Energy Storing Efficient HVAC

A Technology Commercialization Fund Project

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Project Summary

Objective and outcome

Development of a pre-Pilot HVAC system based on NREL's technology that achieves 40% energy savings over traditional AC and has inherent 6+ hours of energy storage. Evaporative Liquid Desiccant Air Conditioner (eLD-AC) paired with an Electrically Driven Desiccant Regenerator (EDDR).

Team and Partners

NREL is the project lead providing technical expertise in materials and system development.

Blue Frontier AC is the commercialization partner and will market the technology through an HVAC-as-a-Service business model.

Stats

Performance Period: Jan 2022 – March 2024

DOE budget: $600k, Cost Share: $600k

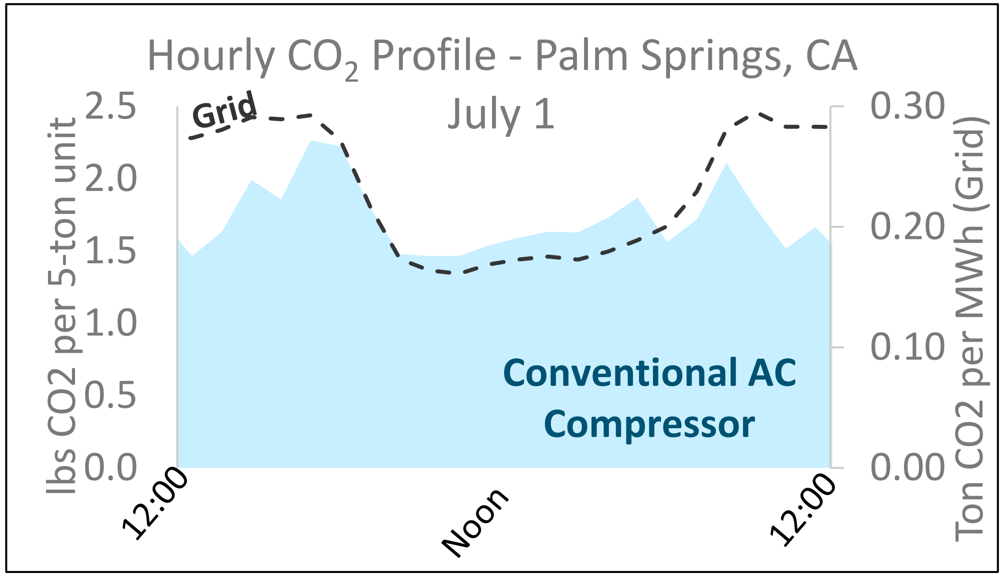
Milestone 1: Desiccant property characterization and system model development

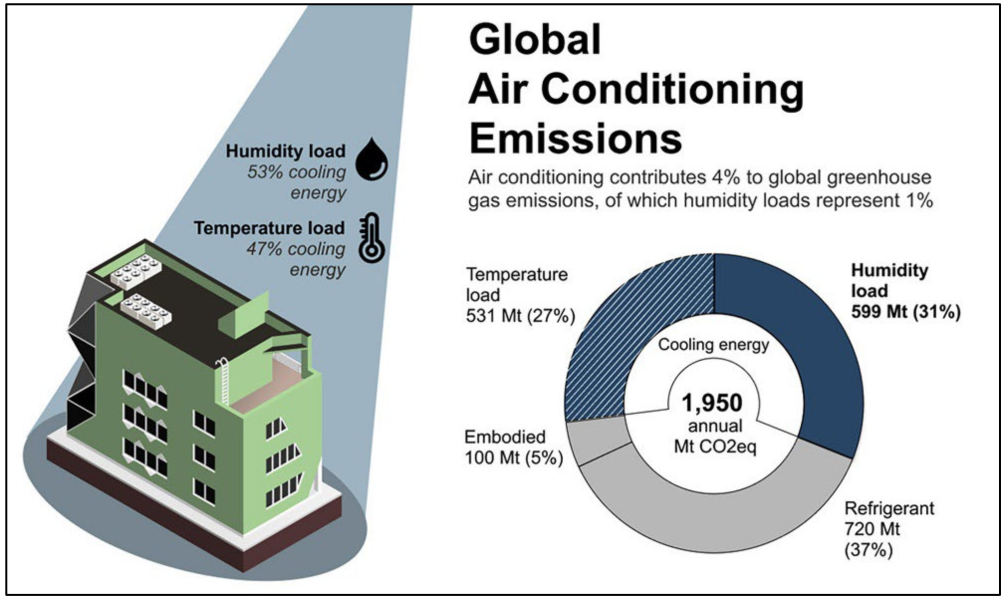
Milestone 2: Journal article submission describing the EDDR and comparing model and prototype performance.

Milestone 3: Summary report describing the outcome of each research task and analysis of prototype performance.

Why Conventional A/C is a Problem

- **Carbon & Energy Intensive[1]**
  - 20% of global electricity in buildings
  - AC contributes 4% of global CO2 emissions - 53% attributed to humidity loads
- **Not Flexible:**
  - On-demand service without storage
- **No incentive to install efficient equipment**
  - Landlords pay capital costs
  - Renters pay electricity bills

