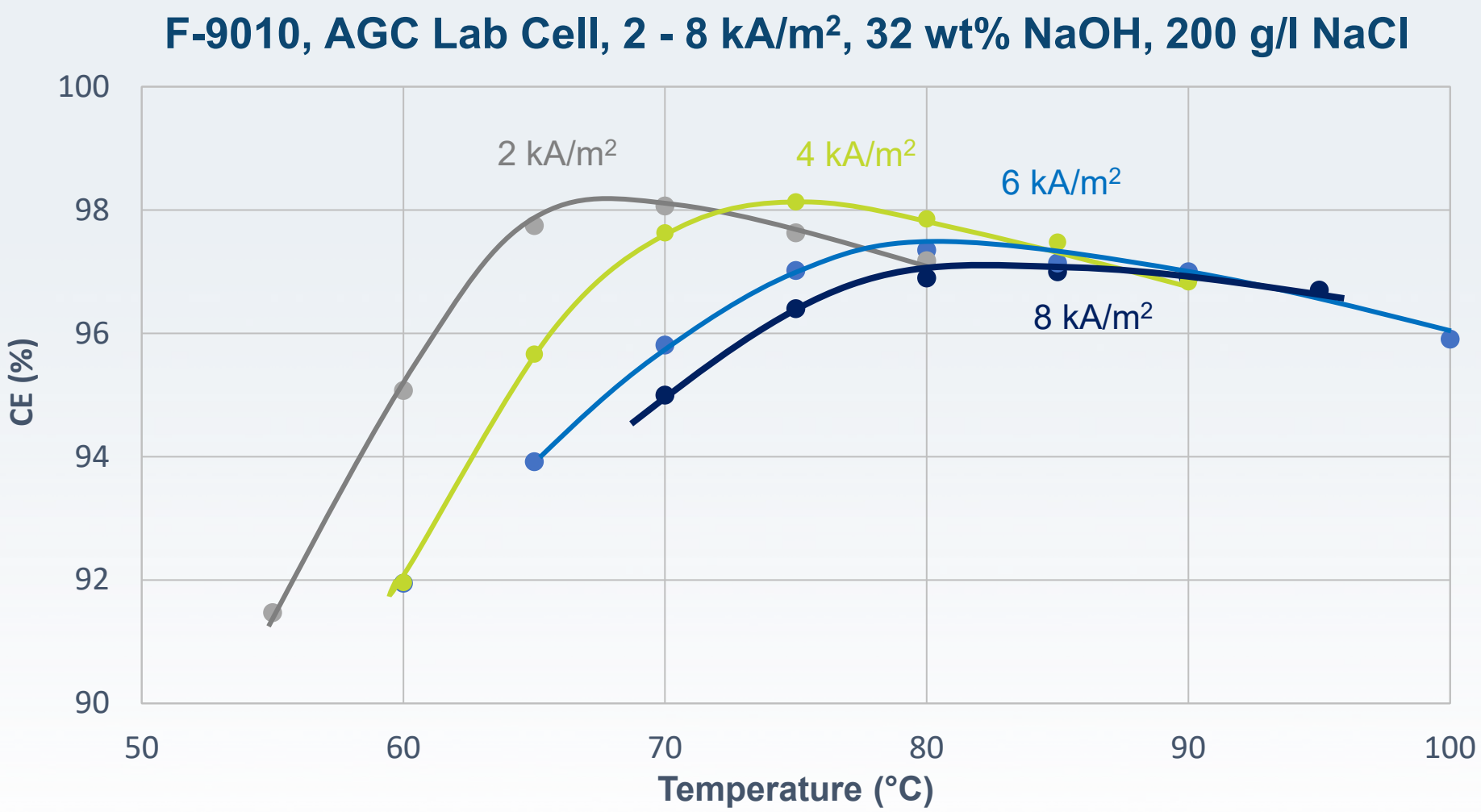
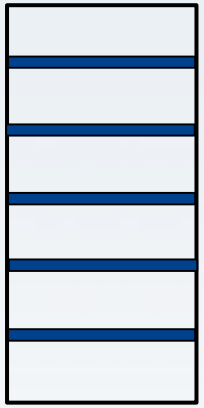
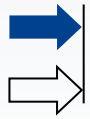
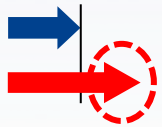
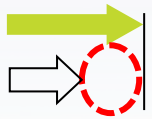
Influence of Current Density



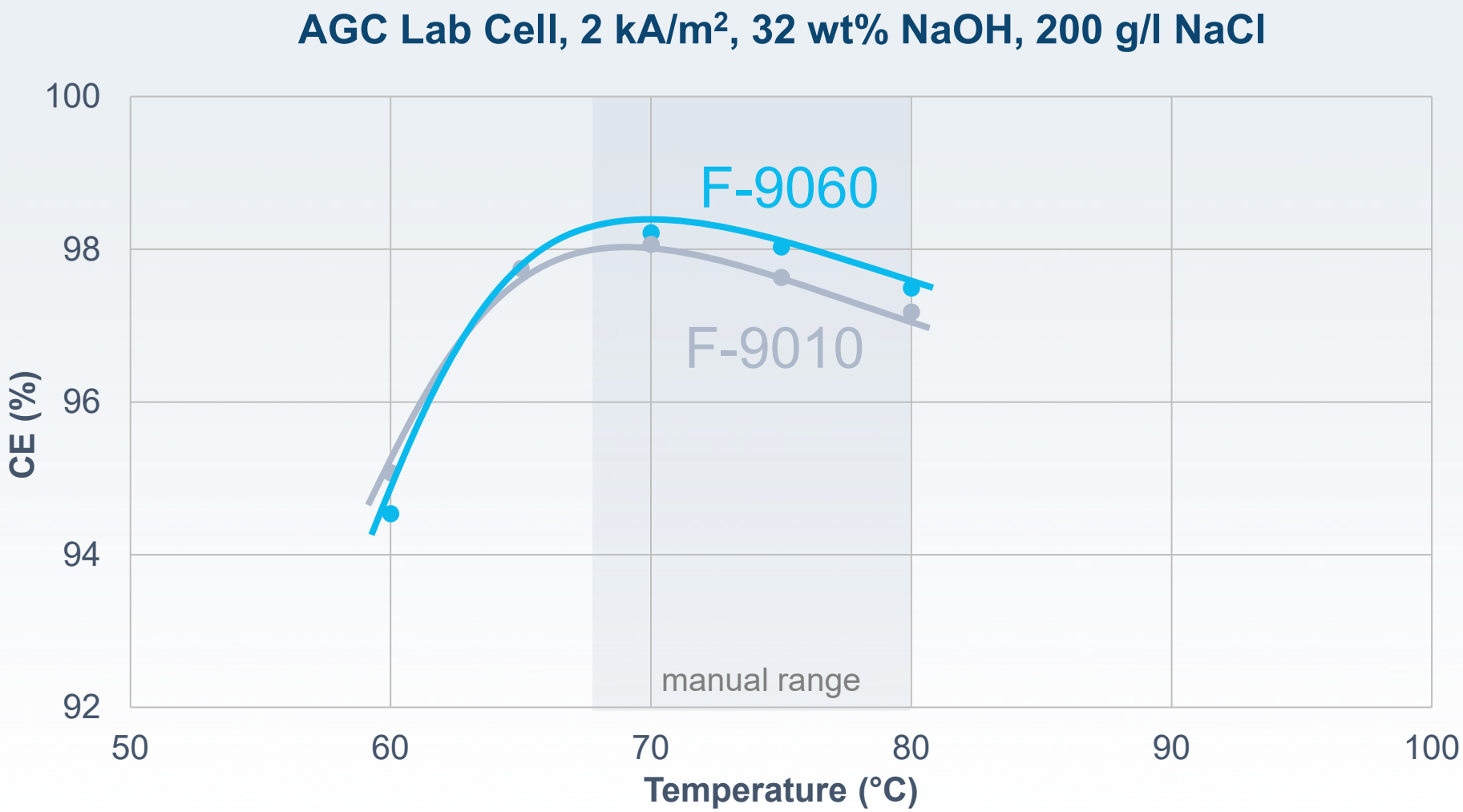
- Peak CE decreases at high current density.
- Peak of CE shifts to high temperature side at high current density.

Change of Ion Channel Structure with Temp. and C.D.

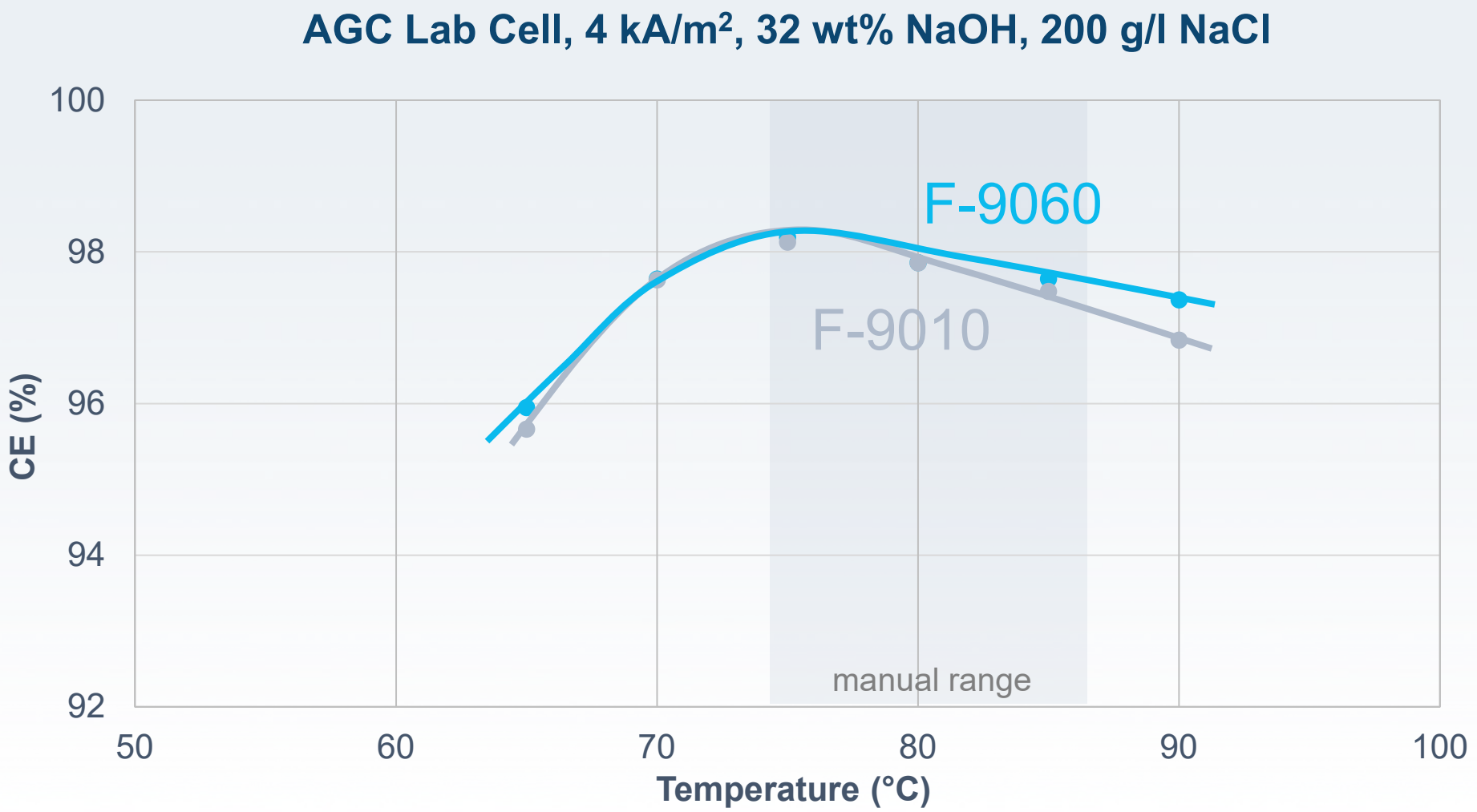
Temperature	Low		High	
Ion Channel Size				
Current Density	Low	High	Low	High
Capacity Ion Flux				
CE	High	Low	Low	High

Proper operating temperature that matches the ion flux leads to high CE.

