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TerraKline ™

A Managed Thermocline Thermal Energy Storage (TES) System

- A Cost-Effective TES for Concentrating Solar Power

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Terrafore Technologies, LLC

TMCES Workshop 2025
Southwest Research Institute, San Antonio, TX

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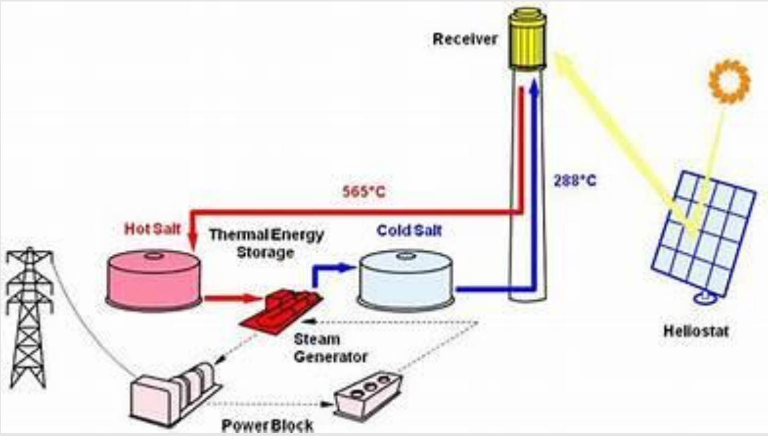
Sensible Heat Storage Systems for Concentrating Solar Power



- Two-Tank Molten Salt TES
  - Conventional TES installed in several systems
  - Energy stored as sensible heat in molten salt (Solar Salt)
  - Typical costs $23 to $28 per kWh for a 2200 MWh store

- Dual Media Thermocline TES
  - Energy stored as sensible heat in a dual media of Molten Salt (~35% by volume) and Rock (~65% by volume)
  - Typical Cost $15 to $18 per kWh for a 2200 MWh store

Motivation for Dual-Media Thermal Energy Storage

Typical Utility Scale Plant = 100 MWe

Typical TES Storage (8h store) = 2200 MWht

Cost of 2-Tank Thermal Storage* = $47MM ($21.4 / kWht)

Cost of *TerraKline* Thermal Storage** = $34MM ($15.5 /kWht)

Reduction in cost = 27.7%

*   Solar Salt Storage Media (565 ^{o}C)

** Solar Salt + Rock Storage Media (565 ^{o}C)

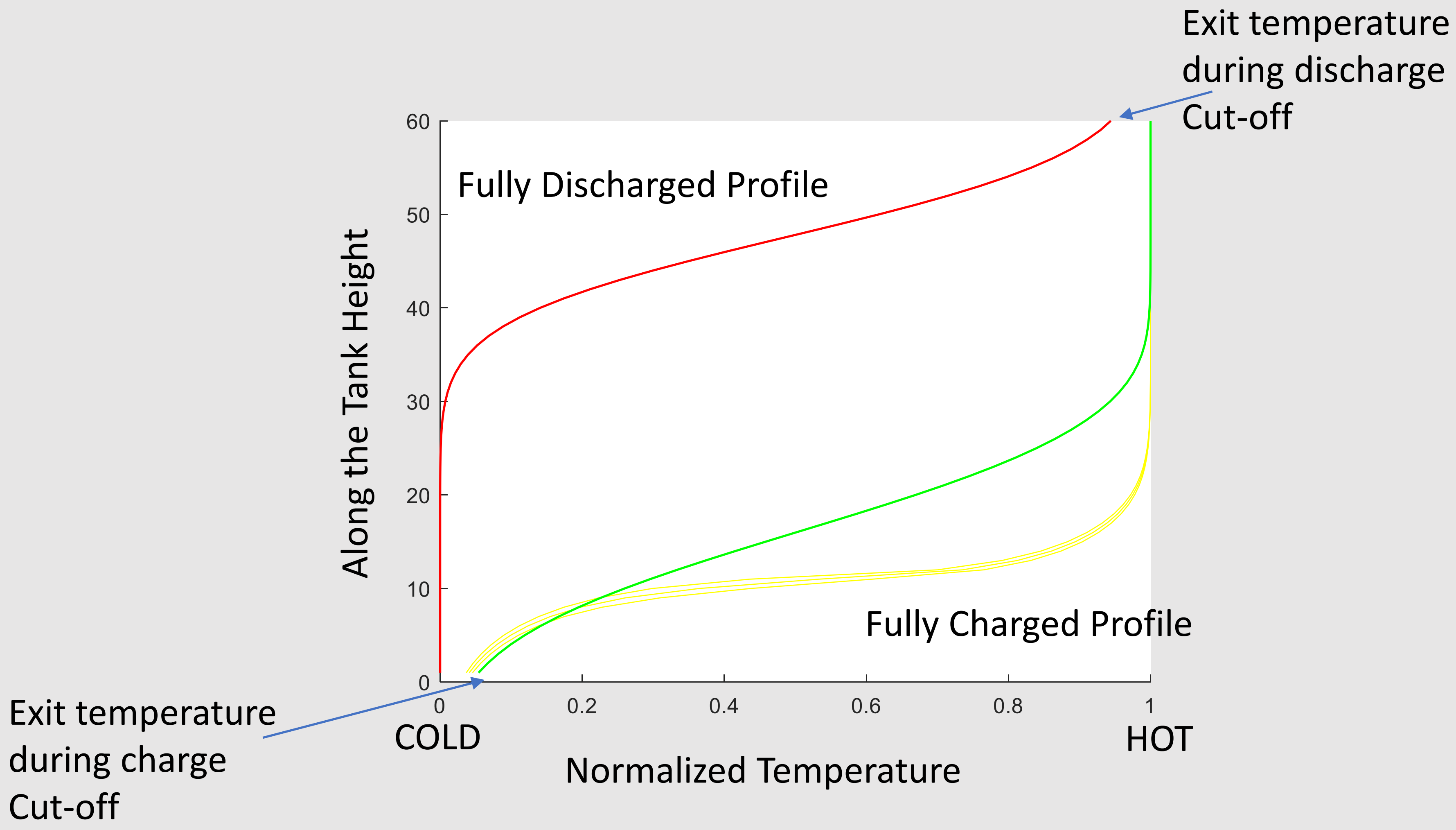
Assumption: Costs are based on data from DOE report of a 2700MWht Abengoa Two-Tank Molten Solar Salt Thermal Storage system

Technology Challenges with Dual-Media Thermal Energy Storage (DMTES)

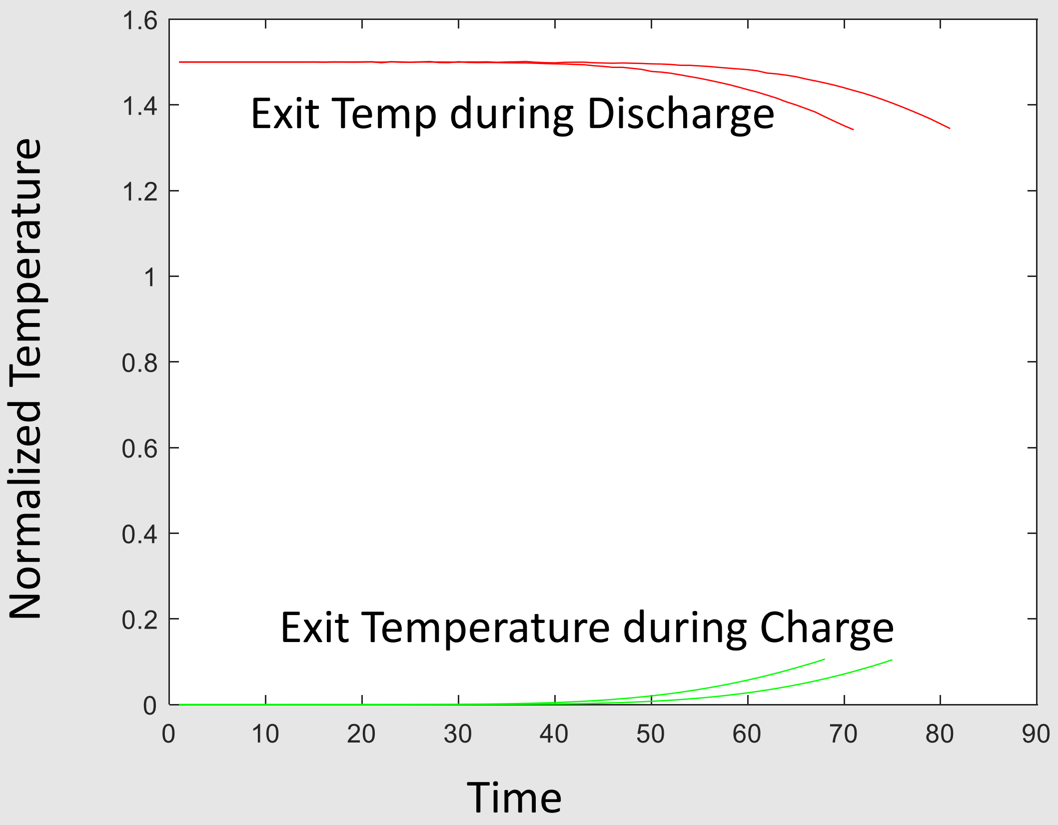
Thermocline degrades during cyclic charge and discharge

Thermal Ratcheting due to contraction and expansion during cyclic charge and discharge

