Advanced Dry-cooling with Integrated Enhanced Air-Cooled Condenser and Daytime Load-shifting Thermal Energy Storage for Improved Power-Plant Efficiency

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U.S. Department of Energy

National Energy Technology Laboratory

Resource Sustainability Project Review Meeting

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Project Overview

Funding (DOE and Cost Share): Total: $1,857,330
Federal - $1,485,086 and Cost Share - $372,244

Overall Project Performance Period:
February 01, 2021 – January 31, 2024

Project Participants

University of Cincinnati
Raj M. Manglik (Principal Investigator)
Milind A. Jog (Co-PI)

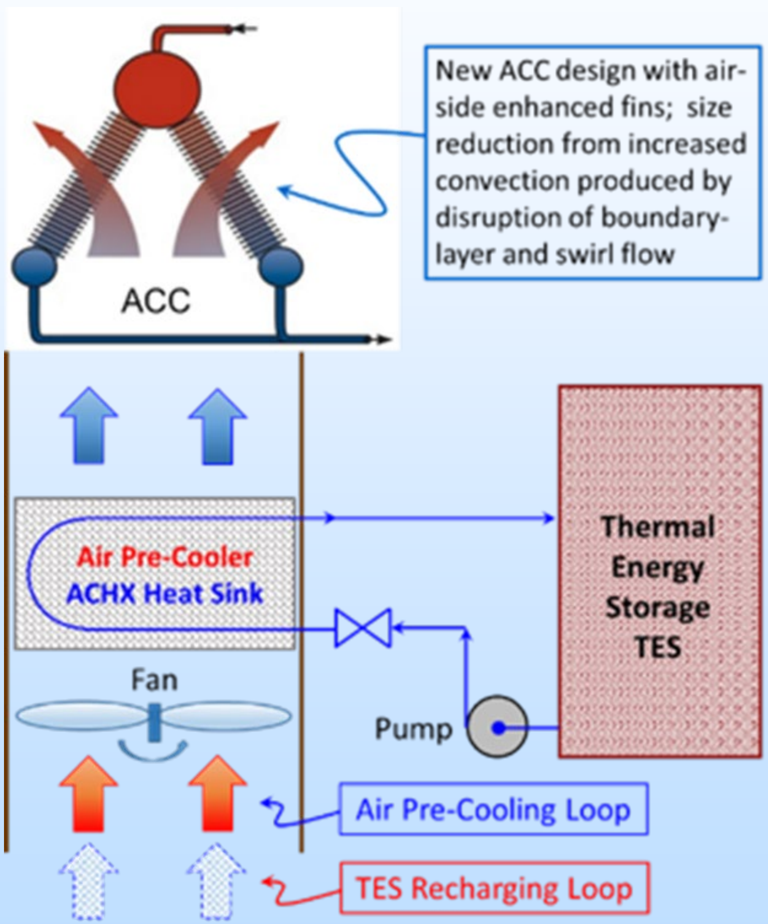
EPRI – Electric Power Research Institute
Andrew Howell (Industry Partner)

evapco
Jean-Pierre Libert (Industry Consultant)

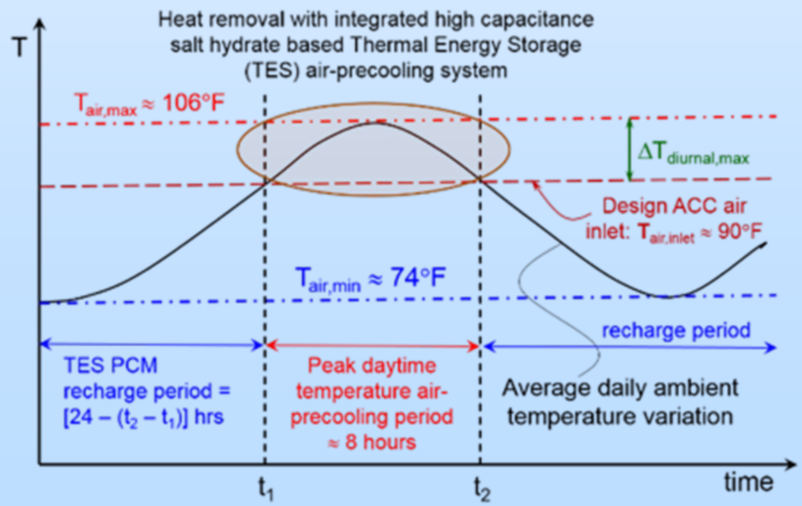
Maulbetsch Consulting
John S. Maulbetsch (Consultant)

Georgia Power, A Southern Company | New York State of Opportunity, NY Power Authority | Dominion Energy | PandaPatriot

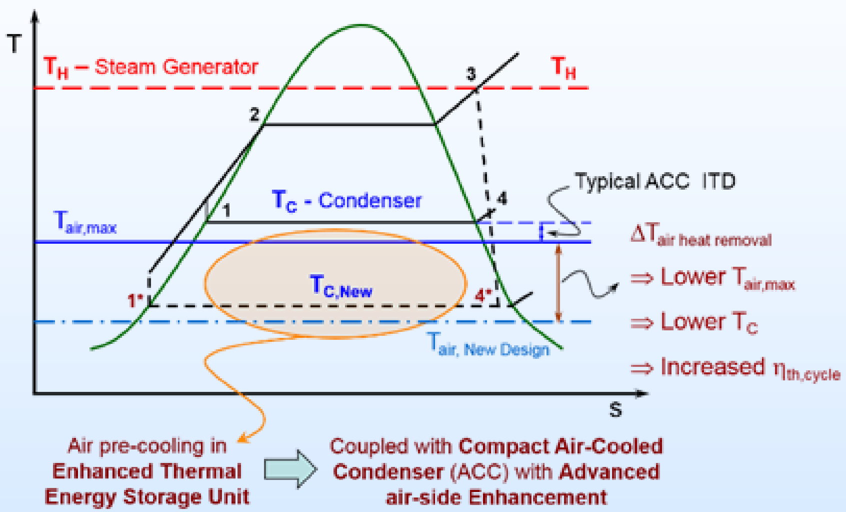
Project Overview (Overall Objectives)



Develop a novel and transformative dry-cooling system that integrates daytime peak air-load shifting thermal energy storage (TES), with an enhanced, highly compact and optimized air-cooled condenser (ACC), to significantly increase power plant efficiency. The TES system, a phase-change-material (PCM) based heat exchanger, is integrated in the inlet air-stream of the ACC via an air pre-cooler (ACHX).

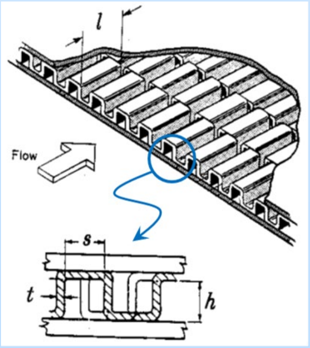


Technology Background

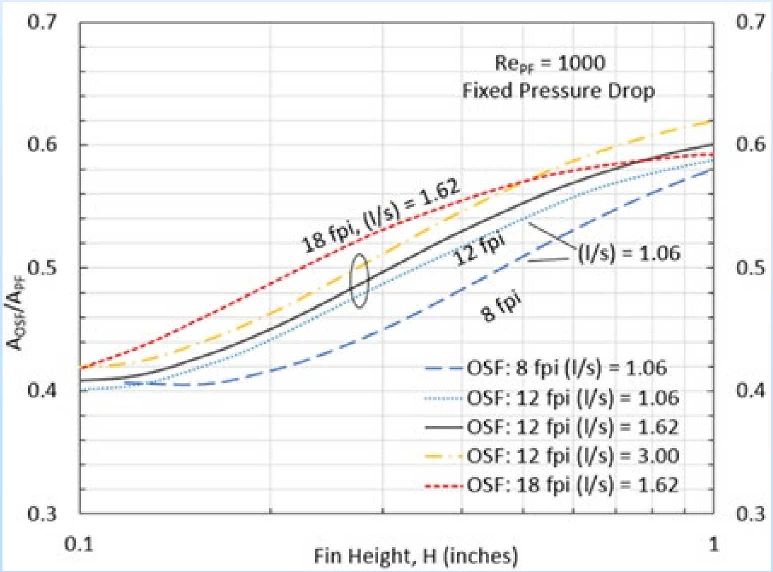


Integrated PCM-TES in air-flow path of air-cooled steam condenser (ACC)

- Reduces T_C operating constraint, and increases Rankine cycle output and efficiency.
- Reduced $T_{air,\ Design}$ increases ACC's ΔT_{lm} thereby increasing both q and effectiveness (reliable steady operation) of ACC.



