LEHIGH UNIVERSITY

FLEXIBLE COAL POWER PLANT OPERATION WITH THERMAL ENERGY STORAGE UTILIZING THERMOSYPHONS AND CEMENTITIOUS MATERIALS

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TRANSFORMATIVE POWER GENERATION PROGRAM

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Thermal Energy Storage (TES) using Thermal Batteries

TES was for CSP -- but now a range of applications foresee use of TES

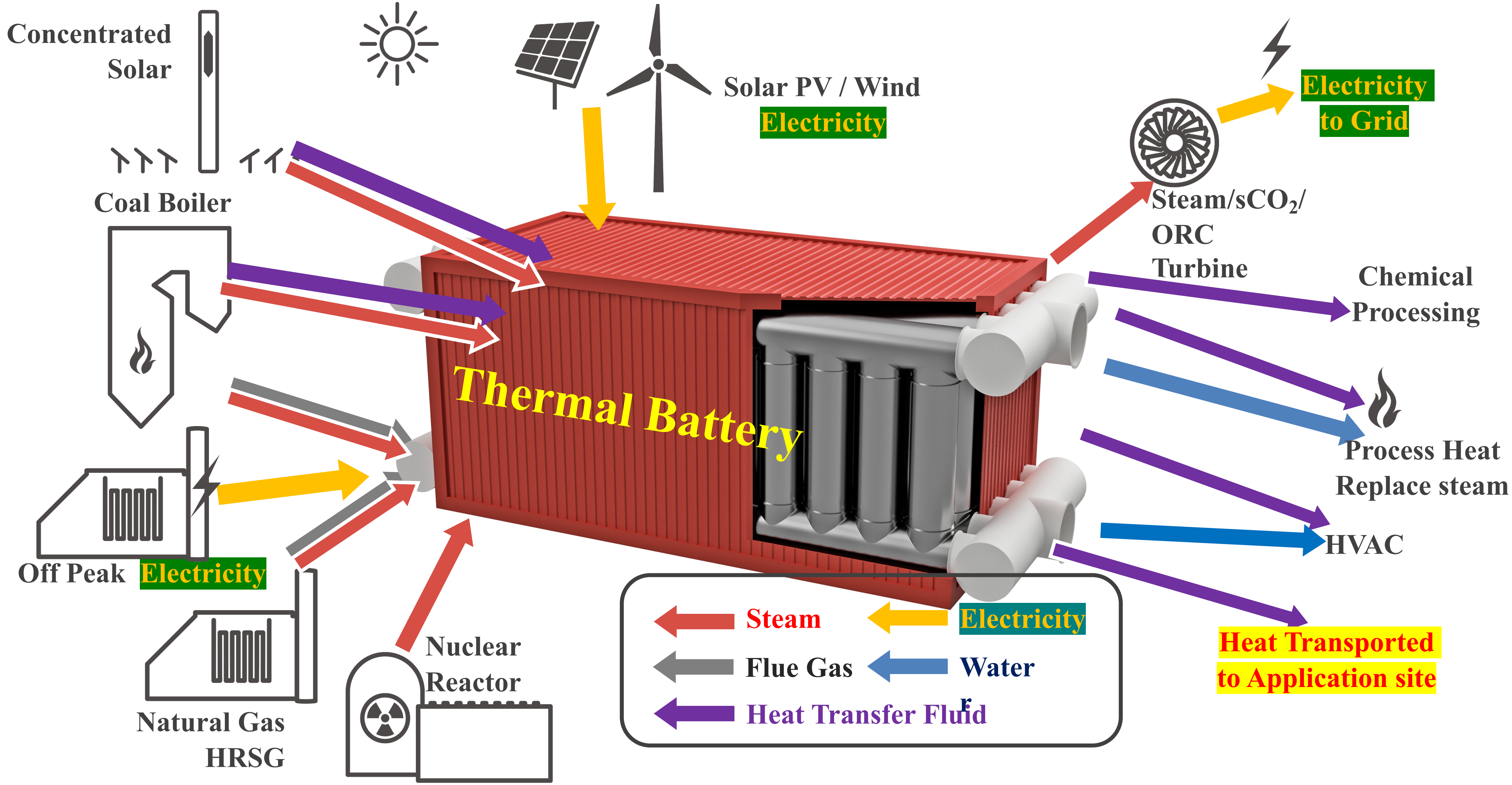
Spatial and Temporal shifted use of energy -- 270 K to 1,000K

Sensible heat, Latent heat, Thermo-chemical TES

Use Inexpensive, Widely available Well characterized Materials for TES

Energy Stored	Thermal Batteries for Spatial and Temporal shits of Energy 270 K to 1,000 K	Use of Energy
Coal Boiler Steam / HTF		Steam, sCO_2 ORC Electricity
Gas Turbine Enthalpy units		Process Heat with Steam / HTF
CSP Steam CSP HTF		Enthalpy Transported to Application Site
Electricity – Off-Peak, Solar PV, Wind		Hot Water and HVAC
Nuclear Plant – Steam, Off-Peak Electricity		Cold Energy for Improving Dry Cooling Towers
Cold Energy from Cold Nights / Other		Cold Energy for Gas Turbine Systems

Temporal & Spatial shift Applications of Thermal Batteries



Project Objectives – Flexible Coal Plant Operation with TES

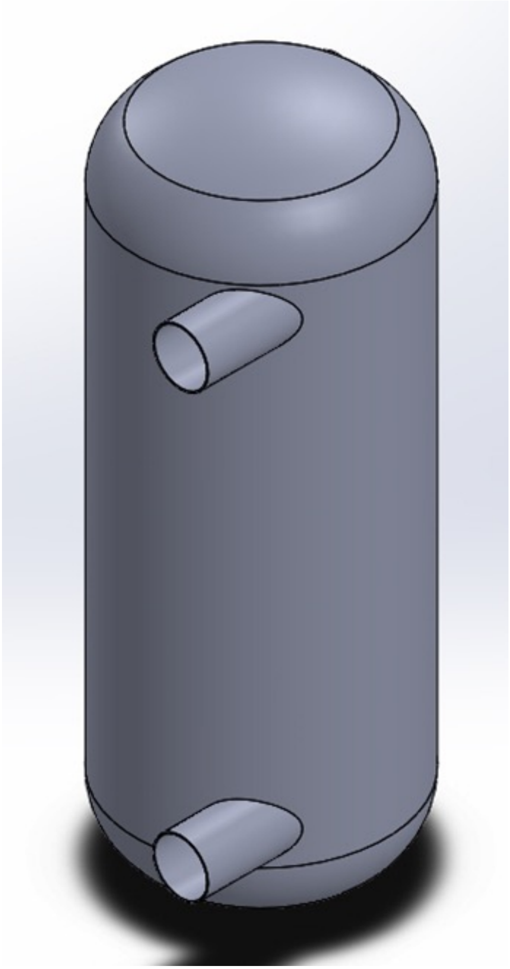
- TES Thermal Battery Concept and Related Challenges:
  - Coal power plants have been base load units
  - With TES, fossil plants could be flexible & deliver power to meet today's and future grid challenges
- Cementitious Materials for TES:
  - Cementitious materials - Inexpensive, Well characterized but poor conductors
  - Thermosyphons have good 'conductivity' – improve energy & power transfer.
  - Integrate system with plant operating conditions – for better plant response.
- Design Goals:
  - Operating temperature up to 400ºC
  - Round-trip efficiency ~ 90%
  - Cost < $25/kWh(th)

Project Objectives – Flexible Coal Plant Operation with TES

Overall Project objectives:

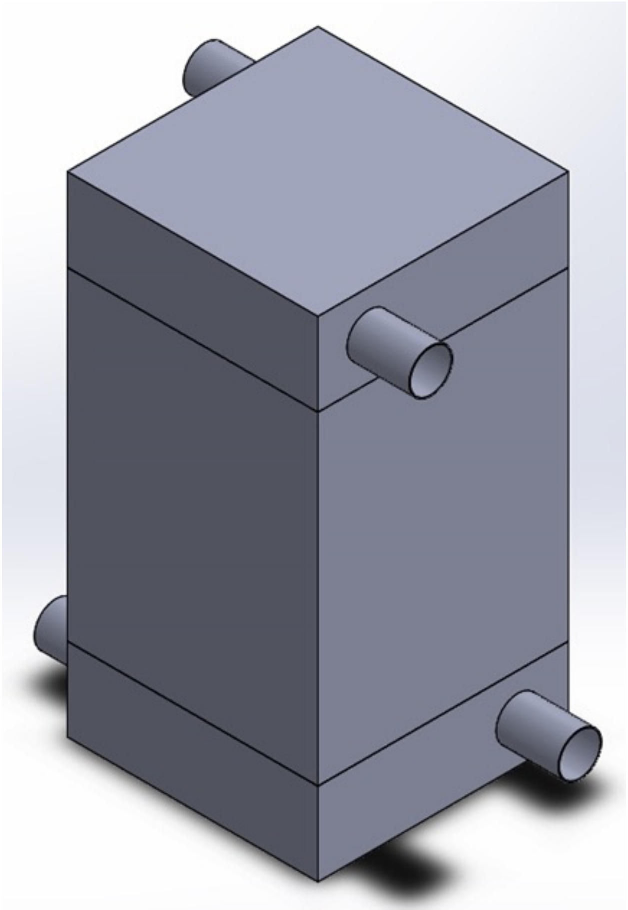
- Engineer concrete matrix for improved thermal/mechanical properties for TES concept at rated temperature.
- Develop and adapt thermosyphon technology into the TES in Cementitious media
- Engineer and optimize heat transfer in concrete and to fluids.
- Integration of the TES concept with a coal-fired power plant, including thermal cyclic response.
- Perform techno-economic analysis of the TCM-TES system.

