Final Technical Report

Project Title: "*Development and Performance Evaluation of High Temperature Concrete for Thermal Energy Storage for Solar Power Generation*"

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Chapter 1: Project Objectives and Introduction

Project Objectives

1. Develop a novel concrete mixture(s) that can withstand operating temperatures of 585 ºC or more and measure the concrete properties.
2. Develop novel construction techniques to increase the rate of heat transfer between the heat transfer fluid (HTF) and the concrete, as well as reduce the difference in thermal expansion coefficient between the concrete and reinforcement material.
3. Develop a computer model to perform parametric studies during charging and discharging.
4. The outcome of the project is to reduce the cost of thermal energy storage from \$25/ $kWh_{thermal}$ using concrete to 2020 goal of costs below \$15/$kWh_{thermal}$ and achieve round trip efficiency greater than 93%.

Introduction

Three mechanisms have been identified for the storage of excess solar thermal energy harvested by CSP plants: sensible heat storage, latent heat storage, or chemical storage. A survey of thermal storage for concentrating solar power (CSP) plants before 1990 is available in the work of Geyer (1991) and a more recent survey is provided by Herrman and Kearney (2002). They report four research groups investigating the chemical storage mechanism, one group investigating the phase change mechanism, and four groups investigating the sensible heat mechanism. Of the three mechanisms, only the sensible heat storage option has been successfully implemented and is the only option deemed viable at this time.

Traditionally, sensible heat thermal energy storage (TES) systems employ a two-tank liquid configuration. In this configuration, liquid media is heated by excess solar energy and stored in a "hot" tank until it is needed. A separate "cold" tank is used to hold the liquid media after it has transferred its energy to the power block and is waiting to be re-heated. Most work to date has been in the relatively low temperature range of 290 ºC to 400 ºC; therefore synthetic thermal oils are used as liquid media. Problems with these systems are that the significant liquid media inventory and the two required tanks are quite costly. Additionally, the low temperature range decreases the efficiency of the power plant's power cycle and decreases the storage density of the TES system.

To decrease sensible heat TES costs, several approaches have been identified: increase the operating temperature of the TES system, replace thermal oils with molten salt, incorporate solid TES media, and eliminate one or both tanks. Molten salts have been identified as a promising option for decreasing TES costs, as they are less costly then thermal oils and afford the much higher operating temperature limits exceeding 565 ºC (compare with 400 ºC for thermal oils). Further cost reduction can be realized by replacing a significant quantity of the liquid media with solid media. This dual-media concept is further sub-divided into two concepts: passive storage or single-tank thermocline storage.

In passive storage, tube-style heat exchanger banks are embedded in cast ceramic or concrete banks; heated liquid media is pumped through these exchangers to store energy and cooled liquid media is pumped through the exchangers to retrieve energy. Concrete has been suggested as a promising solid media for TES applications, providing an approximate storage cost of $1/kWh$_{thermal}$. Herrmann and Kearney (2002) reported that the cost of this type of storage was about $40/kWh$_{thermal}$ in 1994, considering concrete for the solid media, thermal oil for the liquid media, and steel for the heat exchangers. Laing et al. (2006) conducted testing with this same concept, considering temperatures of up to 325˚C, and reported TES costs of about $32/kWh$_{thermal}$. Additionally, they report testing of a castable ceramic, which replaces concrete as the solid media. Though the ceramic demonstrates no cracking, compared with the minimal cracking exhibited by the concrete, the cost and strength of the concrete render it more viable as solid TES media then the castable ceramic. Tamme et al. (2004) conducted modeling to study the influence of various parameters on the passive TES concept; his work optimized system efficiency by a reported 200%.

In single-tank thermocline (STTC) TES, hot and cold media are contained in the same tank. Solid media is incorporated to decrease the necessary liquid media inventory; the hot and cold regions are separated by the natural buoyant forces of the liquid media (hot liquid is less dense than cold liquid, therefore hot media occupies the upper region of the tank) with an intermediate thermal gradient separating the two regions. Most work reported incorporates a "packed bed" of solid media, consisting of silica sand, quartzite, or other aggregates (Pacheco, 2002). Pacheco (2002) reports a cost comparison between two-tank and STTC TES systems, having capacity of 688 MWh$_{thermal}$; both systems incorporate molten salt as liquid media and operate in the temperature range of 290 ºC to 400 ºC. He reported that the STTC option provided significantly less costly TES than did the two-tank option: $40.44/kWh$_{thermal}$ compared with $61.38/kWh$_{thermal}$. The primary problem associated with STTC TES is thermal ratcheting of the tank's walls; this occurs as repeated thermal cycles result in settlement of the packed bed towards the base of the tank. This can lead to catastrophic rupture on the tank's walls.

The goal of this work is to decrease TES cost and increase TES density by increasing the temperature limit to the range of 500 ºC to 565 ºC and improving heat transfer between the solid and liquid media using novel construction techniques. Concrete is considered for solid media and molten solar salt is considered as liquid media. Typical structural concrete explodes violently at high temperatures, in the range of 200 ºC to 300 ºC (John, 2011). Therefore, it is necessary to develop and test high performance concrete for this elevated range. The works of John (2011, 2012) report the properties and costs of Ultra High Performance (UHP) concrete mix designs developed for application in high temperature TES applications. John (2012) reports mix designs providing storage capacity costs in the range of $0.91-$3.02/kWh$_{thermal}$.

The passive storage concept is considered initially. The works of Castro (2010) provide a study of various fin configurations for the heat exchanger; these works establish the optimum fin configurations to provide a balance between TES system efficiency and heat exchanger cost. The works of Skinner (2011) discuss testing of a single concrete cell cast around the exchangers suggested by Castro (2010). Additionally, Skinner reports modeling and testing of several soft interface materials tested to reduce stress and cracking at the concrete/heat exchanger interface.

As stated previously, molten salt is used as liquid media in this work; due to the salt's corrosive properties, the heat exchangers used by Skinner had to be made from stainless steel. Due to this fact, it was realized that the cost of this TES concept would be much higher than the target goal of \$15/kWh$_{thermal}$. For this reason, the STTC option is considered.

As stated previously, a STTC TES system is considerably less costly than the two-tank option. However, the issue of thermal ratcheting associated with this system type renders it somewhat less appealing. Concrete has been suggested as a low-cost solid media option for passive storage systems; incorporating it as structured filler material in a STTC TES system would not only reduce the volume of expensive liquid media but would eliminate the issue of filler settlement and eventual thermal ratcheting of the tank's walls. In the works of Brown (2012), two configurations are considered for the structured filler material: an axisymmetric model and a parallel-plate model. Brown uses 2-D finite-difference-based numeric modeling to optimize various system parameters and reports that the parallel-plate configuration provides superior efficiency (65.59% vs. 62.68%). This efficiency is much lower than the target goal of 93%, therefore, further modeling is conducted in the work of Strasser (2012). Strasser reports an improved parallel-plate model providing an efficiency of 83.97%. Additionally, he reports a cost analysis, finding that the structured concrete thermocline (SCTC) configuration provides the TES capacity cost of \$33.80\$/kWh$_{thermal}$ compared with \$30.04/kWh$_{thermal}$ for a packed-bed thermocline (PBTC) configuration and \$46.11/kWh$_{thermal}$ for a two-tank liquid configuration.

