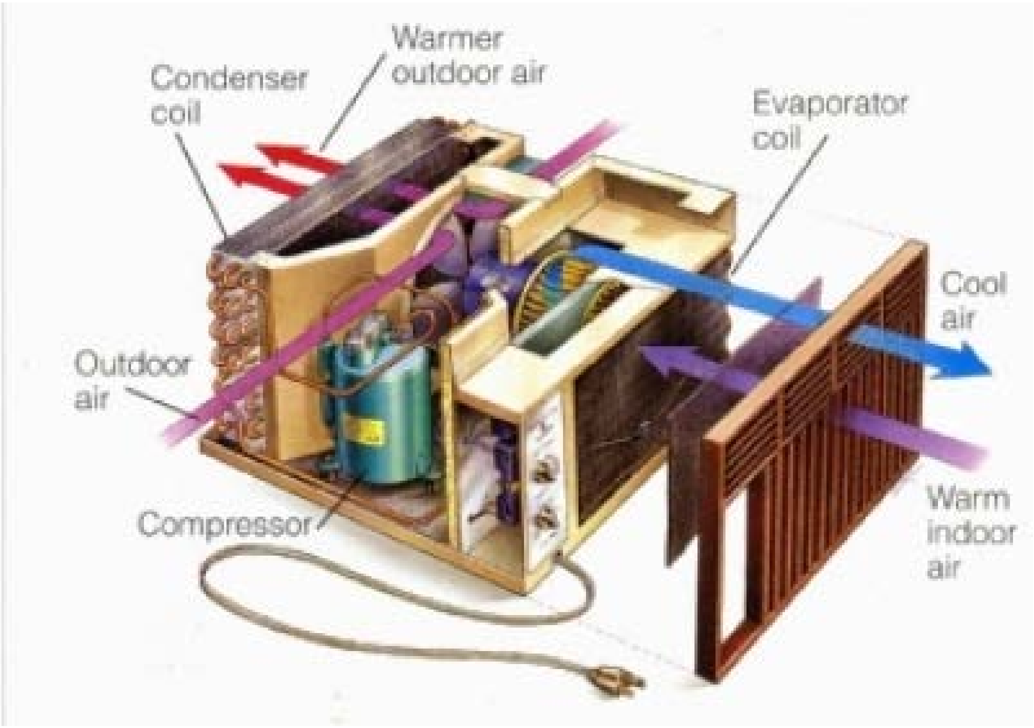
Low-Cost Electrochemical Compressor Utilizing Green Refrigerants for HVAC Applications

2017 Building Technologies Office Peer Review



XERGY

OAK RIDGE National Laboratory

Haier

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

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Xergy, Inc.

Project Summary: DOE BENEFIT ECC BASED HVAC

Timeline:

Start date: June 1 , 2015

Planned end date: June 30, 2017

Key Milestones:

1. Test Novel (low cost) Membranes for each system
2. Develop Advanced MEA/assemblies based on Membranes
3. Design and build prototype ECC system for testing
4. Design and build prototype (Liquid) Desiccant System
5. Design and build Prototype Integrated (Commercial) Unit

Key Partners:

Xergy, Inc.	UD / ORNL / Haier

Budget:

Total DOE $ to date: $1,042,437.94

(6/1/2015 to 3/1/2017)

Total future DOE $:303,542.06

(3/1/2017 to 6/30/2017)

Project Goal:

Develop the most efficient, noiseless, and most environmentally friendly cooling system based on integrating 2 (two) technologies: a) electrochemical compressors (ECC) to replace mechanical compressors for use in building heating, ventilation and air-conditioning (HVAC) applications and b) Ionic Liquid Desiccant Systems.

TRL:

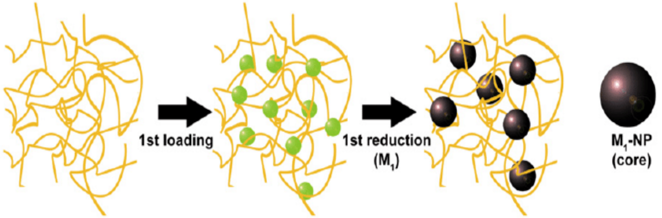
Start: 3 End: 6

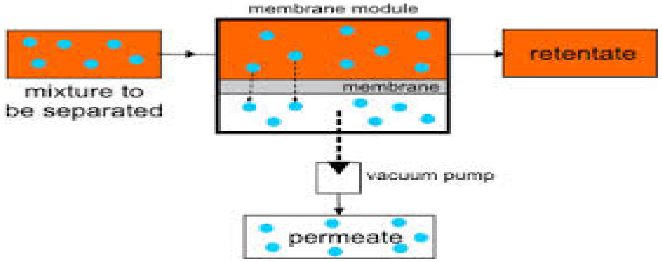
Target Market/Audience:

Residential Window AC Units

Approach – Technology – Membrane Engineering

- "Composite Ion Exchange Membranes"
  - Ion Exchange Media are inherently weak, So we reinforce them to make composites
    - Ultra-thin
    - Ultra-strong
    - Ultra-high Performance
  - Two Key Properties
    - Transport Ions under electric field
      - Cations
      - Anions
    - Transport Active Species
      - Difference in Concentration, Temperature, Pressure …





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Purpose and Objectives

Problem Statement:

- Electrochemical compression (ECC) & ionic liquid desiccants (ILD) are transformative technologies ⇨ significant efficiency gains in HVAC systems
- Overall objective is to develop and build a scalable ILD/ECC-based air conditioning system operating with a COP of 4.5, with a price premium of $70 installed per kBTU/hr.

Target Market and Audience: HVAC systems account for approx. 14 Quads of primary energy annually, or nearly 30% of all energy used in U.S. buildings.

