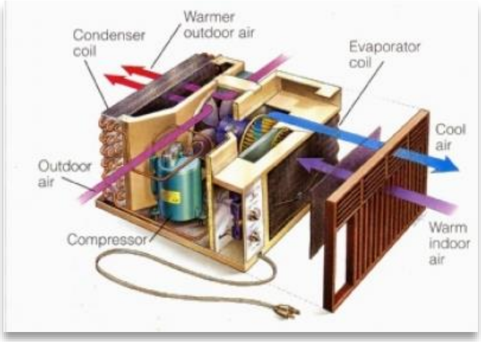
(1) **Advanced Hybrid Water Heater Using Electrochemical Compressor (ECC)**

(2) **Low Cost Electrochemical Compressors utilizing green refrigerants for HVAC applications**

(3) **Hydrogen metal hydride based heat pump system for large HVAC applications utilizing an ionic liquid desiccant sub-system**

Xergy Inc: Bamdad Bahar



Project Summary

Timeline:
Start date: 11/07/2017
Planned end date: 5/31/2020
Key Milestones
1. 3x500 watt demonstration EC compressor unit at target performance as defined in task 2 – Year 1
2. 3x500 watt demonstration MHX unit at target performance as defined in task 2 – Year 1
3. 3x500 watt ILD demo units operational at both MHX and VPCC sink temperatures – Year 1
4. ILD system integration for 10 x 500 watt system – Year 2
5. 10 X 500 Watt fully integrated MHX+EC compressors + ILD unit. – Year 2

Key Partners:

Xergy Inc
University of Delaware
ORNL
NREL
Haier Group

Budget:

Total Project $ to Date:
- DOE: $679,175.52
- Cost Share: $262,867.28

Total Project $:
- DOE: $1,538,290.00
- Cost Share: $767,568.00

Project Outcome:
To simultaneously advance 3 inter-related, transformational, and disruptive heating and cooling technology platforms through delivering functional home appliances: Air Conditioner, and Hybrid Hot water heaters. Technologies are:
1. Electrochemical Compression
2. Metal Hydride Heat Exchangers
3. Ionic Liquid Desiccants

TRL: 6

Team

Xergy Inc. : Advanced Ionic Membranes / Metal Sorption
Mark Golben – P.I. – (MHHX) Metal Hydride Heat Exchangers
Sam Dorman – (ECC) Electrochemical Compressors
Harish Opadrishta – (ILD) Membrane Pervaporation Systems

University of Delaware: Dr. Ajay Prasad – Center for Fuel Cell Research
Core Technology Development (CO2 & NH3 Compressor)

Haier Group: Wei Wei: Haier AC - System Integration

NREL: Jason Woods: ILD System Consulting (and Testing)

ORNL:
Shen Bo: Heat Pump Testing, Appliance Testing
Xiaobing: ILD System Testing, Appliance Testing

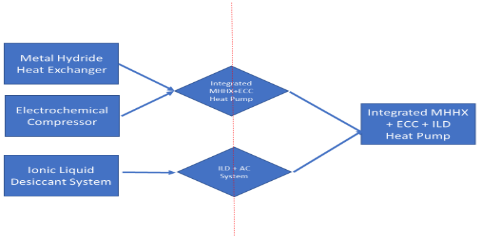
Challenge: Advancing 3 Technology Platforms

Problem:

- HFCs are up to 10,000 times more potent than carbon dioxide in contributing to climate change. Emissions of HFCs are expected to nearly triple in the U.S. by 2030. US is a partner in global action to phase down HFCs.
- HVAC, water heating, and refrigeration systems are the largest energy consuming appliances in buildings, using nearly 50% of all energy in U.S. buildings.

Challenge: THIS IS A BIG HAIRY AUDACIOUS GOAL – TO TRANSFORM HEAT PUMPS

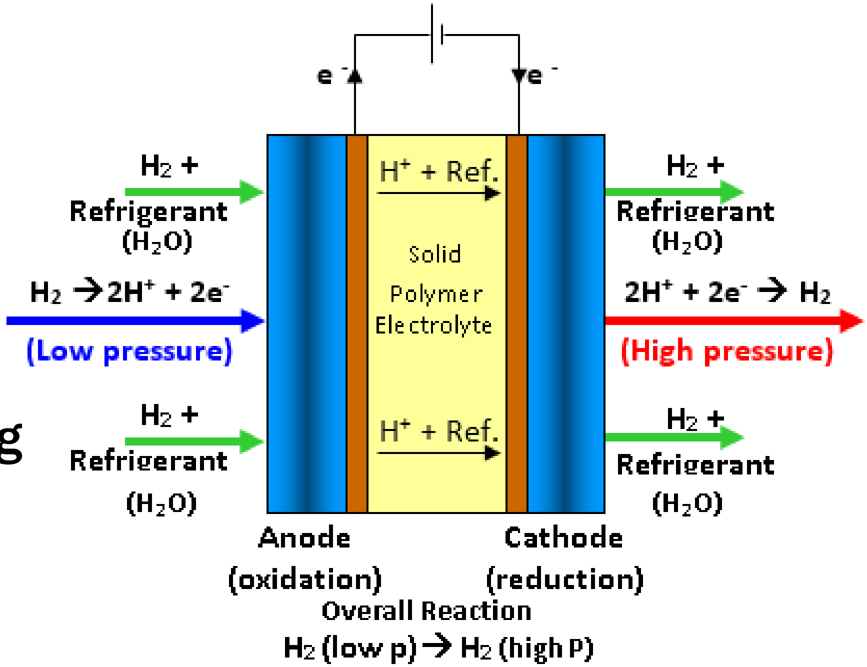
Xergy has proposed the integration of 3 major ‘platform’ technologies into one system. Each one has the potential to transform Heating and Colling systems. Xergy is delivering the following prototype appliances: **Hybrid Hot Water Heater, Window Air Conditioner for residential use, and a Distributed HVAC Unit for commercial buildings**. These units will showcase the following technologies: **(1) Electrochemical Compressors, (2) Metal Hydride Heat Exchangers and (3) Ionic Liquid Desiccants**

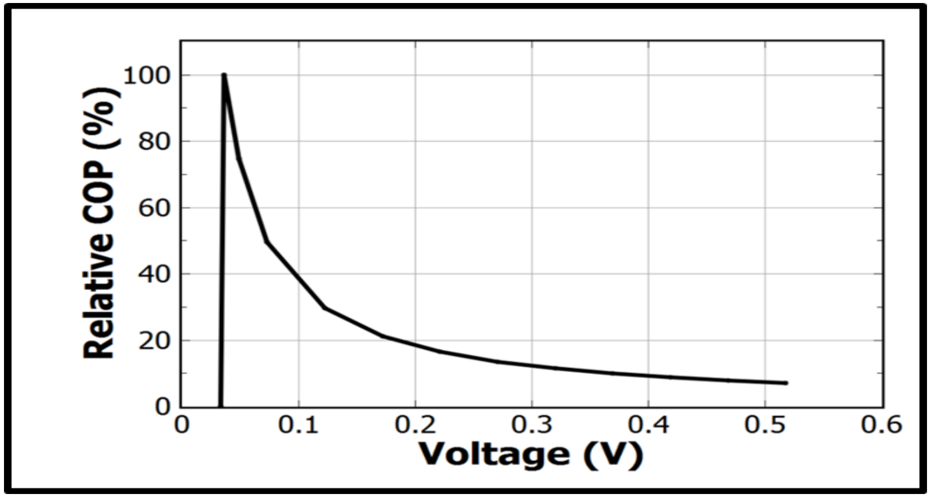


Together with its partners Xergy will not only develop demonstrate units, but put in place a commercialization plan in support of DOE program goals of phasing out HFCs and reducing energy use in commercial and residential buildings.

Approach – Technology - Electrochemical Compressor (ECC) Platform

- ECC uses an external voltage to **pump hydrogen, water or other refrigerants.**
- 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**
- **Many Fluids Feasible:**
  - H2, Water, CO2, NH3, O2
  - Vapor Compression or Absorption
- **Most Efficient system,** No Moving Parts, Reliable, Scalable, Modular, noiseless, vibration free. – wide temp range!