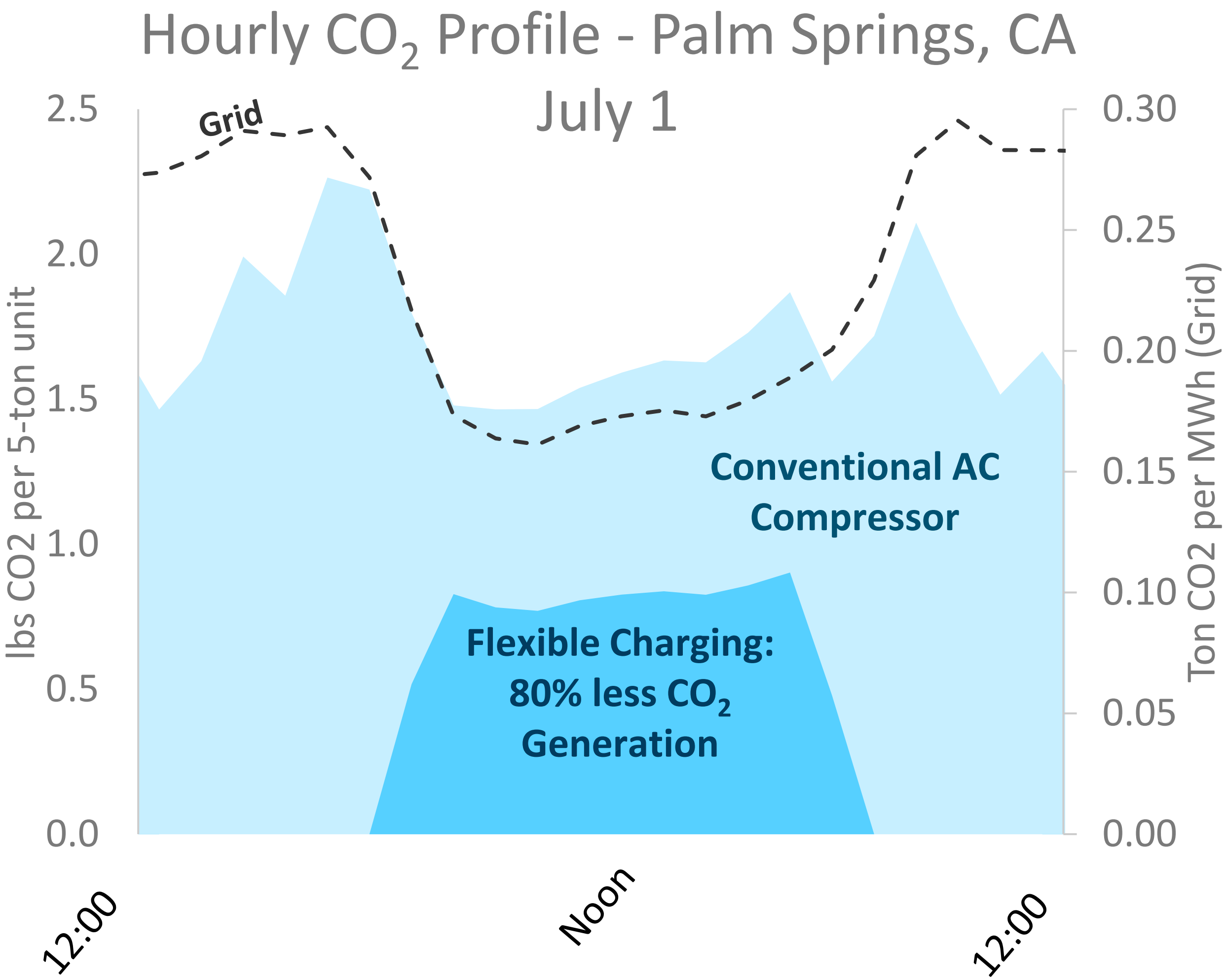




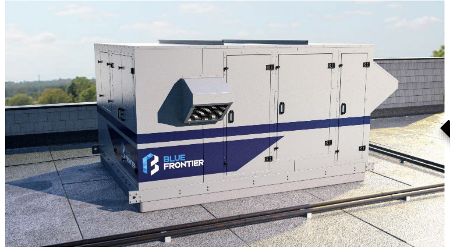
1. Woods, Jason, Nelson James, Eric Kozubal, Eric Bonnema, Kristin Brief, Liz Voeller, and Jessy Revest. 2022. "Humidity's impact on greenhouse gas emissions from air conditioning." *Joule* 6(4): 726-741.

Alignment and Impact: Develop Commercial HVAC (RTU)

- **80% CO_2 Savings**
  - Charging system draws power during low carbon periods
  - Annualized energy savings
    - 40% in humid climates
    - 80% in dry / hot climates
- **Flexible and Equitable**
  - Lifetime energy cost savings >$8,000 / RT
  - Removes capital cost as a barrier
  - Reduces building electrification costs
  - Low energy cost for all occupants (renters or owners)
- **Success Criteria**
  - Modelled & prototype performance shows 40% annualized energy savings in zone 2A
  - Thermal energy storage 6+ hours capable
    - 330 J/g or 123 kWh/m^3



Approach – Vapor compression vs liquid desiccant cooling



Comparison of theoretical and real system humidity removal efficiency[1]

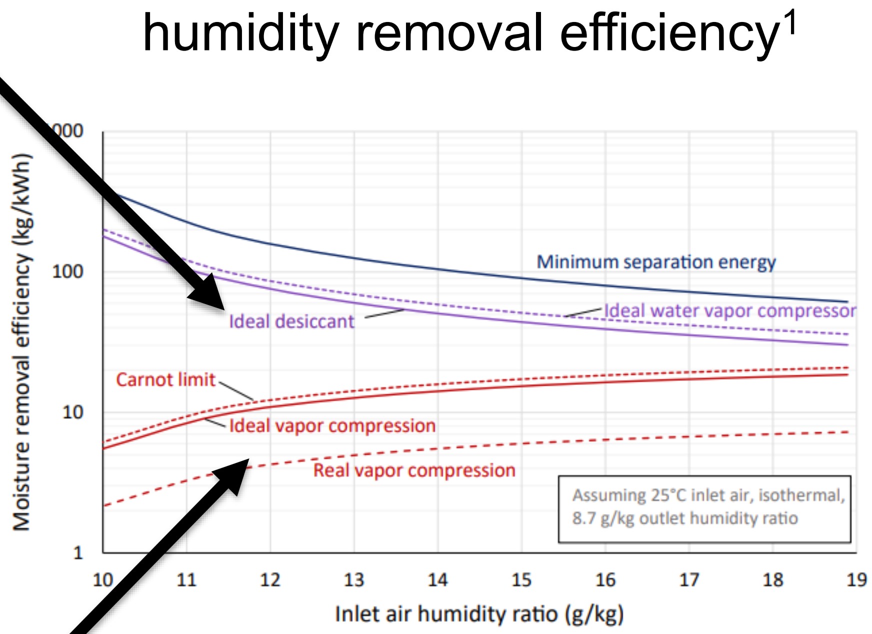


Figure 4. Moisture removal efficiency for existing technologies compared with the minimum separation energy

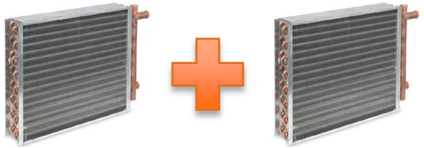
Graph from Woods et al. 2022,
Humidity's impact on greenhouse gas emissions from air conditioning

Liquid desiccant cooling

- **Open-Cycle Process**
  - Desiccant dehumidifier + indirect evaporative cooling
  - Theoretical efficiency is 2X–10X higher than ideal vapor compression