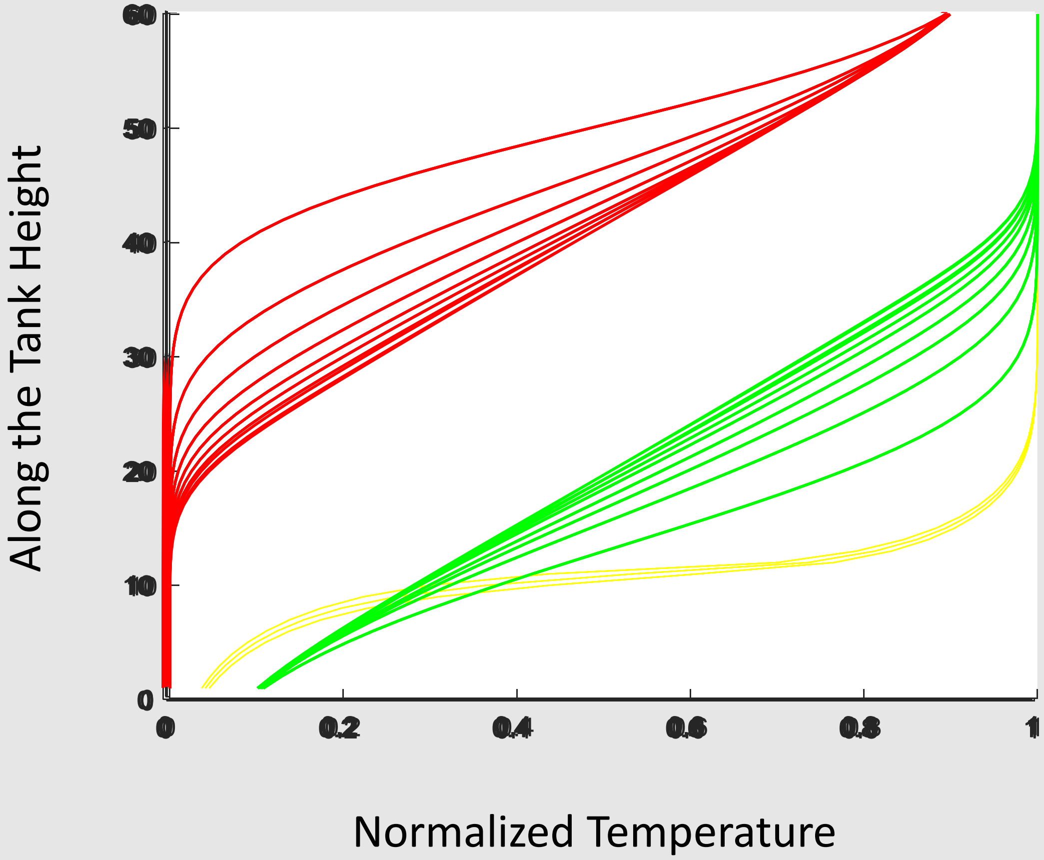
Thermocline Profile



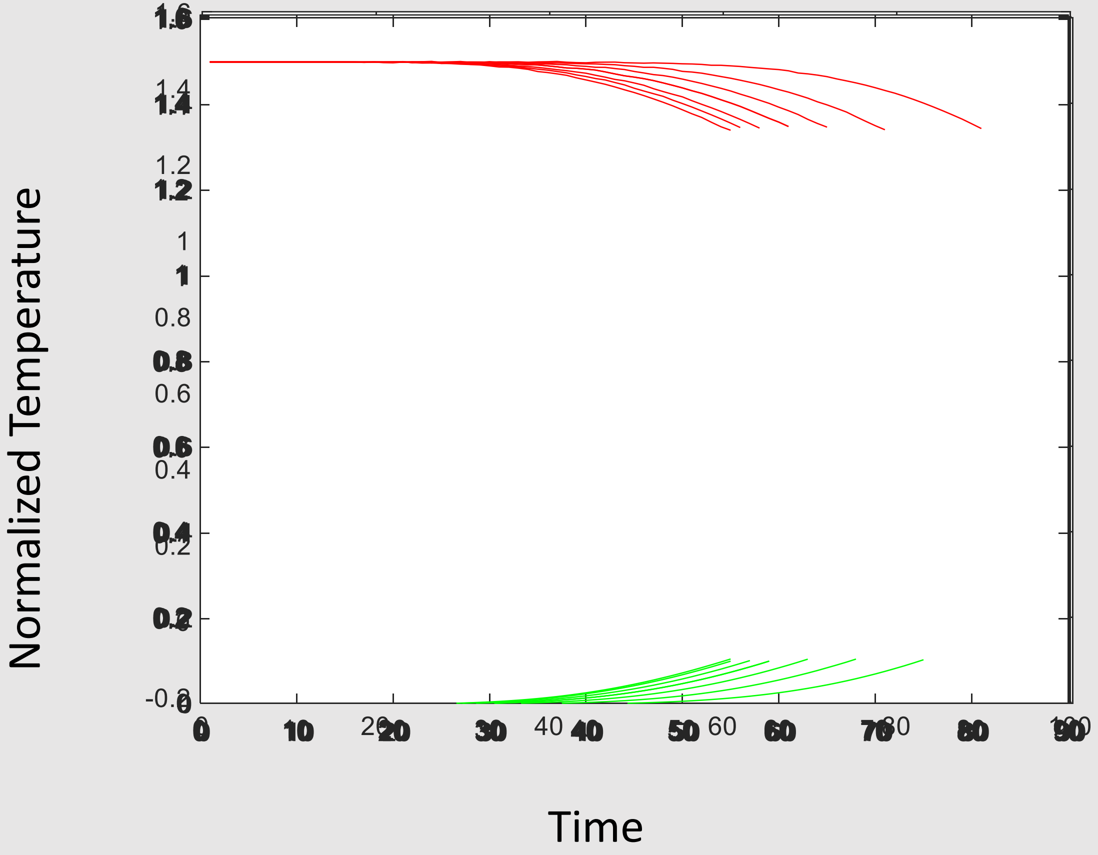
Temperature vs time profile



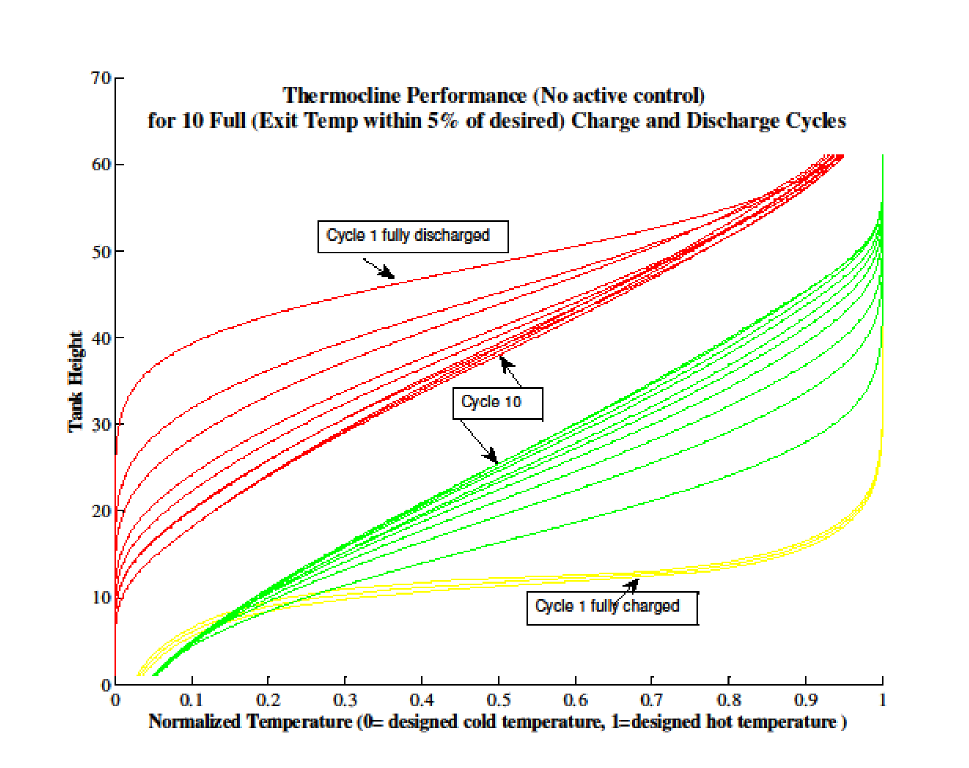
Thermocline Degrades with Consecutive Charge and Discharge Cycles