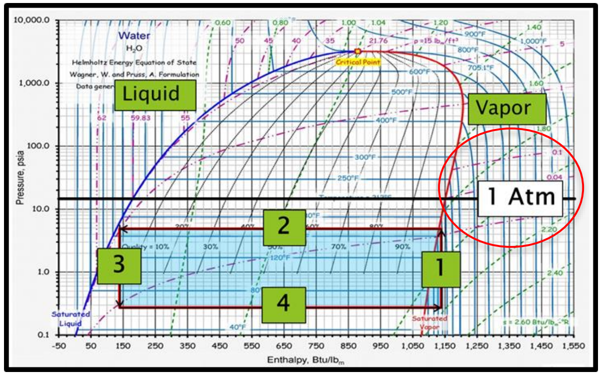


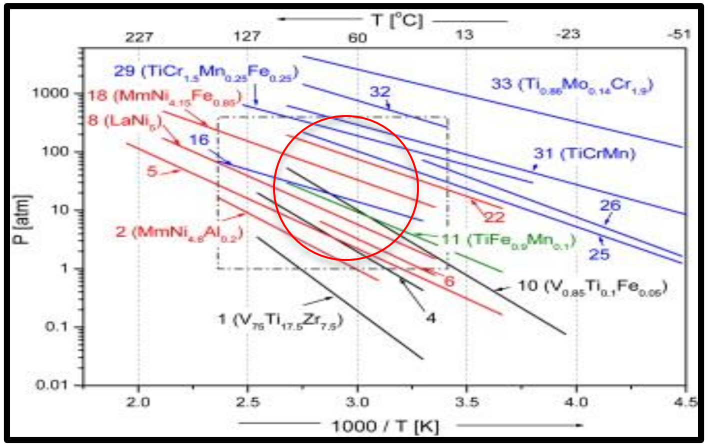


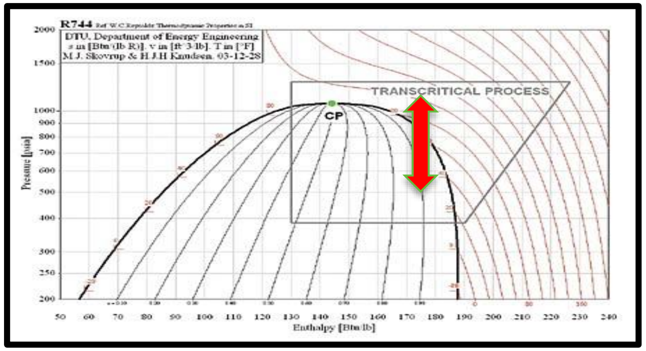
Xergy, Inc. is the world leader in Ionic Membrane technology

Approach – Technology – ECC Driven Cycles

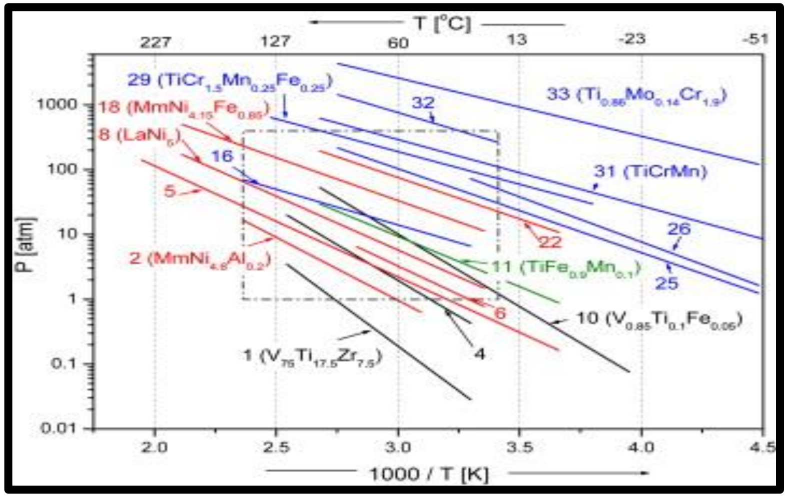
- Water VC: ECC water compressor requires **low pressure** operation (~2 kPa to 26 kPa) which is impractical using traditional compressors.
- Hydrogen (ECC) + Metal Hydride heat exchanger, requires ultra dry compressed hydrogen, at **controlled pressure** operation.
- NH3, CO2 Vapor Compression



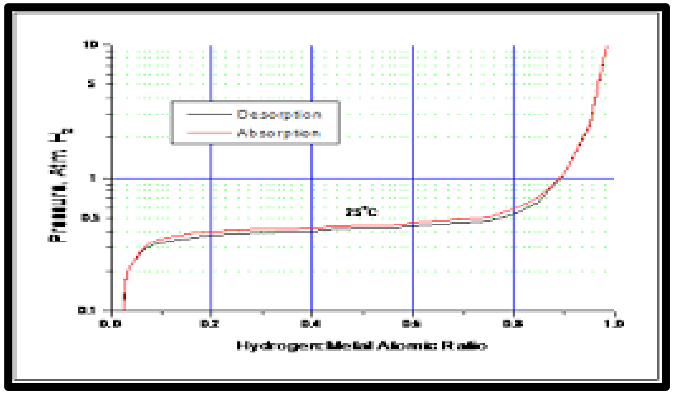




Approach: (ECC +) Metal Hydride Heat Exchangers Systems

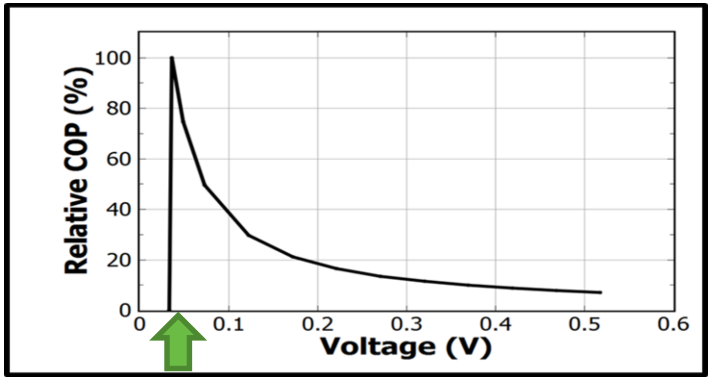


MHHX Heat Exchanger

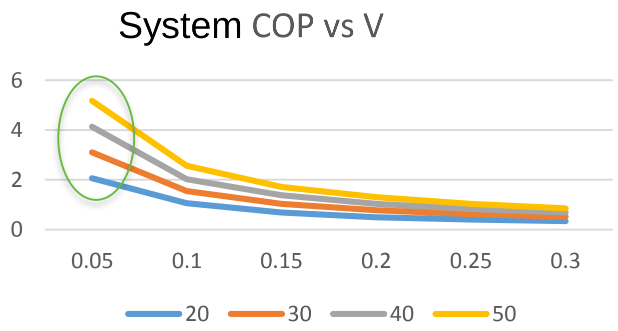


Almost Reversible Reaction
Difference Between Curves is called Hysteresis
< 5% Loss For "Right Hydrides"

Hydrogen Compressor

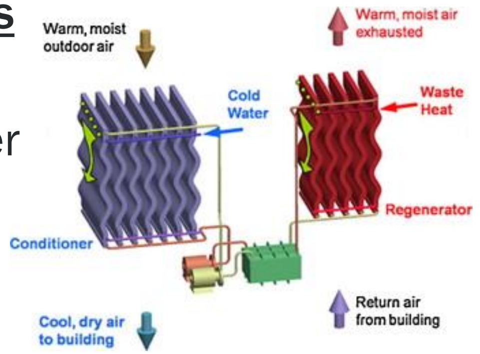


Operating Point (0.05 V)



Approach – Technology – Ionic Liquid Desiccant(s) Integration

- **Key is to create higher efficiency cooling systems: dehumidify air without over-cooling using Pervaporation with across 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**
  - Our Systems are designed for optimized desorption temperatures using low grade heat for regeneration
  - Better performance than traditional salt solutions desiccant systems used in HVAC Applications
- **We are integrating novel ILD's with heat exchangers used in ECC heat pump cycles, to use the heat rejected from heat pump to regenerate ILD's**
  - Goal is to improve COP by 25 to 40% with ILD integration
  - Regenerators and contactors using our ionic membranes