Vapor compression

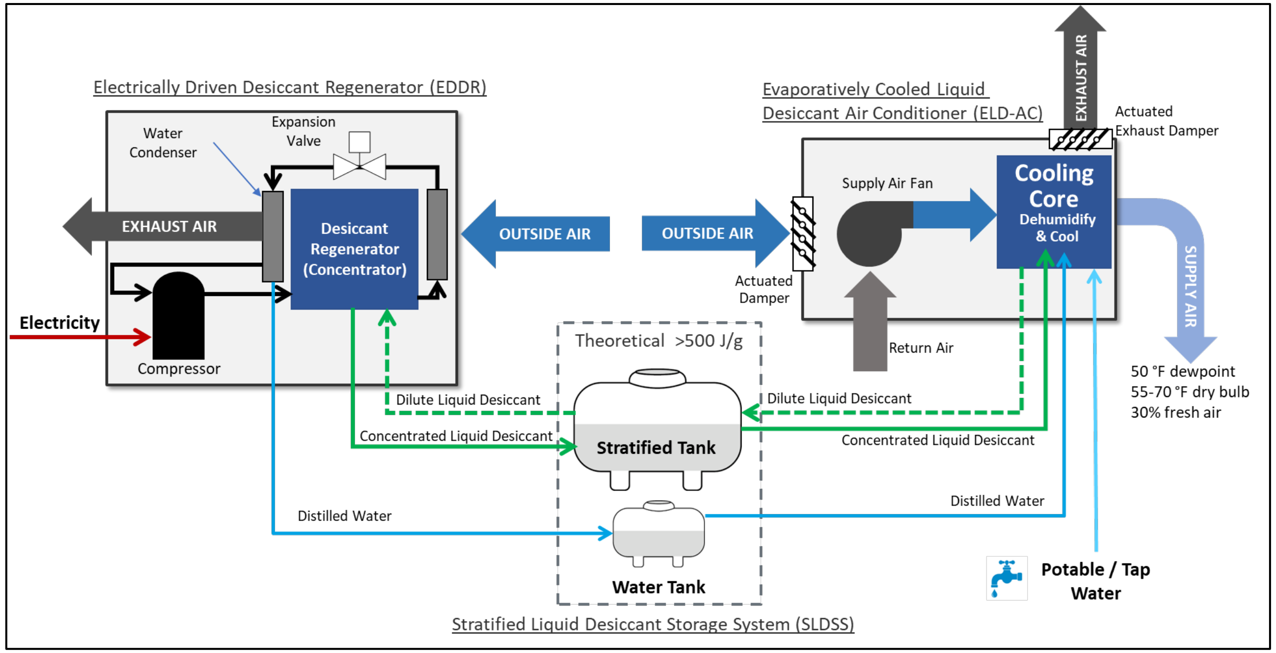
- **Overcool → reheat**
  - Energy intensive because cooling capacity and lift is higher than necessary

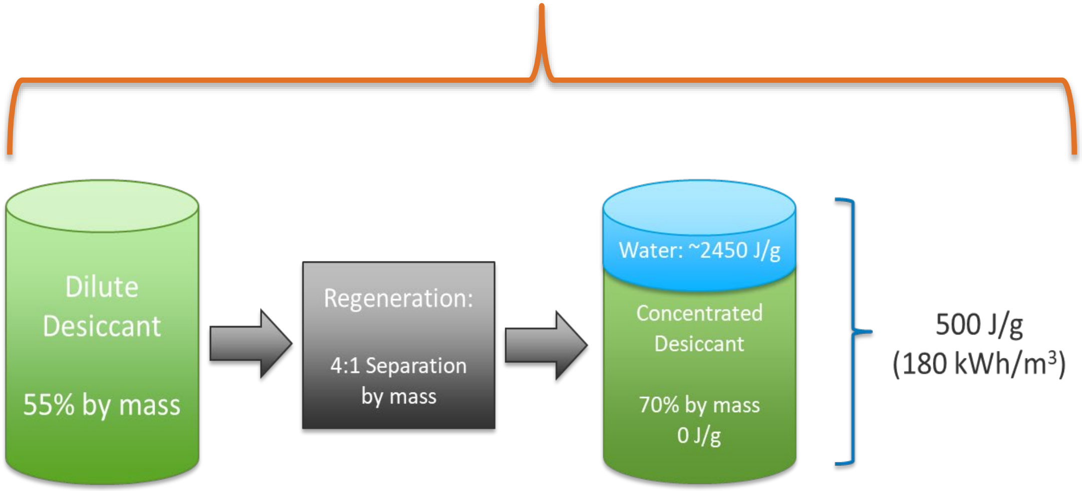


DX Coil Reheat Coil

How it works – 3 Sub-systems

1. **Electric Regenerator: EDDR**
   - Regenerates diluted desiccant into strong desiccant + distilled water
2. **Thermal Storage: SLDSS**
   - Stratified solution tank creates halocline of weak and strong desiccant.
3. **Conditioner: eLD-AC**
   - Separate sensible and latent cooling (SSLC)
   - Open cycle cooling process:
   - Uses strong desiccant to remove moisture
   - Evaporates water (refrigerant) to remove heat

