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Improvement of Coal Power Plant Dry Cooling Technology through Application of Cold Thermal Energy Storage

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Project Overview

– **Funding**
  - Government (DOE): $1,453,179.
  - Cost Share: $ 363,484 (20% of total)

– **Overall Project Performance Dates**
  - 7/1/2020 to 6/30/23 (three years)

– **Project Participants**
  - UNC Charlotte
  - Lehigh University
    – Energy Research Center (ERC)
    – Advanced Technology For Large Structural Systems (ATLSS) Research Center
  - Worley

Project Overview

– **Overall Project Objectives**

- **Main Objective**: Develop and demonstrate a new technology for improving performance of dry cooling based on the concept of "**Cold Thermal Energy**" **Storage (CTES)**.
- CTES involves storing low-temperature heat during nighttime, when temperature of the ambient air is low, and using it to cool air entering a Dry Cooling Tower (DCT) or Air-Cooled Condenser (ACC) during the hot period of the day.
- The proposed concept is also applicable to simple Brayton and combined cycles, industrial, commercial, and residential applications, and concentrated solar power (CSP).
- Increase TRL from 3 to 5.

– **Program Alignment**

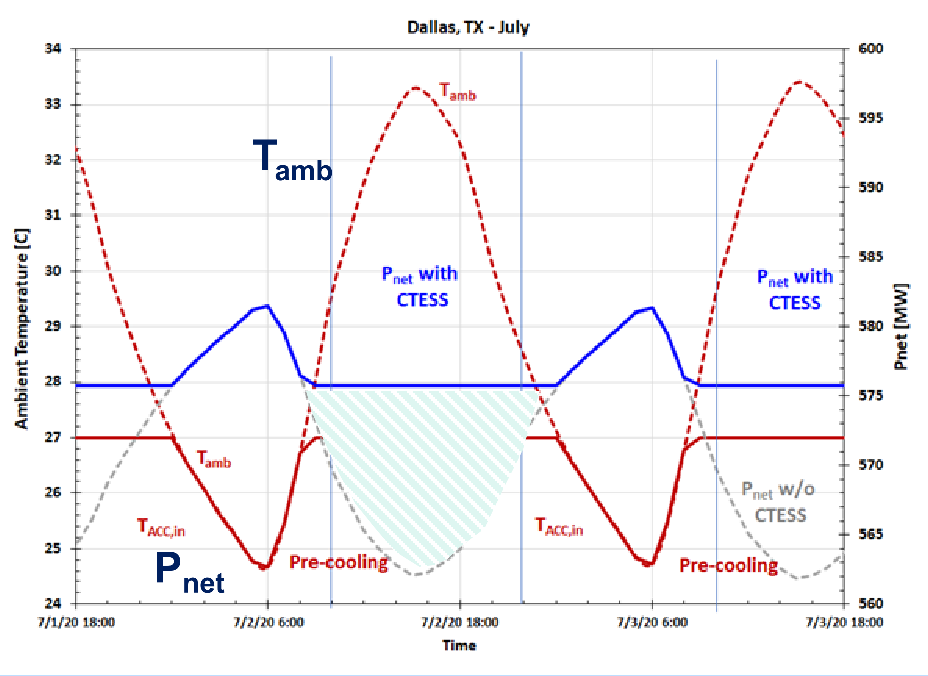
- The project objectives and scope are fully aligned with the DE FOA-0002001 AOI B2 objectives concerning development of advanced technologies that operate efficiently under high ambient air temperatures, while maintaining or improving baseline performance and reduce the capital cost of dry cooling.

