“Applications and future trends in polymer materials for green energy systems: from energy generation and storage, to CO_2 capture and transportation”

United Technologies Research Center

East Hartford, CT 06108

August 24, 2010

United Technologies

Business units

Pratt & Whitney

aerospace systems

Sikorsky

Carrier

power solutions

UTC Power

Hamilton Sundstrand

UTC Fire & Security

building systems

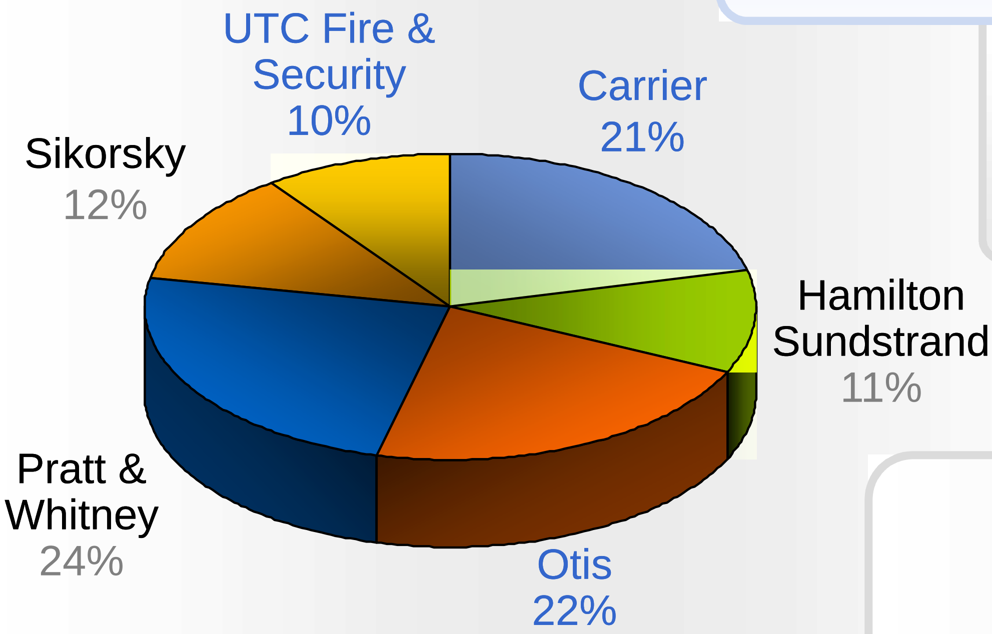
Otis

United Technologies Research Center

United Technologies

2009 Revenues: $52.9 billion

Business unit revenues …

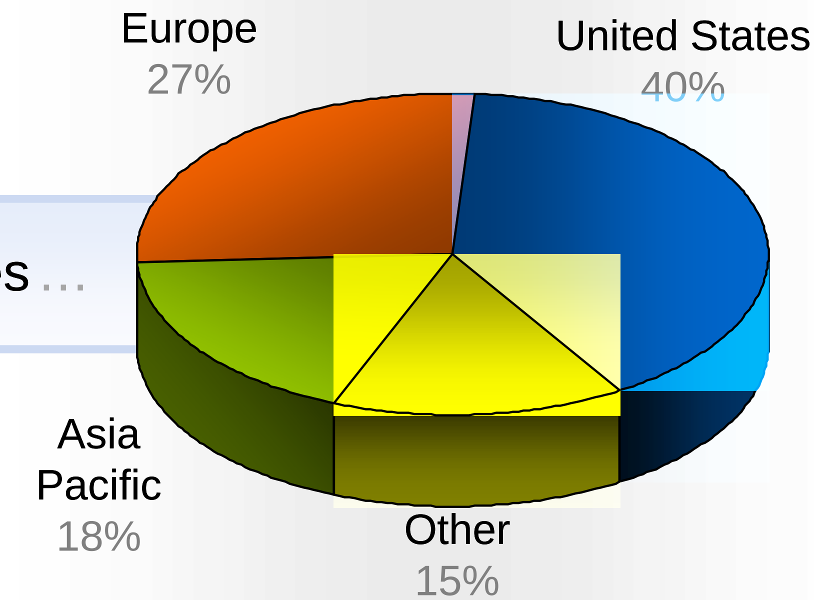


Segment …

58% Commercial & Industrial

42% Aerospace

Geographic revenues …



UTRC...UTC's Innovation Engine

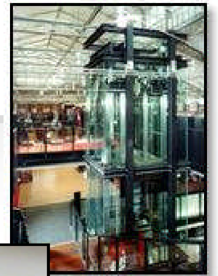
Defining what's next

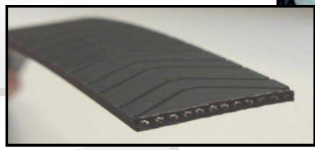
- Define new frontiers...

UTC Fire & Security
intelligent security and fire detection systems

- Co-develop new technologies...

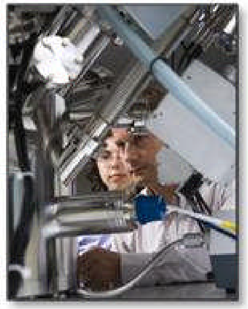
Otis Gen2
coated steel belt





- Solve tough problems...

UTC businesses
UTRC materials characterization for failure analysis and relentless root cause investigation



- Serve as hub for technical interchange...
- Leverage global network of innovation...

UTRC Organization

UTRC Director

Controls

Sustainability

Senior Fellows

Program Offices:

Carrier

Energy Systems

Hamilton Sundstrand

Otis

Pratt & Whitney

Sikorsky

UTC Fire & Security

UTC Power

Technical Departments:

Physical Sciences

Systems

Thermal & Fluid Sciences

Global Presence:

East Hartford, CT
HEADQUARTERS: Est. 1929

Shanghai, China
Est. 1997

Berkeley, CA
Est. 2009

Cork, Ireland
Est. 2010

Operations & Business Services:

Business Development

Communications

Design Engineering & Prototyping

EH&S & Facilities

Finance

Human Resources

Information Technologies

Law

Strategic Business Analysis

UTRC's Physical Sciences Department: Capabilities

Physical Sciences Department

Materials Chemistry
- Materials Synthesis
- Electrochemistry
- Corrosion
- Computational Chemistry

Surface Mechanics
- Manufacturing Processes
- Tribology
- Interface Protection

Separation Science
- Environmental Control
- Membranes
- Catalytic Processes
- Process Design & Modeling

Applied Mechanics
- Structural Analysis
- Material Damage Modeling
- Health Management and Reliability

Applied Physics
- Nanomaterials and Devices
- Functional Interfaces
- Energy Harvesting

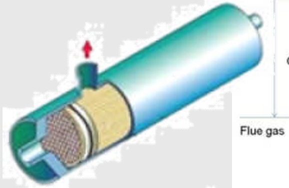
Materials Characterization
- Microscopy & Spectroscopy
- Material Properties
- Mechanical Behavior
- Failure Analysis

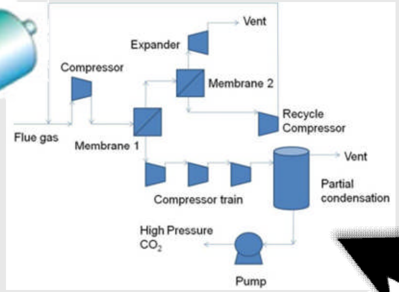
Advanced Materials
- Structural Ceramics/Composites
- Coatings/Engineered Surfaces
- Polymeric Materials
- High Temperature Materials

UTRC: Selective Areas of Polymers Applications

Hamilton-Sundstrand

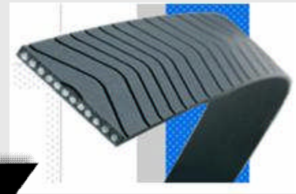
Novel Polymer Membrane for CO_2 Separation