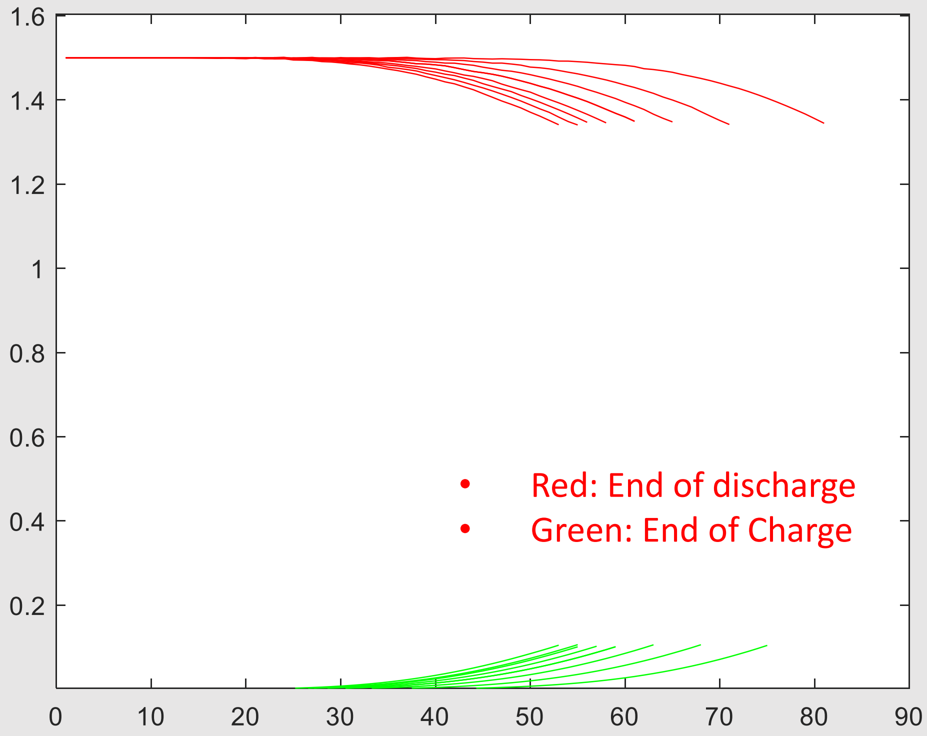


Charge and Discharge Times Decrease with Consecutive Charge and Discharge Cycles



Thermocline Degrades with Consecutive Charge and Discharge Cycles with DMTES





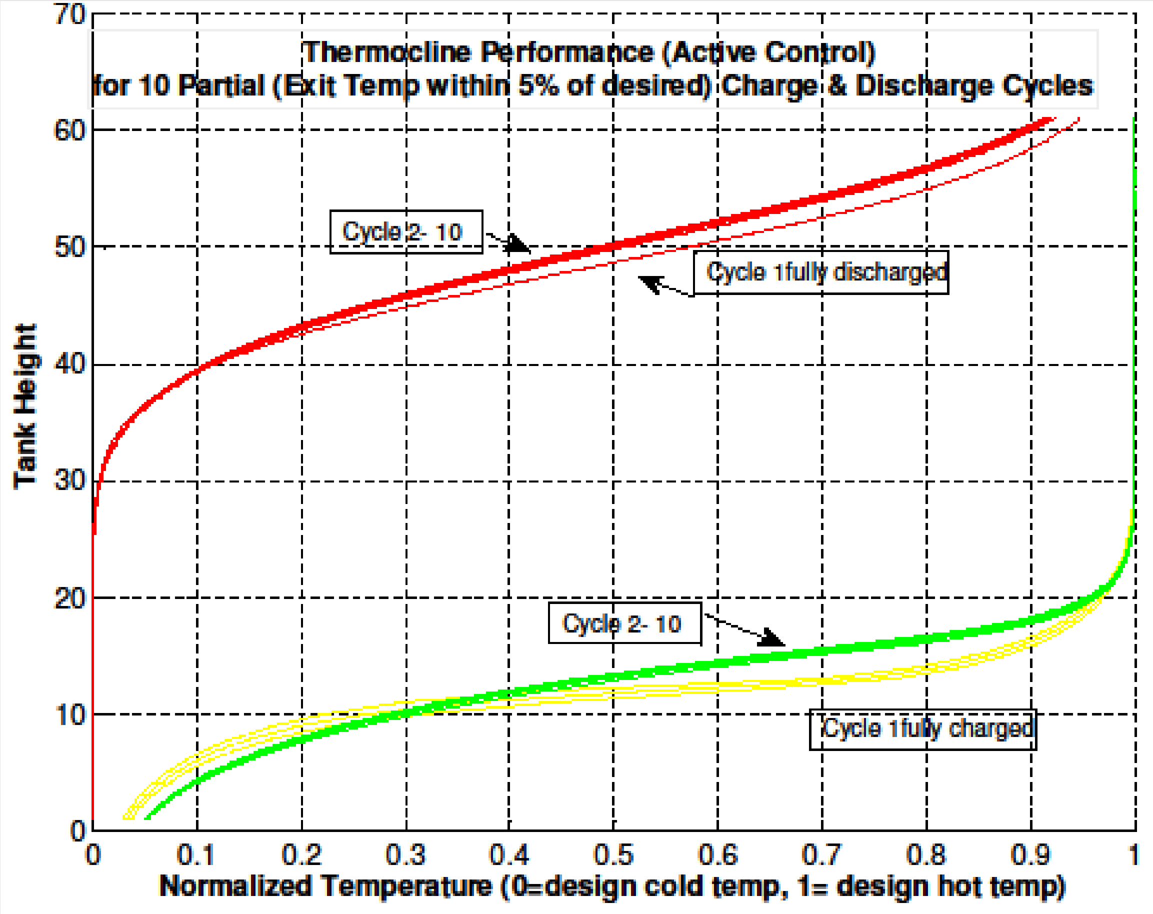
Degradation of Thermocline = Reduced Capacity to Store with Each Cycle

Terrafore's Solution to Thermocline Degradation – *TerraKline* ™

***TerraKline* ™ is a Controller that maintains the Thermocline with every Charge and Discharge Cycle**

- Two Different Methods
  - Actively Managed
  - Passively Managed

No Degradation of Thermocline with *Active TerraKline* Controller

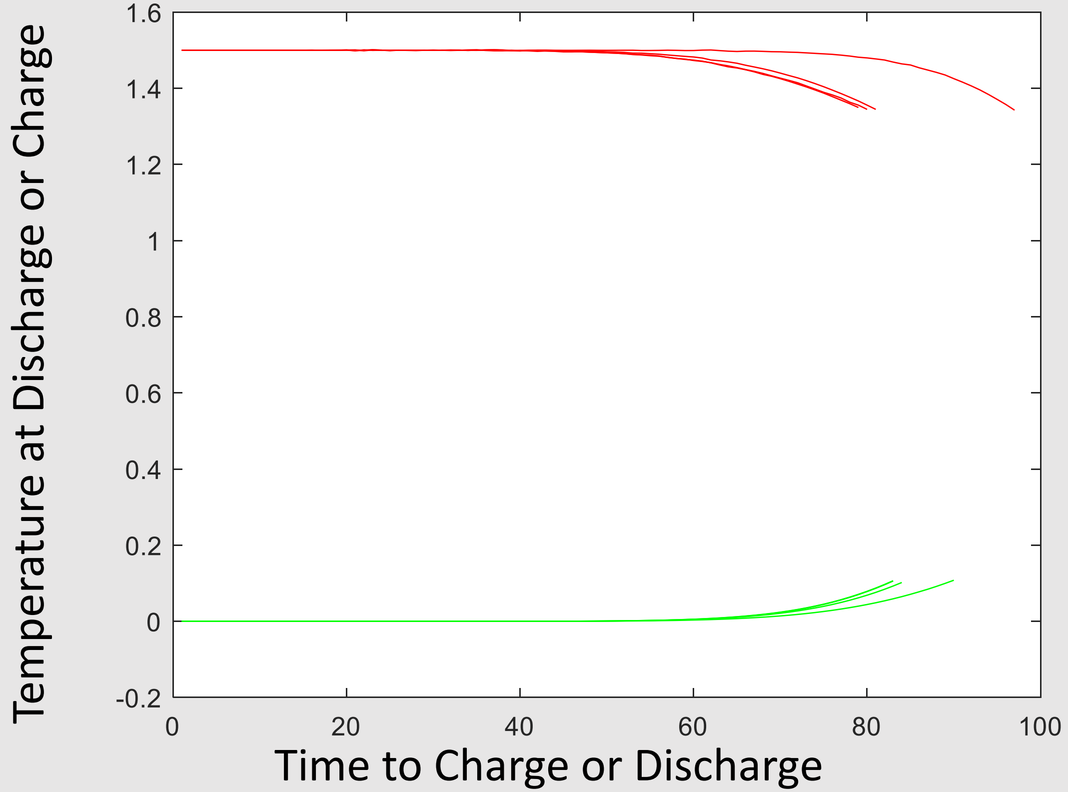


Temperature Profiles for consecutive storage cycles

at end of discharge (red) cut-off temp

at end of charge (green) cut-off temp

Charge and Discharge Times Remain same with Consecutive Storage Cycles



- Red: End of discharge
- Green: End of Charge

Charge and Discharge Times remain as designed

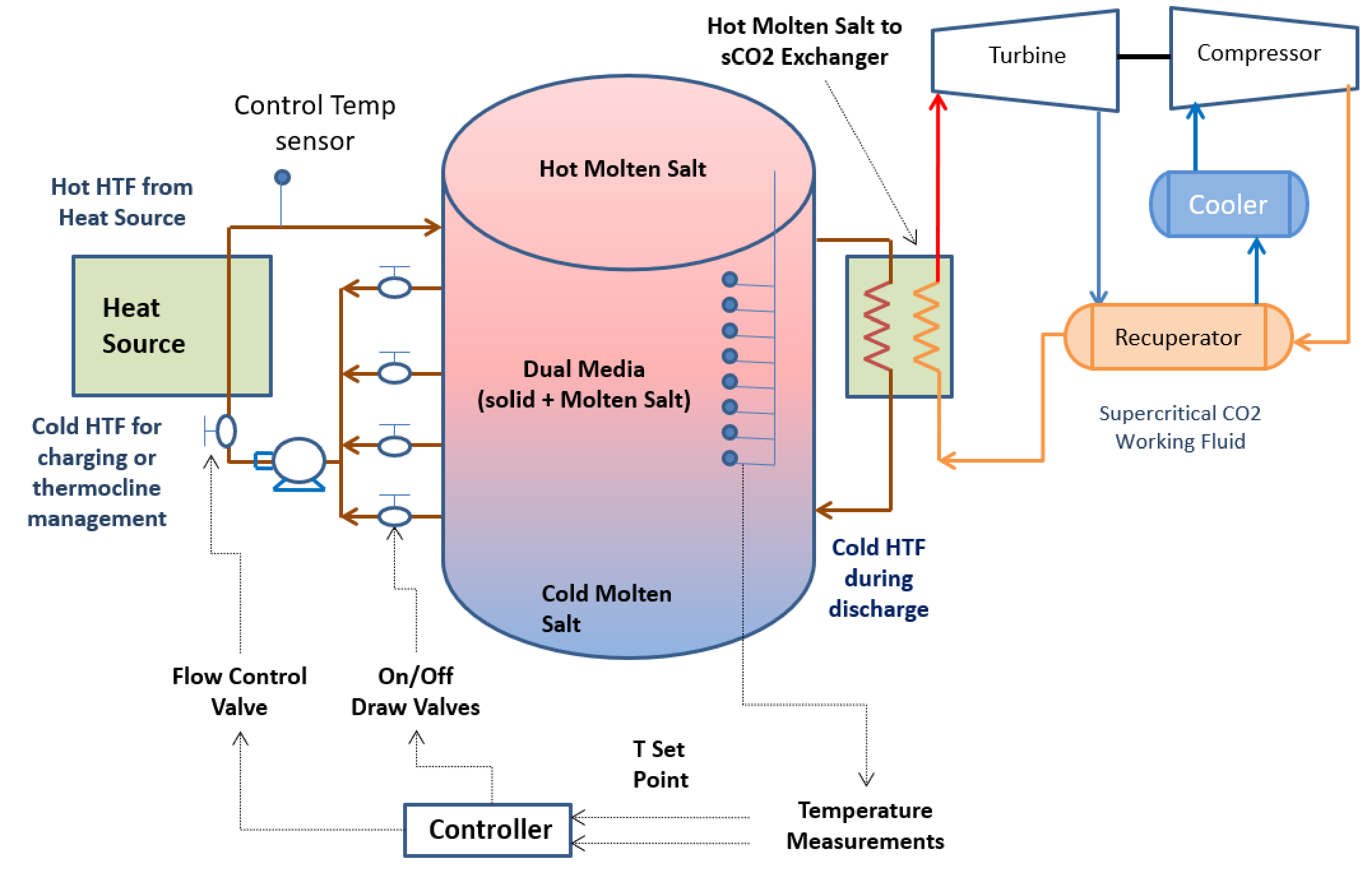
Patented TerraKline Controller Solves the Thermocline Degradation Problem

- Applicable to single media or various combinations of dual media (Solid-Air, Solid-Oil, …)

Two Issued Patents (11473852 issued in 2019, 8554377 issued in 2010)

