# Thermocline Analysis

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# Schumann Equations to Describe Thermocline with Packed Bed

$$(\rho C_p)_f \varepsilon \frac{\partial T_f}{\partial \tau} = -\frac{(\dot{m} C_p)_f}{A} \frac{\partial T_f}{\partial y} + h_v (T_b - T_f)$$

$$(\rho C_p)_b (1-\varepsilon) \frac{\partial T_b}{\partial \tau} = h_v (T_f - T_b)$$

# Pacheco Numerical Computer Model Modified Euler Solution

$$C_1 = \frac{\dot{m}_f}{A\rho_f\varepsilon} = \frac{v}{\varepsilon}$$

$$C_2 = \frac{h_v}{(\rho C_p)_f\varepsilon}$$

$$C_3 = \frac{h_v}{(\rho C_p)_b(1-\varepsilon)}$$

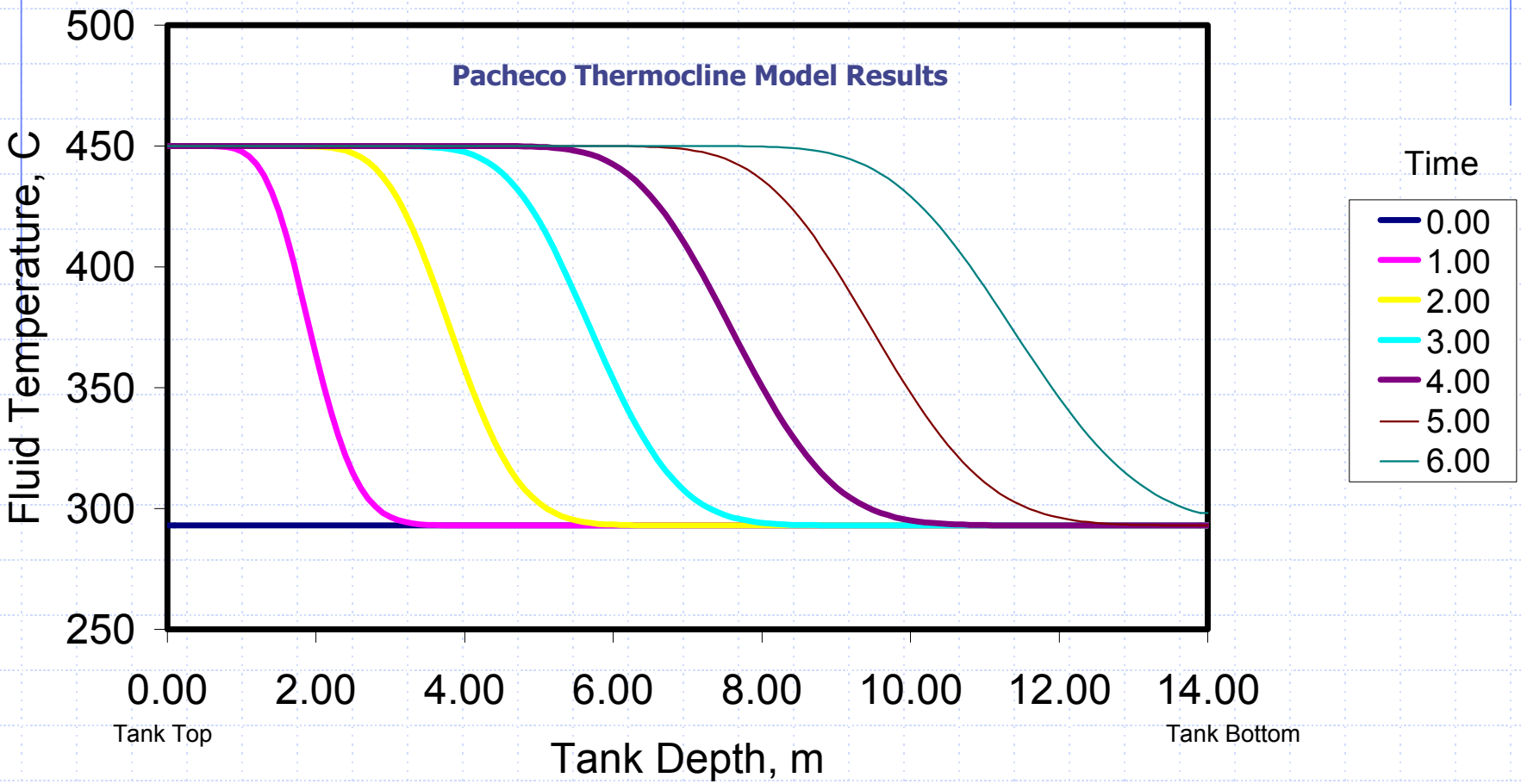
$$\frac{\Delta T_f}{\Delta t} = \frac{-C_1(T_{f,t} - T_{f,t-1})}{\Delta x} + C_2(T_b - T_f)$$