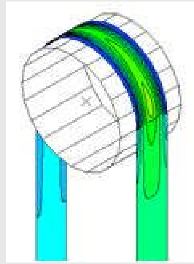




OTIS

Polymer Coated Elevator Steel-Cord Belt

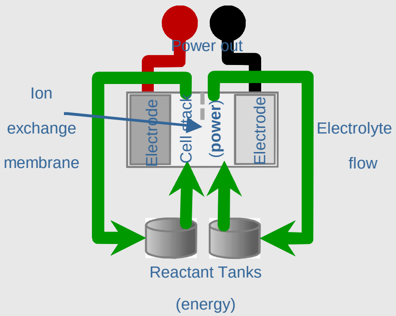




UTRC

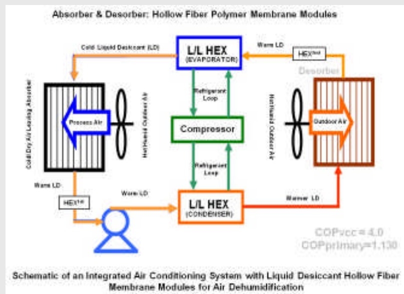
P&W Rocketdyne

Electrochemical Flow Battery

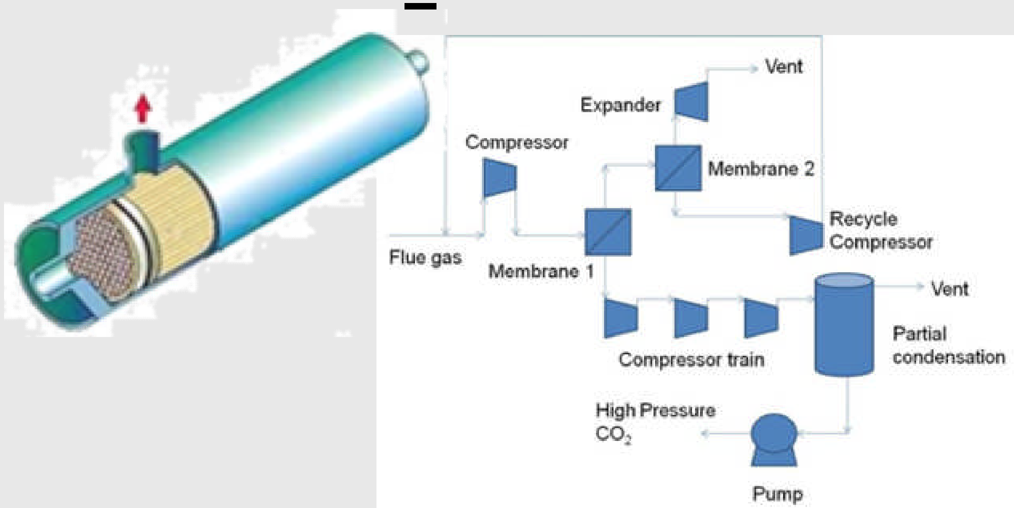


Carrier

Dehumidification Air-Cooling System



Novel Polymer Membrane for CO_2 Separation

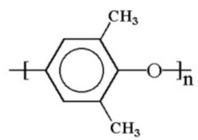


Funded by:

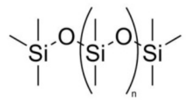
Main-Stream CO_2 Separation Technologies

2.8 billion tons CO_2 emitted per year from existing US coal-fired power plants

- CO2 Separation
  - Absorption
    - Caustic
    - *Mono Ethanol Amine (MEA)* *$H_2N\text{-}CH_2CH_2OH$*
  - Adsorption
    - Zeolite
    - Activated Carbon
    - Pressure-Temperature Swing
  - Membrane
    - ***Polymer***
      - ***Cellulose Acetate***
      - ***PEBAX***
      - ***PolyPhenylene Oxide (PPO)***

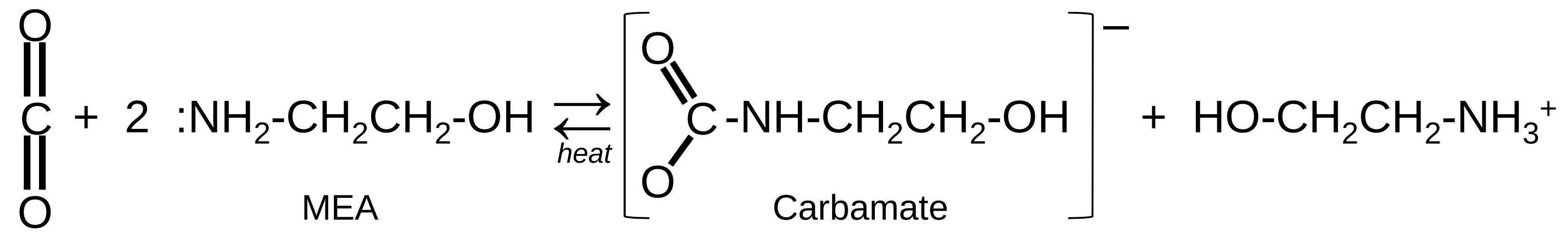


      - ***PolyDiMethyl Siloxane (PDMS)***

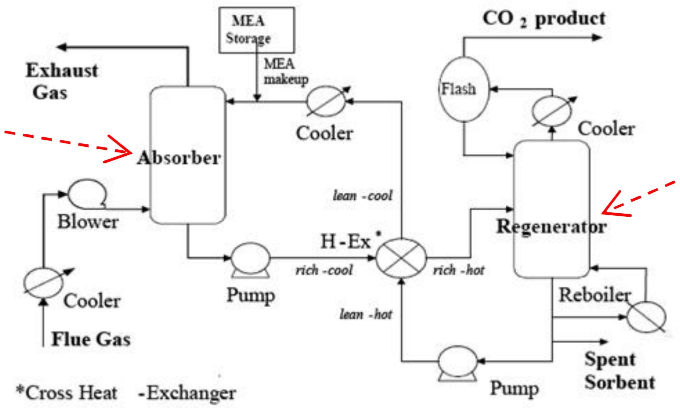


  - Cryogenics

CO_2 Separation from Power Plant Flue Gas: Liquid Amine Process



Low Reaction Rates
- Gas diffusion through liquid
- Slow kinetics
- Large absorber for CO_2 capture



High Regeneration Energy
- Reaction forms stable compound
- ~70% of total mass is water

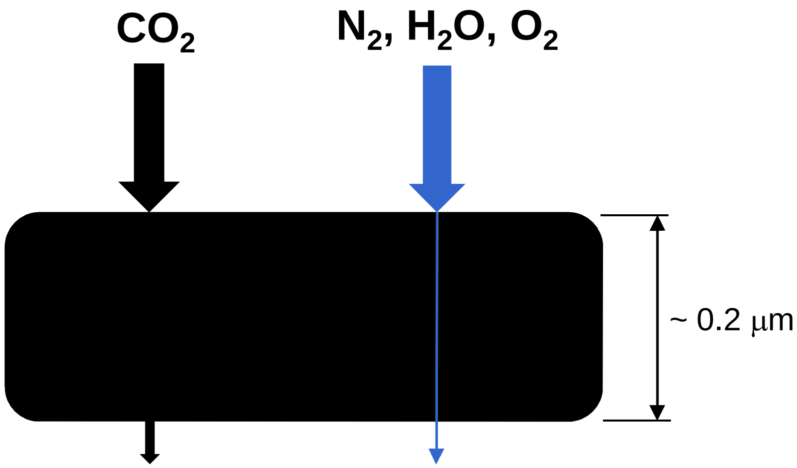
Disadvantages of Liquid Amine Process

- ➢Deactivation of MEA sorbent due to flue gas impurities (SOx) forming stable salts
- ➢Corrosion issues leading to high capital costs
- ➢***Energy Penalty: $50/ton CO_2 captured → 80% increase in cost of electricity***

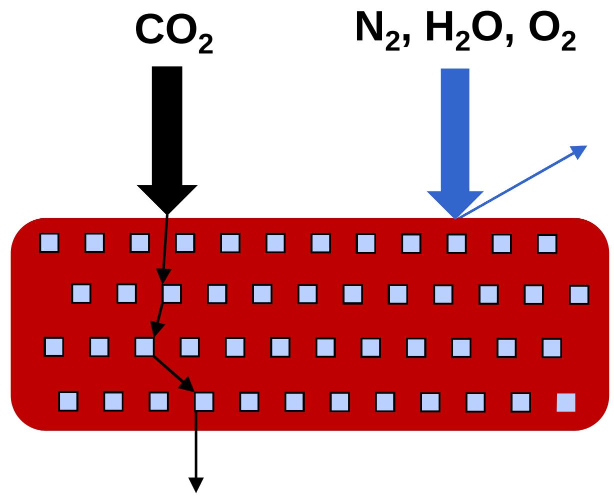
Limitations in liquid amine chemistry lead to high operating & capital costs

