Introduction of FORBLUE™ FLEMION™ F-9060 Membrane

The World’s Lowest Voltage Membrane
FLEMION Continuous Development for Lower Voltage

Unit: mV at 6 kA/m²

2005  2010  2015  2020  2025

Voltage Reduction

F-8020SP  F-8080  F-8080A  F-9010A  F-9010  F-9060  -40mV
Voltage of F-9060 in AGC Commercial Plant

BM2.7v5, 5.8 kA/m², 85°C, 32 wt% NaOH, 210g/l NaCl

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

BM2.7v5, 5.8 kA/m², 85°C, 32 wt% NaOH, 210g/l NaCl

F-9060 also shows stable high CE.
## Table of Initial Performance in Laboratory Cell

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

<table>
<thead>
<tr>
<th></th>
<th>CE</th>
<th>ΔCV</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-8080</td>
<td>≥96.0</td>
<td>+50mV</td>
<td>Previous standard membrane</td>
</tr>
<tr>
<td>F-8080A</td>
<td>≥96.5</td>
<td>+50mV</td>
<td>Higher CE than F-8080 suitable for zero gap technology.</td>
</tr>
<tr>
<td>F-9010</td>
<td>≥96.8</td>
<td>0mV</td>
<td>Standard Membrane suitable for zero gap technology</td>
</tr>
<tr>
<td>F-9010A</td>
<td>≥97.0</td>
<td>+20mV</td>
<td>Higher CE than F-9010 with CV increase suitable for zero gap technology</td>
</tr>
<tr>
<td>F-9060</td>
<td>≥97.0</td>
<td>-40mV</td>
<td>the lowest voltage &amp; the highest CE suitable for zero gap technology</td>
</tr>
</tbody>
</table>

F-9060 has both the lowest voltage and the highest CE.
The voltage of F-9060 in commercial plant is almost as designed.
Impact of F-9060 on Electricity Cost Saving

Voltage

-40 mV

Compared with F-9010 at 6 kA/m²

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
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/m²

CO₂ 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-CO₂/kWh (US average)
ETS price: € 93.3 /t-CO₂, €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

<table>
<thead>
<tr>
<th>Keyword in Market</th>
<th>Main Required Features</th>
<th>Key Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rising Electricity Cost &amp; Decarbonization Society</td>
<td>Low Voltage</td>
<td><strong>New</strong> S-Polymer</td>
</tr>
<tr>
<td>High Current Density Operation</td>
<td>High Durability against Brine Impurities</td>
<td><strong>New</strong> Ion Channel</td>
</tr>
<tr>
<td>Zero Gap Electrolyzer</td>
<td>Wider Operational Range</td>
<td><strong>New</strong> Layer Configuration</td>
</tr>
<tr>
<td></td>
<td>High CE Stability in Zero Gap</td>
<td>Advanced Cloth (as well F-9010)</td>
</tr>
</tbody>
</table>

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 Sulfonic Polymer**
Low Voltage

**Advanced Cloth as F-9010**
Same Mechanical Strength

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

**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

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 Current Density

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

F-9010, AGC Lab Cell, 2 - 8 kA/m², 32 wt% NaOH, 200 g/l NaCl
### Change of Ion Channel Structure with Temp. and C.D.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion Channel Size</td>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
</tr>
<tr>
<td>Current Density</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Capacity Ion Flux</td>
<td><img src="image3" alt="Diagram" /></td>
<td><img src="image4" alt="Diagram" /></td>
</tr>
<tr>
<td>CE</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

Proper operating temperature that matches the ion flux leads to high CE.
Comparison of Operational Range between F-9060 and F-9010

AGC Lab Cell, 2 kA/m², 32 wt% NaOH, 200 g/l NaCl

Chart showing the comparison of CE (%) vs. Temperature (°C) for F-9060 and F-9010, with a manual range indicated.
Comparison of Operational Range between F-9060 and F-9010

AGC Lab Cell, 4 kA/m², 32 wt% NaOH, 200 g/l NaCl
Comparison of Operational Range between F-9060 and F-9010

AGC Lab Cell, 6 kA/m², 32 wt% NaOH, 200 g/l NaCl

Temperature (°C)

CE (%)
Comparison of Operational Range between F-9060 and F-9010

AGC Lab Cell, 8 kA/m², 32 wt% NaOH, 200 g/l NaCl

- F-9060: no manual range (manual max C.D. 7kA/m²)
- F-9010:
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

1. Contacting Cathode parts
   - Ni stain

2. Less Catholyte Flow
   - High Temperature

3. Less Brine Supply
   - Weak brine
F-9060: Resistance to Ni Stain

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

F-9060 shows the highest resistance to Ni stain
F-9060 shows higher CE at higher temperature

AGC Lab Cell, 6 kA/m², NaOH 32 wt%, NaCl 200g/l
F-9060 shows higher CE in all brine concentration.