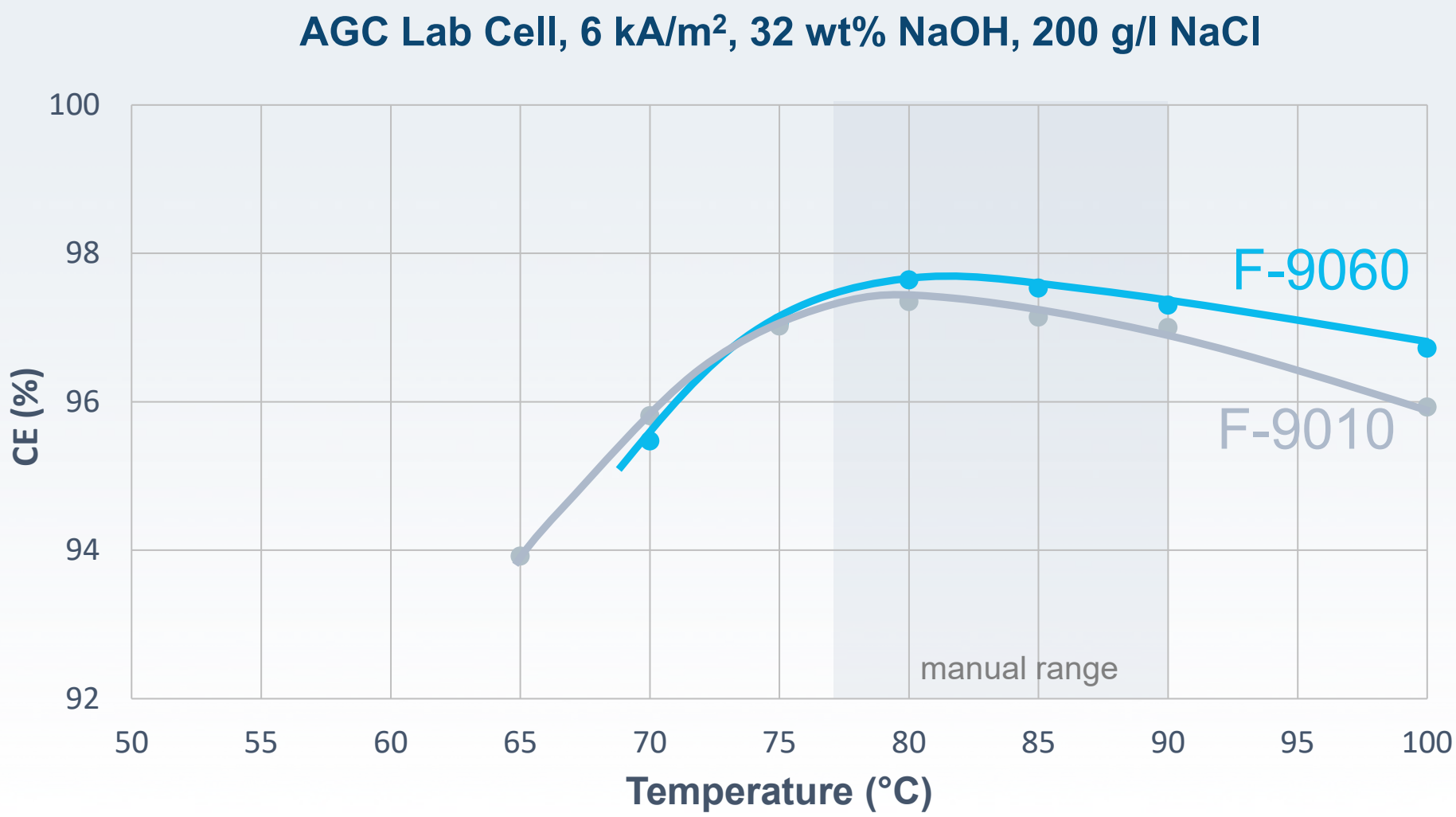
Comparison of Operational Range between F-9060 and F-9010



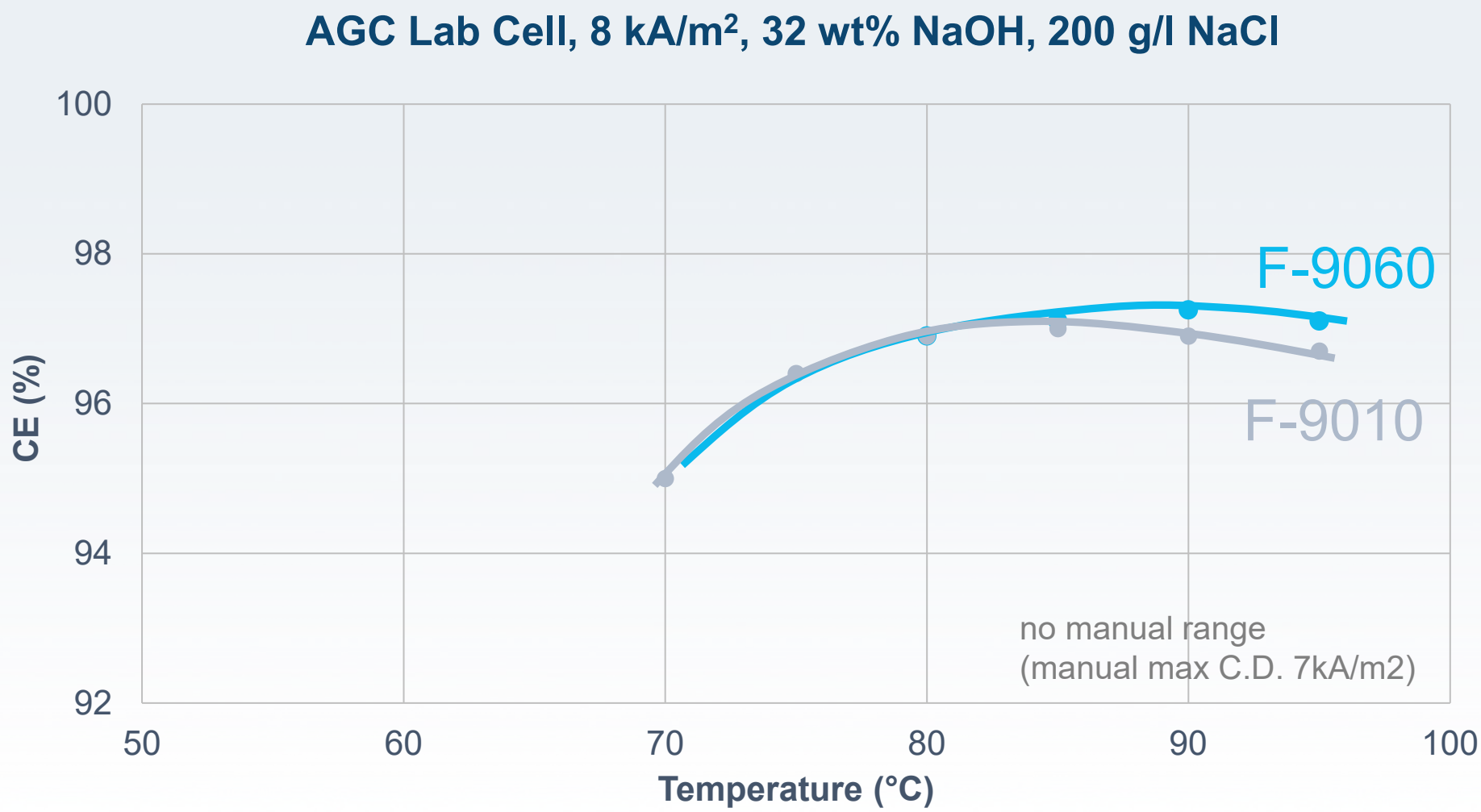
Comparison of Operational Range between F-9060 and F-9010



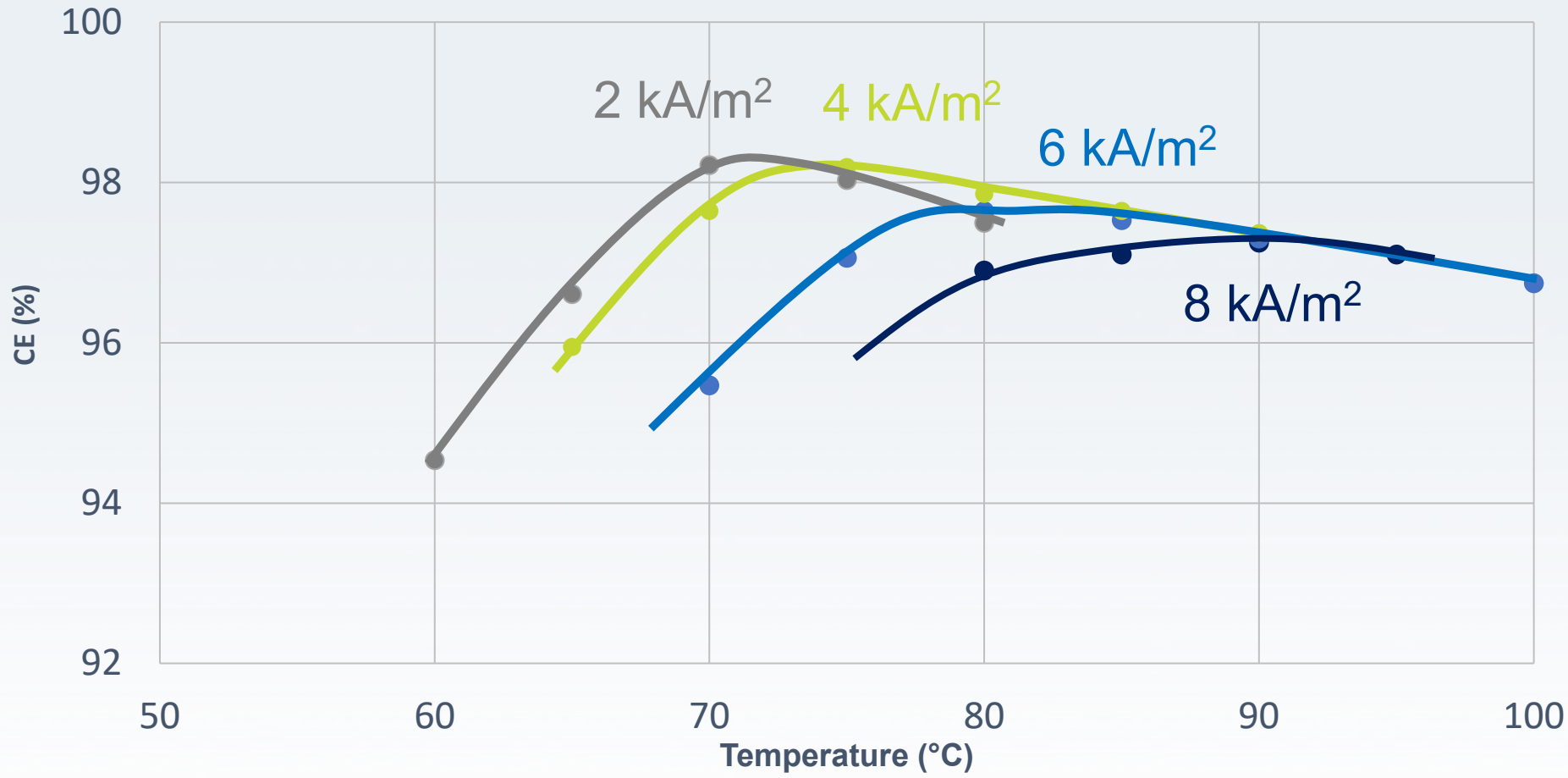
Comparison of Operational Range between F-9060 and F-9010



Comparison of Operational Range between F-9060 and F-9010



F-9060: Operational Temperature Range



F-9060 shows wider operational range, especially at higher temperature.

Concept of Next Generation Membrane F-9060

Keyword in Market

High Current Density Operation

- Increment of Cell Voltage
- Increment of Mass Flow
- Fluctuation of Anolyte and Catholyte Concentration

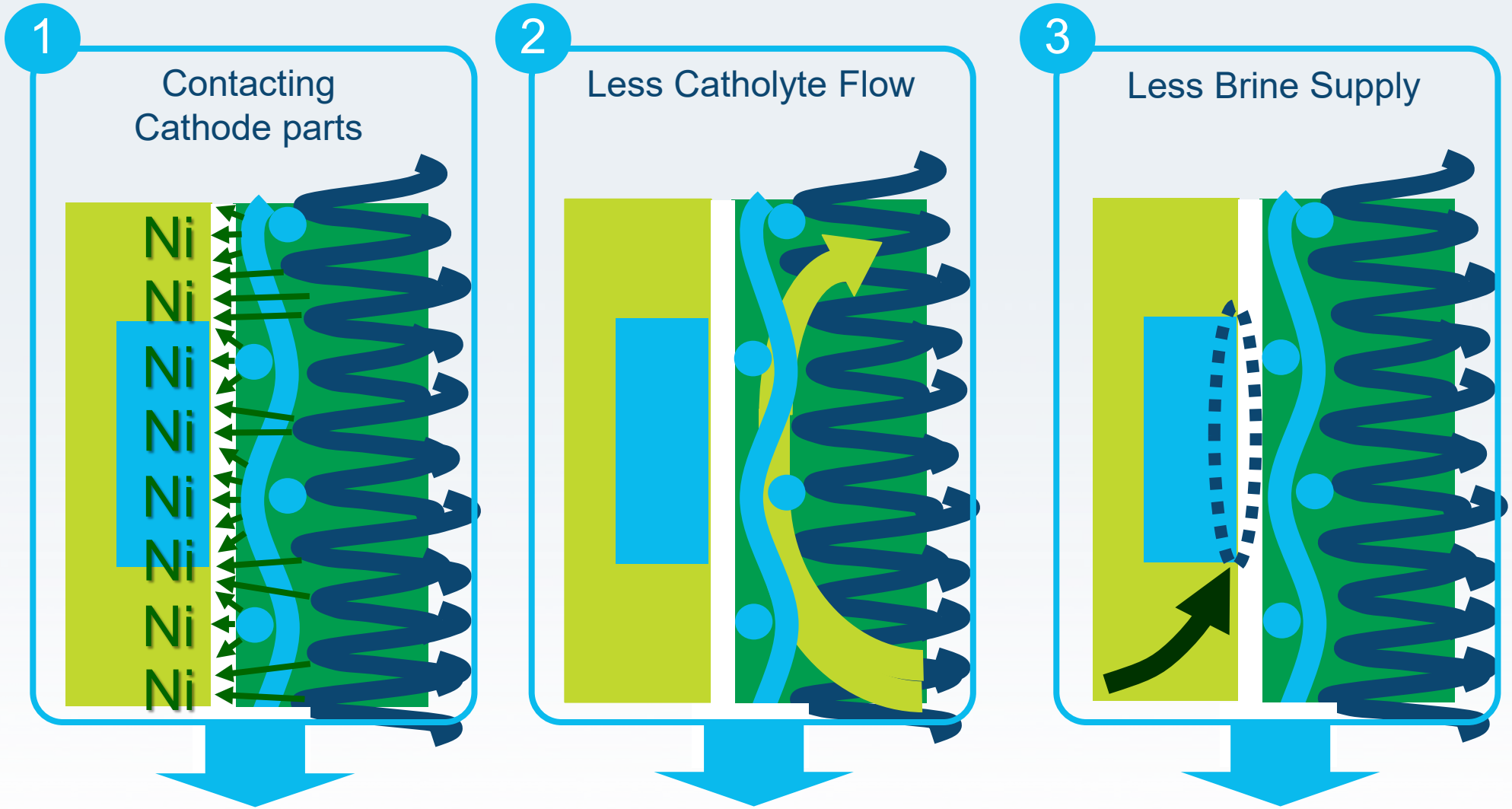
Zero Gap Electrolyzer

- Less Flow of Anolyte/Catholyte at Membrane Surface
- High Membrane Temperature
- Direct Contact with Cathode