The new Air-Cooled Condenser design with enhanced-fin cores for improvement of air-side heat transfer can yield significant reduction in the surface-area requirement and hence the size of the ACC



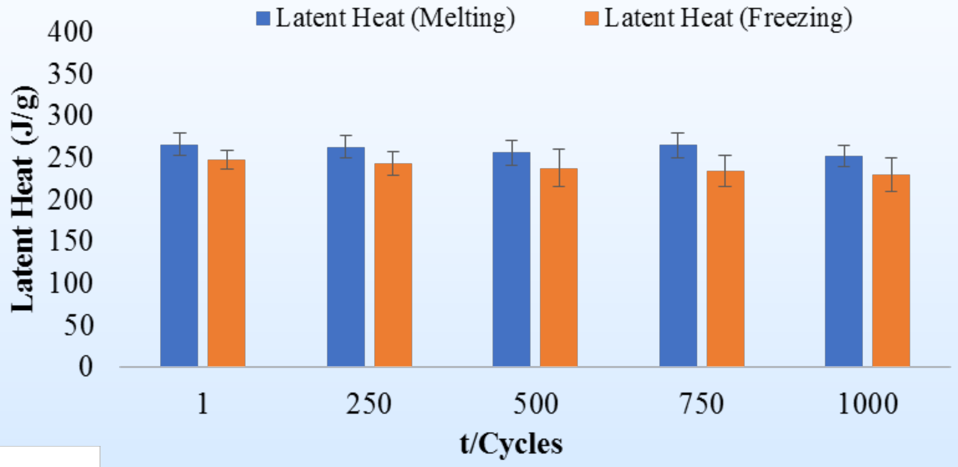
Technology Background

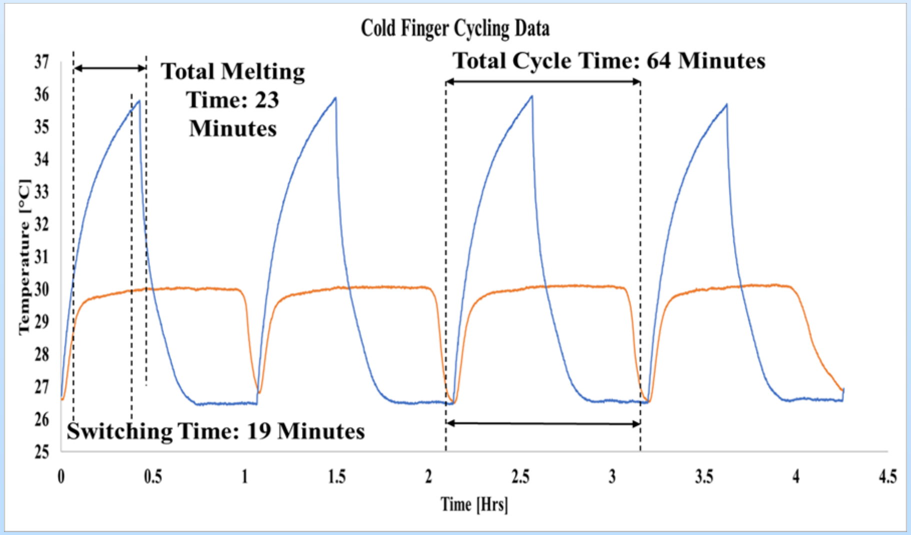
Phase-Change Material (PCM) Selection; Salt Hydrates

PCM	T_{sf} [°C]	ΔT_{sc} [°C]	h_{sf} [kJ/kg]	h_{sf} [kJ/m^3]	Comments
Lithium Nitrate Trihydrate	29.2	3.8	273	650	☑
Calcium Chloride Hexahydrate	29.8	5.9	182	311	High Corrosion
Zinc Nitrate Hexahydrate	34.6	3.1	140	290	High T_{sf}
Sodium Sulfate Decahydrate	32.2	25.2	233	341	Unstable

Technology Background

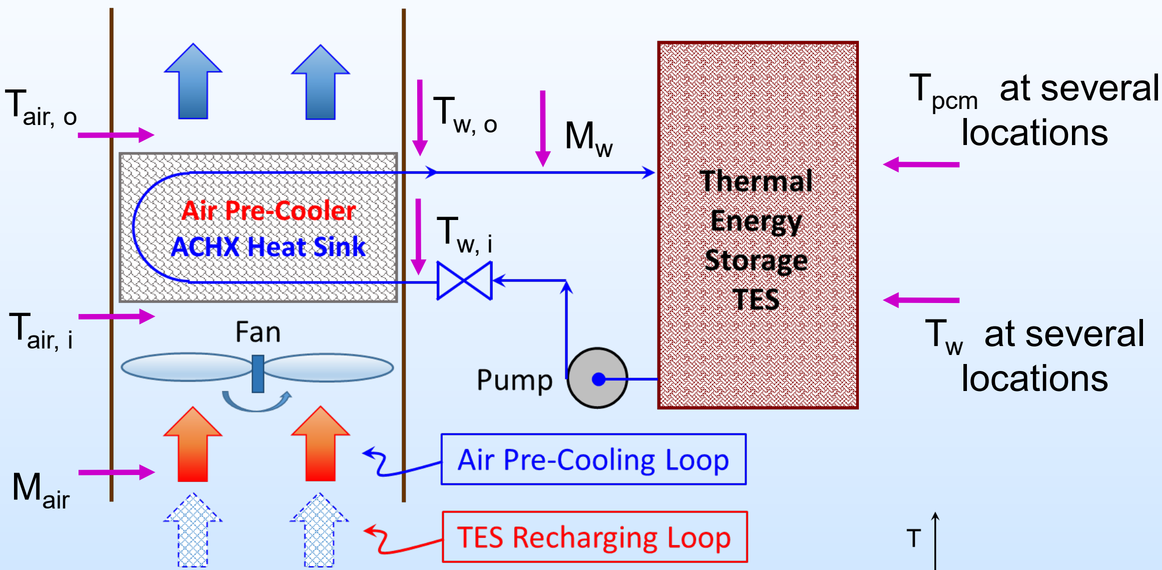
Selection of PCM ($LiNO_3 \cdot 3H_2O$) and Stable Thermal-Cycling Performance – thermal capacity of $LiNO_3 \cdot 3H_2O$ over 1000 heating (melting) and cooling (re-crystalization) cycles





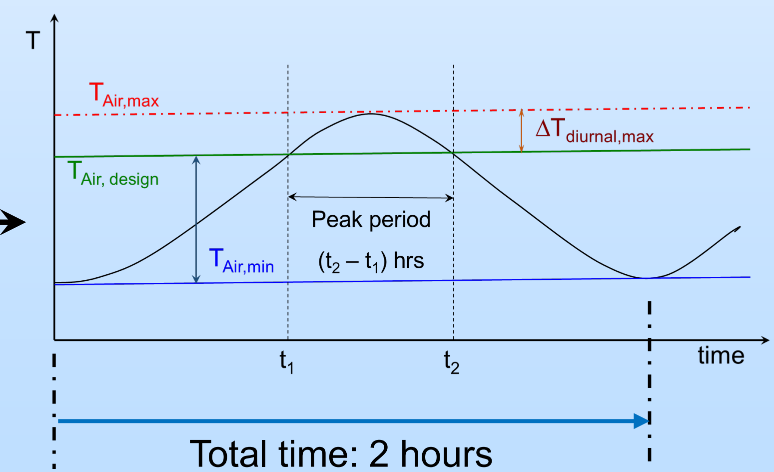
Self-seeded nucleation (or "cold-fingering") and phase-transition stability of $LiNO_3 \cdot 3H_2O$ during thermal cycling