Third Patent (pending) for use in idle oil wells

DMTES with Active *TerraKline* System



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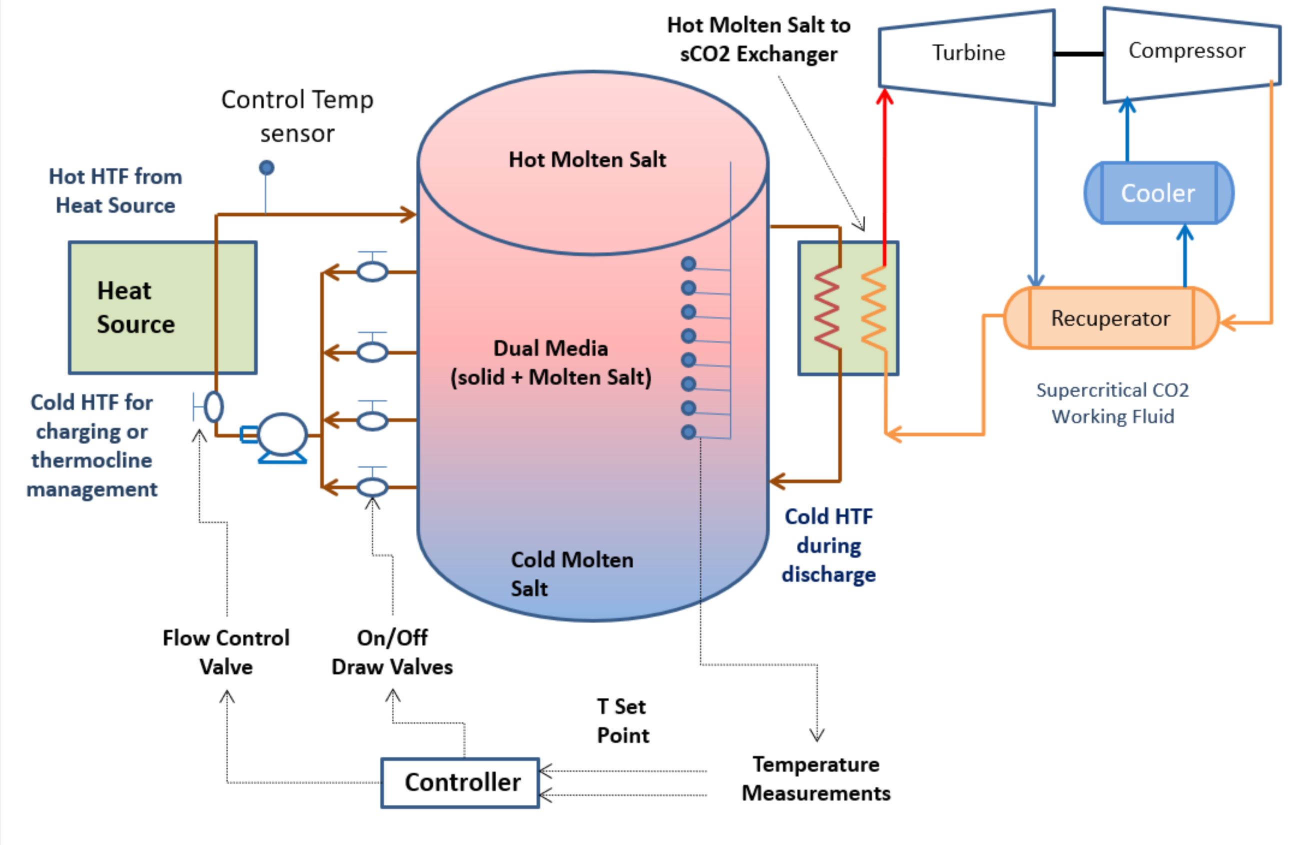
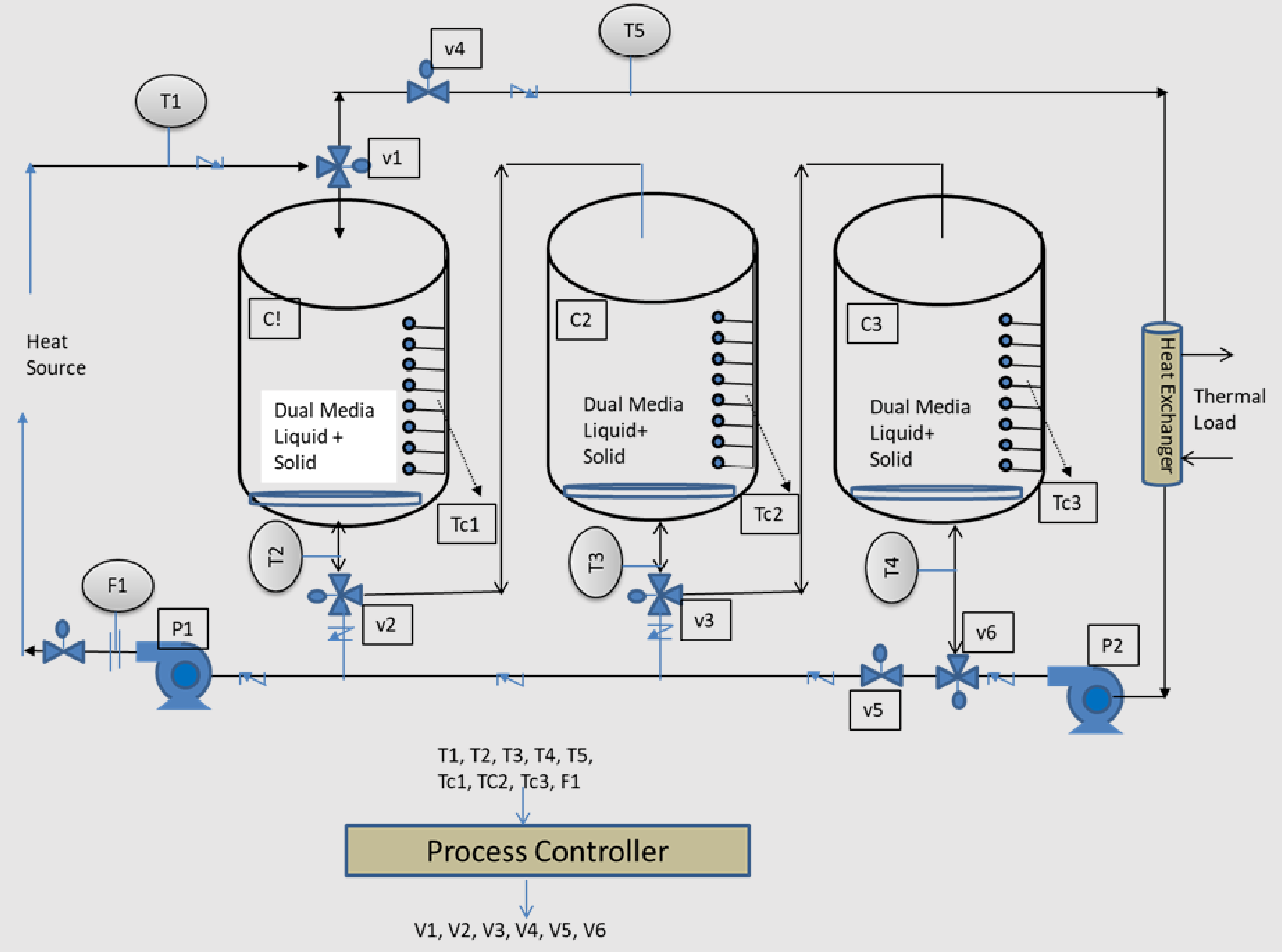
Distributors at Various Levels in the Tank can be Expensive

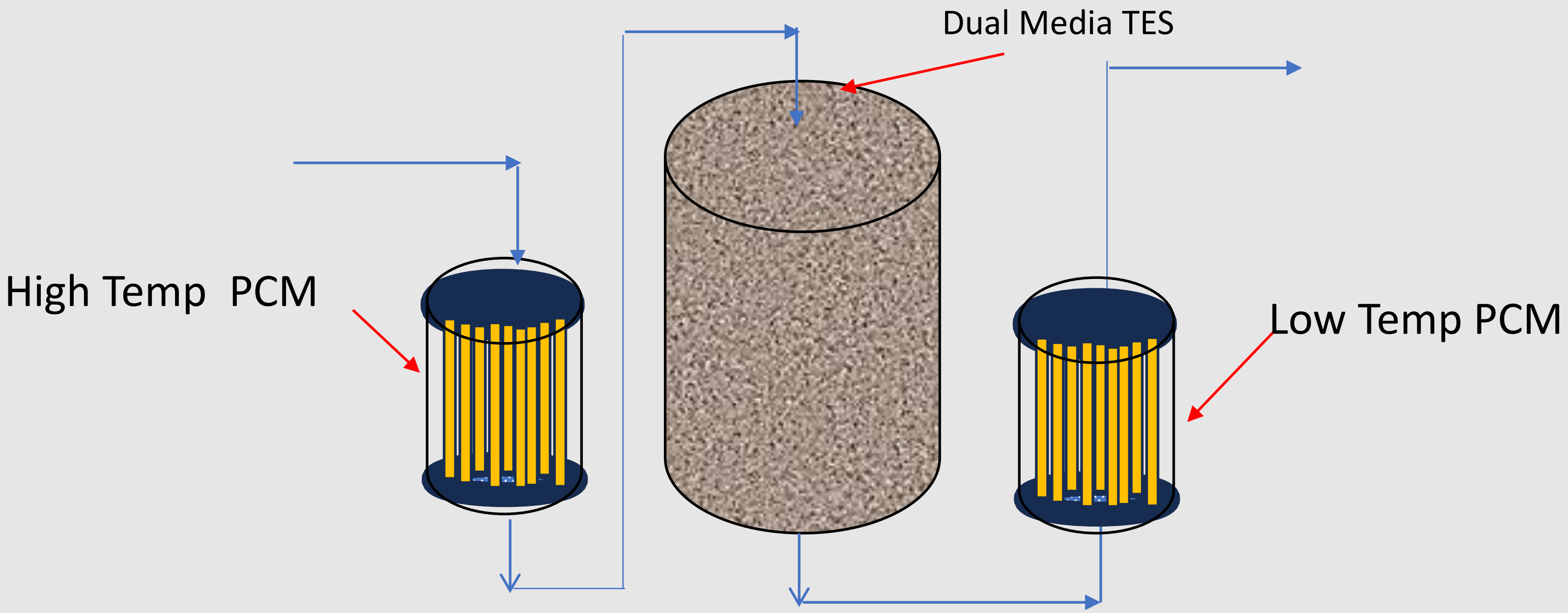


An Alternate Implementation Avoids use of Distributors in the Middle of Container