Main Required Feature

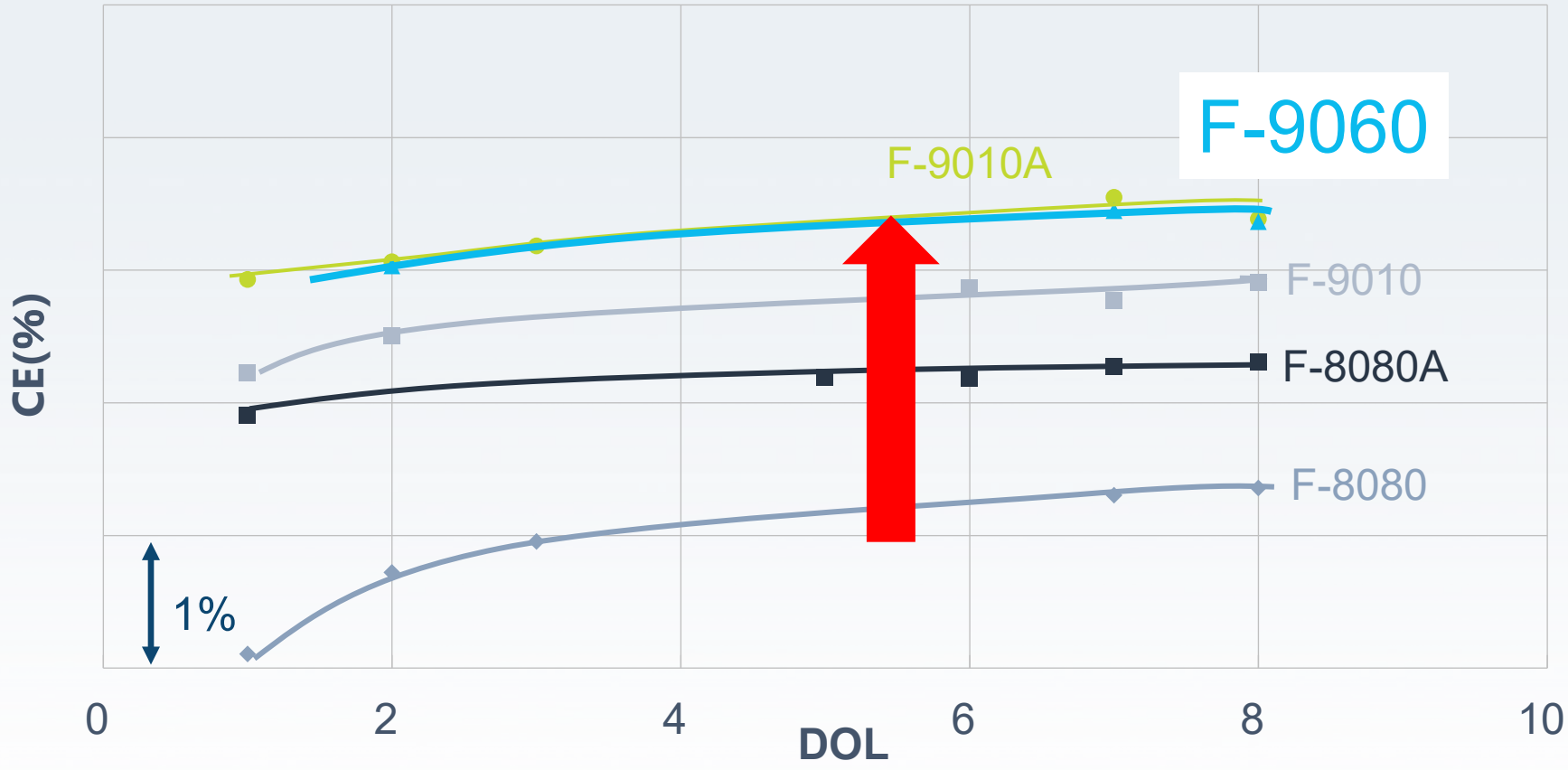
- Low Voltage
- High Durability against Brine Impurities
- Wider Operational Range
- High CE Stability in Zero Gap

“Zero Gap” Advantages



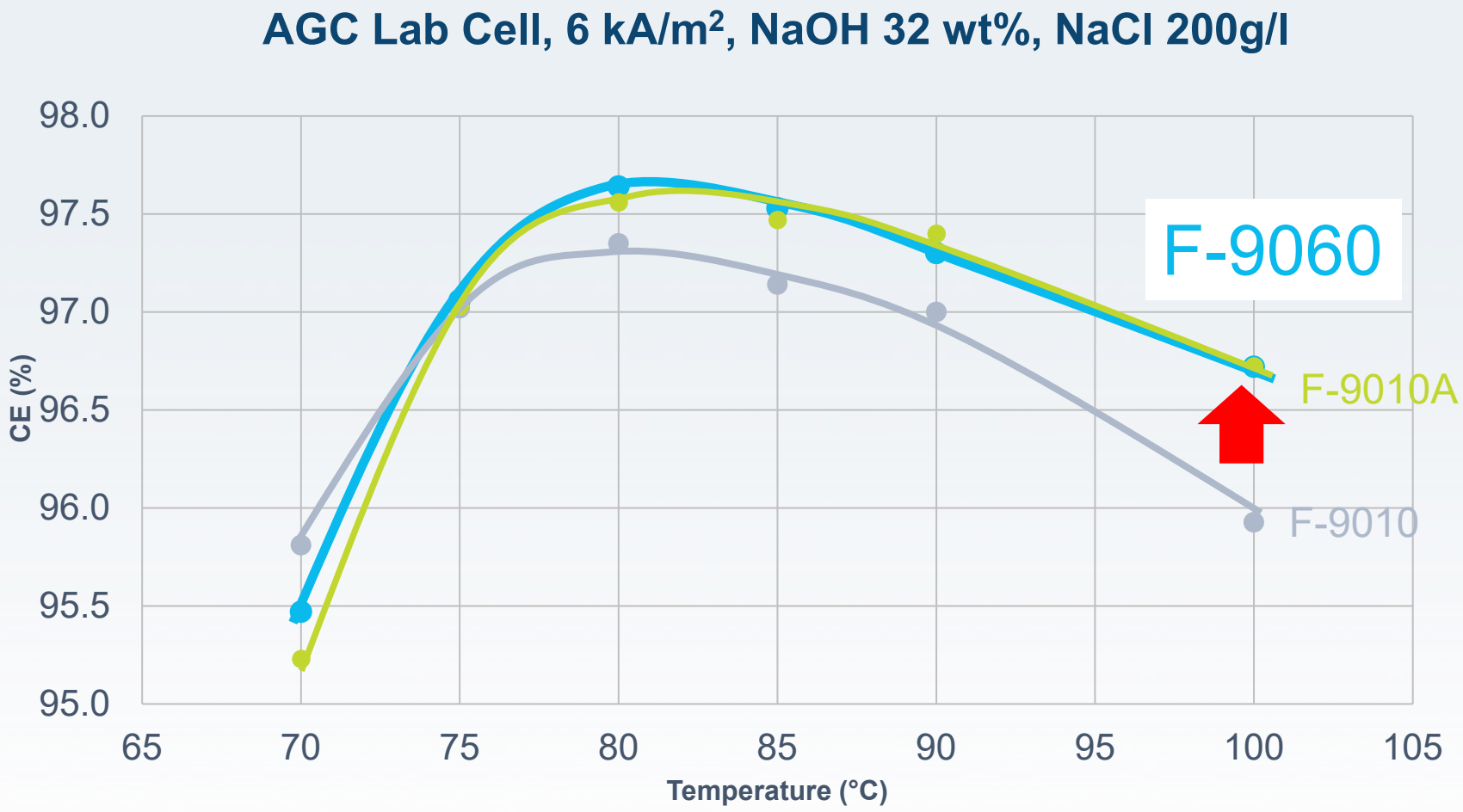
F-9060: Resistance to Ni Stain

Precondition ; Soaked in a Ni solution
AGC Lab Cell, 6 kA/m², 90ºC, NaOH 32 wt%, NaCl 200 g/l



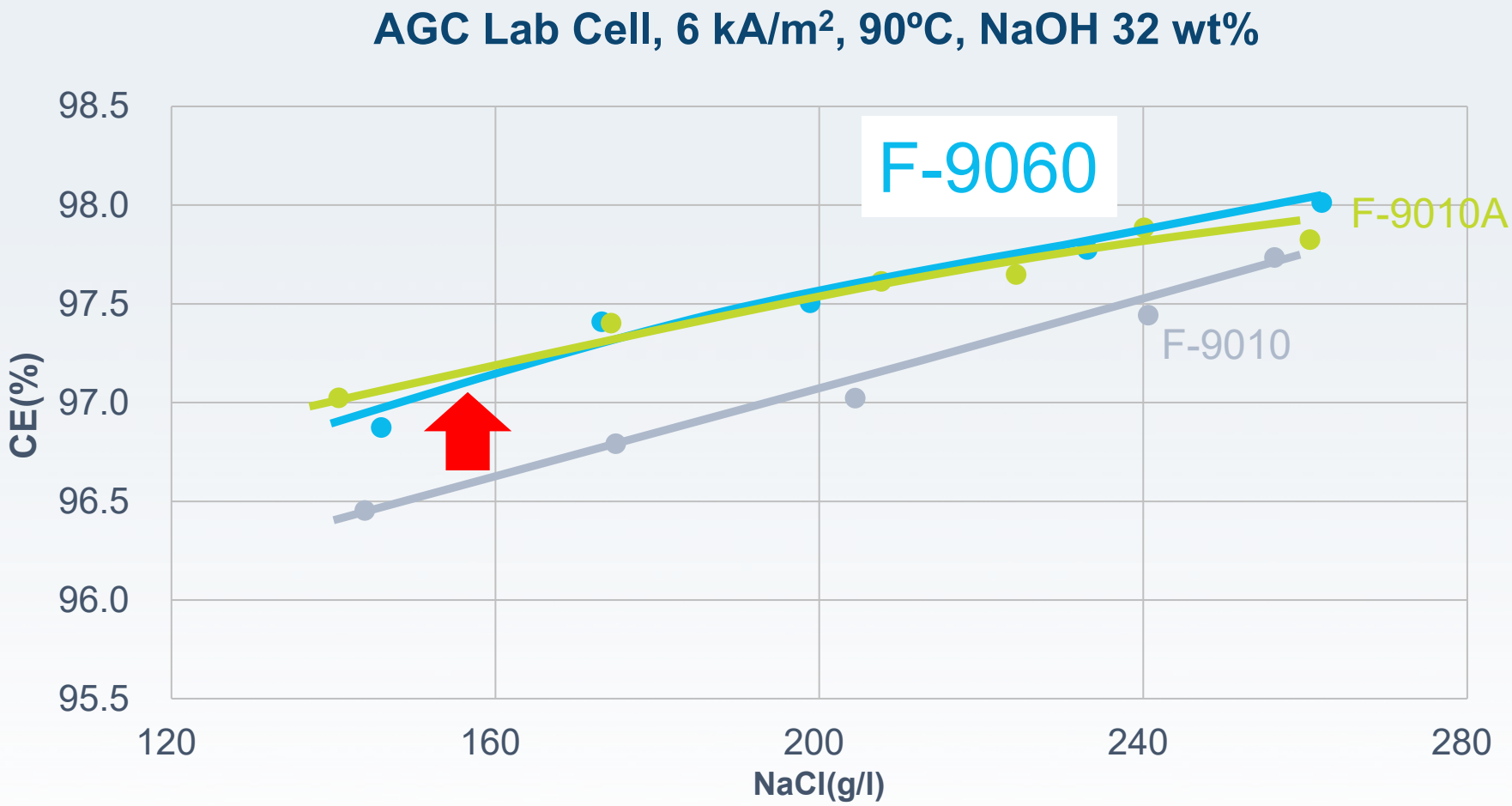
F-9060 shows the highest resistance to Ni stain

F-9060: Temperature Characteristic



F-9060 shows higher CE at higher temperature

F-9060: NaCl Concentration Characteristic

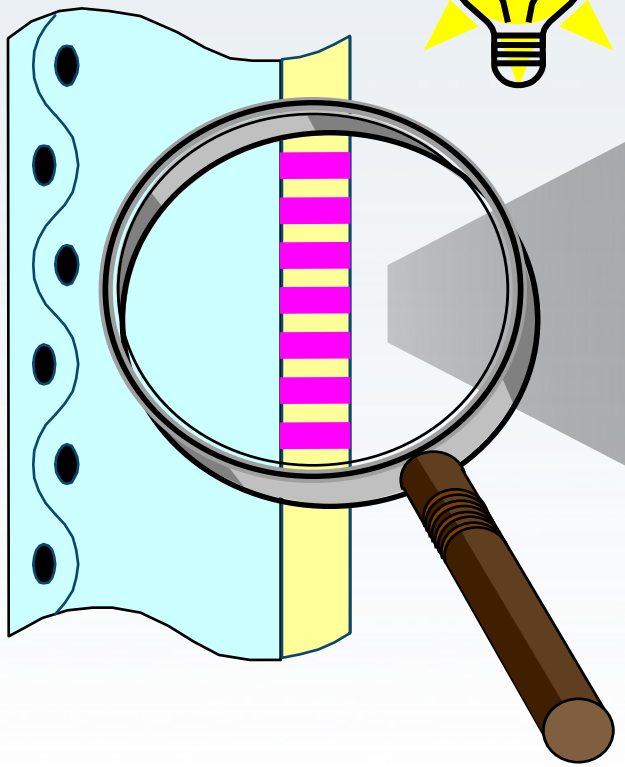


F-9060 shows higher CE in all brine concentration

Design of Uniform Ion Channel

F-9010

Breakthrough !