Impact of Project:

- Near Term (1-3 years)
  - Demonstrate and produce high efficiency ECC Window Air Conditioner at a price point viable for the US residential market
  - Potential of savings of 1 Quad/year
- Long Term (3+ years)
  - Experience will support ECC development to replace mechanical compressors in other appliance applications
  - Potential savings of 5 Quads/year

Program Approach

Goals of this program:

- Build prototype units and test technology viability for each system
- Achieve system performance targets by developing advanced components
- Achieve cycle performance target (COP>4) through advanced ECC heat pump system integration with Ionic Liquid Desiccant System
- Demonstrate pre-commercial system (TRL 6) based on advanced components and design (window AC system)

Key Issues:

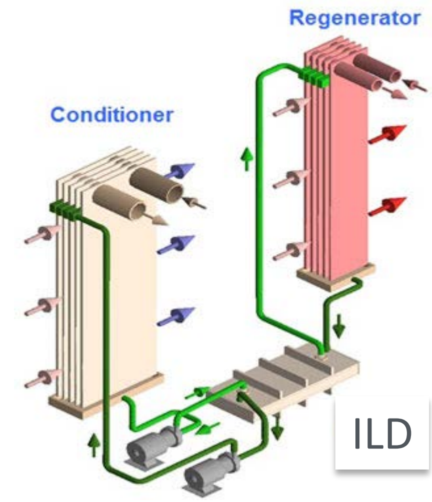
- Achieve Industry Metrics (volume, weight, cost)
- Demonstrate Long term performance
- System integration (integrating heat exchangers, controls and seals)

Distinctive Characteristics:

- ECC driven heat pump, ILD using Low grade heat for regeneration

Approach – Technology – Ionic Liquid Desiccant(s) Integration

- Key is to create higher efficiency cooling systems: dehumidify air without over-cooling using Pervaporation with Xergy membranes
  - Conventional HVAC systems achieve cooling and dehumidification by cooling the air below its dew point in order to condense the moisture and then reheat the air
  - Separate sensible and latent cooling dehumidify air as close (adiabatic if possible) and then sensibly cool it at higher evaporating temperature.

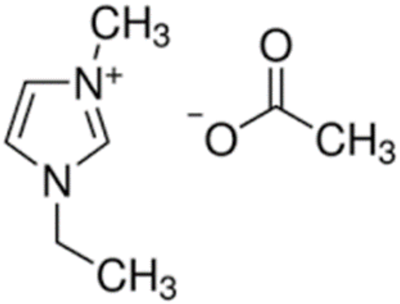


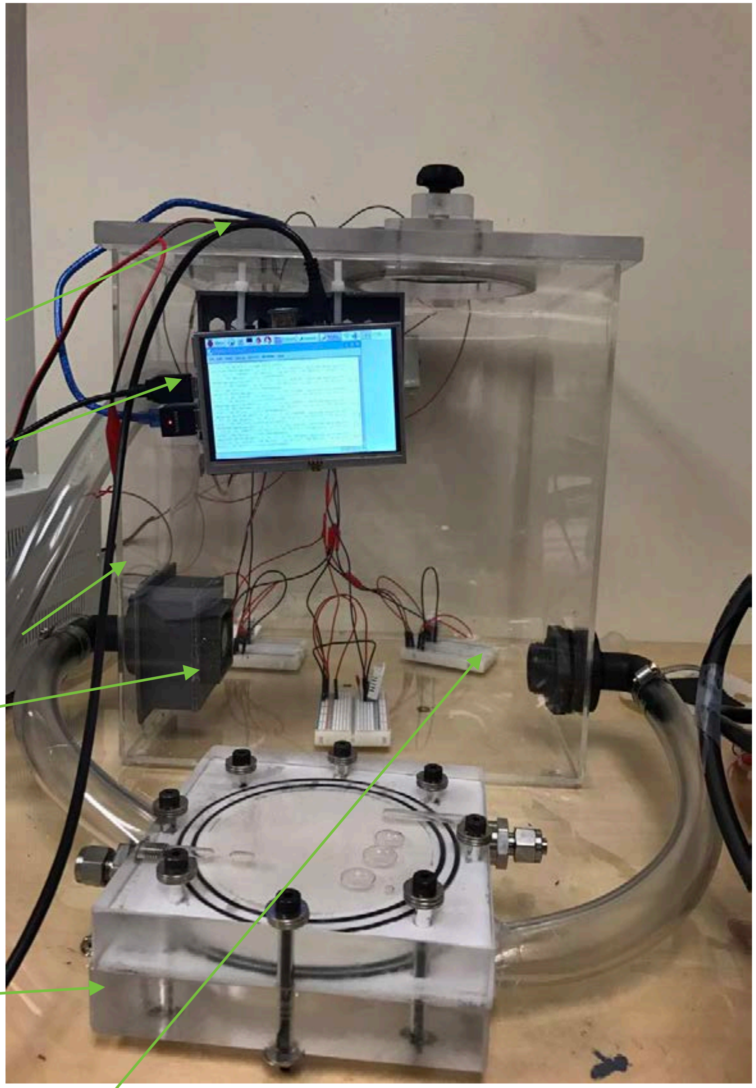
- Ionic Liquid Desiccants (ILD's) are salts in liquid state at room temperature; they can be used as desiccant materials
  - Bulky and asymmetric organic cations
  - Can be designed to optimize the temperature of desorption can use low grade heat for regeneration (i.e. hot side of AC system)
  - Better performance than traditional salt solutions desiccant systems used in HVAC Applications

- In this program, we are integrating novel ILD's with heat exchangers used in ECC heat pump cycles, to use the heat to regenerate ILD's
  - Goal is to improve COP by 25 to 40% with ILD integration
  - Regenerators and contactors using our membranes

Progress and Accomplishments: Ionic Liquid Desiccant

- ORNL Synthesized 8 different candidate ILD's; & Performed Absorption/Desorption tests. Down selected "EMIMOAC" for prototype scale up