Lehigh Thermal Battery Cells (Lehigh TBC)



Higher pressure

- Lehigh Thermal Battery Cell (TBC) is a device enabling TES
- Lehigh TBC houses and encloses storage media and transport phenomenon
- In one design, the Lehigh TBC encloses concrete and thermosyphons
- Provide for user/plant fluid flow to/from TBC for TES
- Designs based on TES Temp., operating pressure, energy storage (MWh), and power (MW).



Lower pressure

Thermal Reactions of Chemical Compounds in Hydrated Concrete

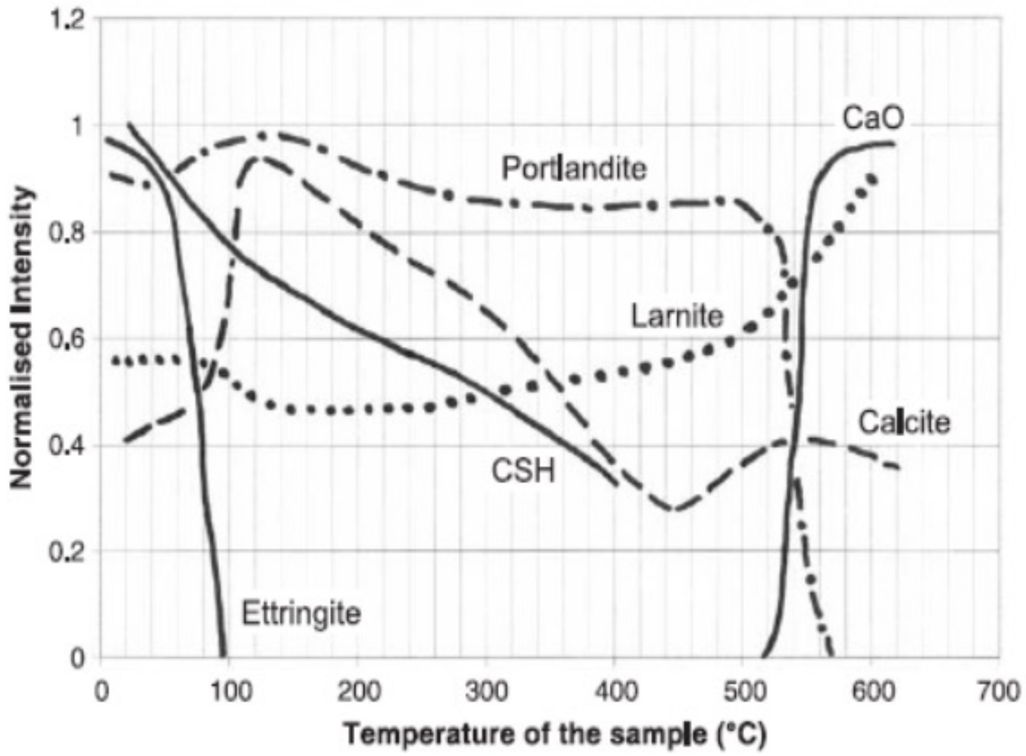


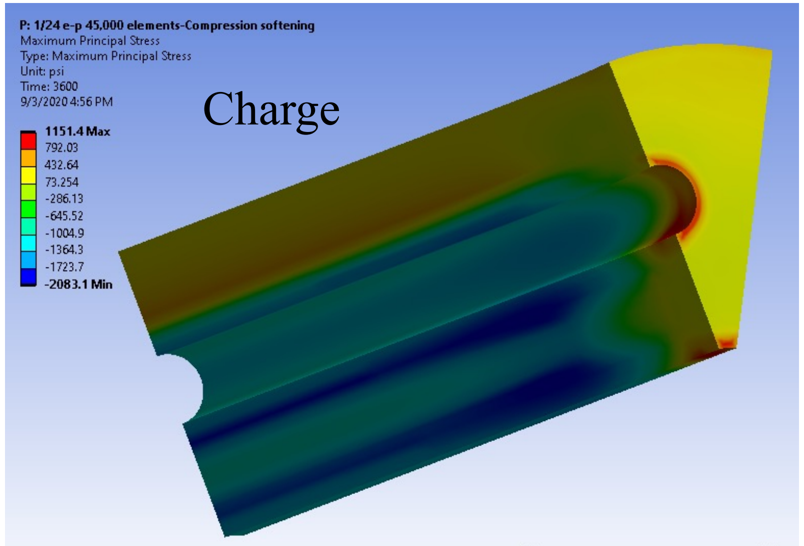
Fig. 12. Evolution of the normalised intensity during heating (exp-1) for the different phases analysed. Cement A.

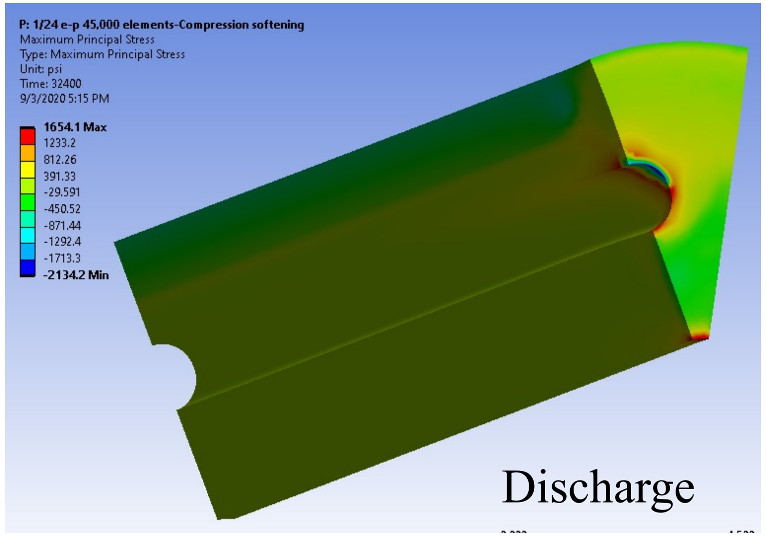
- Free surface water removal before 110°C
- CSH gel ($CaO{\cdot}SiO_2{\cdot}H_2O$) progressively dehydrate from 110°C to 400°C
- Calcium Hydroxide ($Ca(OH)_2$) decomposed from 450°C to 500°C

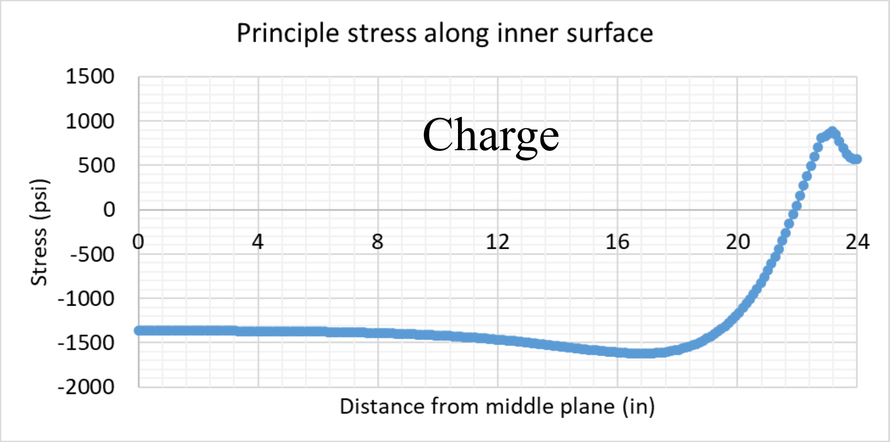
Limiting the temperatures at which concrete can be effectively used for TES

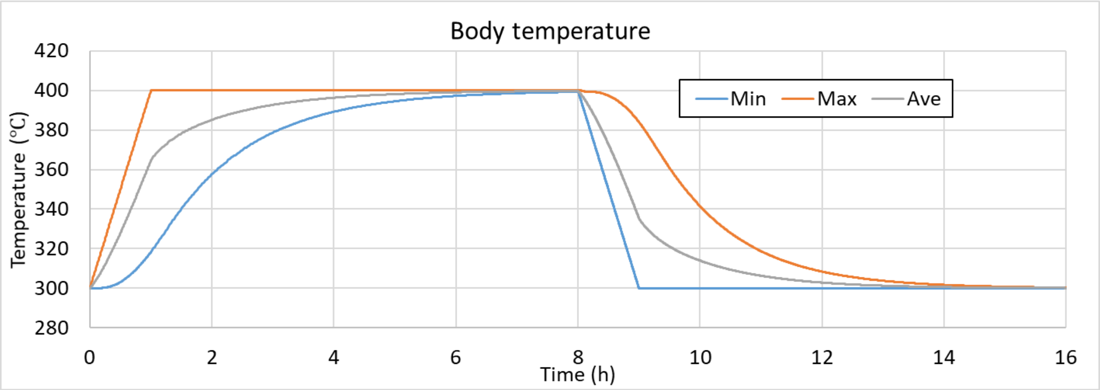
Thermal Stress Behavior of Concretes for TES

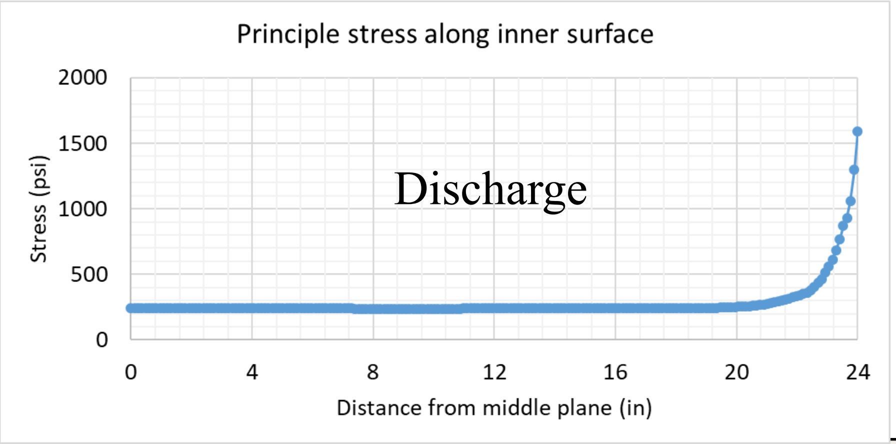
- Thermal demands result in varied stress distributions in TES during charging and discharging
- The Lehigh Concrete TES System is designed to minimize plastic response during operation