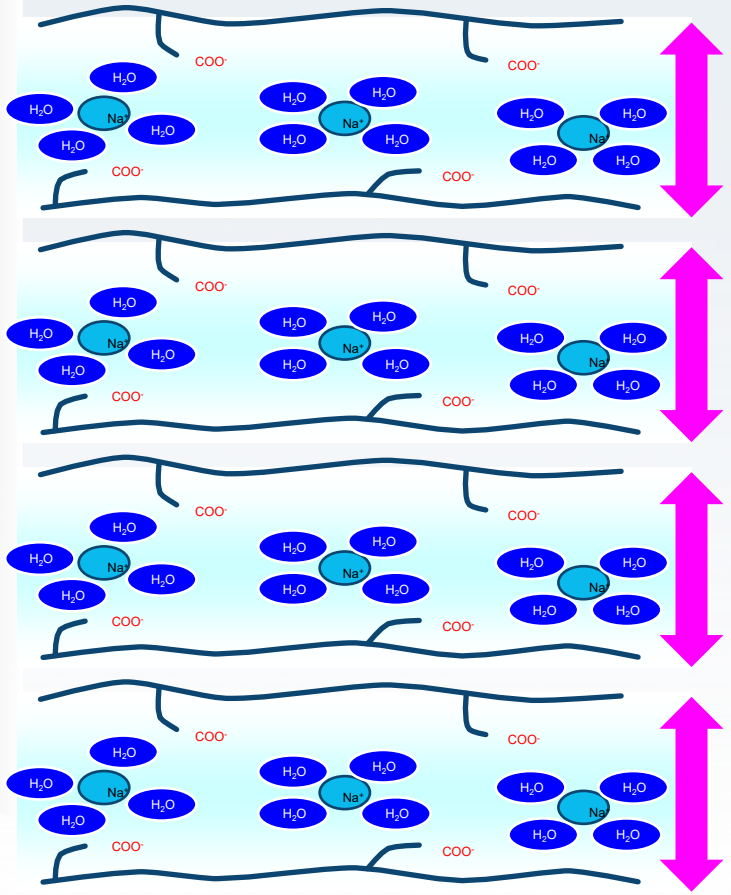
Uniform Ion Channel

Proper

Proper

Proper

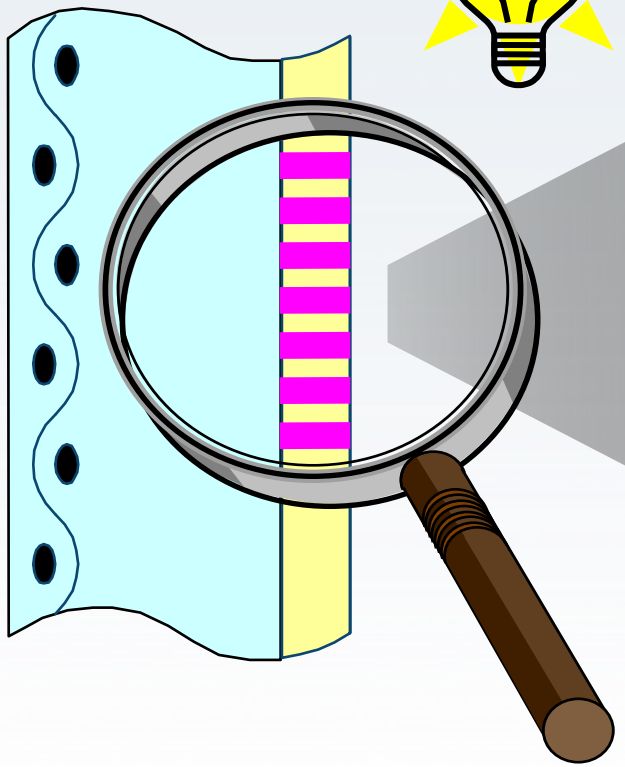
Proper



Further Improvement of Ion Channel

F-9060

Breakthrough !



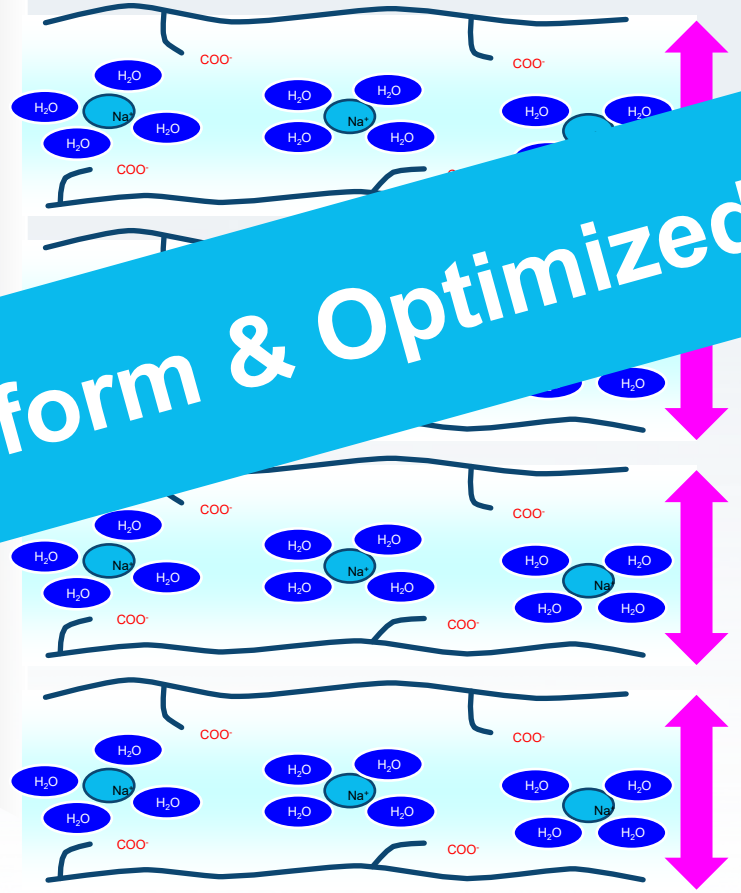
Uniform Ion Channel

Proper

Proper

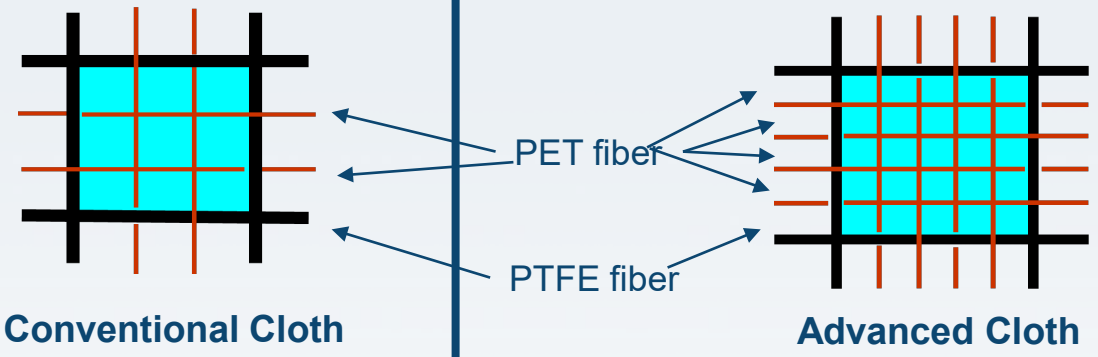
Proper

More Uniform & Optimized



Mechanical Strength

Reinforcement Cloth Type



		F-8080/F-8080A	F-9010/F-9010A	F-9060
		Conventional Cloth	Advanced Cloth	
Same Force Direction as Fiber	Tensile Strength	Approx. 45 N/cm	←	←
	Elongation	Approx. 40 %	←	←
45 Degree Force Direction for Fiber	Tensile Strength	Approx. 15 N/cm	←	←
	Elongation	Approx. 40 %	←	←

Concept of Next Generation Membrane F-9060

Keyword in Market

High Current Density Operation

- Increment of Cell Voltage
- Increment of Mass Flow
- Fluctuation of Anolyte and Catholyte Concentration

Zero Gap Electrolyzer

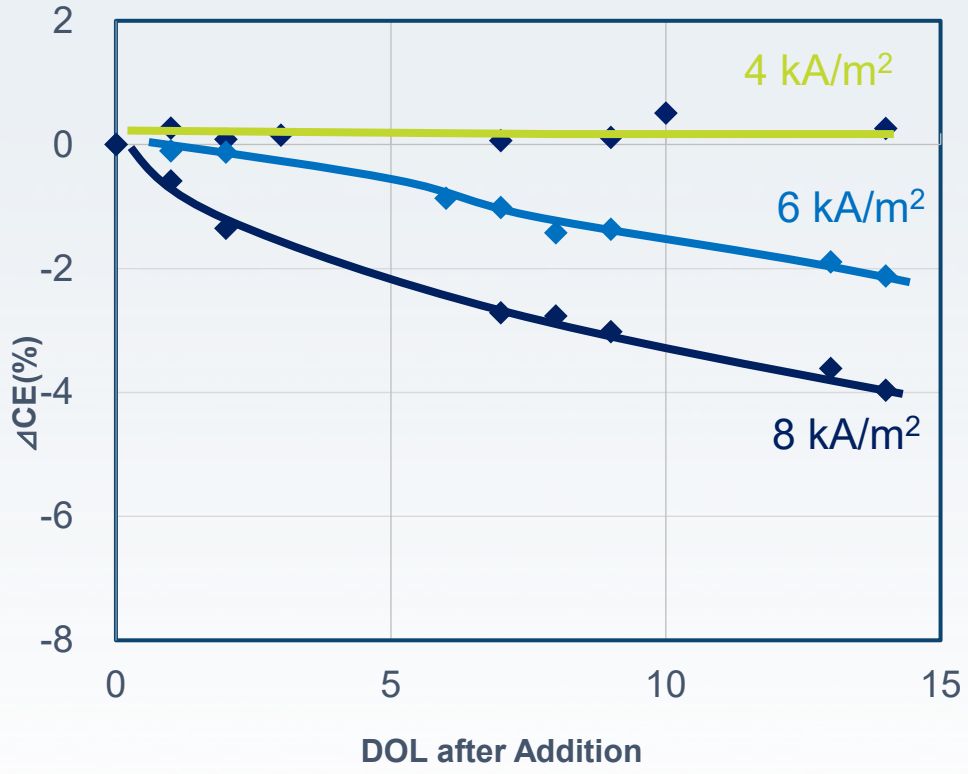
- Less Flow of Anolyte/Catholyte at Membrane Surface
- High Membrane Temperature
- Direct Contact with Cathode

Main Required Feature

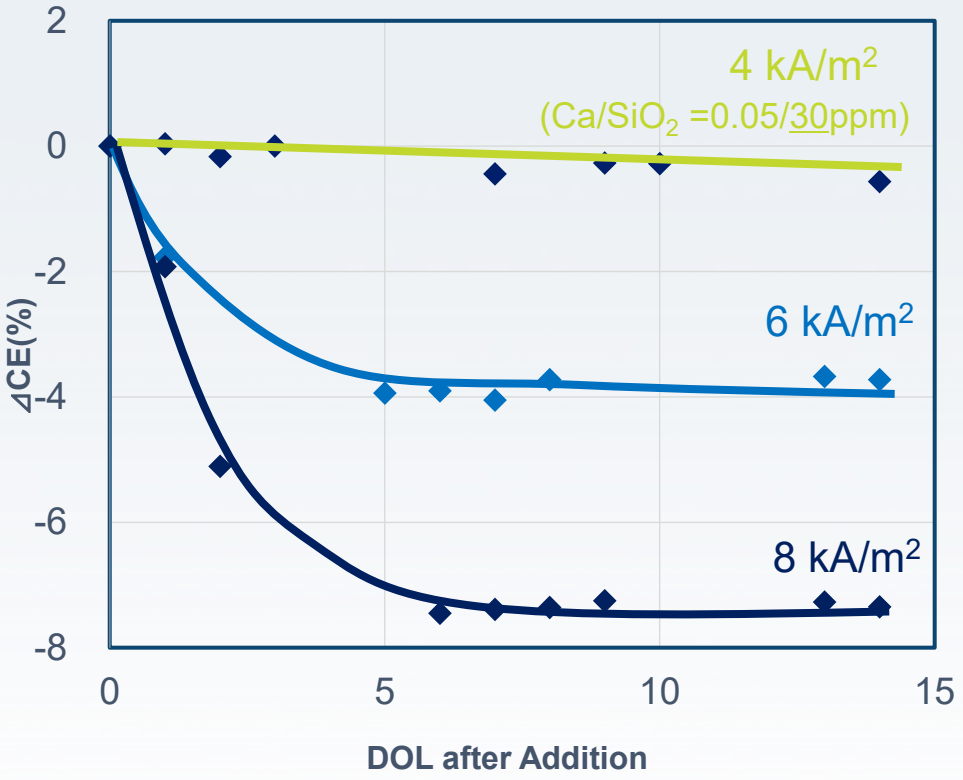
- Low Voltage
- High Durability against Brine Impurities
- Wider Operational Range
- High CE Stability in Zero Gap