Chapter 2: Development of Ultra High Performance Concrete

Typical structural concrete explodes violently in the temperature range of 200˚C-300˚C; therefore, it is necessary to develop ultra high performance (UHP) concrete to allow TES in the targeted range of 500˚C-565˚C. For the passive storage concept, which is the first concept considered, heat exchangers are embedded in a block of concrete and molten salt is pumped through them to transfer and retrieve energy from storage. In this concept, the molten salt is never in direct contact with the concrete, therefore, chemical compatibility of the concrete and salt is not a design concern. However, for the second concept investigated, the SCTC, the salt and concrete are in direct contact, therefore, chemical compatibility is a design consideration. Chapter 2 is divided into two sections, first discussing the design and testing of concrete for the passive application and then discussing the design and testing of concrete for the SCTC application.

UHP Concrete for Passive Concept

During Phase 1, the primary concern in developing concrete mixture designs is that they be compatible with high temperatures; they do not have to be chemically compatible with molten salt. Mix designs 1-3, presented in Table 1, were the first group tested; during preliminary testing, in which cylinder specimens were gradually heated to 500˚C, the specimens spalled and exploded, damaging the oven used for testing (Figure 1, Left). Steel cages were constructed for the cylinder specimens for subsequent testing (Figure 1, Right). It was postulated that the reason for the concrete's explosion was a pressure build-up due to superheated water vapor being trapped within the specimens. Polypropylene fibers were added to mixtures 4-6 to address this issue: when heated the fibers disintegrate, leaving channels for the superheated vapor to escape. Following the addition of polypropylene fibers, mixtures 4-6 retained structural integrity when heated to the temperature of 600˚C at a rate of 9˚C/minute.

Table 1: UHP Concrete Mix Designs for Passive Concept (Phase 1)

	Mixture Designations					
Materials (lb/yd^3)	1	2	3	4	5	6
Cement	900	2000	1004	1004	1500	1125
Silica fume	0	0	112	0	500	375
Coarse Aggregate	1700	0	1420	1420	0	0
Fine Aggregate	1211	1500	1350	1350	1435	1780
Water	270	220	228	228	406	450
w/cm	0.3	0.15	0.22	0.22	0.2	0.3
Steel fibers	0	264	0	0	0	0
Polypropylene fibers	0	0	0	3.375	3.375	3.375

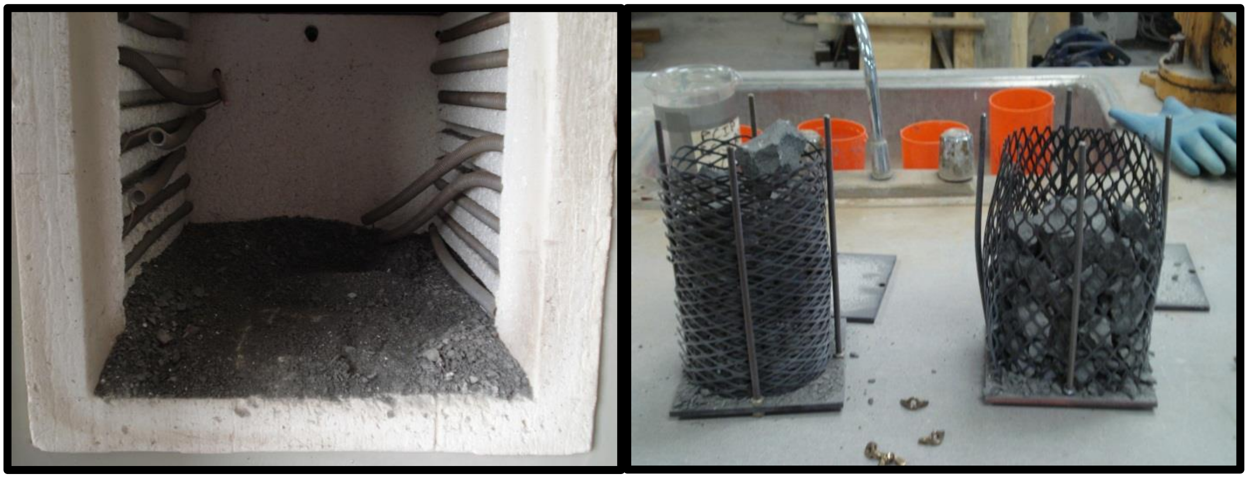

Figure 1: Testing Oven Damaged by Exploding Cylinder (Left) and Exploded Cylinders in Steel Cages (Right)

During Phase 2, concrete mixture designs developed during Phase 1 are modified to improve performance and reduce cost. Table 2 presents the seven concrete mixture designs considered for testing during Phase 2. During this phase, specimens are cast from each of the concrete mixture designs and subjected to ten thermal cycles so that their structural integrity can be assessed. The cycling procedure used is as follows: heat from ambient temperature of 23˚C to 300˚C at the rate of 9˚C/minute, hold at 300˚C for 2 hours, heat to 500˚C at a rate of 9˚C/minute, hold for 2 hours, and finally allow specimens to cool to ambient temperature of 23˚C. Following each cycle, a specimen from each mixture design is crushed so that the mix's integrity can be assessed. Figure 2 provides a plot of each mixture's compressive strength over ten thermal cycles. Mixtures 1 and 2 exhibit the greatest strength retention; it can be seen that after three thermal cycles, all seven mix designs converge to their residual capacity.

Table 2: UHP Concrete Mix Designs for Passive Concept (Phase 2)

Materials	**Mixture Designations**						
(lb/yd^3)	1	2	3	4	5	6	7
Cement	704	704	528	528	457	457	457
Fly Ash	-	-	71	71	71	71	71
Silica fume	-	-	-	-	71	71	71
Sand	559	559	495	495	470	470	464
Water (liters)	108	108	108	108	108	108	108
HRWR (liters)	3.7	2.7	2.7	3.7	5.5	5.5	5.9
Steel fiber	36	36	36	36	36	36	53
PP fiber	1.2	1.2	1.2	1.2	1.2	1.2	1.2

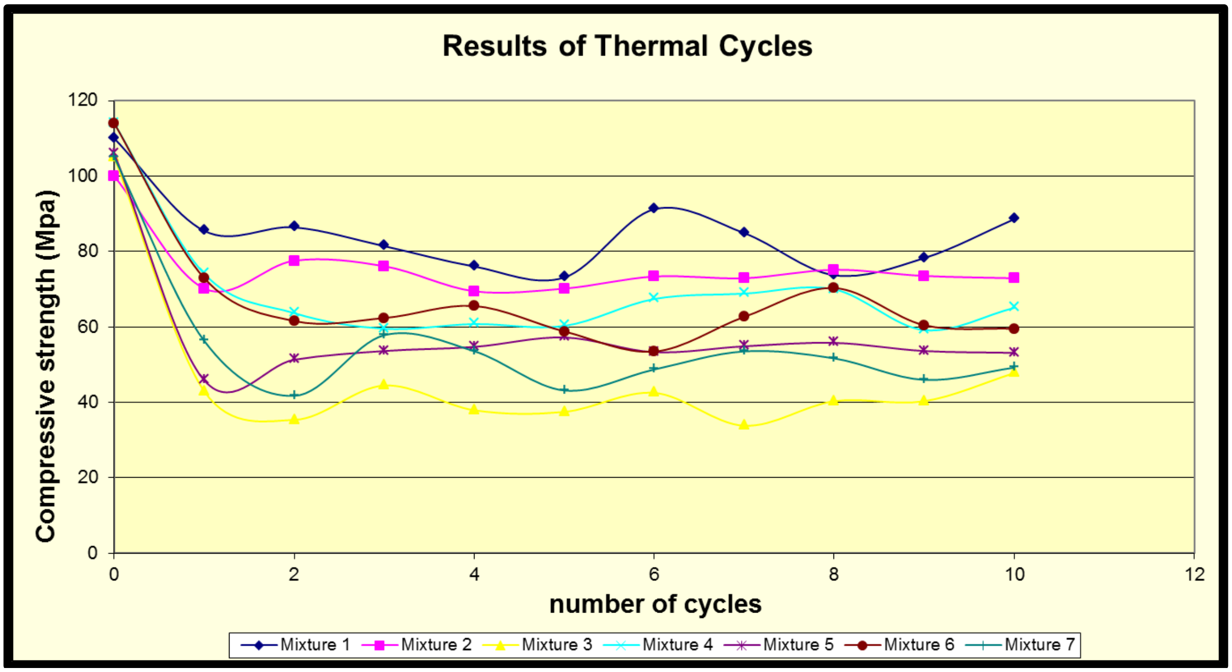

Figure 2: Compressive Strength of Concrete Mixture Designs Over 10 Thermal Cycles

During testing of the passive TES concept, it was concluded that the passive concept would not allow TES at the target capacity cost of $15/kWh$_{thermal}$. Therefore, design considerations for the UHP concrete shifted to include chemical compatibility of the concrete mixture designs with the molten salt, as well as the concrete mix designs' retention of structural integrity in the high-temperature environment.