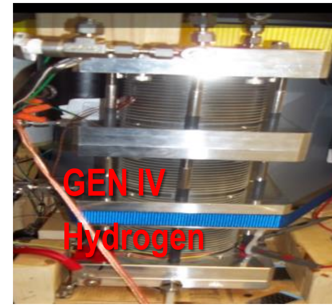
ILD

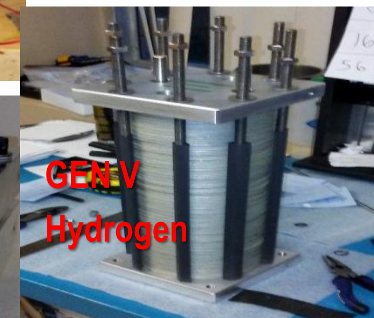
Progress and accomplishments (2019): EC Compressors

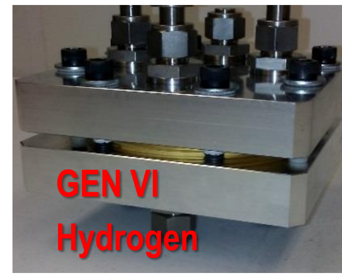
- **Water:**
  - Gen III system built (under SBIR program)
- **Hydrogen:**
  - Gen IV and Gen V systems built (under SBIR program)
  - Gen IV & Gen V stacks integrated with Metal Hydride Heat Exchangers, for 150W Cooling
  - Gen VI & Gen VII ECC small prototype stacks designed and tested
  - Gen VIII & Gen X Built and now being integrated into HHWH, and Air Conditioner
    - Gen X is 3x smaller than Gen VIII, which was 3 x smaller than Gen V …
  - Gen XIII – We backed up (-30%) … Sealing issues…. But,

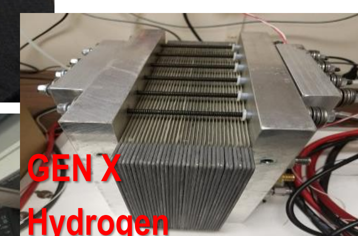
Milestone 1: Successful operation at 750 psi @ 12 Lpm

- **Our goal, however, is 2000 psi for ULT systems**
- **CO2:**
  - Single Cell Prototype system
- **Ammonia:**
  - Mini-Stack Built with Advanced MEA’s

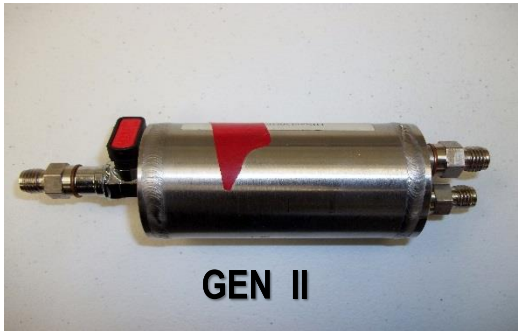




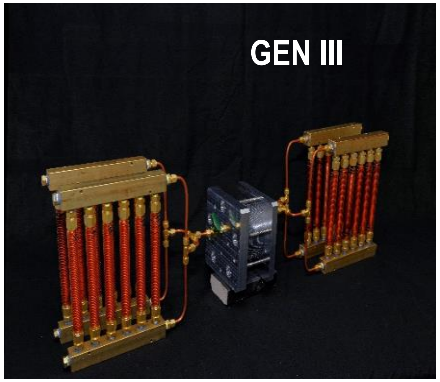




Progress and accomplishments (2019): MHHX Development



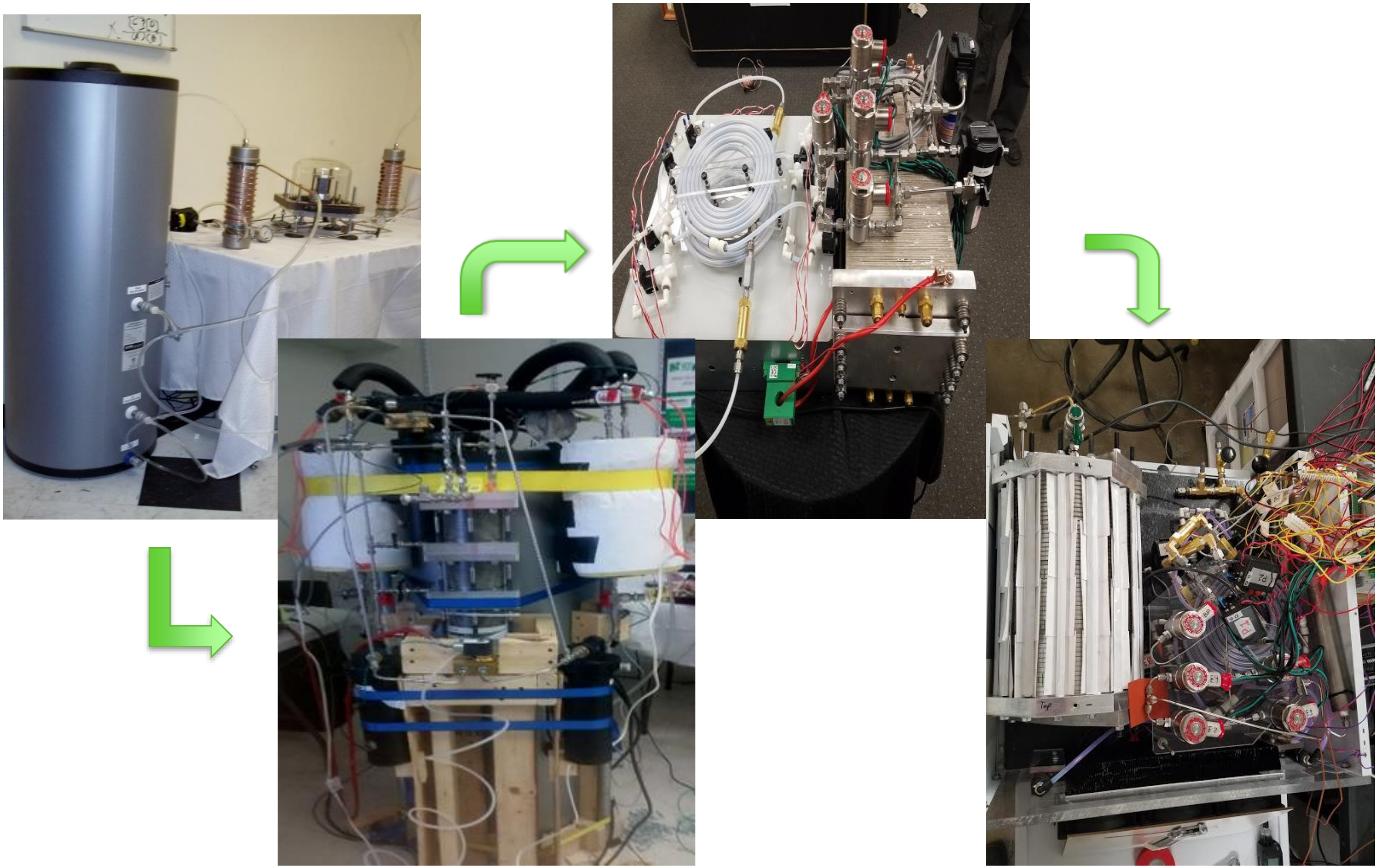
- **GEN II MHHX systems purchased**
  - Tested with a wide range of MH formulations



- **GEN III & GEN IV MHHX Built in house**
  - Air & Liquid exchange
  - Started with one formulation of MH
  - Alternate formulations analyzed