$$\frac{\Delta T_b}{\Delta t} = C_3(T_f - T_b)$$

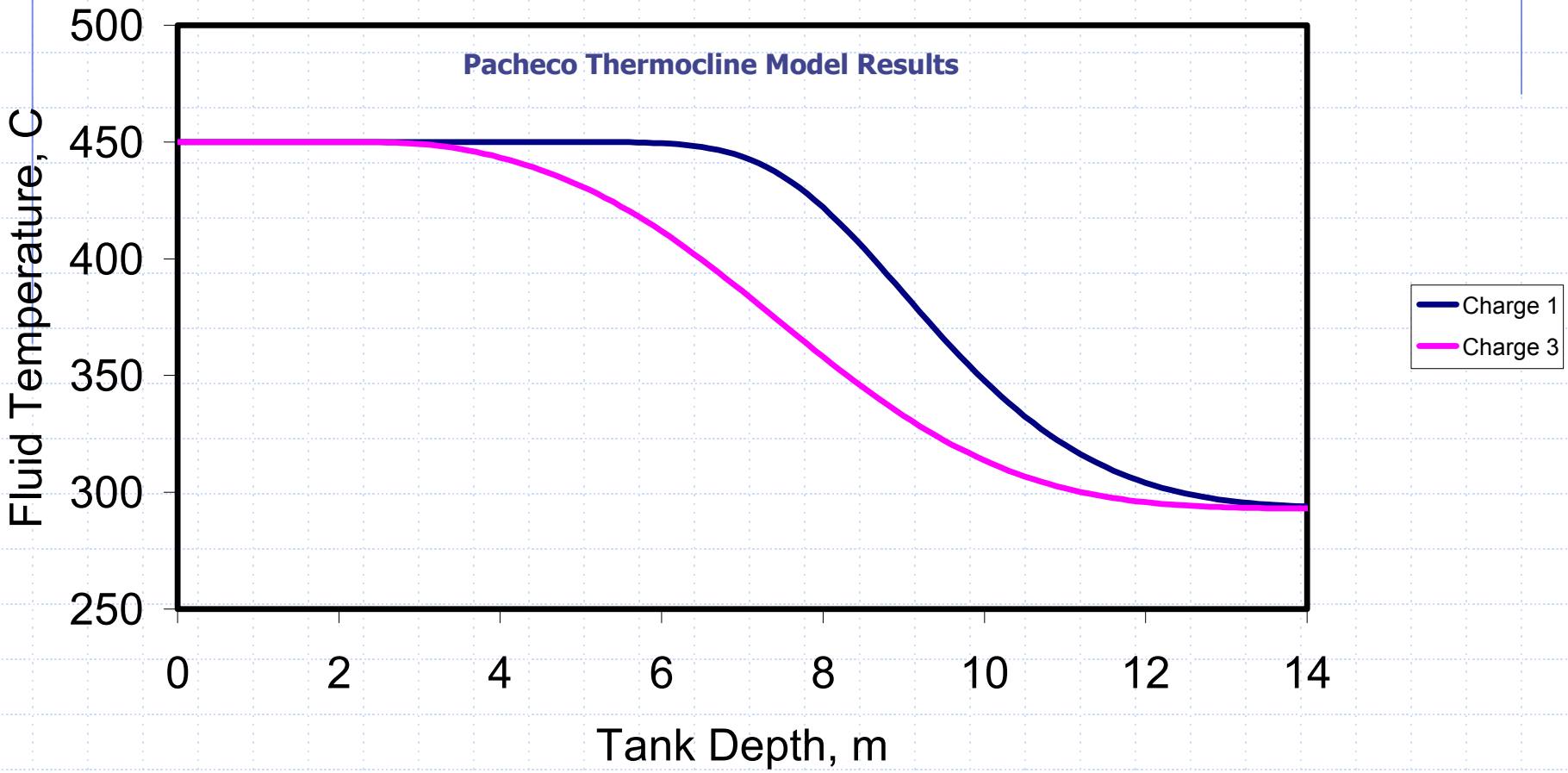
# Thermocline Example

- Theoretical Storage Capacity
  - 7.1 hrs for 50MWe
- Tank Dimensions: 14m high, 37m diameter
- HTF: Hitec XL (293C to 450C)
- Bed Filler: Quartzite
  - 0.5” particle size
  - 0.24 Void fraction (Sand Packed)
- Computer Numerical Model
  - dy=0.1m
  - dt=2-3 seconds