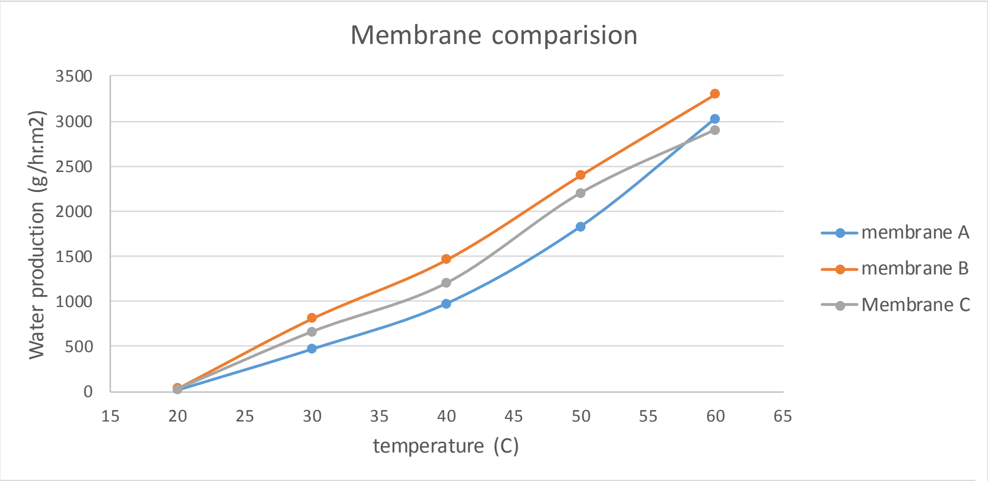




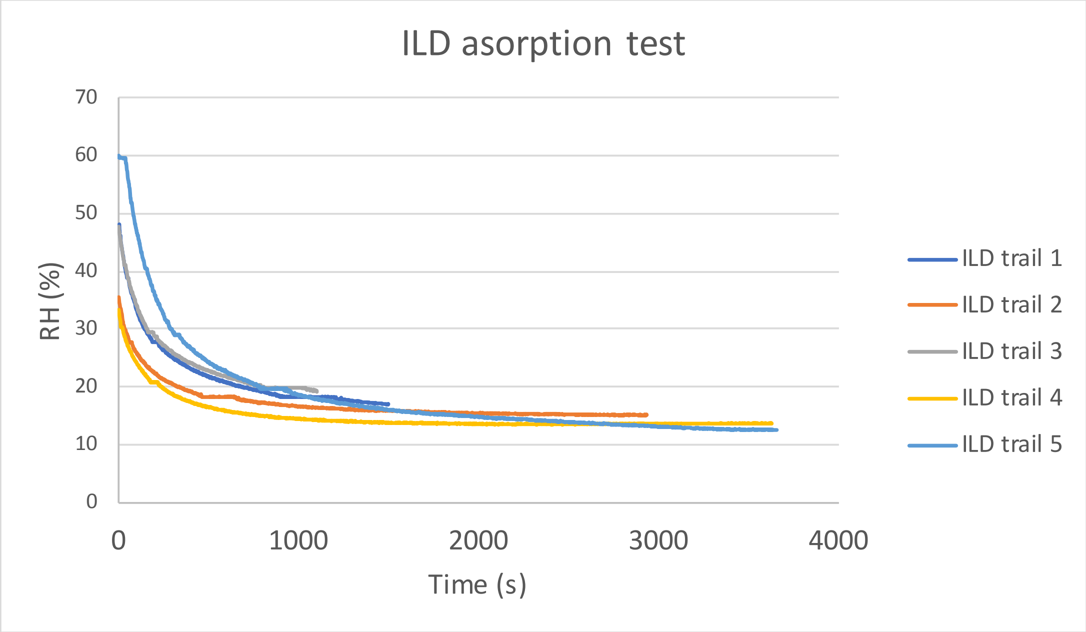
- Filed IP, developed commercial supply, Built AC Prototype testing apparatus.

Progress and Accomplishments: Membrane Selection

- Multiple membranes tested for humidity reduction
- Only one membrane found to be chemically compatible with ILD's.

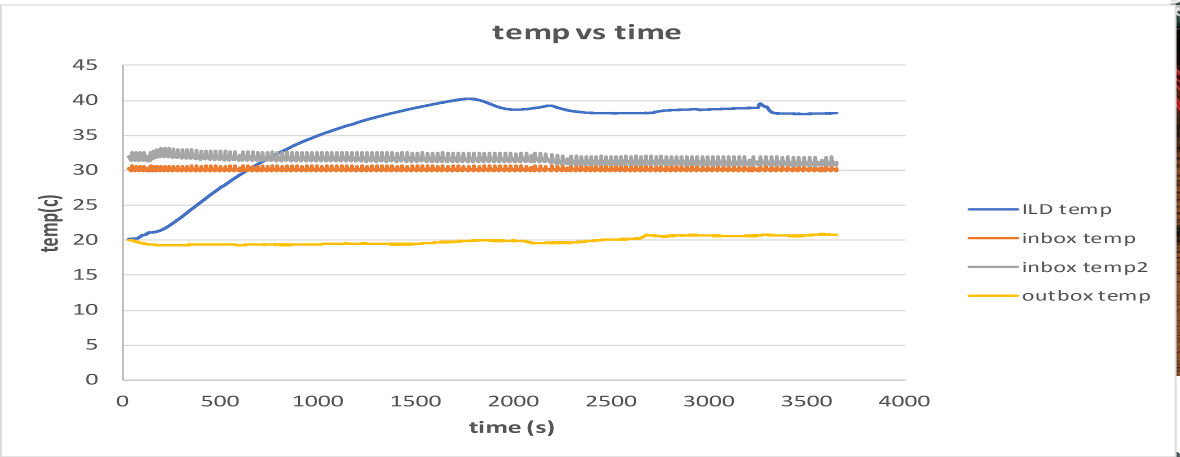


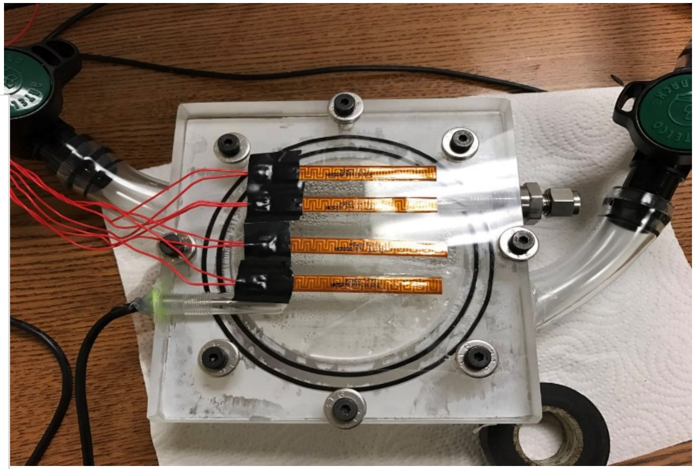
- Membrane Contactor is extremely effective at dehumidification

