BATTERY SOLUTIONS WITH KYNAR® PVDF

LITHIUM-ION FOCUS
By 2025, the world will manufacture 8 billion Li-ion cells.

Continued market growth requires rapid advances in higher energy density, higher performance at elevated temperatures, improved binder adhesion, easier processing, safety, and reductions in VOC emissions.

The world is becoming more extreme™.
ARKEMA OVERVIEW

PARTS OF THE LIB

FUTURE INNOVATIONS

FOCUS ON BINDER
INTEGRATED FROM THE MINE TO POLYMERIZATION

#1 PRODUCER OF PVDF SINCE 1963

KYNAR® FLUOROPOLYMER BATTERY SOLUTIONS
KYNAR® PVDF GLOBAL FOOTPRINT

- Calvert City
- CERDATO
- Changshu
- King of Prussia
- Global Battery Innovation Center
- Manufacturing Facility
- Regional Support Center
- South Korea
- Kyoto/KTC
- CRDC

KYNAR® FLUOROPOLYMER BATTERY SOLUTIONS
ARKEMA APPROACH TO SUPPORT & DEVELOPMENT

BATTERY EXPERTS
Industry
National Labs
Materials Suppliers
Universities

EXPERTISE
- Molecular Design
- Synthesis
- Polymer Analytics

IN-HOUSE SKILLS
- Solution Properties
- Slurry Properties
- Electrode Fabrication
- Coin Cell Performance

CAPABILITIES
- Scale Up
- Pilot Production
- Plant Evaluation

INTEGRATED INNOVATION CENTER ➔ REGIONAL SUPPORT IN USA, FRANCE, CHINA, KOREA, JAPAN ➔ QUICK TURNAROUND

KYNAR® FLUOROPOLYMER BATTERY SOLUTIONS
AN EXAMPLE OF OUR APPROACH

Test Conditions
Cycle 1-4: formation at 0.1-0.2C
Cycle 5-20: C-rate test at 0.1, 0.2, 0.5, 1, 2, 5, 10, 20C
Cycle 21-60: cycle at 0.5C
All test at room temperature ~20°C,
CR2032 half cells.

Reduced binder loading similar cycling
WHERE IS KYNAR® PVDF USED?

- LFP, LCO, NMC
- Graphite
- Lithium ion
- Electrolyte
- Separator
- Kynar® PVDF
  - Separator Coating
  - Safety & high voltage
- Anode
- Cathode

Kynar® PVDF
- High adhesion Binder
- High energy density
- High Voltage
MAIN BATTERY SEGMENTS

**Consumer Electronics**
- Longer Cycling
- Shorter Charging

**Electric Vehicles**
- High Safety
- Longer Lifetime

**Grid Energy Storage**
- Thermal Stability
- Faster Charge & Discharge Rates

**Power Tools**
- Higher Power
- Faster Charge Rate
ARKEMA OVERVIEW

PARTS OF THE LIB

FOCUS ON BINDER

FUTURE INNOVATIONS

ARKEMA OVERVIEW

KYNAR® FLUOROPOLYMER BATTERY SOLUTIONS
**EVOLUTION OF BINDERS**

**1990's**

- **Kynar® 761**
  - Loading: 6-8%
  - NMP Demand: 1
  - Energy Density: 1

**2006**

- **Kynar® 761A**
  - Loading: 3-4%
  - NMP Demand: 0.5
  - Energy Density: 1.09

**2016**

- **Kynar® HSV-900** (Leading Binder Worldwide)
  - Loading: 1-2%
  - NMP Demand: 0.3
  - Energy Density: 1.13

**2021**

- **Kynar® HSV-1800** (New Generation)
  - Loading: <1%
  - Water-based
  - Diminishing Return
  - Higher Voltage (>5V)
  - Higher Temp. (>80°C)
  - Cost Saving

**2025**

- **High Nickel Adhesion Binder**
  - Energy Density: ??
  - NMP Demand: 0

*Energy Density is normalized to 1
*NMP Demand is for 1g of cathode
PARAMETERS THAT AFFECT ADHESION
PARAMETERS THAT AFFECT ADHESION

ADVANTAGE
- HIGHER MW = HIGHER ADHESION
- PVDF IS SEMI-CRYSTALLINE

CONSTRAINT
- COMPLETE DISSOLUTION
- HIGH SLURRY VISCOSITY

MOLECULAR WEIGHT

CONTROL
- ADDITION OF CHAIN TRANSFER AGENTS
- LIMIT CHAIN GROWTH IN POLYMERIZATION
PARAMETERS THAT AFFECT ADHESION

MOLECULAR WEIGHT

Peel Strength

K741  K761  K761A  HSV-500  HSV-800  HSV-900

NMC(111) / Super-P / Binder : 95 / 3 / 3

Increasing MW
PARAMETERS THAT AFFECT ADHESION

ADVANTAGE
- HIGHER = HIGHER COHESION
- LOWER SWELLING
- HIGHER USE TEMPERATURE

CONSTRAINT
- LOW ADHESION TO ALUMINUM
- LIMITED ELECTRODE FLEXIBILITY

CRYSSTALLINITY PHASE-RATIO

CONTROL
- POLYMERIZATION TEMPERATURE CONTROLS
- EMULSION CAN BE 5-150°C
Emulsion and Suspension resins similarly are made by free radical polymerization.