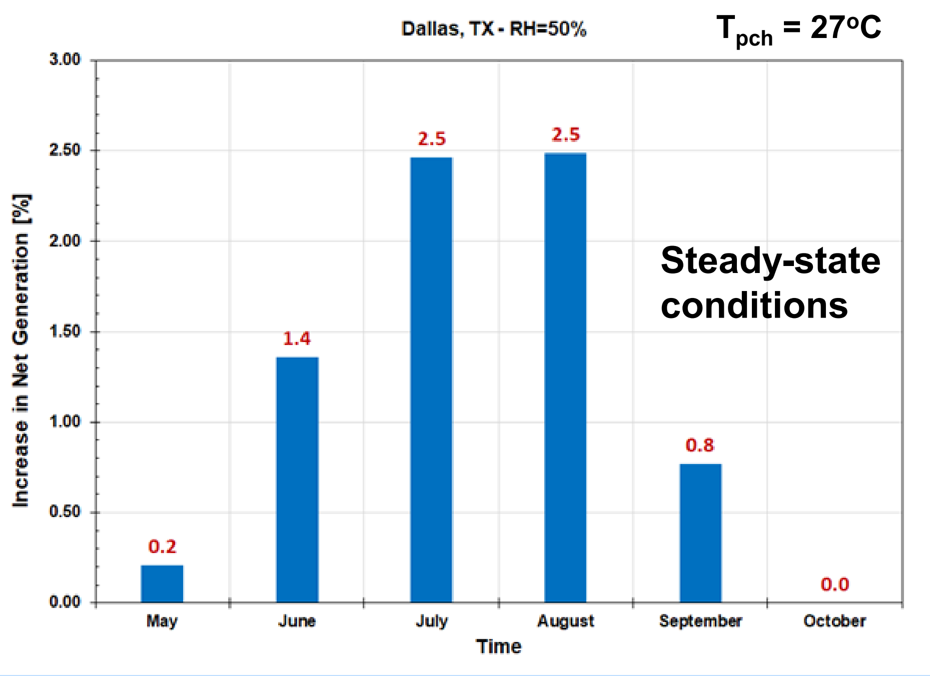
Technology Background

a. The CTES technology for improving performance of dry cooling systems is based on the natural diurnal temperature difference where low-temperature heat stored during nighttime is discharged during the hottest period of the day to cool the DCT/ACC inlet air.

  – Lower temperature of the cooling air improves performance of a dry cooling system and increases power output and net generation of a power plant during period of highest load demand and energy prices.

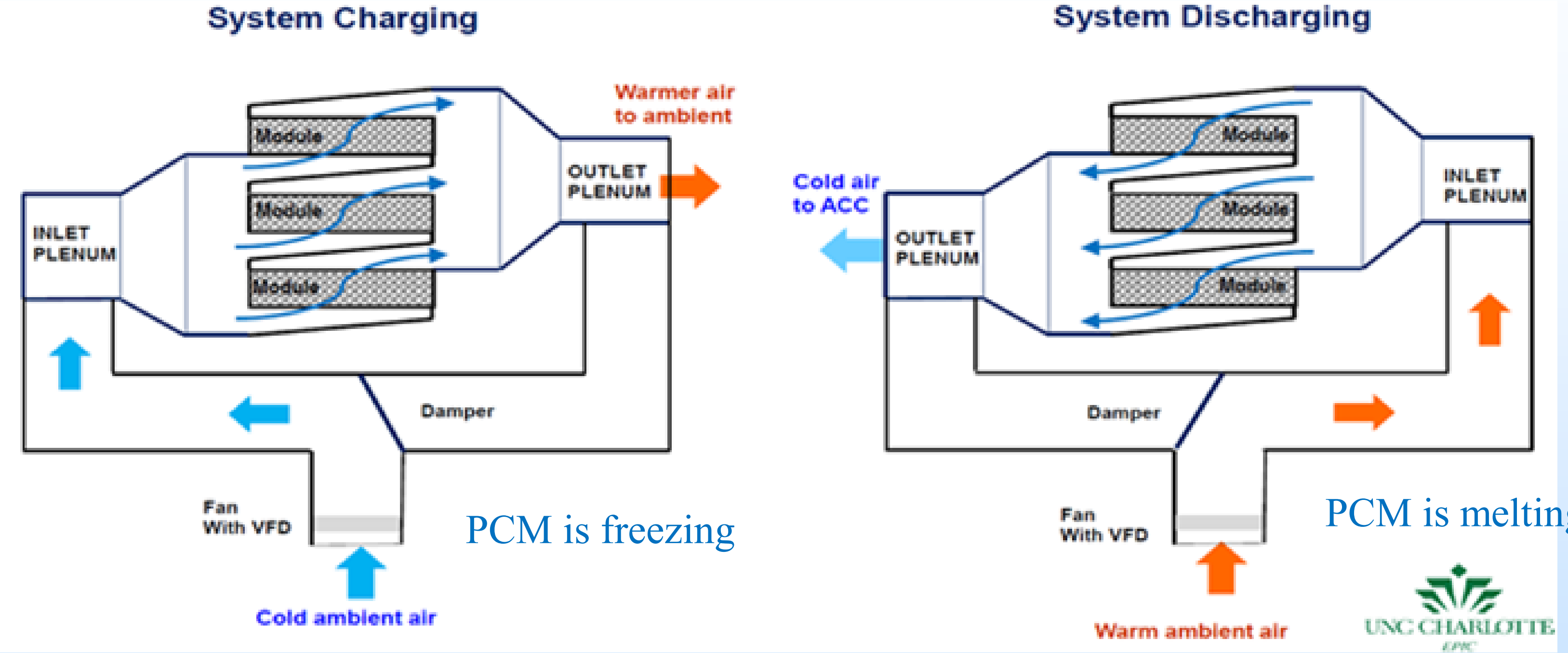
b. Principle of operation **Increase in net generation**