CO_2 Separation Membrane

Facilitated transport could improve performance of current membranes



<u>Current Membranes</u>

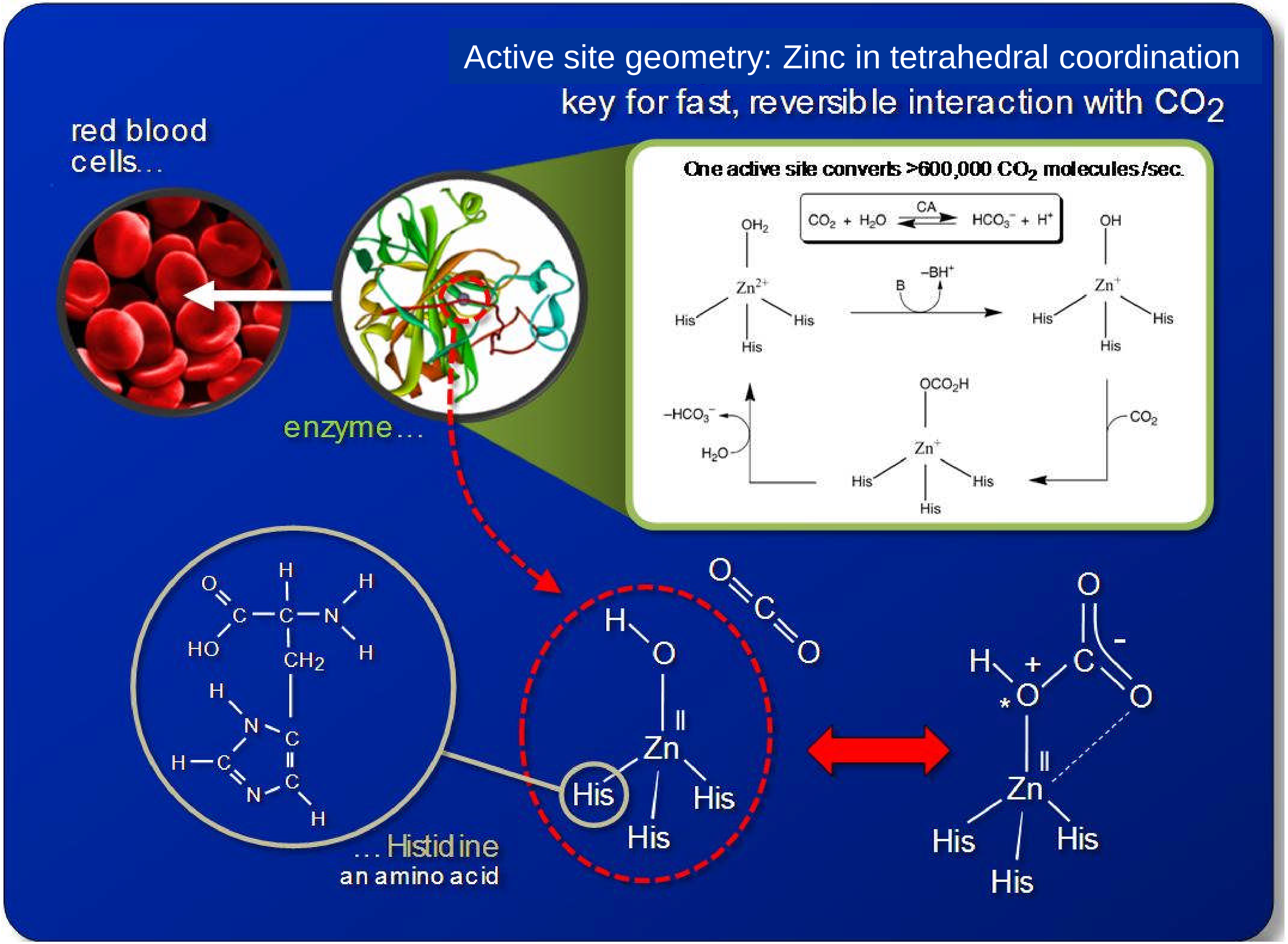


<u>Desired Membrane</u>

- Thin, dense polymer films with more affinity for CO_2 than for other gases
- Low selectivity for CO_2 (barely competitive with amines)

- CO_2 transport is facilitated by specialized "carriers" within a barrier film
- Requires sites exhibiting *fast* and *reversible* interaction with CO_2

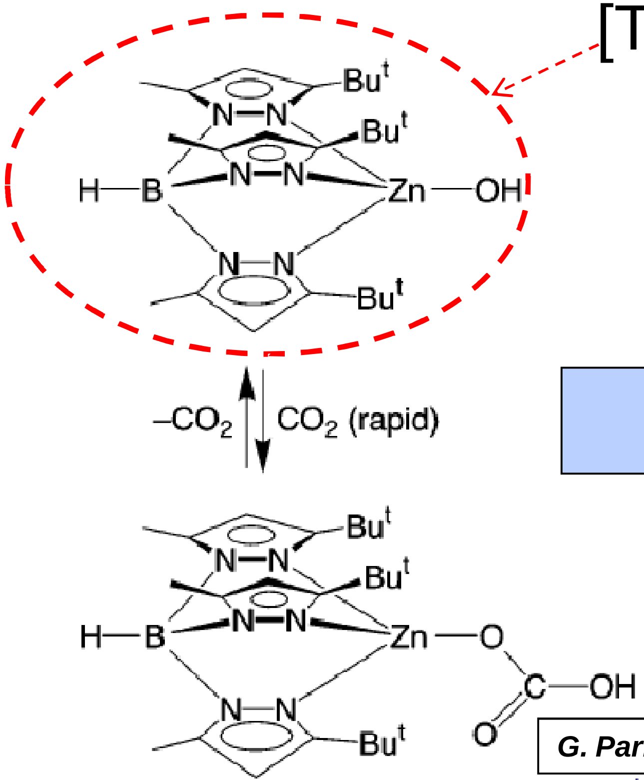
Carbonic Anhydrase: Nature's Solution



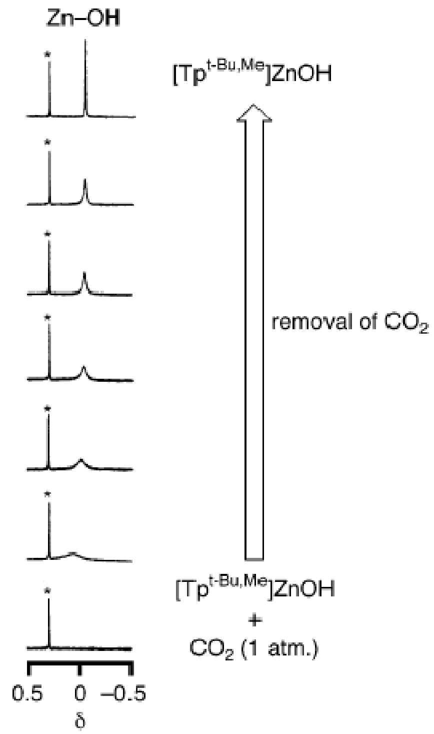
tris(pyrazolyl)borate [$Tp^{t\text{-}Bu,Me}$]ZnOH: CA Synthetic Analogue

CA… Carbonic Anhydrase

[$Tp^{t\text{-}Bu,Me}$]ZnOH



Stable molecule
Fast reaction in
NMR time scale



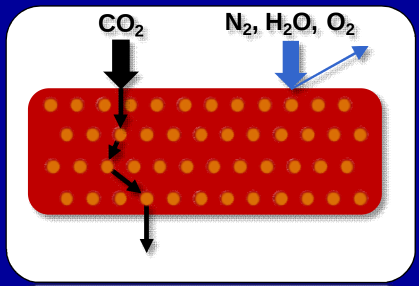
G. Parkin, Chem. Rev. 2004, 104, 699-767