Influence of Brine Impurities on Membrane

F-8080, I/Ba = 20/1ppm, 4-8 kA/m²
85ºC, NaOH 32 wt%, 200 g/l NaCl

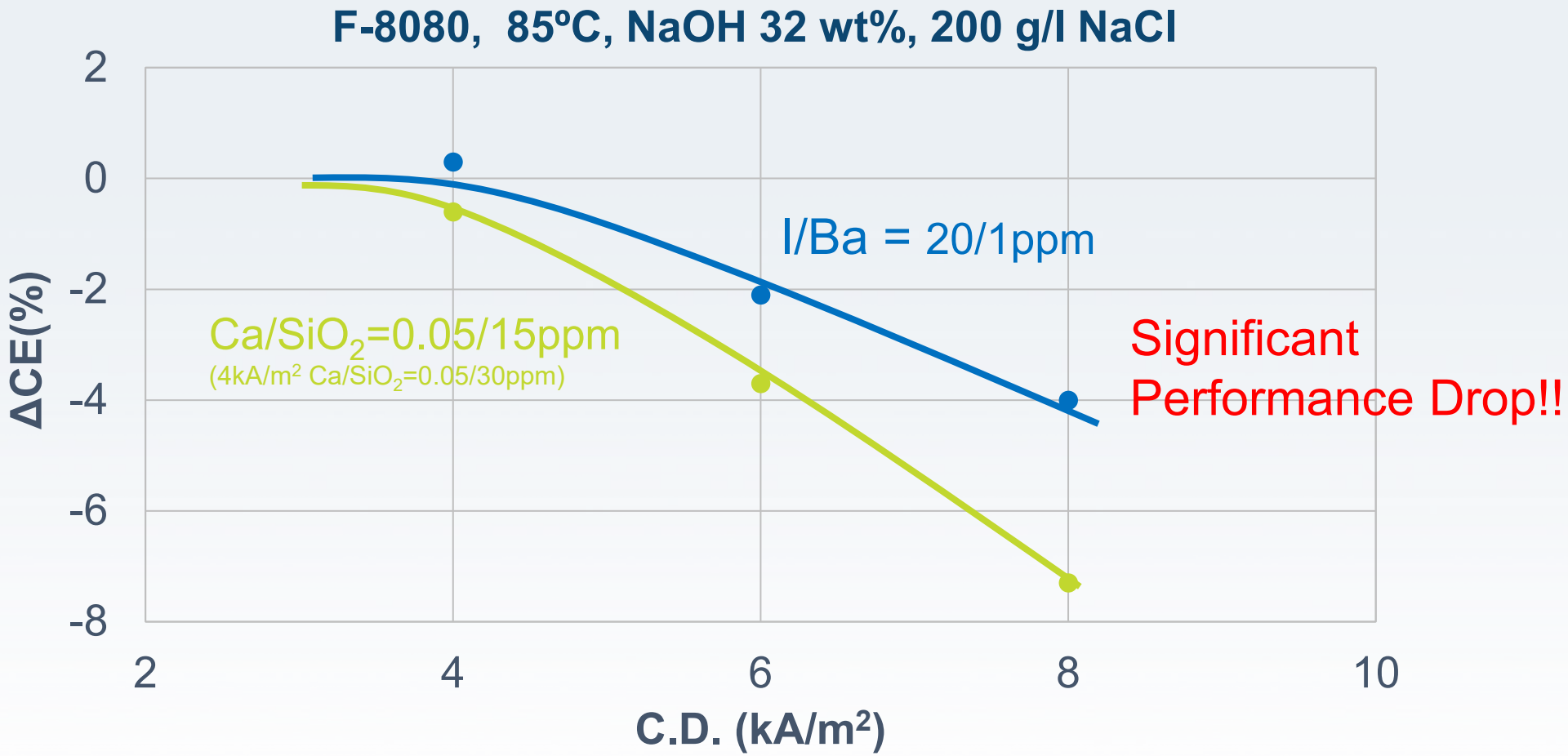


F-8080, Ca/SiO2= 0.05/15 ppm, 4-8 kA/m²
85ºC, NaOH 32 wt%, 200 g/l NaCl



High C.D. operation with impurities causes critical damage to membrane.

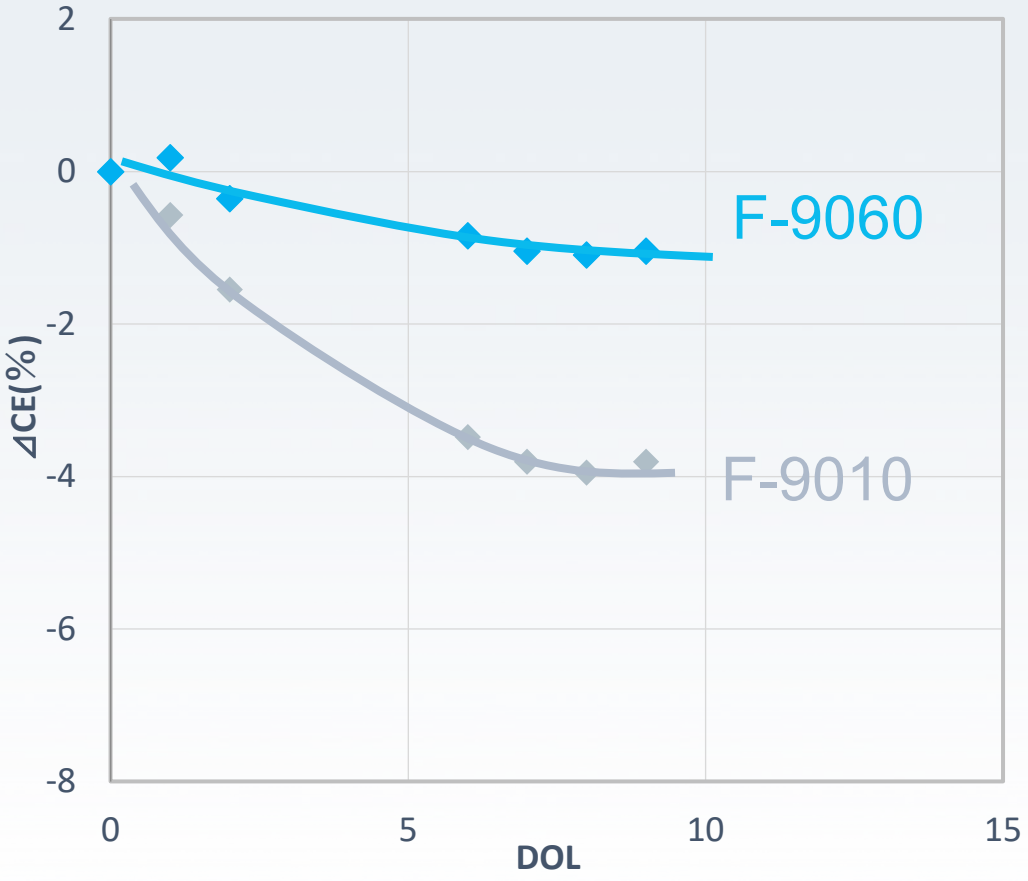
High C.D. Operation with Impurities is Critical Damage



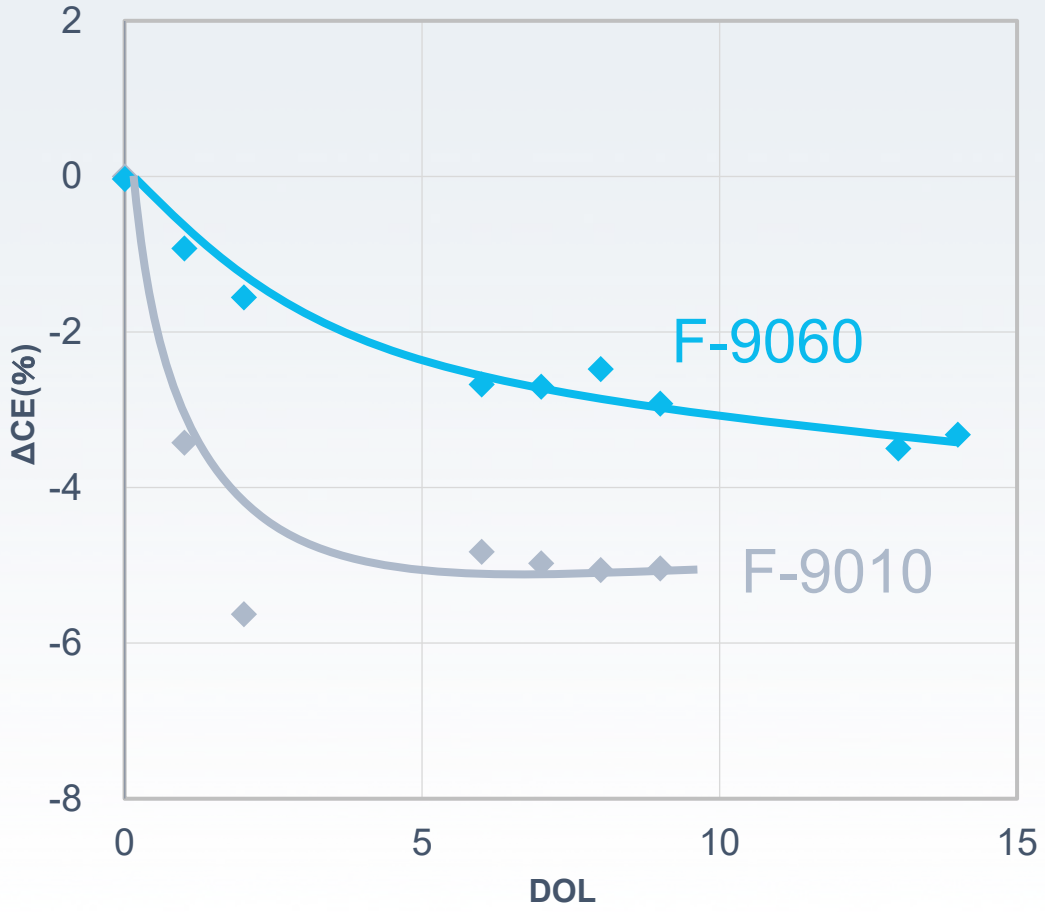
Durability against brine impurities is even more necessary for long-term performance stability under high current density.