# Thermocline Temperature Profile Initial Charge

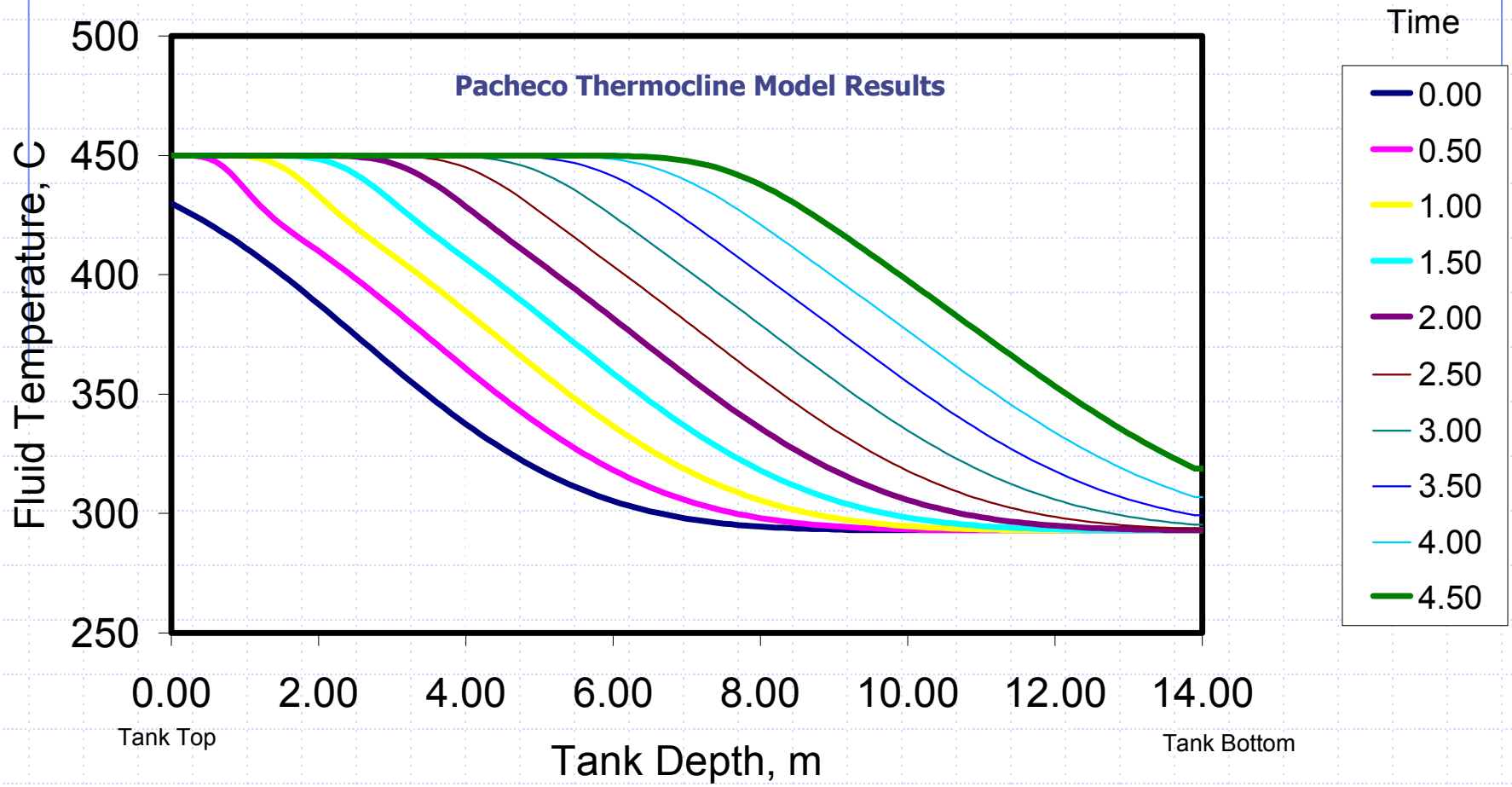


# Change in Thermocline Profile with Repeat Charge and Discharge Cycles

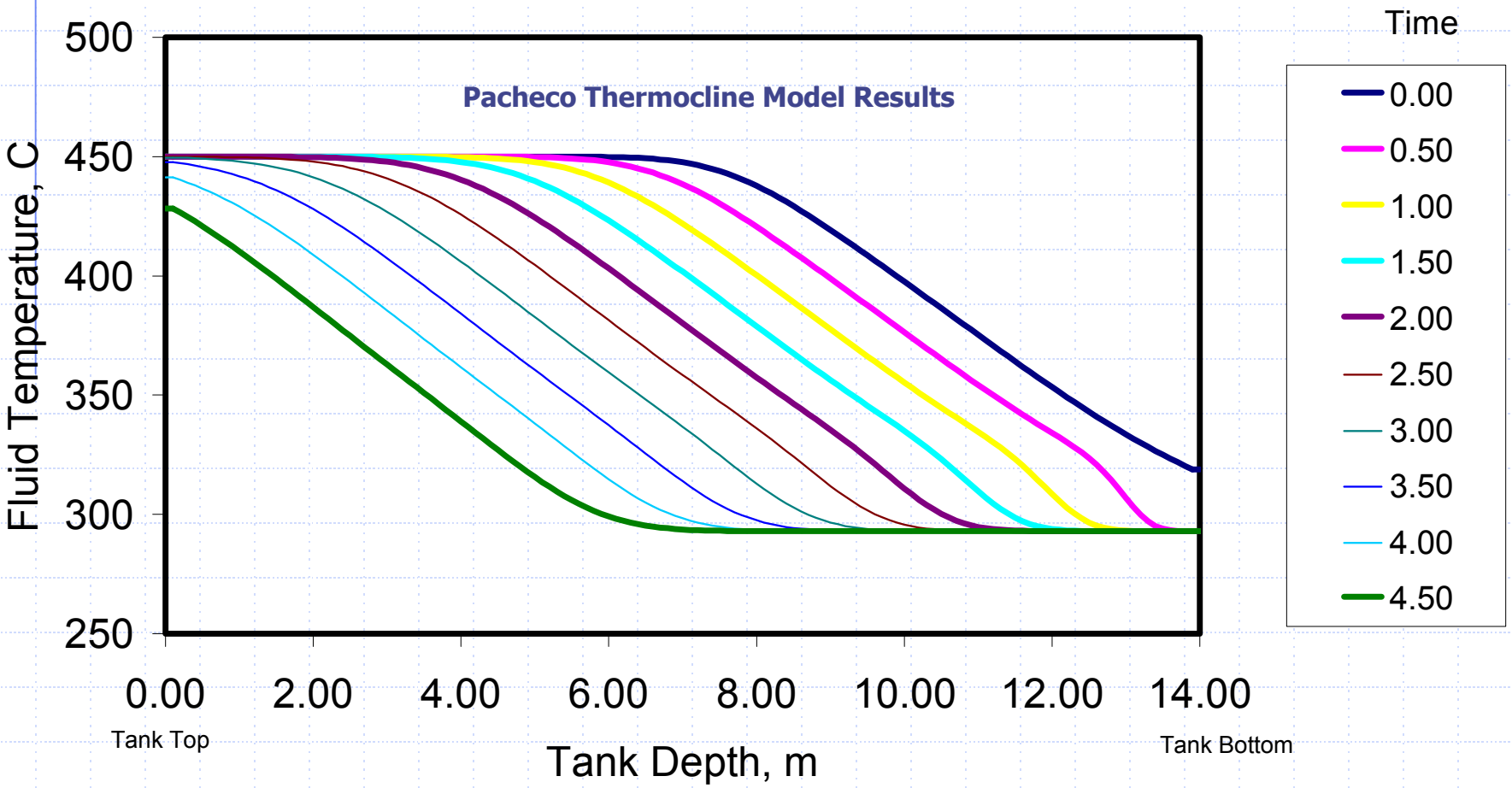


# Charging with 20ºC Temperature Decay

## 4.5 hrs of constant flow (62% Utilization)

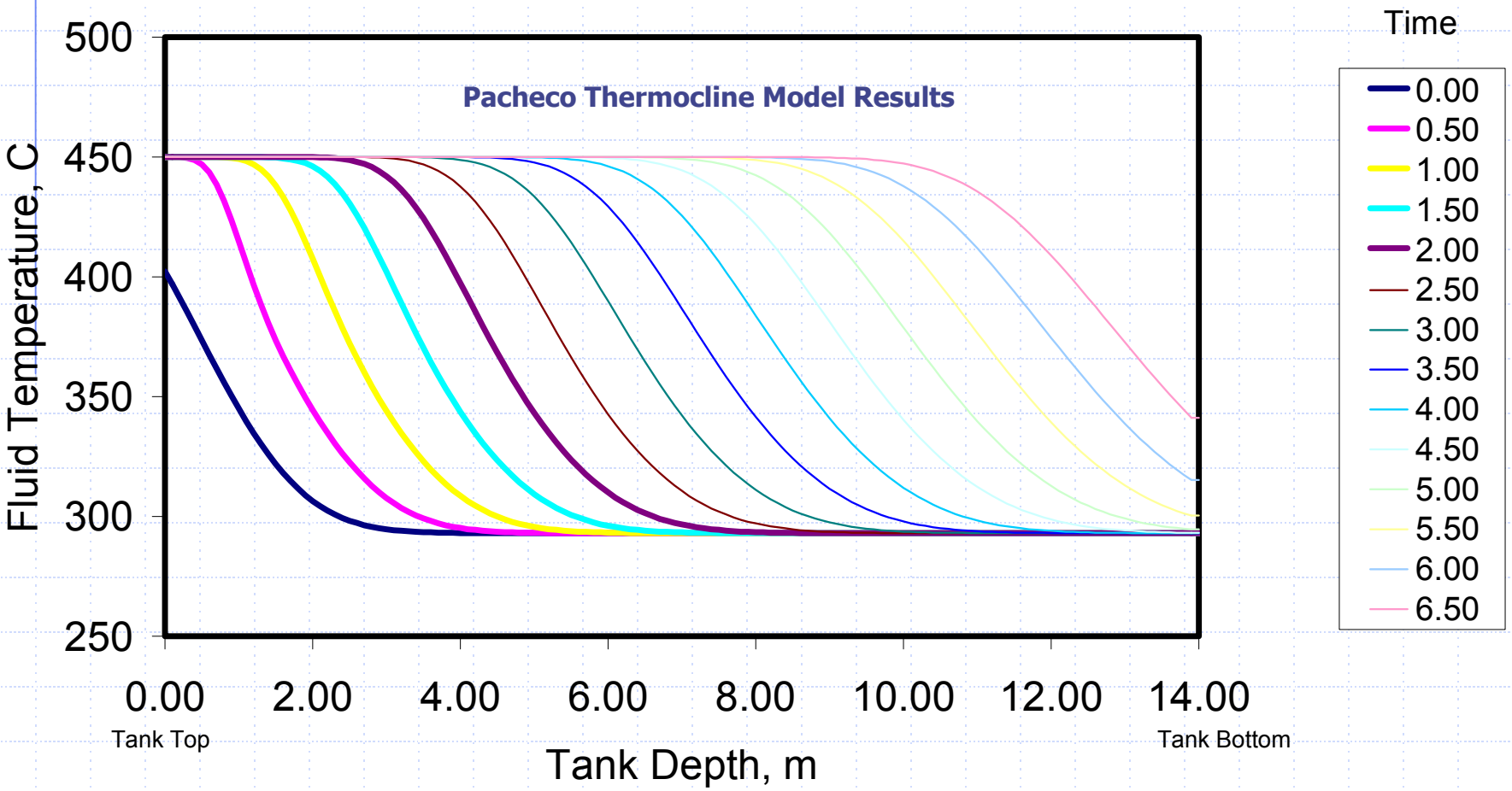