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Fast & reversible interaction of the Synthetic Analogue with CO_2 demonstrated

Approach: Incorporation of Synthetic Analogue in the Polymer

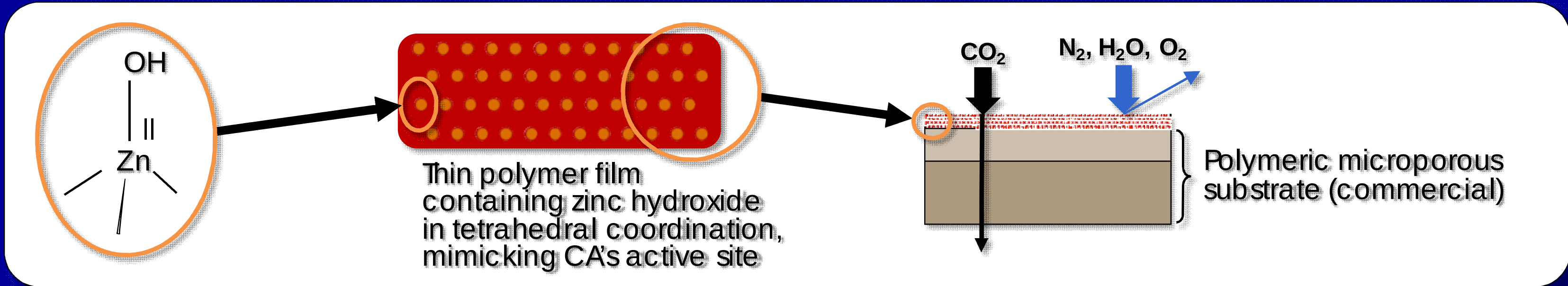
CO_2 transport facilitated by carriers mimicking enzyme active site



Taylor-Designed Membrane

- CO_2 transport facilitated by selective carriers within the barrier film
- Requires sites exhibiting fast and reversible interaction with CO_2

Approach: Synthesize & Incorporate into Polymer Synthetic Analogue of CA



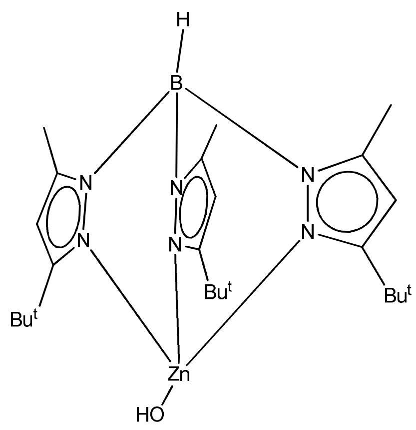
CA … carbonic anhydrase

- *30% lower CO_2 capture cost compared to liquid amines (current technology)*
- *Modular, skid-mounted configuration, with no moving parts*
- *No consumables, toxic chemicals or offensive odors*
- *Flexibility to start with smaller system and gradually increase to 90% CO_2 capture*

Synthetic Analogue Modification for Grafting

Parallel approaches pursued

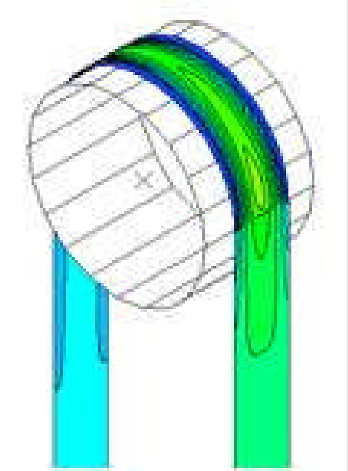
- Functionalization of the [Tp$^{t\text{-}Bu,Me}$]ZnOH (CA synthetic analogue) to graft onto the polymer backbone:
  - Carboxylic functionalization
  - Unsaturated functionalization



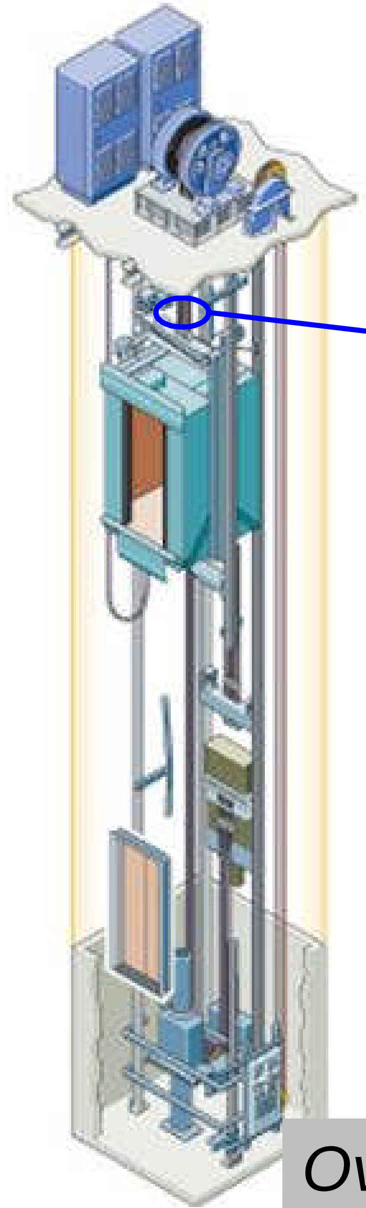
[Tp$^{t\text{-}Bu,Me}$]ZnOH

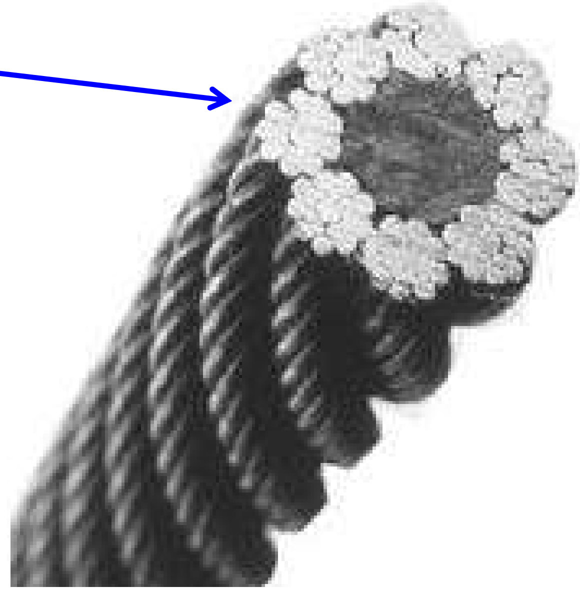
OTIS Elevator Polymer Coated Steel Cord Belt (CSB)