Technical Approach/Project Scope



- TES scale-up (10× scale-up; 100 kJ → 1.0 MJ) and performance testing
  - Performance with diurnal air-side temperature variations (system-level prototype performance)

Inlet air – models diurnal temperature variation (Max 106°F, Min 74°F over a two-hour cycle)
Heating: 1 MJ over 40 min period; Cooling: 1 MJ over 80 min period; Air Pre-Cooler tube-fin heat exchanger size: ~ 420 W (or ~ 450 W, or can be overdesigned for testing purposes)



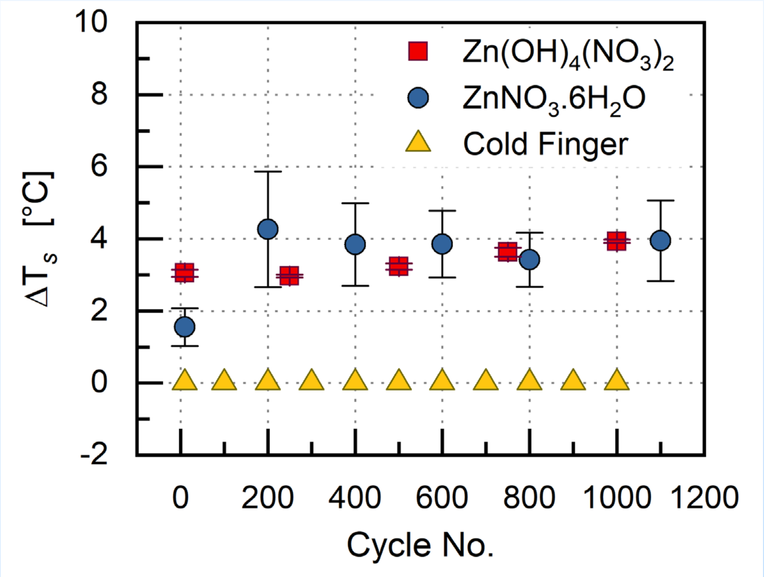
Technical Approach/Project Scope

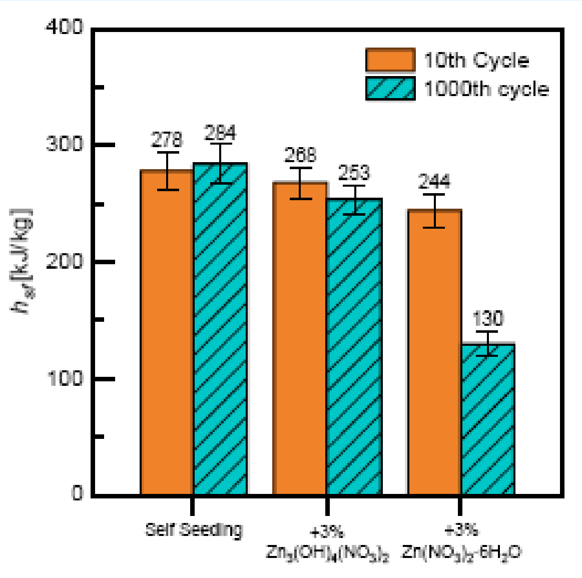
- Task 1: Project Management and Planning (Y1, Y2, Y3)
- Task 2: Design and Performance Evaluation of TES System (Y1, Y2)
- Task 3: Design and Performance Evaluation of Air Pre-cooler (Y1, Y2)
- Task 4: Technology Demonstration (Y3)
- Task 5: Techno-Economic Analysis; and Final Report (Y2, Y3)

- Financial Risk:
  - Inadequate management of funding (Low/Med/Low): Periodic review of the status of the project by the PI with input from the team
- Cost/Schedule Risk:
  - ***Construction delay*** *(Low/High/Med): Complete optimal design early in the project* ◀◀◀
  - Failure to obtain accurate data/interpret data (Low/High/Med): Careful assessment of test protocol with expert review as needed
- Management Planning and Oversight Risk:
  - Personnel unavailability (Med/Med/Med): Team interacts regularly to fill in until replacement can be assigned and trained
- ES & H Risk:
  - Chemical discharge (Low/High/Low): Strictly follow chemical discharge guidelines
- External Factor Risks:
  - Disruptive events (Low/High/Low): Relocate to other test facilities

Progress and Current Status of Project

Stability re-evaluation of PCM (Lithium Nitrate Trihydrate) – Experimental results for 1000 heating/cooling cycles with nucleating agents and self-seeding or cold-fingering

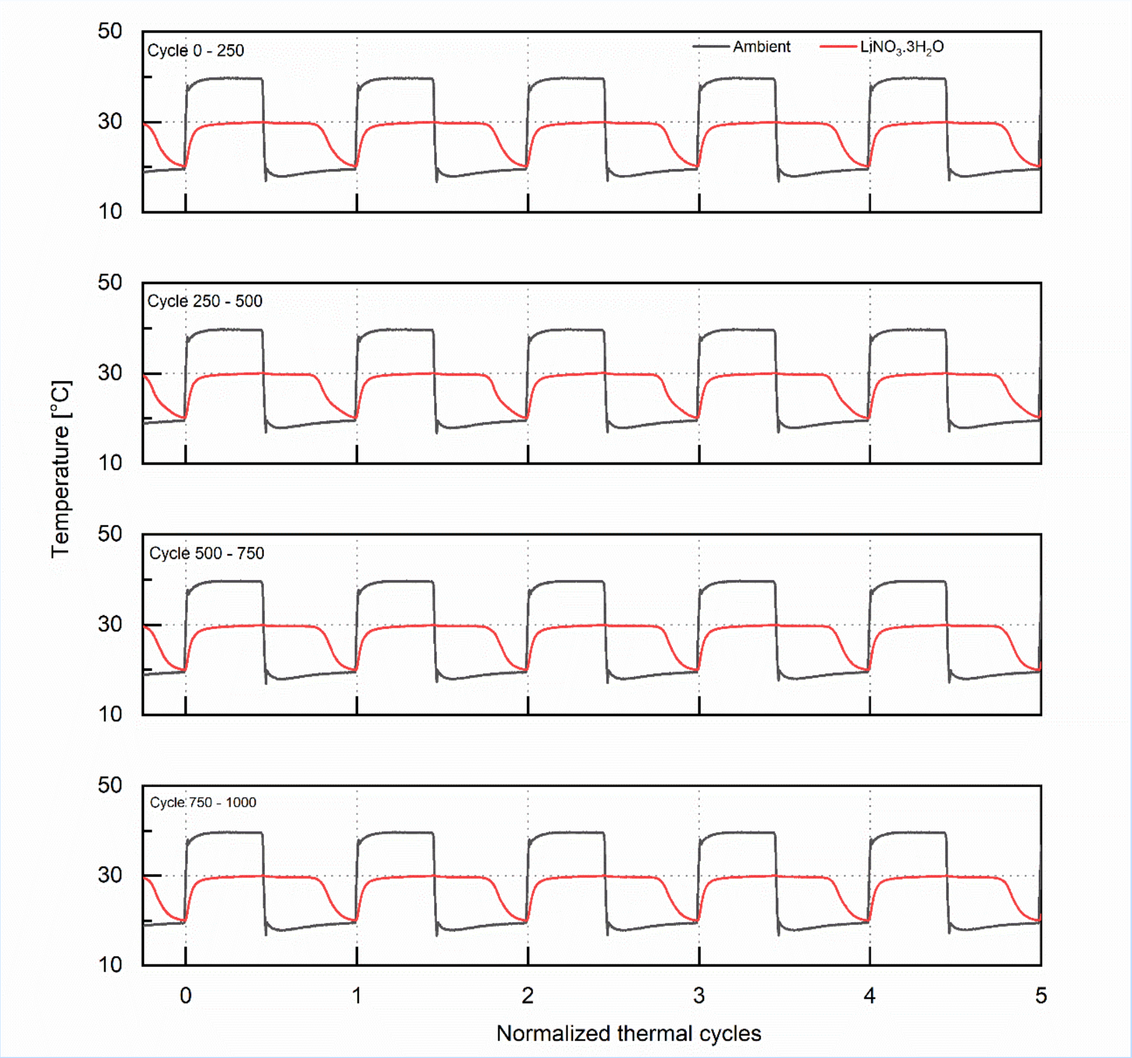




Subcooling, ΔT_s, with and without nucleating agents:

- Results unequivocally <u>establish the efficacy of self-seeding nucleation </u>(or cold finger operation) of PCM, thereby *obviating the need of nucleating agent additives*.