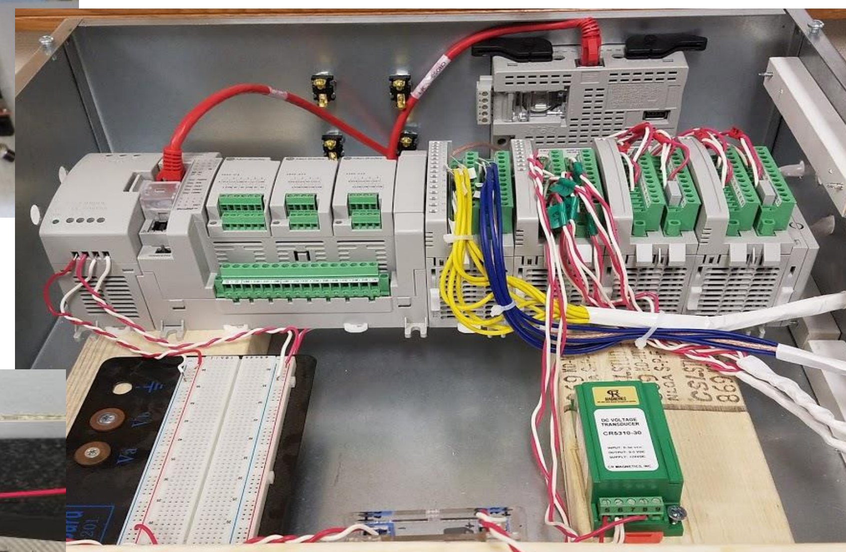
- **GEN V MHHX Built and Integrated**
  - Liquid Exchange System
  - Narrow Diameter System
    - Faster Heat Exchange, Lower Material Cost
    - New (Proprietary) Alloys to Achieve Different Outcomes

Progress and Accomplishments (2019) – Integration

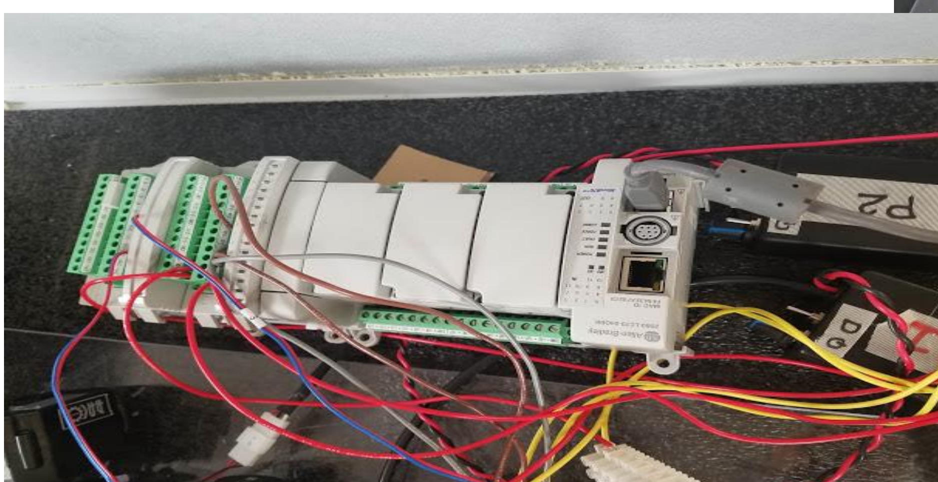


Progress and Accomplishments (2019): System Controls

Basic On/Off switching

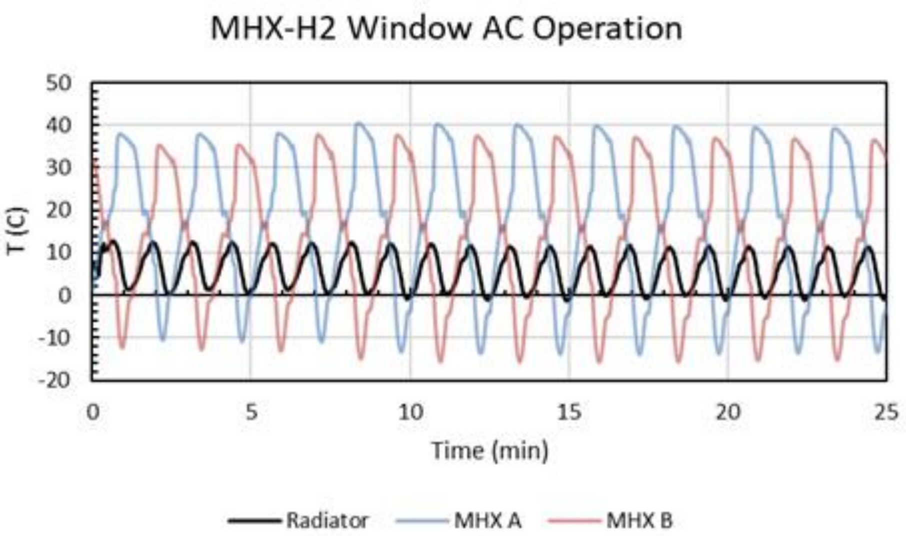


PLC Controls



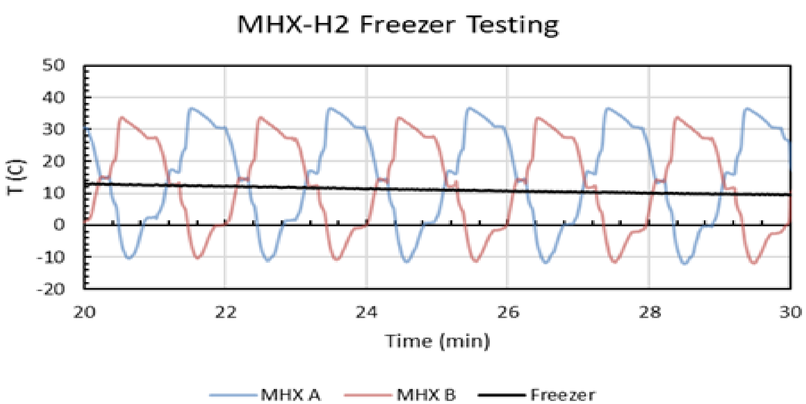
Advanced Logic

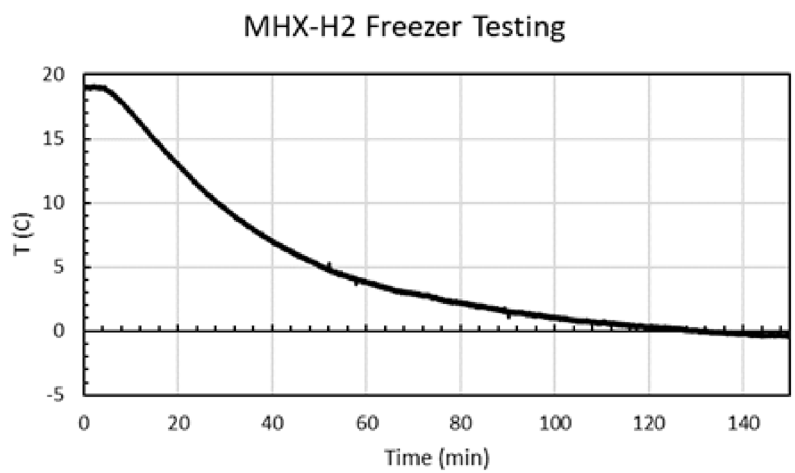
Heat Pump: System Performance Data



- **Milestone 2: Window AC Conditions Met** ✓
- **Hydrogen flow: 12 SLM and 750 PSI**
- **Heat Exchange Fluid: Alcohol, 1 l/min**
- **Nominal Cooling Capacity: 500 Watts**
- **Building 5 Prototype Systems NOW for delivery**

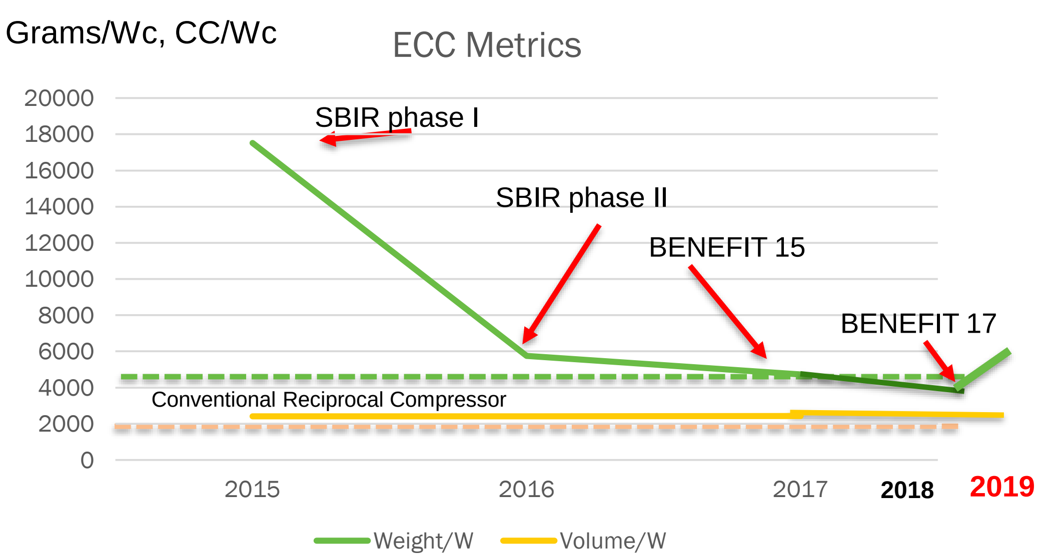
- **Freezer: Achieved -41 C**
  - However, need -85 C for ULT