Technology Background

b. Principle of operation (continued)



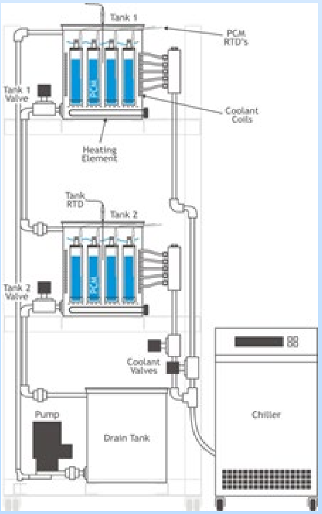
A phase change material (PCM) is used to store low-temperature heat during nighttime and release it during hot period of the day.

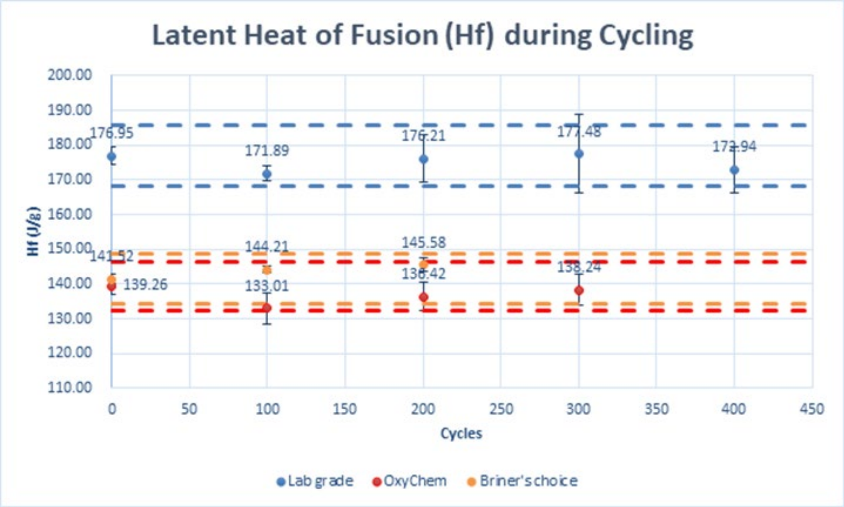
- Heat is stored / released mostly as latent heat at constant temperature
- Small amount of heat is stored / released as sensitive heat
- The PCM selected for this demonstration project is commercially available low-cost hydrated salt, calcium chloride hexahydrate($CaCl_2 \cdot 6H_2O$, or CC6).