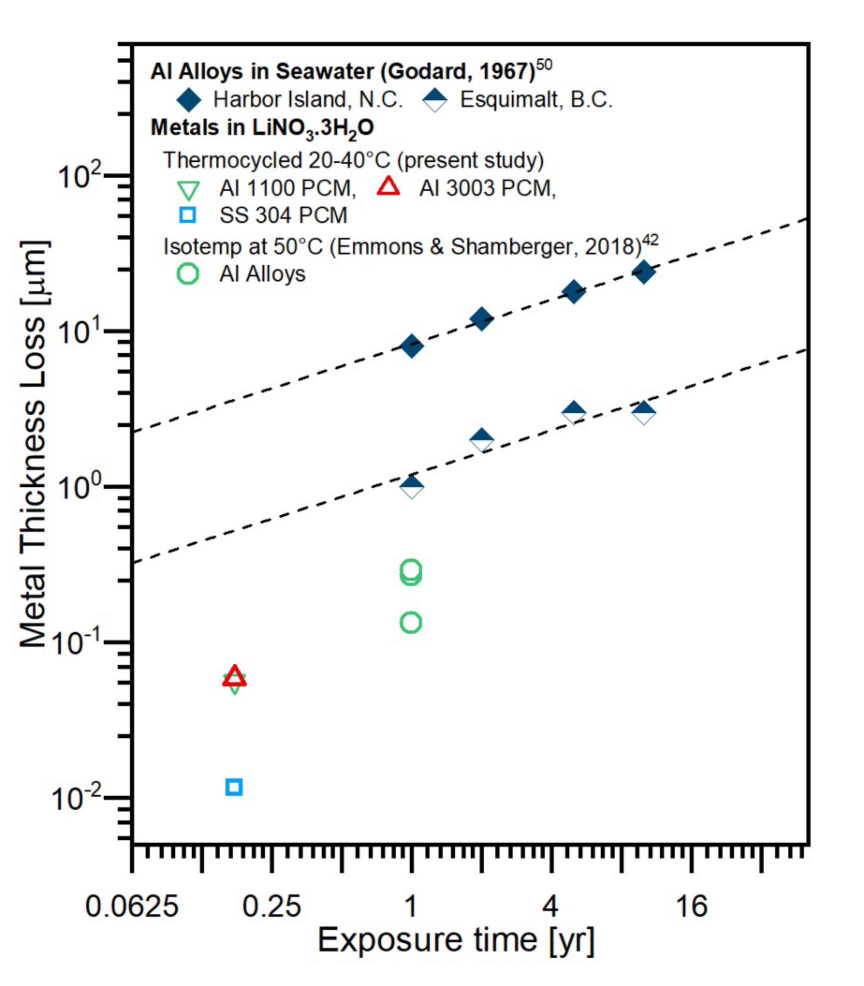
Progress and Current Status of Project



Stability re-evaluation of PCM (Lithium Nitrate Trihydrate) – Experimental results for 1000 heating/cooling cycles with self-seeding or cold-fingering

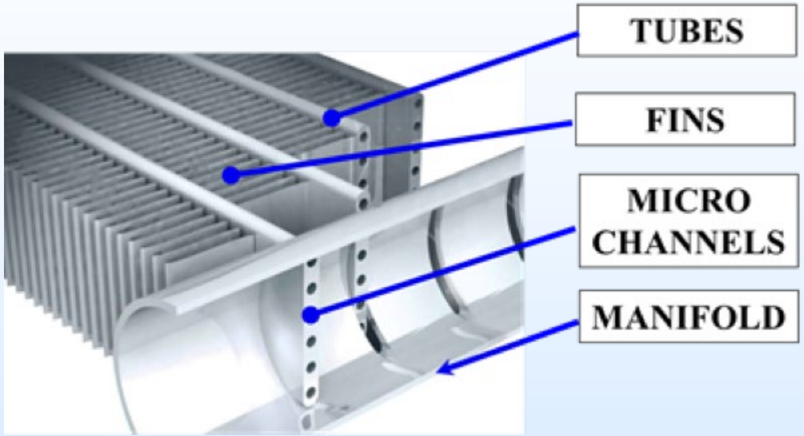
(T-History Method for cyclic performance evaluation)

Progress and Current Status of Project

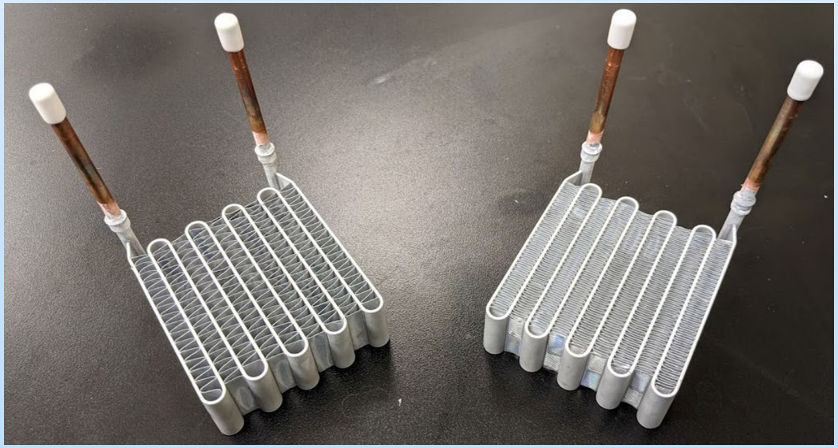


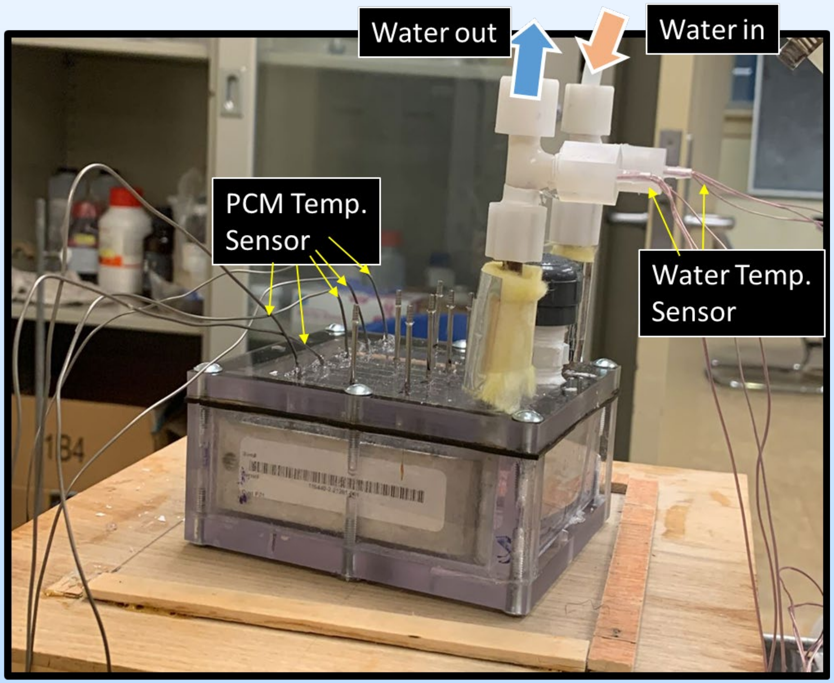
- Metal samples were immersed in PCM holders and exposed to thermal cycling between 20°C and 40°C (30 min/cycle), using self-seeding method (or 'cold finger' protocol) for 4000 cycles (86 days).
- Negligible corrosion is observed in all metals. The loss in surface thickness is negligible; substantially less than sea-water-based corrosion or 0.08 µm/yr.
- These results will inform the eventual design and construction of the TES heat exchanger and its components.