Higher Durability against SiO_2 and Al/SiO_2

SiO_2 =50 ppm, 8 kA/m², 85ºC, NaOH 32 wt%

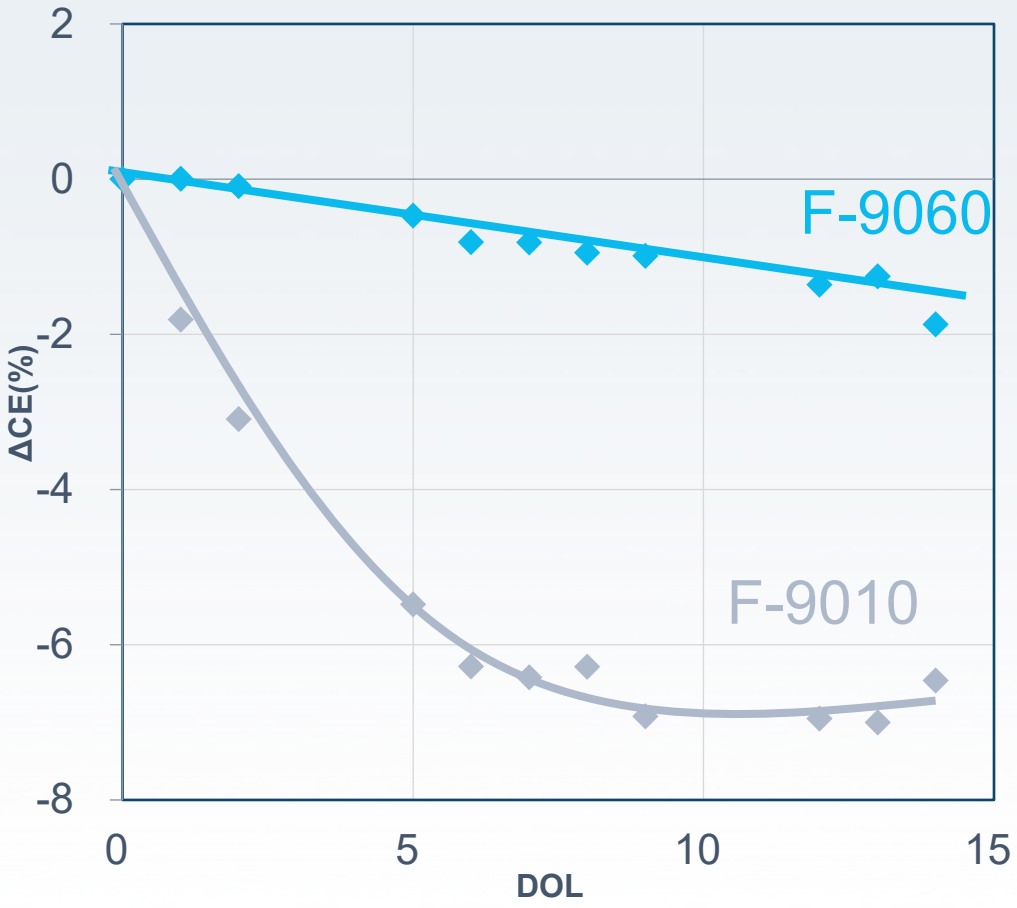


Ca/SiO_2 =0.05/15 ppm, 8 kA/m², 85ºC, NaOH 32 wt%

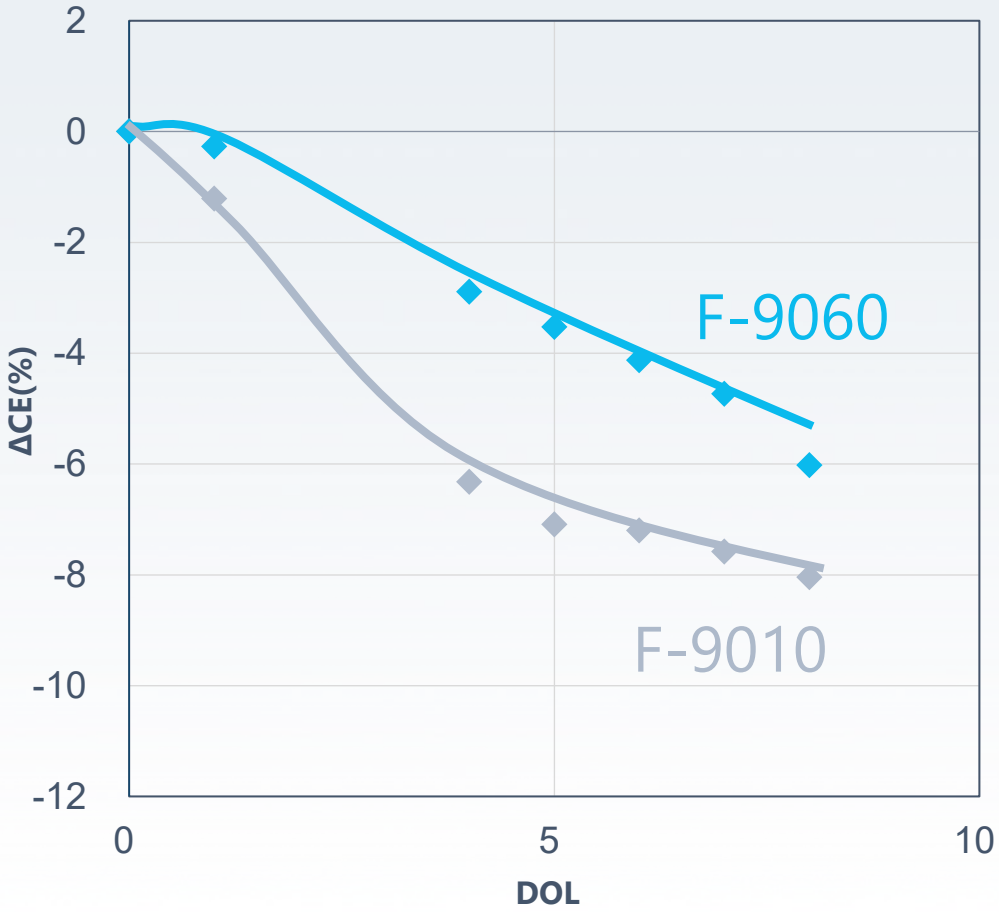


Higher Durability against Sr/SiO_2 and Ca/SiO_2

Sr/SiO_2 =1/30 ppm, 8 kA/m², 85ºC, NaOH 32 wt%

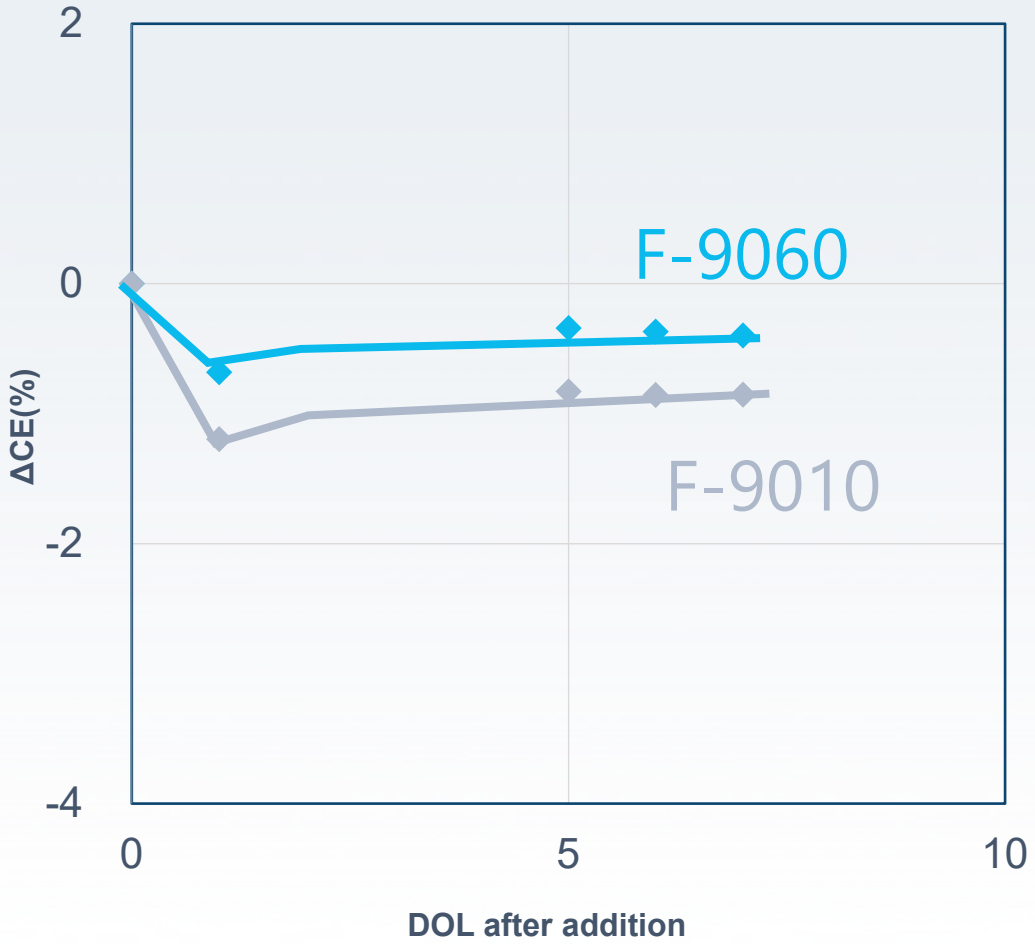


Al/SiO_2 =1/30 ppm, 8 kA/m², 85ºC, NaOH 32 wt%

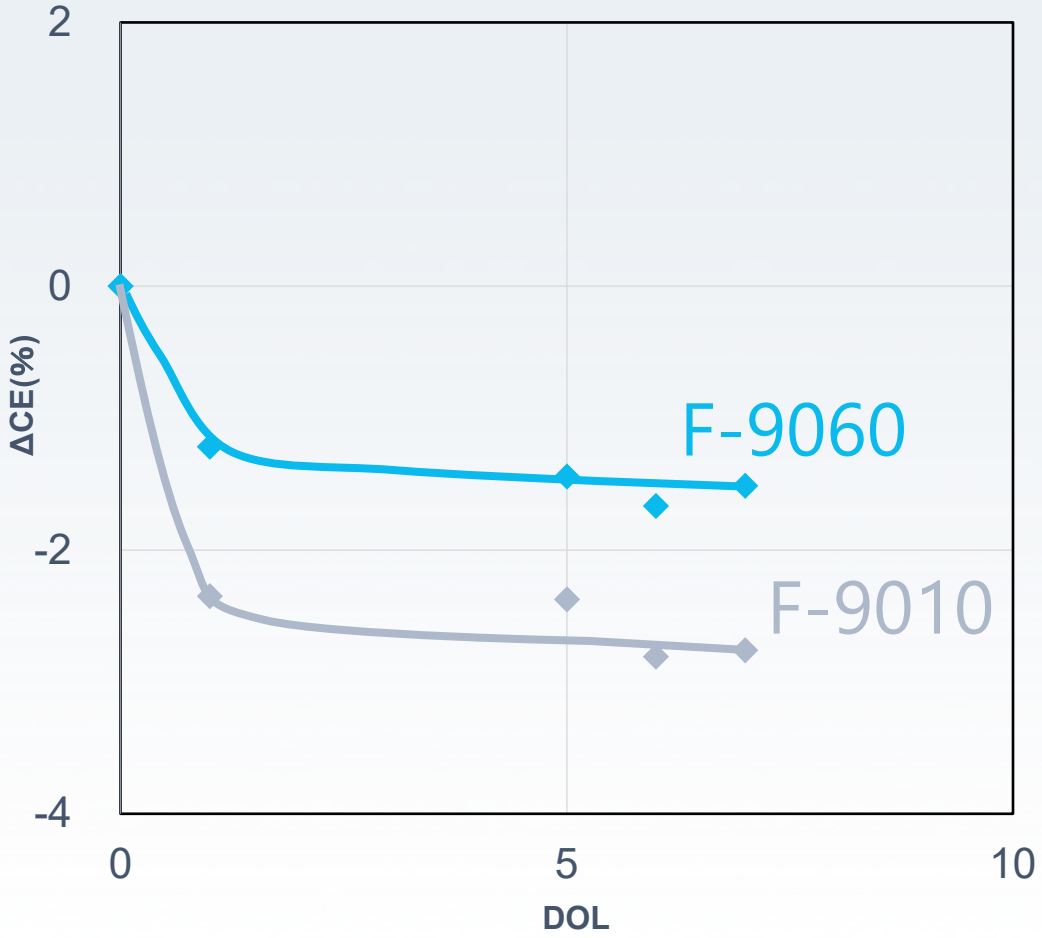


Higher Durability against Ca

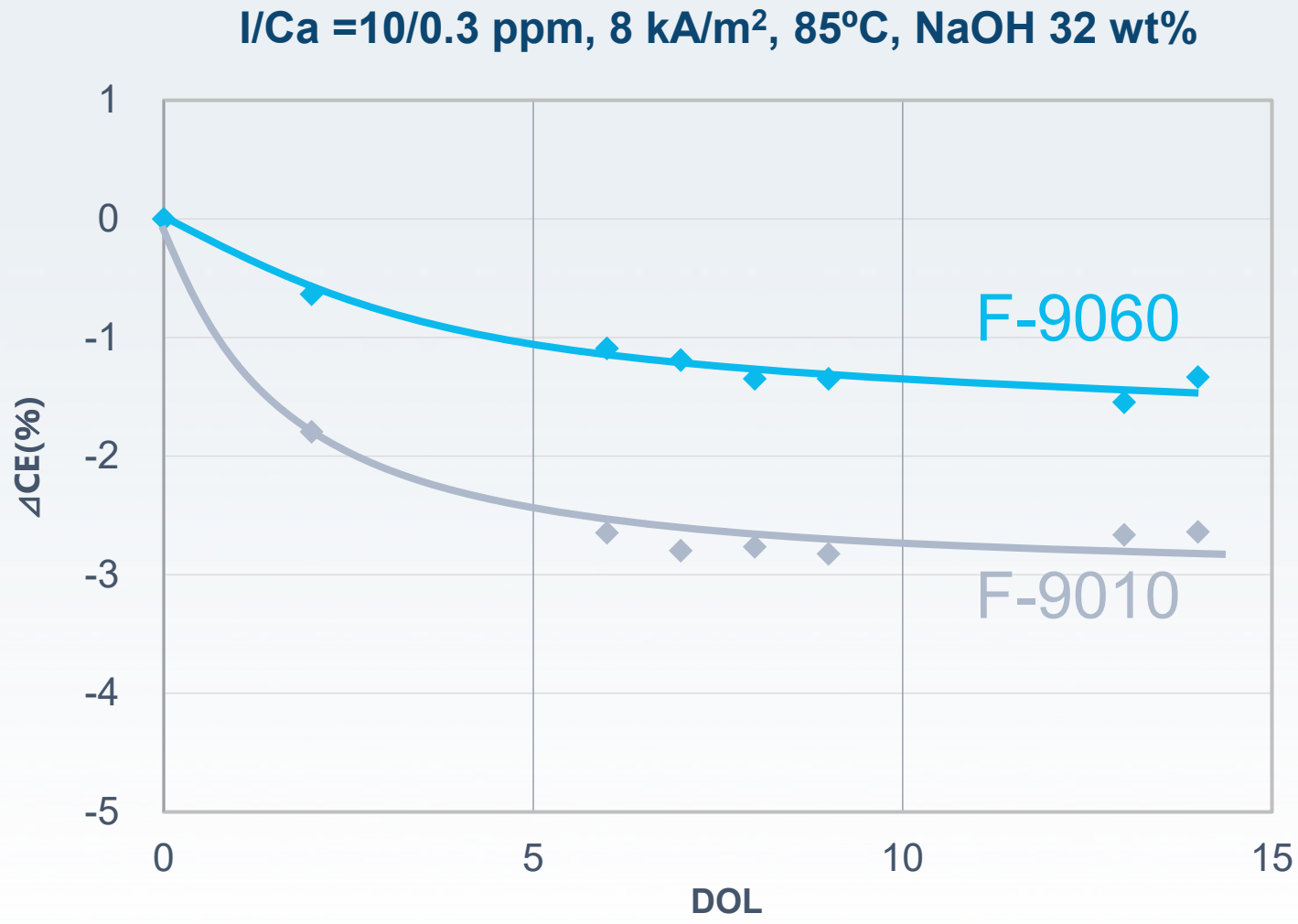
Ca = 0.5 ppm * 4 hr, 8 kA/m², 85ºC, NaOH 32wt%



Ca = 0.4 ppm * Continuous Addition, 6 kA/m², 85ºC, NaOH 32wt%

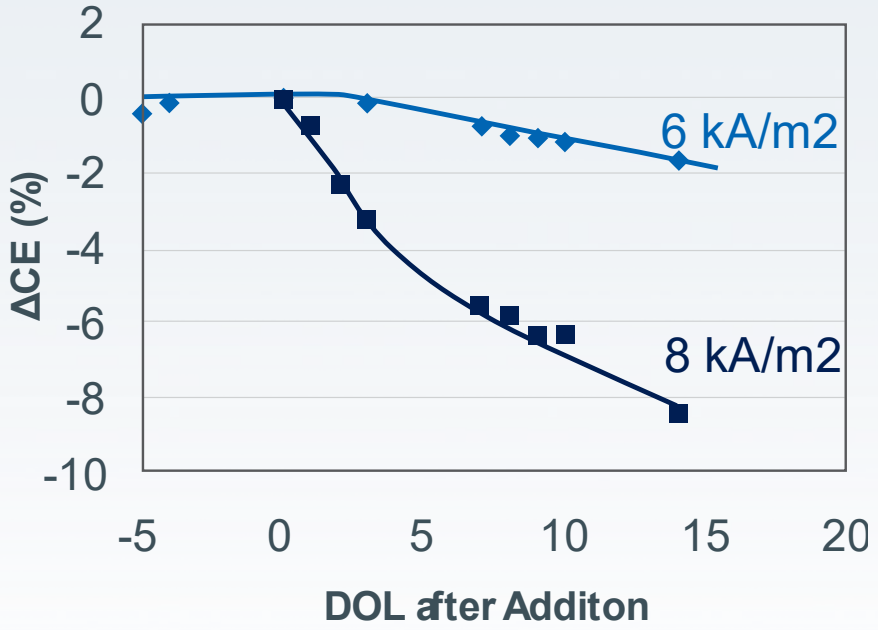


Higher Durability against I/Ca

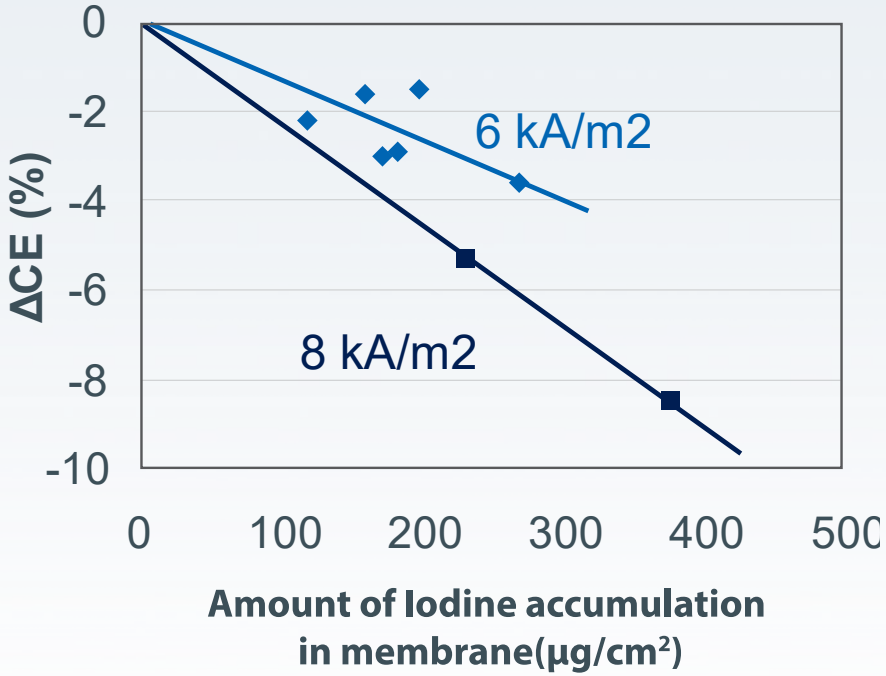


Why does impurity influence become more severe at High C.D.?