UHP Concrete for Structured Concrete Thermocline Concept

During Phase 3, twenty-six concrete mix designs were proposed and tested for application in a structured concrete thermocline (SCTC) TES system; a detailed description of the development process for these mix designs is provided in the work of John (2012). The goal of the testing during Phase 3 is to develop and suggest four concrete mixture designs for testing in a laboratory scale thermocline test system so that response of the concrete mixtures to thermal gradients due to non-uniform heating and circulating molten salt can be assessed. Cube specimens were subjected to the testing regimen bulleted below to assess their compatibility with molten salt.

- Isothermal Bath in Molten Salt
    - 500 Hours at 585˚C
- Thermal Cycling in the presence of Molten Salt
    - 30 Thermal Cycles between 300˚C and 585˚C
        - Increase oven temperature from 300˚C to 585˚C over 4 hours
        - Hold oven temperature at 585˚C for 2 hours
        - Reduce oven temperature from 585˚C to 300˚C over 4 hours
        - Hold oven temperature at 300˚C for 2 hours

It was found that specimens subjected to the isothermal salt bath gained 10% to 50% in compressive strength and mass, while specimens subjected to thermal cycling in molten salt lost 10% to 60% of their compressive strength. Figure 3 depicts cube specimens immediately after being placed in the molten salt bath (Figure 3, Left) and cube specimens during testing (Figure 3, Right). Note the specimen that disintegrated during thermal cycling in the middle of the right-most column (Figure 3, Right).

Figure 3: Concrete Cube Specimens during Thermal Cycling Tests

Based upon the testing of the twenty-six concrete mix designs, four mix designs are suggested for testing in a lab-scale thermocline. Three of the mixtures are developed in-house and the four, mix #26 is a proprietary mixture selected for its superior thermal properties. The components for these mix designs are presented in Table 3; note that each mixture is numbered out of the twenty-six designs developed and tested in John's (2012) work. Table 4 summarizes material properties of these four mix designs and presents cost and TES capacity cost for each mix.

Table 3: UHP Concrete Mix Designs for SCTC Concept

Material (lb/yd^3)	Mixture			
	2	11	15	26
Cement	398	360	675	-
Fly Ash	927	540	675	-
Fine Aggregate	1855	1285	1978	-
Course Aggregate	-	1285	-	-
Water	398	325	378	236
Polypropylene Fiber	3.4	3.4	3.4	3.4
HRWR	-	-	-	51
Premix	-	-	-	3738

Table 4: Properties and Cost of UHP Concrete Mix Designs for SCTC Concept

Item of Interest		Mixture			
		2	11	15	26
Average Specific Heat	Btu/lb.˚F	0.227	0.213	0.192	0.216
	J/kg.K	950	890	804	904
Average Thermal Conductivity	Btu/ft.h.˚F	0.95	1.09	NA	1.63
	W/m.K	1.65	1.89	NA	2.52
Average Density	lb/yd^3	1235.21	1306.99	1249.44	1378.19
	kg/m^3	2082	2203	2106	2323
Cost	\$/yd^3	\$183.50	\$191.14	\$94.80	\$389.92
	\$/m^3	\$240.00	\$250.00	\$124.00	\$510.00
Capacity Cost	\$/kWh$_{thermal}$	\$1.46	\$1.49	\$0.91	\$3.02

Chapter 3: Modeling and Testing of Passive TES Concept

Recall that the storage media considered in this work is UHP concrete; a summary of the development and testing of the concrete can be found in the first section of Chapter 2. Stainless steel heat exchangers are embedded in the concrete, and molten solar salt is circulated through the exchangers to transfer energy to and from storage. For this portion of the work, it is desired to store energy up to the temperature limit of 500˚C. In the first portion of Chapter 3, a 3-D finite-element heat transfer model is used to determine the optimum heat exchanger configuration, considering cost and heat transfer enhancement. In the second portion of Chapter 3, experimental testing of the passive concept is reported. A 2-D stress model is used to study stress at the concrete-heat exchanger interface and three interface materials are investigated as potential stress-relieving materials.

Selection of Fin Configuration for Heat Exchanger Used in Passive Storage Concept

A problem associated with passive TES systems is that they tend to exhibit poor heat transfer, compared with dual media TES systems such as the packed-bed thermocline TES concept. In the works of Castro (2010), modeling is used to investigate heat transfer within a passive system considering the following heat exchanger configurations.

- Plain tube heat exchanger
- Heat exchanger with protruding rods (1-16 rods along axial length)
- Heat exchanger with protruding disks (2-8 disks along axial length)
- Heat exchanger with protruding plates (1-2 plates along axial length)
- Heat exchanger with helicoidal auger (along entire embedded length)

Various fin thicknesses and spacing are considered for each fin configuration. Figure 4 provides temperature profiles of concrete specimens following a charge cycle; the leftmost cross section represents a specimen with an embedded plain tube heat exchanger, and the enhancement in heat transfer attained by adding fins to the heat exchanger may be seen in the middle and rightmost cross sections. Table 5 provides a sampling of Castro's testing results, in which various fin configurations are compared with the plain tube heat exchanger base case.

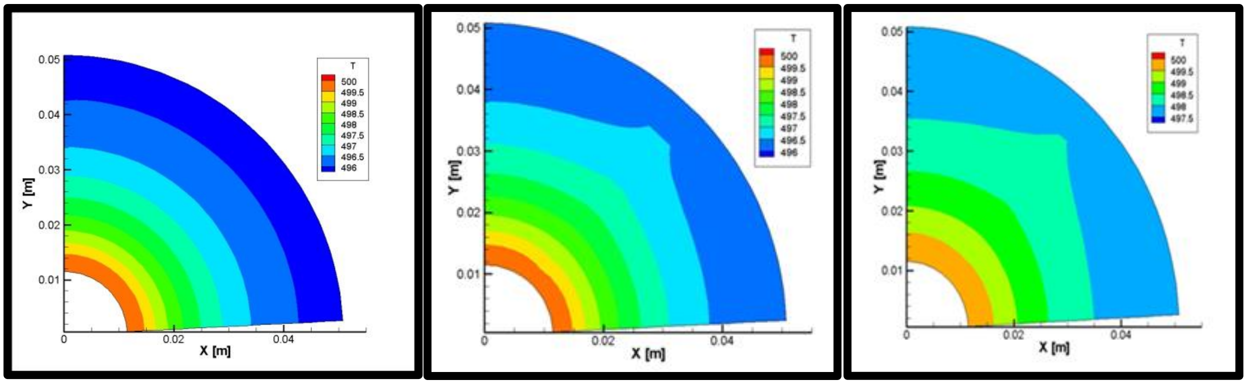

Figure 4: Temperature Profile in Concrete Element with Plain Tube Heat Exchanger (Left) with Rod Protruding from Heat Exchanger (Middle) and with Plate Protruding from Heat Exchanger (Right)