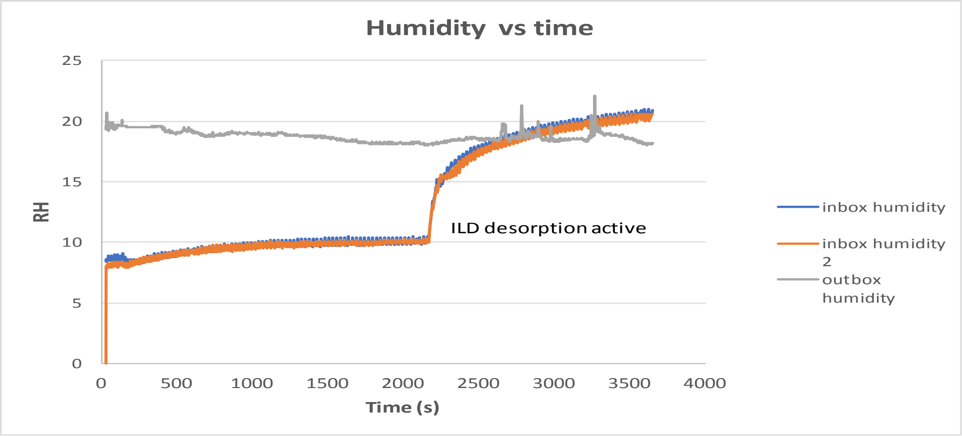


Progress and Accomplishments: Membrane Regenerator

Regeneration Test @ 40 C







humidity increase from 10% to 21% in 1500s

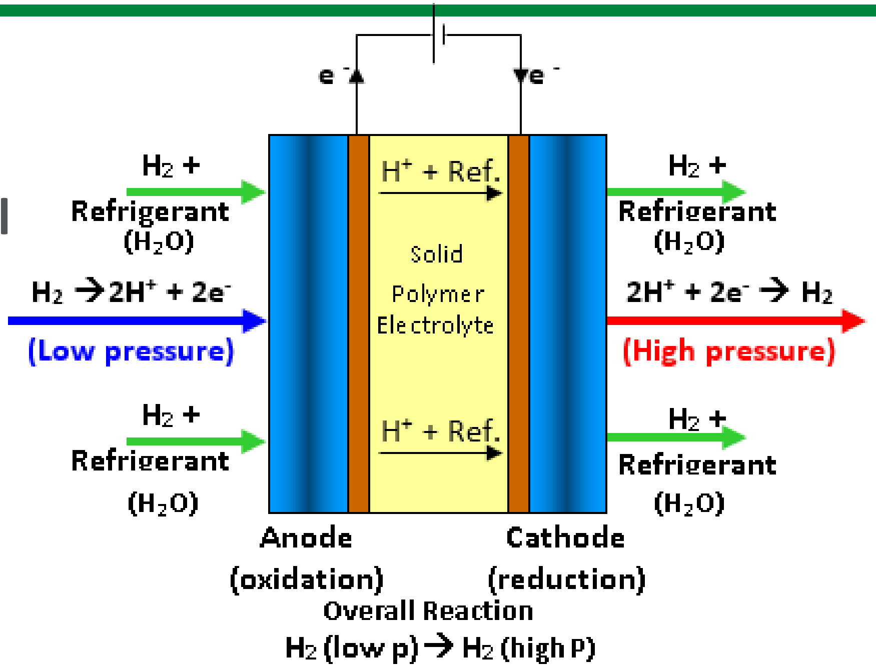
The desorption rate: 1.294*0.02(5.73-2.73)=0.078g/hr.

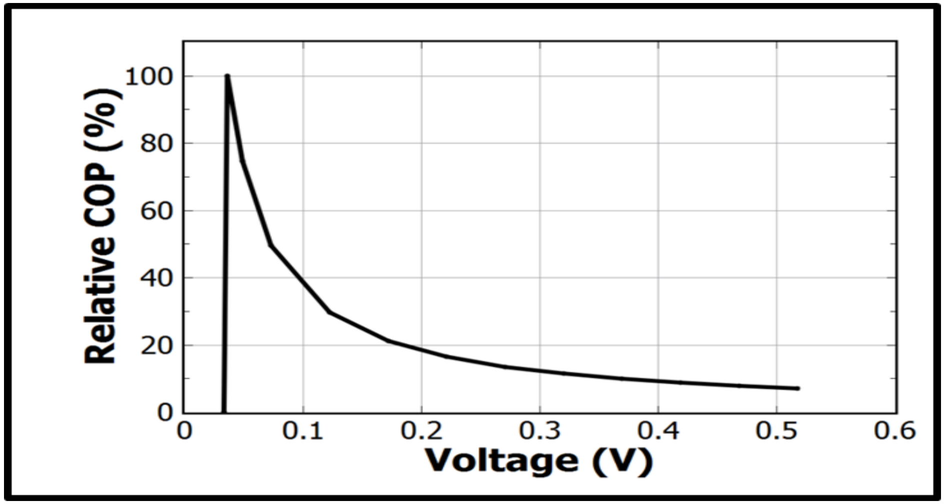
0.078/1500s*3600 = 0.19g/hr.➔ 2.28g/hr.kg ILD

Next step is to produce prototype multi-channel membrane units for system integration with ECC Heat Pumps

Approach – Technology - Electrochemical Compressor (ECC)

- ECC uses an external voltage to **pump hydrogen, water or other refrigerant.**
- The driving force is an **electric potential gradient** governed by the Nernst equation and Ohm's Law
- Multiple **small cells are combined** to create units with the required pumping capability and efficiency for **different refrigeration cycles**
- **Multiple Cycles Feasible:**
  - Water VC Cycle
  - Metal Hydride Heat Exchanger (Absorption) Cycle .. And others
  - NH3 & CO2
- Select Best Cycle for client