Emulsion polymerization → Wider range of crystallinity and melting temperature

Too high of % crystallinity → lower adhesion
LOW SWELLING & LONGEVITY AT HIGHER TEMPERATURES

Swelling in (1:1:1 DMC, DEC, EC) for 24 Hours at Different Temperature

- HSV-900
- HSV-1800
- Comp-A7
- Comp-A3
- Comp-B

Kynar® HSV1800

- High Voltage Stability
- Limited Binder Swelling

- Higher Use Temperatures
- Extended Use Time
- No need for swelling compensation system

Increase in Mass (wt%) vs. Temperature (°C)
PARAMETERS THAT AFFECT ADHESION

**ADVANTAGE**
- ENHANCES ADHESION
- IMPROVES FLEXIBILITY
- REDUCES SWELLING

**FUNCTIONALITY TYPE**

**CONSTRAINT**
- MUST WITHSTAND ELECTROCHEMICAL REACTIONS IN CATHODE
- INCREASES SWELLING
- LIMITS USE TEMPERATURE

**CONTROL**
- CHEMICAL NATURE
- COMPATIBILITY
- INNOVATION INCORPORATION
PARMETERS THAT AFFECT ADHESION

**FUNCTIONALITY TYPE**

**Crystalline region**

**Amorphous region**

**Arkema Innovation**

Modifying amorphous region
by adding function group to its backbone

### Functional Group | Enhancement | Application

- Adhesion to Carbon - LFP, Graphite, LTO
- Flexibility - Flexible Binder
- Swelling - Separator Coating
- Adhesion to Silicon - Silicon Anode
- Adhesion to Metal - High Voltage Cathode

**HSV-XXXX for High Nickel Adhesion**
THE RESULT OF LEVERAGING THESE 3 PARAMETERS

Peel Strength (relative to HSV900)

HSV900  Comp-A2  HSV1800

LCO/DENKA/Binder: 97/1.5/1.5

Kynar® HSV900

Double the Adhesion

Kynar® HSV1800

KYNAR® FLUOROPOLYMER BATTERY SOLUTIONS

ARKEMA
## FURTHER COMPARISON OF PROPERTIES

<table>
<thead>
<tr>
<th>Properties</th>
<th>HSV-900</th>
<th>HSV-1800</th>
<th>RC-10,306A+</th>
<th>Competitor 1</th>
<th>Competitor 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thermal:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tg (°C)</td>
<td>-40.8</td>
<td>-40.9</td>
<td>-40.5</td>
<td>-41.9</td>
<td>-41.0</td>
</tr>
<tr>
<td>Tm (°C)</td>
<td>163.1</td>
<td>162.0</td>
<td>162.1</td>
<td>170.5</td>
<td>163.1</td>
</tr>
<tr>
<td>ΔH (°C)</td>
<td>50.0</td>
<td>50.5</td>
<td>48.4</td>
<td>55.6</td>
<td>46.9</td>
</tr>
<tr>
<td><strong>TGA:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5% weight loss, in air (°C)</td>
<td>448</td>
<td>450</td>
<td>447</td>
<td>441</td>
<td>448</td>
</tr>
<tr>
<td>10% weight loss, in air (°C)</td>
<td>456</td>
<td>460</td>
<td>455</td>
<td>460</td>
<td>461</td>
</tr>
<tr>
<td><strong>pH resistance</strong></td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td><strong>Color formation in NMP</strong></td>
<td>Clear/hazy</td>
<td>Clear</td>
<td>Clear</td>
<td>Light Amber</td>
<td>Dark Amber</td>
</tr>
<tr>
<td><strong>Flexibility (3mm mandrel)</strong></td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td><strong>Swelling</strong> (In electrolyte @ 80 °C)</td>
<td>37%</td>
<td>37%</td>
<td>37%</td>
<td>37%</td>
<td>54%</td>
</tr>
<tr>
<td><strong>Solution Viscosity</strong> @8%, 10 s⁻¹, RT (cp)</td>
<td>3350</td>
<td>1750</td>
<td>1700</td>
<td>2300</td>
<td>5350</td>
</tr>
</tbody>
</table>

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Excellent balance of:
- Flexibility
- Swelling
- Adhesion
NO COMPROMISE OF RHEOLOGY PROPERTIES