Technology Background

c. Previous technology development efforts prior to current project
   - PCM engineering and characterization
   - Determine effect of impurities on phase change temperature and latent heat of fusion
   - Identify additives to suppress supercooling
   - PCM stability under temperature cycling was determined by performing long-term temperature cycling tests
   - Additives were identified to mitigate phase separation
   - Corrosion rate was determined for various materials over temperature range
   - Modeling of plant performance was performed to determine the effect of ambient temperature on performance and power output and the effect of diurnal temperature variation.

Temperature cycling machine for PCM testing.





Technology Background

d. Technical and/or economic advantages of the CTES technology.
   - To produce power, thermal power plants (heat engines) must reject heat.
   - U.S. power plant infrastructure is heavily reliant on water cooling
   - More stringent EPA regulations on water intake and thermal discharge will render once-through cooling obsolete →Water availability will continue to be an issue of increasing concern.
   - Demand for dry cooling is increasing in water scarcity regions and will continue to increase in the future.
   - Performance of an Air-Cooled Condenser (ACC) is governed by the dry bulb temperature (DBT), which varies considerably during the day.
   - A 3^{o}C increase in DBT results in 1% decrease in net power output of the plant.
   - **Implementation of CTES will reduce temperature of the cooling air into ACC increasing power output and net generation during periods of highest load demand and energy prices.**

e. Technical and economic challenges of the CTES technology.
   - PCM stability (solved for CC6)
   - PCM cost (favorable for CC6)
   - PCM has to be matched to the ambient temperature variation at plant location
   - Size of CTES

Technical Approach/Project Scope

a. Project steps and work plan

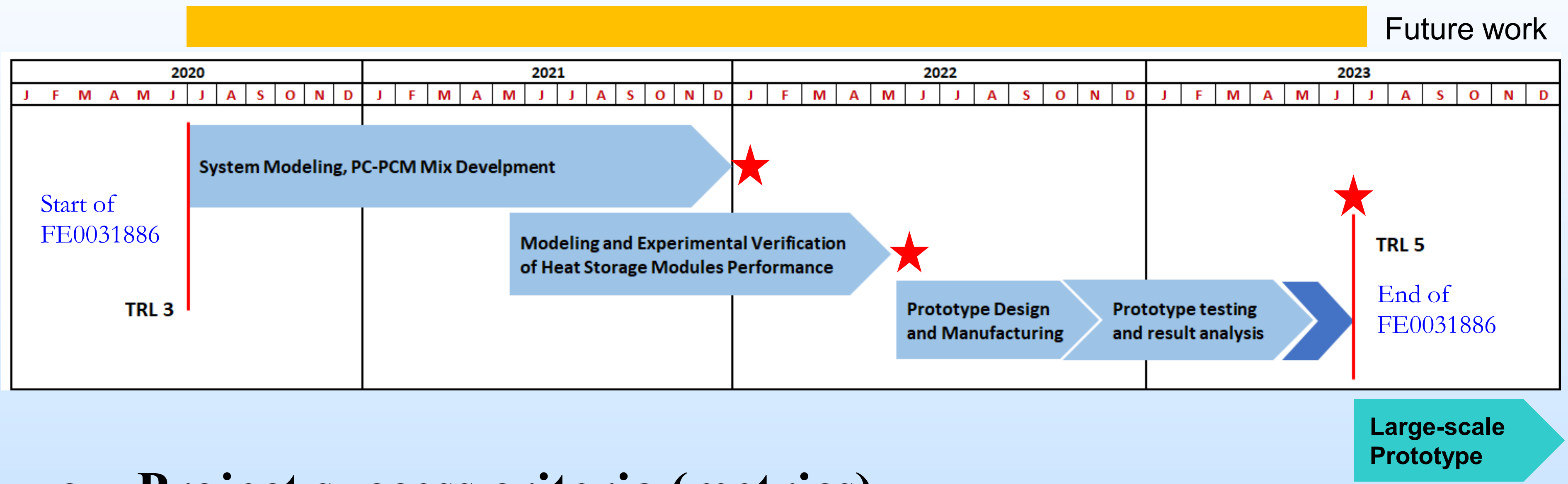
- Engineer and test heat storage medium and modules.
  - The heat storage material, a mix of pervious concrete (PC) and phase changing material (PCM) is a novel concept being developed by the project team.
  - Develop several designs, involving micro-encapsulation of PCM in PC matrix.
  - Engineer and characterize PCM and develop optimal PC and PC-PCM mixes.
- Test heat storage modules using a lab-scale test facility.
- Develop and demonstrate the CTES concept, using best developed PCM and PC designs, on a 10 kWh-scale prototype.
  - Design, fabricate, and test the prototype
- Determine economic viability (perform TEA)
- Project goal is **TRL 5**