OTIS Elevator Polymer Coated Steel Cord Belt



Steel Cables: Old Technology



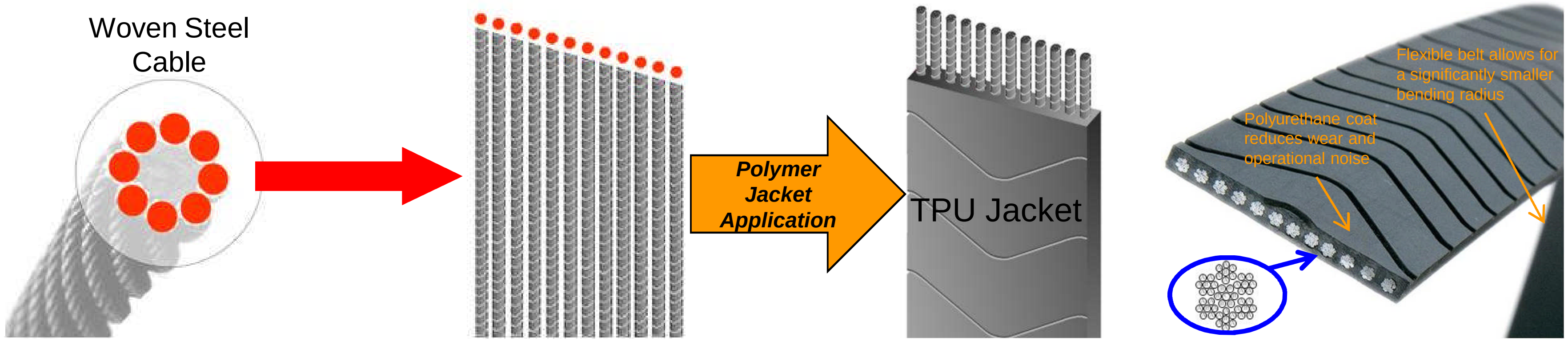


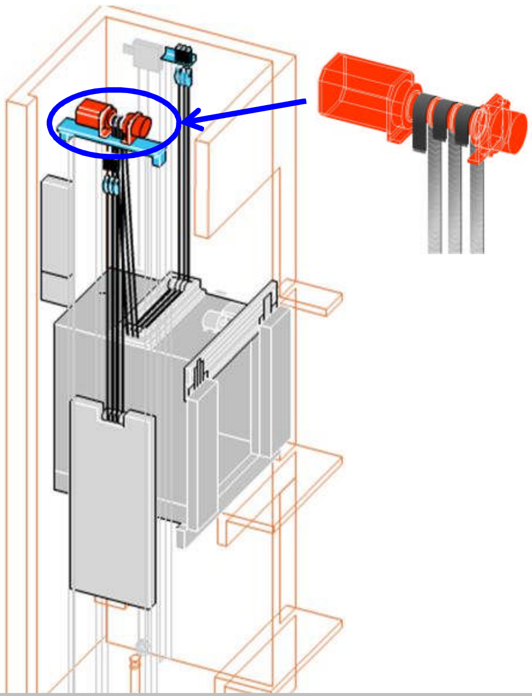
- Had been the industry standard since the 1800's:
  - ➢Steel cables wound around a flexible core
  - ➢Attached to the top of the elevator and the counterweight at the other end
  - ➢Wraps around the drive sheave
- Heavy, excess weight
- Large motor
- Power waste
- Noisy, bumpy ride
- Dedicated machine room requirement

Overdue for a major technology breakthrough

New Industry Standard: OTIS Polymer Coated Steel Cord Belt

Flat TPU Coated Steel Cord Belt





Coated Steel Belt Advantages

- First Generation Belt commercially introduced in 2000's
- Reduction in bending stiffness allowing use of smaller diameter pulleys and motors
  - Allow use of smaller VF gearless machinery and sheaves
  - Elimination of costly machine room need
- 20% weight reduction vs. steel cables
  - Equally strong and more durable, flexible and space-saving than steel cables, even though only 3 mm thick x 30 mm wide
- **Allows for up to 50% power need reduction!!**
- Step change in ride quality and noise reduction
- Higher reliability due to fewer machinery moving parts
- Environmentally friendly operation – no lubrication needed

Over 150,000 Coated Steel Belt OTIS elevators in use to date worldwide

Jacket Polymer Critical Performance Properties

Behavior at low and high operating temperatures:

- Mechanical and tear strength
- Coefficient of friction
- Wear performance

Property retention after long-term exposure to:

- High humidity/high temperature operating environment
- Humidity/temperature cycling