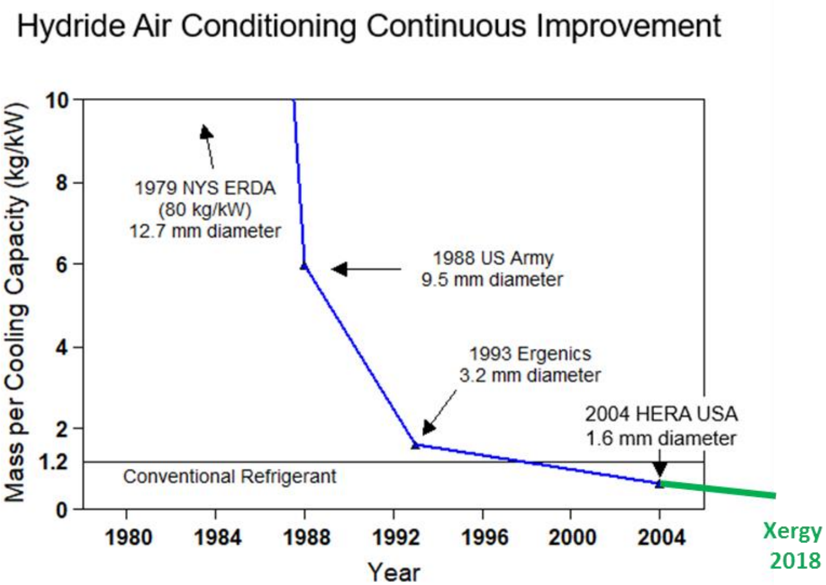




Hydride Heat Pump: System Metrics (2019)

- ECC: Substantial Reduction in both Weight and Volume per Watt of Cooling in 2018; **receded 30%** last year due to 'extra weight and volume' to address sealing issues 2019 (Still close to meeting Reciprocal Vapor Compressors)
- **MHHX: Currently Exceeding Size and Weight for Conventional refrigerant systems**

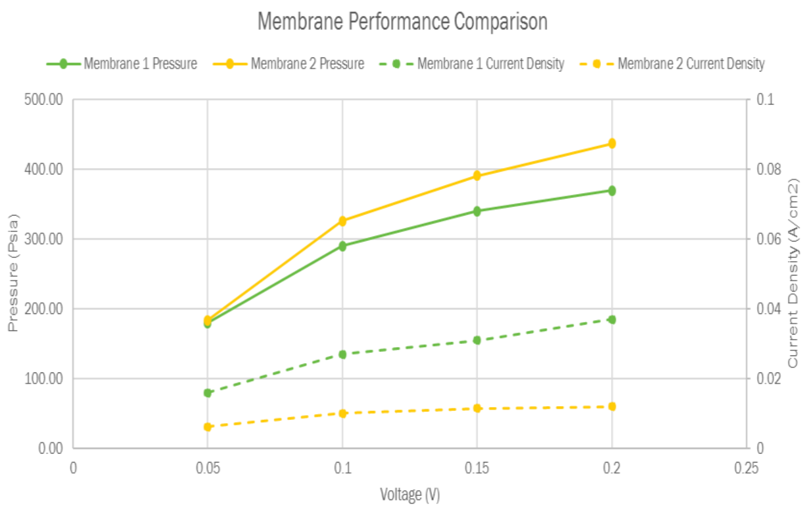


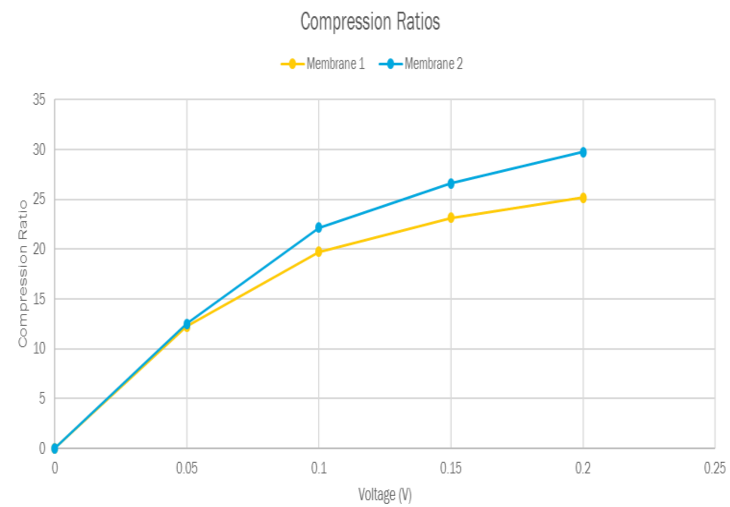


Critical Issues – Heat Pump – BP2

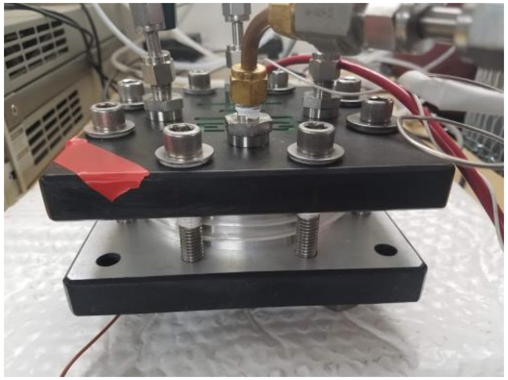
- **Delivering 5 systems to stake holders (for feedback) – 05/19**
- **System Optimization -**
  - Reducing Sensible Load
  - Reducing Distance between troughs and crests in radiator
- **Even More Advanced ECC's**
  - Bi-Polar Plate Production
  - Advanced flow field modeling
  - Advanced Sealing
  - 'Alkaline Systems' key to ULT
- **Balance of Plant**
  - "other components": Pumps

Ammonia Compression



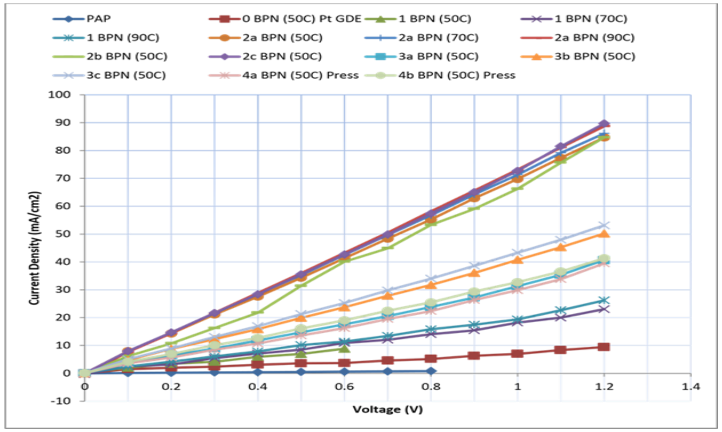


- Exceeded Target Compression Ratio
- Migrated from Single Cell to Gen 1, Multi-Cell Stack System