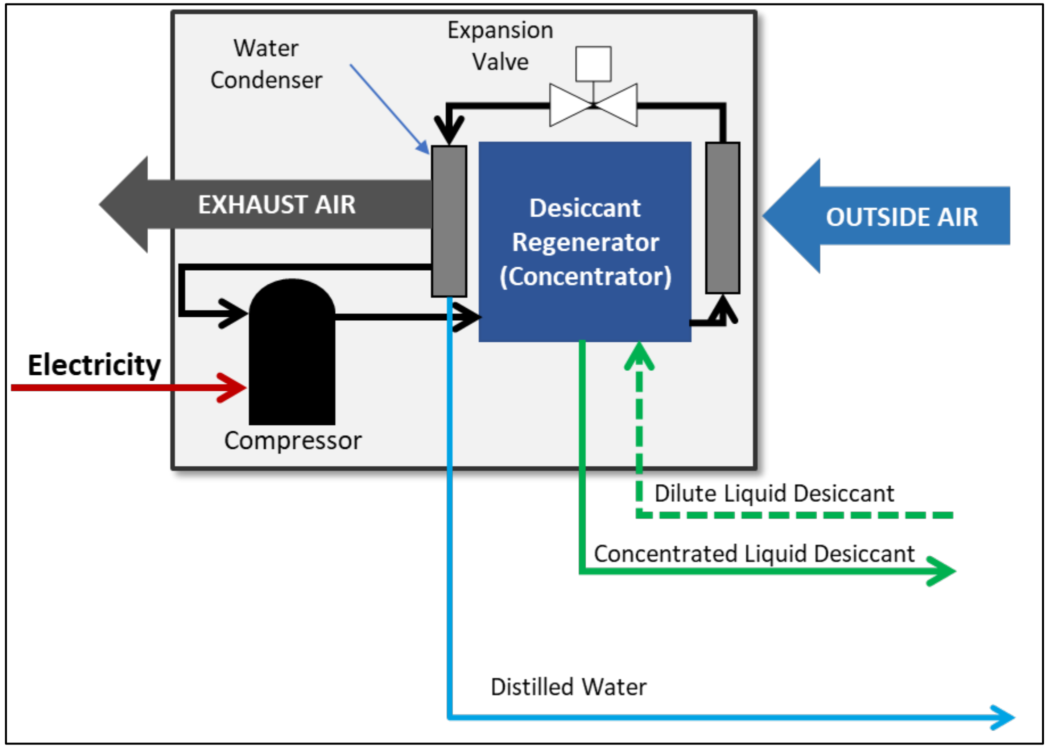




How it works – Electrical regeneration / Air Conditioning

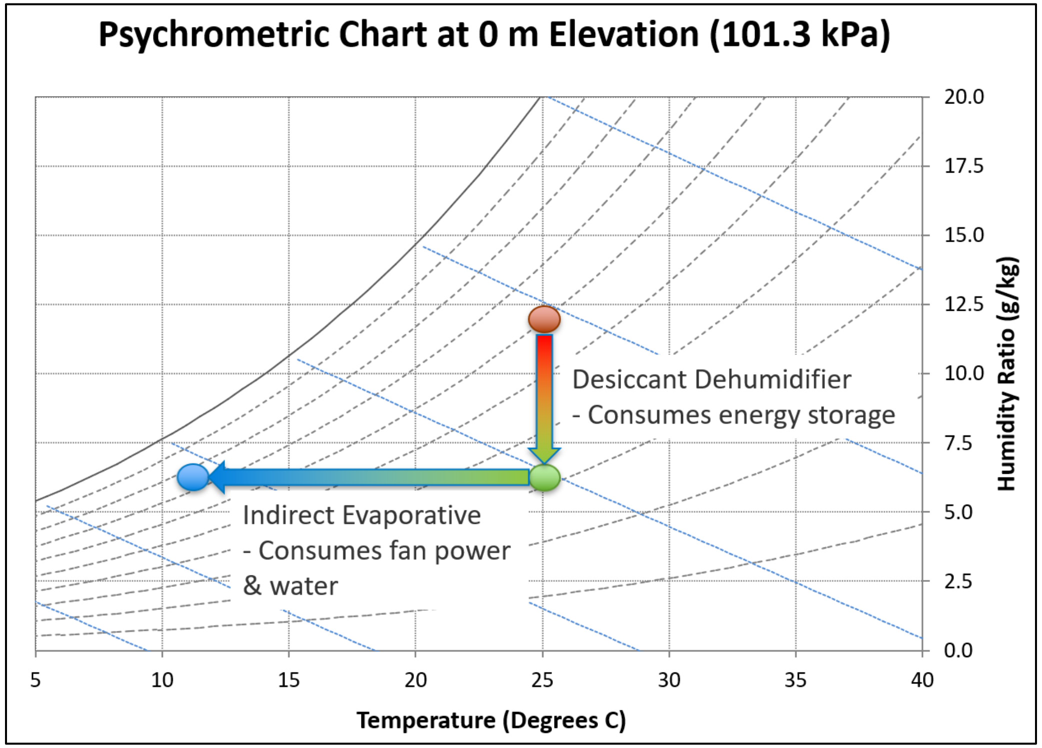
Electrically Driven Desiccant Regenerator

- Thermal regeneration using heat pump technology
  - Heat pump thermal COP >6
  - Desiccant moisture removal efficiency > 5 kg/kWh
- US Patent[4]



Separate Sensible & Latent Conditioning

- Technology initially developed in 2010-2012[3]
- US Patent[5]



Project Overview

Wells Fargo IN^2 – 2020-2021

TCF Project: 2022 - 2024

Pilot Stage

Prior work → TCF project scope:

- Increase regenerator subsystem efficiency
- Increase sensible cooling performance
- Further characterize desiccant properties
- Optimize energy storage

Innovation Incubator IN^2

Proof of concept
in HVAC Laboratory

Task 1: Thermodynamic Modeling	Component / Subsystems	Dynamic Model-based design
Task 2: HMX Design	Prototype HMX Design & Experiments	Physics Validation
Task 3: Desiccant Characterization	1. Research 2. Methods 3. Measure	Formulate Results

Task 4: Gen 2.0 Engineering Prototype

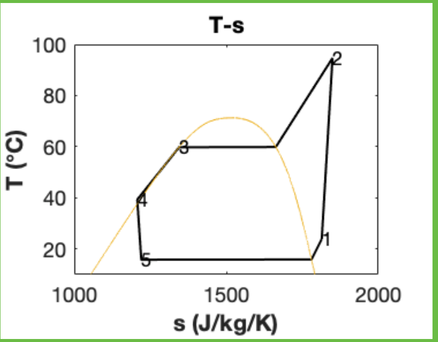
- Manufacture prototype
- Laboratory Evaluation
- Annualized energy simulations
- Publication

Model-based Design + HMX Experiments → Gen 2.0 Design

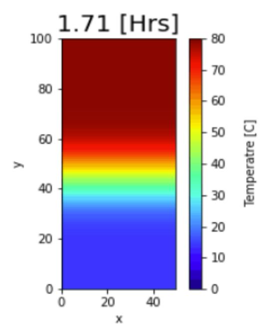
Model attributes:

- Finite difference exchangers[2]
- Dynamic storage tank
- Drive-cycle analysis
  - Charge, Discharge tank
  - Cooling schedule

Thermodynamic Cycle Analysis

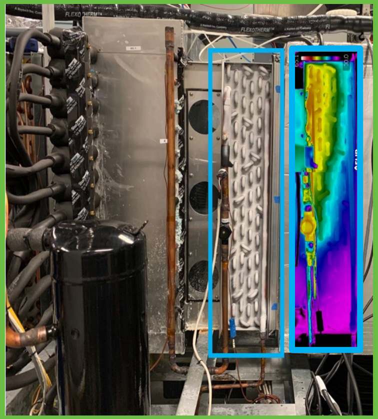


Tank:
Thermocline / Halocline

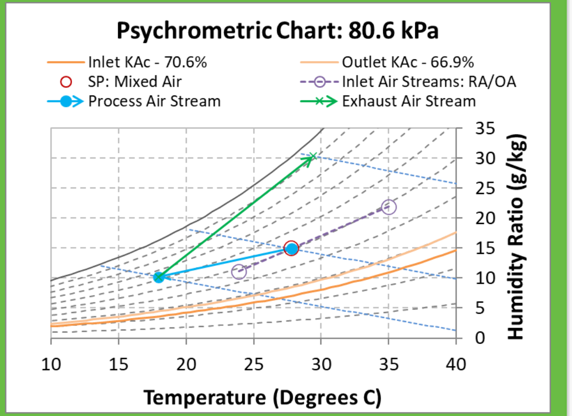


Experiments:

- Model inputs to real-world phenomena
- Model result verification

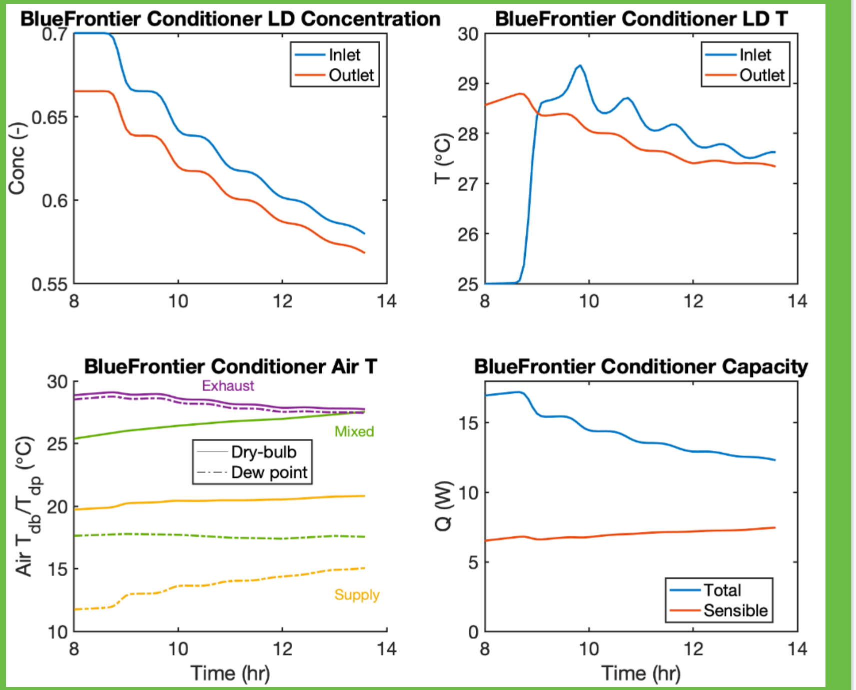


Thermal imagery



Conditioner

Drive Cycle Results → Annualized Energy



2. Woods, Jason, Eric Kozubal. 2013. “A desiccant-enhanced evaporative air conditioner: Numerical model and experiments.” *Energy Conversion and Management 6:* 208-220.

Desiccant Material Characterization

Property	Ranges	Instrument
Vapor Pressure vs T, C	T = 0 °C to 120 °C C = 30% to 70%	Eravap
Water diffusivity - D_AB	T = 0 °C to 120 °C C = 30% to 70%	Nuclear Magnetic Resonance (NMR)
Specific Heat - Cp	T = -40 °C to 120 °C C = 0% to 70%	DSC
Thermal Conductivity - k	T = -40 °C to 120 °C C = 0% to 70%	DTC and Flash diffusivity
Enthalpy of dilution	T = 20 °C to 90 °C C = 10% to 70%	Titration calorimeter or DSC + humidity
Density - rho	T = -40 °C to 120 °C C = 0% to 70%	Density Meter
Viscosity	T = -30 °C to 120 °C C = 0% to 70%	Rheometer
Liquid / Hydrate Phase Boundary	T = -40 °C to 120 °C C = dependent variable	DSC
Liquid / Ice Phase Boundary	T = -40 °C to 0 °C C = dependent variable	DSC
refractive index	T = 0 °C to 80 °C C = 0% to 70%	Atago Refractometer

Lack of data on low-cost / low-corrosive desiccants motivates construction of property library using characterization methods available at NREL

Vapor Pressure Analyzer (eravap)

- Piston expansion measures vapor pressure

Differential scanning calorimetry (DSC)

- Phase-change enthalpy (heat of fusion) and transition temperature

Nuclear Magnetic Resonance (NMR)

- Determines bonding & local conditions of molecules using magnetic fields

Guarded Heat Flow Meter (DTC)

- Applies one-dimensional heat flow through samples

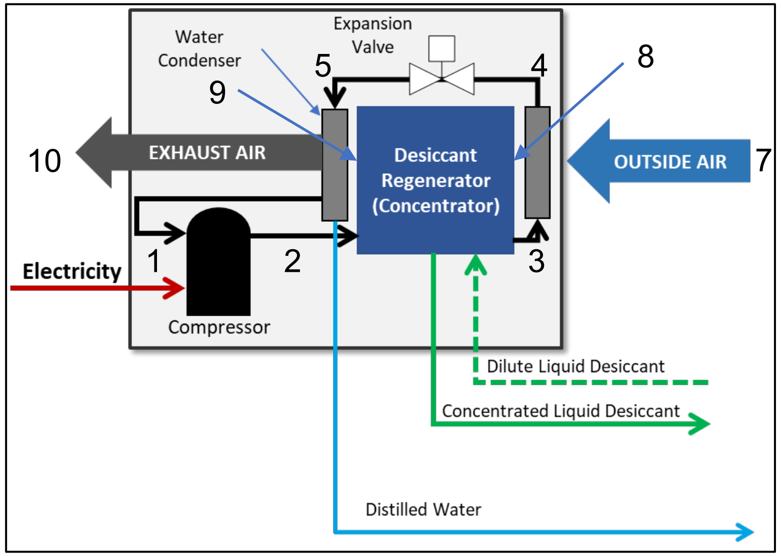
Parallel-Plate Rheometer

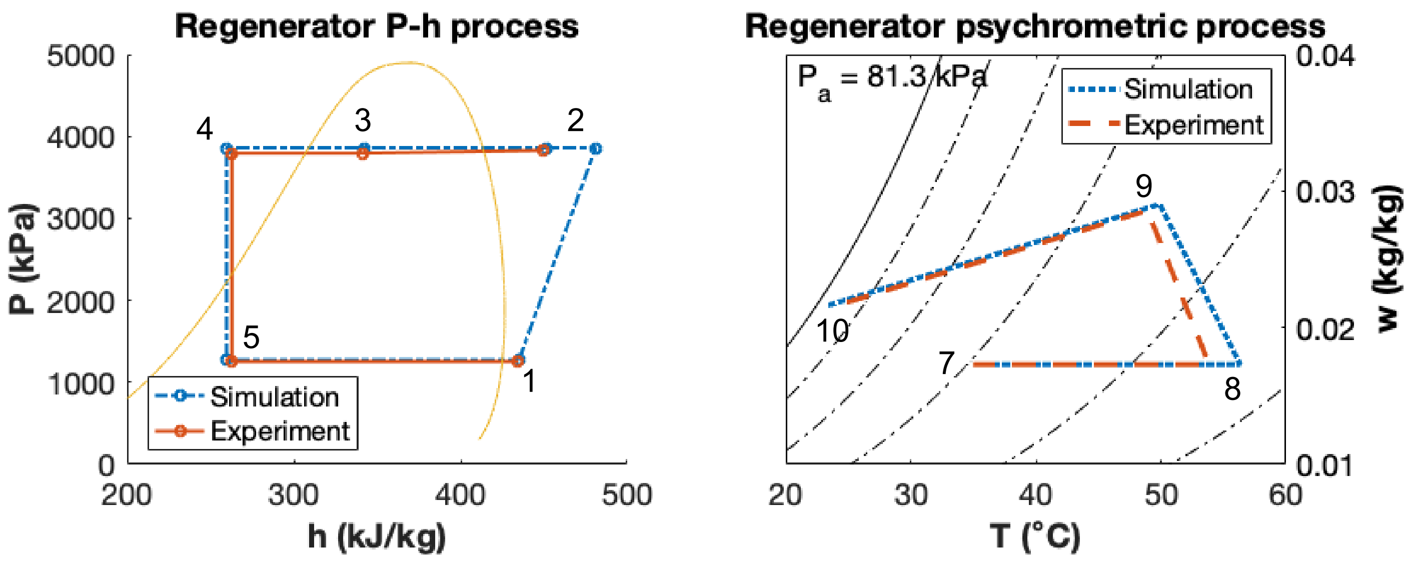
- Rotational force applied to fluids between plates measures viscosity