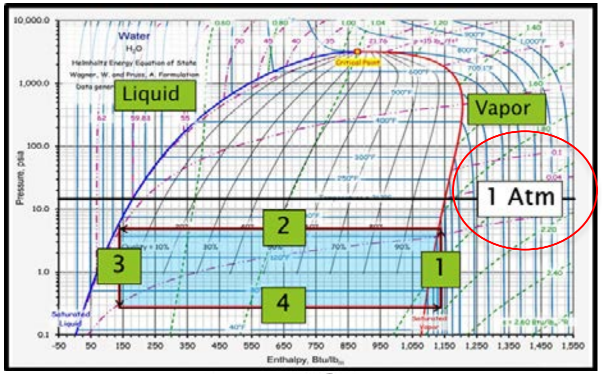


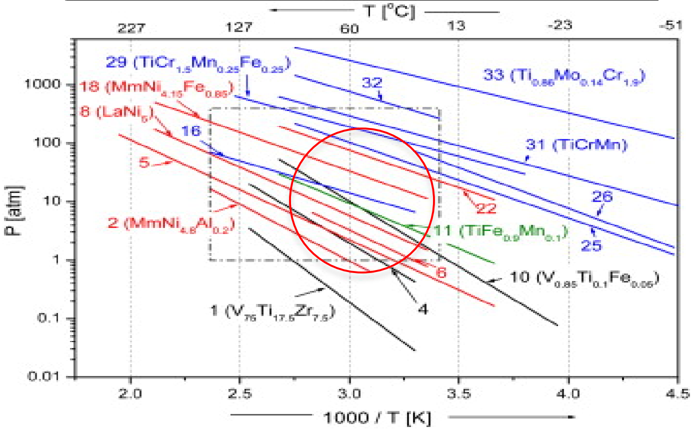


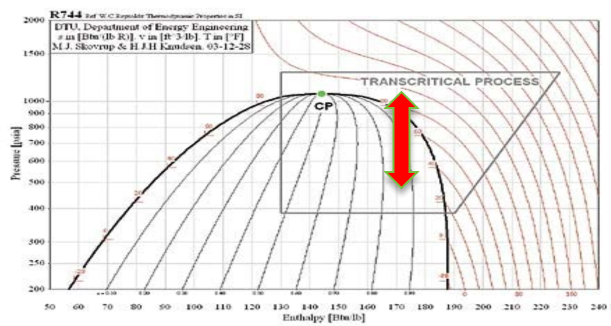
Xergy, Inc. is the world leader in ECC technology

Approach – Technology – ECC Driven Cycles

- Water VC: ECC water compressor requires **low pressure** operation (~2 kPa to 26 kPa) which is impractical using traditional compressors.
- ECC + metal hydride heat exchanger, requires ultra dry compressed hydrogen, at **controlled pressure** operation.
- CO2 VC: requires **low compression ratio**, but large pressure differential (hard to do with mechanical systems).



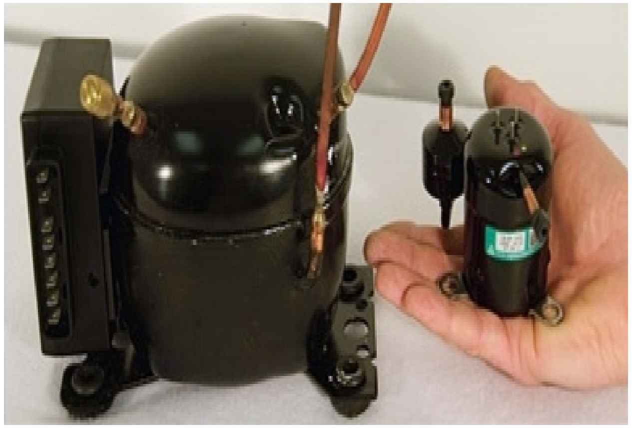




ECC Key Components

- **Key Components:**
  - Polymer Electrolyte Membranes & Electrodes (MEA's) advancements
    - Focus of BENEFIT program
  - Cell Plate advancements
    - Focus of SBIR programs

- **Requirements:**
  - Meet industry Metrics
    - Efficiency, Weight, Volume ..
    - Unit price < $ 70/kBTU installed
  - Identify (low cost) components is required to meet commercial unit targets
  - Integrate with other systems components



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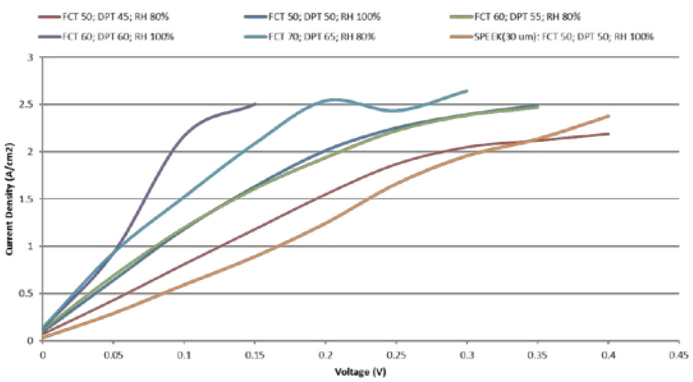
Progress and Accomplishments: ECC Key Components (Membrane)

Advanced PFSA Membrane Composites

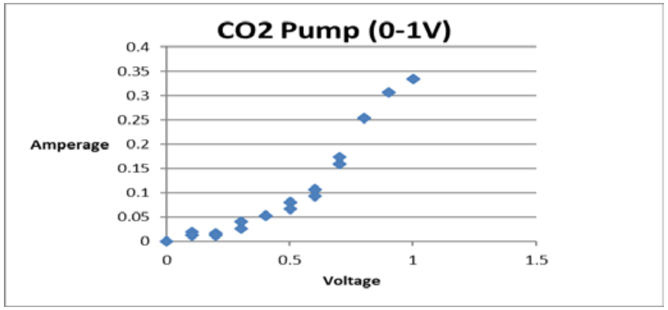
- Advancements made in SBIR programs
- Scaled up and integrated into early BENEFIT System builds

- Our Partner UD, looked At a wide range of cationic membranes For ECC's SPEEK, TPS, PBI, DAIS etc.