Typical Manufacturing Processes

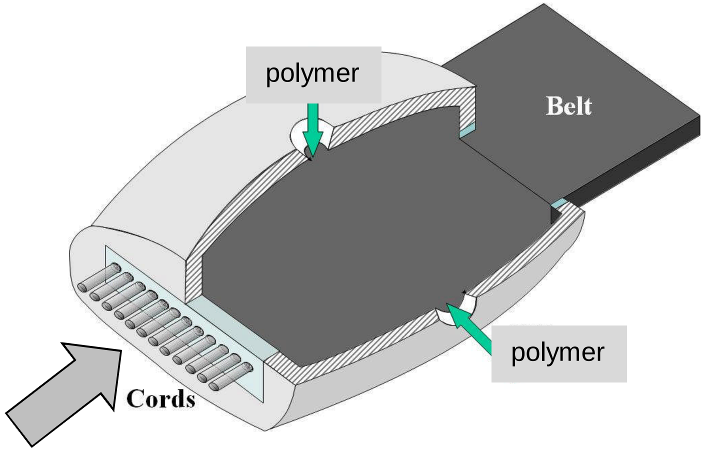
Linear Extrusion

Advantages

- High production speed
- Better polymer penetration

Risks

- Dimensional control



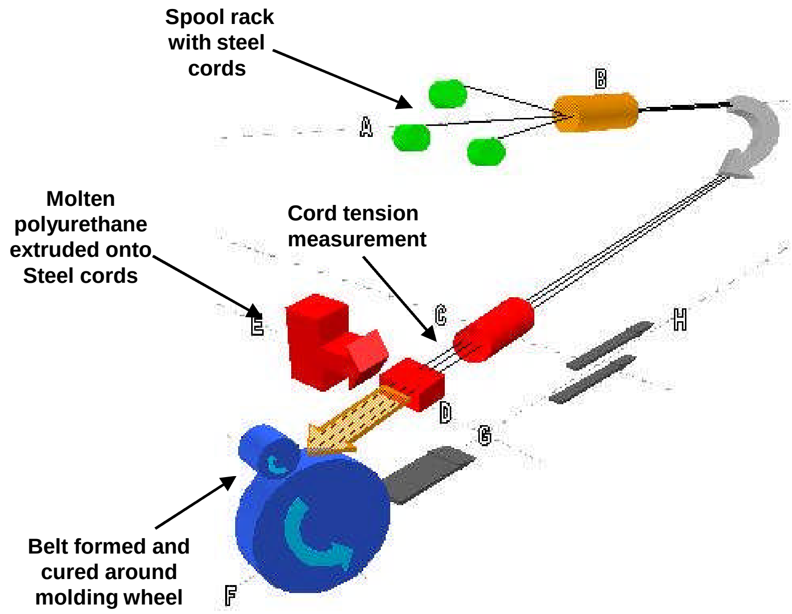
Mold Wheel

Advantages

- Better dimensional control
- More mature process

Risks

- Lower production speed



NextGen Polymer Coated Steel Belt

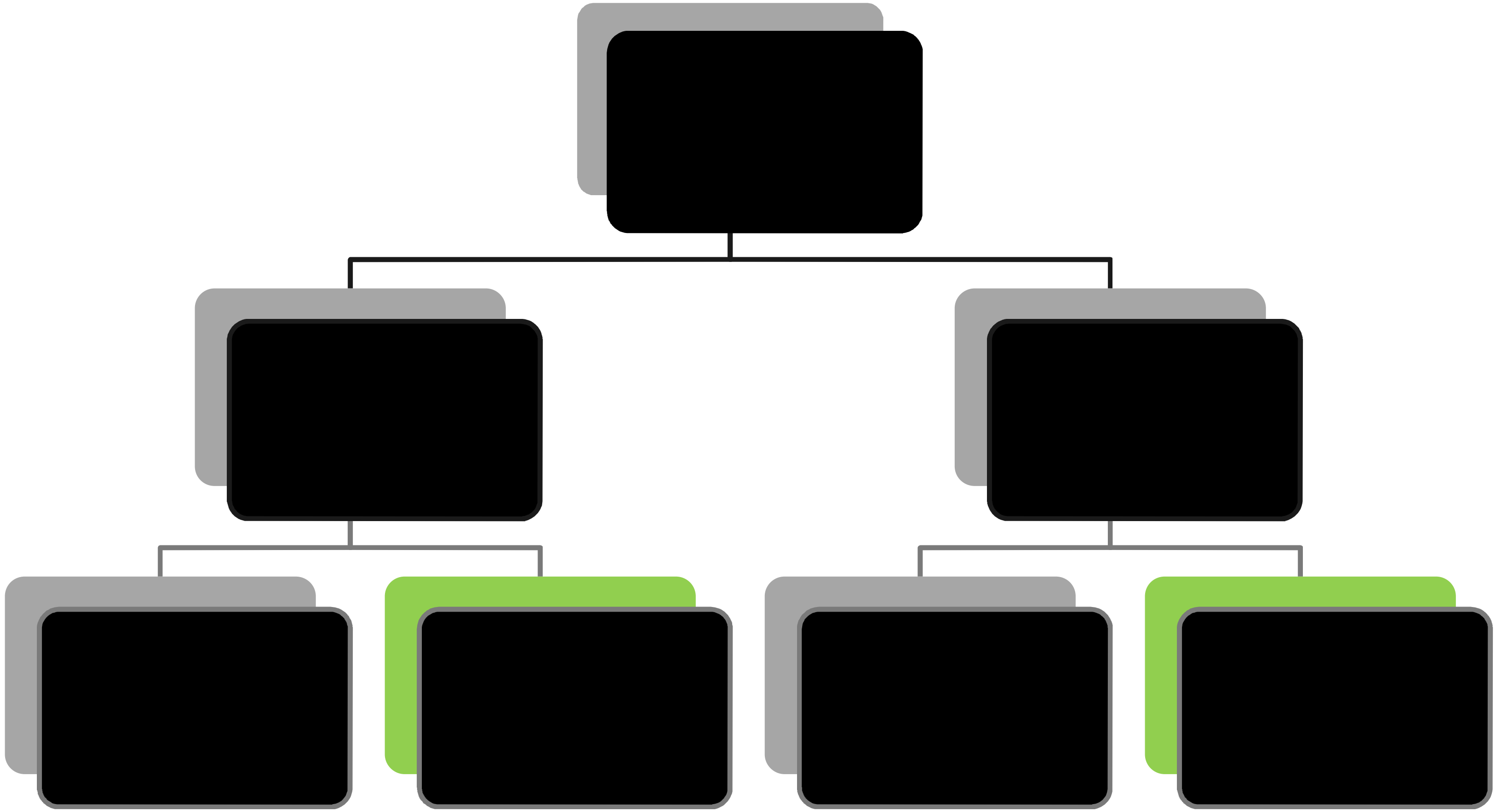
NextGen Belt Requirements

- Further ride quality improvement
- Process and material improvements allowing higher product performance and customer satisfaction

Polymer & Process Candidates

- Alternate TPU or thermoplastic elastomer materials
- New belt jacket design for further ride quality improvement

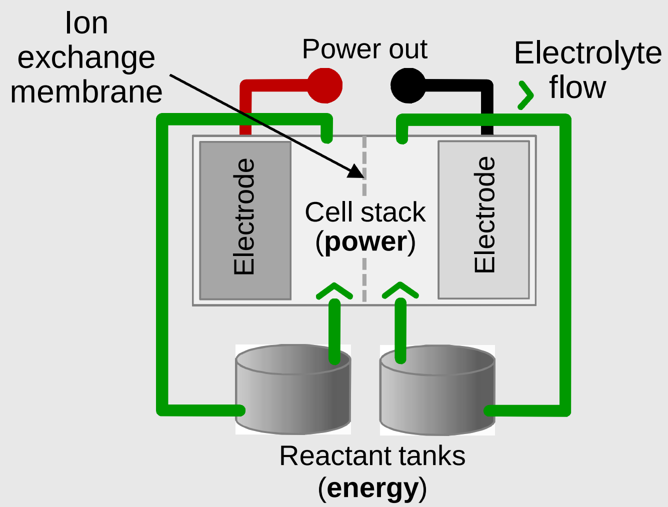
NextGen Polymer Coated Steel Belt: Material & Processes Trends



Higher product performance & customer satisfaction

Electrochemical Flow Battery

Flow Battery System

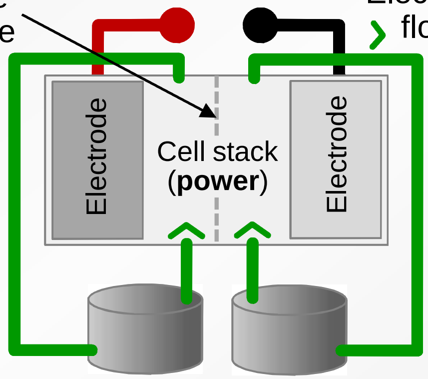


Funded by:

Flow Batteries are essentially rechargeable fuel-cell systems

Combine the best attributes of rechargeable batteries and fuel cells

Flow Battery System



Cell stack attributes

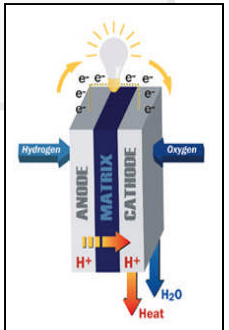
- Energy and power independent
- Long life cycle
- Low self-discharge rates

Battery attributes

- Rechargeable
- High round-trip efficiencies
- No precious-metal catalysts

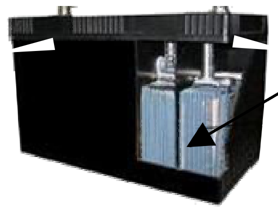
Fuel cell issues (for energy storage)

- Low round-trip efficiencies
- Precious-metal catalysts
- Hydrogen storage



Conventional battery constraints

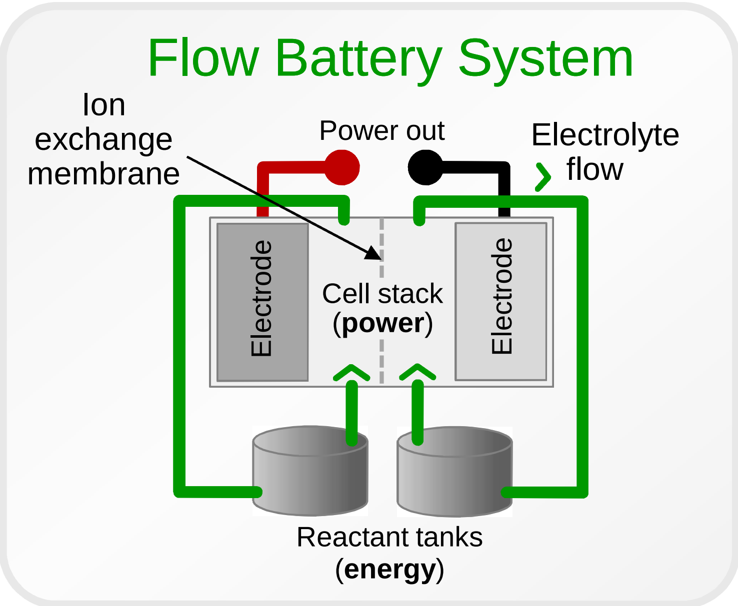
- High power OR High energy
- Limited life cycle
- Continuous self-discharge