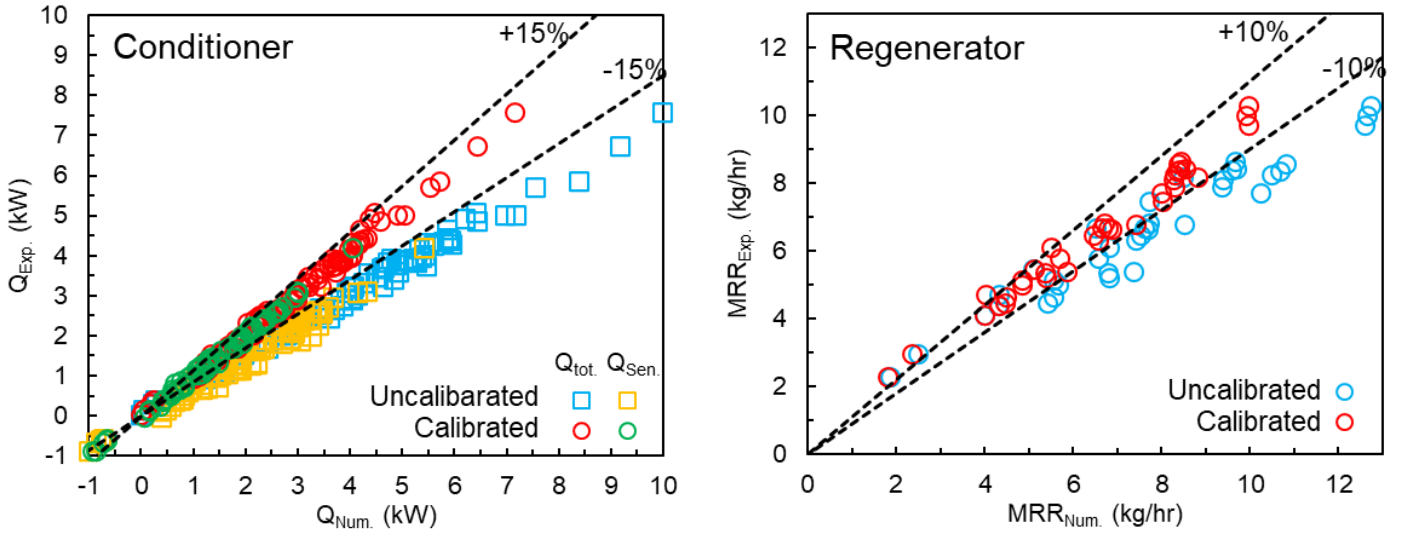
Task 1: Completed work

Generated models:

- **Finite difference:**
  - Conditioner and Regenerator HMXs
  - Dynamic stratified tank
- **Dynamic system model:**
  - Conditioner mode (cooling)
  - Regenerate mode (tank re-charge)
  - Hybrid mode (cool and regenerate)





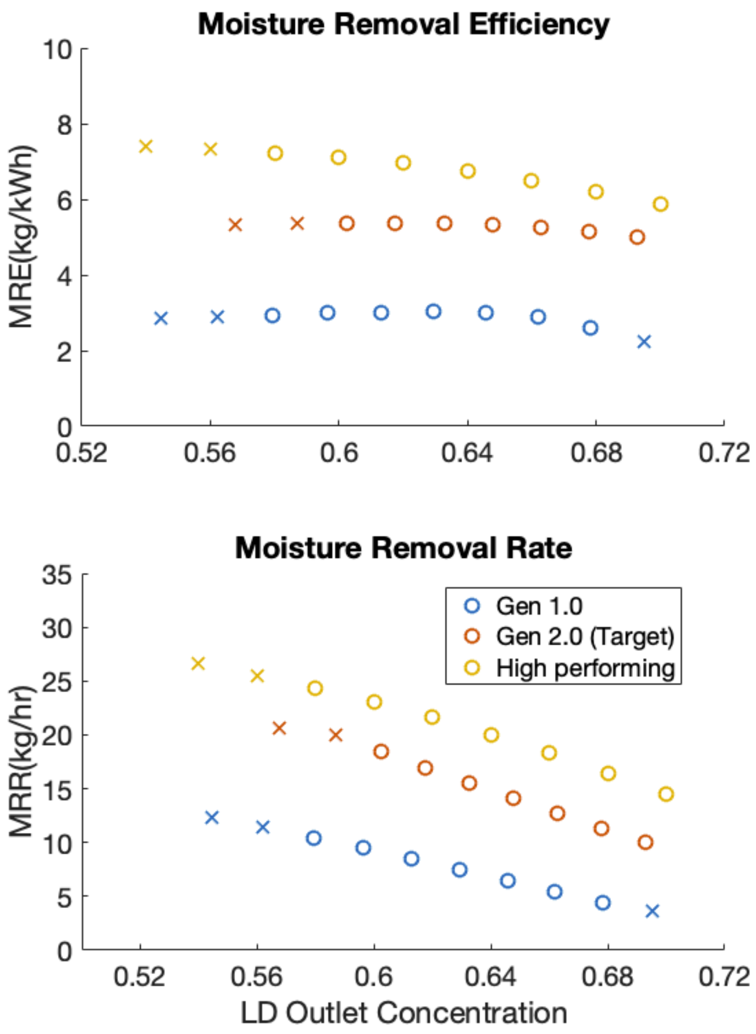


Task 1: Next Steps & Model based design

- **Dynamic Modeling**
  - Model annualized performance of target system (Gen 2.0)
  - Create representative cooling loads using EnergyPlus
  - Representative cooling days for each month

- **Generate and compare annualized energy use and efficiency**
  - Gen 2.0 (Target) engineering prototype design
  - Baseline