Table 5: Modeling Results of Impact of Various Fin Configurations on Performance of Passive TES

Fins		Percent increase		
Number	Type	Energy Stored	Material	Cost
1	Rod	0.40%	16.39%	5.85%
2	Rod	0.66%	32.79%	11.69%
4	Rod	1.28%	65.57%	23.39%
6	Rod	1.77%	98.36%	35.08%
8	Rod	2.24%	131.15%	46.77%
1	Disk	1.36%	57.27%	42.68%
2	Disk	2.70%	114.54%	85.35%
3	Disk	3.97%	171.80%	128.03%
4	Disk	4.70%	229.07%	170.71%
1	Plate	5.11%	368.41%	188.83%
2	Plate	8.83%	736.83%	377.65%
5	Spiral	9.13%	286.36%	382.80%
6	Spiral	10.81%	343.60%	459.40%
7	Spiral	12.19%	400.91%	535.90%
9	Spiral	14.28%	515.43%	689.10%

From Table 5, it can be seen that the most effective fin configuration, the “spiral” configuration, is also the most costly to manufacture. Skinner (2011) reports that an auger-style helicoidal fin is available on the market; this leads to a significant cost reduction, as a specialty fin does not need to be fabricated and ordered. The finned heat exchanger used in Skinner’s work consists of an auger-style heat exchanger welded continuously along the length of a plane tube heat exchanger (both made of stainless steel).

Preliminary Testing of Passive Storage Concept

In Skinner's work, UHP concrete elements having a cross section of four inches by four inches and length of forty-eight inches are cast around 316 stainless steel heat exchangers having inner diameters of three-quarters of an inch. Molten salt is then pumped through the heat exchanger, with the goal of heating the entire concrete specimen to the temperature range of 400˚C-500˚C. Details of the testing equipment are provided in the work of Castro (2010) and Skinner (2011). Figure 5 depicts the testing equipment during a typical test. During testing of the passive storage concept, significant cracking is observed in the concrete specimens. This is obviously a concern in terms of the structural integrity of the energy storage elements. Additionally, cracking in the concrete leads to decreased heat transfer within the storage element. Figure 6 depicts cracking in a concrete specimen following a round of testing.

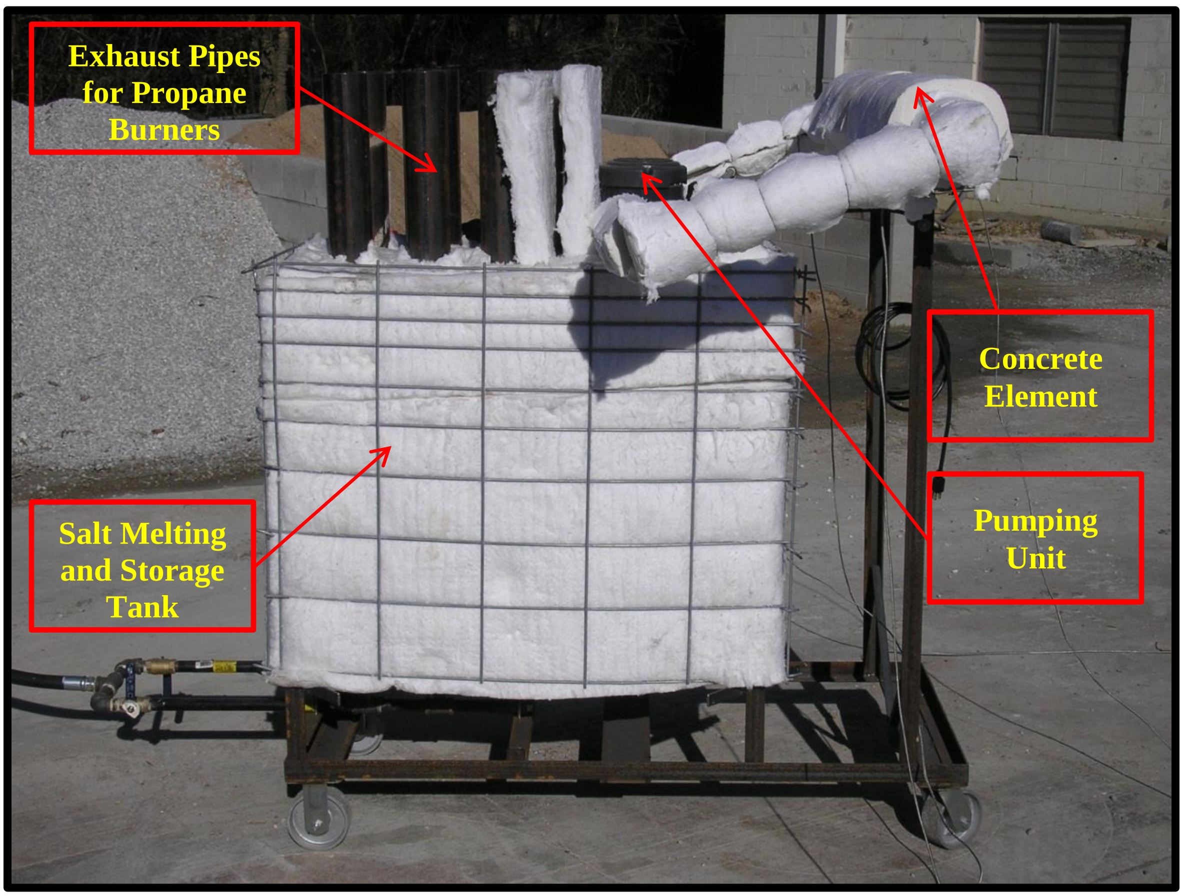

Figure 5: Testing Equipment Used to Test Passive Storage Concept

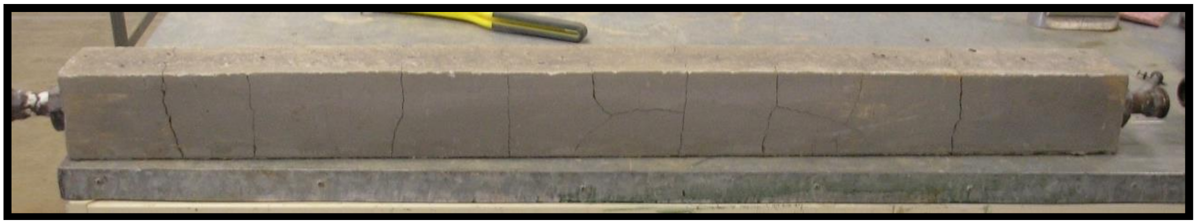

Figure 6: Cracking of Concrete during Testing of Passive Storage Concept

Selection of Interface Materials to Reduce Cracking in Concrete

Skinner (2011) postulates that the cracking is due to dissimilar thermal expansion rates in the stainless steel heat exchanger and the concrete element: stainless steel has a higher coefficient of thermal expansion than concrete does. As the materials expand at different rates when heated, stress builds at the interface between the concrete and heat exchanger until it is great enough to induce cracking in the concrete. He suggests that adding a thin layer of soft interface material between the concrete and heat exchanger will mitigate this stress, thereby significantly reducing cracking within the concrete. Skinner employs a 2-D plain strain finite element model to study this postulation; Table 6 presents a study in which 316 stainless steel, 316 stainless steel with a soft interface material, and carbon steel heat exchangers are considered. The concrete and heat exchangers are considered to be at the specified temperatures, and the resulting tensile stresses due to dissimilar thermal expansion are reported. It can clearly be seen that incorporating an interface material significantly reduces the stress at the concrete/heat exchanger interface.