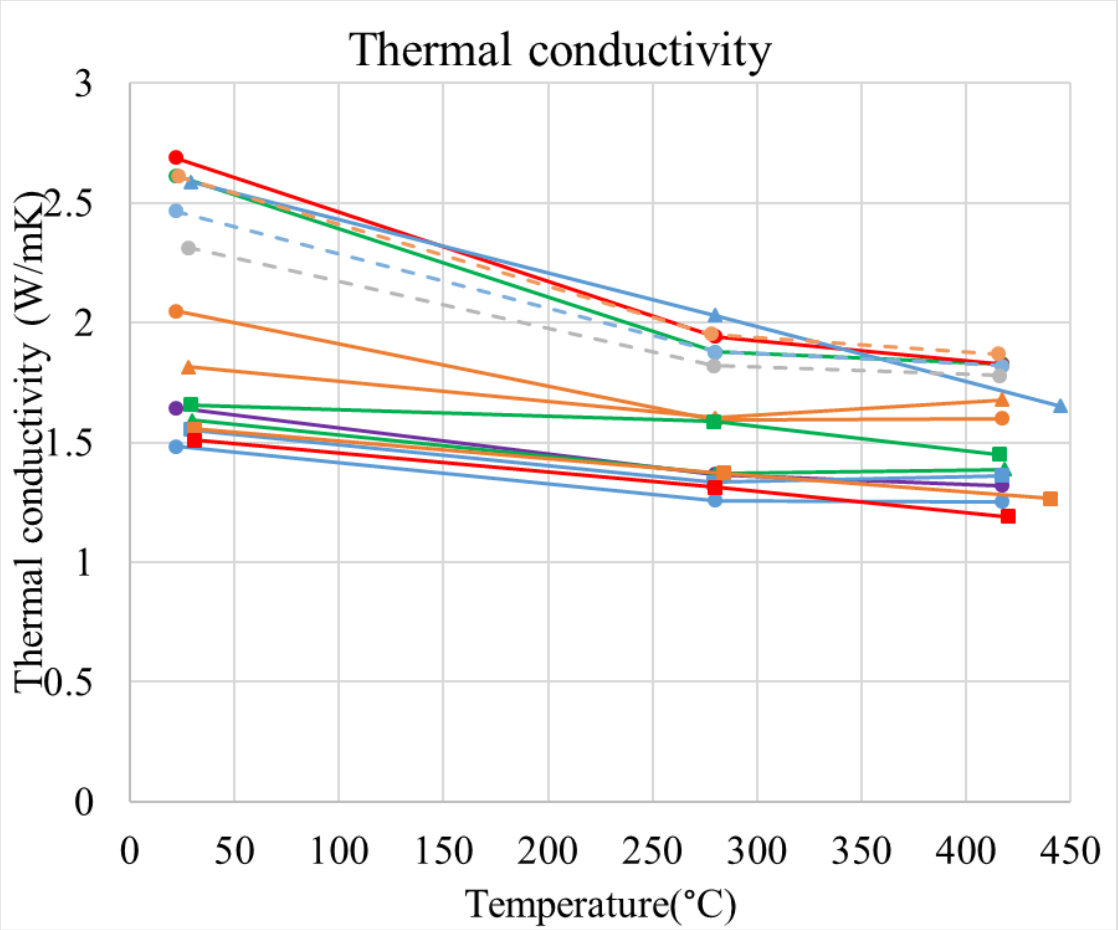


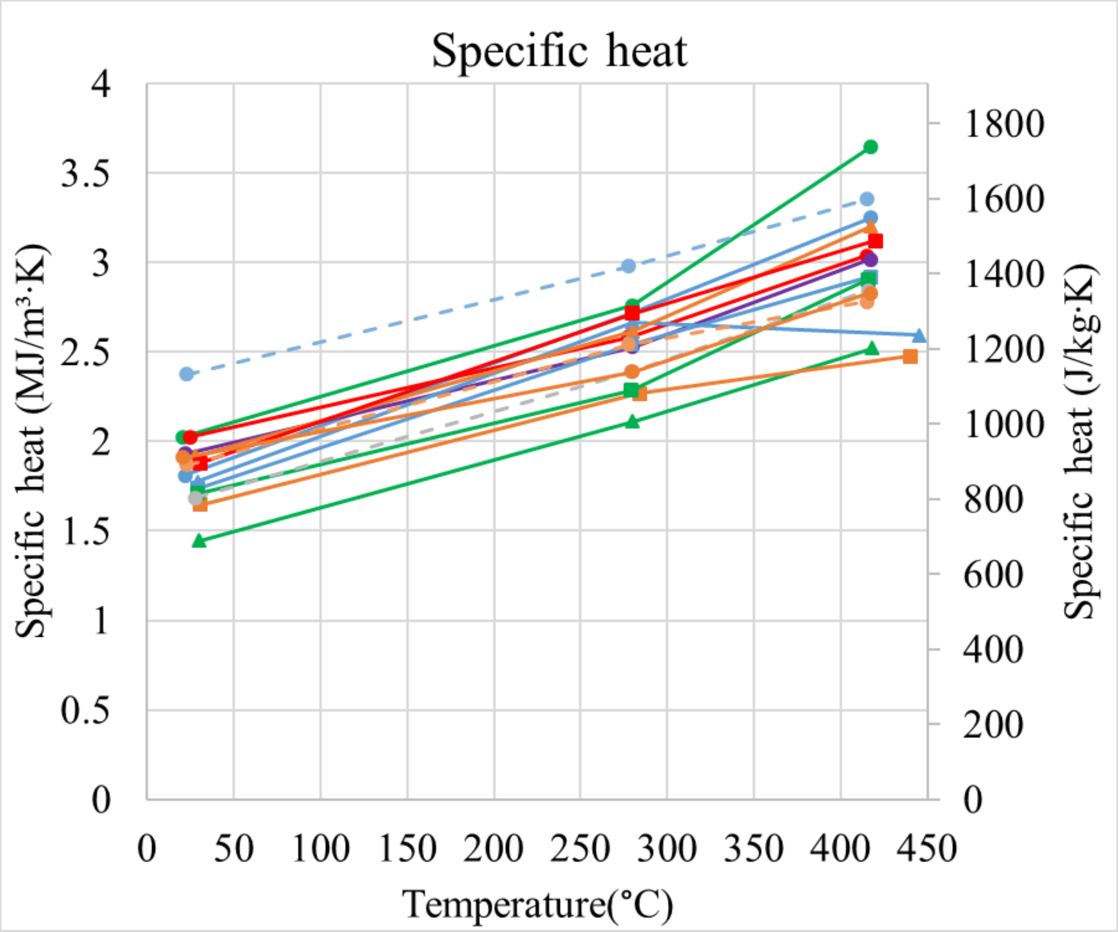






Thermal Conductivity and Specific Heats of Concretes

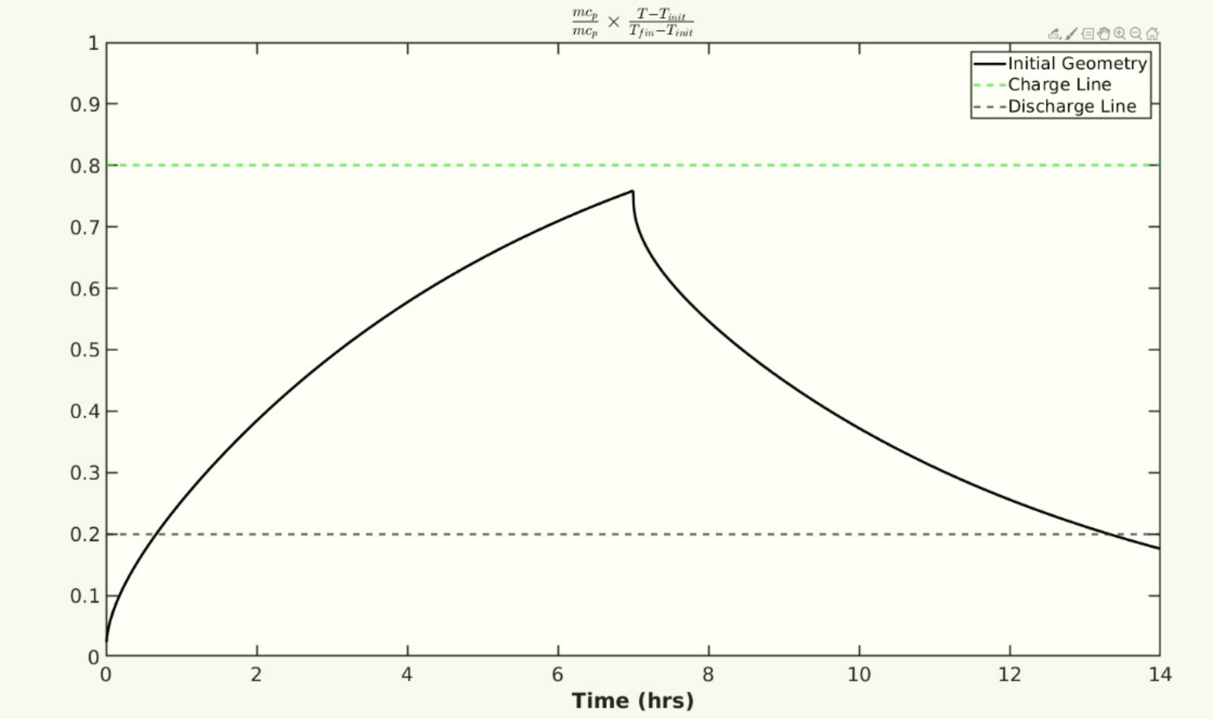


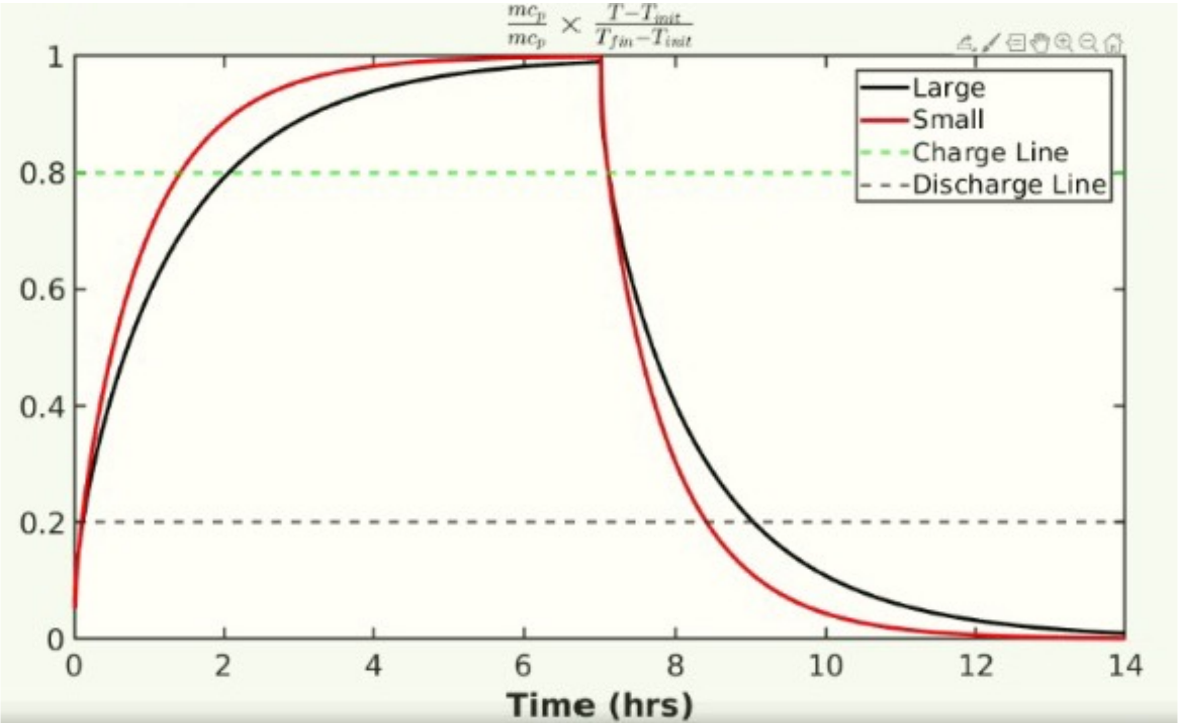


Specific Heat of Concretes Developed are 1.4 to 1.6 here vs. NEST (1 to 1.2) and DLR (0.9 to 1.0) kJ/kg-K

Thermal conductivity 1.88 W/m-K is about the same

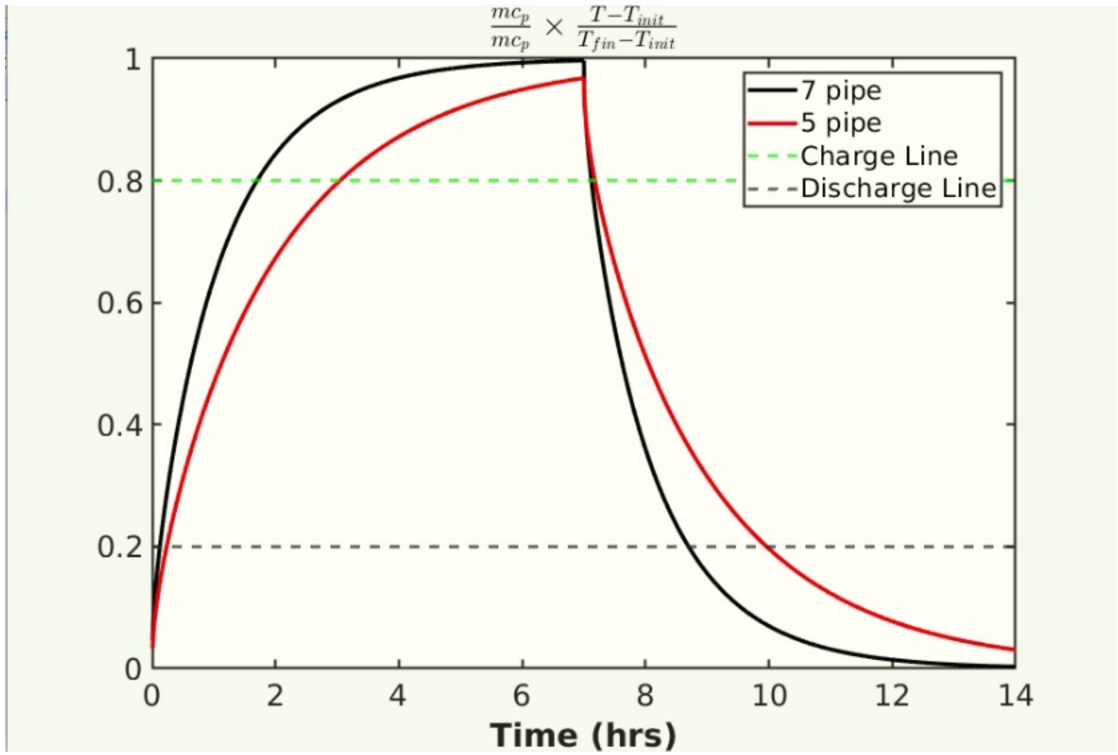
Energy Into/Out of – Charging and Discharging of Concrete

