



Industrial Concepts for Membrane-Based Separations

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Areas of Focus

Improve and **support** our current processes

- Water
 - More efficient desalination
 - Hard to process waters (oil-field, mining, metals)
- Industrial, non-water separations

Transform our processes

- Gas separations
- Lithium ion batteries

Revolutionize our processes

- Unit operation hybridization

Water Separations

Desalination

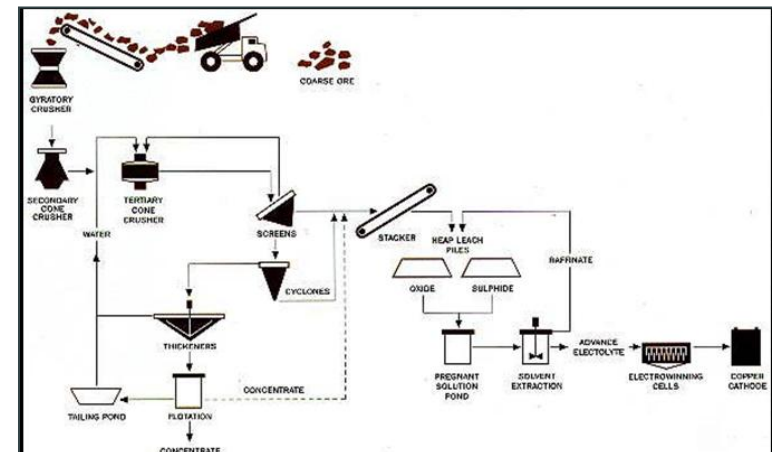
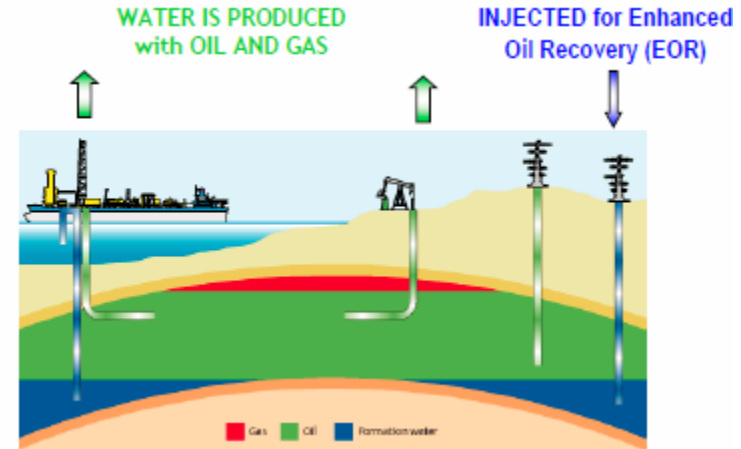
- Fouling resistance
- Cleanability (e.g. resistance to chlorine)
- Energy efficiency
- Step-change robustness
- Large potential gains at system level

Produced Water

- Ability to handle oily water streams
- Hydrophilic, compatible with polymers and flocculants
- High-temperature
- Robustness to extensive chemical cleaning

Industrial and Mining Water

- Ability to handle high suspended solid levels
- Compatibility with organics
- Broad pH usage
- Chemical resistance



Industrial Non-Water Applications

Catalyst recovery – example of needs

- Broad solvent resistance
- Improve upon permeability over current polyimide and ceramic options
- High temperature compatibility ($\gg 50\text{ }^{\circ}\text{C}$)
- Applicable to mining and many other industrial applications

High viscosity processing

- Cross flow configuration with practical fluxes (20 LMH) with viscosities 10-200 cP

Biochemical processing

- Fouling resistance
 - Prevent colloidal species from attaching
 - High temperature, solvent resistant

Solvent Resistance



Industrial



Bioprocessing

Harsh Processing



Industrial



Mining

High Temperature



Industrial



Sweeteners



Food & Beverage

Gas Separations: Scale is a BIG issue



Dow is the top ethylene producer in the world

- 14 Dow crackers worldwide worth over \$15 billion in capital
- Dow crackers globally convert over 5 million pounds of feedstock every hour
- Feedstock demand is **800,000 barrels/day** -- \$15-20 billion/year
 - 40-50% of Dow's total annual operating costs and expenses

