UTC Membrane Applications for Energy & Environment

Polymer membranes significantly enhance the efficiency & safety of multiple products

US Energy Consumption*

39% Buildings
- Air dehumidification
- Flow Batteries
- Fuel Cells

33% Industrial
- N₂ Removal from Natural Gas

28% Transportation
- Aircraft
  - Fuel tank inerting
  - Fuel deoxygenation
- Automotive
  - PEM Fuel Cells
  - Perishable Transport (O₂/N₂ separation)
- Ships
  - LNG

Polymeric Membrane Challenges

Materials:

- Reliability/Durability
- Cost
- Performance
- Effective dialogue between membrane developers and system integrators/end users
- Incorporation of emerging smart materials & scale up
- Applications enabled by stimuli responsive nanomaterials

Module / System:

- Reliability
- Design & system integration for performance, footprint and cost
O₂/N₂ Separation Membranes

Applications safety-focused but membrane challenges application-specific

Aircraft Fuel Tank Inerting

Challenges
- Volume & Weight
- Pressure Drop
- Durability / Reliability

LNG Tank Inerting

Challenges
- Durability / Reliability
- Selectivity
O₂/Fuel Separation for Aircraft Application

Challenges: No fuel leakage, volume & weight, durability, system integration

Coke formation prevents heating jet fuel to high temperature

O₂ concentration gradient provides driving force

Advanced Membrane Developed
- 10X lower fuel leakage
- 5X higher oxygen permeance
- 2X lower membrane mfg. cost
- 40% less membrane needed

O₂ concentration gradient provides driving force

Membrane

Porous support

Fuel In 70 ppm O₂

Jet Fuel

vacuum or oxygen-free gas

Fuel Out < 6 ppm O₂

Membrane

Porous support

Fuel Out < 6 ppm O₂

Membrane

Porous support

Fuel Out < 6 ppm O₂

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Porous support

Fuel Out < 6 ppm O₂
Dehumidification for Energy Efficient Buildings

**Benefits**
- 30% system efficiency vs. traditional system hot and humid climates
- Independent temperature and humidity control
- No liquid desiccant carry-over

**Challenges:** Durability, cost, performance, pressure drop

Liquid Desiccant Membrane-Based Air Conditioning

**Warm & Humid Outdoor Air**

**Cool Dry Air**

**Regeneration Air Exhaust**

**Nano-Engineered Membrane Contactor**

**Vapor Compression System**

**Nano-Engineered Membrane Contactor**

**Regeneration Air**

Membrane performance & durability

Membrane module Development

Humidity mass transport mechanisms in hollow fiber membrane heat and moisture exchangers

United Technologies Research Center
PEM Fuel Cells for Transportation & Flow Batteries

**Challenges: Durability, performance, cost**

### PEM Fuel Cells for Transportation

![Diagram of PEM Fuel Cells for Transportation]

**Function**
- Transport protons
- Separate the reactants

**Desired attributes**
- High proton conductivity
- Low gas cross-over
- High durability (chemical / mechanical)

### Flow Batteries for Energy Storage

![Diagram of Flow Batteries for Energy Storage]

**Commercial Materials**

- **PerFluoroSulphonic**
  
  \[-(\text{CF}_2\text{CF}_2)_n\text{CF}_2\text{CF}_2^-\in \text{(PF}_3\text{O)}_{1n}\text{CF}_2\text{CF}_2^-\text{SO}_2\text{H}\]

- **Hydrocarbon**
  
  \[X\text{ - }\text{SO}_2\text{H}\]

**Desired attributes**
- Low Ohmic resistance
- No ion cross-over
- Good proton conductivity
- High durability (chemical / mechanical)
New Materials for N₂ / CH₄ Separations

Challenges: Durability & performance degradation in real environment; Scale-up and manufacturing cost for emerging materials

Optimize permeance & selectivity by tailoring pore architecture & chemistry

Zeolitic imidazolate frameworks (ZIFs)

Figure 1: N₂/CH₄ tradeoff plot for TR polymers, fluoropolymers (Cytop, AF 2400) and stiff-chain, aromatic polyimides. The line in this graph is the upper bound. The data in this figure represent pure gas measurements at near ambient temperature and at relatively low pressure (<10 bar). There are no data available yet for gas mixtures. The information we have, which is not extensive, suggests that permeability exhibits sensitivity to fugacity as one would expect from dual mode model considerations, which should not be extremely strong for the case of N₂ and CH₄.

Graph provided by Prof. Benny Freeman, U. Texas, Austin