Example: Target EDDR performance



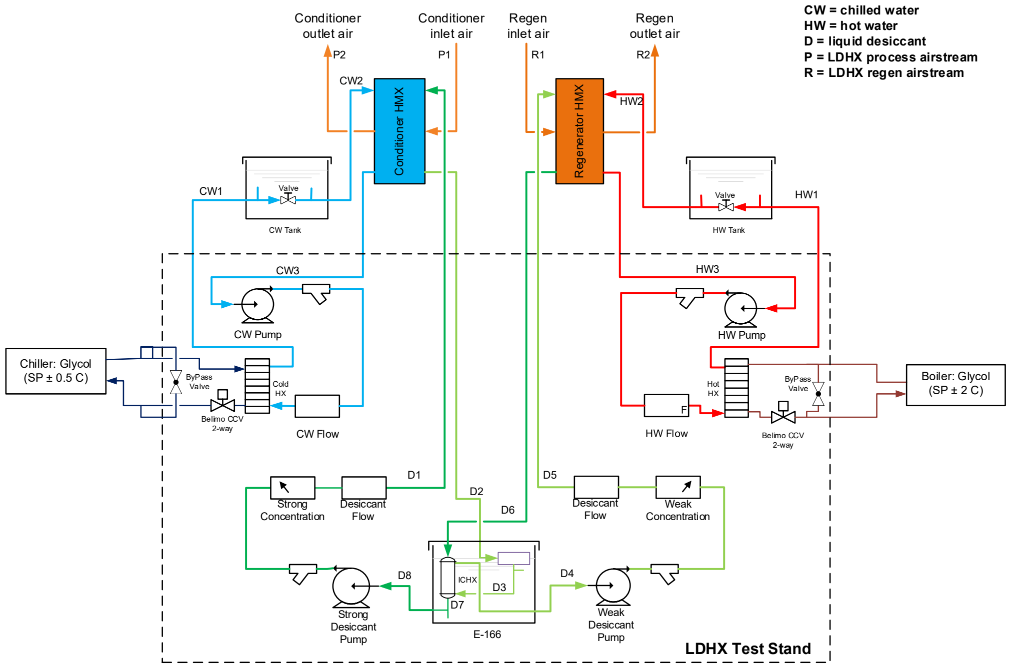
Task 2: Improvement of regenerator heat and mass exchanger

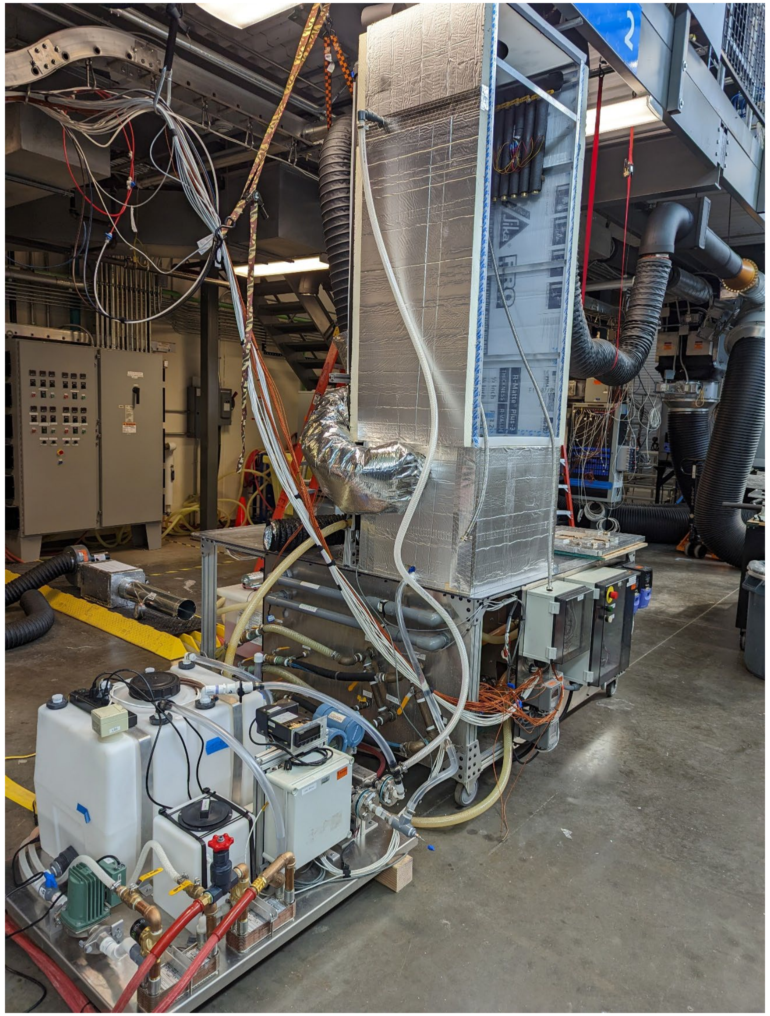
Completed Work

- Generate regenerator prototype samples that achieve counter-flow
- Completed laboratory setup (NREL HVAC Lab)

Next steps:

- Perform experiments
- Feed performance into Gen 2.0 models for model-based design task

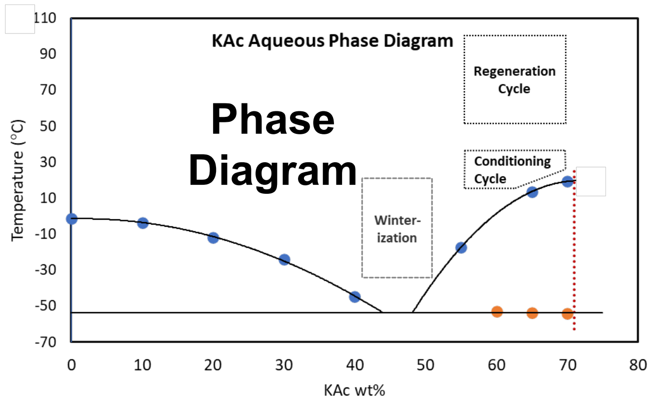


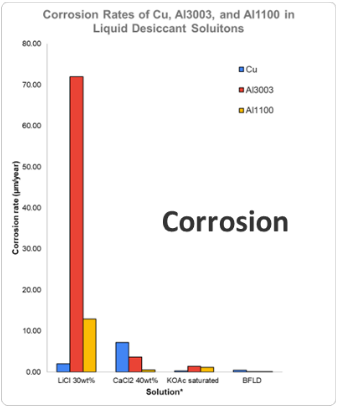


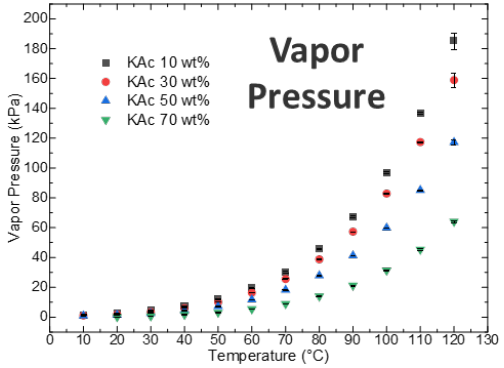
Regenerator HMX Test Setup
NREL's HVAC Laboratory