# Discharging with 20ºC Temperature Decay

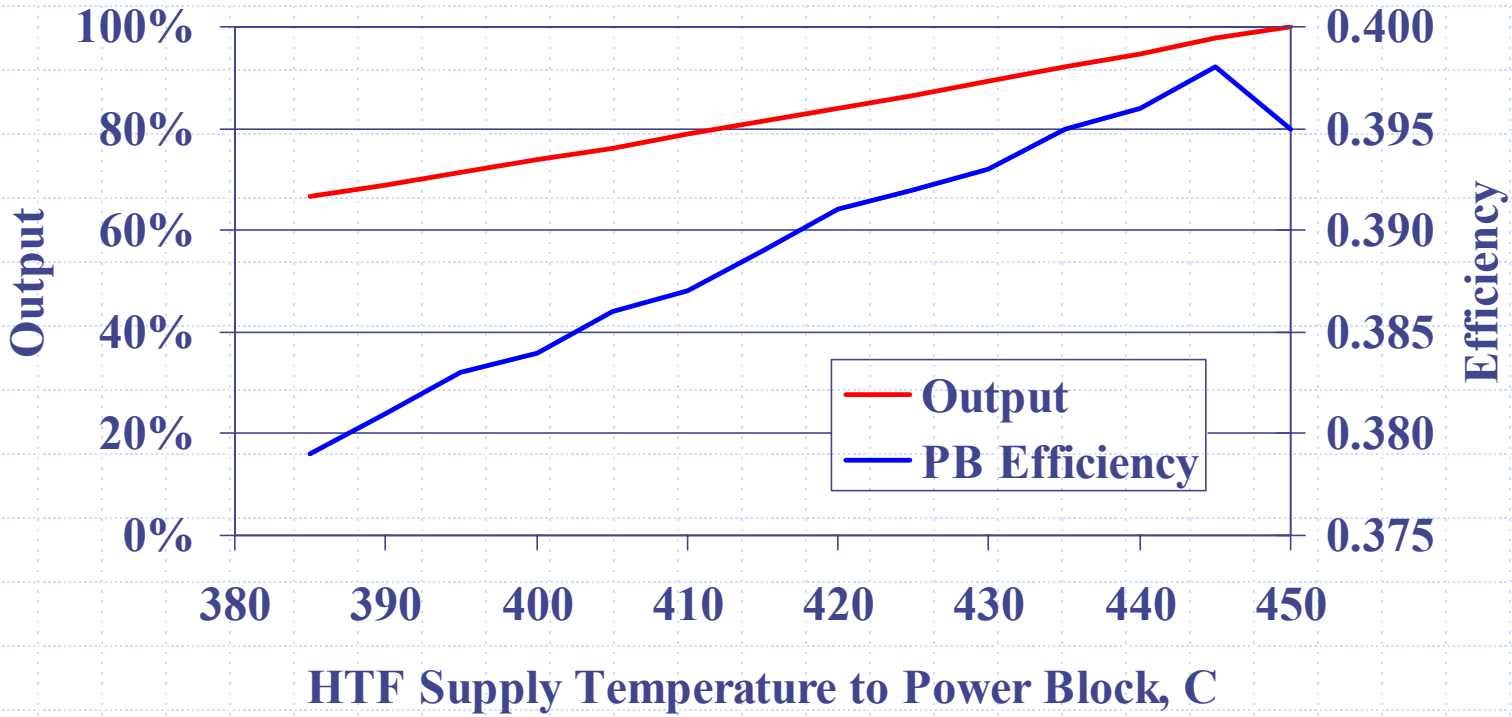


# 50ºC Temperature Decay

## 6.5 hrs of constant flow (90% Utilization)

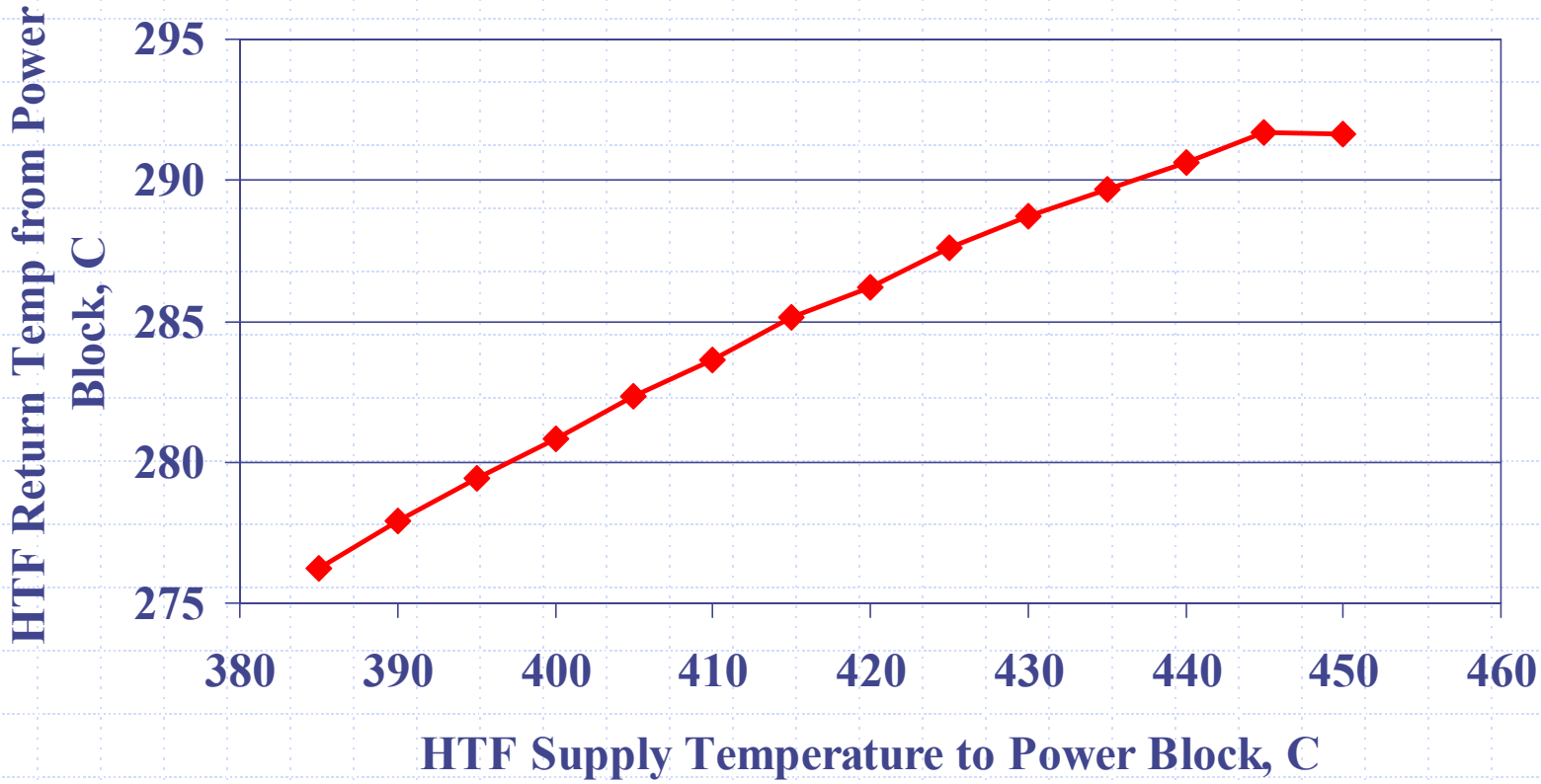


# Impact of Power Block HTF Supply Temp. Decay on Power Block Output and Efficiency




**Source: Nexant**

# Impact of Power Block HTF Supply Temp. Decay on Power Block HTF Return Temp.




**Source: Nexant**

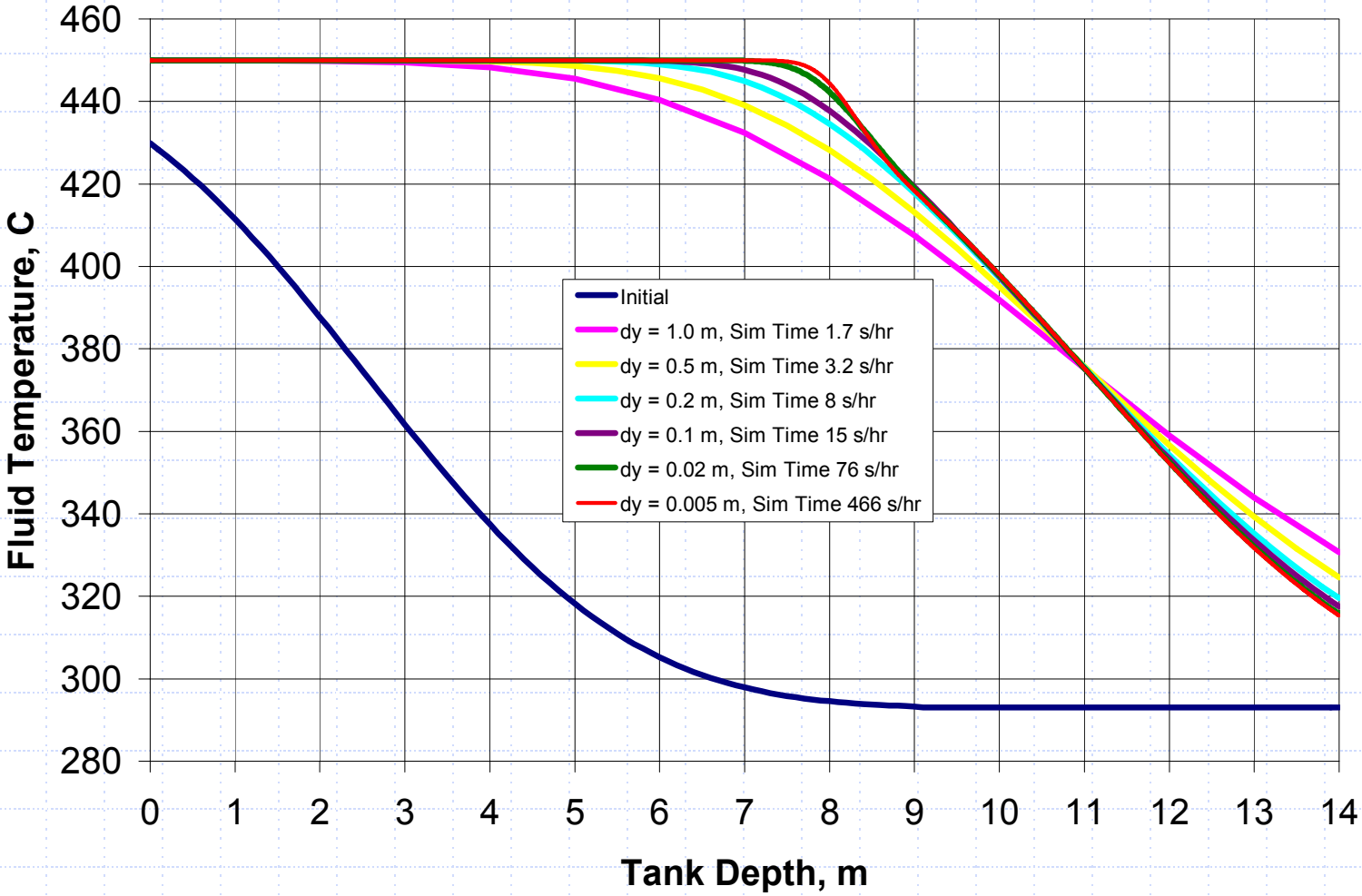