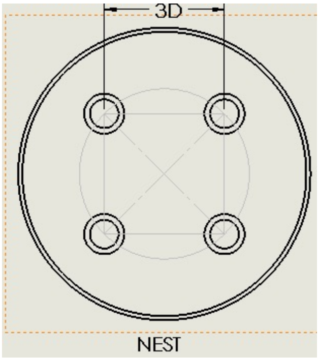


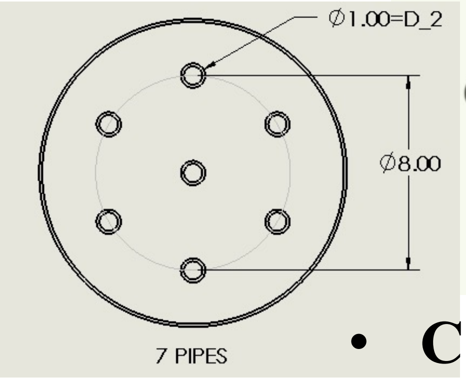


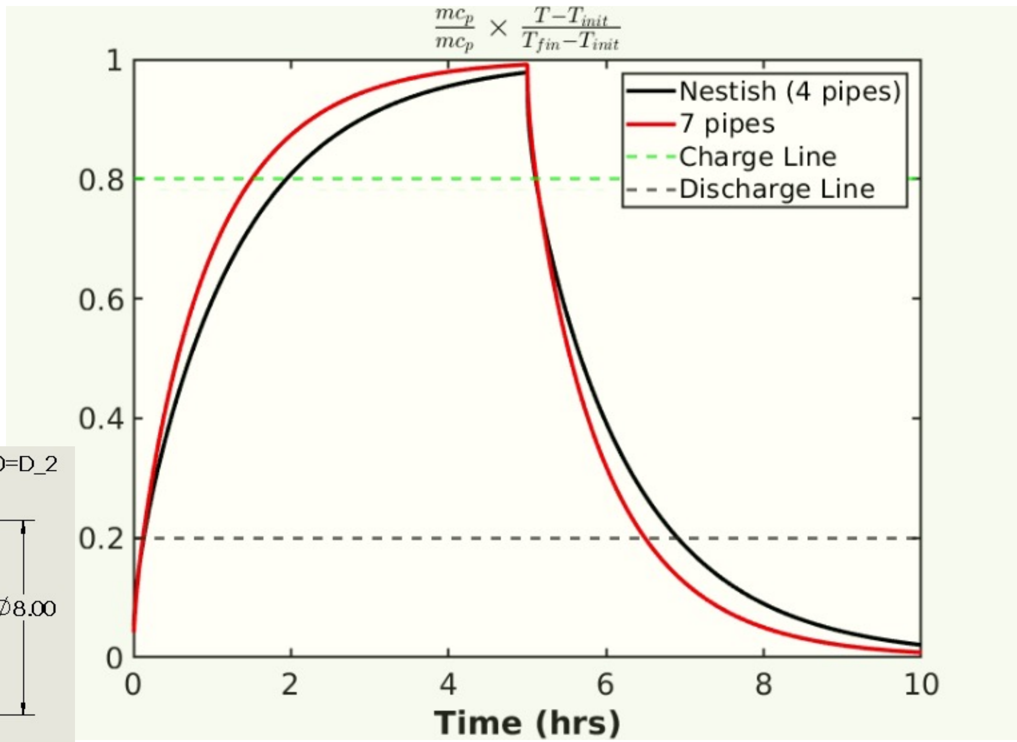
- **Sensible Heat Storage and Retrieval as a function of k, Delta T, Mass, Cp, ID, OD**
- **Capacity kJ → mass and Cp, Delta T**
- **Large Volumes → Large Capacity → May never reach desired Temperatures**
- **Rate of Energy ~ Power → Characteristic Distance and k**
- **More economical larger Concrete modules will be slower in response for in/out.**