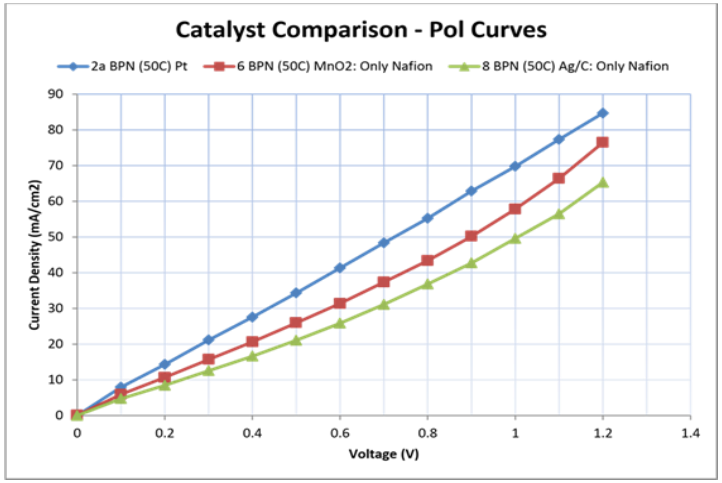


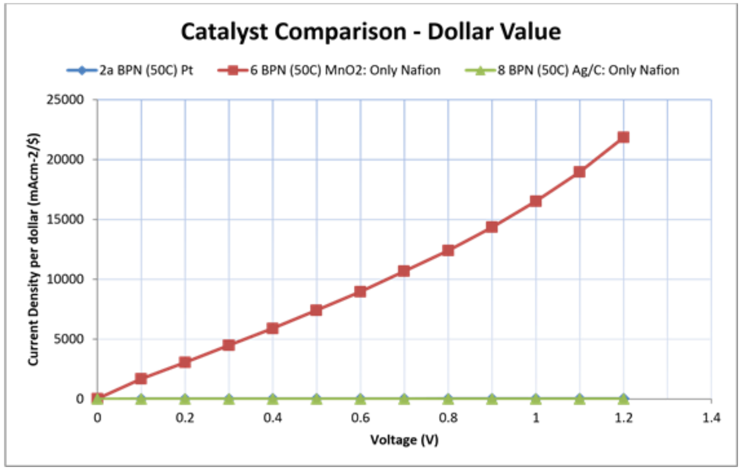
Membrane	Voltage	Current Density (A/cm2)	Anode Pressure (PSia)	Cathode Pressure (Psia)	Compression Ratio (P_cathode/ P_anode)	PP NH3 Anode inlet (Psia)	PP NH3 Cathode outlet (Psia)	Pressure Lift NH3 (Psia)	Cell size
Membrane 1	0.05	0.016	14.70	180.00	12.24	7.35	120.00	112.65	25 cm2
	0.1	0.027	14.70	290.00	19.73	7.35	193.33	185.98	
	0.15	0.031	14.70	340.00	23.13	7.35	226.67	219.32	
	0.2	0.037	14.70	370.00	25.17	7.35	246.67	239.32	
Membrane 2	0.05	0.006	14.70	184.00	12.52	7.35	122.67	115.32	25 cm2
	0.1	0.010	14.70	326.00	22.18	7.35	217.33	209.98	
	0.15	0.011	14.70	391.00	26.60	7.35	260.67	253.32	
	0.2	0.012	14.70	437.00	29.73	7.35	291.33	283.98	

CO2 Compression



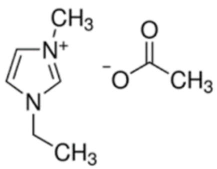
- Identified Optimum Anionic Membrane for this application
- Achieved Exceptional Performance with Very Low Cost Catalyst
- Migrating from Single Cell to Multi-Cell System & Heat Pump
  - Scaling Up membrane production





Progress and Accomplishments (2019): Ionic Liquid Desiccant System

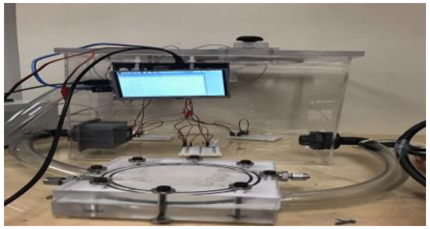
- Down selected "EMIMOAC" for scale up from list of 13 suitable candidates

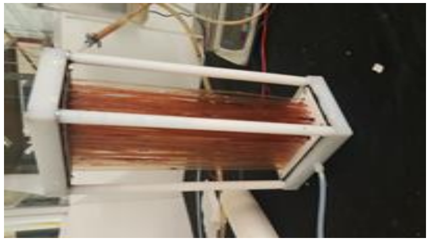


- 2017 Review: Filed IP, developed commercial supply, Built AC Prototype testing unit to demonstrate feasibility (and generate initial performance data)

- 2018: Built a complete system, with plate & Frame ILD Contactors; Delivered to ORNL; Developed Ionic Tube Technology, filed Patent

- 2019: Built Modules based on Tubes, Initial tested @ ORNL, Consulted with ORNL & NRL on Design ; developed 5 Generations of Tubular modules. Designed Gen 2 System. **Now integrating into Window AC for milestone 3.**



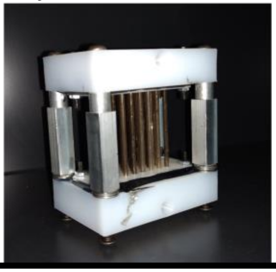


Critical Issues – Key Design Decisions

- EMIMOAC vs Conventional Salts
- Flat Plate vs Tubular
- Micro-Porous vs Nano-Porous Membranes

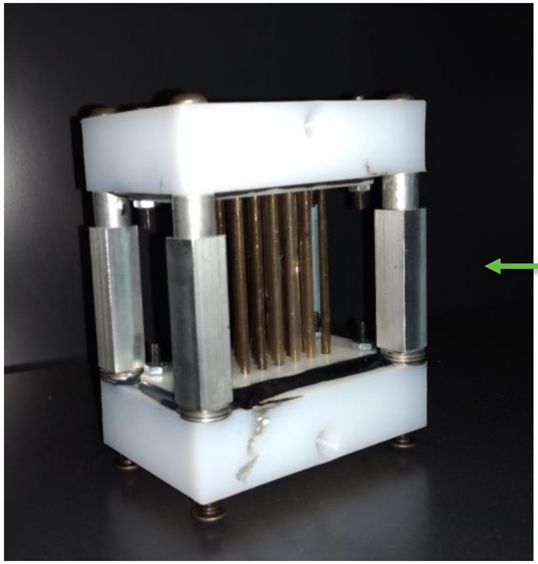
[EMIM][OAc]	vs	Conventional Salts(LiCl, LiBr, etc)
• Ionic organic salt in liquid form ○ No Crystallization inside orifices avoids problems with clogging		• Aqueous solution of solid salts ○ Crystallizes inside orifices and blocks them
• Synthetic salt manufactured in a reactor		• Supply of lithium salts will be constrained by demand in the battery market
• Non-corrosive due to its organic nature and low vapor pressure		• Corrosive salts damage HVAC equipment and duct work over time and may also have adverse health effects when inhaled

Flat Plate Module	vs	Tubular Cassette Based Design
• Packing density: 1.6 • High liquid pressure drop and air pressure drop • Wash ability: Membranes cannot be washed or accessed • Difficult to install and scale in ductwork		• Packing density: 5.3 • Lower liquid side and air side pressure drops compared to flat plate • Wash ability: Membranes can be accessed and washed • Readily installed and scalable in ductwork

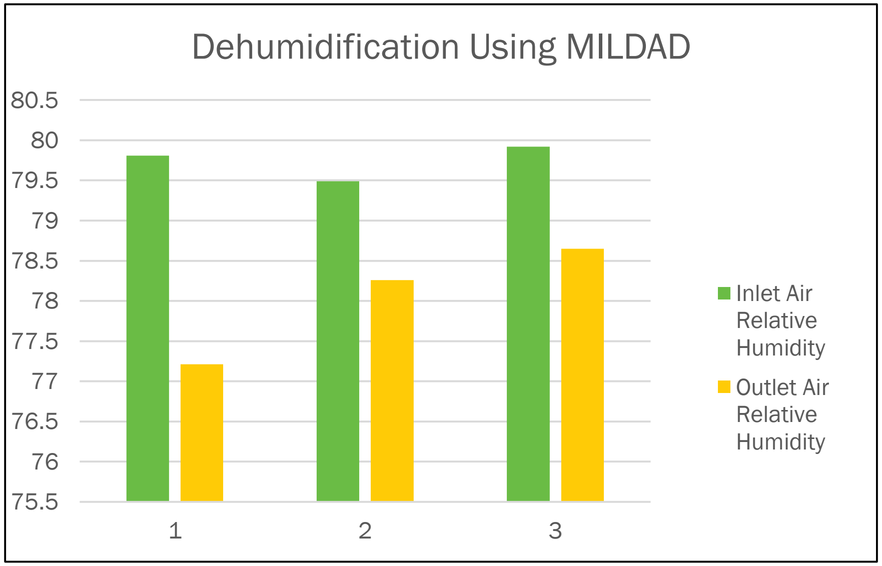


Micro-Porous Membranes	vs	Nano-Porous Membranes
• Microporous membranes may eventually leak, resulting in entrainment of salt solution in air stream and downstream equipment		• Dense membranes do not leak ionic liquid desiccant and hence no entrainment
• Contamination of salt solution due to air impurities		• No contamination of salt solution due to air impurities
• Higher permeance(56.3% higher than dense membranes)		• Lower permeance than porous membranes; R&D on advanced membrane