Progress and Current Status of Project



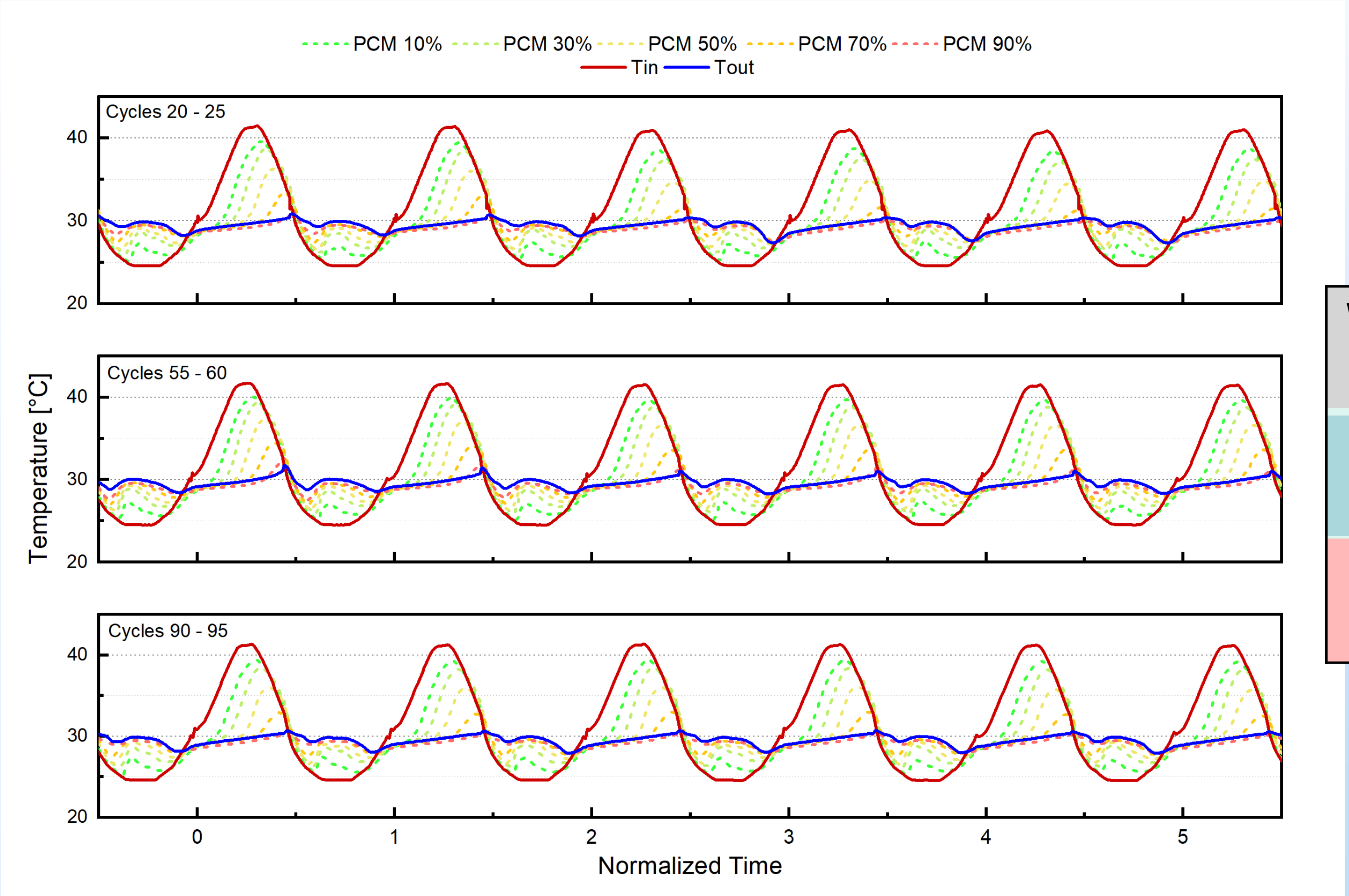
New TES design – micro-channel finned-duct ultra-compact heat exchanger





Progress and Current Status of Project

New TES design with 24 FPI – Performance testing results for 100 heating/ cooling cycles with self-seeding of PCM (Lithium Nitrate Trihydrate)

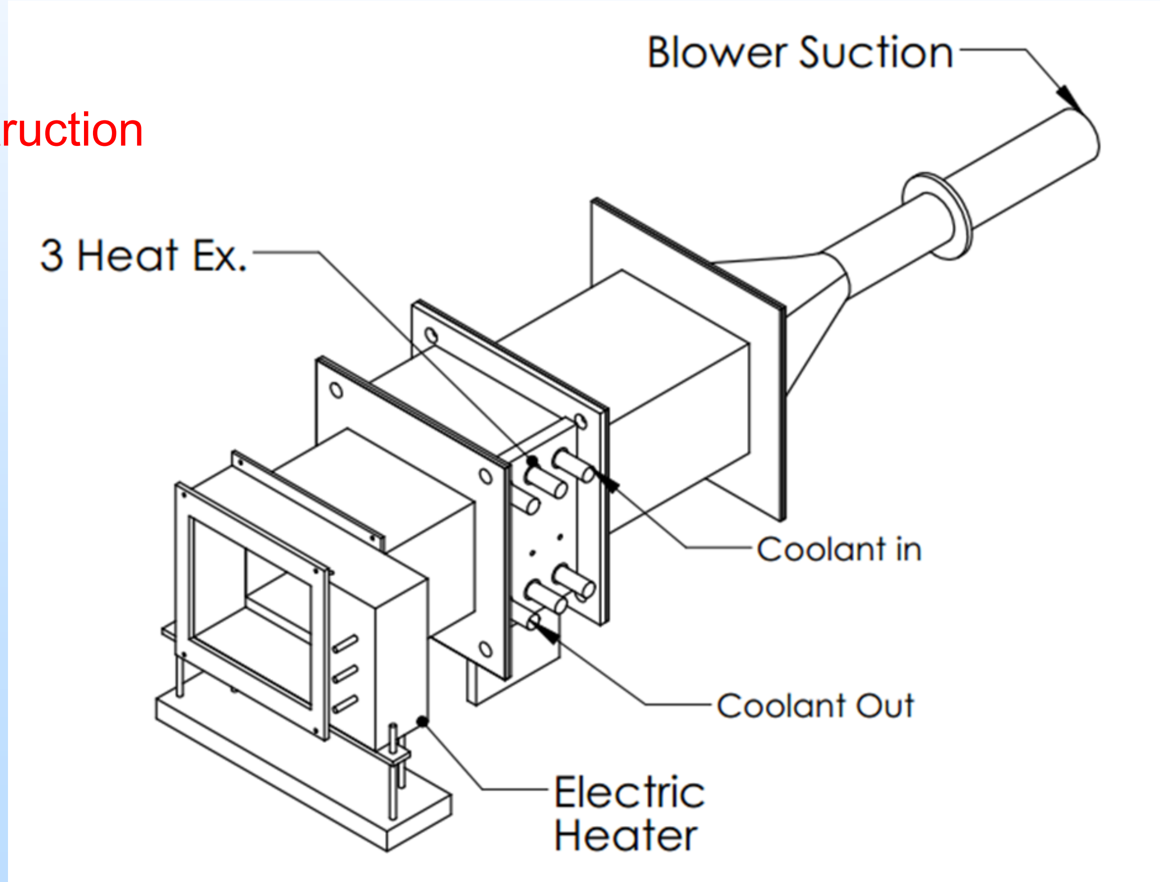


Water Inlet Temperature Flow Rate Time
25 - 30°C 155 ml/min ~ 30 min
30 - 41°C 56 ml/min ~ 30 min