Energy Transport in Concrete – Effect of Multiple Pipes









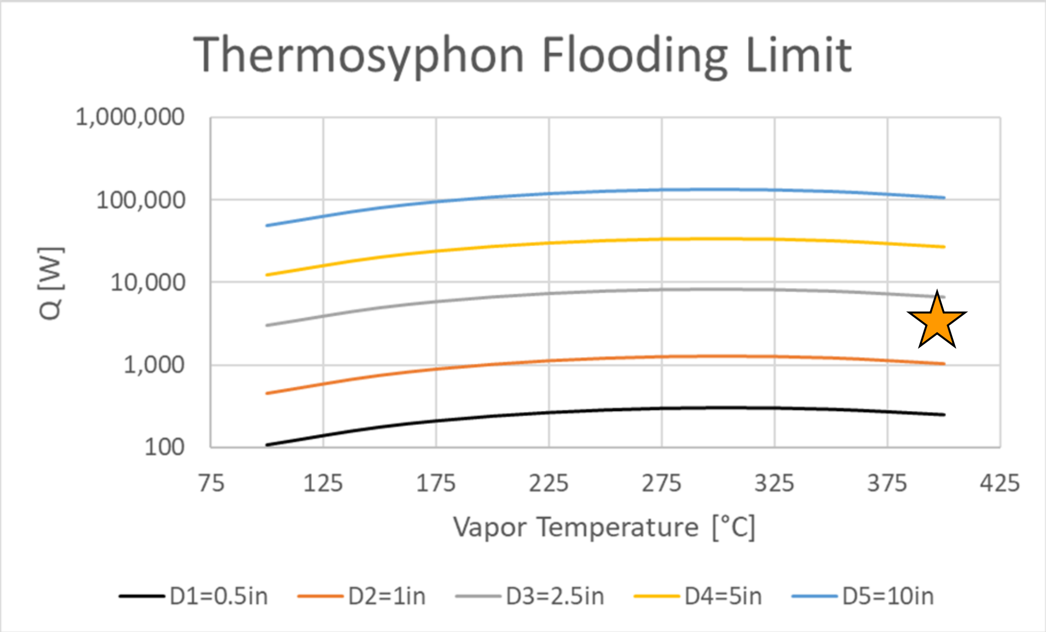
- **Effect of Multiple Thermosyphons to Distribute Energy**
- **More Thermosyphons in effect Decrease the Characteristic length for Heat Transfer in Concrete**

- **Comparison with NEST work**
- **NEST used 4 Steam in Pipes inside Concrete**
- **Lehigh TBC use 7 Thermosyphons to Distribute Energy in Concrete**

Thermosyphon Flooding Limit Behavior

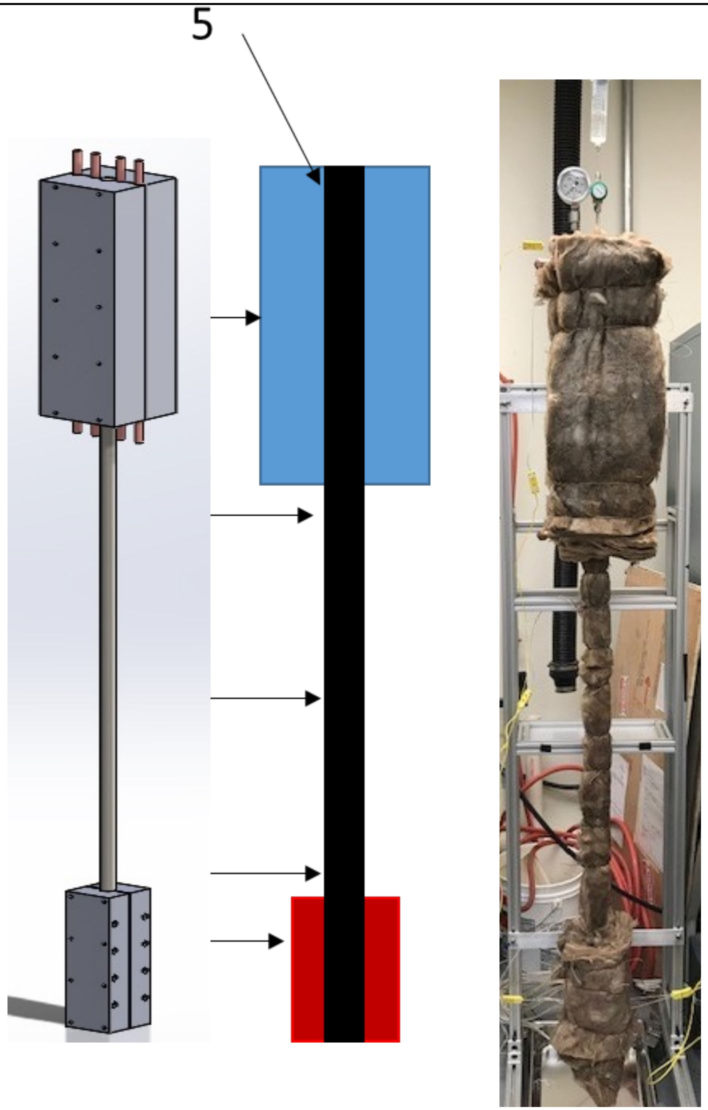
Establish the heat transfer limits of the 1" Thermosyphon

- Heated with Electrical Cartridge Heaters -- Aluminum heater block (bottom)
- Aluminum Cooling block (top) with Air Flow



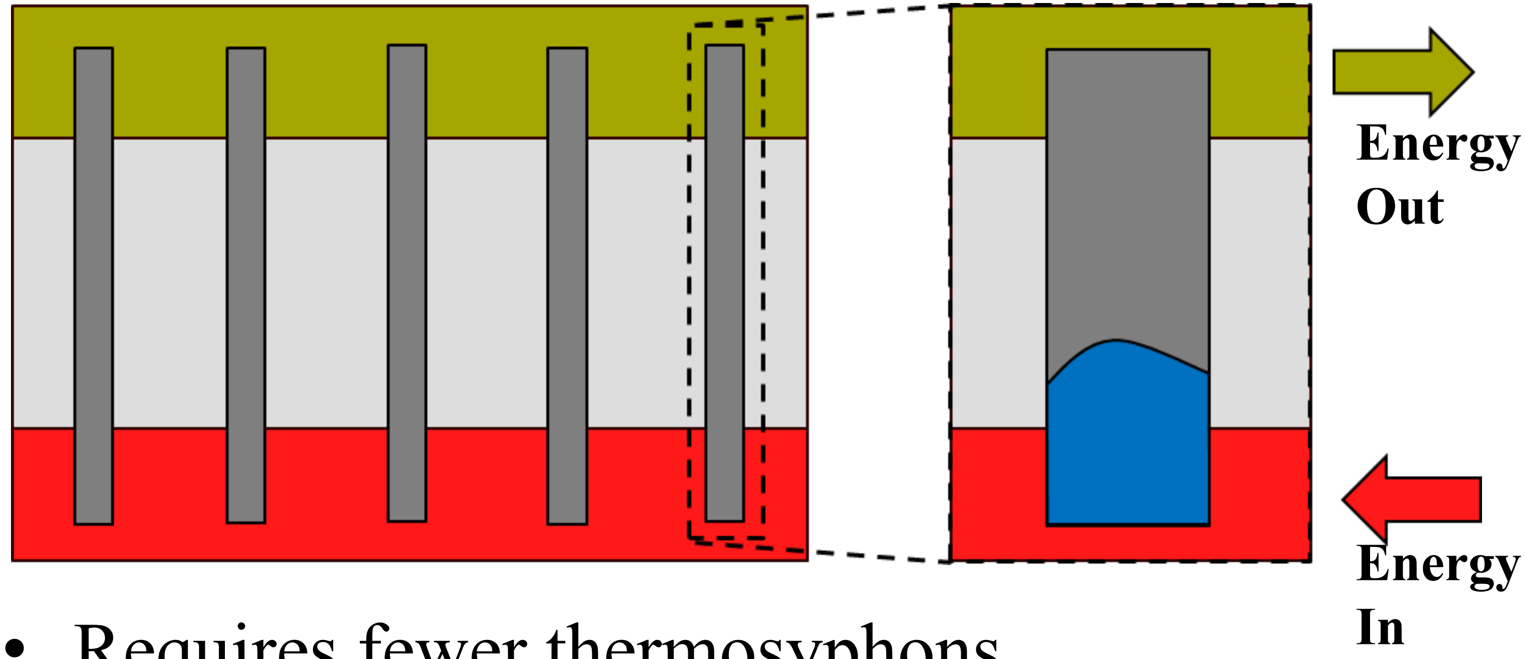
Power Rating for Energy Transported for 1" TS