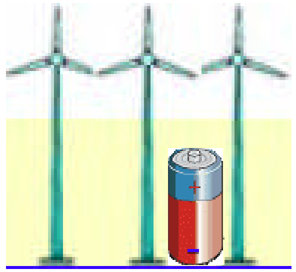
Large-Scale Electrical Energy Storage

Improve energy efficiency and emissions, reduce need for peaker plants

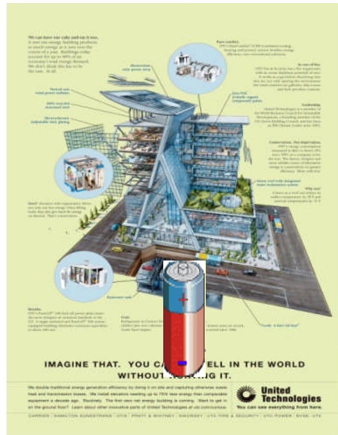
Technology



Applications



Renewable Energy
Smoothing & time-shifting



Commercial Buildings
Bill reduction & UPS

Remote & Off Grid
Minimize fuel usage

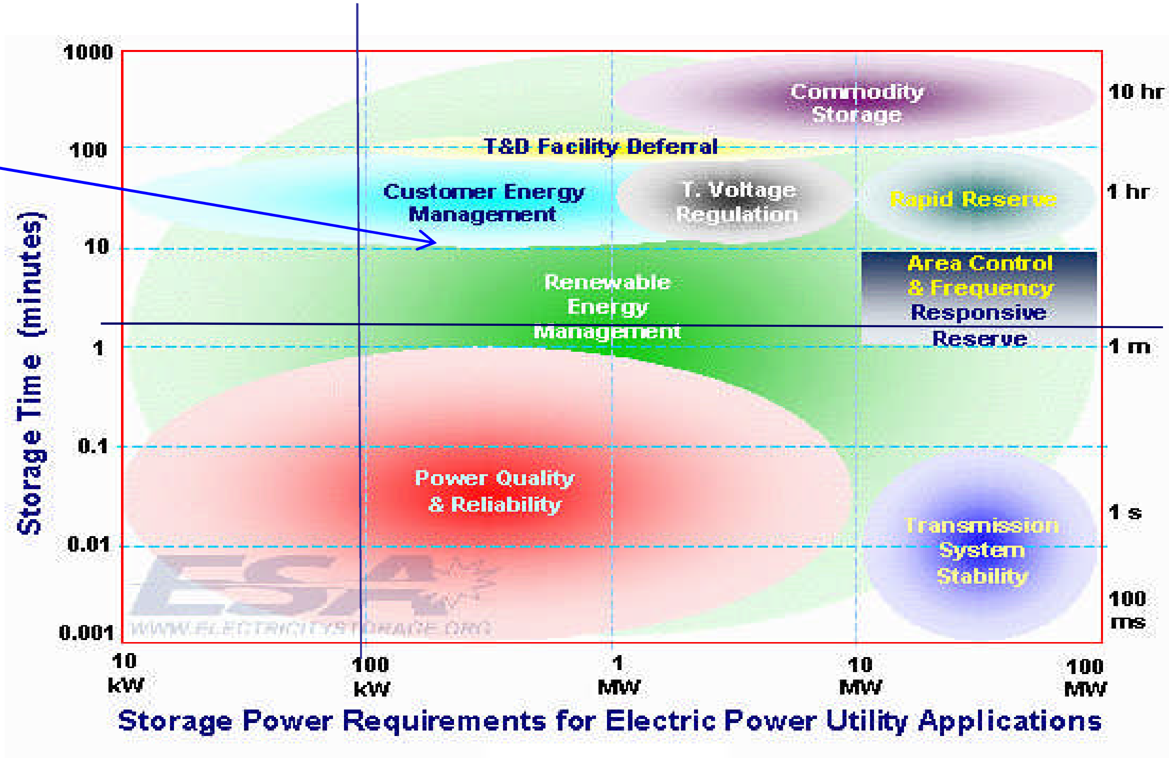
Transmission & Distribution
Infrastructure deferral

Electrical-Energy Storage Market

Large potential market (> $1B/y); need is growing due to multiple factors

- Many potential applications for EES; provides means to balance fluctuating power consumption & generation
- FBS is advantageous for applications that require multiple hours of run time

- Flow Batteries Space
  - Multiple hours of run time
  - > 100-kW peak power capacity
  - Applications:
    - Customer Energy Management
    - Renewable Energy Management
    - T&D Facility Deferral