Table 6: Interface Stress for Various Heat Exchanger Scenarios

CASE		TEMPERATURE (°C)		TENSILE STRESSES (ksi)	
Heat Exchanger	Interface Mat. MOE (ksi)	Heat Exchanger	Prism	Max Principle	Longitudinal
Case (1) 316 Stainless Steel Pipe no Interface		300	300	10.78	1.45
		400	400	14.18	1.91
		500	500	17.57	2.36
		300	0	23.68	3.19
Case (2) 316 Stainless Steel Pipe with Interface	2.0	300	300	0.76	0.098
	2.0	400	400	1.00	0.13
	2.0	500	500	2.07	0.27
Case (3) Carbon Steel Pipe no Interface		300	300	2.34	0.316
		400	400	3.08	0.415
		500	500	3.82	0.514

Testing of Passive Storage Concept with Interface Material to Reduce Concrete Cracking

Based upon the results of the 2-D plain strain modeling, Skinner suggests that Teflon tape, Deacon paste, and aluminum foil are potential candidate interface materials. All three interface materials are tested for the plain tube heat exchanger case and aluminum foil and Deacon paste are tested for the auger-fin case. Figure 7 depicts the plain tube heat exchanger with Teflon tape as interface material and the auger-fin exchanger with Deacon paste as the interface material. Skinner finds that aluminum foil is not a good option, as it leads to the formation of voids, which cause thermal resistance, at the exchanger/concrete interface. Skinner concludes that Teflon tape provides the best balance of functioning as a stress relieving material while allowing the transfer of heat between the exchanger and concrete media. An in-depth description of this investigation is available in the work of Skinner (2011). Testing results incorporating Teflon tape as interface material verify the model's predicted results, as minimal to no cracking of the concrete is present.

Figure 7: Plain Tube Heat Exchanger with Teflon Tape Interface (Left) and Auger-Fin Heat Exchanger with Deacon Paste Interface (Right)

At this point, Skinner concludes that this storage concept is not cost-competitive with the target of $\$15/kWh_{thermal}$ due to the costly stainless steel heat exchangers. An alternative concept is suggested, which allows the usage of the cost-reducing concrete and molten salt combination at high temperatures without the requirement of using costly stainless steel heat exchangers. This new concept, the structured concrete thermocline TES system, is discussed in the upcoming Chapter 4.

Chapter 4: Modeling of Structured Concrete Thermocline Storage Concept

At the end of Phase 2, it was concluded that the passive storage concept is not cost competitive with the TES capacity cost target of $15/kWh$_{thermal}$ due to the high cost of the required stainless steel heat exchangers. However, due to the high temperatures at which molten solar salt and UHP concrete can store energy, it is believed that they are still a promising combination for TES. An alternative concept is proposed at this point: that they concrete be contained in a tank and the molten salt be circulated around it to transfer energy to and from the concrete. This storage concept, known as a thermocline TES system, is known to be a cost-reducing alternative to traditional two-tank fluid systems.

Minimal testing of thermocline TES systems is reported in literature. As stated in Chapter 1, thermocline systems provide a cost-reducing alternative to two-tank TES systems by eliminating one of the required storage tanks and replacing a significant volume of costly liquid media with less costly solid media. Thermocline TES systems reported in literature employ a “packed bed” of solid media, consisting of sand and course aggregate; this solid media type is attributed to the primary operating concern associated with thermocline TES systems: thermal ratcheting of the tank’s walls. As the tank is charged (energy stored), its temperature increases and the stainless steel walls expand; some aggregate composing the packed bed settles and occupies this new space. As the tank is discharged (energy retrieved), its temperature decreases and the stainless steel walls contract; however, there is now an access volume of aggregate in the wall’s initial place. This induces stress into the tank’s walls; repeated charge/discharge cycles can result in catastrophic rupture of the tank.

If a structured solid media is used in place of the loose packed bed of aggregate, the issue of thermal ratcheting can be avoided completely. Therefore, it is determined that structured UHP concrete can be used to replace the packed aggregate bed. Brown (2012) suggests that the geometry of UHP concrete should be investigated and optimized to provide optimum heat transfer to and from the TES system. He proposes two unique configurations: an axisymmetric configuration (Figure 8, Left) consisting of beams with square cross sections and a longitudinal circular channel spanning the beams' length, and a parallel-plate configuration (Figure 8, Right) consisting of rectangular plates standing on end parallel to each other. Figure 8 provides a cross sectional schematic of a tank populated with concrete from each suggested configuration.

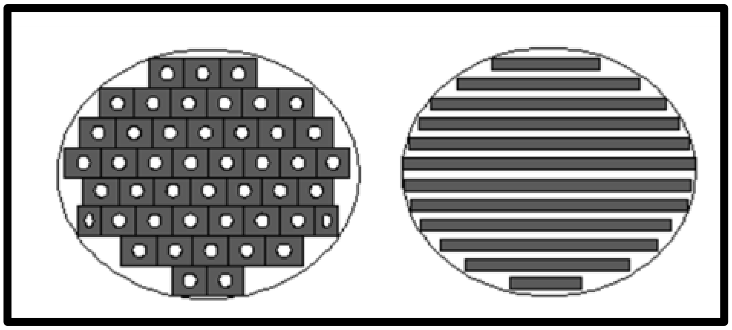

Figure 8: Cross Sectional-View of Tank Populated with Axisymmetric (Left) and Parallel-Plate (Right) Configurations

Brown employed 2-D finite difference-based numeric modeling to investigate the impact of various system parameters on the performance of a thermocline TES system employing each configuration. Thirty-two unique cases of the axisymmetric configuration and twenty unique cases of the parallel plate configuration are investigated and reported in the work of Brown (2012). He reports maximum charge/discharge efficiencies of 62.68% and 65.59% respectively for a structured concrete thermocline populated with the axisymmetric and parallel plate concrete configurations. Based upon the modeling results, Brown concludes that the parallel plate configuration provides the optimum TES efficiency of 65.59%. Parameters for Brown's optimized model are provided in Table 7 and an illustrative schematic is provided in Figure 9.

Table 7: Parameters for Brown's Optimized Parallel-Plate Configuration (2012)

Parameter	Cycle	
	Charge	Discharge
T_i (m)	0.01905	
T_o (m)	0.05715	
L (m)	14.0	
Void Fraction	0.33	
V_{fluid} (m/s)	+ 0.0015	- 0.0012
Duration (hr.)	5	5
Efficiency	65.59%	

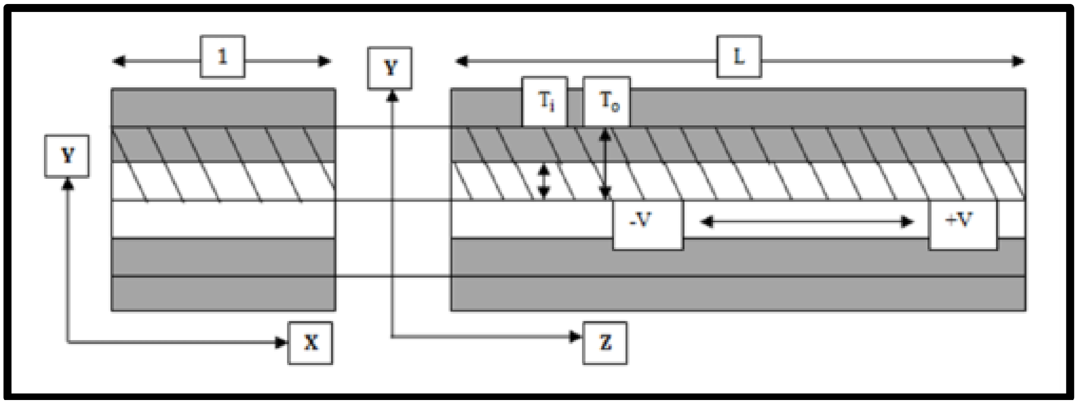

Figure 9: Illustration of Parameters for Brown's Optimized Model (2012)