Q = 1,060 W



Hybrid Thermosyphon

Hybrid thermosyphon -- Used for Charging and Discharging the TBC

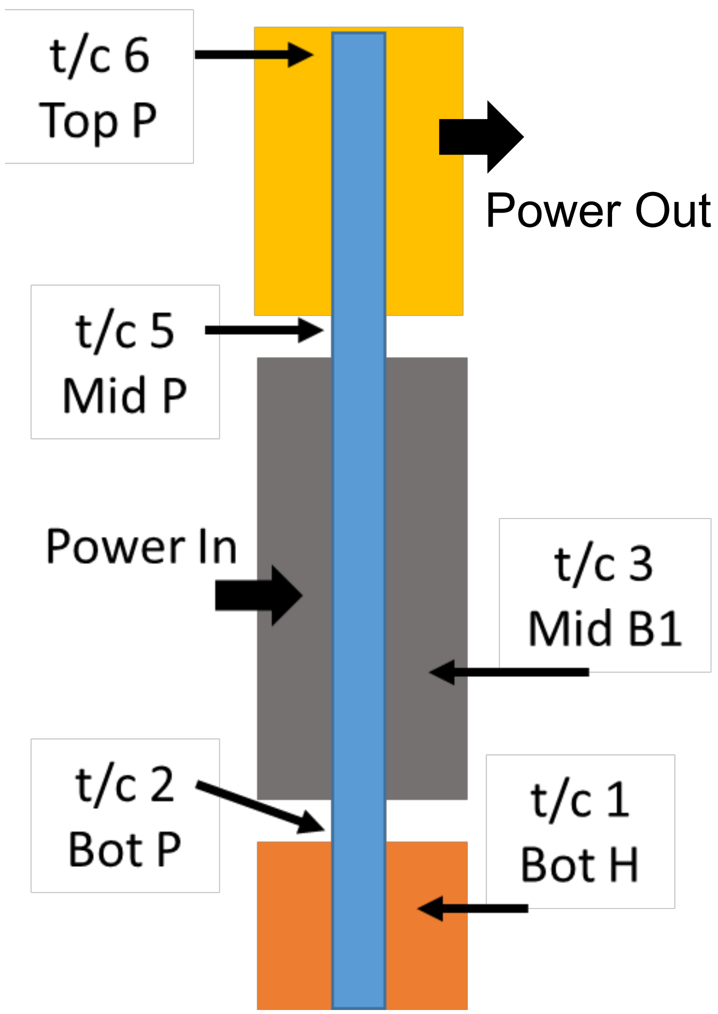


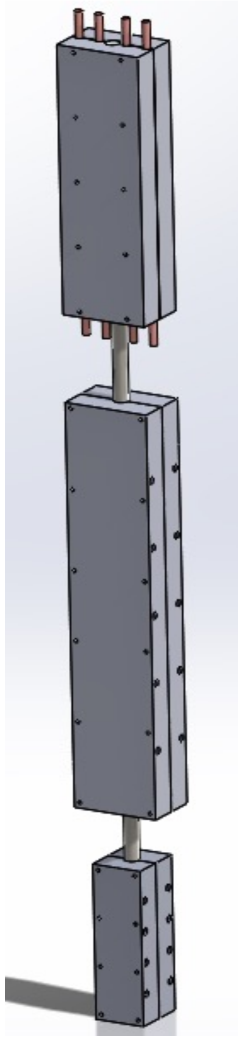
- Requires fewer thermosyphons
- Enhance thermal performance

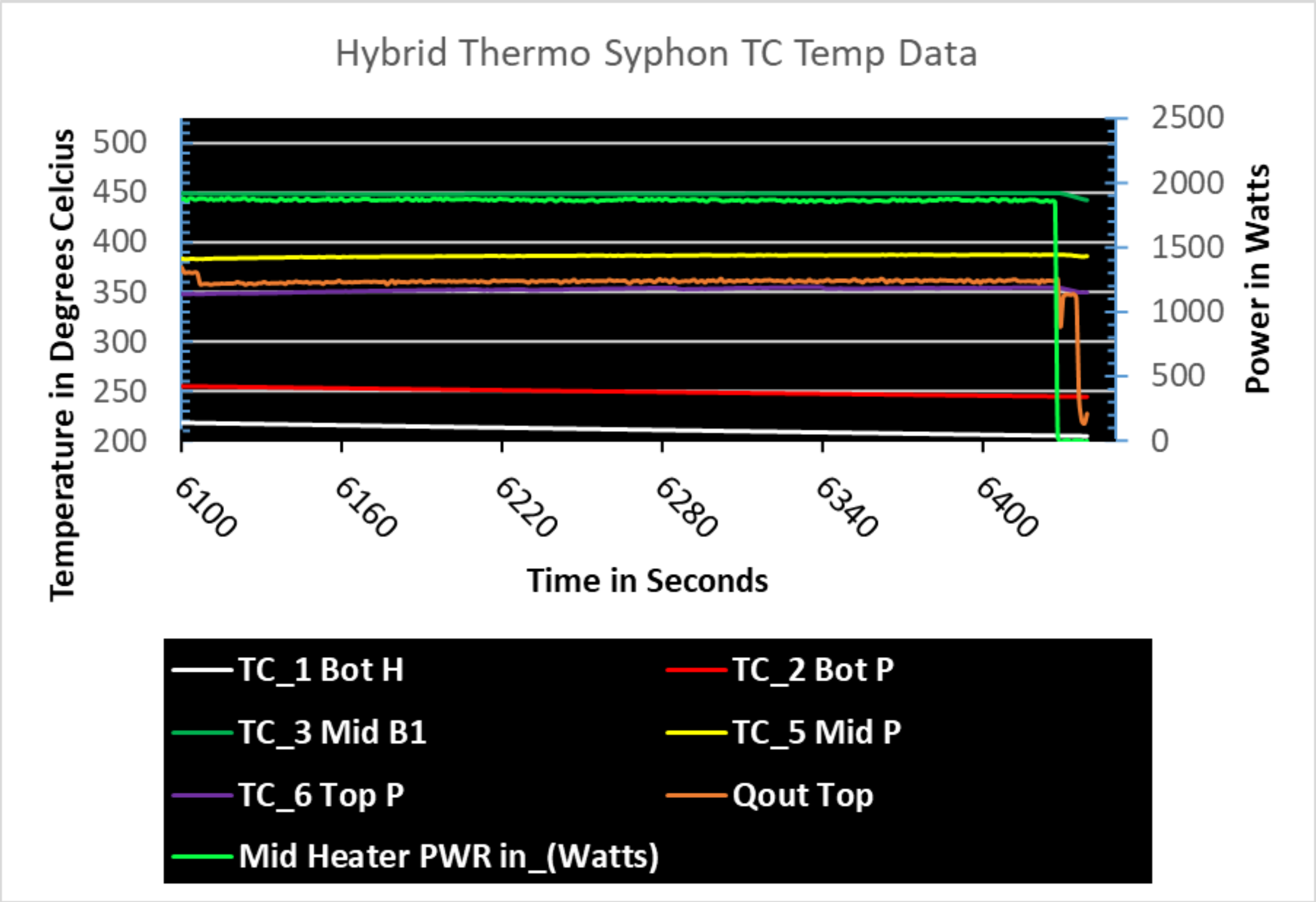
Air cooling

Hybrid Thermosyphon Performance – Discharge Mode

Discharge Phase (Power Into Steam)