# Thermocline TES Cost Example

## Based on Nexant Cost Model

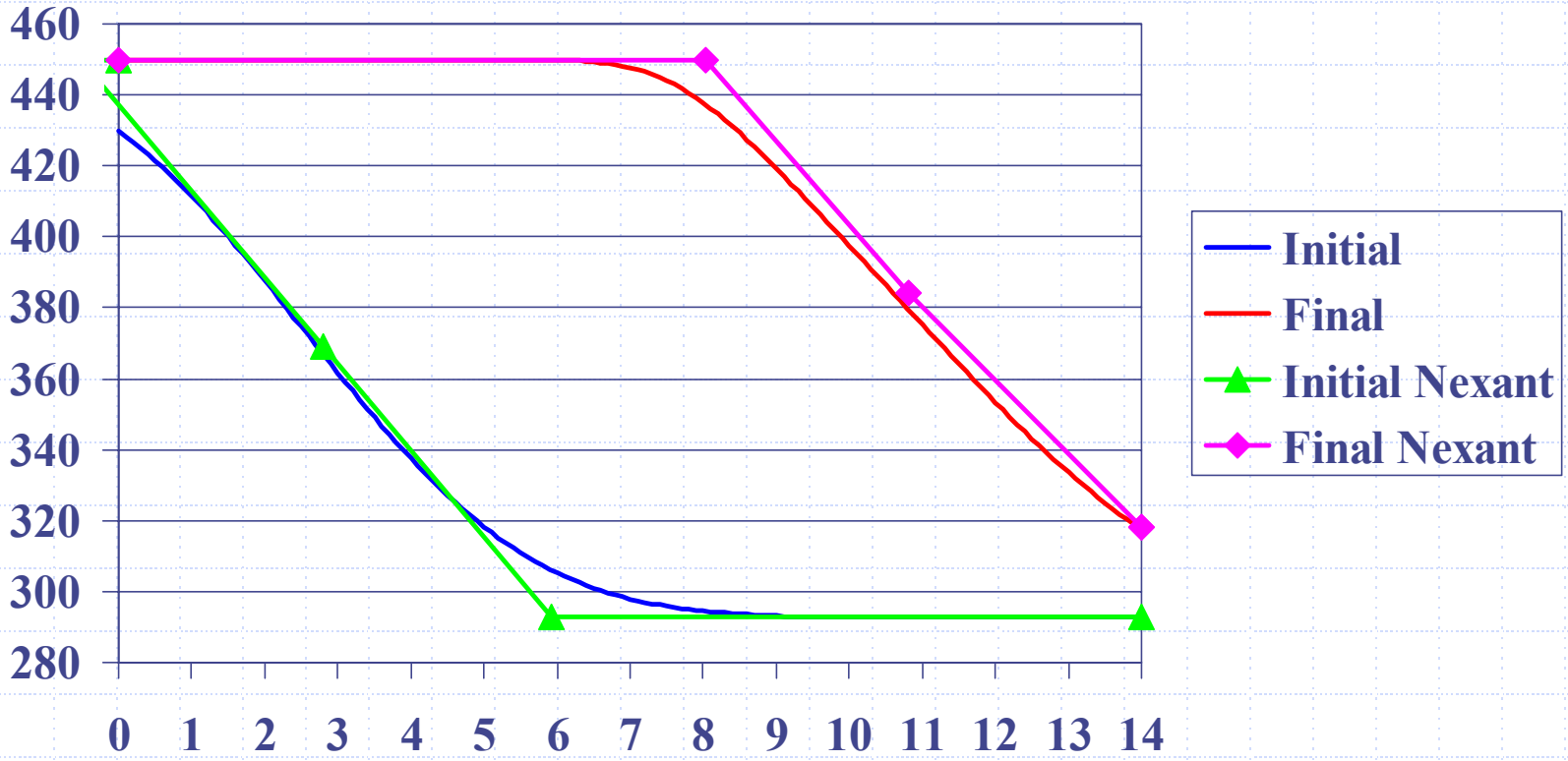
| Cost Model | 2-Tank | Thermocline | Thermocline |
|---|---|---|---|
| TES Hot Temp | 293.0 | 293.0 | 293.0 |
| TES Cold Temp | 450.0 | 450.0 | 450.0 |
| Heat Losses | 194.1 | 145.6 | 145.6 |
| temperature decay | | 20.0 | 50.0 |