Future work

- Prepare for the next phase scale-up.
  - 100 kWh-scale prototype for side-stream testing at a power plant
- The ultimate goal is **TRL 9**.

Technical Approach/Project Scope

b. Project schedule



c. Project success criteria (metrics)

- A conservative performance target of 1.0-1.5% improvement in net energy generation during the hottest time of the day/season, when power and energy demand and prices (MW, MWh) are the highest, at a capital cost increase over cost of current dry cooling technology of less than 30%.

Technical Approach/Project Scope

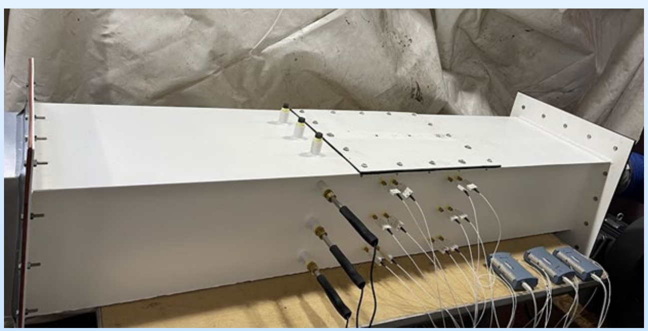
d. Project risks and mitigation strategies

- Data security and preservation → Data security is governed by the University DSP (Data Security Plans)
- COVID pandemic (Vis major) → The COVID pandemic represented a clear and present risk. This risk is being managed by adhering to guidelines and rules issued by the University authorities and by personal diligence and awareness.
- Exceeding project budget → The increase in cost of labor and material caused by COVID and other factors is a clear risk managed by careful project management and design of the test equipment.
- Delay of project execution → COVID-related illnesses are the major concern addressed by personal diligence and awareness. Most of the project meeting are conducted remotely, laboratory activities are governed by the University plans.
- The CTES design developed in the project is a novel concept and as such involves a certain degree of risk. → The risk is managed by collaboration of researchers from two participating universities, professional engineering company Worley, and industrial advisory committee.

Progress and Current Status of Project

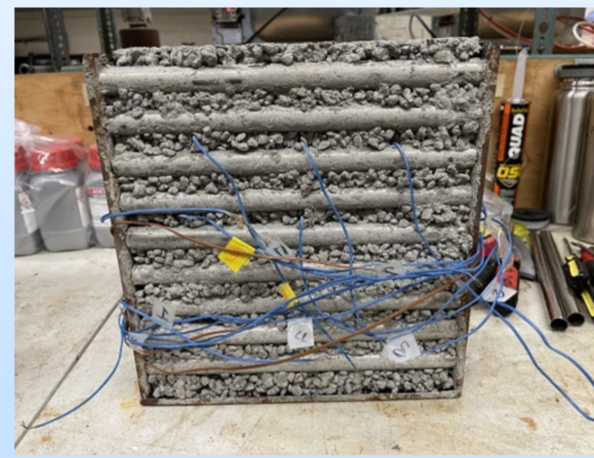
a. The equipment used/built in the project includes