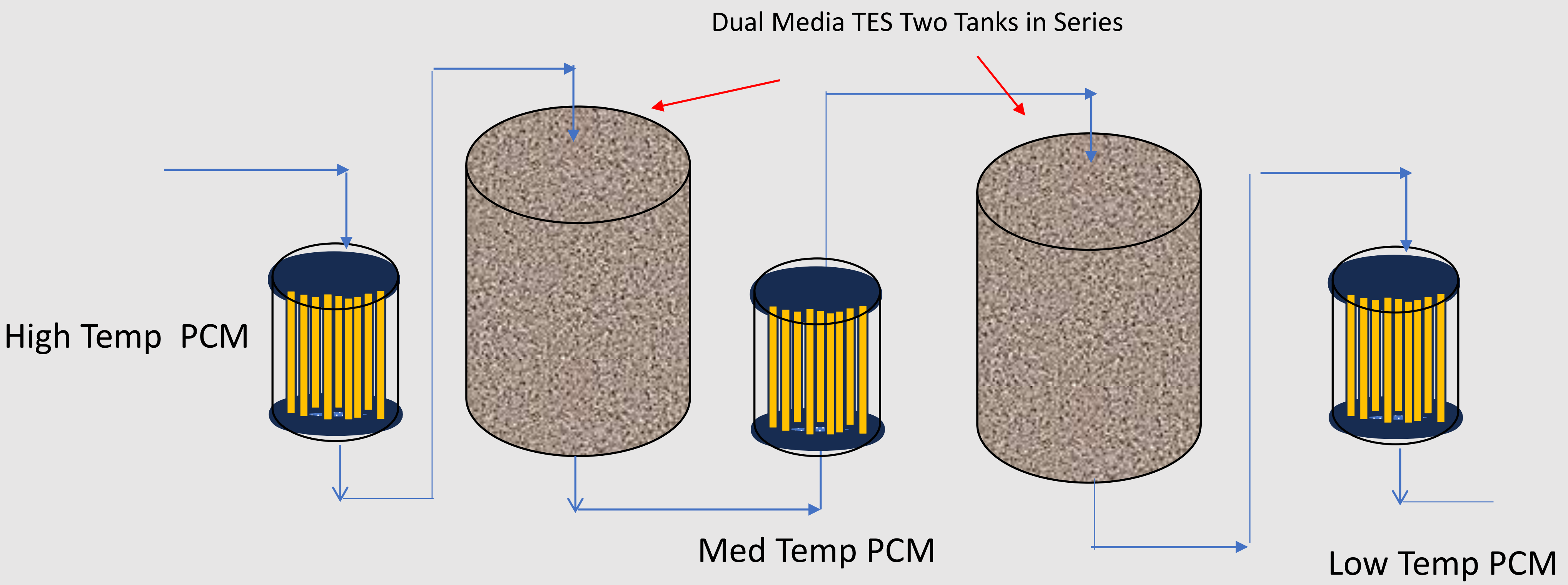
Using Phase Change Material (PCM) at Top and Bottom of Container Flattens the Thermocline

Passive TerraKline Method

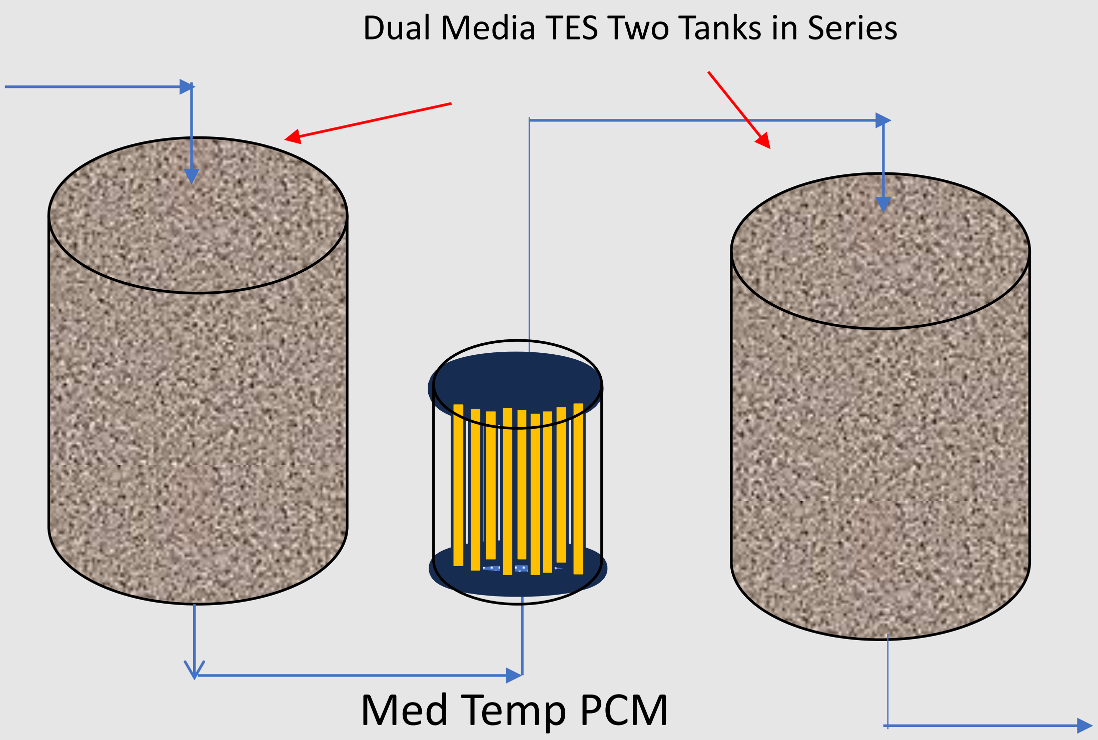


- PCM flattens the thermocline upon exit
- PCM at top, and bottom

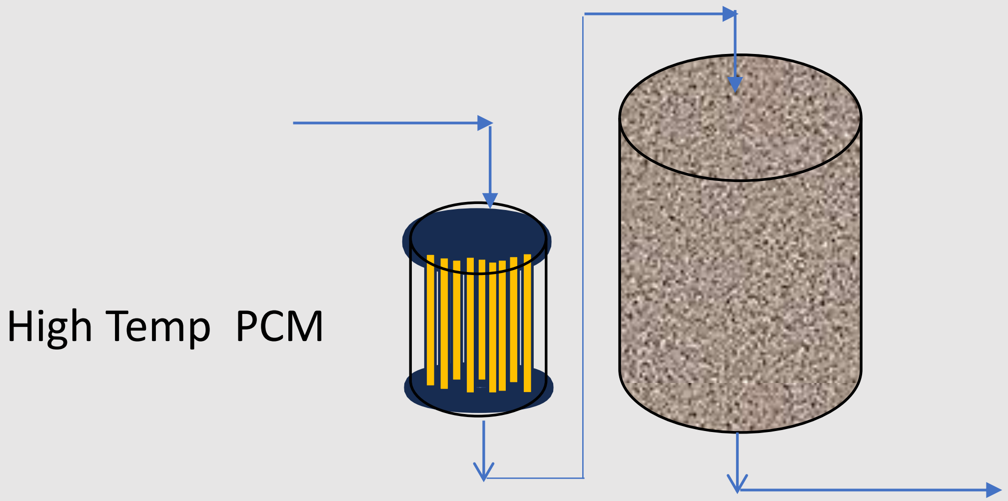
Dual Media Passive TerraKline System with Phase Change Material



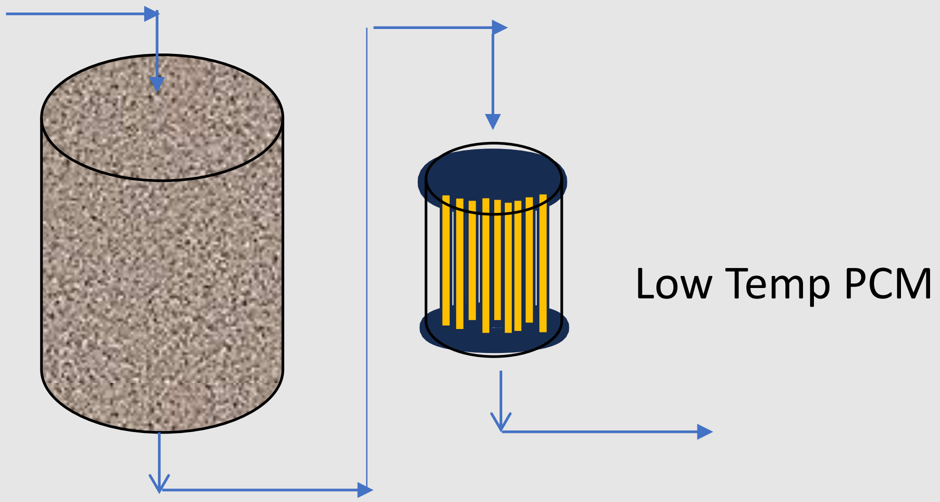
Dual Media Passive TerraKline System with Phase Change Material



Dual Media Passive TerraKline System with Phase Change Material



Dual Media Passive TerraKline System with Phase Change Material



Thermocline Simulation
Unpublished Paper, Anoop Mathur (1982)

THERMOCLINE MODEL AND ITS USE
IN THE DESIGN OPTIMIZATION OF
DUAL MEDIA THERMAL STORAGE SYSTEM

by
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For Presentation at AIAA/ASME Fluids, Plasma, Thermophysics and Heat Transfer Conference - Session on Thermal Storage Heat Transfer

JUNE 7-11, 1982

St. Louis, Missouri

DMTES using Rock + Caloria HT-43

for 10MW Solar Pilot Plant (1979)