F-8080, AGC Lab Cell, 6-8 kA/m2, 80ºC,
32 wt% NaOH, 190 g/l NaCl, I/Ba = 20/1 ppm

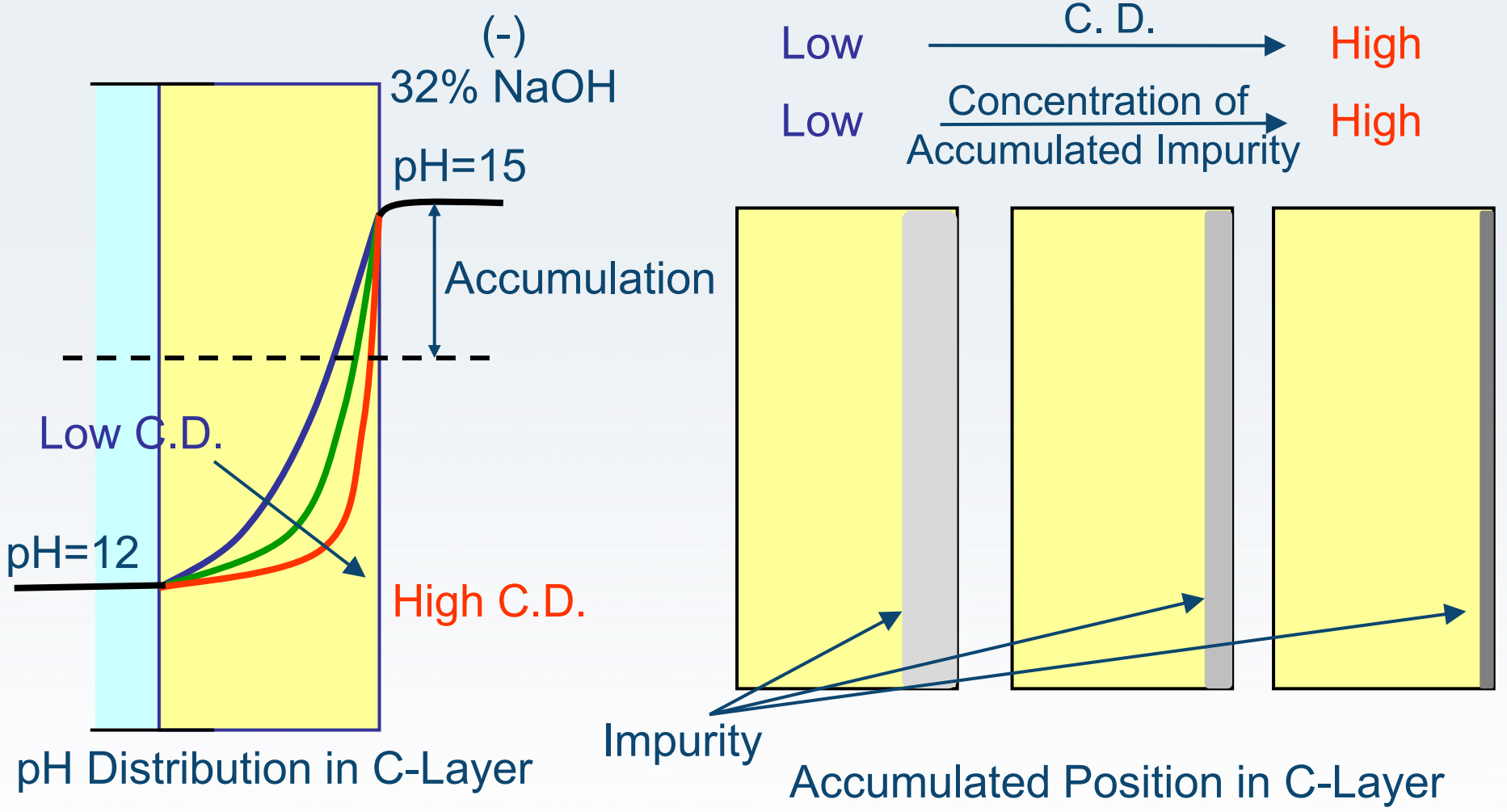


Analyze membranes after addition test



Durability against brine impurities is even more necessary for long-term performance stability under high current density.

Influence of C.D. on Accumulated Position



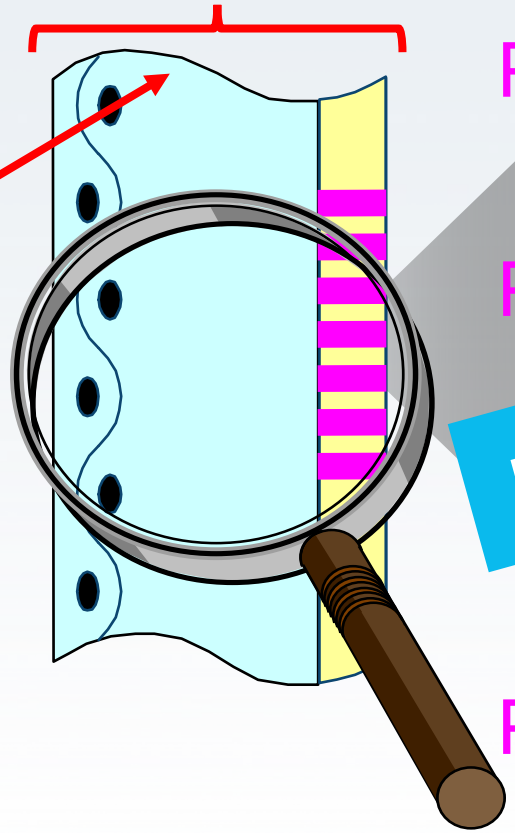
Accumulated impurity becomes more concentrated at high C.D.

Further Improve Durability against Brine Impurity

F-9060

New Ion Channel

Breakthrough !

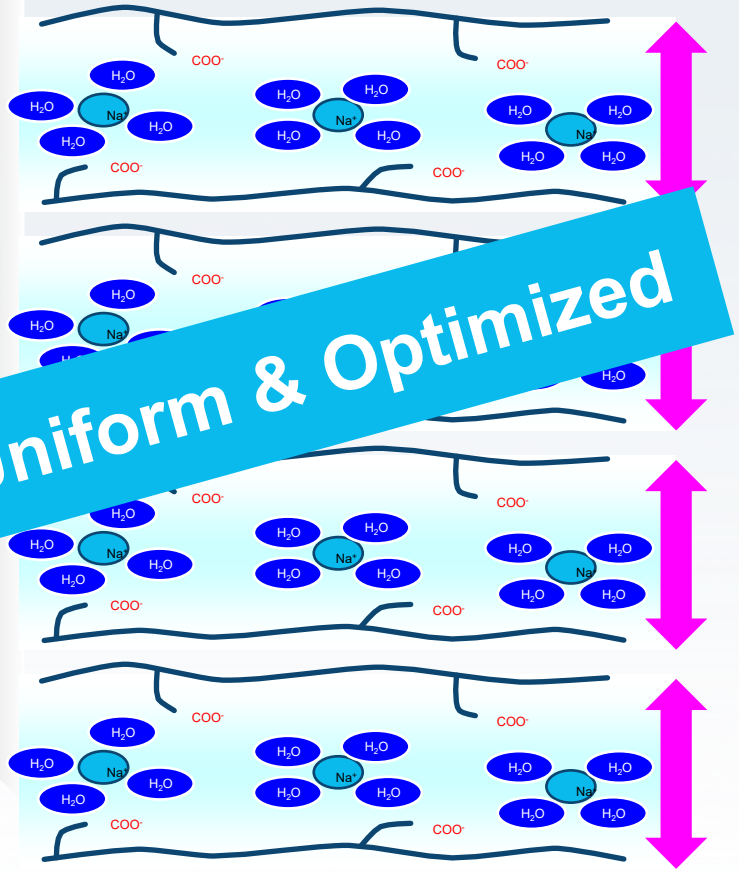


Proper

Proper

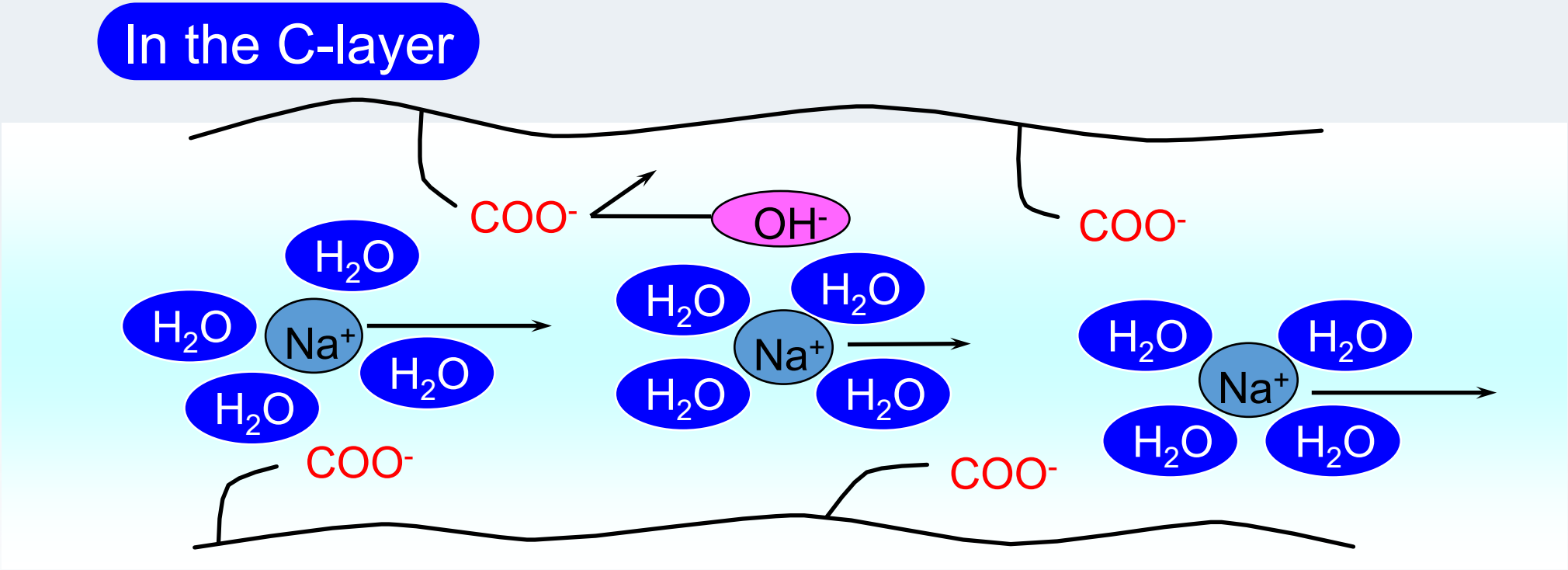
Proper

More Uniform & Optimized



New Layer Configuration also contributes to ion channel stability during impurity deposition.

Mechanism of High Current Efficiency

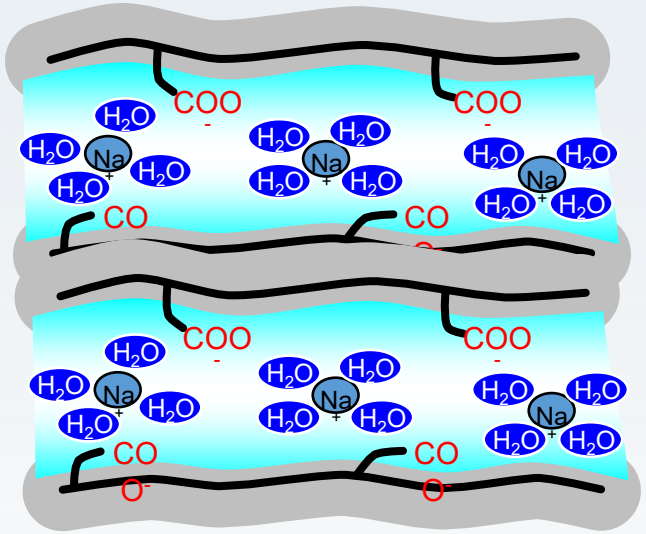


“Simple ion channel model” is useful for easy understanding!

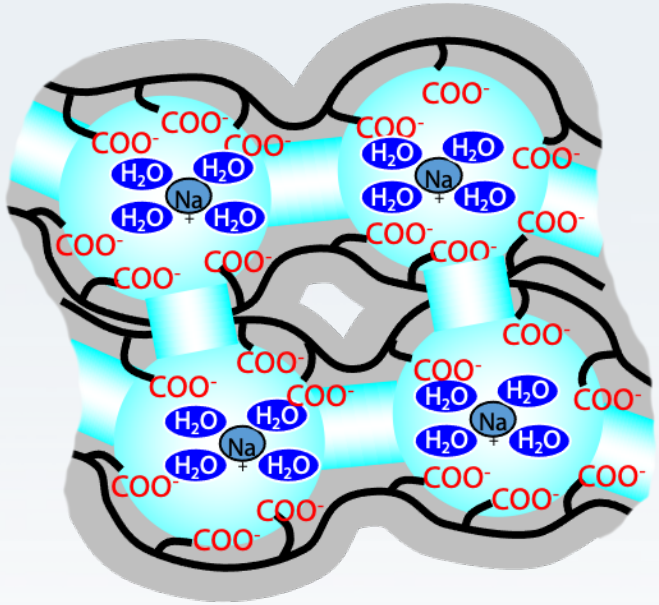
…But it’s not enough for deep understanding & membrane development!