- Gen VI Build Settled on PBI composites
    - Quasi-Anhydrous Operation
    - Highest performance
    - Lowest Cost



- Also Started looking at Anionic Membrane Composites ARPA program partnered with UD, RPI, Wash U
- Low Cost Catalyst Systems (no Precious Metals)
- Can be used for Pumping water, hydrogen … as well as other refrigerants like NH_3 and CO_2!!



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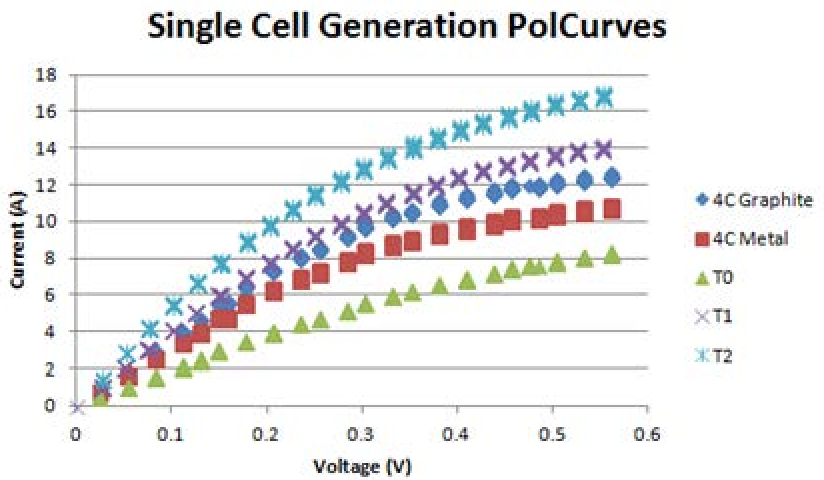
Progress and Accomplishments: ECC Key Components (Bi-Polar Plates)

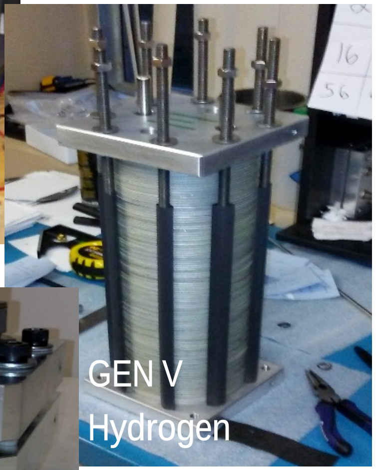
- Different Plate designs developed
- Different Bi-Polar plate materials and coatings tested
- Different Flow geometries for reactants were investigated
- Noted substantial difference in output based on flow design

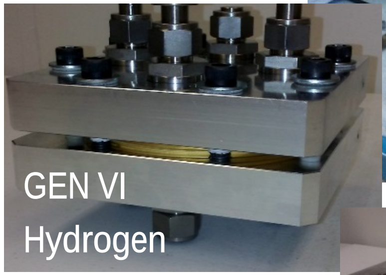


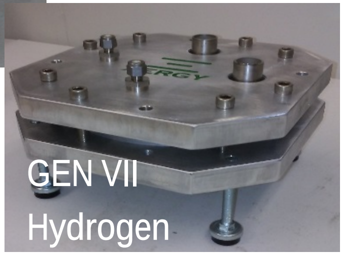



Progress and accomplishments: Compressor Designs

- Water:
  - Gen III system built (under SBIR program)
  - Compressor Performance
- Hydrogen:
  - Gen IV and Gen V systems built (under SBIR program)
  - Gen IV & Gen V stacks integrated with Metal Hydride Heat Exchangers, for 150W Cooling
  - Gen VI & Gen VII ECC small prototype stacks designed and tested
  - Compressor Performance
- CO2:
  - Gen 1 Prototype system built
  - Compressor Performance