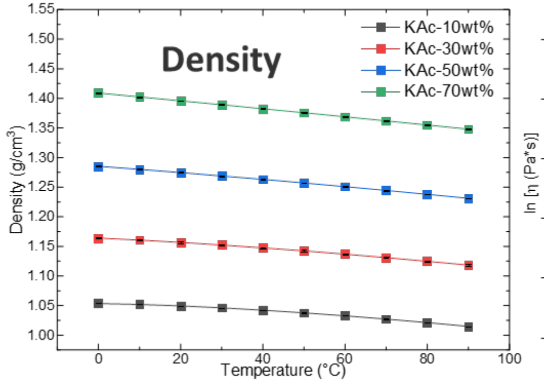
Task 3: Desiccant Material Characterization

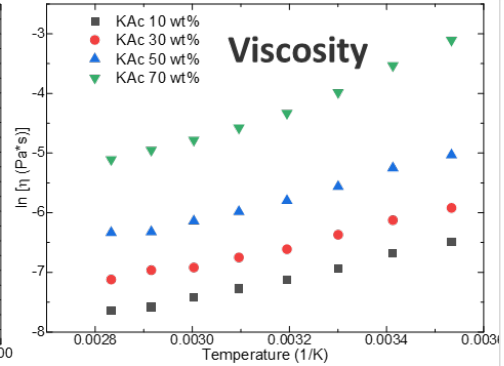
- **Many KAc properties have been well characterized**
  - Data fits well with established theories
  - Some require improved resolution at low T/high KAc
    - Limitations of equipment
- **Future Work**
  - Refine eutectic properties on phase diagram
  - Expand on diffusion coefficient
  - Expand on thermal conductivity
  - Measure refractive index
  - Measure enthalpy of dilution

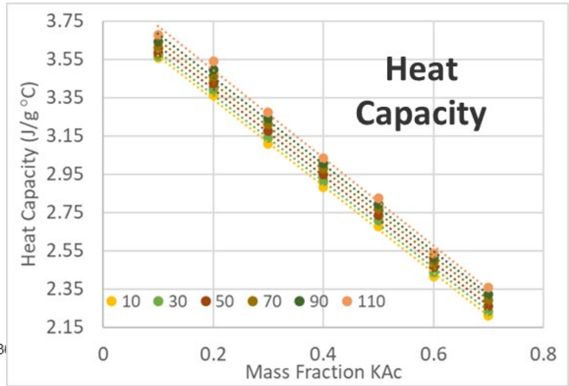


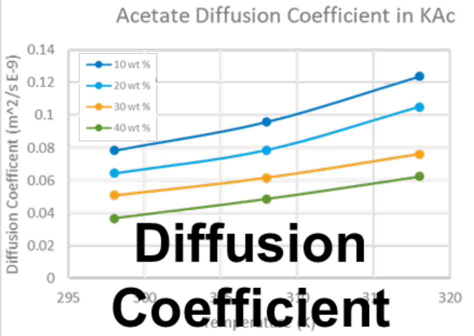










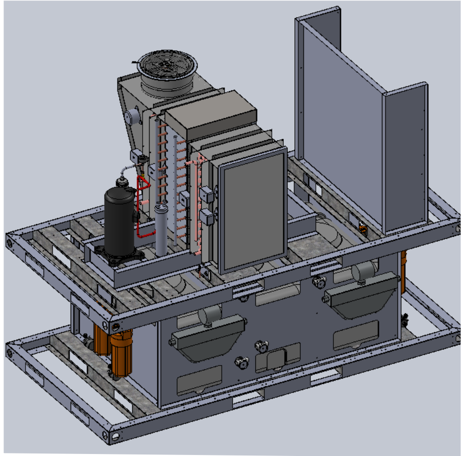


Task 3: Potassium Acetate vs. Lithium Chloride

Data at 20 °C	KAc	LiCl
Salt concentration (wt%)	**70%**	36%
Vapor Pressure (kPa)	0.61	
Relative Vapor Pressure (%)	26.1	
Water Diffusivity ($m^2/s \times 10^{-9}$)	**0.16**	1.6
Corrosion Rate, Al 3003 (μ/yr)	**0.06**	72
Density (g/cm^3)	**1.396**	1.222
Viscosity (mPa*s)	**29.20**	6.35
Storage Density ($kWh_{thermal}/kg$)	**0.139**	0.238
Storage Density ($kWh_{electric}/kg$)	**0.028**	0.048
Storage cost ($\$/kWh_{thermal}$)	**$7.20**	$210
Storage cost ($\$/kWh_{electric}$)	**$36.00**	$1,050

Task 4: Engineering Prototype (Gen 2.0) – Not started

Below: Generation 1.0 Design and Prototype



Future work:

- **Construct prototype**
- **Laboratory characterization**
- **Model calibration**
- **Analysis of performance**
  - Model calibration
  - Re-do energy comparison
- **Published results**

NREL's HVAC Laboratory

Thank You

National Renewable Energy Laboratory
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WBS 3.9.1.60 – TCF – Energy Storing Efficient HVAC

REFERENCE SLIDES

References

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2. Woods, Jason, Eric Kozubal. 2013. *A desiccant-enhanced evaporative air conditioner: Numerical model and experiments.* Energy Conversion and Management 6: 208-220.

3. Kozubal, Eric; Woods, Jason; Judkoff, Ron. 2012. *Development and Analysis of Desiccant Enhanced Evaporative Air Conditioner Prototype.* NREL/TP-5500-54755

4. Kozubal, Eric; Woods, Jason. 2021. *Heat-Pump Driven Desiccant Regeneration*. U.S. Patent No. 11,029,045 B2.

5. Kozubal, Eric. 2017. *Indirect Evaporative Cooler Using Membrane-Contained, Liquid Desiccant for Dehumidification*. U.S. Patent No. 2017/0074530 A1.

Project Execution

	FY2022	FY2023	FY2024*
Planned Budget	$245,000	$300,773	$123,602
Spent Budget ($307k to date)	$181,477	$125,746	$0

Q1 Q2 Q3 Q4 | Q1 Q2 Q3 Q4 | Q1 Q2 Q3 Q4

Past Work

- **Q3-2022**: Heat and mass exchanger code transioned from EES to Matlab
- **Q4-2022**: Preliminary EDDR subsystem results and future design path
- **Q1-2023a**: Desiccant Property Measurements
- **Q1-2023b**: System model developed showing transient example results
- **Q2-2023**: Journal article draft: Desiccant material properties

Current / Future Work

- **Q3-2023**: Report describing advancements in heat and mass exchanger
- **Go / No Go**: System efficiency design pathway to >40% over standardard equipment
- **Q4-2023**: Laboratory scale system construction and test plan
- **Q1-2024**: Laboratory scale system evaluated in HVAC laboratory
- **Q2-2024a**: Journal article draft: desiccant regenerator system and HVAC system results
- **Q2-2024b**: Final summary report to DOE summarizing outcomes of each research task

*FY2024 budget includes carry-over funds not spent in FY2022

Team

NREL — Transforming ENERGY

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