Ion Channel Models

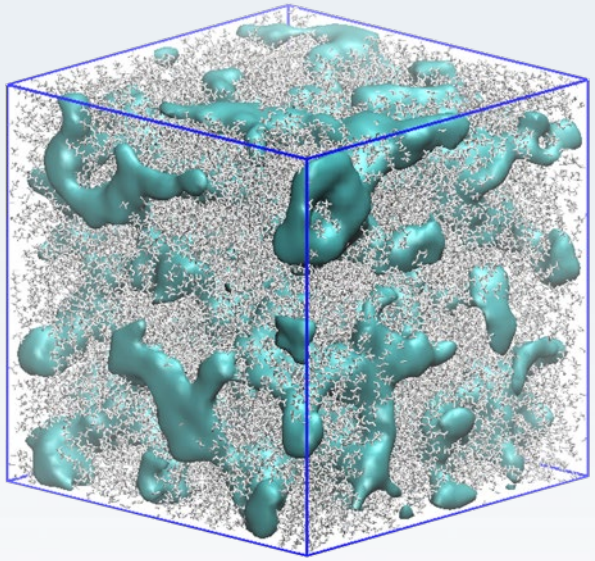
Simple ion channel model



Cluster network model
(It's a little complicated & classic)



Simulation model

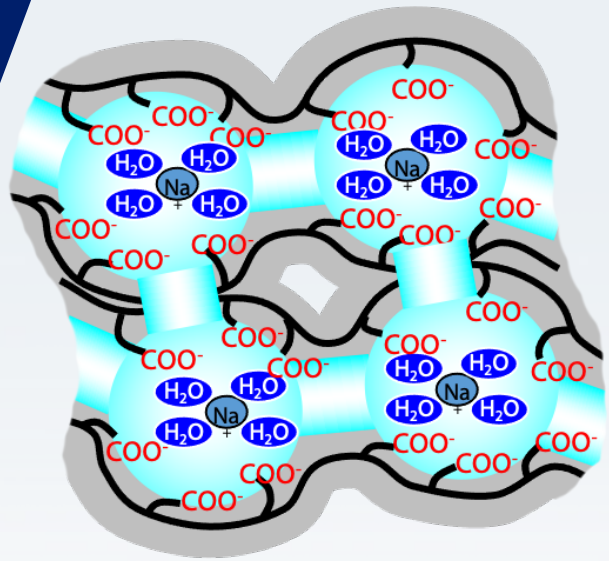


These models can be extended to 2D & 3D

Models on the right side are closer to reality

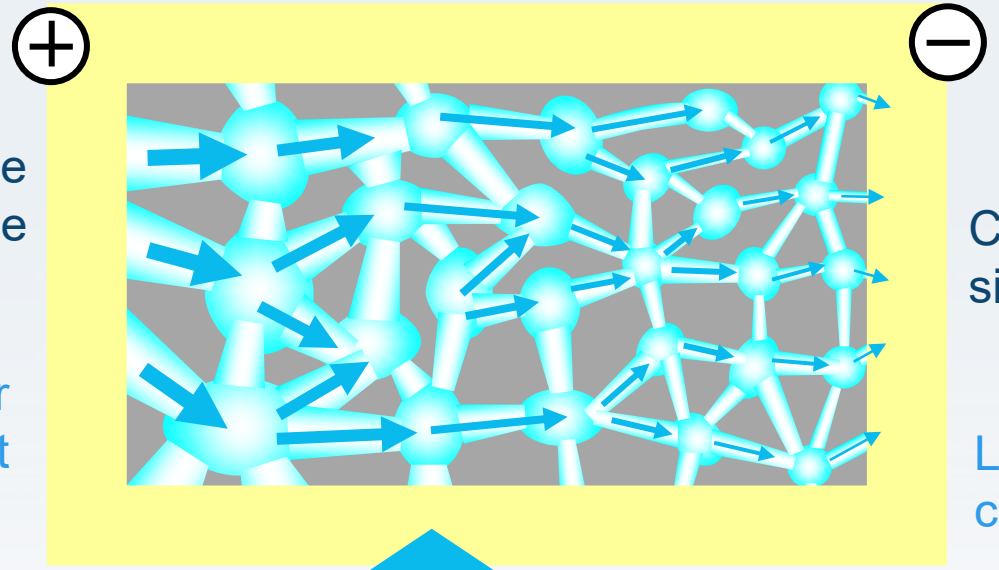
We studied many models, many tests, & many analyses

Further Improve Durability against Brine Impurity



Membrane inside

High water content



Cathode side surface

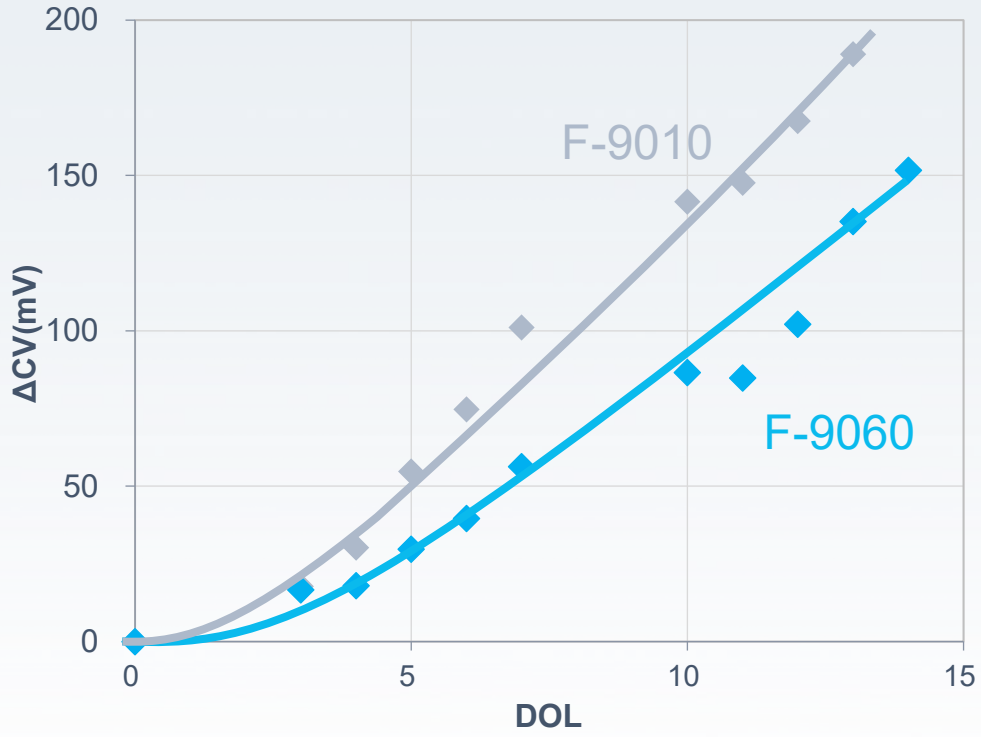
Low water content

Sulfonic polymer layer also influences cluster network of carboxylic polymer layer.

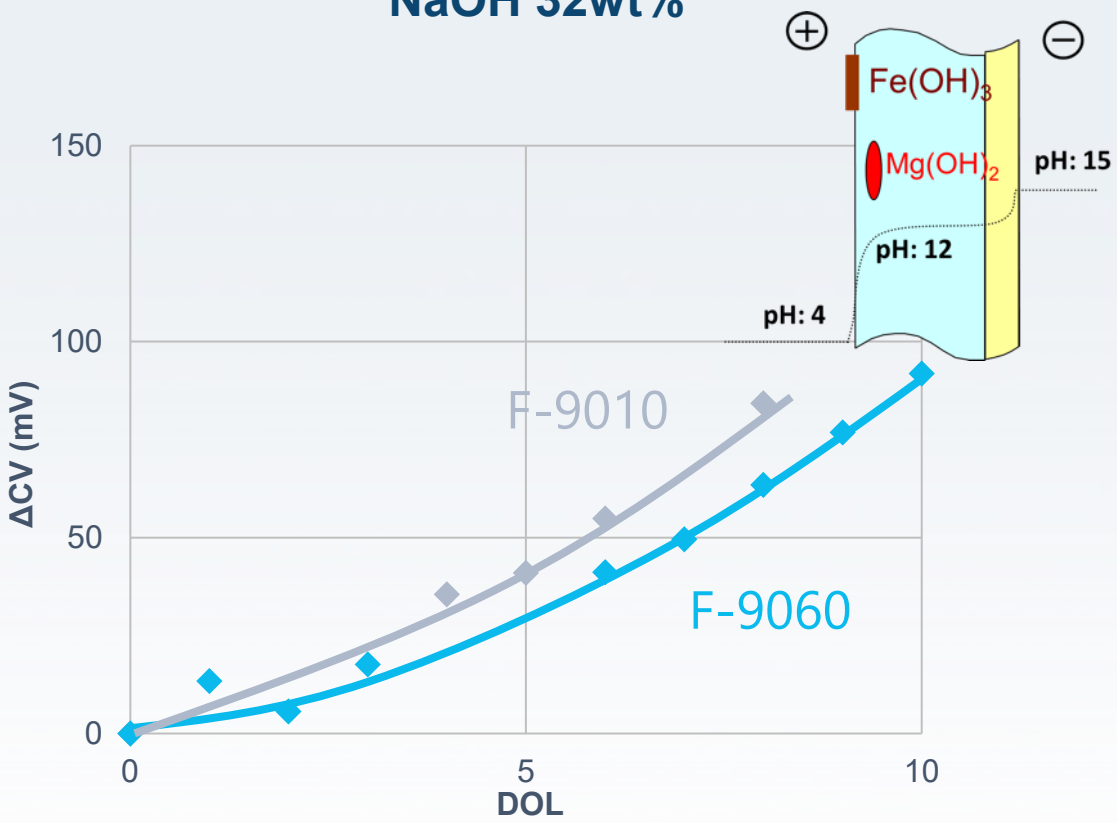
Optimization of cluster network by new layer configuration achieves further improvement of durability against brine impurities.

Higher Durability against Fe and Mg

Fe = 5 ppm, 8 kA/m², 85ºC, NaOH 32 wt%

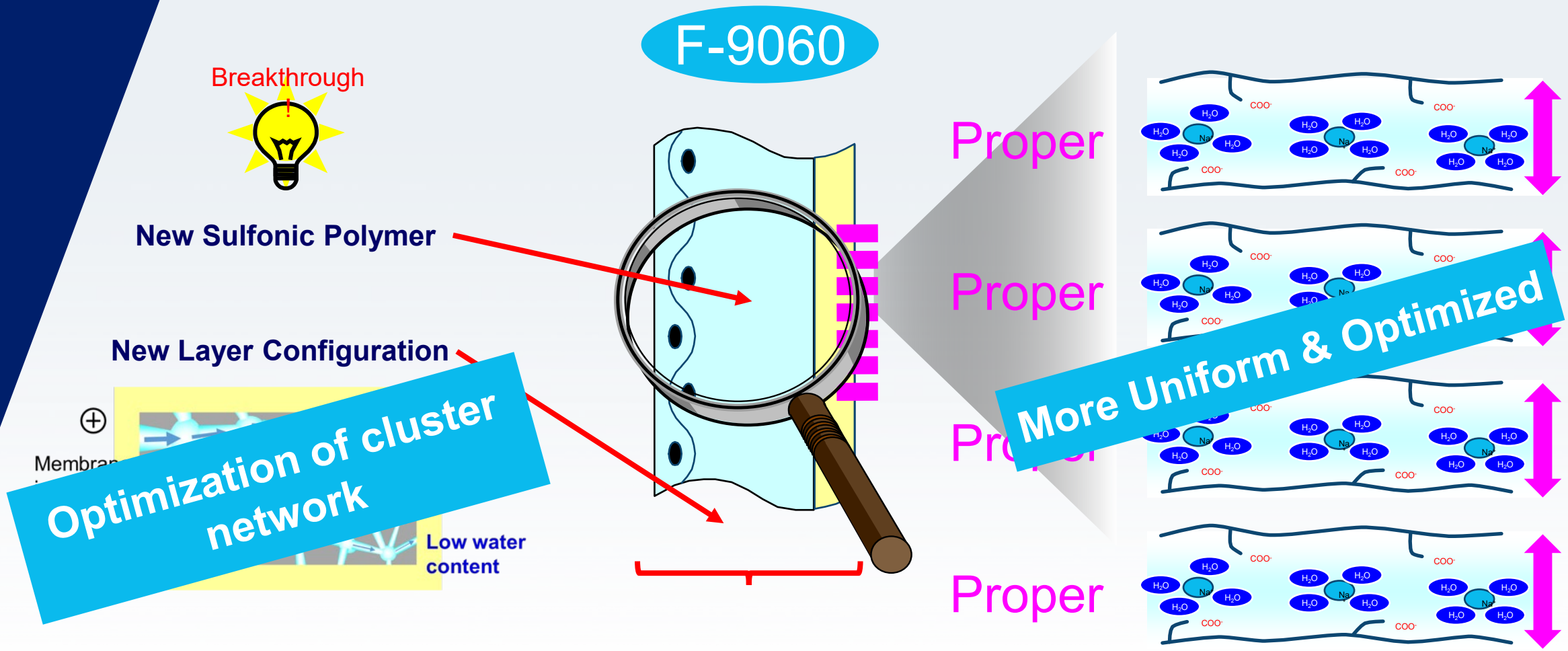


Mg=0.2 ppm, 8 kA/m², 85ºC, NaOH 32wt%



F-9060 also shows higher durability against Fe and Mg, which deposit in sulfonic layer.

Further Improve Durability against Brine Impurity



Next Generation Membrane: F-9060

1. Lowest voltage

- **40 mV lower voltage** than F-9010 at 6 kA/m^2
- Contributes to reducing not only electricity cost but also CO_2 emissions

2. Higher Durability against Brine Impurities

Based on deeply understanding the correlation between polymer and performance, we achieved further improvement of durability against many species of impurities.

3. Higher CE Stability in Zero Gap and Wider Operational Range

- Focusing three key influence factor of zero gap, we improved CE stability in zero gap
- Wider operational range in each current density, especially at higher temperature.

For More Information:

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