Unfortunately, the optimum TES system efficiency found in the work of Brown (2012), 65.59% is substantially less than the target efficiency of 93%. Using the same 2-D models discussed in the work of Brown, Strasser (2012) conducts further optimization of the parallel plate concrete configuration. Maintaining the same volumetric content of concrete and molten salt, he suggests decreasing the thickness of the plates, and consequently increasing the number of plates. In his work, a new parallel plate model is suggested, providing the improved efficiency of 83.97% (Strasser, 2012). Though this efficiency is still nearly 9% less than the target efficiency, the difference is significantly reduced, compared with 29.5% efficiency difference between Brown's optimized model and the target efficiency. Strasser postulates that further improvements are possible, and expresses that the target efficiency of 93% is an attainable goal for a structured concrete thermocline. Parameters for Strasser's parallel plate model are provided in Table 8; these values are illustrated in Figure 9.

Table 8: Parameters for Strasser's Optimized Parallel Plate Configuration (2012)

Parameter	Cycle	
	Charge	Discharge
T_i (m)	0.005581	
T_o (m)	0.016743	
L (m)	16.0	
Void Fraction	0.33	
V_{fluid} (m/s)	+ 0.002	- 0.002
Duration (hr.)	5	5
Efficiency	83.97%	

Chapter 5: Comparative Lifecycle Cost and Performance Analysis of a Structured Concrete Thermocline TES System

The goal of this research is to develop and test cost-effective, high temperature TES for a CSP plant using concrete as solid media and molten salt as liquid media. Having modeled a structured concrete thermocline having an efficiency of 84%, the next item of interest is to compare the structured concrete thermocline TES system with other sensible heat TES systems in terms of cost and performance. System Advisory Model (SAM), a product of National Renewable Energy Labs (NREL) is identified as useful software for this comparison, as it can be used to perform lifecycle cost and performance analysis of a CSP plant with various TES configurations. SAM has the built in case of an optimized 100 MWh_e central receiver type CSP plant; this built in case is exactly what is needed for the desired comparative study, as central receiver plants are capable of operation at temperatures exceeding 565˚C. The central receiver plant is considered as the control in this comparative analysis; four TES scenarios are considered: no TES, two-tank fluid TES, packed-bed thermocline TES, and structured concrete thermocline TES.

When running SAM's built in case, for each of the aforementioned TES scenarios, it is necessary to input the desired number of hours of operation off TES and the TES configuration. Additionally, the capacity cost of the TES system, in $\$/kWh_{thermal}$, is a required input; therefore, it is necessary to develop a procedure for calculating the capacity cost of each configuration. A detailed account of this cost estimation is reported in the work of Strasser (2012). The capacity costs for each TES configuration considered in this work, based on an eight-hour TES capacity, are presented in Table 9.

Table 9: Capacity Cost Estimation for TES Configurations Considered (Strasser, 2012)

Item of Interest	TES Configuration		
	Two-Tank	Packed-Bed Thermocline	Structured Thermocline
Storage ($MWh_{thermal}$)	2164	2164	2164
Total Cost ($)	$99,820,808.00	$65,020,565.00	$73,172,428.00
Capacity Cost ($/$kWh_{thermal}$)	$46.11	$30.04	$33.80

It can be seen that all TES capacity costs are considerably greater than the target of $15/$kWh_{thermal}$. However, using molten salt as liquid media and increasing the upper temperature limit of the TES system reduces storage costs compared with those reported in literature for similar configurations ($40/$kWh_{thermal}$ and $66/$kWh_{thermal}$ for packed bed thermocline and two-tank fluid respectively (Pacheco, 2002)). Additionally, it can be concluded that a structured concrete thermocline is competitive with a packed bed thermocline, in terms of capacity cost, as it provides similar capacity cost and no concerns of thermal ratcheting.

Using the capacity cost input values reported in Table 9, SAM was used to simulate the performance of the optimized 100 MWh central receiver plant considering no TES and each of the three configurations listed above over a twenty year lifecycle. The capacity factor and levelized cost of electricity (LCOE) produced by the plant for each scenario are the metrics considered in evaluating the plant's performance. This comparison is presented and discussed in the work of Strasser (2012). Table 10 summarizes the cost and capacity cost of the CSP plant for each of the four TES scenarios considered.

Table 10: Summary of CSP Plant Cost and Performance for Four TES Configurations (Strasser, 2012)

Item of Interest	TES Configuration			
	No TES	Two-Tank	Packed-Bed Thermocline	Structured Thermocline
Installed Plant Cost ($)	$557,007,170	$679,829,020	$637,103,744	$647,039,236
Plant Capacity Cost ($/kWhe)	$5,571.00	$6,799.00	$6,372.00	$6,468.00
Plant Capacity Factor (%)	32.40%	50.00%	49.70%	48.90%
LCOE (¢/kWhe)	20.53	15.96	15.18	15.64

Based upon the lifecycle performance analysis, it can be seen that incorporating any of the three TES configurations considered in this study increases the capacity factor of the plant by more than 15% and reduces the LCOE of the electricity that it produces by nearly 25%. Both thermocline options provide lower LCOE than the two-tank TES configuration; though the packed bed thermocline yields superior performance and LCOE than the structured thermocline, it bears concerns of thermal ratcheting. Therefore, it is concluded that a structured concrete thermocline is a viable and cost-effective TES option.

Unfortunately, none of the LCOE values presented in Table 10 are near to the DOE's 2020 target of 6¢/kWhe. Table 11 summarizes the average LCOE and capacity factors for the most common methods of electrical production. It should be noted that not even the oldest and most refined technologies are able to provide electricity at the DOE's target LCOE. Comparing LCOE and capacity factor values, as provided in Table 10, with those in Table 11 for solar thermal energy, it can be seen that the addition of TES significantly improves the performance of a solar thermal plant, making it cost-competitive with the much older PV technology.

Table 11: LCOE and Capacity Factors for Various Production Methods (EIA 2012)

Source of Power for Production of Electricity	Cost Prediction (2010 $) for 2017	
	Average LCOE (¢/kWht)	**Capacity Factor (%)**
Coal		
Conventional	9.96 ¢	85.00%
Advanced	20.39 ¢	85.00%
Natural Gas	6.18 ¢	87.00%
Wind		
Inshore	9.68 ¢	34.00%
Offshore	33.06 ¢	27.00%
Solar		
Photovoltaic	15.69 ¢	25.00%
Thermal	25.1 ¢	20.00%
Nuclear	11.27 ¢	90.00%
Geothermal	9.96 ¢	92.00%
Biomass	12.02 ¢	83.00%
Hydro	8.99 ¢	53.00%

Chapter 6: Testing of UHP Concrete Mix Designs in a Lab-Scale Thermocline Test Sytem

Having completed a comparative cost and performance analysis of a structured concrete thermocline, the final part of this work is to conduct further testing of the four concrete mix designs suggested in Chapter 2 in a thermocline TES system. John (2012) reports testing cube specimens cast from each of the four mix designs in the presence of molten salt; in this testing, the specimens were heated to a constant temperature or thermally cycled in a molten salt bath. This testing was conducted in an oven, therefore, the cubes were heated uniformly; this means that no significant thermal gradients, therefore no significant thermal stresses, were established in the specimens. In an actual thermocline TES system, such as considered in this work, significant thermal gradients (equivalent in magnitude to the difference in the high and low operating temperatures of the system) will exist within the concrete specimens. Though the four mix designs performed well during the oven testing, it is necessary to test them in the presence of circulating molten salt and significant thermal gradients before the possibility of their application in a structured concrete thermocline may be assessed.