Solution viscosity profile at 8% in NMP 25°C

- HSV-900
- Comp-A7
- RC-10,306A1
- HSV-1800

Kynar® HSV1800

Lower Solution Viscosity
More Newtonian Behavior
Easier Processing
ENHANCED PERFORMANCE IN LFP

Peel strength (relative to HSV900)

LFP/SuperP/Binder 93/4/3

Kynar® HSV1800

Higher Adhesion

Allows for Higher Energy Density

- Increased Carbon
- Lower IR
- Higher Output
- Reduced NMP Demand

24 KYNAR® FLUOROPOLYMER BATTERY SOLUTIONS
ENHANCED PERFORMANCE IN LFP

LFP/SuperP/Binder: \((100 - 2.3x)/1.3x/x\)

<table>
<thead>
<tr>
<th>Binder loading</th>
<th>Peel Strength (relative to HSV900@3%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0%</td>
<td>0.0</td>
</tr>
<tr>
<td>2.5%</td>
<td>0.5</td>
</tr>
<tr>
<td>3.0%</td>
<td>1.0</td>
</tr>
<tr>
<td>3.5%</td>
<td>1.5</td>
</tr>
<tr>
<td>4.0%</td>
<td>2.0</td>
</tr>
<tr>
<td>4.5%</td>
<td>2.5</td>
</tr>
<tr>
<td>5.0%</td>
<td>3.0</td>
</tr>
</tbody>
</table>

**Kynar® HSV1800**

- Higher Adhesion
- Allows for Higher Energy Density
- Increased Carbon
- Lower IR
- Higher Output
- Reduced NMP Demand

25 KYNAR® FLUOROPOLYMER BATTERY SOLUTIONS
ENHANCED PERFORMANCE IN LCO

Higher Adhesion
Allows for Higher Energy Density

Increased Carbon
Lower IR
Higher Output
Reduced NMP Demand

Kynar® HSV1800

LCO/Denka/Binder: 97/1.5/1.5

Peel strength (relative to HSV900)

HSV-900  HSV-1800  Comp-A7  Comp-A2
ENHANCED PERFORMANCE IN LCO

Kynar® HSV1800

Higher Adhesion
Allows for Higher Energy Density
Further Opportunities
- Increased Carbon
- Lower IR
- Higher Output

LCO/Carbon/Binder 97/1.5/1.5

<table>
<thead>
<tr>
<th>Relative Peel Strength</th>
<th>HSV-900</th>
<th>HSV-1800</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denka black</td>
<td>1.0</td>
<td>3.0</td>
</tr>
<tr>
<td>SuperP</td>
<td>1.5</td>
<td>3.5</td>
</tr>
</tbody>
</table>
ENHANCED PERFORMANCE IN GRAPHITE (ANODE FORMULATION)

Graphite/SuperP/Binder: 94/2/4

Peel Strength (N/m)

- HSV-900
- HSV-1800
- Comp-A7

Kynar® HSV1800
- Higher Adhesion
- Allows for Higher Energy Density
- Further Opportunities
  - Increased Carbon
  - Lower IR
  - Higher Output

SBR/CMC
ARKEMA OVERVIEW

PARTS OF THE LIB

FOCUS ON BINDER

FUTURE INNOVATIONS
Water-Based Binders: *Kynar® WB Binder*

- Potential to eliminate organic processing solvents (NMP, Acetone, etc)
  - Today: NMP/PVDF usage ≈20/1 (NMP usage estimation ~100,000 mt/y and increasing rapidly)
- Advantages in cost, safety, and performance

*Needs Emulsion Process*

- Arkema is Kynar® PVDF is made by emulsion GLOBALLY

*Needs Nano-Scale Particle Size*

- Enables increased contact points and surface area
- Arkema has patented technology

*Needs WB Formulation Expertise*

- Formulation of fluoropolymer latexes requires a different set of tools and processes for optimization vs. solvent-borne
- Arkema is the leader with an extensive patent portfolio in waterborne technology, especially aqueous fluoropolymer coatings and formulations
SEPARATOR COATING – NEEDS/TRENDS

High Voltage: requires polyolefin to be protected at > 4.3 V
- LCO voltage 4.5-4.6V soon
- NMC, NCA are pushing to higher voltage than 4.2-4.4V
- Kynar Flex® PVDF copolymers are used to coat polyolefin separators
- Kynar Flex® solution with 5V performance available
  - Arkema is working on high voltage electrolyte salt solutions

xEV Battery: requires safety and longevity
- Dimensional stability at elevated temp above 70°C
- No lithium dendrite growth across PO separator
- High ionic transportation across of PO separator

Kynar Flex® PVDF copolymers plus nano-ceramic are well-suited to coat polyolefin separators
BATTERY SOLUTIONS WITH KYNAR® PVDF

DISCUSSION & QUESTIONS