Initial Test Results of Xergy's 2-G System



Outer Dia.	0.125	inch
Outer Dia.	0.13	inch
Tube length	2.5	inch
Tube number	26	

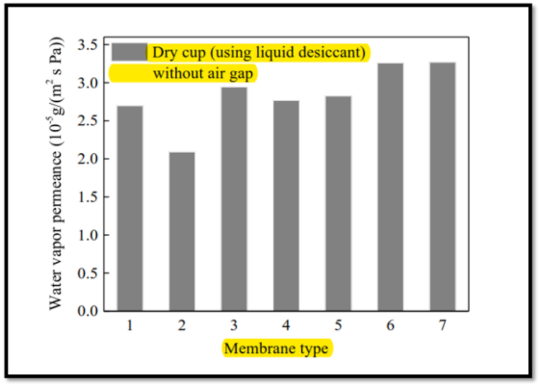


- Developed tube production process
- Developed tube sheet potting and sealing system
- Designed tube system layout and airflow patterns
  - Tremendous assistance from both ORNL and NREL
- Built proof of concept (2G), Integrating into Window AC
- Designing 3G systems based on learnings

Critical Issues – ILD BP2

- **Membrane Optimization: Higher Rates**

Index	1	2	3	4	5	6	7
Model number	A	B	C	D	SF13867	SF14555	SF14837
Dense/Porous	Non-porous				Porous		
Wettability	Hydrophilic				Hydrophobic		
Pore size (μm)	-	-	-	-	1.0	0.2	1.0
Porosity (-)	-	-	-	-	80-90%	60%	60%
Thickness (μm)	~25	~25	~25	~25	150-220	150-250	150-250



- **Alternate Regeneration Systems**
  - Ionic Liquid Polishing (Electrodialysis)
  - Vacuum Desalination

- **Further Validation of Advanced Systems**

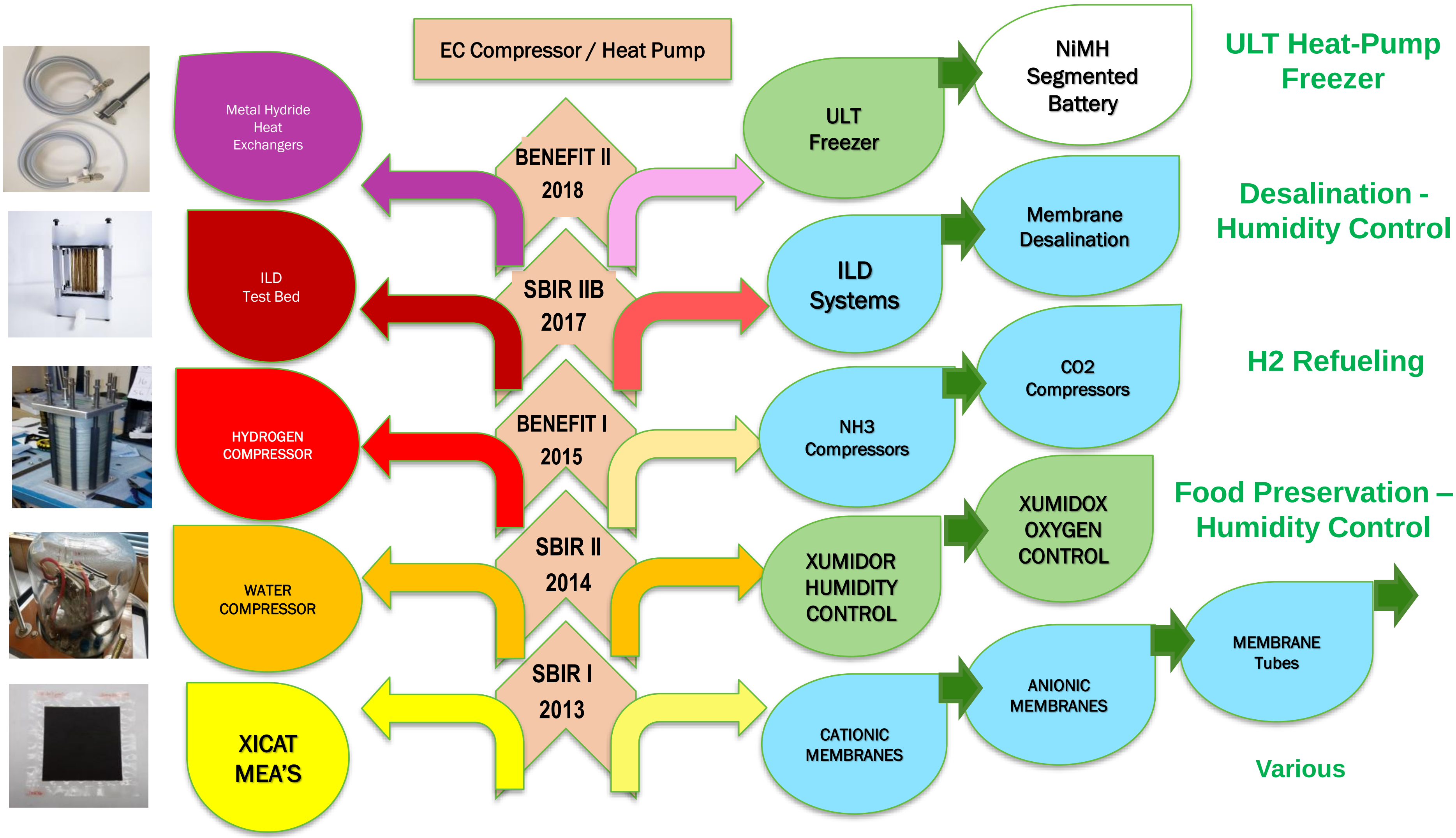
Impact – Xergy Strategic Intent

- **<u>Xergy's Strategic Intent:</u> To Commercialize Heat Pumps based on this research and/or derivative products from this program**
  - Filed over 50 patents, published 5+ papers
  - Surveyed the market, exhibited at industry shows

- **Identified Market Entry Opportunity: ULT Freezers**
  - Highest Value Entry Point: \$5000/KWc vs \$50/Wc (AC)
  - There is a problem:
    - Banned by both Kyoto and Montreal Protocols
  - Excellent Strategic Partners (across whole industry)