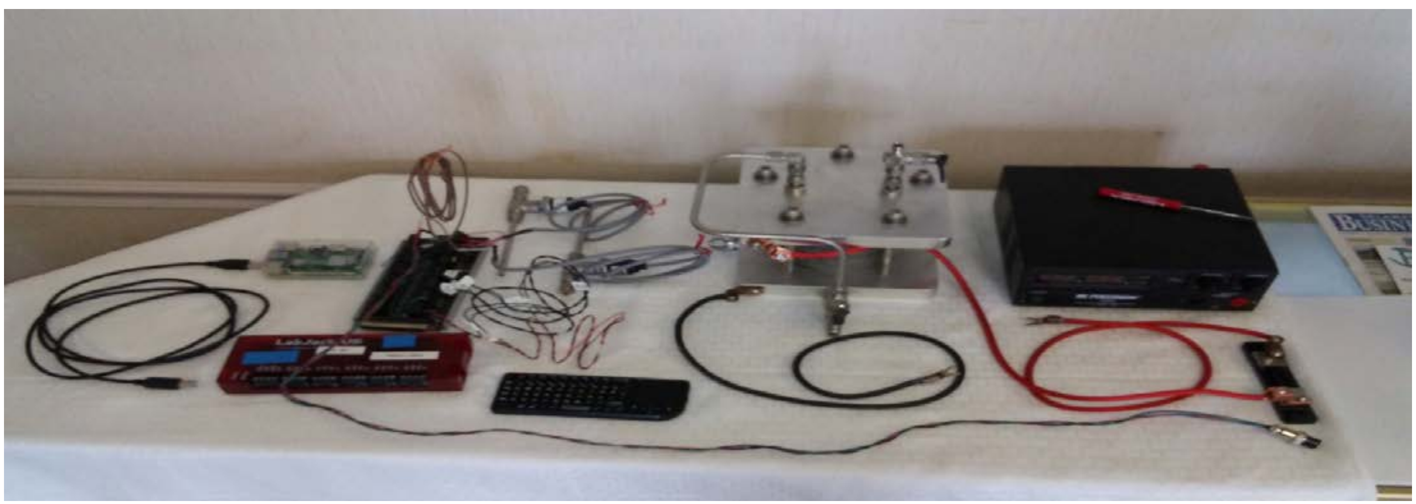


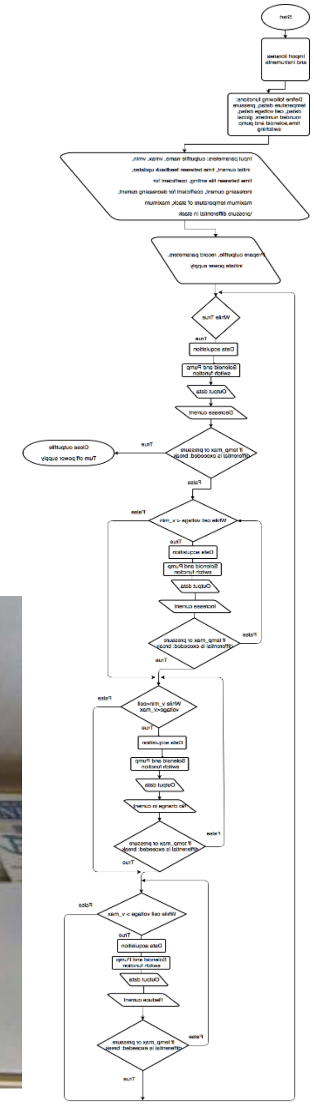




Progress and Accomplishments: Operating Controls

- Developed algorithms for ECC controls
- Built electronics associated with compressors useful for all deliverables (for all programs)
  - Maintains stable operation throughout operation
  - Improves system durability





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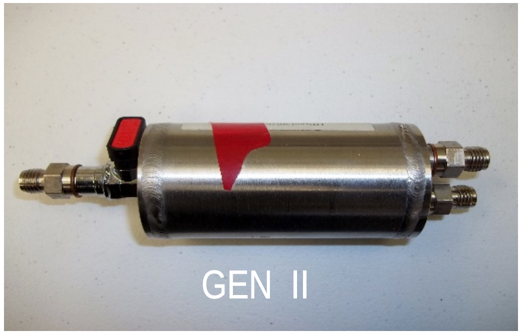
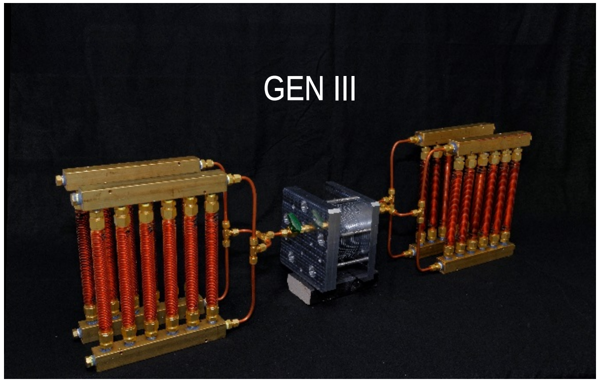
Progress and accomplishments: MHHX Development

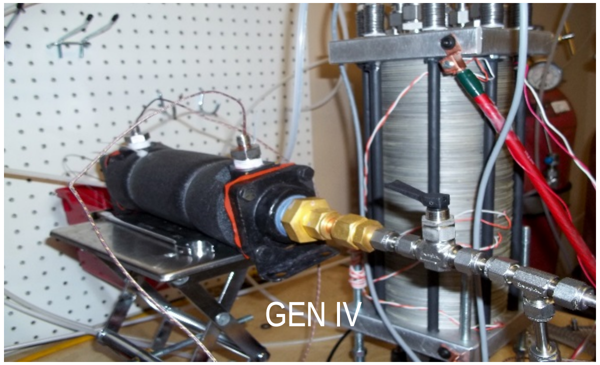
- GEN II MHHX systems purchased
  - Tested with a wide range of MH formulations



- GEN III & GEN IV MHHX Built in house
  - Air & Liquid exchange
  - Started with one formulation of MH
  - Look at alternate formulations, and need to Finalize design



- MHHX units were integrated into ECC systems
  - Delivered 1 system to Haier, second now
  - Haier pushed us for a liquid exchange system
  - Need to integrate ILDs with MHHX



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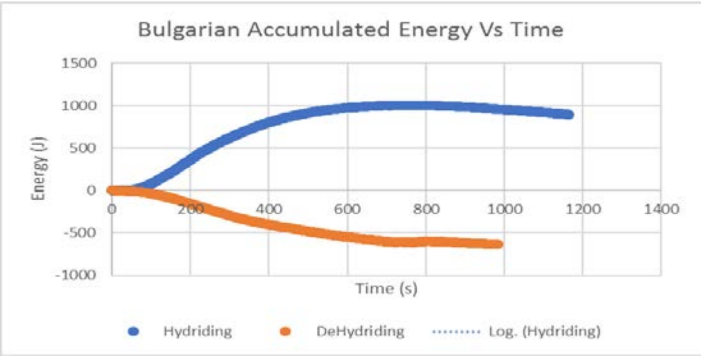
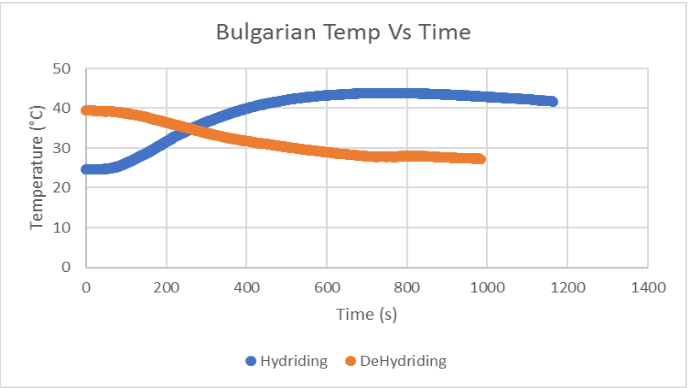
Initial Heat Pump Performance