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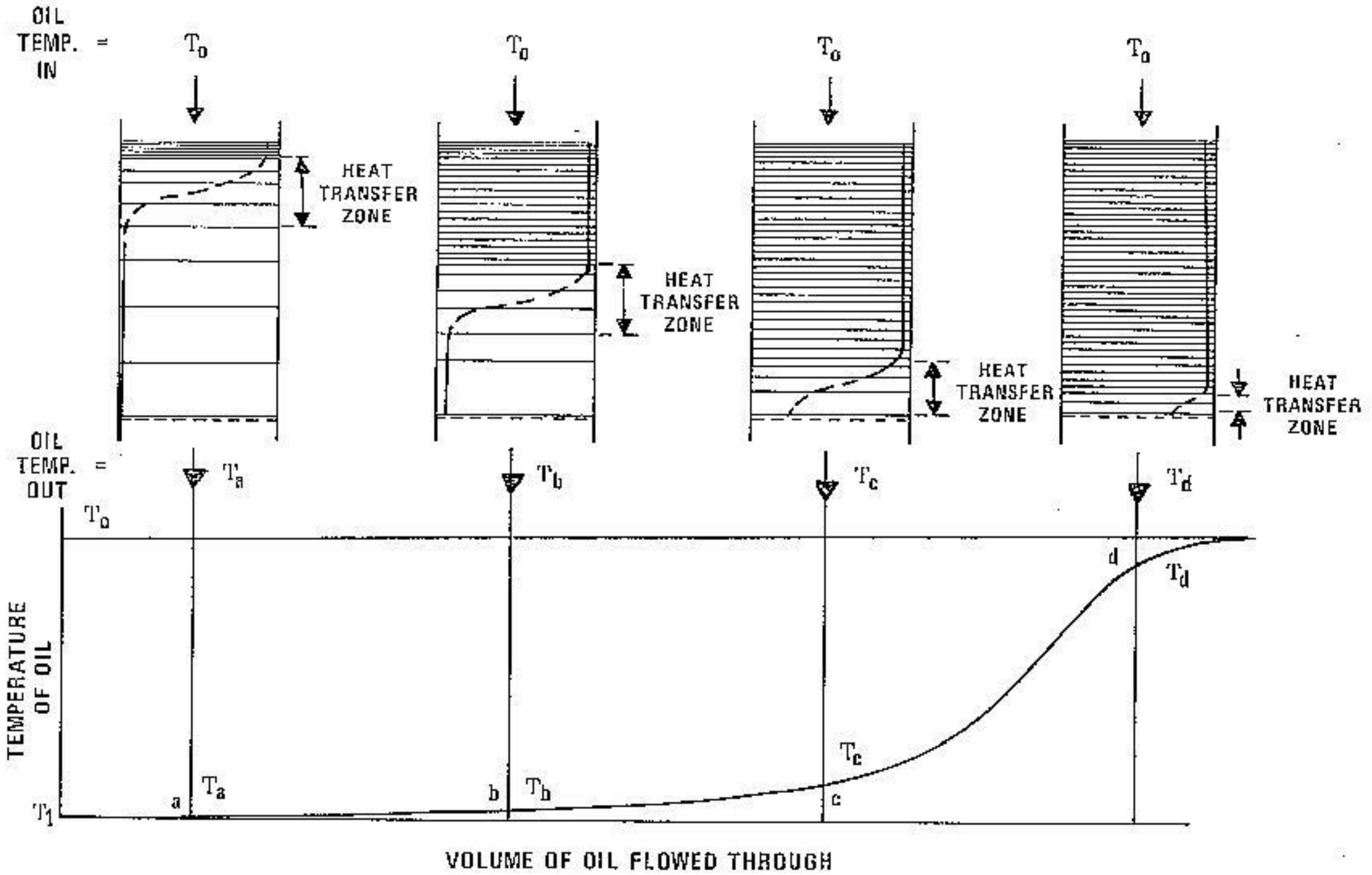


Figure 9. Thermocline Principle (Heat Transfer Zone)

Design Equations for Dual-Media Storage

Table 2. Cost Equations

Cost Item	Equation	Constants
Tank Cost, C_T	$K\left\{T_1\left[\frac{5}{(5-P)[\phi(\beta)]}\right]^{2/3}\cdot\left[\frac{\beta+0.8}{\beta^{2/3}}\right]\cdot\left[T_2\left(\frac{5-\beta^{1/2}}{(5-P)[\phi(\beta)]}\right)^{2/3}+X\right]\right\}^a$	$T_1 = 159.8 \cdot V_D^{2/3}$ $T_2 = 1.15 \times 10^{-6} \cdot \rho \cdot V_D^{2/3}$
Material Cost, C_M	$M \cdot \frac{5}{(5-P)[\phi(\beta)]}$	$M = V_D \cdot \hat{C}_M$
Insulation Cost, C_I	$I \cdot \beta^{1/3} \cdot \frac{(\beta+0.25)^2}{P[(5-P)[\phi(\beta)]]^{1/3}}$	$I = \frac{6.82 \times 10^{-4} V_D^{4/3} k(t_s - t_a)\hat{C}_I}{Q_D}$
Energy Cost, C_E	$E \cdot \frac{P}{(5-P)[\phi(\beta)]}$	$E = 552.7 \cdot Q_D \cdot \hat{C}_E$
Total Cost, C_{Tot}	$C_T + C_M + C_I + C_E$	$V_D = \frac{Q_D \cdot 3413 \times 10^3}{\rho C_p \cdot \Delta t}$
	$C_{Tot} = f(P, \beta)$	$Q_D = \frac{MW(e) \times Hrs \times fMS}{(\eta_{turb})}$
	$\phi(\beta)$ = Thermocline utilization factor as a function of β	K, a = Constants in tank cost equation $C_T = KW^a$

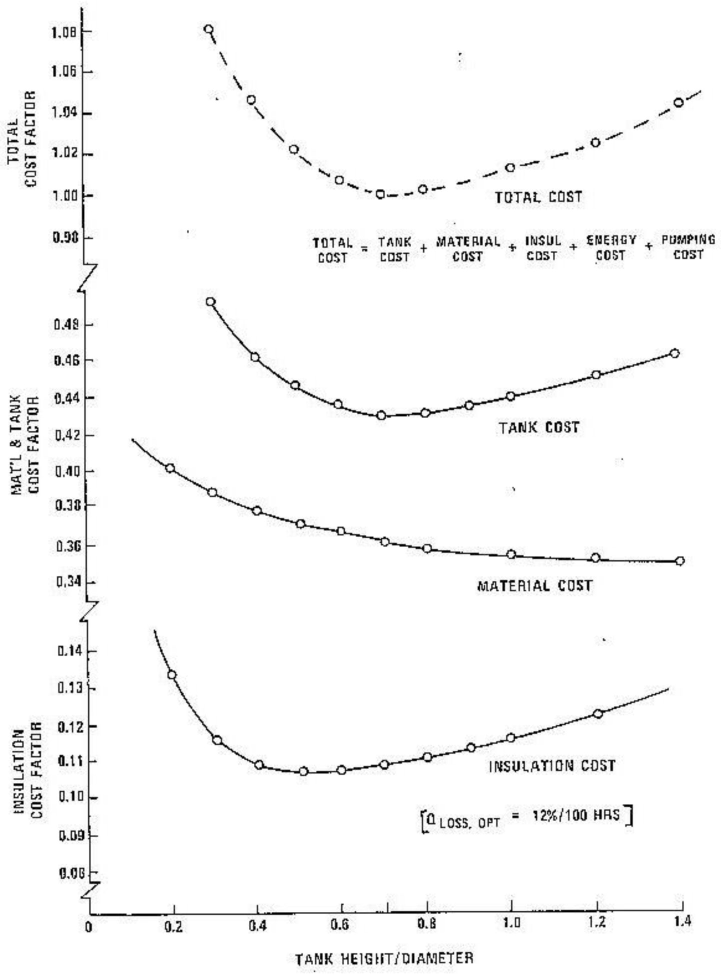


Figure 2. Main Storage Tank Tradeoff -- Cost versus Height/Diameter

Cost Optimum Design Tank Height to Diameter

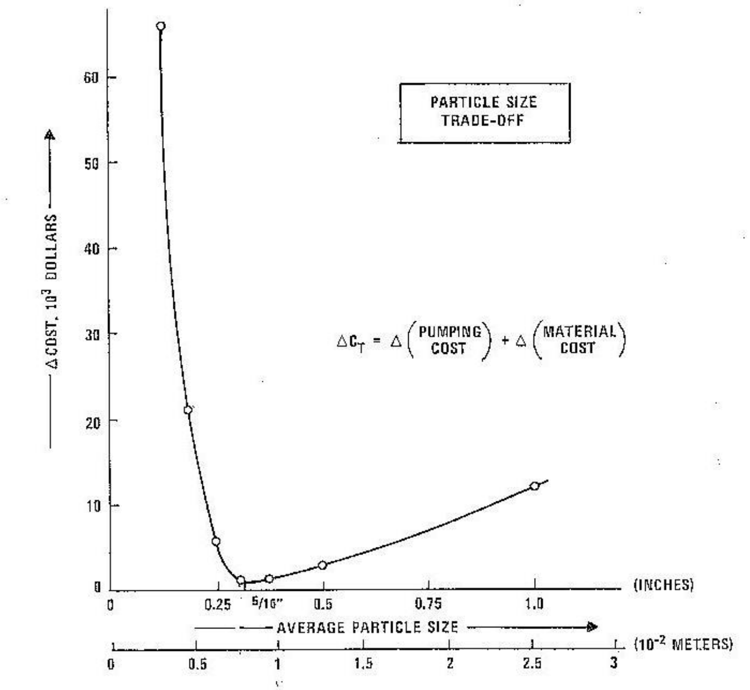


Figure 8. Particle Size Tradeoff

Optimum Particle Size

Thermocline Profiles during discharge

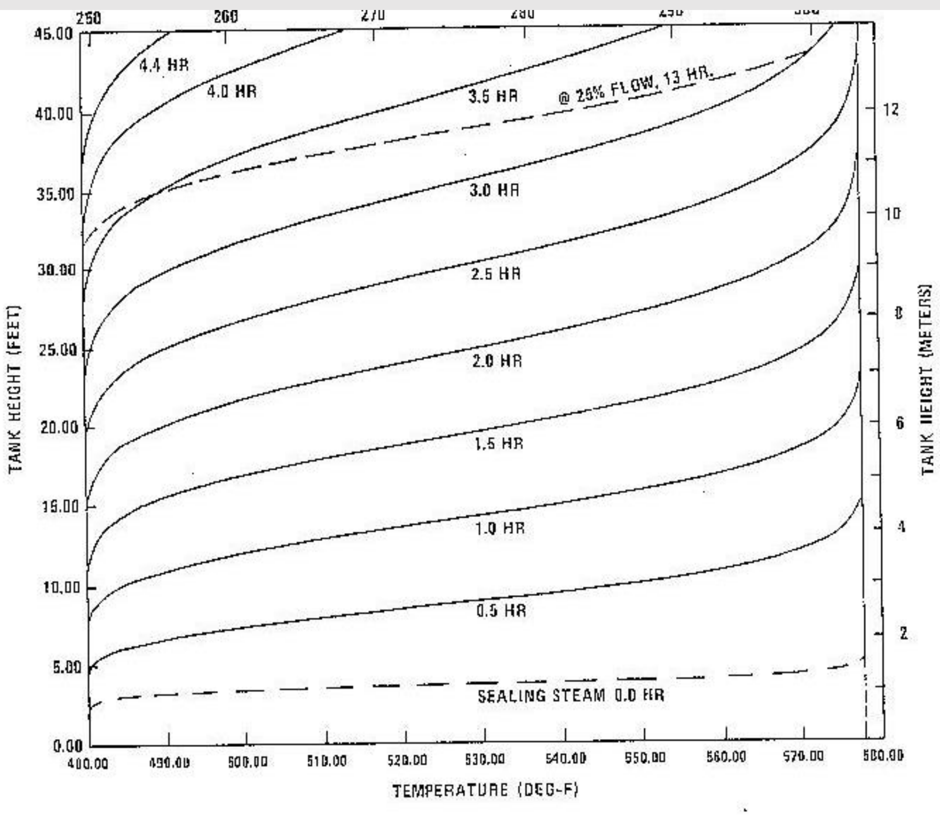
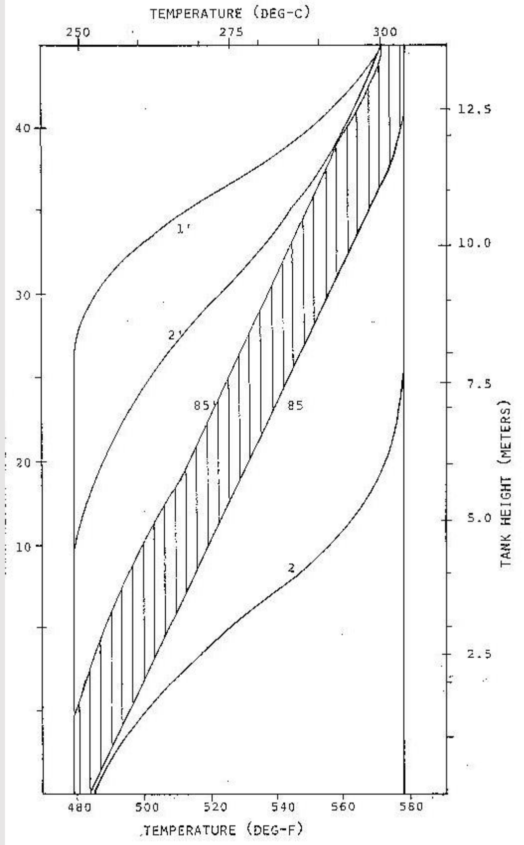