Thermocline Test System

A thermocline test chamber, having a square cross section of sixteen by sixteen inches and a height of 40 inches was designed and constructed from stainless steel to house the concrete specimens being tested. The salt storage tank and pumping unit used in the testing of the passive concept (Chapter 3) were modified to circulate molten salt through the thermocline test chamber. Figure 10 provides a schematic of the test system, and Figure 11 depicts the test system.

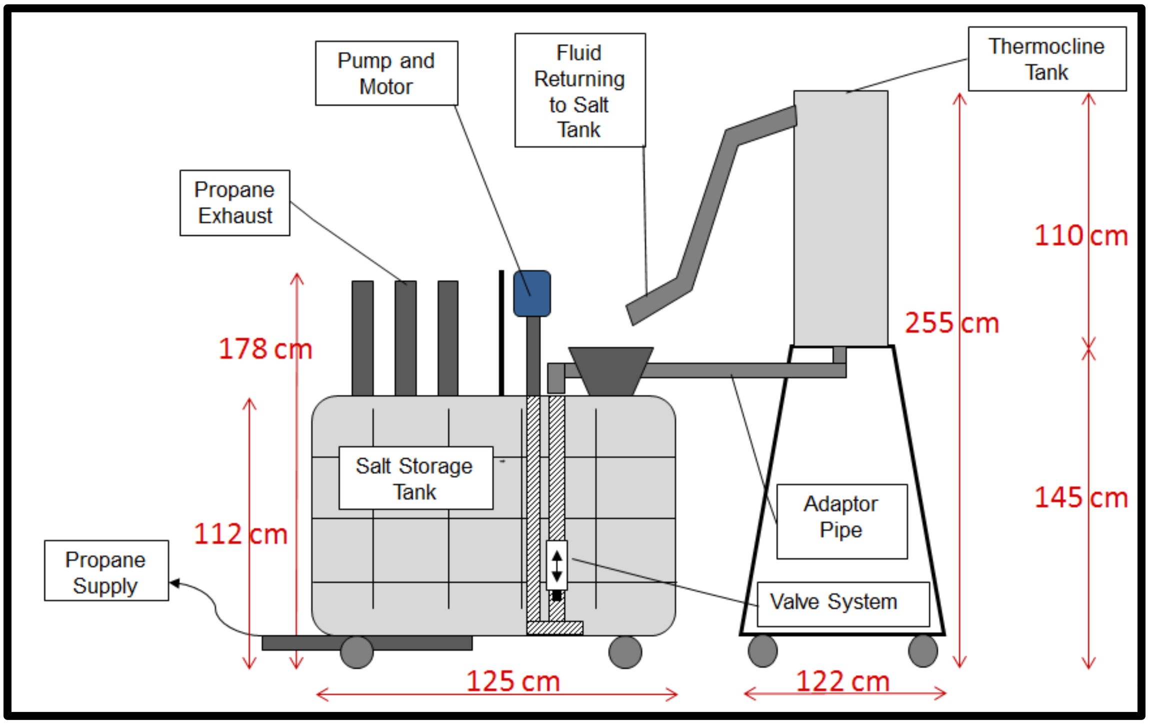

Figure 10: Schematic of Thermocline Test System (Strasser, 2012)

Figure 11: Assembled Thermocline Test System (Strasser, 2012)

Testing of Concrete Specimens in Thermocline Test System

In Chapter 4, it is reported that they parallel plate concrete configuration provides the optimum TES system efficiency. However, to construct and install numerous, uniform concrete plates for the purpose of evaluating the purpose of evaluating the concrete's performance would not be time or cost-effective. Therefore, nine concrete beams, having square four inch by four inch cross sections, lengths of thirty-six inches, and a circular three-quarter-inch channel spanning their length were cast from each of the four concrete mix designs for testing. Figure 12 depicts a view of concrete beams installed in the thermocline test chamber before (Figure 12, Left) and after (Figure 12, Right) preliminary testing of the system.

Figure 12: Concrete Beams in Thermocline Tank before (Left) and After (Right) Preliminary Testing

During preliminary testing, it was quickly concluded that it would not be possible to establish a thermocline within the test chamber. This was due to the small height of the thermocline test chamber and the difficulty in regulating the rate of molten salt flow through the tank. Regardless of the fact that a thermocline would not be established within the system, it was determined that the system could still perform the desired function of testing the concrete's performance in the presence of thermal gradients and circulating molten salt. The testing procedure is outlined in the work of Strasser (2012) and appears in bulleted form below. The concrete beam specimens are to be evaluated based upon their chemical and structural compatibility with molten salt.

- Attach hose between propane tank and burners on salt storage tank (10 min).
- Position fan to circulate air over pump to prevent overheating (5 min).
- Install 'type K' thermocouple in salt storage tank to monitor salt temperature (10 min).
- Fire burners and allow entire tank to heat to 550°C (5-6 hr).
- Connect salt storage tank and thermocline tank using the adaptor pipe. Apply anti-seize to threads to prevent seizing of joints (20 min).
- Turn on pump, circulating molten salt through system (3 hr).
- Turn off pump and allow salt to drain back to salt storage tank before removing adaptor pipe (5 min).

A detailed account of the testing conducted on the beam specimens cast from the four UHP concrete mix designs is provided in the work of Strasser (2012). Testing was plagued with numerous problems due to the high temperature of the molten salt and the salts high melting temperature of 220˚C. During preliminary testing (tank depicted in Figure 12), the top of the thermocline test tank was left open so that the salt's flow rate could be gauged. After establishing salt circulation through the system, the pump was shut off and the thermocline chamber was allowed to gravity-drain. The specimens were exposed to an extreme change in environmental temperature (from molten salt at approximately 500˚C to open air at approximately 10˚C). This caused significant spalling damage to the beam specimens which are depicted in Figure 13.