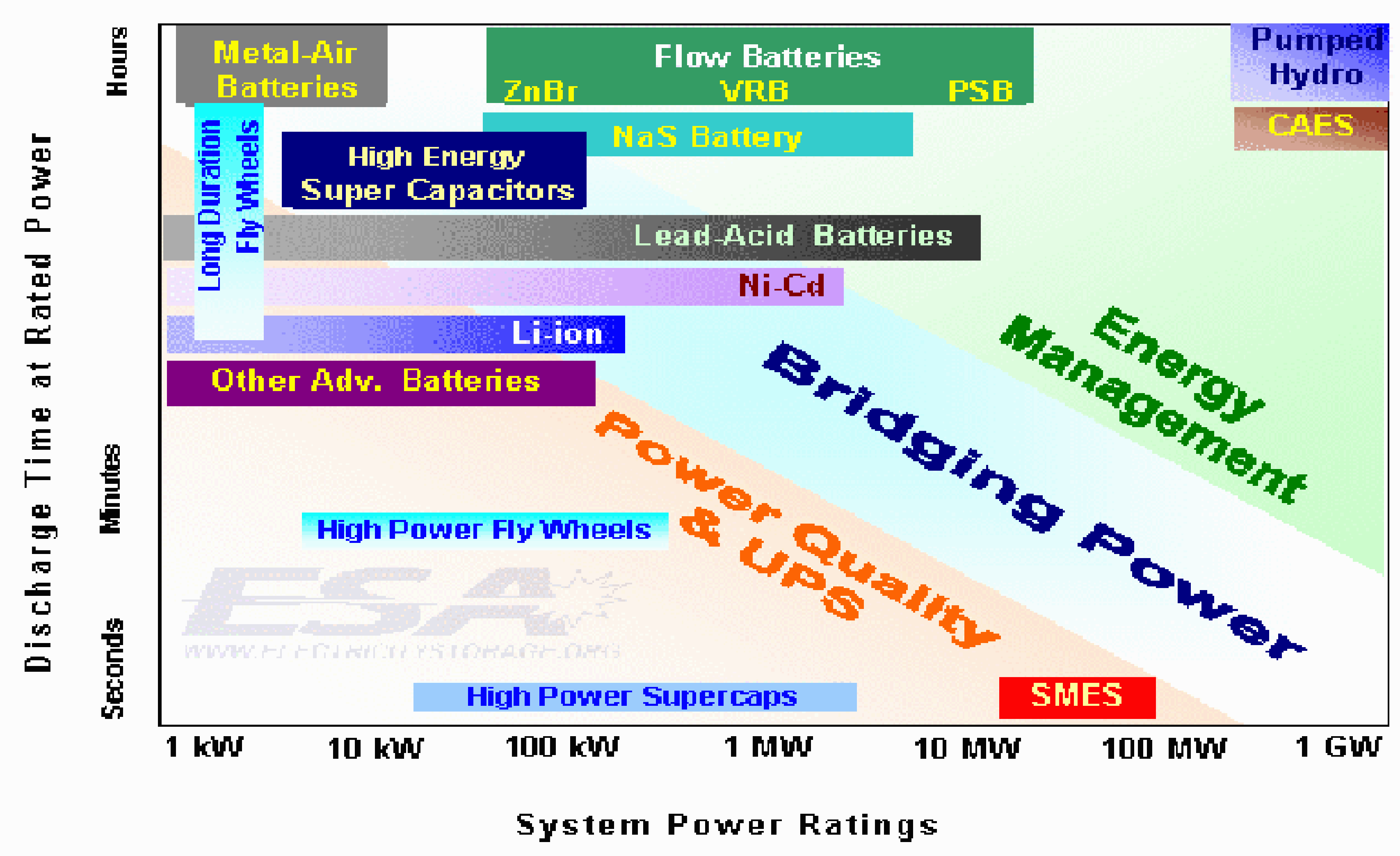


Data from Sandia Report 2002-1314

United Technologies Research Center

EES Technologies

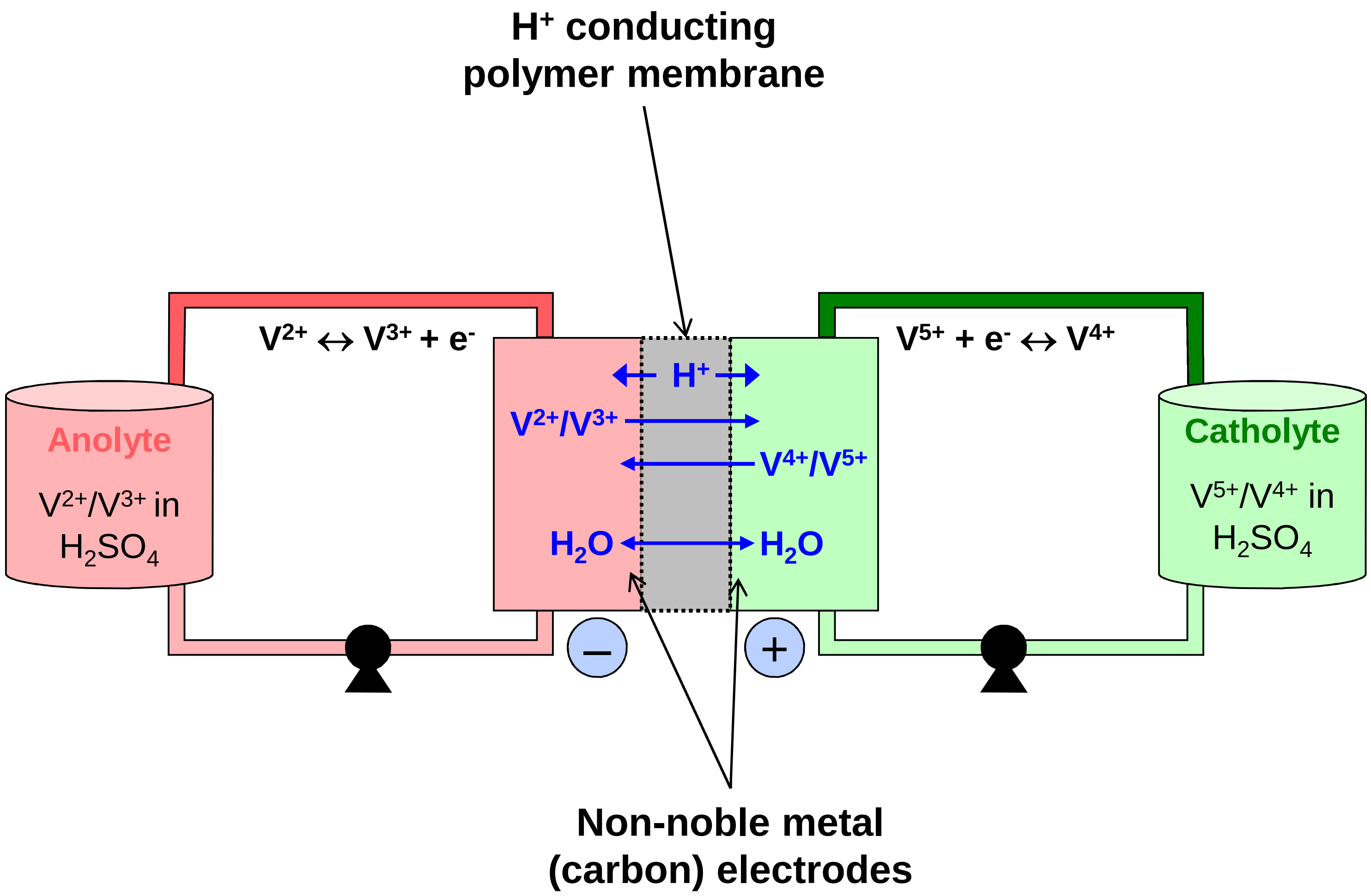
Limited options in area of interest (multiple hours of run time at > 100 kW)



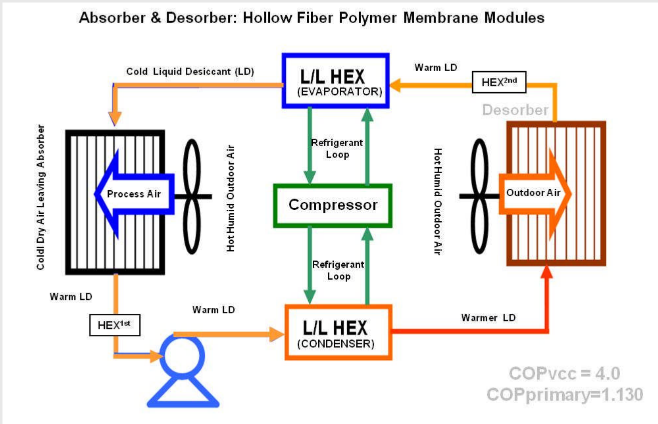
Source: Courtesy of Energy Storage Council - www.energystoragecouncil.org

United Technologies Research Center

Flow Battery Chemistry



Dehumidification Air-Cooling System



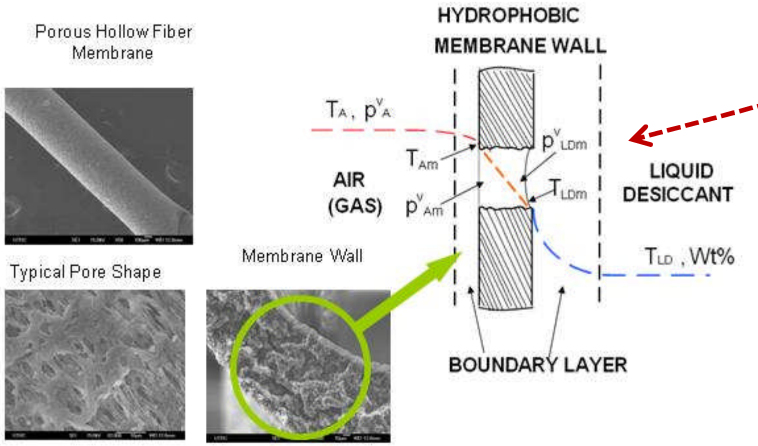
Schematic of an Integrated Air Conditioning System with Liquid Desiccant Hollow Fiber Membrane Modules for Air Dehumidification

Funded by:

Hollow Polymer Fiber Membrane Dehumidifier

Polymer Hollow-Fiber Membrane

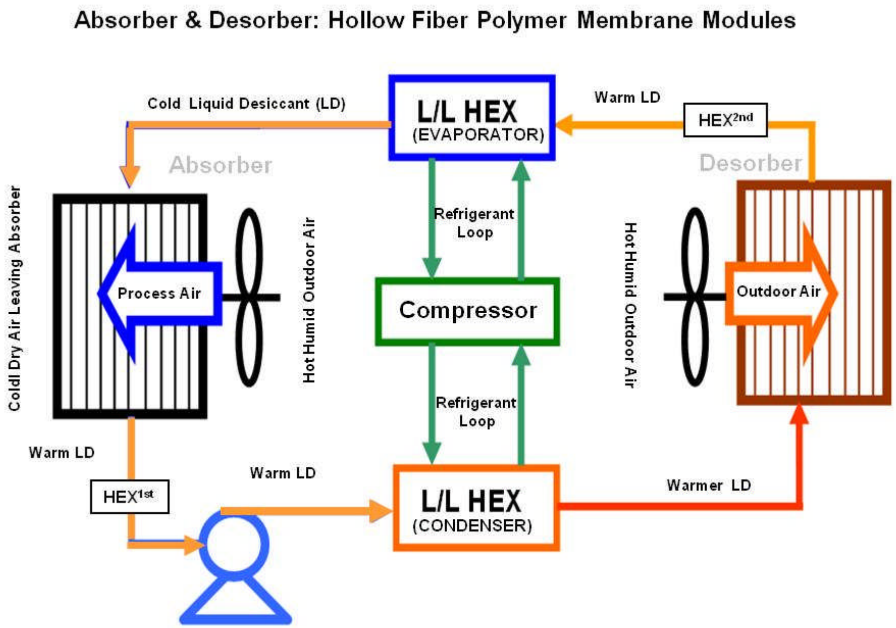
- PVDF preferred membrane material
- High flux membrane (at least 3X current state of the art) for high efficiency



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

Regeneration Air Stream (part of cooled air)
Lower humidity, higher temp

Desiccant Regenerator



Schematic of an Integrated Air Conditioning System with Liquid Desiccant Hollow Fiber Membrane Modules for Air Dehumidification

Operation Concept

- Liquid Desiccant: LiCl aqueous solution
- Air humidity transfer thru hollow fiber membrane to liquid desiccant solution
    - ➢ Temp increases and LiCl concentration decreases
- Warm liquid desiccant stream gets cooled and stripped of water in the regeneration & evaporator step

Acknowledgements

- Dr. Harry Cordatos – Novel CO_2 Separation Polymer Membrane
- Dr. John Wesson and Dr. Gopal Krishnan – Polymer Coated Elevator Belt
- Dr. Michael Perry and Dr. Rachid Zaffou – Flow Battery
- Dr. Zidu Ma, Dr. Zissis Dardas, and Dr. Tim Wagner – Liquid Desiccant Dehumidification System

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