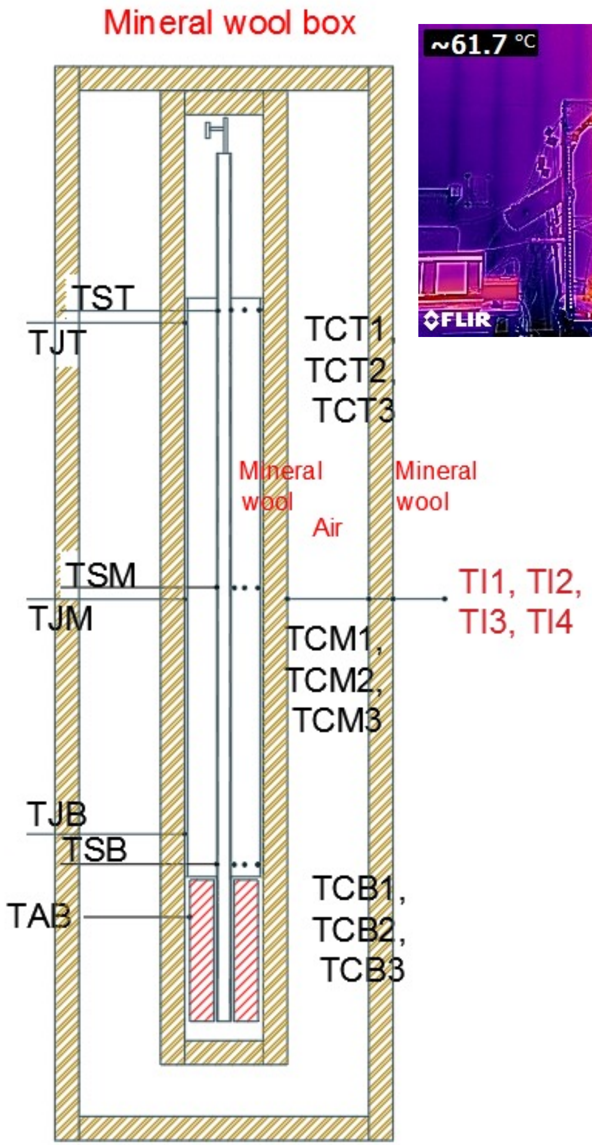


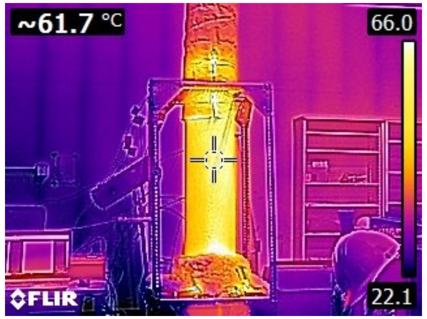


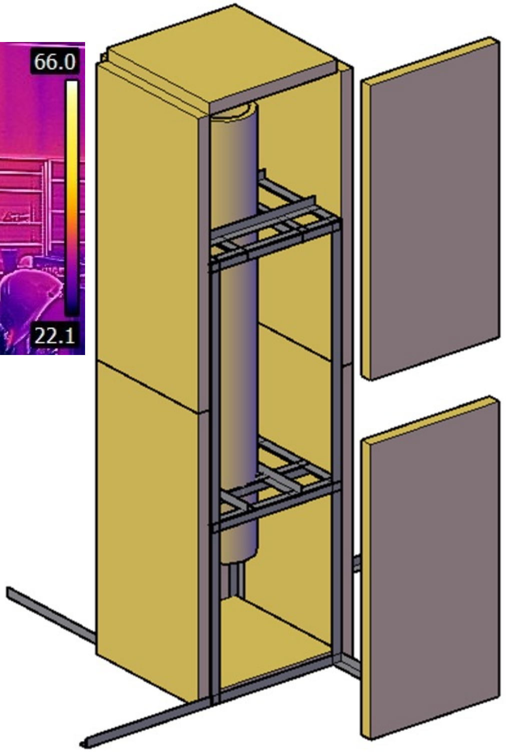


Power Out: ~1260W

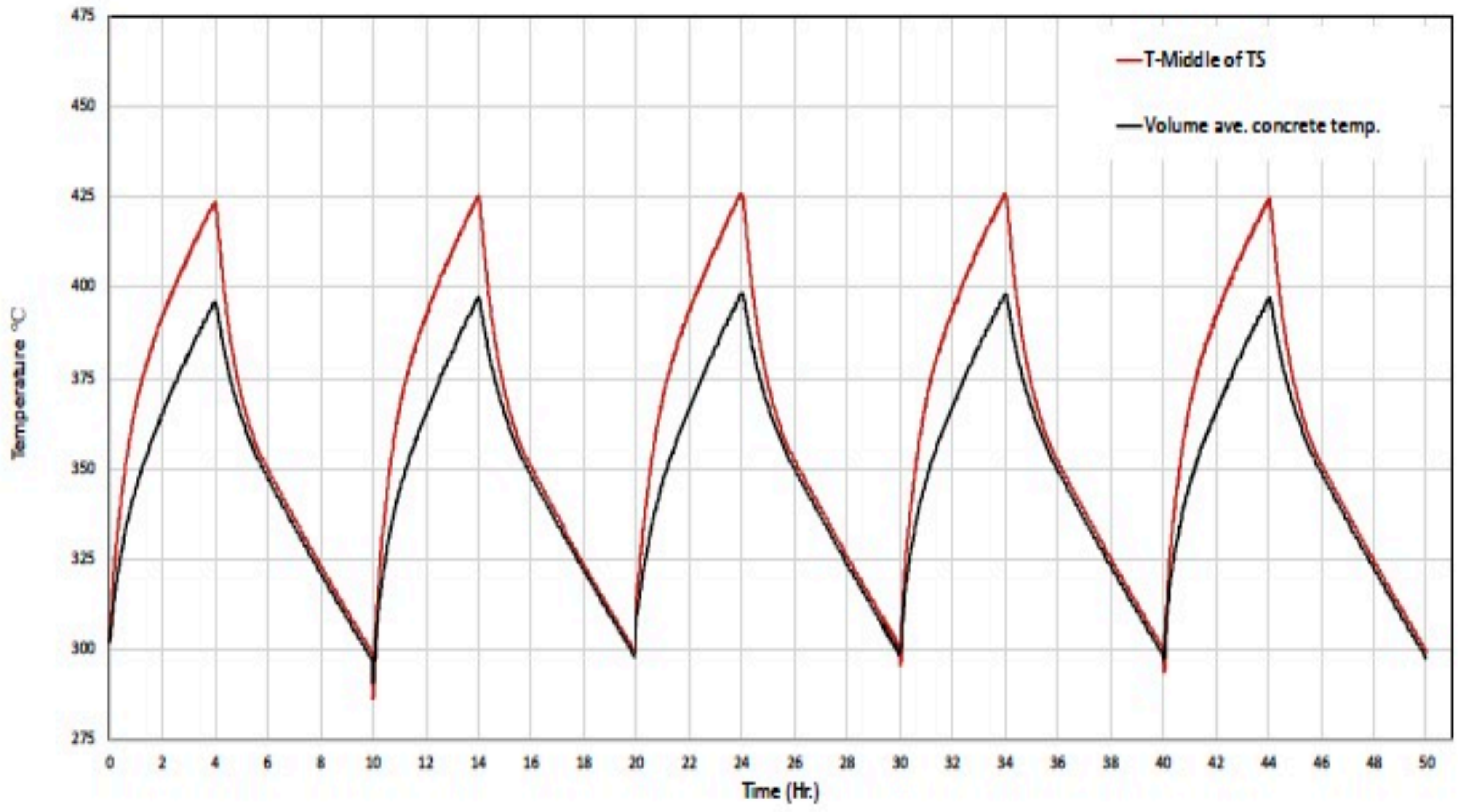
Thermosyphon - Concrete TES Charging with Electrical Energy

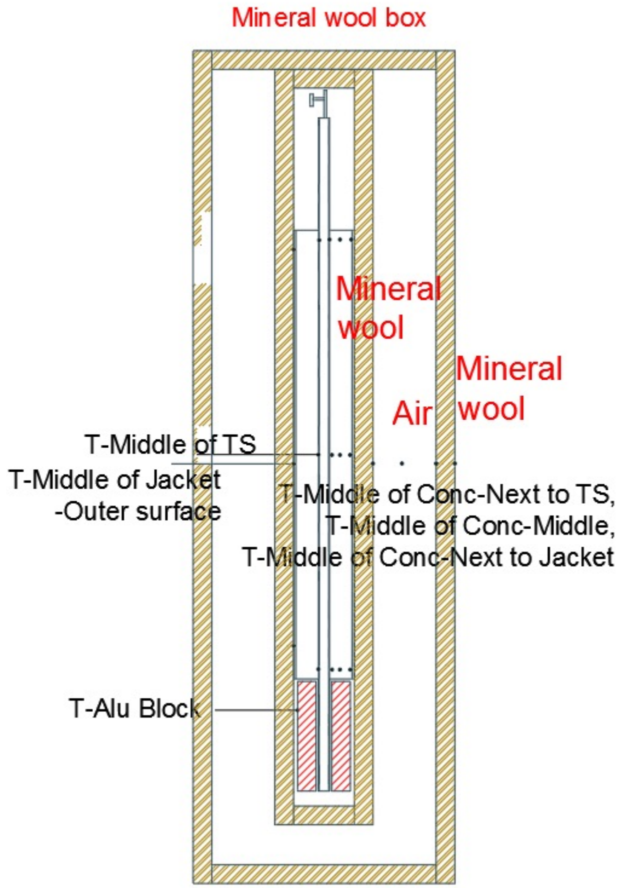






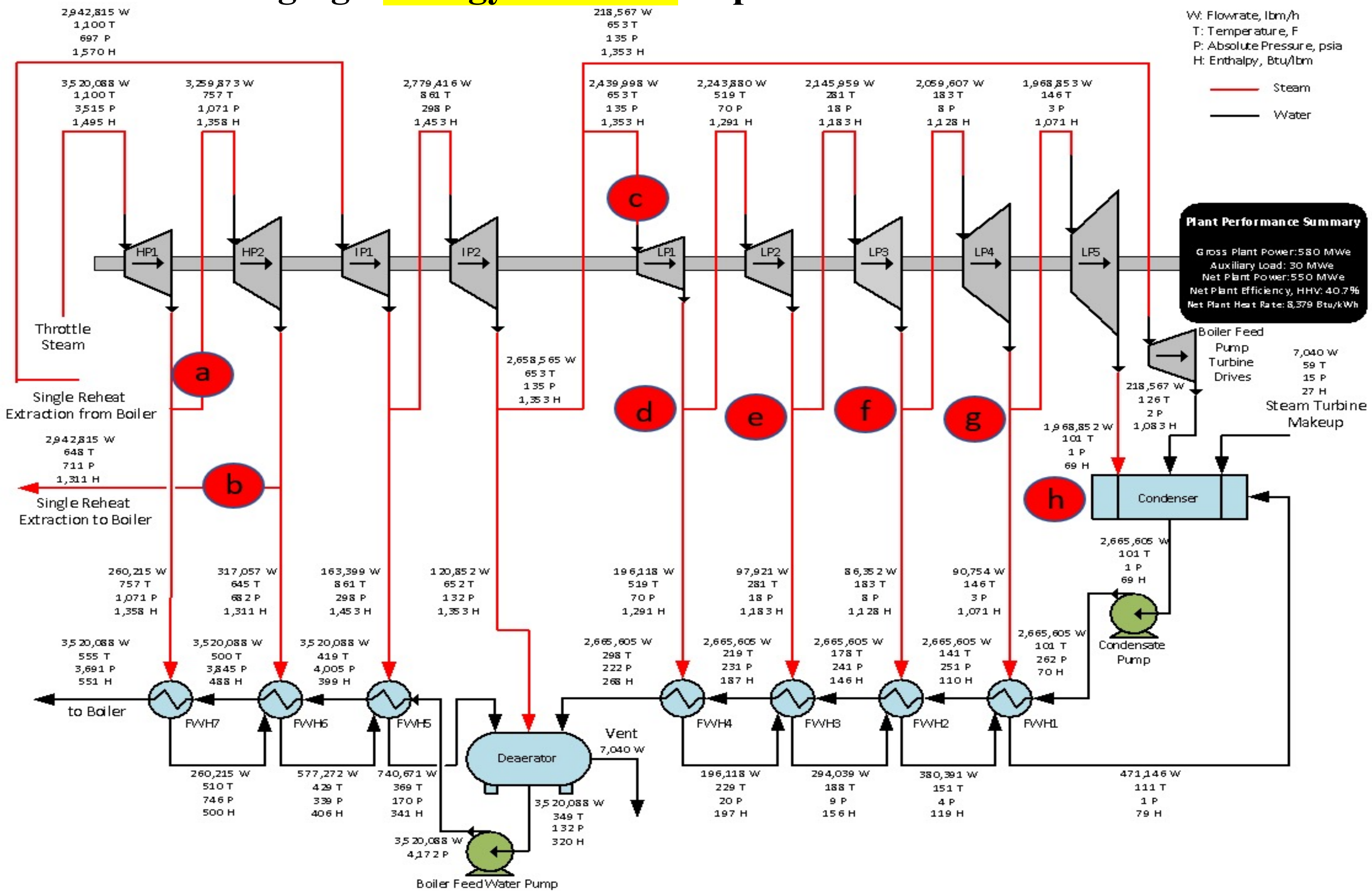
Thermosyphon - Concrete TES Charging with Electrical Energy