- Equipment for PC and PC + PCM engineering
- Equipment for characterization of PC and PC + PCM properties and measuring its thermo-physical properties
- Laboratory-scale test facility
- Equipment for manufacturing and testing of heat storage modules
- Design and manufacturing (in progress) of prototype scale test facility



Lab-scale test facility: Test Section

Design 4: PCM tube array in air



Design 3: PCM tube array embedded into PCM-infused PC

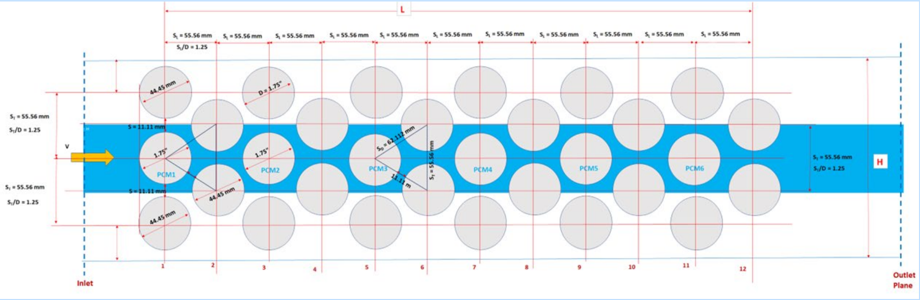
Tube partially filled with frozen PCM

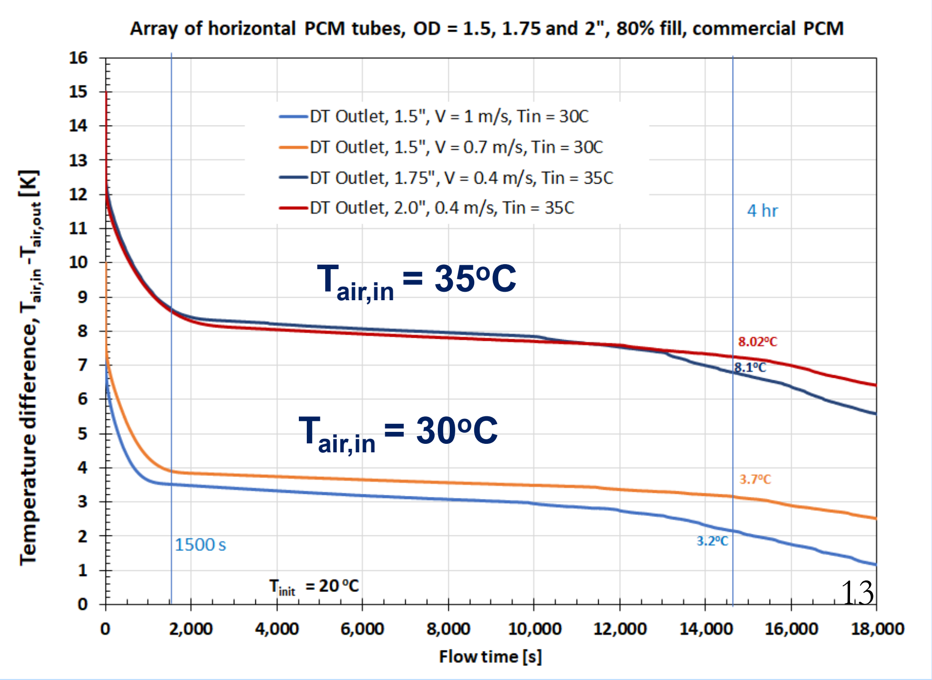
Progress and Current Status of Project

b. Significant accomplishments and how they tie to the technology challenges
   - Engineering of PC, PCM, and PC+PCM materials having required thermo-physical and mechanical properties→ enables development of CTES technology
   - Design and manufacturing of heat storage modules (two designs were developed)
   - Development of computational tools for modeling PCM melting and freezing processes → allows prediction of transient charging and discharging processes and enables optimal design of a heat storage module.
   - Experimental determination of charging and discharging on a laboratory-scale test facility allows verification of numerical models and design of the prototype-scale test facility.