Progress and Current Status of Project

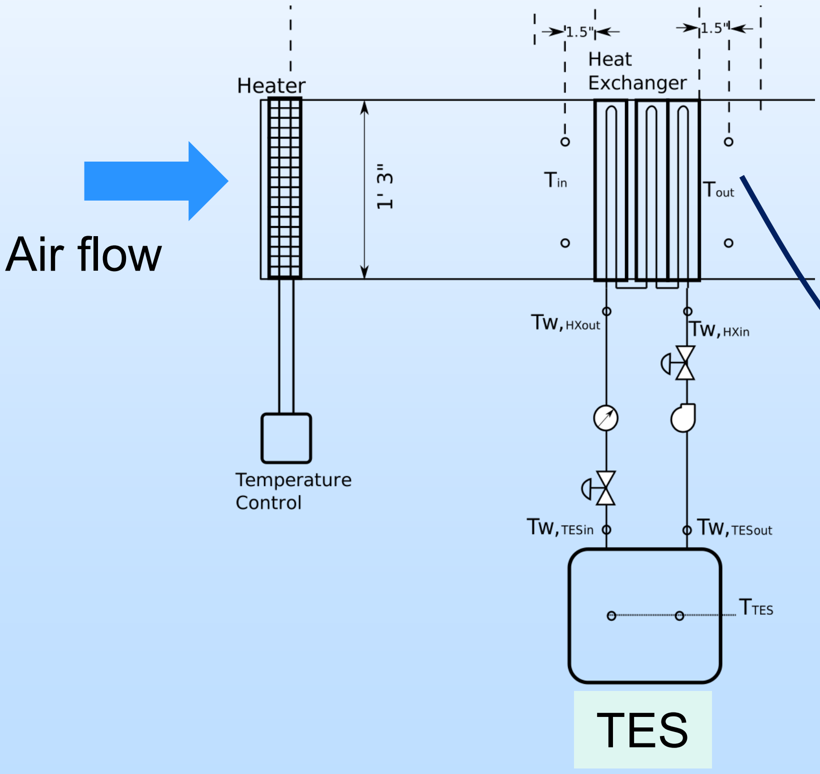
Design and sizing of the air pre-cooler heat exchanger, TES and simulated diurnal air-temperature variation performance test system – Coupled TES and Air Pre-Cooler Heat Exchanger System

Under Construction

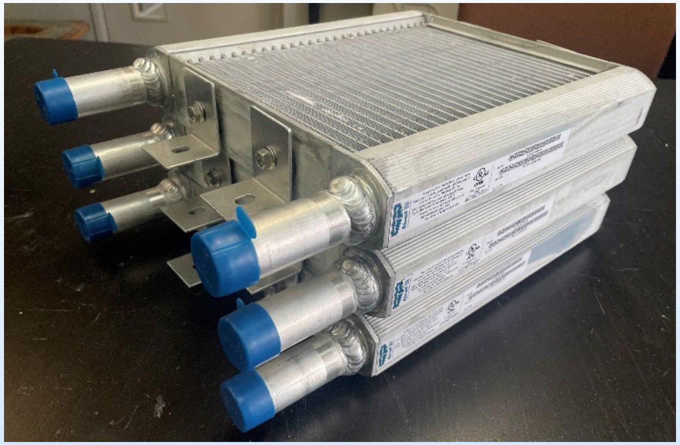


Progress and Current Status of Project

Air Pre-Cooler – Micro-Channel Heat Exchanger Design



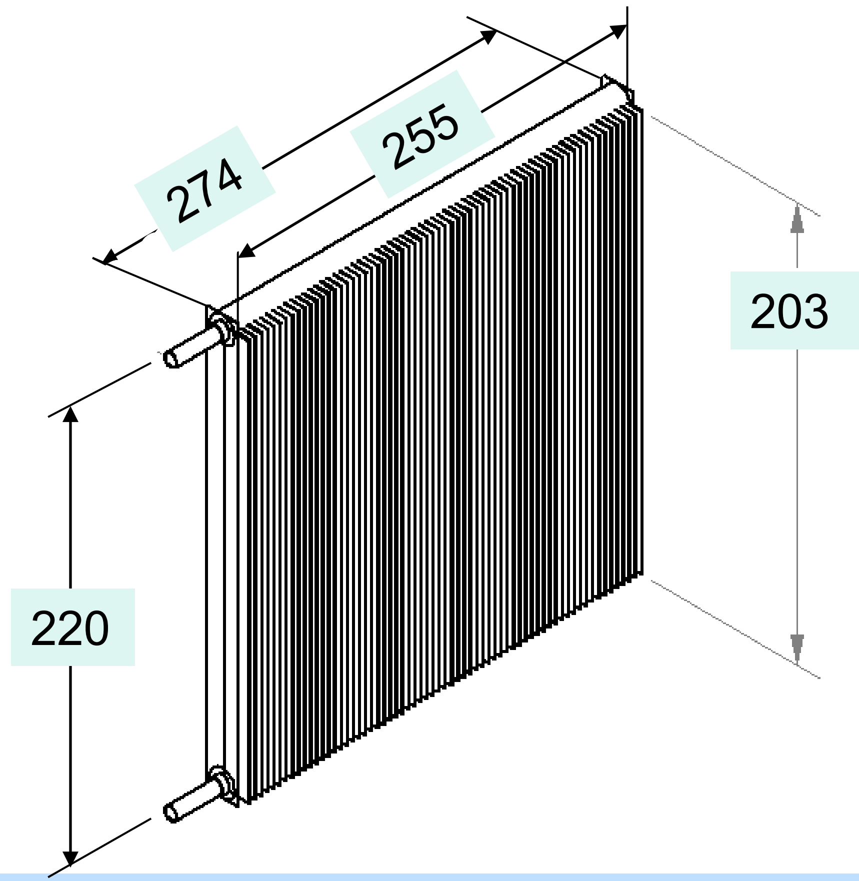
Fabricated and Acquired



	HX 1		HX 2		HX 3	
Fluid	T_i [°C]	T_o [°C]	T_i [°C]	T_o [°C]	T_i [°C]	T_o [°C]
Air	23	25.8	25.8	27	27	27.6
Water	28	27.7	27.7	27.2	27.2	25.9
Capacity	560 W		260 W		120 W	

Progress and Current Status of Project

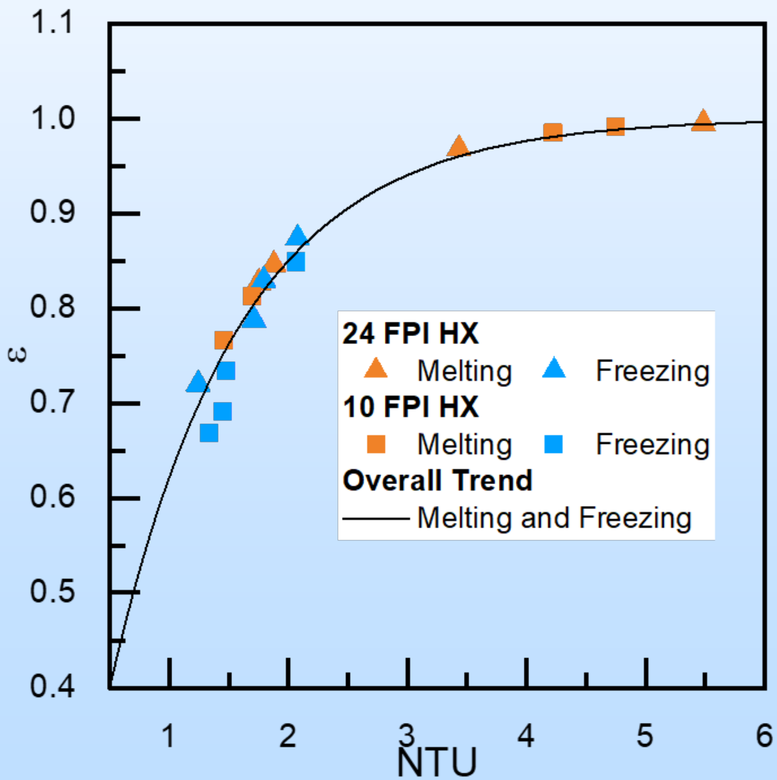
Air Pre-Cooler – Micro-Channel Heat Exchanger Design