ACQUIRED

HEAT EXCHANGER





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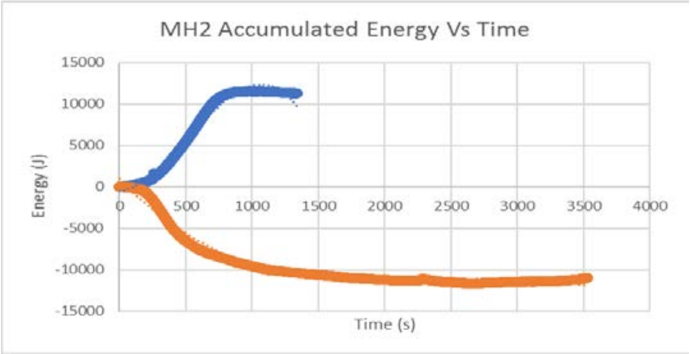
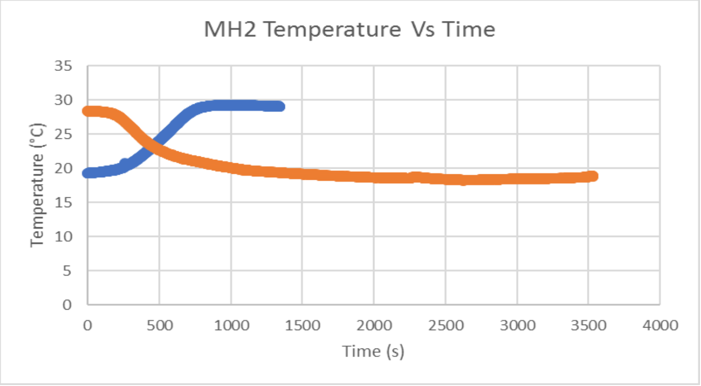
HEAT EXCHANGER





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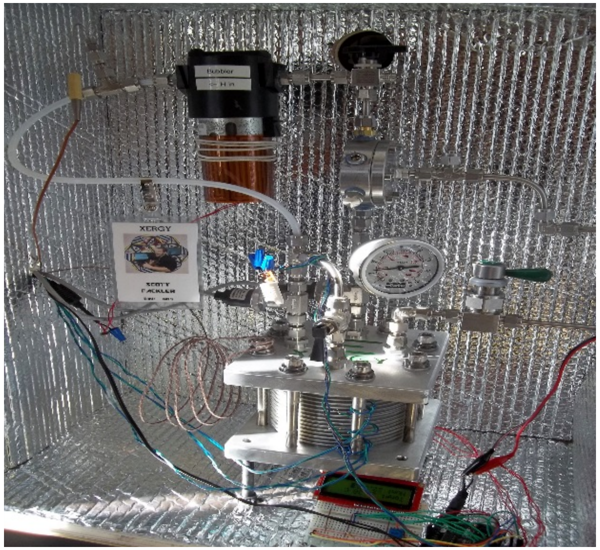
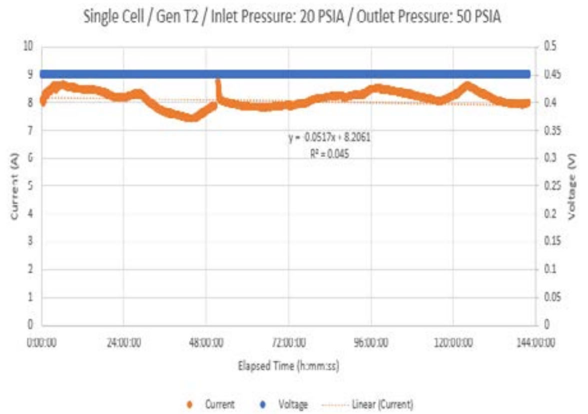
Progress and accomplishments: Endurance Testing

A test station has been built and tested to demonstrate (constant temperature)

- Extended operation at multiple temperatures demonstrated
- All pressure changes were initiated or accounted for by changes in temperature.



Need to continue to perform endurance tests with ECC's, and also on Metal Hydride Heat Exchangers and ILD systems independently, and then as a 'system'.



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Accomplishment Summary

- √ ILD prototype worked very well and is ready for scale up for commercialization (will require unique component development and endurance testing)
- √ Gen III water compressor is operational (proven) and one system based on this design was delivered to a client
- √ Gen VII hydrogen compressor operates very well, AND is competitive with current commercial Mechanical Compressors. Gen V system has been delivered to initial clients (for non-heat pump applications)
- √ Gen IV liquid coolant metal hydride heat exchanger built in house, integrated into a heat pump system and tested.
- √ Endurance testing and system integration with ILD's in process.
- **Final Deliverable of an integrated 1000 Btu Heat Pump System will be completed by June. Haier will integrate that unit into a window AC unit.**

Progress and Accomplishments

Lessons Learned:
- **Packaging is 'the' critical issue -** requires creative designs / plumbing / sealing
- **System integration is key** – different components need to be 'orchestrated'

Market Impact:
- Higher Efficiency cycles for HVAC are VERY significant
  - Low GWP, No direct environmental impact
- Target Market: HVAC units

Awards/Recognition: GE Ecomagination Award 2011, Clean-tech Award Finalist 2012, Defense Energy Technology Challenge Finalist 2014; Partnered in 3 ARPA programs for advanced membranes.

Project Integration and Collaboration

Project Integration: **Xergy Inc. has**

- Established Strategic relationship with major (global) market leader
- Sponsored related work at the University of Delaware & Delaware State

Partners, Subcontractors, and Collaborators:

- Xergy, Inc.
  - Dr. William Parmelee, PI
  - Bamdad Bahar, President Xergy, Inc.
- ORNL
  - Omar Abdelaziz
- University of Delaware
  - Ajay Prasad
- HAIER
  - Innovation Group

Communications: Currently have 50+ patents in process, presented numerous papers including ACEEE Hot Water Forum 2013, exhibited at Fuel Cell Seminar 2015, ECS 2015, AHR 2016, Art of Compression Colloquium 2016, IHR Rotterdam (2 Papers) 2017

Next Steps and Future Plans

- ILD commercialization is a must! This is important
- Building multi-ton compressors is the next logical step.
- Endurance testing, must be continued to validate long-term performance
- Heat Exchangers advancement and system integration with ILDs are 'critical issues'. Xergy is working with our partners to address 'system integration' needs in balance of time. This is a 'big body' of work!