| storage utilization | | 0.63 | 0.87 |
| ColdTank Diameter | 22.8 | | |
| Hot Tank Diameter | 23.6 | | |
| Thermocline Tank Diameter | | 27.0 | 27.0 |
| material and labor costs for tank(s) | $2,503,246 | $2,283,168 | $2,283,168 |
| insulation costs for tank(s) | $532,182 | $360,546 | $360,546 |
| foundation costs for tank(s) | $820,605 | $455,082 | $455,082 |
| fluid cost | $10,040,595 | $4,586,209 | $4,586,209 |
| bed cost | $0 | $2,033,801 | $2,033,801 |
| collector to storage fluid heat exchanger | $0 | $0 | $0 |
| storage fluid pumps | $0 | $0 | $0 |
| total storage system cost | **$13,896,628** | **$9,718,806** | **$9,718,806** |
| /kWht unit storage system cost | **$22.04** | **$15.41** | **$10.67** |

# Impact of Tank Slice/Grid Size

## Thermocline profile after 4.5 hour charge cycle



# Nexant Non-Dimensional Thermocline Model

- Speed up thermocline calculation time
- Large lookup table (3600 entries)
- Initial slope and thermocline midpoint
- Specify flow and time increment
- Calculates final thermocline slope and midpoint, discharge temperature rise.

# Example of Nexant Approach