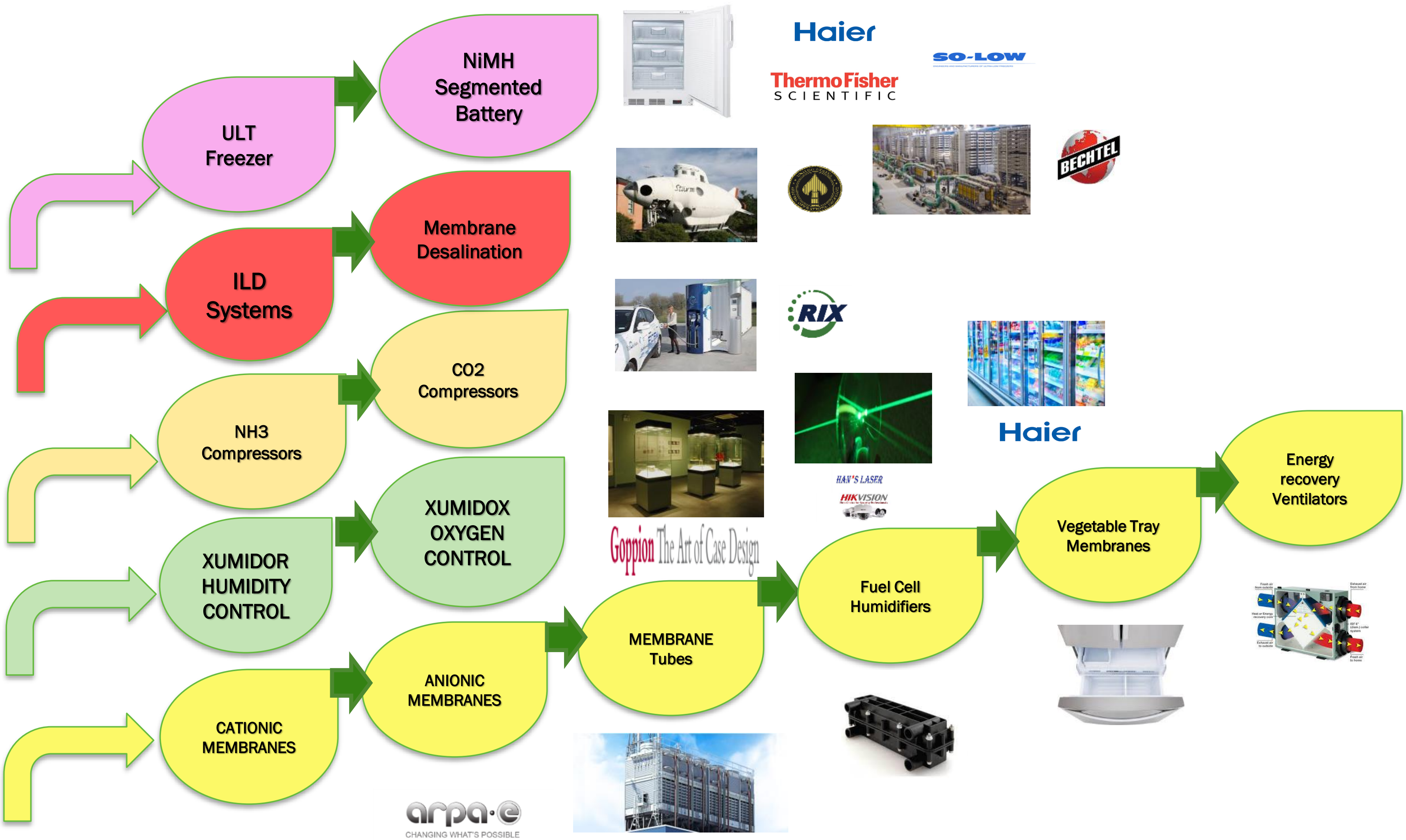
ThermoFisher SCIENTIFIC Haier SO-LOW ARCTIKO true cooling specialists

Impact: New Investments in 1^{st}, 2^{nd}, 3^{rd} & 4^{th} Order Derivatives



Developed many strategic relationships with each derivative

Impact: Xergy Rapid Innovation System
Identify Derivative Opportunity, Develop Channel Partners



REFERENCE SLIDES

Project Budget

Project Budget: 1,538,290.00
Variances: The Original Budget BP1 had $399,640.00 allotted for equipment. We have changed to stamped plates, so we moved most of that budget to supplies.
Cost to Date: 40%
Additional Funding: None

Budget History					
11/07/2017 – FY 2018 (past)		FY 2019 (current)		FY 2020 – 5/31/2020 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
485,245.40	213,055.52	606,433.0	356,259	252,680	148441

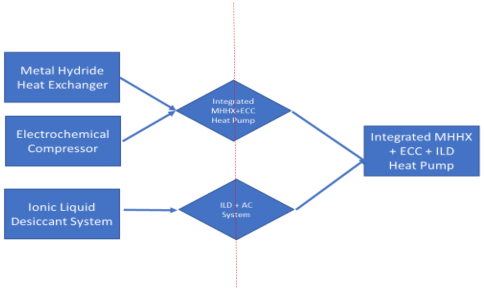
Project Plan and Schedule

Describe the project plan including:

- Start: 11/07/17 & Completion: 5/31/20
- Milestones:

1. 3x500 watt demonstration EC compressor unit at target performance as defined in task 2 – Year 1
2. 3x500 watt demonstration MHX unit at target performance as defined in task 2 – Year 1
3. 3x500 watt ILD demo units operational at both MHX and VPCC sink temperatures – Year 1
4. ILD system integration for 10 x 500 watt system
5. 10 X 500 Watt fully integrated MHX+EC compressors + ILD unit.

- Go/no-go decision point @ May 2019



				Month																							
Task	Subtask	Milestone	Description	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1.0			IPMP																								
		1.0.1	IPMP signed by all parties																								
2.0			Market evaluation																								
	2.1		Selling Price																								
	2.2		Specify system size, cost, and performance																								
		2.2.1	Prototype criteria defined																								
3			Evaluate new ionomer chemistry																								
	3.1		H2 pumping																								
	3.2		CO2 pumping																								
	3.3		NH3 pumping																								
		3.3.1	Polarization performance with new chemistry																								
	3.4		Downselect working fluid																								
4			Develop commercially feasible ILD																								
	4.1		Define feasibility																								
	4.2		Model ILD heat and moisture flow																								
	4.3		Produce ILD thin tube exchangers																								
		4.3.1	Create two variants of ILD contactor																								
	4.4		Modification of ILD contactor																								
	4.5		Minimization of parisitic losses																								
		4.5.1	Validate 25% reduction in parasitic losses																								
	4.6		5000W ILD concept design																								
		4.6.1	Provide design																								
5			Increase MHX performance by 75%																								
	5.1		Modelheat/fluid flows																								
	5.2		Minimization of parasitic losses																								
		5.2.1	Validate 75% improvement in performance																								
6			ILD system integration																								
	6.1		ILD desorption with waste heat																								
		6.1.1	Create designs for full commercial																								
			Go/No-Go																								
7			Flow optimization of compressor																								
	7.1		Model fluid flows/mechanical components																								
	7.2		Double performance per compressor plate																								
	7.3		Improve sealing and electrical																								
		7.3.1	Validate 75% improvement in power density																								
	7.4		Design a stampable plate																								
		7.4.1	Validate power density and cost decrease																								
8			Reduce parasitic losses of compressor																								
	8.1		Reduce moisture requirement of membrane																								
	8.2		Moisture exchange between inlet and outlet																								
		8.2.1	Validate 50% improvement on parasitic losses																								
9			2x increase in MHX performance																								
	9.1		Minimize weight of non-MH components																								
	9.2		Improve absorption/desorption kinetics																								
	9.3		Test higher enthalpy hydride																								
		9.3.1	Validate 2x improvement in performance																								
10			Improve compressor deflection																								
	10.1		Internal load balance to reduce deflection																								
		10.1.1	Validate design																								
11			Evaluate NH3, CO2 VPCC heat pump																								
	11.1		Polarization curves for working fluids																								
	11.2		Define ECC requirements for working fluids																								
	11.3		Create ECC for working fluids																								
	11.4		Prototype heat pump for working fluids																								
		11.4.1	Validate prototype system																								
12			Validate IL as HX fluid																								
	12.1		Determine IL HX characteristics																								
	12.2		Evaluate IL in system																								
		12.2.1	Downselec to final HX fluid																								
13			Evaluate alternate means of H2 compression																								
	13.1		Evaluate energy requirements of other systems																								
	13.2		Create working prototypes																								
		13.2.1	Downselect means of compression																								
14			Fabricate prototpye heat pump system																								
	14.1		Durability test of each subcomponent																								
		14.1.1	Project subcomponent lifetime																								
	14.2		Durability test prototype system																								
		14.2.1	Project heat pump lifetime																								
	14.3		Cost analysys of system																								
		14.3.1	Compare to cost target																								
	14.4		Deliver prototype system for validation testing																								
		14.4.1	Operating prototype																								
15			Validate prototype with federal lab																								
	15.1		Lab testing of prototype system																								
		15.1.1	Validate system performance																								
	15.2		Assess energy savings potential																								
		15.2.1	Validate economic and environmental impact																								
16			Define commercialization plan																								
	16.1		Define market niche and price																								
	16.2		Define manufacturing strategy																								