Temperature decrease of ACC cooling air flowing through CTES

Design 4: PCM tube array in air, commercial grade PCM, 80% tube fill, 12 tube rows

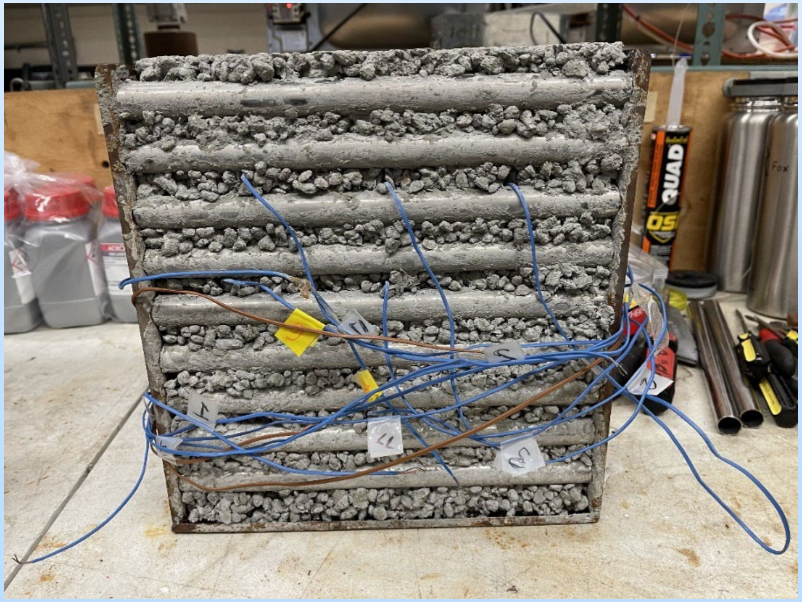




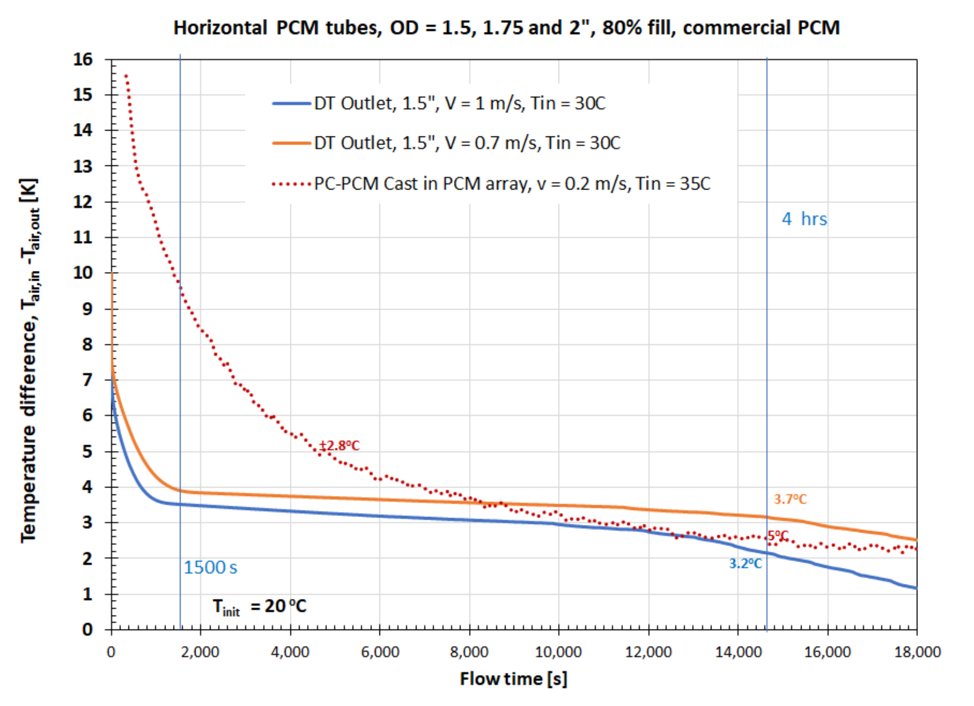
Progress and Current Status of Project

b. Significant accomplishments and how they tie to the technology challenges
   - Development of computational tools for modeling PCM melting and freezing processes → allows prediction of transient charging and discharging processes and enables optimal design of a heat storage module.

Design 3: PCM tube array embedded into PCM-infused PC, commercial grade PCM, 80% tube fill, 4 tube rows



Temperature decrease of ACC cooling air flowing through CTES



Progress and Current Status of Project

c. Performance levels achieved so far when compared to project goals and how the performance relates to the economic and technical advantages.
   - Considering difference in properties of commercial grade PCM compared to laboratory grade PCM (used to develop performance criteria), the achieved results are in line with expectations.
   - Considerably lower cost of commercial grade PCM compared to laboratory grade PCM has a significant positive effect on economic performance of the CTES design developed in this project.

Progress and Current Status of Project

d. Identify synergy opportunities; discuss how collaboration could have a synergistic effect on advancing the technologies described during the session.
   - The project benefited from collaboration of faculty and researchers experienced in material development and characterization, power plant operation and modeling of its performance, numerical analysis of heat transfer and fluid flow, PCM, and laboratory-scale and large-scale testing and system analysis.

Plans for future testing/development/ commercialization

Plans for future testing/development/commercialization

a. This project
   - Demonstration of two heat storage designs on a prototype (10 kWh) scale
   - Perform TEA to determine economic viability of CTES
   - Pre-FEED level accuracy (+/- 35%) will be performed by Worley