AGC Lab Cell, 6 kA/m², 90°C, NaOH 32 wt%
Design of Uniform Ion Channel

Proper
Proper
Proper
Proper
Proper

Breakthrough!
Further Improvement of Ion Channel

F-9060

Breakthrough!

Uniform Ion Channel

More Uniform & Optimized

Proper

Proper

Proper

Proper
## Mechanical Strength

### Reinforcement Cloth Type

<table>
<thead>
<tr>
<th></th>
<th>F-8080/F-8080A</th>
<th>F-9010/F-9010A</th>
<th>F-9060</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conventional Cloth</strong></td>
<td><img src="chart.png" alt="Diagram" /></td>
<td><img src="chart.png" alt="Diagram" /></td>
<td><img src="chart.png" alt="Diagram" /></td>
</tr>
<tr>
<td><strong>Advanced Cloth</strong></td>
<td><img src="chart.png" alt="Diagram" /></td>
<td><img src="chart.png" alt="Diagram" /></td>
<td><img src="chart.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reinforcement Cloth Type</th>
<th>Tensile Strength</th>
<th>Elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Same Force Direction as Fiber</td>
<td>Approx. 45 N/cm</td>
<td>Approx. 40 %</td>
</tr>
<tr>
<td>45 Degree Force Direction for Fiber</td>
<td>Approx. 15 N/cm</td>
<td>Approx. 40 %</td>
</tr>
</tbody>
</table>

- **PET fiber**
- **PTFE fiber**

- **Mechanical Properties**
  - **Approx. 45 N/cm**
  - **Approx. 40 %**

- **Reinforcement Cloth Types**
  - **Conventional Cloth**
  - **Advanced Cloth**
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

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.

F-8080, 85°C, NaOH 32 wt%, 200 g/l NaCl

I/Ba = 20/1ppm
Ca/SiO$_2$ = 0.05/15ppm
(4kA/m$^2$, Ca/SiO$_2$ = 0.05/30ppm)

ΔCE(%)

C.D. (kA/m$^2$)

Significant Performance Drop!!
Higher Durability against SiO$_2$ and Al/SiO$_2$

SiO$_2$ = 50 ppm, 8 kA/m$^2$, 85°C, NaOH 32 wt%  

Ca/SiO$_2$ = 0.05/15 ppm, 8 kA/m$^2$, 85°C, NaOH 32 wt%
Higher Durability against Sr/SiO$_2$ and Ca/SiO$_2$

Sr/SiO$_2$ = 1/30 ppm, 8 kA/m$^2$, 85ºC, NaOH 32 wt%

Al/SiO$_2$ = 1/30 ppm, 8 kA/m$^2$, 85ºC, NaOH 32 wt%

![Graphs showing ΔCE(%) vs. DOL for F-9060 and F-9010 for Sr/SiO$_2$ and Al/SiO$_2$.](image-url)
Higher Durability against Ca

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

Ca = 0.4 ppm * Continuous Addition, 6 kA/m², 85°C, NaOH 32wt%
Higher Durability against I/Ca

I/Ca = 10/0.3 ppm, 8 kA/m², 85°C, NaOH 32 wt%
Why does impurity influence become more severe at High C.D.?

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

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

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

Breakthrough!

Proper

F-9060

New Ion Channel

More Uniform & Optimized
Mechanism of High Current Efficiency

In the C-layer

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

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

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

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

Membrane inside

High water content

Cathode side surface

Low water content
Higher Durability against Fe and Mg

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

Mg = 0.2 ppm, 8 kA/m², 85°C, NaOH 32 wt%

F-9060 also shows higher durability against Fe and Mg, which deposit in sulfonic layer.
Further Improve Durability against Brine Impurity

New Sulfonic Polymer

New Layer Configuration

Optimization of cluster network

Low water content

Proper

Proper

Proper

Proper

More Uniform & Optimized

F-9060

Breakthrough

COO$^-$

H$_2$O

COO$^-$

H$_2$O

Na$^+$

H$_2$O

Na$^+$

H$_2$O
1. Lowest voltage
   - 40 mV lower voltage than F-9010 at 6 kA/m²
   - Contributes to reducing not only electricity cost but also CO₂ 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:

Katie Jarvis
katie.jarvis@agc.com