Figure 13. Discharge of Design Flow

Cyclic Performance of Thermocline



Thermoclines for up to 85 Cycles in a Charge/Discharge at Constant Input/Output Heat Rate with a Fluid Temperature Limit on a Charge (252°C) and Discharge (300°C)

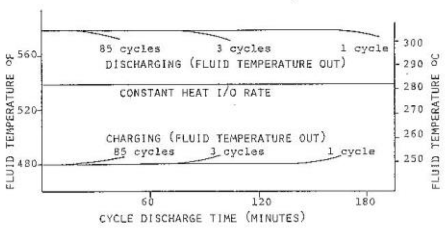
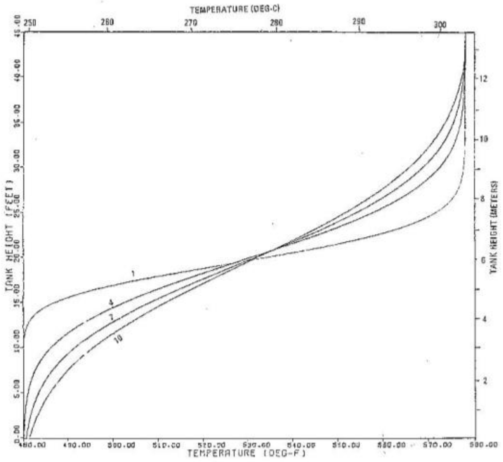
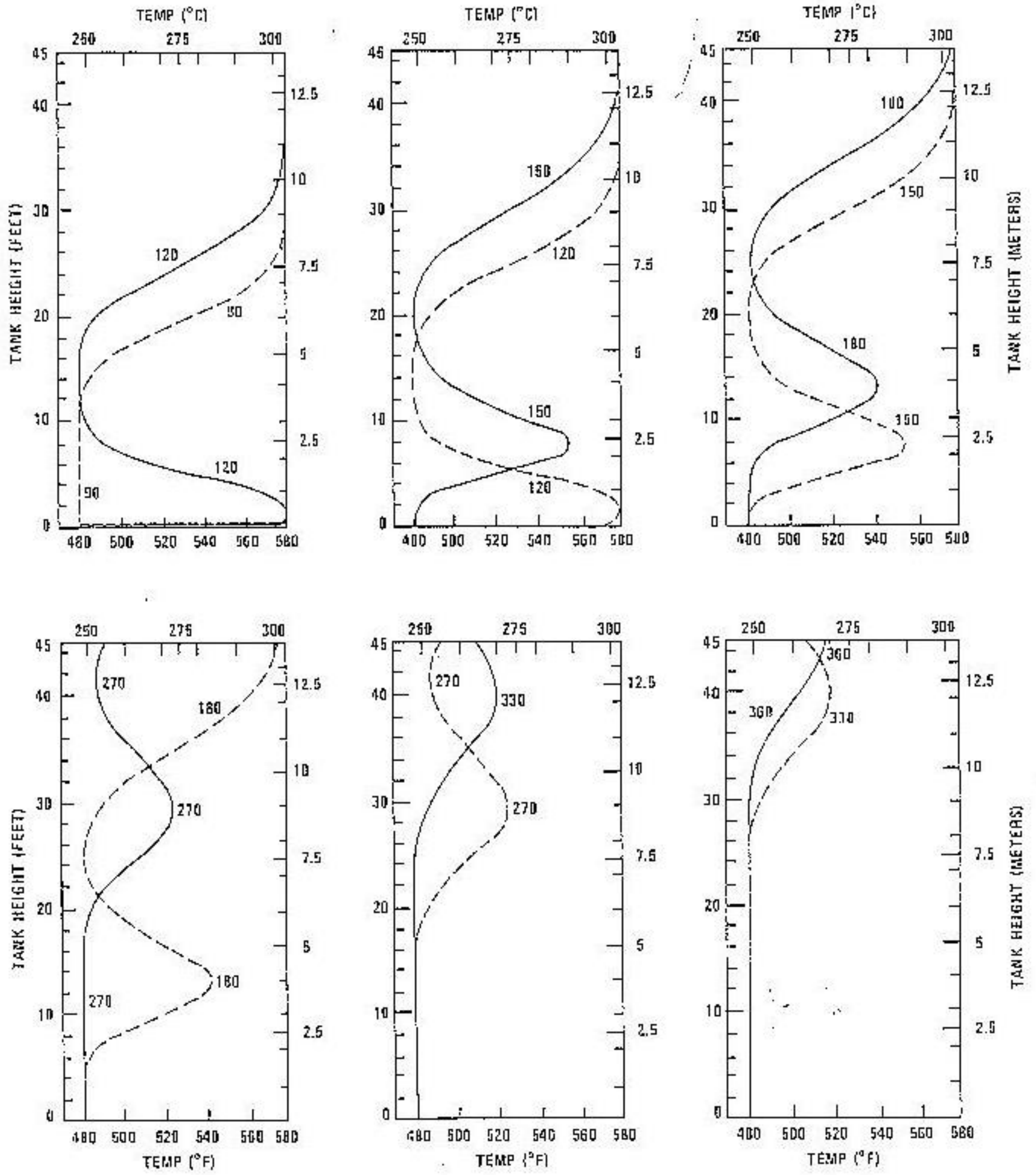


Figure 33. Fluid Temperatures: Charge and Discharge Cycles at Constant Rate





Hot Oil introduced at bottom of tank - illustrates spreading of thermocline

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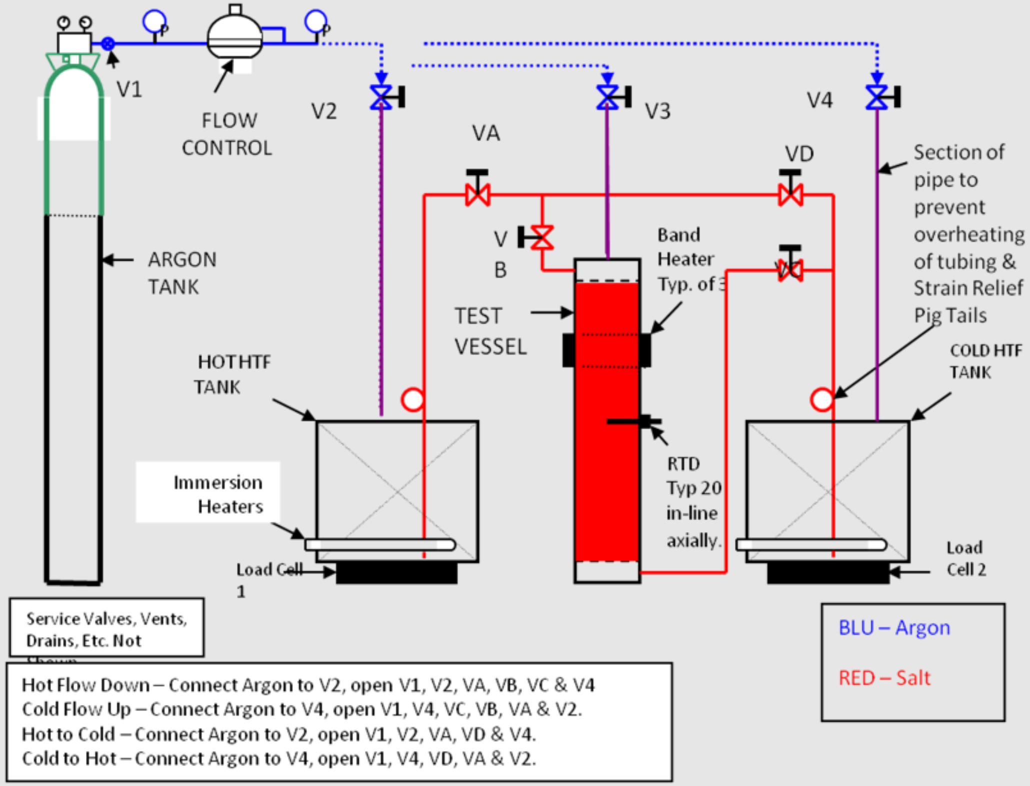
DOE Project (Pending) – Dual Media TES