   - Baltimore Air Coil (BAC) and Gas Technology Institute (GTI), world leaders in the cooling equipment design and manufacturing, will assist in commercialization effort.

b. After this project
   - Large scale (100 kWh) prototype
   - Design, manufacturing, and testing in a side stream arrangement at a power plant

c. Scale-up potential
   - The CTES system is envisioned and designed as modular system
   - **Scalability is part of the system design**

Workforce Development Effort

Workforce Development

- The project is a multidisciplinary effort involving mechanical and civil engineering
- Graduate students from UNC Charlotte and Lehigh University and a postdoc from UNC Charlotte were trained in the following areas:
  - Modeling of power generation and dry cooling systems
  - Analysis of performance data
  - Material engineering: PCM, PC, and PC + PCM mix
  - PCM characterization
  - Numerical modeling of flow and heat transfer in a porous medium
  - Numerical modeling of PCM melting and freezing processes
  - Test design
  - Design of the test equipment
  - Data analysis
  - Techno-economic analysis (future effort)

Summary

- Project started at an estimated TRL 3, based on previous work
- The project goal is to take the CTES technology to TRL 5.
- PCM, pervious concrete (PC) and PC + PCM mixes were engineered, and their characteristics determined.
- Four PC+PCM designs were developed and tested, two were selected for laboratory and prototype scale testing.
- Numerical models simulating transient charging and discharging of heat storage modules were developed and verified against experimental data obtained on a laboratory scale test facility.
- The laboratory-scale results are used to design a 10 kWh-scale prototype test facility.
- The prototype-scale test facility will be used to evaluate performance of heat storage module designs under cycling conditions and relevant environment.
- Techno-economic analysis is in progress to select the best design.
- **The project results will be used to improve performance of a dry cooling system and power plant performance through design and implementation of a cost-effective CTES system.**
- Additional effort is needed to take the CTES technology to TRL 9.