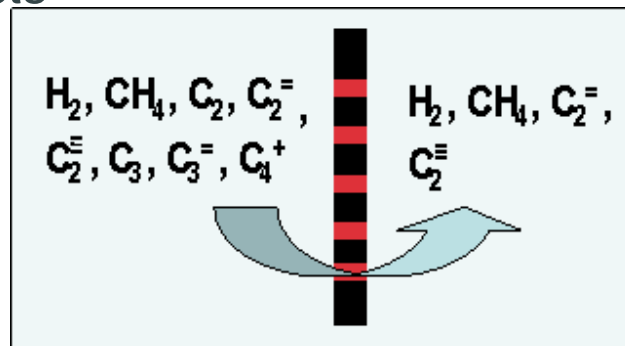
Standard is cryogenic distillation = energy & capital intensive



Gas Separations

Olefin / Paraffin

- Prime products are distributed as very pure products
- Highly unlikely membranes can do it alone
- First stage “concentrator” is of value
- Flux is of utmost importance
- Scalable, defect-free



Water Recovery from Steam/Furnace Vents

- Boiler and furnace vents contain water and latent heat
- Low pressure plant steam/low quality heat is valuable and often vented
- High purity water in steam is quite valuable
- Challenging because going below dew point causes corrosion

Numerous others

- CO_2 removal for natural gas sweetening
- Hydrogen separations
- Argon recovery, etc

Lithium Ion Battery Separator Membranes

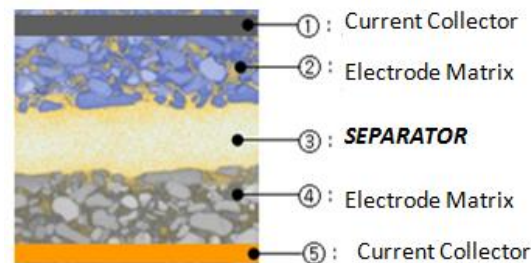
Function: Prevent direct electrical contact between electrodes while allowing ionic transport through membrane: critical to operation and safety

Key Properties: Thickness, porosity, pore size, tensile & puncture strength, chemical & electrochemical stability, wettability with electrolyte

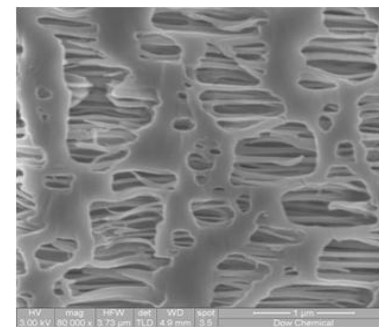
- Thinner, more porous = better performance but lower strength – need to balance properties

Challenges:

- **Lower cost:** Electric & hybrid vehicle battery price goal is \$1/m²
 - Must reduce cost of manufacture, improve yield
- **Improved electrochemical stability:** Advanced cell materials operate at higher voltage
 - Cells operating at 5V can cause separator oxidation – need improved stability at separator/cathode interface
- **Long lifetime:** 10+ years in automotive batteries vs. 1-3 years in consumer electronics



Li-ion battery cross-section



Battery separator surface
(Dry stretch fabrication process)

Hybridized Processes

Example: Dehydrogenations limited by thermodynamics

Need to remove hydrogen or olefin to drive to higher conversion

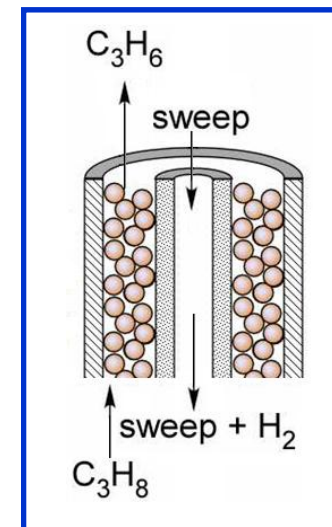
- 40% conversion at 550°C; 60% conversion at 625°C

Membranes to selectively remove hydrogen or olefin

- Must function at high temperature (>500°C)
- Non-reactive to olefins
- High flux to drive equilibrium
- Must be affordable

Hybridized separations

- Membrane distillation
- Membrane and ion exchange
- Membranes and adsorption



Summary and Questions

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Questions? Thank you.