U.S. DOE Funding Opportunity DE-FOA-0003080, Topic Area 2

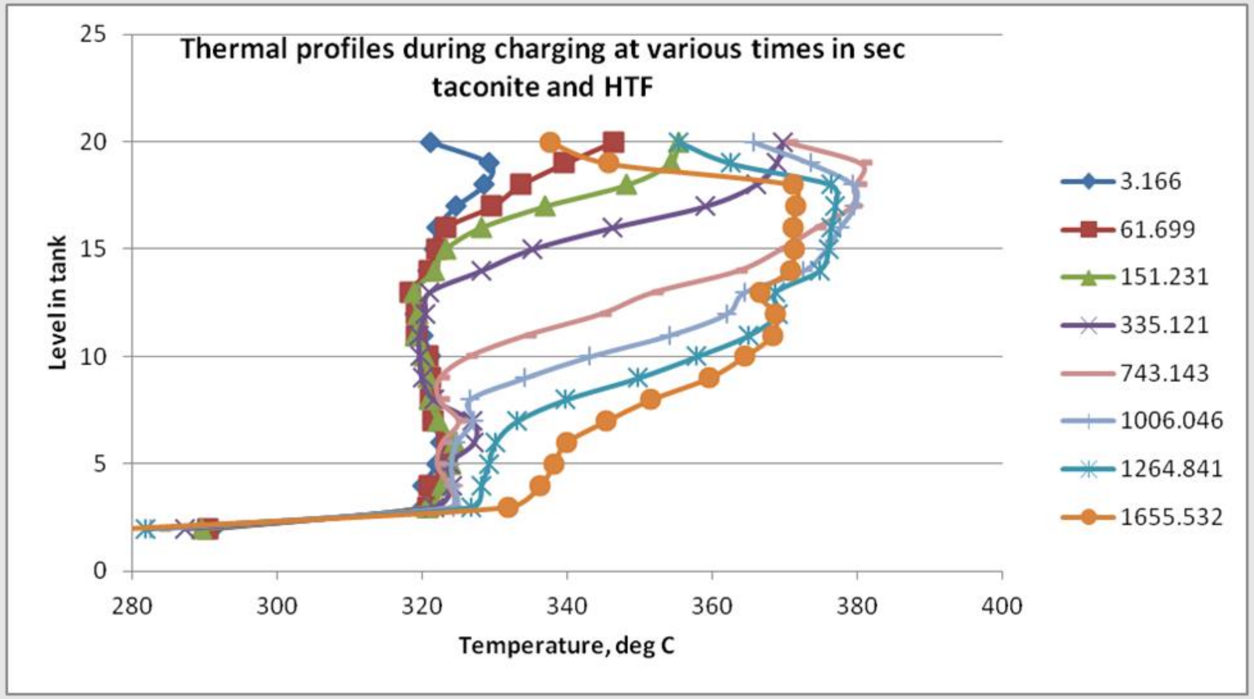
- **Budget Period 1 (~ One Year)**
  - Engineer a test scale TES (~5MWht)
- **Budget Period 2 (~ One year)**
  - Build and Install the TES with sCO2 Heat Exchanger at SWRI, San Antonio, TX
  - Perform tests with active control system to re-establish the thermocline and measure performance

Terrafore's test rig to test TerraKline™ Taconite+Molten Salt



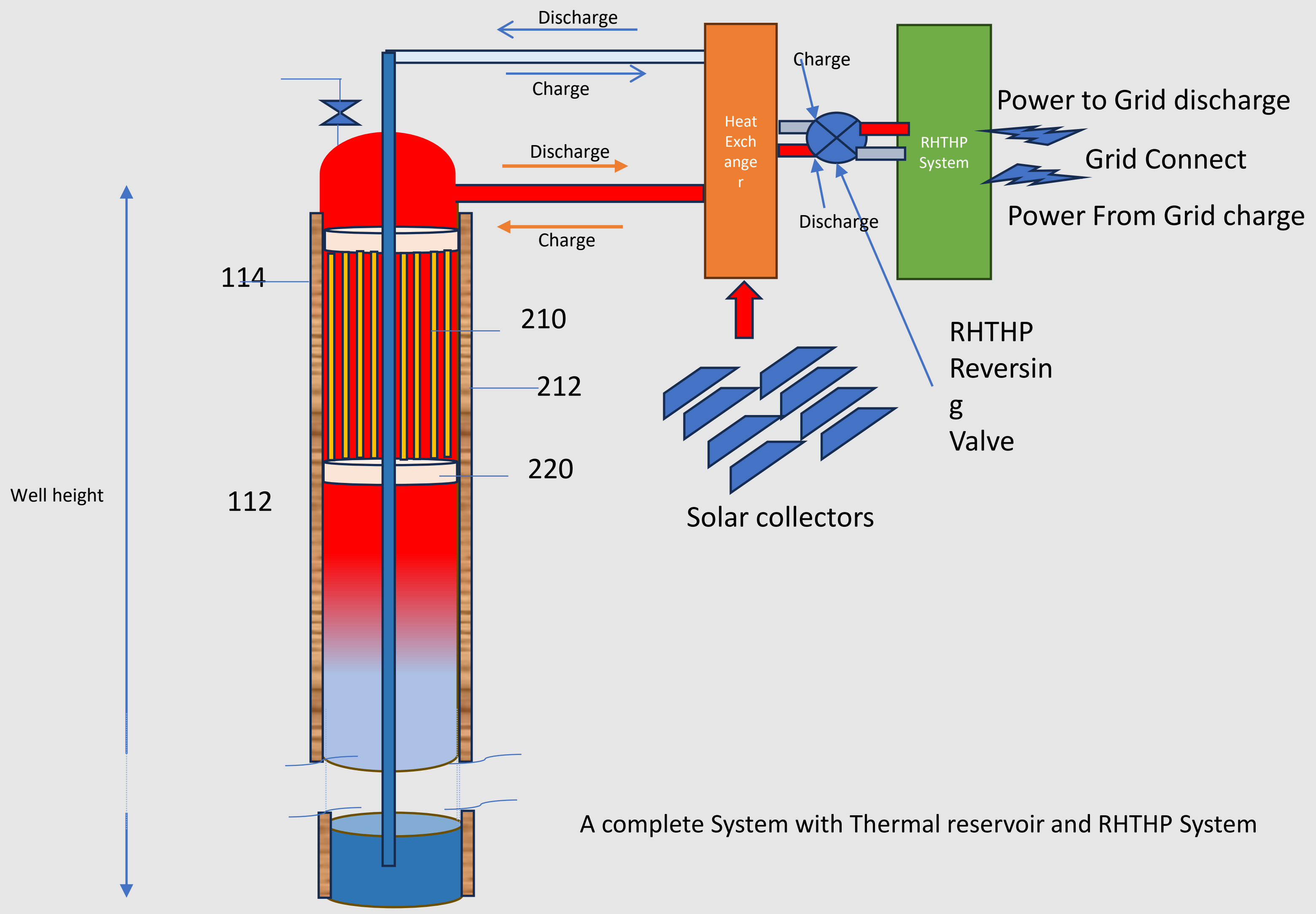
used an air pump to pump molten salt

Temperature Profiles during charging Taconite+ Molten Salt



Questions

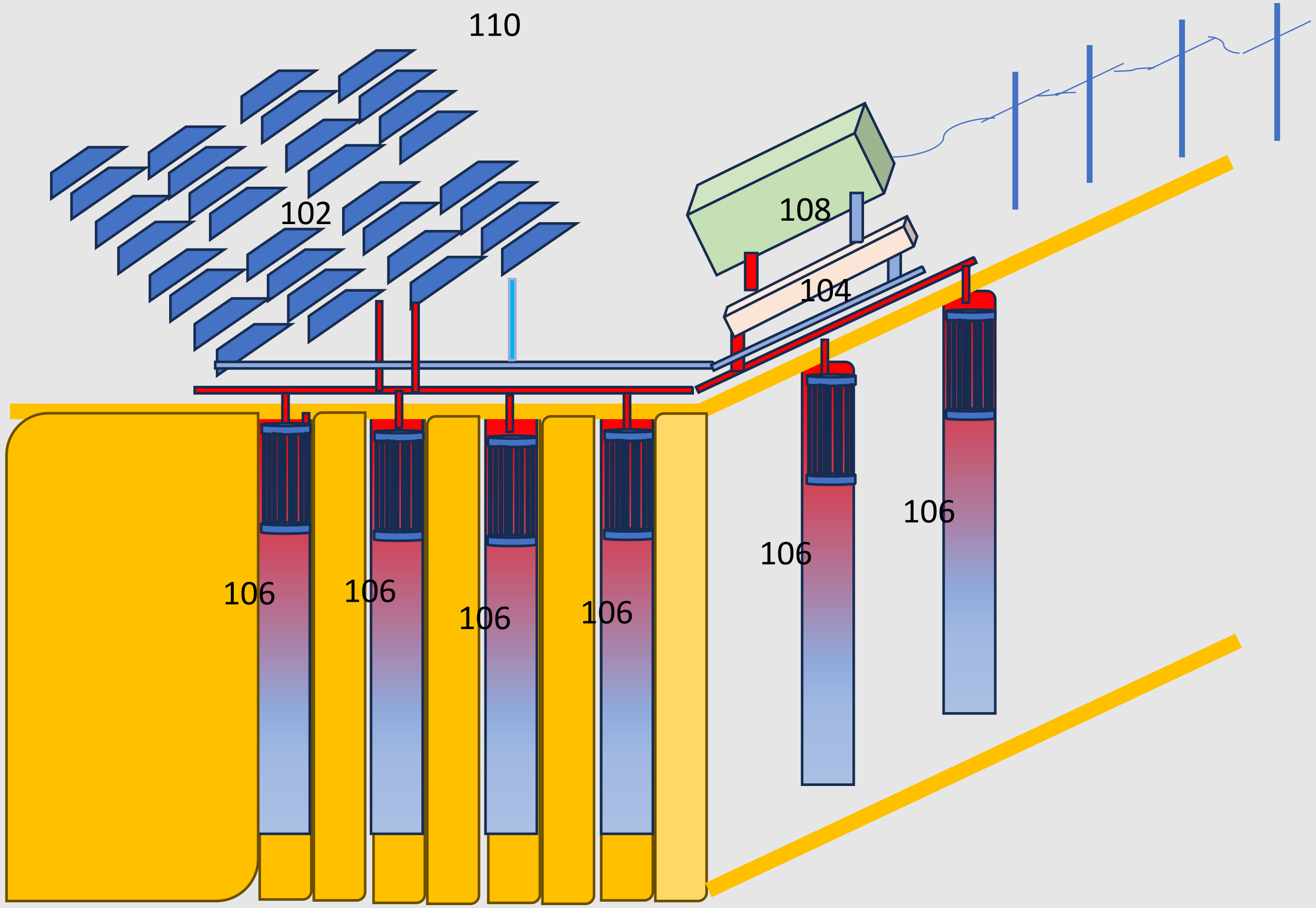
Passive TerraKline System for a Borewell TES



A complete System with Thermal reservoir and RHTHP System

Borewell Thermal Energy Storage

With Heat Pump and Power Generation using RHTHP System



110 Distributed Energy Resource

102 Solar collectors / panels

104 Thermal Storage to RHTHP Heat Exchanger

106 Thermal Storage reservoirs

108 Reversible high Temp Heat pump (RHTHP)