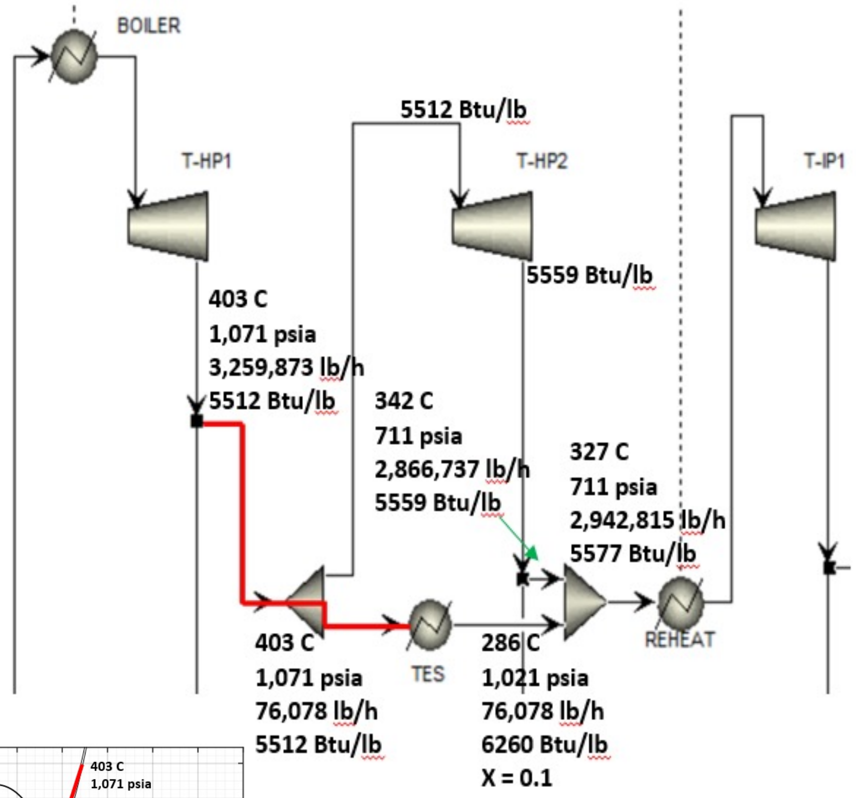


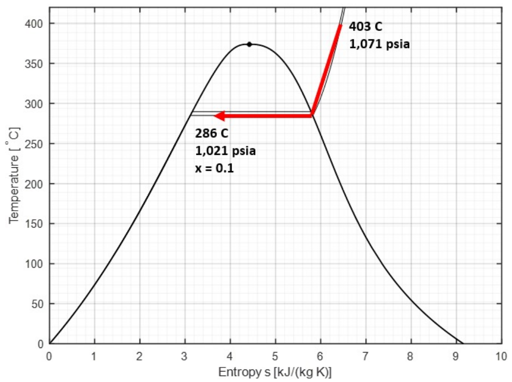
Energy Input to/from Lehigh TBC to/from Coal Power Plant

Charging - Energy into TES - Options for a 580 MWe Unit



Energy Input to/from Lehigh TBC to/from Coal Power Plant

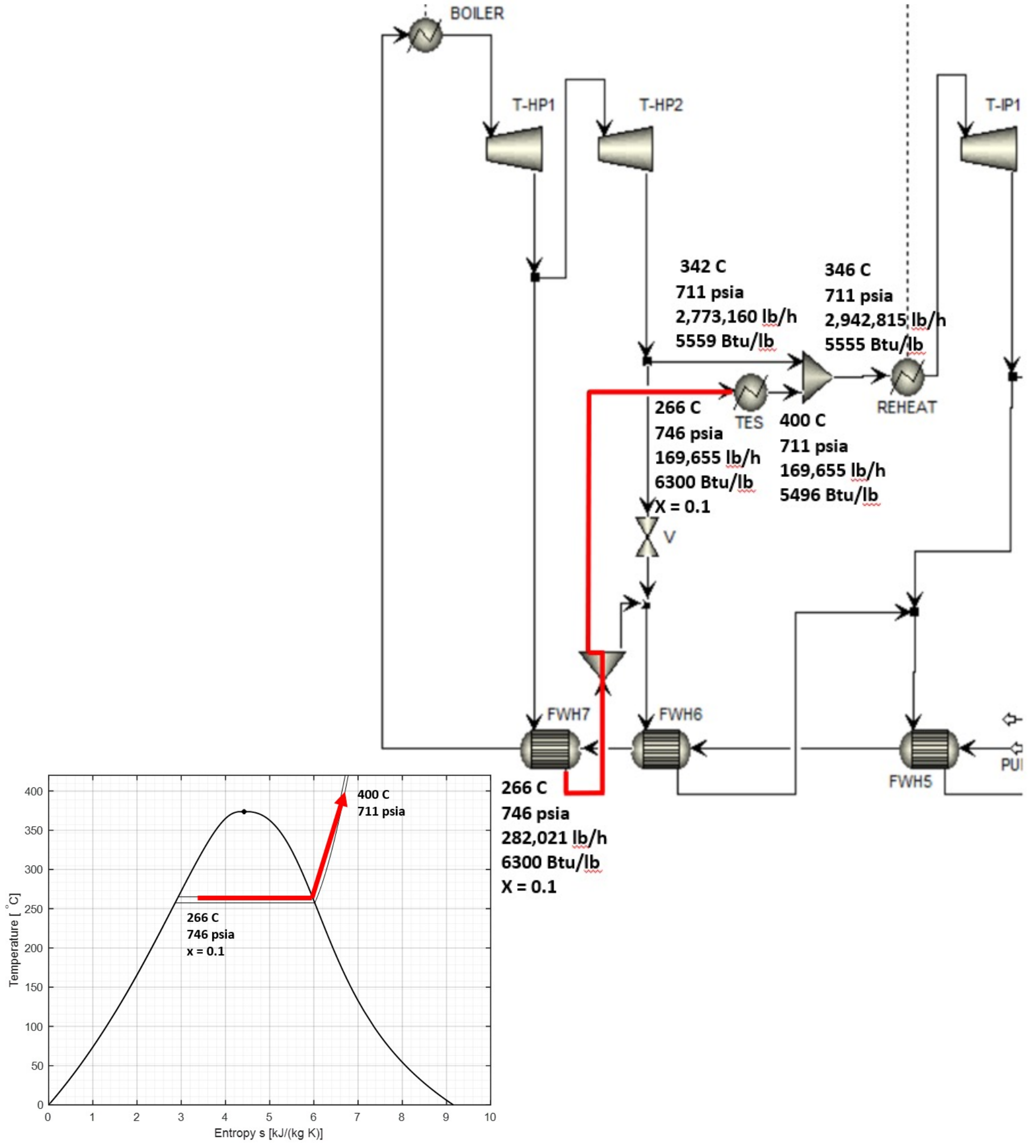




Potential TES Charge Option

- Before TES: Superheated vapor at 403 C, 1,071 psia, extracted from high pressure turbine stage 1 (T-HP1).
- After TES: Steam at 286 C and 1,021 psia and 10 % quality is mixed with superheated steam at 342 C and 711 psia from high-pressure turbine stage 2 (T-HP2) and sent to the cold reheater.
- TES power input = 16.67 MW(th).
- Charging will take place at 16.67 MW(th) for 6 hours. Total energy stored is 100 MW(th)h.
- Charging process will incur in an increment in total coal mass flow to maintain cold reheat setpoint.
- Steam mass flow through TES is 76,078 lb/h which represents 2 % of the total mass flow extraction of the T-HP1 and 3 % of the mass flow extraction of the T-HP2.

Energy Input to/from Lehigh TBC to/from Coal Power Plant



Potential TES Discharge Option

- Before TES: Steam at 266 C, 746 psia and 10 % quality extracted from feed water heater No. 7 (FWH7) .
- After TES: Superheated vapor at 400 C and 711 psia (after TES) is mixed with superheated steam at 342 C and 711 psia from high-pressure turbine stage 2 (T-HP2) and sent to the reheater and sent to the cold reheat.
- Discharging cycle starts with 40 MWth and the power is reduced by 10 MWth linearly for 4 hours. Total discharged energy is 100 MWhth.
- Power output is increased from 580 MWe to 592 MWe during the first hour.
- Steam mass flow through TES is 169,655 lb/h which represents 60 % of the total mass flow leaving the FWH7 and 6 % of the mass flow from T-HP2.
- The boiler is running at 100 % of steam production (3,520,088 lb/h) and the coal mass flow is reduced from 388,445 lb/h to 387,491 lb/h due to the temperature increase in cold reheat.

Summary – Lehigh Thermal Battery Cells (TBC) Design

- ❑ Thermosyphon design for Lehigh TBC – Performance tests for Hybrid thermosyphon.
- ❑ Choice of Concrete and Property determination for use in Lehigh TBC – Better TES performance than other data reported in the literature.
- ❑ Numerical modeling – COMSOL and FLUENT - Design of concrete modules for Lehigh TBC.
- ❑ Thermal tests for Concrete + Thermosyphon to prove charging of a Lehigh TBC.
- ❑ ASPEN Analysis for potential Charging and Discharging of Lehigh TBC for a Coal Power Plant.

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