Coil face width	255 mm
Coil face height	203 mm
Fin type	Louvered fin
Fin density (fins per inch)	24 fpi
Coil configuration	1 row
Volumetric flow rate of air	602 m^3/hr
Volumetric flow rate of water	6.6 liters/min
Total capacity	1.2 MJ
Total cycle time	2 hours
Total capacity	850 W
Designed capacity (HX1+HX2+HX3)	**560+260+120 = 940 W**

Progress and Current Status of Project

TES Design (24 FPI and 10 FPI) – e-NTU characteristics for microchannel fin-tube HX designs



The experimental data fits the standard phase change e-NTU equation

$$e = 1 - e^{-NTU}$$

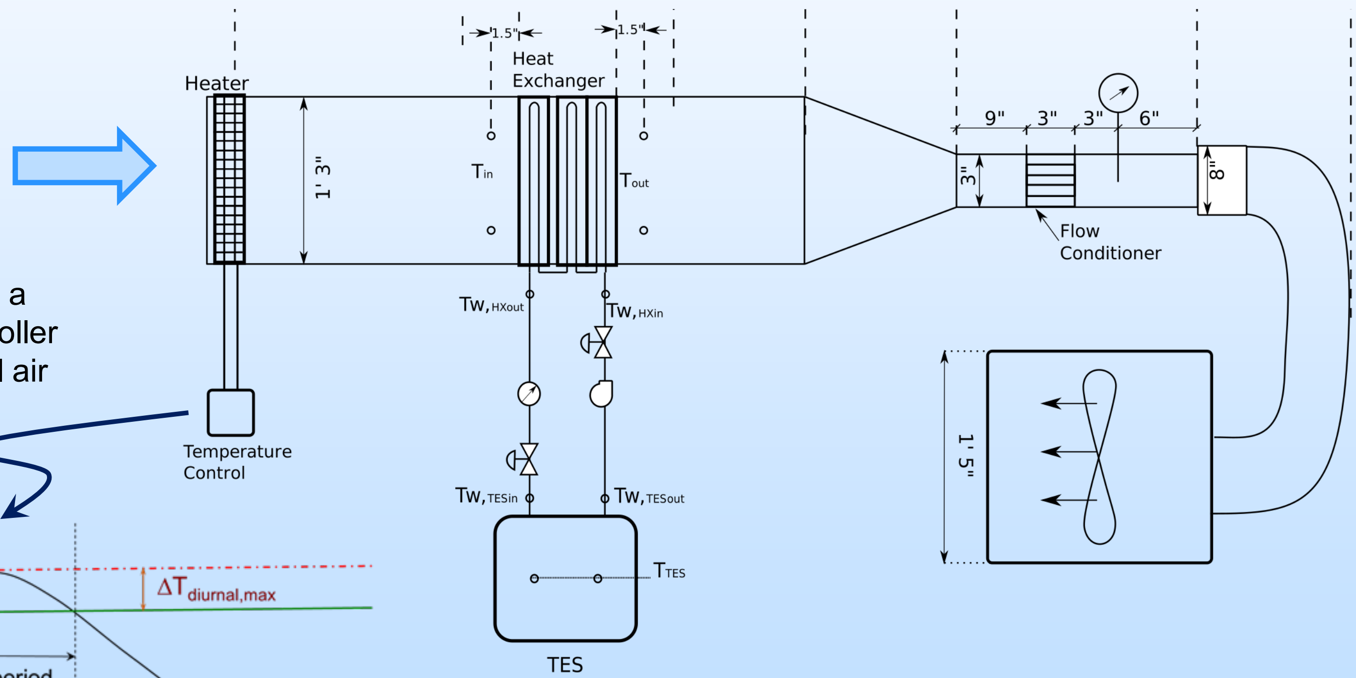
TES scale-up (10× scale-up; 100 kJ → **1.0 MJ**) and performance testing

- Performance with diurnal air-side temperature variations (system-level prototype performance)

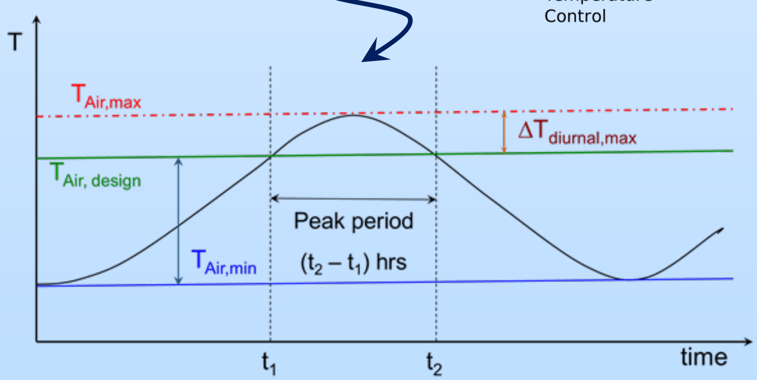
Plans for future testing/development/ commercialization

Coupled TES and air pre-cooler heat exchanger performance test system with simulated diurnal temperature variation of inlet air

Air flow



Heating varied via a temperature controller to simulate diurnal air temperature



Under Construction

Outreach and Workforce Development Efforts or Achievements

- Workforce Development –
  - Trained and graduate two PhD and one MS students, including one woman PhD engineer.
  - Current training of two PhD students and one female MS student.

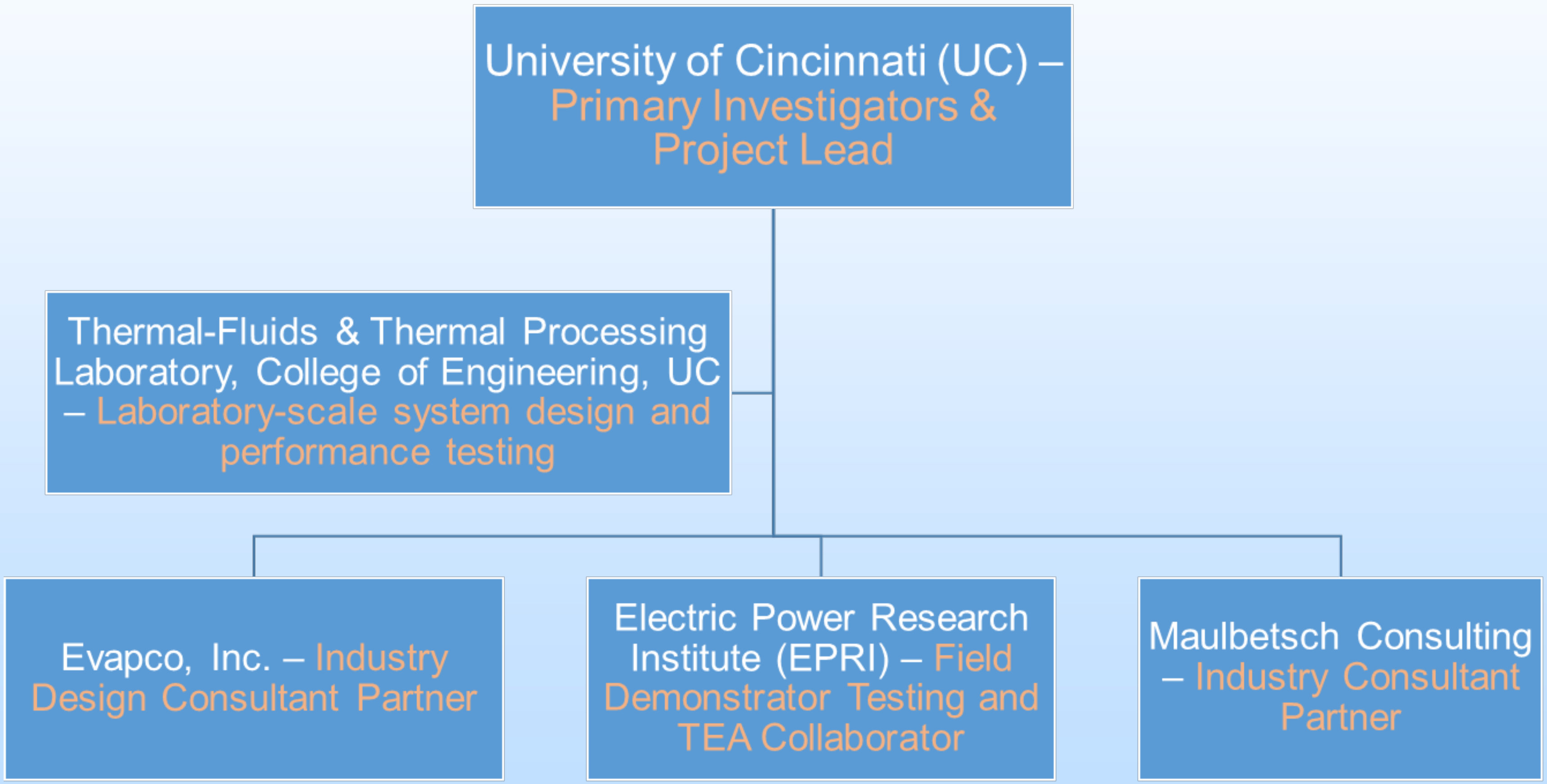
Summary
(Y1 Accomplishments and Completed Milestones)