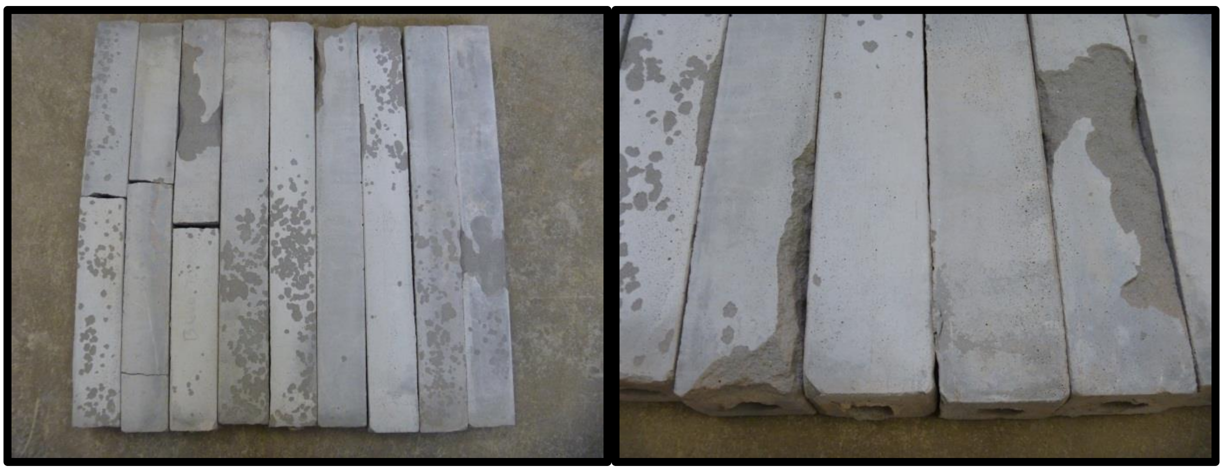

Figure 13: Spalling Damage to Beams during Preliminary Testing

Problems Encountered During Testing

Following preliminary testing, a series of problems with the motor and pumping unit prevented the completion of any significant thermal cycling tests. Testing problems culminated when the weekend pump and motor, having enough head to fill the thermocline chamber with molten salt but not to circulate it, pumped the thermocline chamber full of molten salt and held it in place long enough to allow the salt in the base to solidify. This resulted in a solidification of the entire volume of the thermocline test chamber. After experimentation with numerous attempts to free the solidified mass of salt and concrete from the test chamber, a solution was finally found. The thermocline test chamber was inverted and suspended while a rose-bud tipped acetylene torch was used to heat the sides of the tank until the solidified mass fell free. This process is depicted in Figure 14.

Figure 14: Heating Frozen Thermocline Test Chamber (Left) and Cleared Thermocline Chamber with Concrete/Salt Blockage on the Ground (Right)

Following the freeing of the mass from the thermocline test chamber, the motor driving the pump was replaced; however, problems in the pumping unit prevented any full tests from being completed before the end of the project's timeline.

Chapter 7: Summary and Conclusions

Objective 1: *Develop a novel concrete mixture(s) that can withstand operating temperatures of 585 ºC or more and measure the concrete properties.*

- Summary: Numerous concrete mixture designs were developed and tested in the work of John (2012). Four UHP concrete mixture designs were exposed to thermal cycling and isothermal baths in molten salt at temperatures of up to 600˚C and performed favorably. Strasser (2012) reports attempted testing of beam specimens cast from each of these mix designs in the presence of circulating molten salt.
- Conclusions: The concrete mixture designs proposed by John (2012) proved to be chemically and structurally compatible with molten salt when heated and cycled uniformly in an oven. Strasser (2012) reports that no significant conclusions can be drawn from the thermal cycling that was conducted in the thermocline test system, as no full tests were completed.
- Suggested Work: Sustained testing of the concrete mix designs in the presence of circulating molten solar salt before their potential for application in a structured thermocline can be assed.

Objective 2: *Develop novel construction techniques to increase the rate of heat transfer between the heat transfer fluid (HTF) and the concrete, as well as reduce the difference in thermal expansion coefficient between the concrete and reinforcement material.*

- Summary: At the end of Phase 2, the passive storage concept was replaced with the structured concrete thermocline storage concept; as no heat exchangers are used within the concrete in the thermocline concept, the difference in thermal expansion between concrete and stainless steel is no longer a concern. Brown (2012) proposed an axisymmetric and a parallel plate concrete configuration for structured concrete filler material in the thermocline TES system. Brown uses numeric modeling to optimize both configurations and finds that the parallel plate configuration offers the greater efficiency of the two, with a maximum value of 65.59%. Strasser (2012) conducted further modeling and optimized the parallel plate to provide an efficiency of 83.97%.

- Conclusion: Of the two configurations considered, the parallel plate configuration offers the optimum efficiency. Though short of the target system efficiency of 93%, Strasser's reported system efficiency of 83.97% is very promising. Further modeling may lead to the development of configuration providing the desired efficiency.
- Suggested Work: Conduct further modeling efforts to determine if the efficiency of the structured concrete thermocline can be improved.

Objective 3: *Develop a computer model to perform parametric studies during charging and discharging.*

- Summary: A computer model was developed to study and optimize the configuration of structured concrete filler material for a structured concrete thermocline TES system. See Objective 2 above for further information.

Objective 4: *The outcome of the project is to reduce the cost of thermal energy storage from \$25/ $kWh_{thermal}$ using concrete to 2020 goal of costs below \$15/$kWh_{thermal}$ and achieve round trip efficiency greater than 93%.*

- Summary: A structured concrete thermocline is suggested to replace two-tank and packed bed thermocline TES systems. Cost analysis performed in the work of Strasser (2012) indicates that a structured concrete thermocline TES system provides storage at the capacity cost of \$33.80/$kWh_{thermal}$. Strasser also reports an optimized concrete thermocline providing an efficiency of 83.97%.
- Conclusions: Both the cost and efficiency of the structured concrete thermocline TES system optimized in this work fall short of the target goals. Further optimization of the concrete geometry and other system parameters can lead to increased system efficiency. However, it is not possible for a structured concrete thermocline to meet the target capacity cost of \$15/$kWh_{thermal}$ considering the specified temperature limit of 585˚C. TES system component cost, other than media costs, render this target unattainable.
- Suggested Work: In the TES system cost analysis performed in the work of Strasser (2012), it can be seen that the concrete and molten salt used as energy storage media represent a fraction of the cost of TES systems. Though using less costly storage media may reduce TES costs by a small amount, it will not significantly impact the cost of the system. At this point, it is suggested that alternative storage configurations will be required to achieve the DOE's target goal of \$15/$kWh_{thermal}$ by the year 2020.

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Thesis and Dissertation Publications

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Castro, M. (2010). *3-D FEM Model to Study and Improve the Heat Transfer in Concrete for Solar Thermal Energy Storage (Master's Thesis).* Fayetteville: University of Arkansas.

John, E. E. (2012). *The Development of a High Performance Concrete to Store Thermal Energy for Concentrating Solar Power Plants (Doctoral Disseration).* Fayetteville: University of Arkansas.

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Conference Proceedings

Brown, B., Strasser, M., & Selvam, R. P. (2012).“Development of a Structured Concrete Thermocline Thermal Energy Storage System”. *World Renewable Energy Forum.* Denver: ASES.

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Project Team

<u>Project Management</u>

- R. Panneer Selvam (PI)
- Micah W. Hale (CO-PI)

<u>Graduate Researchers</u>

- Marco Castro (MS, August 2010)
    - Used numeric modeling to investigate various fin configurations for heat exchangers imbedded in concrete prisms.
- Joel Skinner (MS, May 2011)
    - Conducted testing of concrete prisms with imbedded heat exchangers.
    - Conducted finite element modeling to investigate impact of soft interface materials at concrete/heat exchanger interface.
- Bradley Brown (MS, December 2011)
    - Assisted in testing of concrete prisms with imbedded heat exchangers.
    - Conducted modelling to select geometry for structured concrete material for structured concrete thermocline concept.
- Emerson John (PhD, May 2012)
    - Developed and tested concrete for storage concept of prisms with imbedded heat exchangers.
    - Developed and tested concrete for structured concrete thermocline.
- Matt Strasser (MS, December 2012)
    - Optimized geometry of structured concrete for structured concrete thermocline.
    - Conducted cost and performance analysis of TES configurations for a CSP plant.
    - Worked of testing of concrete mix designs in lab scale TES system.
- Piotr Gorecki
    - Assisted in testing of concrete mix designs in lab scale TES system.

<u>Technicians</u>

- Mark Kuss
  - Supported by the University of Arkansas civil engineering department.
- David Peachee
  - Supported by the DOE and the University of Arkansas civil engineering department.

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