- Successfully completed stability re-evaluation of PCM ($LiNO_3 \cdot 3H_2O$) with results for 1000 heating/cooling cycle
  - Results establish efficacy of self-seeding nucleation of PCM (cold finger operation), thereby obviating need for nucleating agent additives
- Completed experimental evaluation and modeling of "length scale" effects for PCM TES design for stable cyclical operation
- Successfully tested revised new design of TES (10 fpi and 24 fpi fin-tube micro-channel heat exchanger) under cyclical heating and cooling conditions for 100 continuous cycles
  - Stable phase-transition and storage behavior of new TES design.
- The air pre-cooler heat exchanger (coupled to the TES in the complete system) was designed (sized for required heat load) and procured.
- The complete air-cooling system (TES coupled with Air Pre-Cooler HX) is under construction

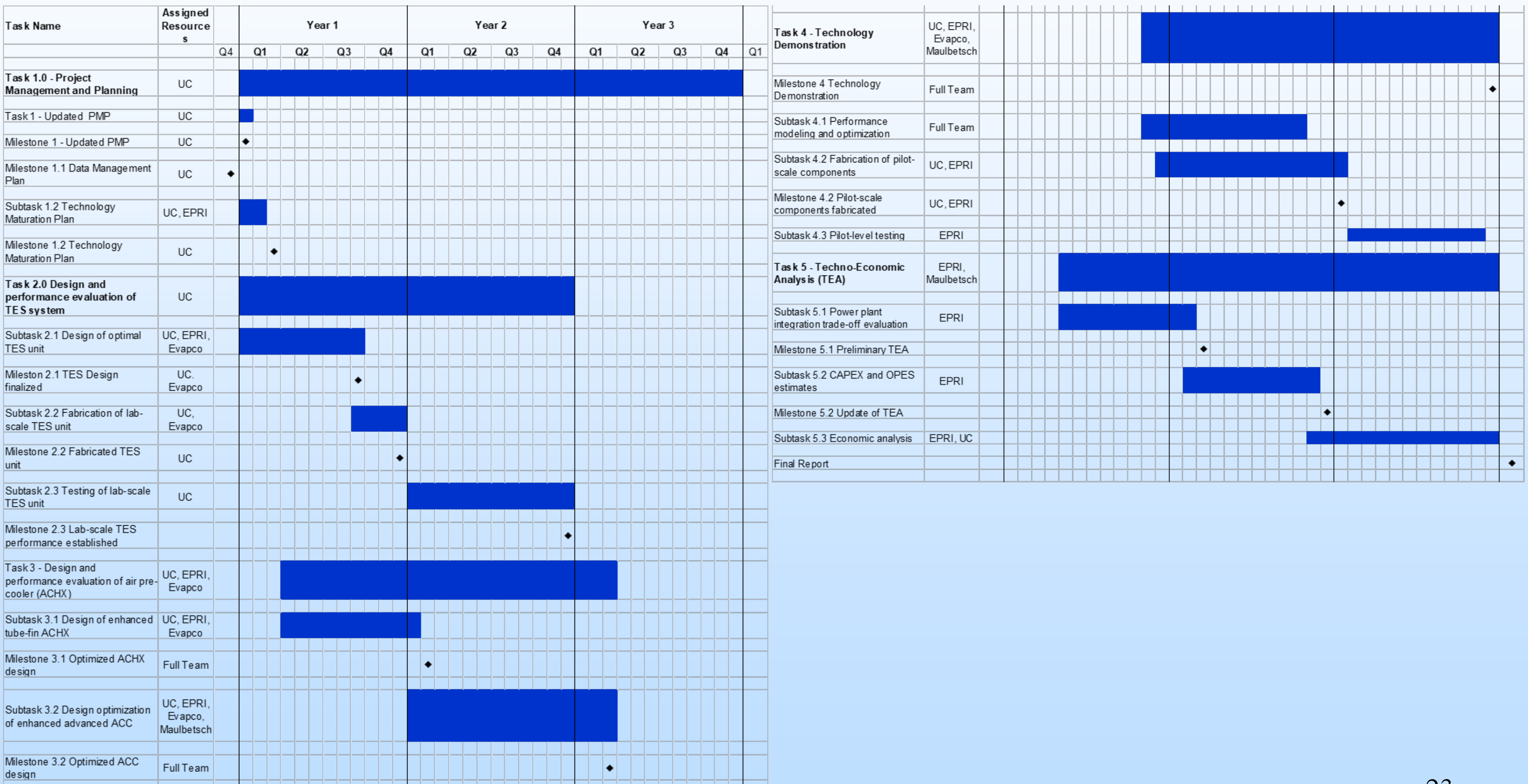
Appendix

– These slides will not be discussed during the presentation but are mandatory.

Organization Chart



Gantt Chart


Task Name
Assigned Resources
Year 1
Year 2
Year 3
Q4
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Q1
Task 1.0 - Project Management and Planning
UC
Task 1 - Updated PMP
UC
Milestone 1 - Updated PMP
UC
Milestone 1.1 Data Management Plan
UC
Subtask 1.2 Technology Maturation Plan
UC, EPRI
Milestone 1.2 Technology Maturation Plan
UC
Task 2.0 Design and performance evaluation of TES system
UC
Subtask 2.1 Design of optimal TES unit
UC, EPRI, Evapco
Mileston 2.1 TES Design finalized
UC. Evapco
Subtask 2.2 Fabrication of lab-scale TES unit
UC, Evapco
Milestone 2.2 Fabricated TES unit
UC
Subtask 2.3 Testing of lab-scale TES unit
UC
Milestone 2.3 Lab-scale TES performance established
Task 3 - Design and performance evaluation of air pre-cooler (ACHX)
UC, EPRI, Evapco
Subtask 3.1 Design of enhanced tube-fin ACHX
UC, EPRI, Evapco
Milestone 3.1 Optimized ACHX design
Full Team
Subtask 3.2 Design optimization of enhanced advanced ACC
UC, EPRI, Evapco, Maulbetsch
Milestone 3.2 Optimized ACC design
Full Team
Task 4 - Technology Demonstration
UC, EPRI, Evapco, Maulbetsch
Milestone 4 Technology Demonstration
Full Team
Subtask 4.1 Performance modeling and optimization
Full Team
Subtask 4.2 Fabrication of pilot-scale components
UC, EPRI
Milestone 4.2 Pilot-scale components fabricated
UC, EPRI
Subtask 4.3 Pilot-level testing
EPRI
Task 5 - Techno-Economic Analysis (TEA)
EPRI, Maulbetsch
Subtask 5.1 Power plant integration trade-off evaluation
EPRI
Milestone 5.1 Preliminary TEA
Subtask 5.2 CAPEX and OPES estimates
EPRI
Milestone 5.2 Update of TEA
Subtask 5.3 Economic analysis
EPRI, UC
Final Report